State of Florida
Department of Transportation

HIGH RECLAIMED ASPHALT PAVEMENT (RAP) ASPHALT MIXES FOR LOW VOLUME ROADS

BE194

FINAL REPORT

NOVEMBER 2018

Submitted by the
TEXAS A&M TRANSPORTATION INSTITUTE

DISCLAIMER

CONVERSION TABLE

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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16. Abstract

The Florida Department of Transportation yearly maintenance and rehabilitation activities include milling and resurfacing of approximately 2,000 lane miles of roadway, with an average resurfacing depth of about 2.1 inches (55 mm). These activities result in the generation and accumulation of roughly 1.8 million tons of reclaimed asphalt pavement (RAP) each year. The use of elevated quantities of RAP in low volume roads provides an environmentally responsible solution to the accumulated RAP surplus in some urban areas, while at the same time offering an economical pavement maintenance and rehabilitation option to local agencies facing budget constraints. The objective of this project was to develop mix design guidelines for mixtures with high RAP contents to be used on low volume roads (average daily traffic < 750 vehicles). To accomplish this objective, three types of high RAP mixtures were considered, having RAP contents ranging from 60 percent–100 percent: hot, cold with emulsion, and cold with foamed binder. Performance testing included moisture susceptibility, rutting, intermediate temperature cracking, durability, and stiffness. The hot recycled mixtures showed good moisture susceptibility and cracking resistance, especially when recycling agents were incorporated. The cold recycled mixtures showed poor moisture susceptibility and durability characteristics, which were alleviated when hydrated lime or Portland cement was incorporated in the emulsified and foamed mixtures, respectively. Most hot recycled mixtures, and all the cold recycled mixtures, exhibited poor rutting behavior. A first-cost and life-cycle cost analysis demonstrated significant savings when increased amounts of RAP were incorporated in the recycled mixtures.

17. Key Words

Reclaimed Asphalt Pavement, Hot Recycling, Cold Recycling, Emulsion, Emulsified Binder, Foaming, Foamed Binder, Low Volume Roads, Mix Design, Performance Testing

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EXECUTIVE SUMMARY

The benefits of using reclaimed asphalt pavement (RAP) in asphalt pavements include economics, conservation of natural resources (aggregate, binder, fuel), reductions in energy consumption, and decreases in emissions (including greenhouse gases). In contrast, the incorporation of elevated quantities of RAP in asphalt pavements presents several challenges, such as the variability of the RAP, design methodology, and adequate long-term performance. Thus, the environmental and economic benefits must be weighed against the potential increased risks associated with construction and short- and long-term performance issues to ensure the engineering benefits of high RAP mixtures can be realized.

The Florida Department of Transportation yearly maintenance and rehabilitation activities include milling and resurfacing approximately 2,000 lane miles of roadway, with an average resurfacing depth of about 2.1 inches (55 mm). These activities result in the generation and accumulation of roughly 1.8 million tons of RAP each year. The use of elevated quantities of RAP in low volume roads could provide an environmentally responsible solution to the accumulated RAP surplus in some urban areas, while at the same time offering an economical pavement maintenance and rehabilitation option to local agencies facing budget constraints. Florida county representatives and other agency representatives expressed their interest in searching for an economical solution to (a) paving unpaved roads and (b) resurfacing existing low volume roads.

Currently, there is no national standard method for a mix design of high RAP mixtures. In addition, most of the mix design procedures currently available were developed when recycled materials and other additives were not predominant components of mixtures. Today, with the incorporation of modified binders, additives, recycling agents, and recycled materials, conventional mix design approaches do not always yield mixtures that perform adequately. Many state agencies are now advocating for the application of a *balanced mix design* approach that includes not only volumetric factors but also an evaluation of rutting, cracking, and moisture susceptibility of the mixtures.

Therefore, the objective of this project was to develop guidelines for the design of pavement layers employing high quantities of RAP (e.g., 60 percent–100 percent) to be used on low volume roads (i.e., roads having an average daily traffic less than 750 vehicles).

To accomplish this objective, three types of high RAP mixtures were considered in this project: hot, cold with emulsion, and cold with foamed binder. Typical virgin aggregates (granite and limestone), RAP sources (limestone and granite/limestone), binders (performance grade [PG] 52-28 and PG 67-22), and emulsion (CSS-1H) from the state of Florida were procured and shipped to the Texas A&M Transportation Institute for material characterization, mixture preparation, and performance testing.

For the hot recycled mixtures, only 60 percent RAP content was considered, and different types of recycling agents were evaluated to assess their effectiveness with aging. One petroleum-based product that has been used successfully in the past in Florida and one organic-based product were selected for further mixture preparation and testing. Performance testing included moisture susceptibility, rutting, intermediate temperature cracking, and stiffness.

For the cold recycled mixtures, 60 percent, 80 percent, and 100 percent RAP amounts were considered. The optimum moisture content, curing, and emulsion/foamed binder contents were determined for each case using the indirect tensile (IDT) strength test. Performance testing for these mixtures included moisture susceptibility, rutting, durability, and stiffness.

The laboratory test results showed that all hot recycled mixtures (unconditioned and moisture conditioned) had adequate moisture susceptibility performance with respect to the minimum IDT strength and tensile strength ratio criteria. In addition, most of the hot recycled mixtures fabricated with limestone RAP and granite virgin aggregate did not show evidence of stripping in the Hamburg wheel tracking test. However, most hot recycled mixtures experienced accelerated rutting, reaching the maximum rut depth of 12.5 mm in less than 5,000 load cycles. In contrast, the hot recycled mixtures with recycling agents improved their intermediate temperature cracking resistance (flexibility index) and decreased their stiffness.

The emulsified cold recycled mixtures with higher RAP contents were moisture susceptible. Mixtures with limestone RAP and virgin aggregate showed better moisture susceptibility compared to mixtures with granite/limestone RAP with granite virgin aggregate. The inclusion of hydrated lime in cases of poor moisture susceptibility helped alleviate the performance issue. All mixtures experienced accelerated rutting at early load cycles. The rut depth failure criteria of ½ inch (12.5 mm) was reached in less than 5,000 load cycles in all cases. In addition, high Cantabro mass loss and low stiffness were observed in mixtures with granite virgin aggregate.

In the case of the foamed cold recycled mixtures, the unconditioned specimens yielded IDT strengths that barely met the minimum requirement, and none of the mixtures met the minimum requirement after moisture conditioning. Adding Portland cement to the mixtures with low IDT strength was helpful in increasing their strength and was not detrimental to their moisture resistance. All mixtures experienced accelerated rutting at early load cycles. The rut depth failure criteria of ½ inch (12.5 mm) was reached in less than 2,500 load cycles by nearly all mixtures. In addition, all mixtures presented poor durability, with considerably higher Cantabro mass loss.

A *first-cost* comparison was conducted for new pavement construction and two hypothetical rehabilitation scenarios involving various deterioration conditions, materials, and thicknesses for surface layers. According to the results, savings on the order of 20 percent to 50 percent were possible when cold recycling was compared to removal and replacement of pavement regarding first-cost savings based on equivalent structural pavement sections.

Further, a life-cycle cost analysis (LCCA) was conducted using data from four recycled mixtures with limestone RAP and limestone virgin aggregate: (a) hot recycled with 60 percent RAP, (b) foamed cold recycled with 60 percent RAP, (c) foamed cold recycled with 80 percent RAP, and (d) foamed cold recycled with 100 percent RAP. The purpose of this evaluation was to compare hot versus cold recycled mixtures as well as RAP content. Additional laboratory tests, including dynamic modulus, flow number, and Texas overlay tests, were performed and used in the Texas Mechanistic-Empirical analysis software to predict service life. This information was combined with a cost analysis performed using the Federal Highway Administration RealCost software to perform the LCCA. The most favorable option was the foamed cold recycled mixture with 100 percent RAP content.

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I. INTRODUCTION

The Florida Department of Transportation (FDOT) yearly maintenance and rehabilitation activities include milling and resurfacing approximately 2,000 lane miles of roadway, with an average resurfacing depth of about 2.1 inches (55 mm). These activities result in the generation and accumulation of roughly 1.8 million tons of reclaimed asphalt pavement (RAP) each year. Some of this RAP gets recycled as hot-mix asphalt (HMA) component, stabilizing subgrade material used as a base for non-trafficked shoulders, or employed in other FDOT cold and hot asphalt applications. However, FDOT is not able to incorporate all generated RAP back into its roadways. The use of elevated quantities of RAP in low volume roads could provide an environmentally responsible solution to the accumulated RAP surplus in some urban areas, while at the same time offering an economical pavement maintenance and rehabilitation option to local agencies facing budget constraints.

Therefore, the objective of this project was to develop guidelines for the design of pavement layers employing high quantities of RAP (e.g., 60 percent–100 percent) to be used on low volume roads. FDOT defines low volume roads as those having an average daily traffic (ADT) of less than 750 vehicles. According to the 2014 Federal Highway Administration (FHWA) Highway Statistics, Florida has 36,508 rural and 85,883 urban miles (Table 1), of which about 60 percent and 98 percent are paved, respectively (Table 2 and Figure 1). Bituminous, concrete, and composite pavements are included under the *Paved* category.

Table 1. Total Length by Functional System in Florida (Table HM-57, FHWA 2014)

Functional System	Rural (mi)	Urban (mi)	Total (mi)
Interstate	717	778	1,495
Other Freeways & Expressways	173	573	746
Other Principal Arterials	2,620	3,974	6,594
Minor Arterial	2,191	4,201	6,392
Major Collector	4,015	6,419	10,434
Minor Collector	3,207	1,864	5,071
Local	23,586	68,074	91,659
Total Length (mi)	36,508	85,883	122,391
% of Total Length	29.8%	70.2%	100%

Table 2. Paved Length by Functional System in Florida (Table HM-51, FHWA 2014)

Functional System	Rural (mi)	Urban (mi)	Total (mi)	% Paved
Interstate	717	777	1,494	100
Other Freeways & Expressways	173	567	740	99
Other Principal Arterials	2,620	3,973	6,593	100
Minor Arterial	2,191	4,183	6,374	100
Major Collector	4,015	6,379	10,394	100
Minor Collector	3,149	1,729	4,878	96
Local	8,915	66,712	75,628	83
Total Paved (mi)	21,780	84,320	106,100	87
% Paved of Total Length	60	98	87	–

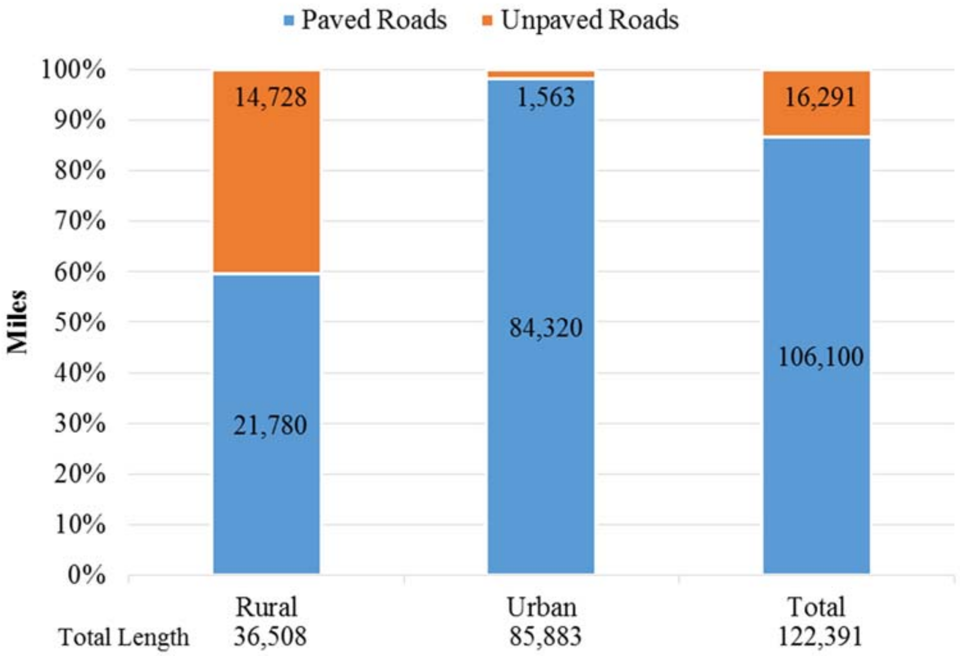


Figure 1. Paved and Unpaved Proportions for Rural and Urban Roadways in Florida (Table HM-51, FHWA 2014)

Table 3 presents the length in miles per type of functional system with an ADT less than 1,000 vehicles. According to these values, 1,336 miles, or 3.7 percent, of the total rural and 363 miles, or 0.4 percent, of the total urban functional systems carry this level of traffic.

Table 3. Length by Functional System with Less Than 1,000 ADT in Florida (Table HM-57, FHWA 2014)

Functional System	Rural (mi)	Urban (mi)	Total (mi)	% ADT < 1,000
Interstate	–	–	–	–
Other Freeways & Expressways	–	–	–	–
Other Principal Arterials	20	–	20	0.3
Minor Arterial	105	14	119	1.9
Major Collector	1,210	232	1,442	13.8
Minor Collector	–	118	118	2.3
Local	–	–	–	–
Total (mi)	1,336	363	1,699	
% of the Total Length	3.7	0.4	1.4	

– : data not available.

II. BACKGROUND

The benefits of using RAP in asphalt pavements include economics, conservation of natural resources (aggregate, binder, fuel), reduction in energy consumption, and a decrease in emissions (including greenhouse gases) (Robinett and Epps, 2010). In contrast, the incorporation of elevated quantities of RAP in asphalt pavements presents several challenges, such as the variability of the RAP, the design methodology, and adequate long-term performance. Thus, the environmental and economic benefits must be weighed against the potential increased risks associated with construction and short- and long-term performance issues to ensure the engineering benefits of high RAP mixtures can be realized.

Two major concerns regarding the use of RAP in asphalt pavements are its variability and the level of aging of the RAP binder. To address the variability issue, researchers have proposed best practices related to stockpile processing, mix design, plant production, and field construction (Copeland 2011; West et al., 2013; Zhou et al., 2010; Zhou et al., 2011). With regard to the level of aging, the rheology of the binder extracted from the RAP is usually determined, and softer virgin binders (with or without polymer modification) and/or recycling agents are added to restore the stiffness of the recycled binder blend to the target binder performance grade (PG) (i.e., the binder PG that would be specified based on climate and traffic conditions). Incorporating warm-mix additives or foaming technologies or producing the mixtures via cold process could preclude additional aging of the RAP and virgin materials employed in the mixture; however, the availability of the RAP binder, the degree of blending of the virgin and recycled binders, and the compatibility between the materials and additives need to be considered.

The properties of the RAP vary depending on the characteristics of the exiting pavement, the method used to remove the RAP, and the type of processing after removal. In Florida, samples of raw (i.e., milled) and processed (i.e., crushed) RAP from 50 geographic locations across the state showed variations in average binder content (determined by the ignition oven method) of between 3.5 percent–11.0 percent (Cosentino et al., 2014). Binder contents for typical milled RAP ranged between 5.5 percent–8.0 percent, while typical values for crushed RAP were between 4.5 percent–7.0 percent. Moreover, the binder content of RAP materials obtained from state highways ranged from 6.1 percent–7.5 percent, and the Big Bend and Tallahassee regions had higher RAP binder contents than other parts of the state (e.g., 6.8 percent–8.0 percent).

Recycling asphalt pavements is not novel within the pavement community, and guidelines have been established for hot and cold recycling of asphalt pavements in previous studies (Epps et al., 1980; Epps 1990; McDaniel and Anderson, 2001; National Cooperative Highway Research Program [NCHRP] 1978; Stroup-Gardiner, 2011, 2016; West and Copeland, 2015). Asphalt recycling and reclaiming methods have been classified in five broad categories, as shown in Figure 2. Hot and cold recycling are methodologies to produce pavement layers that can be used as base or surface courses where the resulting mixture contains RAP at a defined percentage. The difference between both procedures is the temperature at which the mixture components are processed; hot recycling uses heat while cold recycling is conducted at ambient temperature.

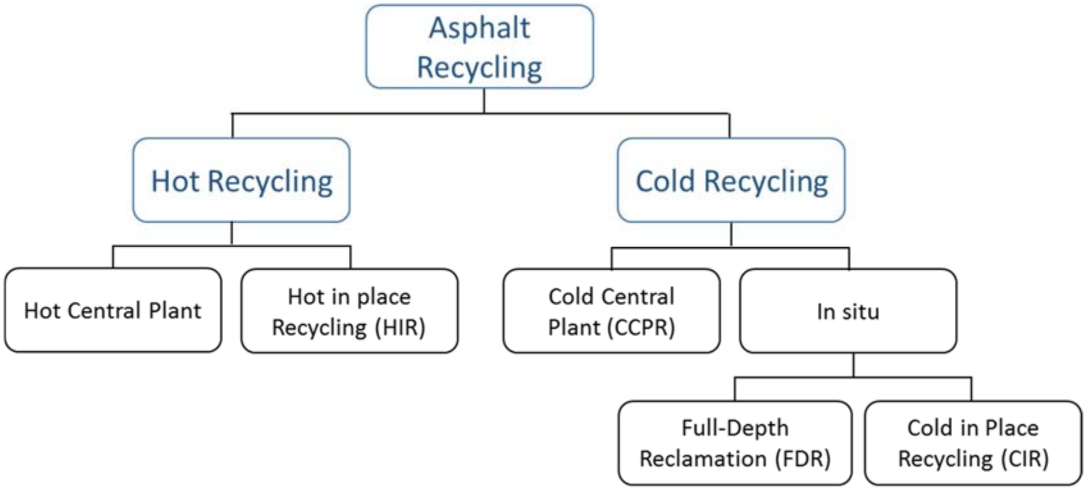


Figure 2. Asphalt Recycling and Reclaiming Methods (Adapted from Asphalt Recycling and Reclaiming Association [ARRA], 2015)

At the beginning of the project, FDOT's Technical Committee, Florida county representatives, and other agency representatives expressed their interest in searching for an economical solution to (a) paving unpaved roads and (b) resurfacing existing low volume roads. Several options, listed in Table 4, were outlined and input from Florida's county representatives was requested via survey. Their answers are shown in Appendix A.

Table 4. Proposed Improvement Strategies for Low Volume Roads

Type of Existing Roadway	Improvement Strategy
Soil/Base surfaced roadway (not hard surfaced)	SC-RAP: Spread and Compacted RAP with or without aggregate base addition (no emulsion or foamed binder stabilization).
	Full-Depth Reclamation (FDR): cold full-depth in-place recycling (includes untreated base or subgrade materials) with emulsion, foamed binder, or other stabilizer with or without RAP addition.
	CCPR: cold central plant recycling of RAP with or without aggregate base addition with emulsion or foamed binder.
Thin asphalt-bound surface with limited base material	FDR: cold full-depth in-place recycling (includes all asphalt-bound materials plus untreated base or subgrade materials) with emulsion, foamed binder or other stabilizer with or without RAP addition.
	Pulverize existing surface/compact and add cold central plant recycling (CCPR).
	Pulverize existing surface/compact and add SC-RAP.
Thick asphalt-bound surface with aggregate base course	CIR: cold partial depth in-place recycling (asphalt-bound materials only) with emulsion or foamed binder.
	FDR: cold full-depth in-place recycling (includes all asphalt-bound materials plus untreated base or subgrade materials) with emulsion or foamed binder.

Based on that input and comments received from FDOT's project director and Technical Committee, a literature review was conducted that included the following topics:

1. Summary of mix design and construction considerations for hot and cold recycling.
2. Recent national experience with hot and cold recycling.

3. Review of national specifications.
4. Review of life-cycle cost analysis (LCCA) RealCost software.

A summary of the literature review findings is presented in Chapter III. The experimental plan is described in Chapter IV, and the results of the hot and cold recycled mixtures (emulsion and foamed binder) are given in Chapters V through VII. Chapter VIII details the LCCA of selected hot and cold recycled mixtures. Further, Chapter IX summarizes and compares the laboratory test results. Conclusions are offered in Chapter X, followed by References and Appendices.

III. LITERATURE REVIEW

III.1. Hot Recycling

Hot recycling is a technique in which a portion of the mixture that is prepared to pave or maintain an existing road is comprised of RAP and processed at warm or hot mixing and compaction temperatures. Two types of hot recycling are usually identified: hot central plant and hot in-place recycling (HIR; see Figure 2). Hot central plant recycling refers to the use of RAP and virgin aggregates, virgin binder, and/or recycling agents in plant-produced mixtures. HIR utilizes the same mixture components as the plant-produced mixtures in hot central plant recycling; the difference is that the pavement is heated and scarified on-site. Therefore, the RAP may be obtained in-place by heating and scarifying the existing pavement or hauled from existing stockpiles. Soft binders with or without recycling agents are added to the RAP and virgin materials to improve the characteristics of the mixture.

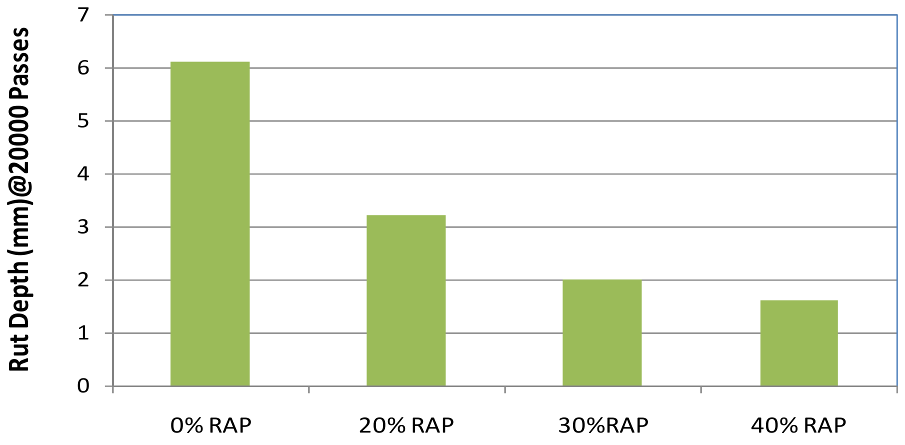
The main advantages of hot recycling include (ARRA, 2015):

- Conserving natural resources.
- Decreasing energy consumption.
- Reducing costs by limiting the need of virgin materials.

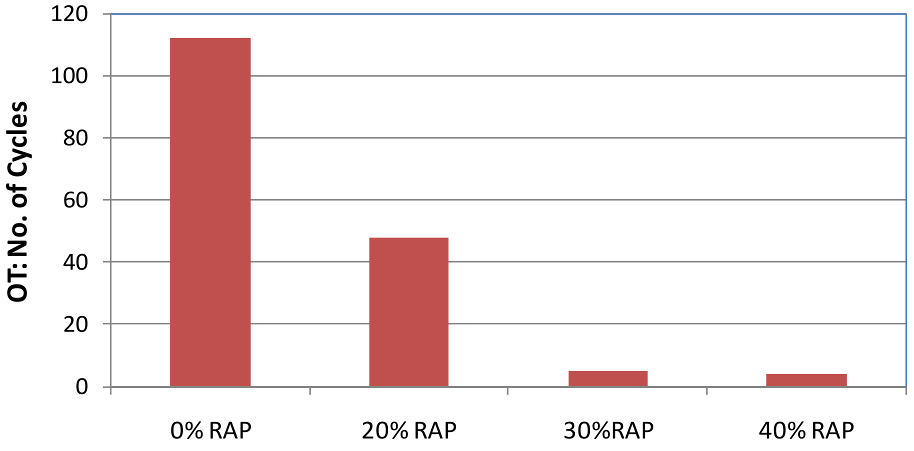
The concern regarding the performance of mixtures that employ large quantities of RAP is their ability to resist cracking and, to a lesser extent, raveling. The laboratory performance of recycled mixtures has been extensively evaluated using a variety of tests, including resilient and dynamic modulus, indirect tensile strength, flexural fatigue, repeated shear load, flow number, Hamburg, overlay cracking, semicircular bending, and others (Alavi and Hajj, 2013; Daniel et al., 2010; Epps et al., 1980; Hajj et al., 2009; Holmgreen et al., 1982; Kandhal and Mallick, 1997; Li et al., 2008; McDaniel and Anderson, 2001; Mogawer et al., 2012, 2013a, 2013b; Newcomb et al., 1993; West et al., 2009, 2013; Zhou et al., 2011, 2013).

Figure 3 shows an example of the impact of recycled materials on mixture rutting and cracking resistance using the Hamburg wheel tracking test (HWTT) and the Texas overlay test. These results illustrate that the use of recycled materials may lead to poor fatigue performance (fewer cycles), although rutting resistance is improved. It is noteworthy that the magnitude of the influence of the RAP content on the performance parameters presented in Figure 3 is particular to that research project and that different levels of influence are plausible and have been observed.

Furthermore, the observed field performance of mixtures with recycled materials also confirms their cracking susceptibility (Anderson, 2010; Bennert and Maher, 2013; Hong et al., 2010; West et al., 2011; Zhou et al., 2011), although in most cases these mixtures have similar performance to virgin mixtures in terms of rutting, International Roughness Index, block cracking, and raveling (West et al., 2011).



(a)



(b)

Figure 3. Impact of Increasing Quantities of RAP on Performance: (a) Rutting and (b) Cracking (Zhou et al., 2011)

Asphalt pavements become more susceptible to cracking when the asphalt coating the aggregate particles becomes brittle, which usually occurs with aging. Since the RAP materials are obtained from asphalt pavements that have already been in service for a certain period, the asphalt in the RAP has aged. Extracted binder from RAP materials shows an elevated high-temperature performance grade (PGH) between 80°C and 100°C or more, which is significantly higher than the PGH of a virgin binder (Zhou et al., 2015).

In order to avoid cracking and other performance issues in the recycled mixture, it is important to measure the rheological properties (i.e., stiffness and phase angle at high, intermediate, and low temperatures) of the RAP binder and attempt to restore them to the level of the virgin binder. The stiffness and phase angle of the RAP binder can be measured at a set temperature and frequency (e.g., 59°F and 0.005 rad/s), and represented in a Black space diagram like the one shown in Figure 4. Each point in Figure 4 represents the stiffness and phase angle of a binder with no aging, rolling thin-film oven (RTFO) aging, and various pressurized aging vessel (PAV) aging levels; with further aging, the stiffness increases, and the phase angle decreases. It is important to note that the two asphalts depicted in Figure 4 start at different locations in the Black space diagram and have a different rate of progression from the lower right to the upper left corner of the diagram.

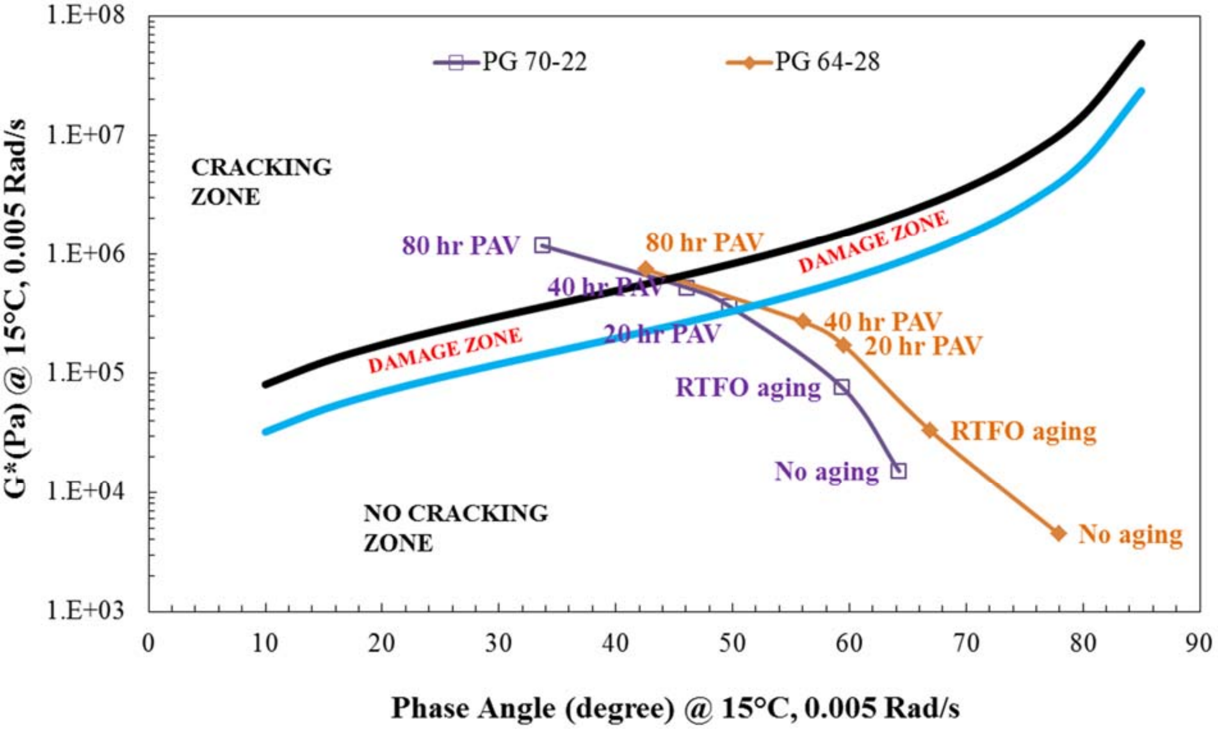


Figure 4. Black Space Diagram for Two Virgin Binders with Various Levels of Aging

Figure 4 also shows a damage zone where cracking likely begins due to embrittlement of the binder. The damage zone is defined by an intermediate temperature dynamic shear rheometer (DSR) parameter called the Glover-Rowe (G-R) parameter, which is set between 180–600 kPa and correlates to low asphalt ductility values of 5 cm to 3 cm, respectively, for field sections located in a PG 58-28 climate (Glover et al., 2005; Kandhal, 1977). These limits were previously related to surface raveling and cracking by Kandhal (1977). Glover et al. (2005) originally defined the G-R parameter as $(G'/(\eta'/G'))$, and it was reformulated for practical use by Rowe (2011) in a discussion of Anderson et al. (2011) as $G'/(\eta'/G') = G^* \times (\cos \delta)^2/(\sin \delta)$. In Figure 4, the data point for the PG 64-28 binder with no aging is located lower and further in the right corner of the diagram, and it requires more than 40 hours of PAV aging to reach the damage zone. In the case of the PG 70-22 binder, only 20 hours of PAV aging are required to reach the damage zone.

Anderson et al. (2011) and Hanson et al. (2010) also recognized the importance of phase angle for cracking resistance characterization of asphalt and used the bending beam rheometer (BBR) to determine the difference between the low temperatures where highly aged binders reach their respective limits of 300 MPa stiffness (S) and 0.30 m-value. This difference in low temperatures is commonly labeled with the term ΔT_c. Although BBR test temperatures are much lower than the temperature where ductility and the G-R parameter are measured, Anderson et al. (2011) showed that ΔT_c correlates well with both. Thus, to characterize the complete rheological behavior of aged binders contained in recycled materials, a DSR or BBR is needed to capture both stiffness (G* or S) and phase angle, or stress relaxation ability (δ or m-value), at intermediate to low temperatures for adequate cracking resistance.

One way to improve the cracking resistance of recycled mixtures is to incorporate higher amounts of virgin binder to increase the mixture's compacted density, reduce water and aging sensitivity, and provide thicker films of asphalt. This method has been reported as effective in laboratory and field studies (Zhou et al., 2011; Zhou et al., 2013). As a result, some agencies specify for mix design purposes a density of 97 percent–98 percent for recycled mixtures as compared to the standard 96 percent for virgin mixtures.

Besides increasing the density of the recycled mixture, the effect of asphalt aging endured by RAP materials can be restored through the addition of soft virgin binders and/or recycling agents. Using a virgin binder with a high phase angle (i.e., S-controlled) has demonstrated better restoring ability than using one with a low phase angle (m-controlled).

In instances of heavily aged RAP asphalts, when the rheological properties align them closer to the upper left corner in the Black space diagram (see Figure 4), it is likely that besides restoration with the addition of a soft virgin binder, the incorporation of a recycling agent is also needed. The primary objectives of recycling agents are to soften or restore the stiffness of the aged recycled materials, add molecular stability to restore the phase angle, and maintain chemical compatibility between the various mixture components. In addition to rheological considerations, the additive must meet the following prescreening criteria: not be (a) hazardous to worker health and safety, (b) volatile per mass loss and flash point specifications, (c) high in wax content such that it precipitates as a wax, (d) chemically incompatible such that asphaltenes precipitate or phase separate over time, and (e) unavailable in sufficient quantities or at a competitive cost.

Much of the early work with recycling agents was done by Rostler and co-workers at Witco/Golden Bear (Rostler and White, 1959; Kari et al., 1980) and led to ASTM D4552 for recycling agents (ASTM, 2010), with six different grades covering a range of blending proportions of byproduct oil from lube processing with a virgin binder to restore stiffness (in terms of viscosity or penetration) while maintaining compatibility. More recent FHWA guidelines (Kandhal and Mallick, 1997) define the following purposes for adding recycling agents to mixtures with recycled materials (Epps et al., 1980; Newcomb et al., 1984; Newcomb and Epps, 1981): (a) to restore the aged binder by decreasing the stiffness for construction purposes and mixture performance in the field; (b) to restore the recycled mixture in terms of durability or resistance to cracking by increasing the phase angle of the binder; (c) to provide sufficient additional binder to coat the recycled and virgin aggregates; and (d) to provide sufficient additional binder to satisfy mix design requirements.

Recycling agents have been successfully employed to improve the cracking resistance of recycled mixtures. Tran et al. (2012) recently evaluated one type of recycling agent and found that it improved the binder and mixture fatigue response. Booshehrian et al. (2013) investigated the impact of three types of recycling agents on performance of recycled mixtures through a variety of laboratory tests, and similar findings were reported. Most recently, Im and Zhou (2013) performed a similar study with three types of recycling agents and found that their effectiveness depended on the type of recycled materials used in the mixture and their proportion.

Ongoing national Project NCHRP 09-58 is looking at ways to increase the amount of recycled materials in the mixture with the use of recycling agents in order to minimize possible negative impacts to performance. Other researchers have also studied the use of recycling agents and polymer-modified binders to improve performance of mixtures with high RAP contents.

Zaumanis et al. (2014), for example, tested the workability and performance of 100 percent RAP mixtures produced with pavement millings of various layers and locations in New Jersey and modified with five generic types (waste vegetable oil, waste vegetable grease, tall oil, aromatic extract, waste engine oil) and one proprietary type (organic oil) of recycling agents. The selected dose for all recycling agents was 12 percent. All recycling agents improved workability of the RAP mixture but not to the level of the virgin mixture. In terms of performance, however, all recycling agents except the waste engine oil improved the fatigue life of the 100 percent RAP mixture without compromising rutting resistance.

Mogawer et al. (2016) also studied the effect of five types of recycling agents (one aromatic, one paraffinic, and three organic) on the performance of a surface mixture with 50 percent RAP. Rutting, fatigue, and low temperature cracking were used as performance indicators. Their findings indicate that a combination of recycling agents and polymer-modified binder yielded the best performance for the 50 percent RAP mixture when compared to the virgin mixture. The use of the polymer-modified binder was particularly important to offset any possible rutting in the 50 percent RAP mixture once the recycling agents were incorporated.

III.1.1. Mix Design Considerations

Most of the mix design procedures currently available were developed when recycled materials and other additives were not predominant components of mixtures, and they provided adequate performance assurance as long as the materials met set specifications. With the incorporation of polymer-modified binders, asphalt additives such as polyphosphoric acid and recycled engine oil bottoms, warm-mix additives, as well as significant amounts of various types of recycled materials, the conventional mix design approaches do not always yield mixtures that perform adequately in terms of cracking and/or raveling.

About a decade ago, the *balanced mix design* procedure was developed for the Texas Department of Transportation (TxDOT) and included (a) volumetric factors, (b) rutting and moisture susceptibility, and (c) cracking of mixtures. The procedure illustrated in Figure 5 considers a blend of virgin aggregate and RAP to a specified gradation and various binder contents to prepare compacted specimens. The asphalt content that achieves a 98 percent density is considered the maximum allowable to prevent rutting and bleeding. Then, mixtures with a minimum of three asphalt contents in 0.5 percent decrements from the maximum value are prepared for performance testing at a density of 93 percent. Further, the asphalt contents corresponding to 300 overlay test cycles and 12.5 mm of rutting in the HWTT are determined, and the highest value of binder content is selected while not exceeding the maximum allowable value based on the 98 percent density criteria.

Since the recycled mixture field performance is influenced by factors other than just the properties of the mixture, such as traffic, climate, pavement structure, and existing pavement conditions, it would be impractical to set a unique threshold for the performance tests used in the balanced mix design procedure. Rather, the cracking, rutting, and moisture susceptibility requirement should be determined for each specific project's conditions. TxDOT employs a simplified asphalt overlay design program called S-TxACOL to account for traffic, weather, pavement structure, and material properties to predict cracking performance of asphalt pavements. The output of the program is the number of overlay test cycles to guarantee adequate performance for a set number of months in service for a specific combination of pavement location, weather, traffic, and pavement conditions.

An example of the performance evaluation portion of the balanced mix design procedure is shown in Figure 6. Three binder contents were evaluated. First, the binder content to achieve a maximum density of 98 percent was determined to be 5.4 percent (Figure 6a). Then, specimens were prepared for three binder contents (5.4 percent, 4.9 percent, and 4.4 percent) and compacted at a 93 percent density in order to conduct the overlay test (OT) and HWTT. The HWTT shows that 0.5 inches (12.7 mm) of rutting corresponds to 5.3 percent binder (Figure 6b), while the OT shows that 300 cycles corresponds to 4.9 percent binder (Figure 6c). Therefore, 5.3 percent was selected as the balanced binder content for this example.

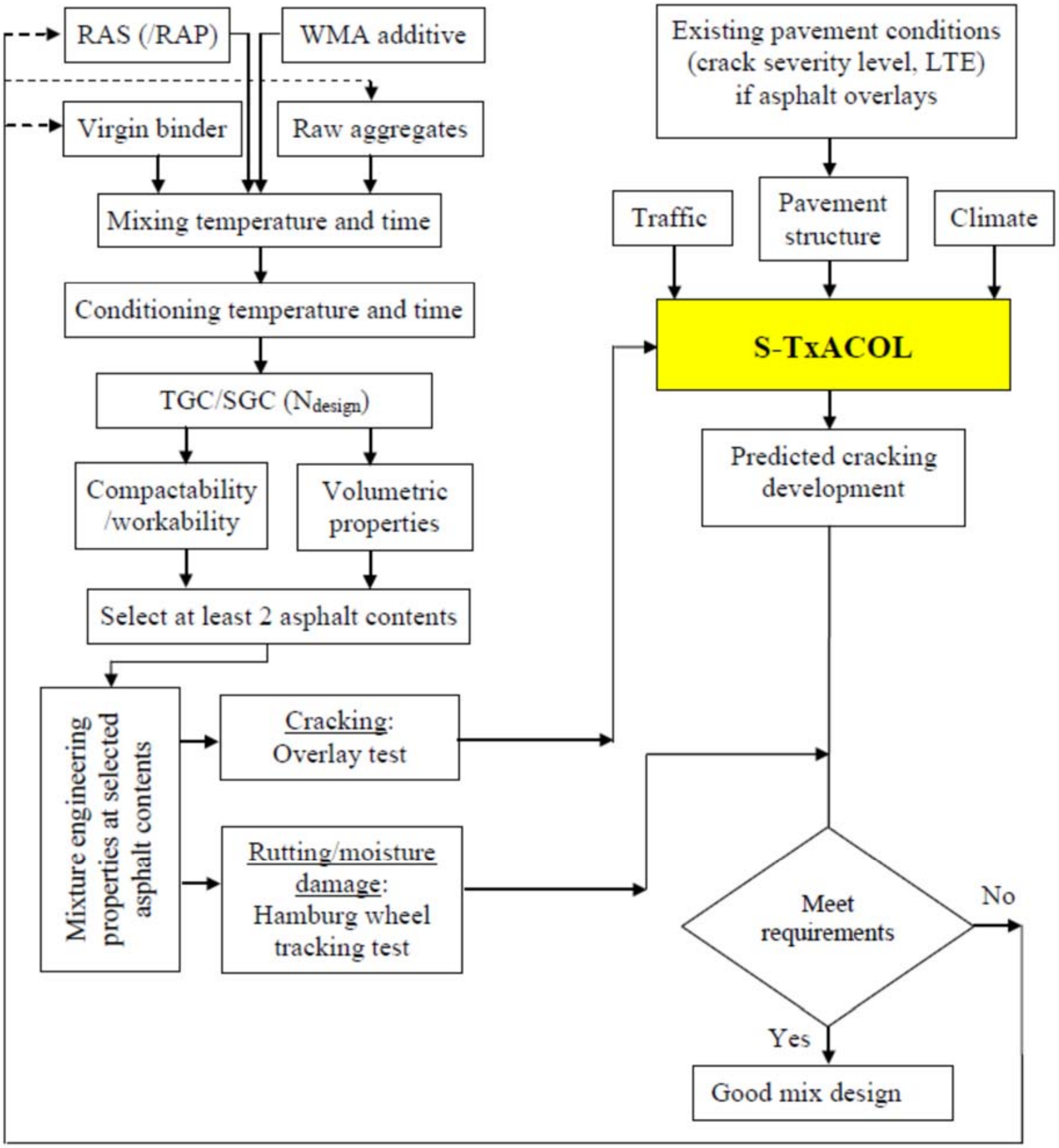


Figure 5. Balanced Mix Design and Performance Evaluation Procedure (Zhou et al., 2013)

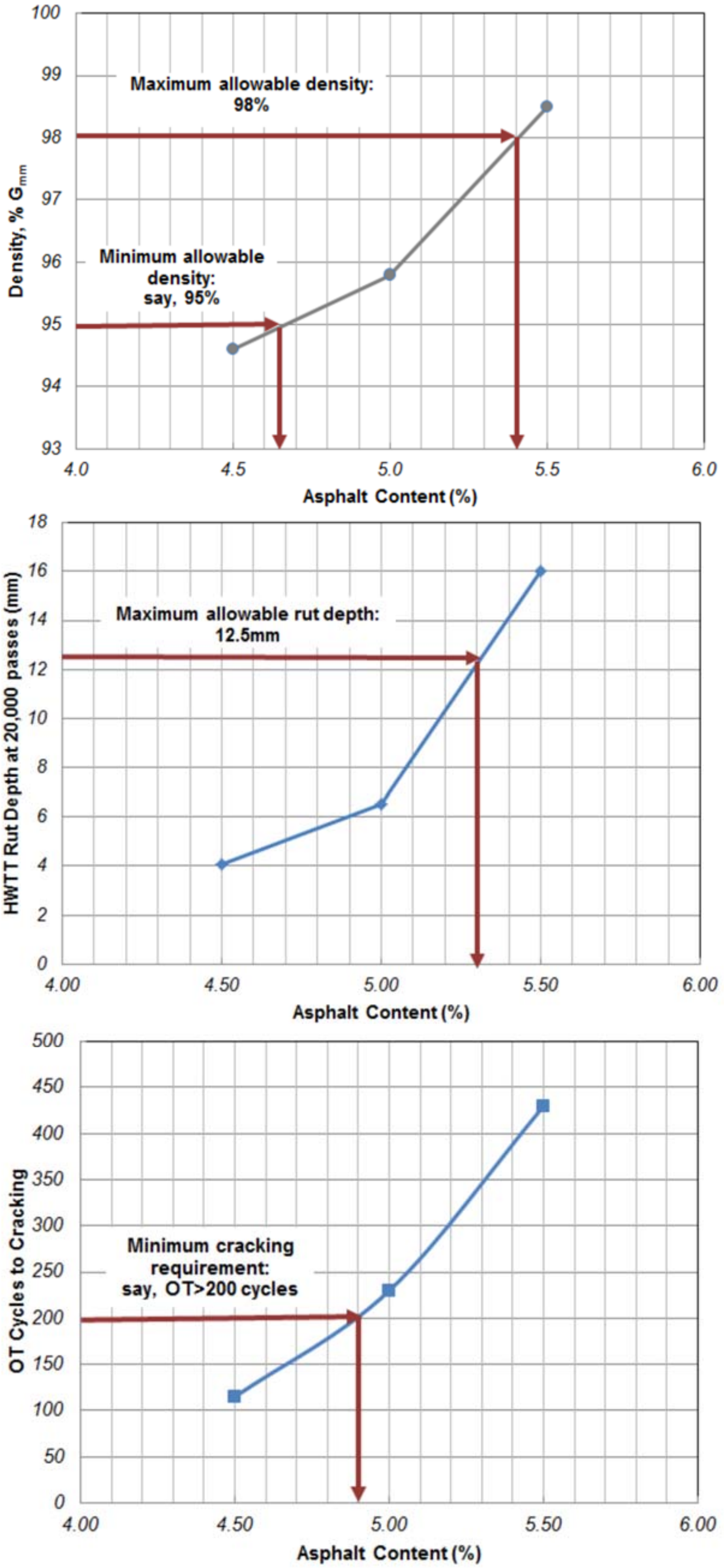


Figure 6. Balanced Mix Design Performance Evaluation Example

Currently, there is no national standard method for mix design of hot recycled mixtures. In general, the goal of the mix design is to select an optimum binder content while restoring the properties of the existing aged asphalt pavement to those of the virgin mixture. Usually a set of steps as shown in Figure 7 are followed.

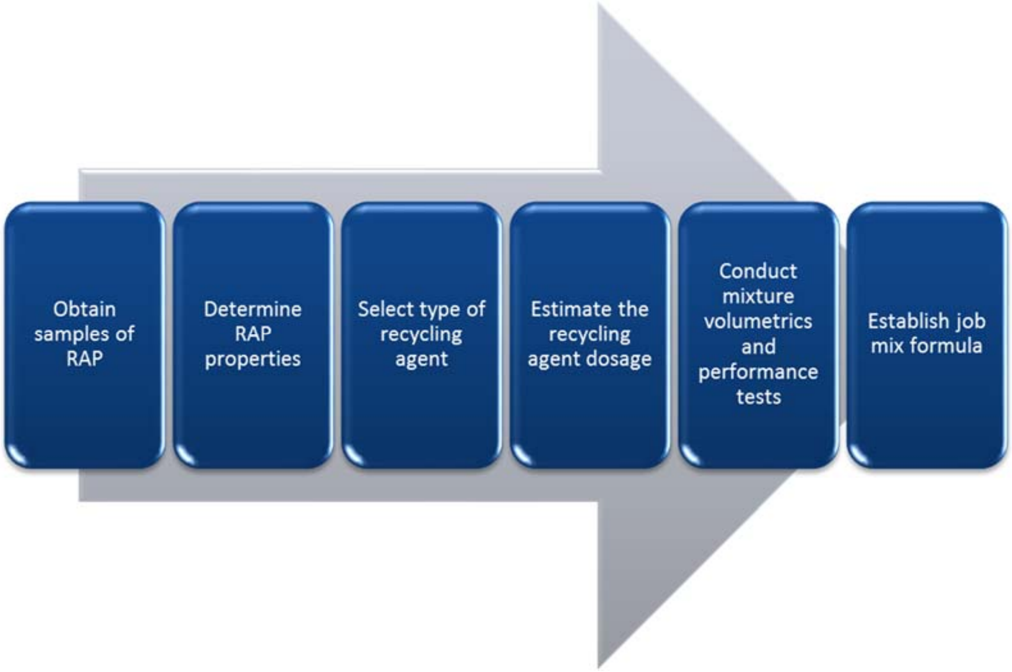


Figure 7. General Mix Design Procedure for Hot Recycling

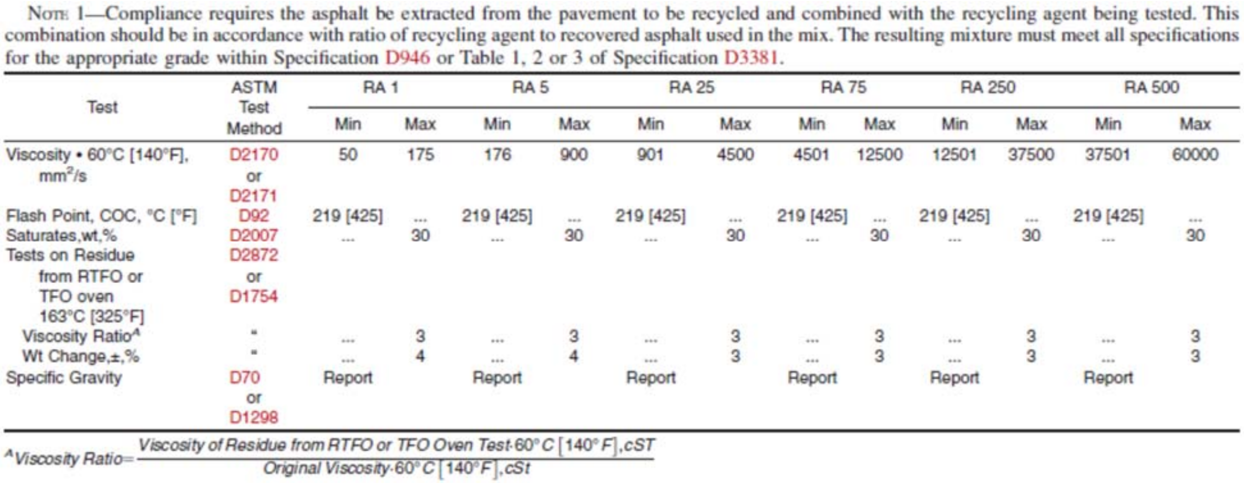
III.1.1.1. RAP Sampling and Characterization

Representative samples of RAP are obtained and tested to determine its characteristics. If HIR is used, the RAP is acquired through heating and scarification of an existing pavement, and samples are obtained every half-mile along the length of the project. Otherwise, RAP stockpiles are sampled using similar principles to the ones followed when sampling aggregate stockpiles (American Association of State Highway and Transportation Officials [AASHTO] T 2): using power equipment to develop a separate sampling pile and using material drawn from the top third, the middle, and bottom third of the main stockpile while avoiding the outer layer of the stockpile.

The RAP material is mainly characterized by means of tests, like (a) moisture content, (b) gradation, (c) binder content, and (d) recycled binder grade. RAP gradation and binder content are obtained via ignition oven method (AASHTO T 308) while the recycled binder grade is established after solvent extraction (AASHTO T 164 or ASTM D2172) and recovery (ASTM D1856 or ASTM D5404) of the recycled binder from the RAP. Likewise, some other RAP properties are often determined, like maximum gravity (AASHTO T 209), aggregate gravity (FM 1-T084), and binder viscosity (AASHTO TP 48-97).

III.1.1.2. Recycling Agent Type and Dose

ASTM D4552 provides a standard classification for recycling agents using six groups as shown in Figure 8. The choice of the recycling agent group usually depends on the hardness of the recycled binder; RA1, RA 5, RA 25, and RA 75 are considered suitable for mixtures with high quantities of RAP. A more recent classification of recycling agents, along with some of the names of commercially available products, is listed in Table 5.



NOTE 1—Compliance requires the asphalt be extracted from the pavement to be recycled and combined with the recycling agent being tested. This combination should be in accordance with ratio of recycling agent to recovered asphalt used in the mix. The resulting mixture must meet all specifications for the appropriate grade within Specification D946 or Table 1, 2 or 3 of Specification D3381.

Test	ASTM Test Method	RA 1		RA 5		RA 25		RA 75		RA 250		RA 500	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Viscosity • 60°C [140°F], mm²/s	D2170 or D2171	50	175	176	900	901	4500	4501	12500	12501	37500	37501	60000
Flash Point, COC, °C [°F]	D92	219 [425]	...	219 [425]	...	219 [425]	...	219 [425]	...	219 [425]	...	219 [425]	...
Saturates,wt,%	D2007	...	30	...	30	...	30	...	30	...	30	...	30
Tests on Residue from RTFO or TFO oven 163°C [325°F]	D2872 or D1754												
Viscosity Ratio[A]	"	...	3	...	3	...	3	...	3	...	3	...	3
Wt Change,±,%	"	...	4	...	4	...	3	...	3	...	3	...	3
Specific Gravity	D70 or D1298	Report		Report		Report		Report		Report		Report	

$$^{A}\text{Viscosity Ratio} = \frac{\text{Viscosity of Residue from RTFO or TFO Oven Test} \cdot 60^{\circ}C\,[140^{\circ}F], cST}{\text{Original Viscosity} \cdot 60^{\circ}C\,[140^{\circ}F], cSt}$$

Figure 8. Physical Properties of Hot-Mix Recycling Agents (ASTM, 2010)

Table 5. Common Types of Recycling Agents (National Center for Asphalt Technology [NCAT], 2014)

Category	Types	Description
Paraffinic Oils	Waste Engine Oil Waste Engine Oil Bottoms Valero VP 165® Storbit®	Refined, used lubricating oils
Aromatic Extracts	Hydrolene® Reclamite® Cyclogen L® Valero 130A®	Refined crude oil products with polar aromatic oil components
Napthenic Oils	SonneWarmix RJ™ Ergon HyPrene®	Engineered hydrocarbons for asphalt modification
Triglycerides & Fatty Acids	Waste Vegetable Oil Waste Vegetable Grease Brown Grease Oleic Acid	Derived from vegetable oils
Tall Oils	Sylvaroad™ RP1000 Hydrogreen®	Paper industry by-products. Same chemical family as liquid anti-strip agents and emulsifiers

Other common sources of recycling agents include:

- Aliphatic, Naphthenic, and Paraffinic Rubber Processing Oils—These by-products of lube oil production are good candidates because they are not very volatile, likely compatible with binders at lower concentrations, and likely low in wax content.
- Maltenes and Resins from Solvent De-Asphalting—These potential recycling agents are left after butane or pentane precipitates the asphaltenes from refinery vacuum tower bottoms.

- Re-Refined Waste Lube Oils—While lube oils are too expensive, recovered and recycled lube oils from diesel train engines are good candidates in terms of performance as long as compatibility is assessed, especially at higher concentrations in highly aromatic binders.
- Derivatives of Lipid-Based Vegetable Oils—Bio-based oils from plants such as soybeans, sunflowers, and palm are expensive but are potential recycling agents.

The effect of the recycling agent can be determined by (a) testing the rheological properties of the recycled binder recovered from RAP after blending with various percentages of a selected recycling agent; (b) treating the RAP material with various amounts of a selected recycling agent, recovering the recycled binder from the treated RAP, and testing its rheological properties; or (c) treating the RAP material with various amounts of a selected recycling agent, preparing recycled mixtures, and testing their performance. The most common practice to determine the initial dose of the recycling agent is to use blending charts like the one illustrated in Figure 9, where the high and low temperature virgin binder PG are plotted in the primary y-axis and the high and low temperature recycled binder PG in the secondary y-axis. In the horizontal axis, the RAP content is expressed in terms of replacement of the virgin binder.

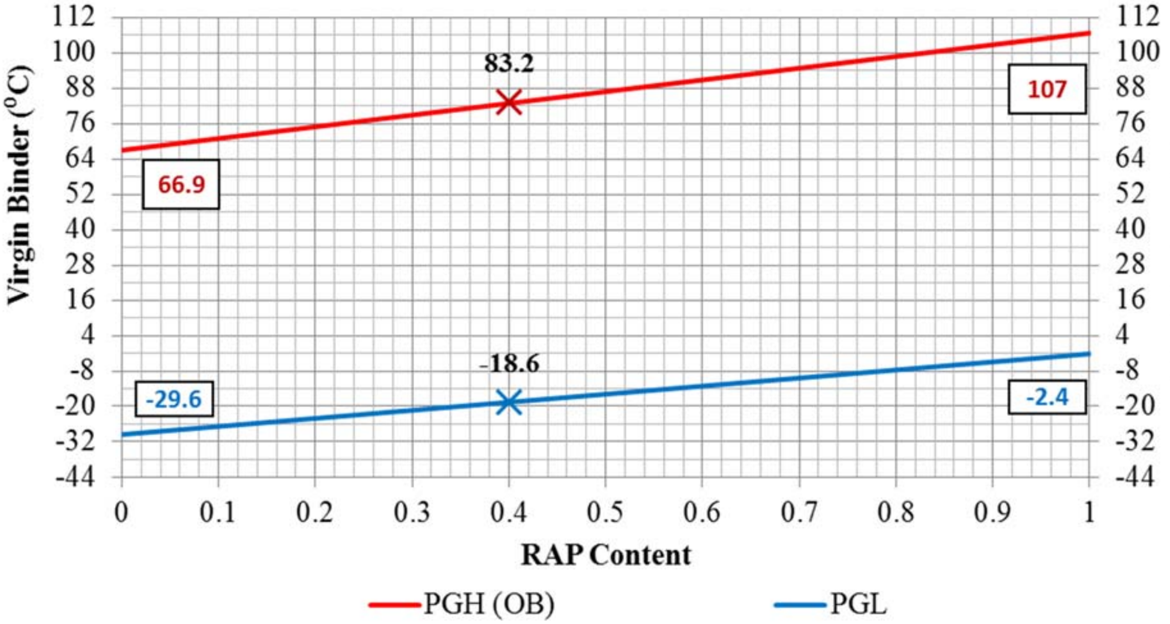


Figure 9. Example of a RAP Blending Chart

Using Equation 1, the high temperature grade of the blend of virgin and RAP binders at a specific RAP content can be estimated.

$$PGH_{Blend} = PGH_{V.\,binder} + (PGH_{RAP} - PGH_{V.\,binder}) \times RAP_{Content} \quad \text{Equation 1}$$

Then, by using recycling agent dose charts, an initial dose can be estimated, taking into account the traffic and climate demands of the specific location where the recycled mixture will be used (i.e., PGH_{Target}). NCHRP Project 09-58 has studied multiple sources and grades of virgin binders, recycled materials, and types of recycling agents and has established Equation 2 as a general guideline to estimate the initial recycling agent dose. Blending charts from recycling agent suppliers, if available, can be used in lieu of Equation 2.

$$Recycling\ Agent\ Dose = \frac{PGH_{Blend} - PGH_{Target}}{1.7} \qquad \text{Equation 2}$$

The selected dose can be further verified by preparing recycled blends with 0 percent, 2 or 5 percent, and 10 percent recycling agent and measuring the high and low temperature PG. The validation procedure utilizes the high temperature recycled binder grade to estimate how much of a dose can be incorporated for durability and cracking resistance without causing a rutting problem. This is done by limiting the dose to match the PGH_{Blend} to that of the PGH_{Target}. An example of this estimation for a PGH_{Target} = 70-22 is shown in Figure 10.

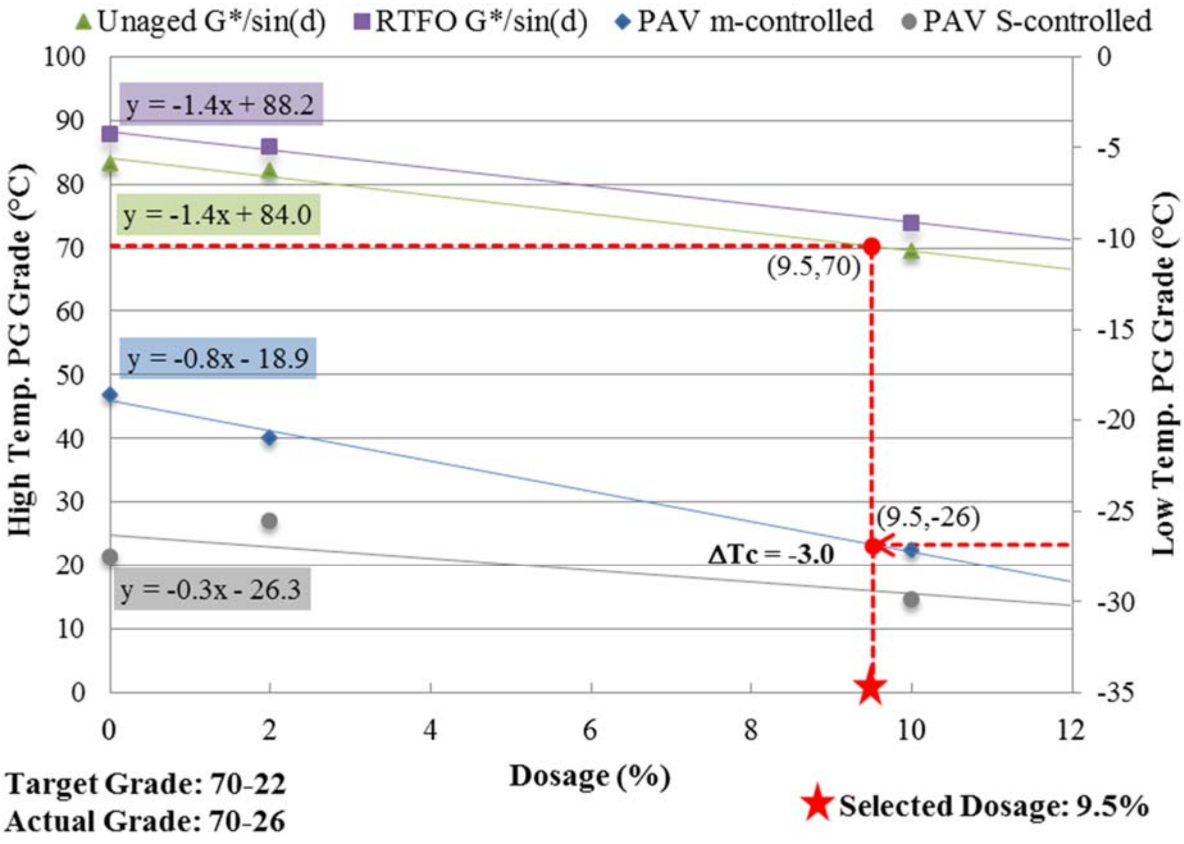


Figure 10. Example of a Recycling Agent Dose Validation

III.1.1.3. Mixture Volumetrics and Performance Tests

Some agencies consider a *simplified* mix design process and skip the step of determining volumetrics and performance tests for mixtures. However, it is recommended to not only consider the rheological properties of the virgin binder, RAP binder, and recycled blend, but to also consider the performance properties of the recycled mixture. This verifies the effect of the recycling agent on the mixture in terms of compatibility and degree of blending.

Using a pre-established aggregate gradation, the RAP, aggregates, and virgin binder are combined and heated in the oven for about 2 hours at the mixing temperature. About half an hour before mixing, the recycling agent at the selected dose is incorporated in either the heated binder or directly into the RAP material. Previous experience indicates that the way the recycling agent is added has an impact on the performance of the recycled mixture, with better results usually observed when the recycling agent is added directly to the RAP than to the virgin binder. Next, the mixture is short-term oven-aged for about 2 hours at the compaction temperature.

Specimens are then compacted in the Superpave gyratory compactor (SGC) at a specified number of gyrations or target density. Afterwards, the specimens are cooled down and tested. Performance tests used on conventional dense-graded HMA mixtures can also be employed in mixtures with high RAP, including:

- Resistance to rutting per AASHTO T 340.
- Resistance to rutting and moisture damage per AASHTO T 324.
- Resistance to moisture damage per AASHTO T 283.
- Resistance to cracking per semicircular bending test per AASHTO TP 124.
- Resilient modulus per ASTM D7369.
- Dynamic modulus per AASHTO TP 79.

One or several of these tests are usually incorporated in the mix design procedure to verify the adequacy of the recycling agent and binder content to satisfy the mixture rutting and cracking performance criteria.

III.1.2. Construction Considerations

Hot recycling employs conventional HMA equipment for mixture production, placement, and compaction. The main difference is the incorporation of recycling agents and other additives (e.g., warm-mix additives) during production that can help reduce the stiffness and improve the workability of the mixture. In the case of HIR, preheater units are used to heat and soften the existing pavement, allowing it to be scarified to a specified depth. The process is done using a single-stage or multi-stage process depending on the desired depth of scarification.

An industry scan tour to Japan with the objective of learning how this country has achieved a national average of 47 percent RAP in recycled mixtures revealed that during production, moisture in the raw materials is minimized by limiting the water used during crushing and by covering the RAP stockpiles. Most asphalt plants in Japan have a parallel drum to dry the RAP during production. The recycling agent used to restore the characteristics of the RAP binder is added directly to the heated RAP inside a pugmill to speed its diffusion into the recycled material. The delegation conducting the tour recommended longer mixing times of the virgin aggregates and RAP, high shear mixing, and longer storage time to facilitate the softening and blending of the RAP binder with the virgin binder and recycling agent (West and Copeland, 2015).

Before construction, performing a project analysis, repairing defective areas of the pavement, improving drainage, and removing excessive vegetation is recommended. Once the material is mixed, the process of compaction is similar for hot recycling and HIR. During the industry scan tour to Japan mentioned previously, unique aspects of the paving operation were noted by the delegation, such as a slower paving speed of about 6.5–10 ft/min, no signs of segregation in the recycled mixture, and compaction using a three-wheel roller for breakdown plus two pneumatic rollers (West and Copeland, 2015). Traditional compaction equipment in the United States consists of a pneumatic roller for breakdown and a double-drum vibratory roller for finishing.

HIR operations should be used on pavements with asphalt-bound materials of about 3 inches (76.2 mm) or greater to avoid removal of the entire asphalt-bound layer during the recycling process, which causes considerable construction and performance problems. If proper mix design and construction operations are not followed, the recycled asphalt-bound layer can be relatively stiff and will not perform adequately on pavements with high deflections. These pavements have high strains at the bottom of the asphalt-bound layer and are subject to premature fatigue cracking. Therefore, pavements with high deflections (poor quality base courses, for example) and relatively thin layers of asphalt-bound materials should not be considered for HIR.

Common HMA production equipment is capable of producing recycled mixtures of up to about 40 percent RAP content. With some changes, asphalt plants are capable of producing up to 50 percent RAP content. A few locations in the United States (e.g., Los Angeles and New York City) and internationally are producing recycled mixtures with RAP content in excess of 50 percent. This plant capability is not widespread and requires specialty equipment and/or processes. In addition, European technology and Japanese technology is available.

Three forms of HIR are defined by the ARRA (2015):

- Surface recycling.
- Remixing.
- Repaving.

All three of these processes use similar equipment that typically includes the following:

- Preheater units.
- Heater scarification/auger/milling units.
- Mixing units.
- Windrowing equipment.
- Spreaders or laydown units.
- Compaction equipment.

III.1.2.1. Surface Recycling

The existing asphalt-bound surface is heated and scarified (¾–2 inches [19.05–50.8 mm]) with tines, an auger, or a milling head. The scarified material is typically mixed with a recycling agent, placed with an HMA paver, and compacted. A pavement surfacing material can be placed on top of the recycled and compacted material depending on traffic volumes. Both chip seals and HMA overlays have been used as surfacing materials.

New aggregate or new mixture is not added during the process, and the thickness of the asphalt-bound layer in the existing pavement remains the same. Thus, no structural or load-carrying capacity is added to the pavement section unless an overlay is placed on the section.

Figure 11 shows a typical preheating unit that is used on all three forms of HIR trains. The preheating and heating units are responsible for heating the existing asphalt-bound pavement. The existing pavement is loosened by use of tines or low energy milling heads, as shown on Figure 12 and Figure 13. Auger systems are used to loosen, distribute, and mix materials (Figure 14).

Figure 11. Typical Preheating Unit (photo courtesy of ARRA)

Figure 12. Existing Pavement Loosened by Tines (photo courtesy of ARRA)

Figure 13. Low Energy Milling Heads (photo courtesy ARRA)

Figure 14. Auger System (photo courtesy of ARRA)

Figure 15 shows a screed used to lay down the loosened and mixed material. Compaction is performed with typical HMA compaction equipment (steel wheel static and vibratory compactors and pneumatic tired compactors).

Figure 15. Laydown Screed (photo courtesy of ARRA)

III.1.2.2. Remixing

The existing asphalt-bound surface is heated in one or more separate operations, and the scarified or milled materials are elevated off the roadway and mixed with new HMA. The blended or mixed materials are placed and compacted. Typically 18 percent to 25 percent new HMA materials are added in the process, which increases the thickness of the layer ¼–½ inch (6.35–12.7 mm). Typical depths of the remixed pavement are about 1.5–2.5 inches (38.1–63.5 mm). Some structural or load-carrying capacity is added to the pavement section. New surfacing materials are added on top of the recycled layer on some projects depending on traffic and other requirements.

Heating the roadway is typically performed with pre-heaters and heaters that are part of the scarifying or milling units, as shown above. The new HMA is hauled to the recycling unit and placed in a hopper. The new HMA is elevated and mixed with the recycled materials in a pugmill. Typical laydown and compaction equipment is utilized. Figure 16 and Figure 17 show the addition of new HMA to the recycling train.

Figure 16. Addition of New Hot Mix (photo courtesy of ARRA)

Figure 17. Remixing Train (photo courtesy of ARRA)

III.1.2.3. Repaving

The existing asphalt-bound surface is heated and scarified or milled and spread without compaction. A new HMA layer is placed on top of the loose scarified or milled materials within the same machine and compacted simultaneously. Two screeds are used in this process—one for the recycled pavement materials and other for the new HMA layer.

Overlay materials can range in thickness from ½ to about 2.25 inches (12.7–57.2 mm). Thus, structural or load-carrying capacity can be added to the structure section. Figure 18 shows the repaving process.

Figure 18. Repaving Process (photo courtesy of ARRA)

III.1.3. Past Experience and Case Studies

FDOT has executed hot recycling projects throughout the state. In 2010, a milling and HIR project was executed on SR 700 from Lake Okeechobee to SR 80 in Western Palm Beach County. The 28-mile-long, two-lane rural highway was located in an agricultural area and experiencing 3,000 vehicles per day with at least 85 percent trucks. The existing pavement had a rideability rating of 2.3 (out of 5.0) before treatment. During construction, the surface of the pavement was heated using four separate machines; the last heater milled 2.0 inches (50.8 mm) from the surface and combined it with a liquid recycling agent. A paver picked up the treated RAP and placed it back on the road. Then, the material was compacted to 92 percent density. The recycled surface was overlaid with a virgin 1.0-inch (25.4-mm) FC 9.5 friction course. The reported savings were $600,000 over conventional milling and resurfacing, in addition to a reduction in emissions and material hauling costs (Zeyher, 2011). A few additional examples of hot recycling with known field performance are described next.

III.1.3.1. Florida CR 315 and SR 19

In 2001, FDOT rehabilitated two projects utilizing HIR (Sholar et al., 2002). The first project was located on CR 315 in Putnam County between SR 100 and SR 20, with a total length of 7.58 miles. The second project was located on SR 19 between SR 40 and the town of Pittman in Lake County, with a total length of 9.73 miles. FDOT decided to evaluate in-place milling on CR 315 and scarification on SR 19 because, at the time these projects were being considered, industry representatives were concerned about the method employed to reclaim the surface layer of the existing pavement.

The recycled mixture for both projects was designed following Marshall criteria of 50 blows per sample face. For CR 315, 2.0 percent by weight of mix of Type S-I structural mixture and 0.04 percent by weight of binder with AES-300RP recycled agent were added. For the SR-19 project, 8.0 percent by weight of S-1-B South Florida limestone mix and 1.5 percent by weight of binder with Reclamite recycling agent binder were added. The reclamation depth on both projects was 1.5 inches (38.1 mm), and compaction was done using a steel-wheeled vibratory roller and/or a rubber-tire roller to a target density of 92 percent. The average densities measured via field cores after construction were 92.6 percent for CR 315 and 94.4 percent for SR 19.

In order to evaluate the bond strength between the recycled mixture and the underlying layer, researchers employed a shear device on field cores obtained from various locations throughout the project and also on cores obtained on a nearby section where conventional milling and virgin HMA resurfacing was used. The results for CR 315 showed no differences between the two sets of field cores. No comparison was performed for SR 19, but the bond strength results for the recycled mixture were higher than the ones obtained for the recycled mixture on CR 315. Other performance indicators measured after construction, such as friction and ride quality, were also acceptable.

However, about 2 weeks after completing construction on CR 315, cracking and delamination became apparent, as shown in Figure 19. The distress progressed in extent and number of affected locations until about 50 percent of the project was affected. Researchers conducted a forensic evaluation and determined that a combination of several factors could have caused the failure, including excess dust generated during milling, higher dust content and lower binder content in the mixture, low mixture temperature during construction, and variable layer thickness. Due to the extent and severity of the distress, the entire project was milled and resurfaced in 2002 using conventional HMA.

Figure 19. Cracking and Delamination on CR 315 (Sholar et al., 2002)

Although not all the parameters (i.e., high Marshall flow, low air voids, and low mixture temperature during construction) measured during construction of SR 19 met specifications, performance in terms of rutting, cracking, friction and ride quality of that project was adequate.

III.1.3.2. Florida SR 471

In 2002, the FDOT employed HIR to rehabilitate a 5-mile section of SR 471 south of Tarrytown in Sumter County that had severe cracking (cracking rating of 4.5 out of 10). This road was two lanes wide with paved shoulders and an annual ADT of 2,800 vehicles. During construction, the top 2.0 inches (50.8 mm) were removed and combined with clean concrete sand to increase the air void (AV) content and an oil-based recycling agent named Sundex 540T. Marshall Type S-III HMA was also added to correct the cross-slope as needed. The mix designs for the northbound and southbound directions were lightly different, given the in-situ properties (Sholar et al., 2004).

The roadway rehabilitation was completed in 22 calendar days, after which the produced surface presented a ride quality equivalent to a conventional HMA. Specifications requirements for rideability and friction were met as well. Additionally, the designers reported the mixture fulfillment of laboratory properties requirements for AV content, density and viscosity. However, after 6 months of service life, the surface began to present incipient rutting, apparently in the same locations where rutting was present prior to the rehabilitation. After one year of service, rutting exceeded the contract defined warranty threshold of 0.25 inch (6.35 mm).

Since this project required a 3-year performance warranty by the contractor, a forensic investigation on the failed layer was conducted in a separate research project in an effort to determine the cause of rutting (Hammons and Greene, 2006). Researchers found, based on falling weight deflectometer (FWD) results, a relevant composite pavement stiffness difference between the lots that exhibited high rutting and those who did not. Likewise, tests performed on reclaimed cores indicated that compaction due to traffic loading was a contributing factor to the observed rutting.

III.1.3.3. New Hampshire I-93

In 2015, the New Hampshire Department of Transportation (DOT) sponsored a research project to evaluate the performance of high RAP pavements (up to 40 percent) through a series of field assessments and laboratory tests. The study corresponds to the second phase of an NHDOT-sponsored project and was conducted on six sections of Interstate Highway 93 (I-93) in Woodstock and Lincoln. The test sections were constructed in 2011 and had about 3.5 years of service (Daniel et al., 2015).

The test sections were divided in two categories according to the binder grade; a PG 58-28 binder and RAP contents of 0 percent, 15 percent, and 25 percent were part of the first group, while a PG 52-34 binder and RAP contents of 25 percent, 30 percent, and 40 percent were part of the second group. Accordingly, six different mixtures were produced using two different binder grades and RAP contents with a nominal maximum aggregate size (NMAS) of 0.5 inch (12.7 mm) and an optimum binder content of 5.8 percent.

The laboratory investigation included measurements of dynamic modulus, fatigue resistance, flow number, rutting/moisture susceptibility via HWTT on field cores, plant-mixed plant-compacted specimens, plant-mixed laboratory-compacted specimens, and laboratory-mixed laboratory-compacted specimens. All laboratory specimens were compacted using the SGC to a target AV content of 6 percent. Ten field cores were extracted per test section.

The laboratory results showed that mixtures with the PG 58-28 binder were stiffer than those with the PG 52-34 binder and that the stiffness of the mixture increased with added RAP content, as expected. The binder grade had a bigger influence on stiffness than the increased RAP content. The rutting /moisture susceptibility also showed expected trends, with increasing rutting resistance for higher RAP contents. Regardless of binder grade or RAP content, all mixtures exhibited adequate rutting and moisture susceptibility. Within each mixture type, all specimen types followed similar trends except for the plant-mixed laboratory-compacted specimens. The observed differences are likely due to the reheating process of the loose mix necessary for compaction.

Field performance evaluation of the section via surface distress survey after 3.5 years in service showed better thermal and fatigue cracking performance for the mixtures with the PG 58-28 binder, whereas no difference was observed with increased RAP content. Therefore, researchers concluded that the use of a softer binder (e.g., PG 52-34) did not have a significant impact on field performance.

III.1.4. Cost Assessment

The cost savings associated with the use of RAP in hot recycling is dependent on the cost of the virgin binder, recycling agent, virgin aggregate, RAP, and the amount of binder available in the RAP.

A cost savings calculation associated with HMA production was conducted employing mix design and assumptions based on current industry average costs for low-cost and high-cost economic scenarios. Representative costs and ranges were determined and are shown in Appendix B.

The low-cost economic scenario assumed relatively low prices for the virgin binder and aggregate and relatively high recycling agent and RAP costs. Conversely, the high-cost economic scenario considered relatively high prices for the virgin binder and aggregate and relatively low recycling agent and RAP costs. The prices employed in the analysis are shown in Table 6.

Table 6. HMA Components Costs for the Low- and High-Cost Scenarios

HMA Component	Low-Cost Scenario	High-Cost Scenario
Virgin Binder	\$400/ton	\$800/ton
Recycling Agent	\$700/ton	\$700/ton
Virgin Aggregate	\$12/ton	\$15/ton
RAP	\$8/ton	\$5/ton
Binder in RAP	4%	4.75%

Table 7 presents the outcome of the first-cost analysis for the low-cost economic scenario. The economic incentive (cost difference) ranged between \$0.16 to \$0.20 per percent RAP in the mixture. A mixture with 40 percent RAP would yield cost savings of about \$6.35/ton, while a mixture with 20 percent RAP would yield cost savings of about \$3.65/ton. Therefore, the additional savings associated with increasing the RAP content from 20 percent to 40 percent is about \$3.00/ton of HMA, or about 5 percent of the production cost of the HMA mixture.

Table 7. Economic Incentive for the Low-Cost Scenario

RAP (% of Total Mix Weight)	Recycling Agent (% of Total Binder Weight)	Material Costs ($/ton)	Cost Difference	
			$/ton of HMA	$/percent RAP
0	0.0	33.34	—	—
10	0.0	31.34	2.00	0.20
20	2.0	29.67	3.67	0.18
30	5.0	28.17	5.17	0.17
40	10.0	26.99	6.35	0.16

The high-cost economic scenario shown in Table 8 provided an economic incentive on the order of about $0.50 per percent RAP utilized in the mixture. A mixture with 40 percent RAP would yield cost savings of about $20.00/ton, while a mixture with 20 percent RAP would yield cost savings of about $10.00/ton. Therefore, the additional savings associated with increasing the RAP content from 20 percent to 40 percent is about $10.00/ton of HMA, or about 15 percent of the production cost of the HMA mixture.

Table 8. Economic Incentive for the High-Cost Scenario

RAP (% of Total Mix Weight)	Recycling Agent (% of Total Binder Weight)	Material Costs ($/ton)	Cost Difference	
			$/ton of HMA	$/percent RAP
0	0.0	58.18	—	—
10	0.0	53.34	4.84	0.48
20	2.0	48.47	9.71	0.49
30	5.0	43.5	14.68	0.49
40	10.0	38.43	19.75	0.49

In summary, considerable costs savings are achieved when virgin material costs are relatively high and recycling agent and RAP costs are relatively low. This supports the observed interest in recycling when virgin material costs and in particular binder costs are high.

III.2. Cold Recycling

Cold recycling refers to rehabilitation techniques done to a paved or unpaved surface without the application of heat during construction. Three types of cold recycling are usually identified: cold in-place recycling (CIR), CCPR, and FDR. Although the latter is not included within the scope of this research, it is briefly compared with CIR. The CIR technique employs a "train" of equipment that includes cold planning machines, crushing and screening units, mixers, pavers, and compaction rollers. CIR occurs on-site, and 100 percent of the RAP generated in the milling process can be used in the operation. The process usually requires the use of emulsions or foamed binder as well as chemical additives to achieve the desired strength soon after construction.

Although CIR could be considered a partial depth reclamation, important differences exist between CIR and FDR, which include the following: CIR gradation is generally coarser than FDR gradation, FDR depth is approximately more than twice the depth for CIR treatments, moisture content is considerably larger in FDR than in CIR, and CIR stabilization is most commonly done with bituminous products, whereas FDR utilizes chemical stabilization (Cox and Howard, 2015).

In the CCPR process, recycling occurs at a stationary cold mix plant or by employing a CIR train in stationary mode without the planning machine. The RAP used in CCPR mixtures is often obtained from existing stockpiles and processed at the plant to achieve a target size/gradation and to also often combine it with recycling agents.

After compaction of either CIR or CCPR mixtures, a curing period is often needed when emulsions or any other stabilizer agent is employed. A fog seal is sometimes applied to prevent raveling during the curing process. In addition, it is often recommended to place within a few days of construction a surface-wearing course, such as a chip seal or thin overlay, to protect the surface of the CIR or CCPR layer from raveling and moisture damage.

Some of the advantages of CIR and CCPR include (ARRA, 2015; Wirtgen Group, 2012):

- Conserving natural resources.
- Controlling input materials.
- Correcting surface irregularities.
- Mitigating reflective cracking.
- Eliminating existing pavement distress.
- Preserving existing base and subgrade materials.
- Restoring pavement profile and drainage.
- Reducing traffic disruptions during construction.
- Correcting underlying material (i.e., structural) deficiencies.

Cold recycling is often most effective on roads with high frequency and high severity of non-load associated distresses. When used to resolve load-related distresses, it is advisable to add an asphalt overlay to increase the pavement structure’s capacity. An array of pavement distresses that can be addressed by cold recycling (ARRA, 2005) from raveling, to potholes, low skid resistance, and even thermal cracking (longitudinal, transverse, block, and edge). Other considerations for project selection include existing pavement structure, condition, structural capacity, geometric features, and traffic volume, among others.

The expected service life of CIR with surface treatment is 6–10 years, while 7–20 years are expected when an asphalt overlay is placed on top of the CIR mixture, depending on the level of traffic. Similarly, depending on the level of traffic, CCPR mixtures usually span 6–10 years with a surface treatment and 12–20 years when an asphalt overlay is employed (ARRA, 2015).

III.2.1. Mix Design Considerations

Mix design guidelines for cold recycled mixtures aid in achieving a job mix formula that meets certain specifications and performance requirements. Usually, the mix design details the type and amount of recycling agent, water content, and additive to be employed and specifies the water content of the mixture. When incorporating RAP in cold mixtures, three possible scenarios are usually considered: (a) RAP will act as a “black rock,” and its binder will not interact with the other components of the mixture; (b) all the binder in the RAP will be softened by adding a recycling agent and interact with other mixture components; and (c) a portion of the RAP binder will interact with other mixture components through partial softening after combining with the recycling agent.

One of the first standardized mix designs was published in the AASHTO-AGC-ARTBA Report on Cold Recycling of Asphalt Pavements, which contained procedures for Marshall and Hveem equipment (AASHTO, 1998). More recent mix design procedures recommending the use of the SGC have gained popularity. In general, mix designs include testing specimens for initial and cured strength, resistance to moisture damage, and resistance to cracking. In addition, some designs specify testing of the binder and the recycling agent to meet environmental requirements based on the Superpave PG criteria. The general steps involved in a mix design procedure for cold recycled mixtures are illustrated in Figure 20 (ARRA, 2015).

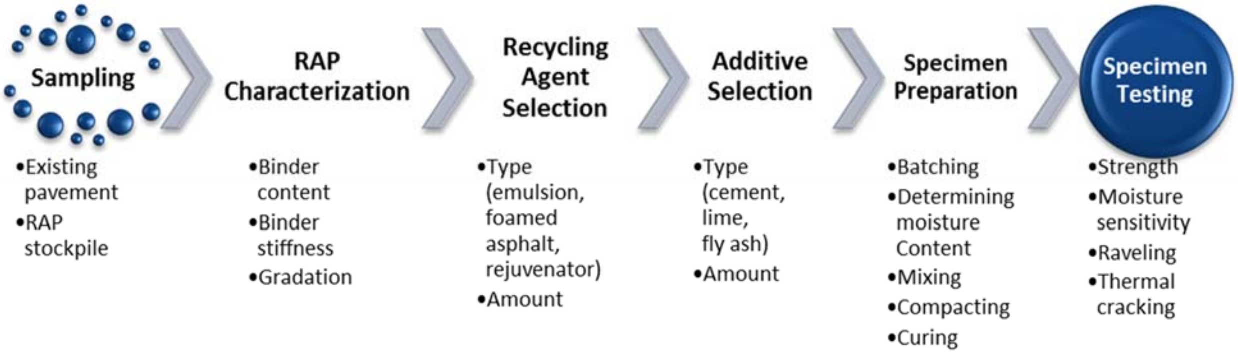


Figure 20. Cold Recycling Mix Design Step

III.2.1.1. Sampling and Characterization

Representative samples of RAP are obtained to assess gradation, binder content, and binder stiffness. For existing pavements, the length, width, and depth of the project should be sampled through coring or milling. For stockpiled RAP, representative samples based on the uniformity of the stockpile are obtained and preferably fractionated in two or three sizes for better precision and uniformity of the measurements. At a minimum, the gradation and binder content of the RAP are determined via sieving and ignition oven procedures. Extraction and recovery of the RAP binder are also recommended for establishing binder content and PG of the binder.

III.2.1.2. Recycling Agent Selection

Two types of recycling agents are usually employed for cold recycling: emulsion or foamed binder. An emulsion is a mixture of binder, water, and emulsifier and can be classified as anionic or cationic and medium set or slow set. The objective of emulsion is to disperse the binder in the water and “break” (i.e., separate the binder from the water) after contact with the recycled material. Compatibility and curing times are key variables that should be considered when selecting the emulsion type.

Foamed binder is defined as a mixture of hot binder, water, and air. Foaming occurs when reduced quantities of water at cold or ambient temperature are introduced to a heated binder inside an expansion chamber. The water causes the binder to reduce viscosity and expand, allowing proper dispersion and coating of the recycled materials.

The recycling agent amount can be determined using nomographs like the one illustrated in Figure 21. In that example, the gradation of the RAP is used to input the percent passing sieve No. 40 and No. 200 and estimate the optimum asphalt content. The RAP binder content is subtracted from this amount and the percent emulsion calculated, taking into account the residual binder in the product. The recycling agent amount is usually adjusted in the field based mostly on visual evaluation. Samples of the recycled mixture are spread and air dried; then, the material is packed tightly together in a sphere-like shape (like making a snowball). The material is then dropped from about waist level (approximately 3 ft high) and examined visually: if the ball of material breaks in half or in several large pieces and the hands of the examiner are covered with a slight film of asphalt, the material has the right amount of asphalt; if the ball of material slumps or only cracks slightly and the hands of the examiner are covered in a thick layer of asphalt, the material has excess asphalt; if the ball of material breaks into many small pieces and only specks of asphalt remain on the hands of the examiner, the material has insufficient asphalt.

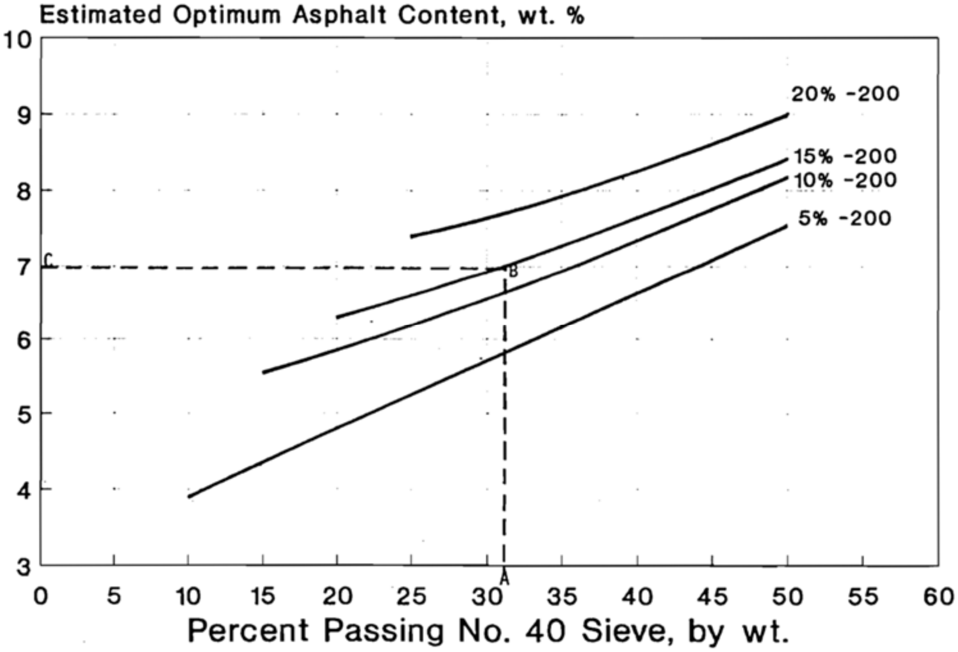


Figure 21. Nomograph for Estimating the Optimum Asphalt Content for Cold Recycled Mixtures (Estakhri, 1993).

Schwartz et al. (2017) conducted a research project with the support of the Virginia DOT to determine relevant properties of CIR, CCPR, and FDR materials with emulsified and foamed binder. The project evaluated dynamic modulus and repeated load permanent deformation (RLPD) characteristics (e.g., flow number) of recycled mixtures sampled from 26 field projects across the United States and Canada. Given the limitation in size of the core specimens and the thickness of the cold recycled layers in them, the researchers developed a small-scale testing procedure. Specimens 2.5-inch (50.8-mm) in diameter by 4.3-inch (109.2-mm) tall were extracted from the field cores perpendicular to the cylindrical axis.

The laboratory test results showed that all three recycling processes had similar RLPD characteristics and similar range of dynamic modulus values at intermediate/high reduced-frequencies. No significant difference was observed in the statistical tests. The presence of chemical additives in the recycled mixture was also evaluated. The results proved the addition of chemical additives to be beneficial with respect to stiffness and resistance to permanent deformation (i.e., rutting problems). Relationships between mixture volumetrics, gradation, density, and stiffness were also evaluated, but no strong correlation was found. Furthermore, the researchers found that the maximum acceptable coefficient of variation according to AASHTO standards did not reflect typical variability of cold recycled materials and that exceptions should be considered.

Other types of recycling agents most commonly used for HMA recycling that were listed in the previous section of this chapter are also available for cold recycling applications.

III.2.1.3. Additive Selection

Chemical additives such as hydrated lime, Portland cement in dry or slurry form, and—to a lesser extent—fly ash have been used in cold recycling to improve strength and increase rutting and moisture resistance. The amount of additives is usually a function of cost and a function of balance between strength and brittle behavior since a large amount of these additives will tend to stiffen the mixture excessively and make it prone to cracking.

III.2.1.4. Specimen Preparation

RAP material with or without the addition of virgin aggregate is used in laboratory specimen preparation. The incorporation of virgin aggregates is usually done to improve the gradation and stability of the mixture. A single gradation or several gradations can be considered during mix design. Specimens are batched according to the required size of the test specimen and the compaction method. Moisture content is then determined for coating and compactability. The amount of water added to the RAP usually ranges between 1.0 percent and 3.0 percent, and is determined by incorporating small increments of water to the RAP and recycling agent and selecting the minimum amount that visually maximizes coating of the RAP material.

Mixing of the RAP with the recycling agent, water, and additives is done at ambient temperature (approximately 73°F [23°C]). If foamed binder is used, the binder is heated between 320°F–375°F (160°C–190°C) depending on the PG. The batches are combined with various contents of the recycling agent (typically three or four) to estimate the optimum based on strength and stability. The emulsion contents range between 0.5 percent and 4.0 percent by weight of RAP, although some researchers warn against the use of more than 2.5 percent emulsion because it could result in mixtures that are initially more workable but eventually shove or rut under traffic (Estakhri, 1993). Adequate mixing time with the emulsion needs to be observed to prevent overmixing and subsequent premature braking, or undermixing and subsequent poor coating. Foamed binder content ranges between 1.5 percent and 3.0 percent by weight of RAP.

Specimens are also compacted at ambient temperature using a target energy that will produce a comparable density to the one achieved in the field. Typical values are 75 blows when using the Marshall hammer or 30 gyrations using the SGC. After compaction, a period of curing is needed to eliminate excess water. This removal is usually accomplished by placing the specimens in a force-draft oven at a specified temperature of 60°C for emulsion and 40°C for foamed binder until constant mass of the specimen is achieved but no longer than 48 hours. The specimens are allowed to cool after curing.

III.2.1.5. Specimen Testing

The final step of the mix design process is to verify the strength, moisture sensitivity, raveling, and cracking potential of the mixtures. The bulk specific gravity is also determined to verify AV content. The requirements from ARRA are noted in Table 9.

Table 9. Minimum Mix Design Requirements for Cold Recycling with Emulsion (ARRA, 2016)

Test Method	Criteria	Property
Asphalt Content of RAP [a] AASHTO T 308 (ASTM D6307)	Report Only	Quantity of Existing Binder
Gradation of Unextracted RAP [a] AASHTO T 11[b] & T 27 (ASTM C117[b] & C136)	1.25-inch (31.5-mm) Maximum Per Table 3	Maximum Particle Size
Bulk Specific Gravity of Compacted, Cured Specimens [c] AASHTO T 166 (ASTM D2726)	Report Only	Density as Compacted
Maximum Theoretical Specific Gravity [d] AASHTO T 209 (ASTM D2041)	Report Only	Maximum Specific Gravity
Air Voids of Compacted, Cured Specimens [c,d] AASHTO T 269 (ASTM D3203)	Report Only – Recycling agent content should not be adjusted to meet an air void content.	Compacted Air Voids
Either		
Indirect Tensile Strength [c,e] AASHTO T 283 (ASTM D4867)	Minimum 45 psi (310 kPa) [f,g]	Cured Strength
Or		
Marshall Stability [c,e] AASHTO T 245 (ASTM D6927)	Minimum 1,250 lbs. (5,560 N) [g]	Cured Stability
Tensile Strength Ratio/Retained Marshall Stability based on Moisture Conditioning [c,e,h] AASHTO T 283 (ASTM D4867) AASHTO T 245 (ASTM D6927)	Minimum 0.70 [i]	Resistance to Moisture Induced Damage
Raveling Test of Cold Mixed Bituminous Mixtures [j] ASTM D7196	Maximum 7.0% loss [j]	Resistance to Raveling
Ratio of Residual Asphalt to Cement	Minimum 3.0:1.0 (refer to section 4.3.1 and 4.3.2 of CR101)	Prevent Rigid Behavior
RAP Coating Test [k] AASHTO T 59	Minimum Good	Coating of Binder
Maximum Emulsified Asphalt Heating Temperature	Report Only (Obtained from Supplier)	Maximum Heating Temperature
PG Grade of Recycling Agent AASHTO M 320	Select low temperature PG grade of recycling agent to meet or be one grade higher that the requirements for location of project and depth in pavement structure. [l]	Resistance to Low Temperature Cracking

III.2.2. Construction Considerations

CIR and CCPR are usually considered partial depth recycling because only the upper layers of the materials are recycled. CIR is usually faster, less disruptive, and environmentally preferable to CCPR, especially because of the reduction of material hauling to and from the job site. The depth of the treated pavement in CIR application usually ranges from 2 inches and 4 inches (50.8 mm and 101.6 mm). Thinner sections are applied in instances where proper structural support is available. Thicker layers are often constructed in various lifts. The typical construction steps for CIR and CCPR are shown in Figure 22 and Figure 23, respectively.

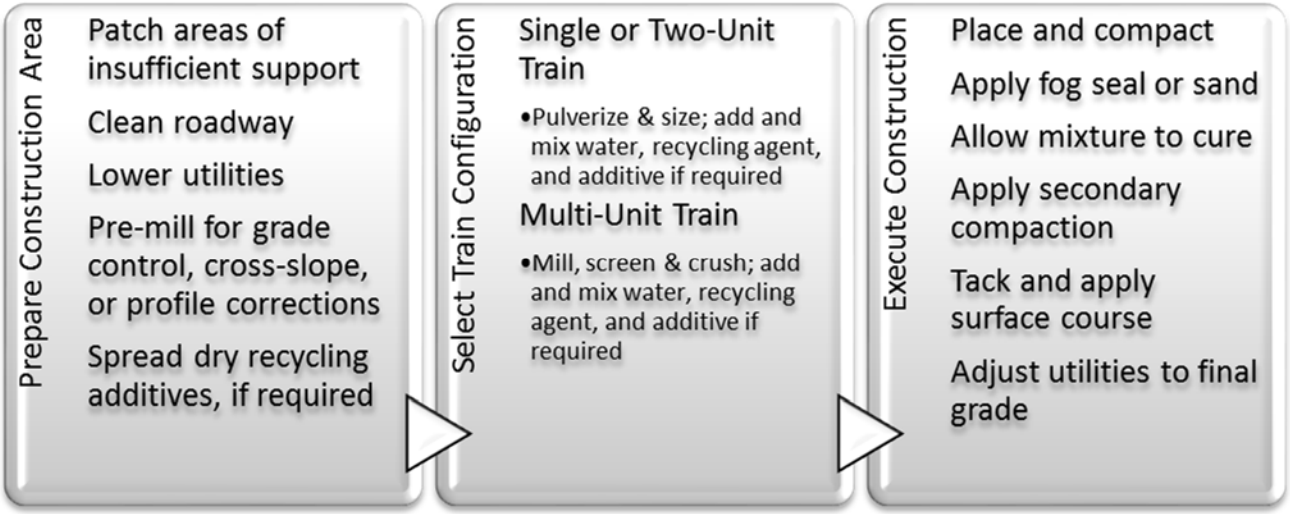


Figure 22. Typical Sequence for CIR Construction (adapted from ARRA, 2015)

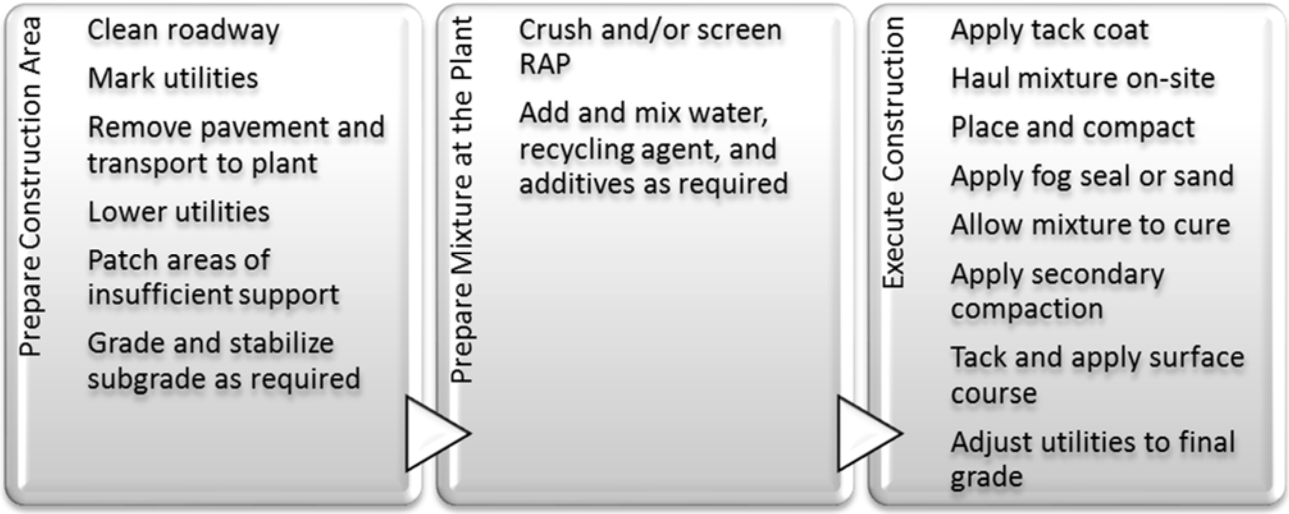


Figure 23. Typical Sequence for CCPR Construction (adapted from ARRA, 2015)

For both CIR and CCPR, the construction area needs to be prepared by correcting areas with insufficient support; removing dirt, vegetation, and other foreign materials; adjusting utilities below the height of the recycling depth; verifying the grade and cross-slope of the section; and similar steps. Removal of RAP is done with cold planers of various widths and extensions.

For CIR, several train configurations are available—single unit, two units, or multi-units; single units are not capable of screening and crushing. A single-unit train usually consists of a cutting head, a spray bar that incorporates the recycling agent by estimated volume of road being milled, and a screed that places the recycled mixture (Figure 24a). The two-unit train consists of a full-size cold planer to mill and size the RAP and a paver that incorporates the recycling agent by weight of RAP via pugmill and places the recycled mixture. A multi-unit train typically consists of a full size cold planer, a screening/crushing unit, and a pugmill mixer (Figure 24b).

The recycling agent is added based on the actual weight of the RAP measured as it is transported from the screening/crushing unit to the pugmill. After the material is processed in the pugmill, it is either deposited directly in the paver hopper or picked up by a windrow and placed in the paver. Multi-unit trains offer greater control of the construction process than the single- or two-unit trains but are harder to maneuver.

(a)

(b)

Figure 24. CIR Train: (a) Single Unit, (b) Multi-Unit (ARRA, 2015)

The preparation of the mixture in CCPR takes place in an asphalt plant where the RAP—obtained by cold planning or already stockpiled—is processed by screening/crushing and mixing with the recycling agent, water, and additive. The amount of each component is proportioned based on the weight of the RAP measured on the conveyor belt of the RAP feed. The cold mixture can be stored in silos, stockpiles, or placed in dump trucks for transportation. Placement of the recycled mixture on site is done with a conventional paver or a motor grader if the smoothness of the road is of secondary importance.

During construction, adjustments to the water, recycling agent, and additives may be necessary to accommodate changes in the RAP gradation, ambient temperature, or humidity. In addition, visual observation of the color and cohesiveness of the mixture may prompt for adjustments. The AV content of the compacted CIR or CCPR recycled mixture is typically between 8 percent and 16 percent or higher.

Typical compaction equipment includes pneumatic-tire and double-drum vibratory rollers. For foamed mixture, compaction starts right after placement, but emulsified mixtures are compacted after the mixture starts to break. This period is dependent on the type of emulsion and environmental conditions. The rolling pattern is established using a control strip with periodic density checks.

The curing periods to achieve moisture contents below 3 percent usually spans 2 to 3 days The rate of curing of the recycled mixture usually depends on one or more of the following factors:

- Ambient temperature (preferably 40 to 50°F minimum with overnight above 35°F).
- Ambient humidity.
- Rainfall (preferably none; light precipitation is acceptable).
- Moisture content of the recycled mixture.
- Level of compaction.
- AV content.
- Drainage characteristics of the pavement.
- Presence of shoulders.
- Type of recycling agent.

Some of the activities listed in Figure 22 and Figure 23 as part of the last step are optional and should be considered on a case-by-case basis. For example, if raveling is a concern, application of a fog seal is recommended, along with delaying reopening the road to traffic until the fog seal has cured. Sand can be used to absorb the excess fog seal and expedite reopening the road to traffic. Figure 25 shows a fog seal and sand being applied on a completed CIR mixture. Secondary compaction is also sometimes recommended to re-level the surface after some consolidation of the wheel paths may have occurred under traffic. Finally, the placement of a surface course on top of the CIR or CCPR mixture is frequently recommended to protect it from moisture damage. For low volume roads, a chip seal, slurry seal, or microsurfacing treatment are often employed with success.

Figure 25. Fog Seal and Sand Treatment over CIR Layer (ARRA, 2015)

With regard to the weather, construction should be avoided on rainy days because the rain can wash off the emulsion or cause premature reaction with the additives. The recommendations listed in Table 10 are usually considered depending on the type of additive (ARRA, 2005).

Table 10. Recommended Weather Conditions for Cold Recycling Construction

Additive	Weather Condition
Emulsion, Foamed Binder, Emulsion-Lime, Emulsion-Cement	Air temperature > 50°F RAP should not be frozen
Fly Ash, Fly Ash-Lime, Cement, Cement-Fly Ash	Air temperature > 40°F RAP should not be frozen Complete construction at least one month before first freeze

III.2.3. Case Studies

Some of the drawbacks of cold recycling techniques are that (a) they have been primarily used for and therefore are considered suitable for only low volume roads, and (b) there is a lack of knowledge regarding their long-term performance (Stroup-Gardiner, 2011). Several CIR projects built around a decade ago in Iowa, New Mexico, Nevada, and Pennsylvania have demonstrated good in-service performance (Chen and Jahren, 2007; McKeen et al., 1998; Morian et al., 2004; Sebaaly et al., 2004). Other more recent efforts are listed in Table 11. A few relevant examples with known field performance are described in more detail below.

Table 11. Examples of Recent Local and State Cold Recycling Projects

Year	Agency	Location	Project	Length (mi)	Existing Condition	Treatment Depth (inches)	Overlay Type & Depth	Additive Type	Est. Cost Savings
2007	Barnes County	Barnes County, ND	Kathryn Rd S	9.5	Rutting, transverse cracking	4	Chip Seal	Emulsion	55%
2007	Oklahoma DOT	Beaver and Harper Counties, OK	US 412	0.3	Transverse cracking	3–4	2-3-inch HMA	Emulsion CSS-1	—
2010	City of Palm Desert	Palm Desert, CA	Residential streets	950k ft^2	Severe cracking	2.5–4	1.25-inch asphalt rubber WMA	Emulsion PASS-R	$450k
2010	Illinois DOT	Astoria to Summun, IL	US 24	2.3	Extremely poor condition	2	2-inch HMA	Emulsion	$250k
2010	Texas DOT	Ochiltree County, TX	US 83	6.1	Fatigue and longitudinal cracking	5	1.5-inch HMA	Emulsion CSS-1H	30 - 50%
2011	Los Angeles Department of Public Works	Los Angeles County, CA	Angeles Forest Highway	25	Poor condition	3	1.5-inch asphalt rubber HMA	Emulsion PASS-R	40%
2011	Utah DOT	Bluff, San Juan County, UT	US 191	9	Block cracking	3	Fog seal	Emulsion + Lime	—
2012	Los Angeles Department of Public Works	City of Lancaster, CA	50th St. W btw K Ave. and M-8 Ave.	2	Poor condition	1–2	1.5-inch Asphalt rubber HMA	Emulsion	—
2013	City of Glendale	Glendale, CA	Central Avenue	0.5	Poor condition	4–5	2-3-inch asphalt rubber HMA	Emulsion PASS-R	30–35% ($340k)
2013	Delaware River Joint Toll Bridge Commission	Solebury Township, PA, and Delaware Township, NJ	Rte. 202	5	Rutting, alligator cracking	8–6	2-inch HMA	Foamed binder	60%
2013	Texas DOT	Hemphill County, TX	US 83	6.1	Rutting, transverse cracking, delamination	4	1.5-inch HMA	Emulsion + Lime Slurry	30–50%
2013	West Virginia Division of Highways	Morgantown, WV	Monogalia CR 53/Fort Martin Rd.	1.8	Cracking, potholes, delamination	6	2-inch HMA	Emulsion CSS-1h + Portland cement	—
2014	Lassen and Plumas counties	Sierra Nevada Mountains, CA	Mooney Rd. btw Hwy. 36 and Hwy. 44	7	Rutting	3	20% RAP HMA	Emulsion HFMS-2p	$296k

III.2.3.1. Iowa CIR Long-Term Performance Evaluation

In 2007, the Iowa Highway Research Board in collaboration with the Iowa DOT sponsored field and laboratory performance evaluations of 24 CIR-rehabilitated roads. Of the total sample, 18 roads were constructed between 1986 and 1998 and initially investigated by Jahren et al. (1998). The remaining six roads were constructed between 1999 and 2004.

Researchers evaluated the influence of various external factors, such as traffic level, support condition, and age on performance. Roads carrying an annual ADT from 0 to 800 vehicles were classified as low traffic volume, and those with more than 800 annual ADT were regarded as high traffic volume. Similarly, researchers created two categories for the support condition according to the subgrade elastic modulus (SEM): adequate for an SEM above 5,000 psi or inadequate for an SEM below 5,000 psi.

In order to properly compare the performance of the pavements with the results previously obtained by Jahren et al. (1998), researchers performed the same series of tests, including collecting qualitative and quantitative surface distress data, defining the support condition based on field deflection, and determining the engineering properties of the CIR materials through a series of laboratory tests conducted on field cores.

A pavement distress survey was performed on each road using an automated image collection system, which allowed for an efficient evaluation of the pavement surface while traveling at highway speed. The dimensions/areas of cracks and other distresses were measured, and the pavement condition index (PCI) calculated. A field deflection test was performed using FWD; data were acquired every 100 ft (30.5 m) on a 1,500-ft (457-m) long section of the road. Through back-calculation, the elastic modulus of the pavement layers was determined and related to the support condition. All FWD data were analyzed assuming a tree layer pavement structure comprised of an HMA surface layer over a CIR layer and a foundation layer (FND), as shown in Figure 26.

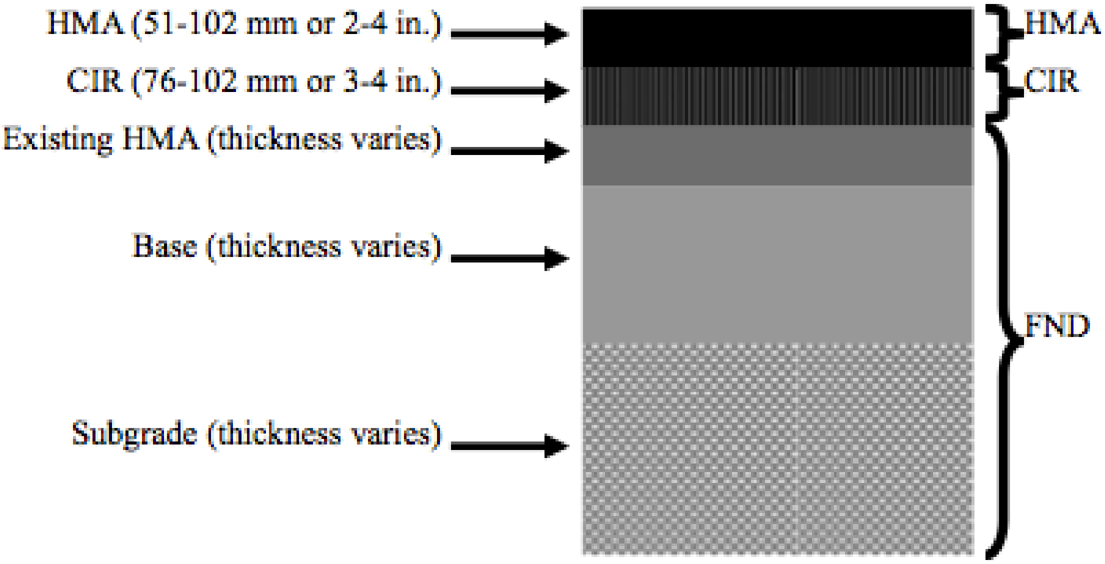


Figure 26. 3-Layer Model CIR Pavement (Chen and Jahren 2007)

For the laboratory investigation, researchers employed six 4.0-inch (101.6-mm) diameter field cores that were extracted every 300 ft (91 m)—three field cores from the right wheel path and three field cores from the center of the lane between wheels paths. The CIR layers were isolated from the top and bottom layers by trimming, which yielded a 4.0-inch (101.6-mm) diameter by 2.0-inch (50.8-mm) tall test specimen. Indirect tensile strength (IDT), AV content, complex shear modulus (G*), flexural creep stiffness (S), and stiffness-time relationship (S(t)) were measured on the trimmed CIR field cores.

A statistical analysis was done to correlate field pavement performance (i.e., PCI), laboratory test results (IDT, AV, G*, S(t)), and external factors (traffic level, support condition, and age). Separate multivariable models were developed for (a) all roads, (b) high traffic roads, and (c) low traffic roads. The results for the first model indicated better pavement performance for higher AV content, lower CIR modulus, and lower traffic load. For the second model, the analysis displayed better pavement performance for lower CIR modulus, and higher IDT, while for the third model better performance was observed for higher G* and lower CIR modulus. All three models showed better pavement performance with lower moduli and/or higher AV content in the CIR layer, suggesting that CIR acted as a stress-relieving layer, a concept previously supported by Abd El Halim (1985, 1986). Additionally, the high values of IDT and G* determined on the regressions for the low and high traffic road models suggest good moisture and rutting resistance of the CIR layer.

III.2.3.2. Mississippi US 49

In 2010, the Mississippi DOT sponsored a laboratory and field study on FDR on an 8.7-mile (14-km) section of US Highway 49 near Madison County, Mississippi. The performance of the pavement was monitored from construction through 53 months in service. The study was unique in the sense that the FDR was significantly deep (i.e., 8 inches [20.3 cm]), it included a high amount of fine particles smaller than 3×10^{-3} inches (75 μm), and the selected four-lane divided section of highway carried a significant amount of traffic (Strickland, 2010).

The existing pavement consisted of two distinct pavement structures: an asphalt concrete over joint concrete pavement built in 1959 and a full-depth asphalt concrete pavement built in 1980. Several types of distresses, including longitudinal cracking, potholes, transverse cracking, and rutting, were present. Therefore, this section of US 49 was heavily patched, making it a suitable candidate for in-place recycling.

The initial construction plan was to perform a 6-inch (152.4-mm) CIR on the full-depth asphalt concrete pavement, and a 9-inch (22.9-cm) CIR on the asphalt concrete over joint concrete pavement. However, as construction progressed, it was apparent that some areas of the existing subgrade did not have the sufficient structural strength to support the recycling equipment. Therefore, FDR was done on the existing full-depth asphalt concrete pavement.

For the CIR portion of the field project, the laboratory and field characterization considered single and multiple stabilizing agents. The researchers conducting the project developed a single framework applicable to any cementitious or bituminous stabilizer or combination thereof. The procedure consisted of preparing specimens at 6.0 percent moisture content, compacting them in the SGC with 30 gyrations – 40 gyrations, determining the maximum specific gravity (G_{mm}) and bulk specific gravity (G_{mb}), curing the specimens in an oven at 40°C and 35 percent–50 percent relative humidity, and testing the specimens via Asphalt Pavement Analyzer and indirect tension. Based on this procedure, the optimum stabilizing agents for US 49 resulted in a combination of

1.5 percent cement and 3.0 percent emulsion (Cox and Howard, 2015). Even though this combination was not the most economical, it provided the best balance between rutting and cracking resistance.

The CIR construction process consisted of milling the top 3.0 inches (76.2 mm) of the existing pavement surface, spreading the chemical stabilizing agent, pulverizing 6.0–9.0 inches (15.2–22.9 cm) of the existing pavement, mixing the reclaimed material in a pugmill with the emulsion, smoothing the material with a motor grader, compacting with a steel pad compactor, smoothing a second time, and conducting the final compaction with a vibratory steel roller. The process is illustrated in Figure 27.

Periodic post-construction monitoring activities spanning 53 months in service consisted of FWD testing, automated road profiling, and coring. Performance was rated as "good" according to Mississippi DOT's Pavement Condition Rating, with acceptable roughness, rutting, fatigue cracking, block cracking, longitudinal cracking, and transverse cracking values. Field cores showed variation with respect to layer thickness and differences between emulsified and cement stabilization specimens. The emulsified CIR demonstrated better cracking resistance, while cement CIR had better modulus and strength properties.

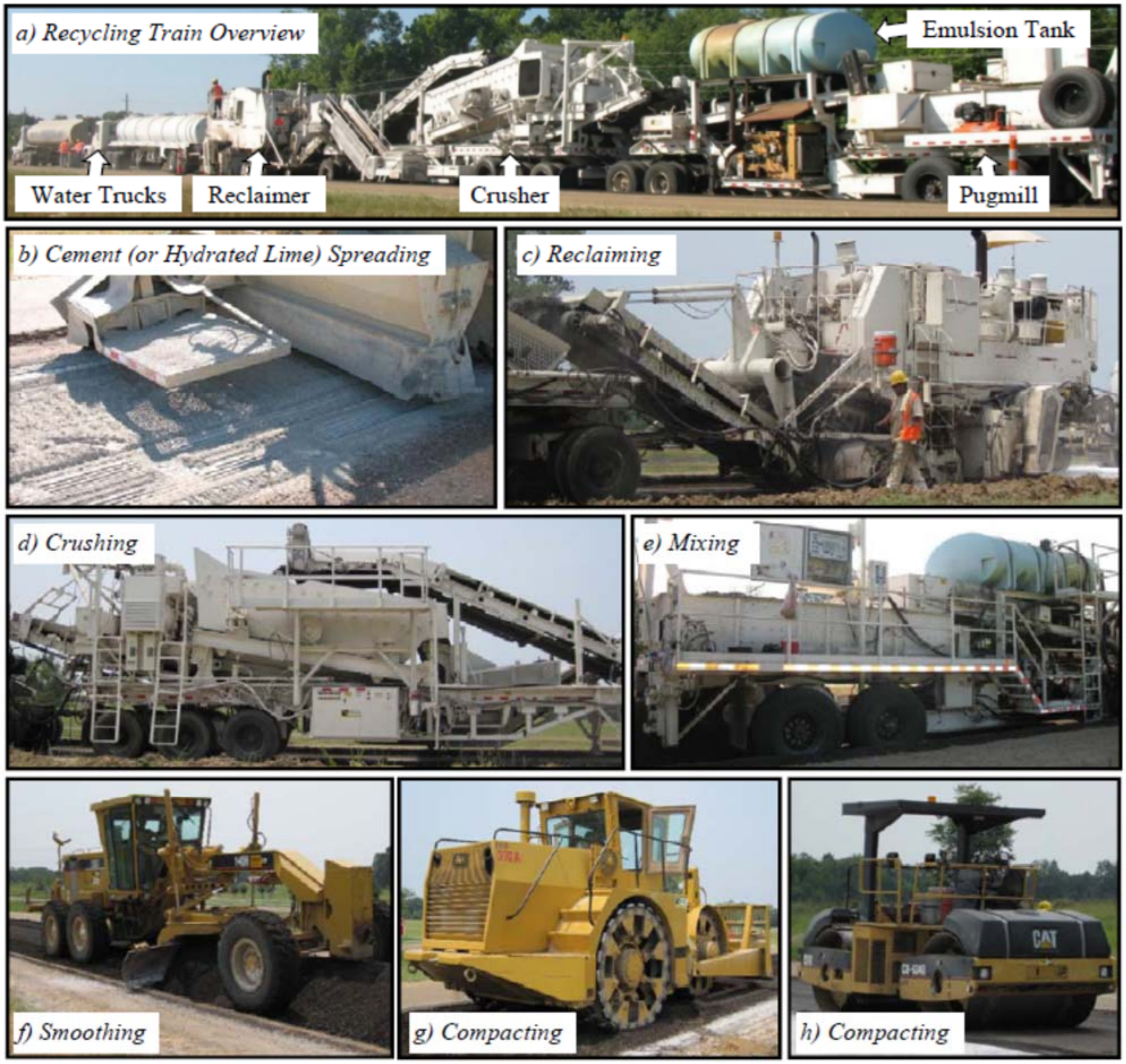


Figure 27. US 49 CIR Construction (Cox and Howard, 2015)

III.2.3.3. Virginia I-81

In 2011, the Virginia DOT (VDOT) completed the rehabilitation of Interstate Highway 81 (I-81) in Augusta County near Staunton, Virginia (Diefenderfer and Apeagyei, 2014). Three in-place recycling techniques, including FDR, CIR, and CCPR, were included in the project. The CIR and CCPR techniques used 1.0 percent hydraulic cement and 2.0 percent foamed binder, whereas 3.0 percent of a mix of lime kiln dust and hydraulic cement were employed in the FDR process. VDOT was interested in gaining experience with these types of rehabilitation techniques with regard to mix design, quality assurance (QA) procedures, and field evaluation. In addition, the performance of the section was monitored during the first 3 years after construction via ride quality and rutting measurements, with good observed performance despite high traffic volumes on this four-lane divided section of I-81.

Ground penetrating radar and FWD measures were also conducted to verify the thickness and structural soundness of the pavement after construction. From these evaluations, the structural layer coefficient for the CIR was 0.39 and for CCPR between 0.37–0.44, and the combined structural layer coefficient for CCPR and FDR was 0.37. The typical structural layer coefficients recommended by AASHTO for these types of materials are between 0.25–0.35, with FDR tending to be on the lower end and CIR/CCPR on the higher end of the range (AASHTO, 1993).

The laboratory tests conducted on the materials collected prior, during, and after construction (field cores obtained 3 and 20 months after construction) included gradation, resilient modulus, IDT strength, dynamic modulus, and flow number. A mix design procedure to determine the optimum moisture content (OMC), density at OMC, and the selection of the recycling agent content was done for all mixtures. The CIR and CCPR mixtures were designed in accordance with the Wirtgen manual (Wirtgen Group, 2006). Several foaming water contents were used in a laboratory-scaled foamer to determine the optimum water content for the PG 64-22 binder. Trial mixtures were prepared by compacting in the SGC using a 3.9-inch (100-mm) diameter mold to a predetermined density equivalent to the density that would be obtained with 75 blows in the Marshall compactor. The 2.5-inch (62.5-mm) tall specimens were cured in an oven at 40°C for 72 hours before IDT strength testing. The specimens with 1.0 percent hydraulic cement and 2.0 percent foamed binder achieved the minimum IDT strength of 45 psi (310 kPa). For the FDR materials, the optimum hydraulic cement plus lime kiln dust content (i.e., 3.0 percent) was determined via maximum unconfined compressive strength of 300 psi (2068 kPa) to control cracking.

The right lane of the section was treated with FDR plus CCPR and an asphalt overlay, whereas the left lane was constructed with CIR and an asphalt overlay. No tack coat was applied between layers. A few images illustrating the construction process are shown in Figure 28. During construction, QA and acceptance testing of the CIR and CCPR mixtures included depth of the recycled layer, gradation, recycling agent dose, dry and wet IDT strength, and compacted density. The requirement for dry IDT strength was 95 percent of the design value (i.e., 48.5 psi [334 kPa]), and the tensile strength ratio (TSR) was only reported. Additional laboratory testing using materials collected during construction and field cores was also performed. The cores were used to determine gradation, binder content, density, IDT strength, resilient modulus, and flow number. The results from the laboratory evaluation indicated similar performance between CCPR and CIR specimens.

Field evaluation of rut depth and ride quality showed minimal rutting (< 0.1 inch [2.5 mm]) after 34 months in service. In addition, the ride quality improved from the time of construction (i.e., International Roughness Index [IRI] = 72 inches/mile) to after about 34 months after construction (i.e., IRI = 45–56 inches/mile). The CCPR over FDR had lower IRI values than the CIR; however, VDOT could not conclude that the differences in IRI values were exclusively due to the different treatments since the structure of the pavement was slightly different in terms of thickness of the layers. The structural capacity of the layer seemed to also improve with time, as demonstrated by larger back-calculated structural numbers from FWD measurements. VDOT will continue to monitor the long-term performance of this section of I-81.

(a)

(b)

(c)

Figure 28. I-81 Construction: (a) CCPR Production, (b) Laydown of the CCPR Mixture, (c) CIR on the Left Lane (Diefenderfer and Apeagyei, 2014)

III.2.3.4. VDOT Test Sections at the NCAT Test Track

In 2012, VDOT tested three pavement structures (N3, N4, S12) at the NCAT test track in order to evaluate the performance of CCPR and FDR recycling technologies under heavy traffic loading conditions (10 million 18-kip equivalent single axle loads [ESALs]). The test sections were 200 ft long and comprised a 5.0-inch CCPR base under virgin asphalt concrete (AC) overlays 4.0 or 6.0 inches thick. A cement-stabilized base was included under the CCPR layer in one of the sections to simulate the FDR layer (see Figure 29).

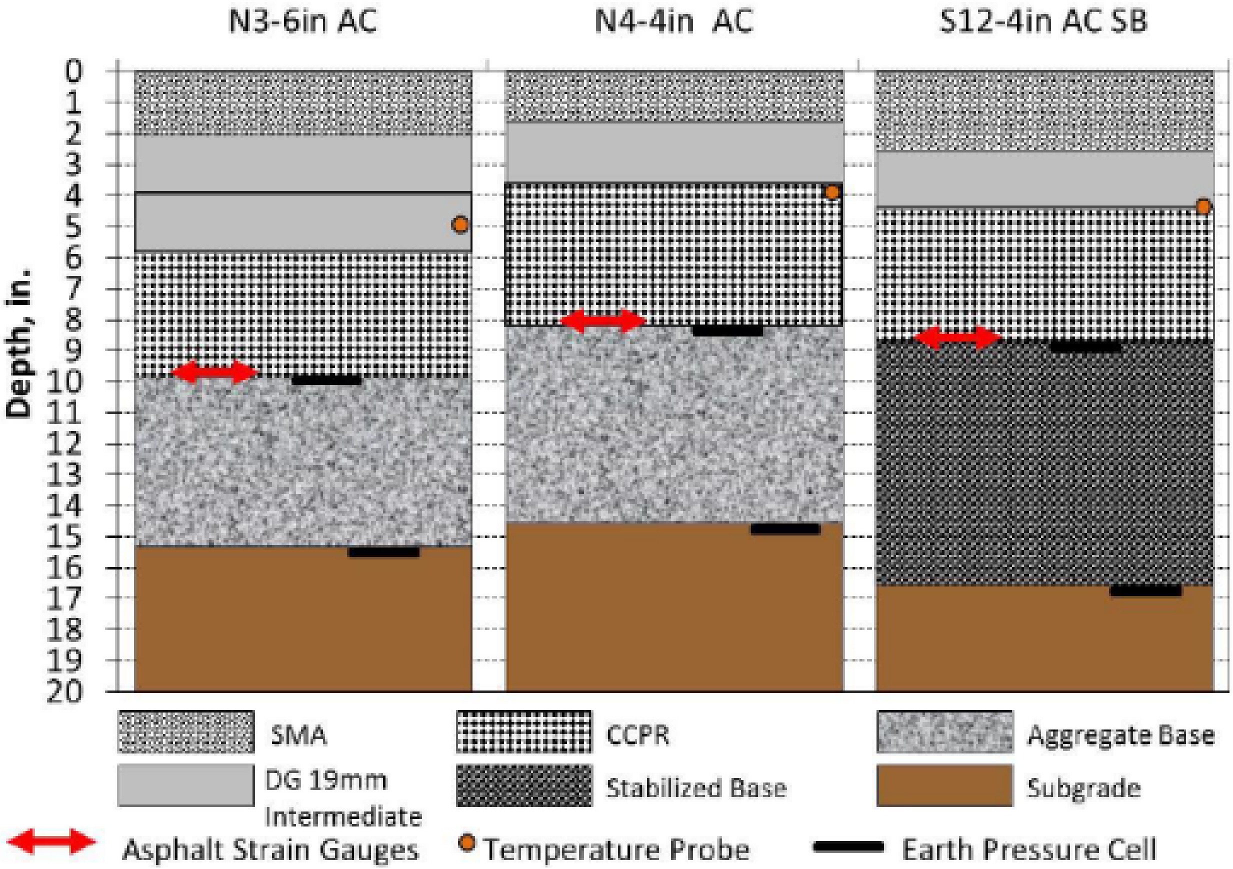


Figure 29. Schematic of the Pavement Structure of the VDOT Sections at the NCAT Test Track

By means of gauges, probes, and cells embedded during construction within the pavement structure, as shown in Figure 29, strain, temperature, and pressure were recorded at various depths. Besides the instrumentation, researchers conducted gradation and binder content tests on loose CCPR material obtained during construction of the test sections. In addition, dynamic modulus tests were conducted on specimens fabricated from the same material using an SGC. To assess field performance, rut depth and ride quality (i.e., IRI index) were measured employing a vehicle-mounted sensor. Additionally, measurements of structural capacity were made at four locations within each test section using FWD.

The time required to apply the defined traffic load was 2 years, after which, the researchers found no observable surface distresses in any of the test sections. The strain measurements at 68°F (20°C) showed an average deformation on Section N3 that was 40 percent lower than that of Section N4, whereas Section S12 displayed an average strain at 68°F (20°C) that was

69 percent and 49 percent lower than the measurements recorded in Sections N3 and N4, respectively. According to the strain response, researchers ranked the sections from better performance to worst as S12 > N3 > N4. In addition, a time-increasing strain response for Section N4 was detected, while Section N3 remained constant along the loading period. This difference in strain response was attributed to the presence of damage in Section N4, which was prevented in Section N3 due to the additional thickness of the surface layer. Nevertheless, researchers concluded that all sections were suitable for high traffic applications because less than 0.3-inch rutting was measured on them.

III.2.4. Cost Assessment

Prices of pavement layers produced from cold recycling operations is of interest to determine comparative first costs associated with various rehabilitation alternatives. The costs associated with cold recycling operations vary by individual project. The size of the project, mobilization, material prices, and quantity of materials (stabilizers) and the cost of pulverization, mixing, laydown, and compaction are all significant variables on a project. Representative costs and ranges are determined and shown in Appendix B.

A first-cost comparison was conducted for new pavement construction and two hypothetical rehabilitation scenarios involving various deterioration conditions, materials, and thicknesses for the surface layer. A minimum of two rehabilitation alternatives were assessed per scenario based upon cost assumptions provided in Appendix B. The cost information is presented in units of dollars per square yard of surface area per inch of pavement thickness ($/sq yd-inch) due to the convenience for comparison of different pavement structures alternatives.

Scenario 1 involved the repair of an existing roadway that is unsurfaced and has a 6-inch (152.4-mm) aggregate base. The assumption is that traffic has been using the unsurfaced roadway for a number of years, the traffic volume has increased, and the dusting due to traffic has become a more serious problem. The repair strategies provide for both strengthening of the roadway and the placement of an all-weather/dust free surface. In Scenario 1, Alternative A applied 6 inches (152.4 mm) of additional aggregate base (either on top of existing base or mixed with existing base) plus CCPR and a chip seal. Alternative B retained the existing aggregate base and added HMA as the surfacing material. The representative costs for Scenario 1 are listed in Table 12.

Table 12. Rehabilitation Scenario 1 Representative Costs

Alternative	Layer	Description	AASHTO Coefficient	Layer Thickness (in.)	Costs ($/sq yd-in.)	Costs ($/sq yd)
A	1	Chip Seal	0.00	0.5	2.5	2.5
	2	CCPR	0.35	5.0	2.4	12.5
	3	Aggregate base	0.12	6.0	1.2	7.2
	4	Existing aggregate base	0.10	6.0	0.0	—
					Subtotal	**21.7**
B	1	HMA	0.44	5.5	4.00	22.00
	2	Existing aggregate base	0.10	6	0.00	0.00
					Subtotal	**22.0**

Scenario 2 assumed the repair of an existing roadway that had a surface of 4 inches (101.6 mm) of asphalt-bound materials (chip seal and/or hot-mix and/or cold-mix build-up over the years) on top of 6 inches (152.4 mm) of aggregate base. The asphalt surface had numerous types of distress and needed repair. In addition, the traffic volume was forecast to increase over the next 20 years. In Scenario 2, Alternative A used the CIR process to recycle the top 3 inches (76.2 mm) of the existing pavement and placed a 3-inch (76.2-mm) HMA layer as the surface. Alternative B was a typical HMA overlay placed to a depth of 3.75 inches (95.3 mm). The existing pavement remained in place without major repair prior to overlay. The life of this pavement could be less than predicted from a pavement structural design standpoint. The representative costs for Scenario 1 are listed in Table 13.

Table 13. Rehabilitation Scenario 2 Representative Costs

Alternative	Layer	Description	AASHTO Coefficient	Layer Thickness (in.)	Costs ($/sq yd-in.)	Costs ($/sq yd)
A	1	HMA	0.44	3	4.00	12.00
	2	CIR	0.35	3	2.10	6.30
	3	Existing aggregate base	0.10	7	0.00	0.00
					Subtotal	18.30
B	1	HMA	0.44	3.75	4.00	15.00
	2	Existing HMA	0.20	4.00	0.00	0.00
	3	Existing aggregate base	0.10	6.00	0.00	0.00
					Subtotal	15.00

According to the results obtained for the first-cost analysis of cold operations, both CIR and CCPR are cost-effective recycling options. This economic assessment showed that savings on the order of 20 percent to 50 percent are possible when cold recycling is compared with removal and replacement of pavement regarding first-cost savings based on equivalent structural pavement sections. However, the data developed in this analysis are for general comparison, and actual values may change.

III.3. National Recycling Specifications

Florida's experience with CIR at the state level has been limited to aviation projects, with about five projects constructed between 1997 and 2010 and three projects constructed between 2011 and 2014 (Fowler, 2011). However, local governments, including St. Johns and Bradford counties have done a handful of CIR projects. In-place recycling has been performed mainly on roads with less than 3 million ESALs, with dense-graded surface courses, and no structural issues.

A review of FDOT's *Standard Specifications for Road and Bridge Construction* (2017) indicated that as of July 2016 no specifications were available for CIR (partial depth) or CCPR operations (a developmental specification for FDR is available). Table 14 summarizes some of the sections on FDOT specifications that are relevant to this project. Section 210 for *Reworking Limerock Base* allows the existing asphalt-bound surfacing materials to be mixed with limerock as part of the reworking operation. Sections 901 and 911 define the properties of recycled concrete aggregate (RCA): RCA shall not contain in excess of 1.0 percent bituminous concrete. FDOT specifications, Section 283, defines the properties and use of *Reclaimed Asphalt*

Pavement (RAP) Base, where RAP is placed and compacted in a base course layer. Additional binders (emulsion or foamed) or other stabilizers are not specified for use. Milling of an existing asphalt pavement is defined under Section 327: cold milling machines are used to remove existing asphalt-bound pavement layers.

Table 14. FDOT Specifications—July 2016

Section	Title	Description	Comments
200	Rock Base	Base course with base rock	Do not use recycled concrete aggregate base on Interstate Highway (IH). May reuse existing base. Material requirements in Section 911.
204	Graded Aggregate Base	Base course of graded aggregate	Gradation and material requirements in specification.
210	Reworking Limerock Base	Rework existing base by adding new limerock	Limerock meet requirements of Section 911. May mix existing asphalt surface with limerock.
230	Limerock Stabilized Base	Base course of roadbed soil stabilized with limerock	Mix limerock with existing soil.
234	Superpave Asphalt Base	Hot-mix asphalt	RAP can be used.
283	RAP Base	Base course composed of RAP material	Use only on non-traffic bearing applications. RAP from milling or crushing. Does not use additional binder or other stabilizers.
285	Optional Base Course	Base course of graded aggregate (204), asphalt (234), limerock (200), shell base (200), shell rock (200), cemented coquina (200), or recycled concrete aggregate (200) (RCA)	RCA not allowed on IH.
290	Granular Subbase	Granular subbase as a component of an optional base-graded aggregate (204-2), limerock (911), bank run shell (911), shell rock (911), cemented coquina (911), recycled concrete aggregate (RCA) (911)	RCA not allowed on IH.
327	Milling of Existing Asphalt Pavement	Removal of existing AC pavement by milling	
338	Value Added Asphalt Pavement	AC with 3-year warranty period	
339	Miscellaneous Asphalt Pavement	Asphalt pavement where no vehicular traffic	

Table 14 (Continued). FDOT Specifications—July 2016

Section	Title	Description	Comments
901	Coarse Aggregate	Coarse aggregate requirements	Reclaimed Portland cement concrete aggregate (RCA) requirements defined. RCA Shall not exceed 1.0% bituminous concrete. Standard gradations of coarse aggregate (passing/retained basis).
902	Fine Aggregate	Fine aggregate requirements	
911	Base and Stabilized Base Materials	Materials to be used for base and subgrade stabilization	Reclaimed Portland cement concrete aggregate (RCA) requirements defined. RCA Shall not exceed 1.0% bituminous concrete.
914	Stabilization Materials	Materials used for subgrade stabilization	May use asphalt coated base, RAP.
916	Bituminous Materials	Approved products list specification	Specifications for asphalt cements (PG), emulsions.

Florida's Local Agency Program (LAP) provides towns, cities, and counties with the ability to develop, design, and construct transportation facilities using federal funds through the Federal-Aid Highway Program. LAP Specification 324, *Reworked Asphalt Concrete Pavement for Local Agency Use*, was reviewed due to its relevance to this project (FDOT, 2011). The general objective of this specification is to "construct a binder course asphalt pavement layer using milling and plant-produced hot-mix asphalt or the hot-in-place recycling process." For mix design, the specification prescribes preparing mixtures in the laboratory using the SGC at 50 or 75 gyrations to an AV content of 3.5 to 4.5 percent and a minimum effective binder content of 4.5 percent. Prior to construction, all defective portions of the existing pavement are to be repaired. Cold milling or hot scarifying are given as options to remove an existing pavement layer. Quality control measures and remedial work in case pavement distress occurs are also outlined in the specification.

Other state DOT and agency specifications were reviewed to assess current practices regarding mix design of cold recycling. Table 15 summarizes several of these specifications and provides details about type of bituminous stabilizing agent, mixing and compaction requirements, curing methods, density requirements, procedure to determine the optimum binder content, and test criteria. As can be observed in Table 15, the majority of the states recommend 30 gyrations in the SGC for compaction, with some still employing the 75-blow Marshall method. With respect to curing, about half the states utilize a temperature of 40°C and the other half 60°C. Oven drying at a lower temperature usually requires more time to achieve constant mass. The optimum binder content (OBC) is selected mostly based on IDT strength or Marshall stability with various criteria.

Table 15. Summary of Mix Design Criteria for Bituminous Stabilization

Agency/ State	**ARRA**	**Wirtgen Group**	**Wirtgen Group**	**California**	**Texas**	**Texas**	**Colorado**	**Illinois**	**Kansas**	**Iowa**
Specification Name	CR201	Cold Recycling Manual	Cold Recycling Manual	LP-8	Trial Specification	S.S. 3017	CP-L 5111	S.P. LR 400-5	C.M. Part V-5.3.4	I.M. 504 App. B
Specification Year	2016	2012	2012	2005	Draft	2015	2014	2012	2014	2016
Stabilizing Agent	Emulsion	Emulsion	Foamed Binder	Emulsion	Emulsion	Foamed Binder	Emulsion	Emulsion	Emulsion	Emulsion
Mix & Compaction Moisture Content (MC)	1.5 to 3.0%	OFC (Optimal Fluid Content) AASHTO T-180	75% OMC	1.5 to 2.5%	OMC Tex-113-E	OMC (Tex-113-E)	2%MC	MC needed for emulsion dispersion	1.5 to 2.5%	1.5% MC
Compaction	75 blows per side by a Marshall 30-Gyrations SGC	Modified Marshall (75 blows per face)	Modified Marshall (75 blows per face)	75-blows Marshall or 30-gyration SGC	Minimum of 50 and a maximum of 60 blows of a10-lb rammer.	Compact test specimens (Tex-206-F)	30-Gyrations SGC	30-gyration SGC	30-gyration SGC	30-gyration SGC
Curing	60 ± 1 °C to constant weight for at least 16 hours but not more than 48 hours	Oven at 40°C to constant mass (72 h)	Oven at 40°C to constant mass (72h)	60°C to constant mass (in 16 to 48 h)	72 hr. at 40°C before testing	Oven-dry test specimens at 40°C for a minimum of 72 hr	60°C to constant mass	Not Specified	60 °C to constant mass (in 16 to 48 h)	60 °C for 48 h

Table 15 (Continued). Summary of Mix Design Criteria for Bituminous Stabilization

Agency/ State	ARRA	Wirtgen Group	Wirtgen Group	California	Texas	Texas	Colorado	Illinois	Kansas	Iowa
Density	Bulk Specific Gravity of Compacted, Cured Specimens AASHTO T 166 (ASTM D2726) Maximum Theoretical Specific Gravity AASHTO T 209 (ASTM D2041)	Bulk Specific Gravity	Bulk Specific Gravity	Maximum Theoretical Specific Gravity AASHTO T 209 (ASTM D2041) Bulk Specific Gravity of Compacted, Cured Specimens AASHTO T 166 (ASTM D2726)	Maximum Dry Density (DA) Tex-113-E	Maximum Density determined (Tex-113-E)	Maximum specific gravity of the sample according to CP 51 (AASHTO T 209 or ASTM D2041)	Bulk Specific Gravity (Density), ASTM D 6752 or ASTM D 2726 Rice (Maximum Theoretical) Specific Gravity, ASTM D 2041	Maximum Theoretical Specific Gravity AASHTO T 209 (ASTM D2041) Bulk Specific Gravity of Compacted, Cured Specimens AASHTO T 166 (ASTM D2726)	Bulk specific gravity ASTM D 2726

Table 15 (Continued). Summary of Mix Design Criteria for Bituminous Stabilization

Agency/ State	ARRA	Wirtgen Group	Wirtgen Group	California	Texas	Texas	Colorado	Illinois	Kansas	Iowa
Design Binder Content Selection Test	1. Gradation of Un-extracted RAP. AASHTO T 11b & T 27 (ASTM C117b & C136) 2. Indirect Tensile Strength AASHTO T 283 (ASTM D4867) 3.Marshall Stability AASHTO T 245 (ASTM D6927) 4.Tensile Strength Ratio/Retained Marshall Stability based on Moisture Conditioning AASHTO T 283 (ASTM D4867)	1. Indirect Tensile Strength Dry. 2. Indirect Tensile Strength Soak. 3. Tensile Strength Ratio (TSR)	1. Indirect Tensile Strength Dry. 2. Indirect Tensile Strength Soak. 3. Tensile Strength Ratio (TSR)	1. Marshall Stability. AASHTO T245 2. Retained Marshal Stability. AASHTO T245 3. Raveling Test. ASTM D7196	1. Unconfined Compressive Strength (UCS), Tex-117-E Part II 2. Indirect Tensile Strength (IDTS), Tex-226-F1. 3. Retained UCS, Tex-117-E	1. Indirect Tensile Strength (IDT), psi Tex 226-F 2. Moisture Conditioned IDT, psi Tex 226-F 3. Moisture Conditioned UCS, psi Tex 117-E, Part II	HVEEM Stability: CP-L 5106 (T246) Resistance to Moisture-Induced Damage—Lottman Testing: CP-L 5109	1. Indicator Marshall Stability, ASTM D 1559. 2. Retained Stability AASHTO T245 3. Raveling Test. ASTM D7196	1. Marshall stability, KT-14. 2. Retained stability based on cured stability. 3. Raveling Test, KTMR-38	1. Marshall Stability ASTM D 1559 Part 5 2. Retained Stability AASHTO T245 3. Thermal Cracking FHWA LTPPBind software for 50% reliability at 3 inches below the pavement surface 4. Raveling Test. ASTM D7196

Table 15 (Continued). Summary of Mix Design Criteria for Bituminous Stabilization

Agency/ State	ARRA	Wirtgen Group	Wirtgen Group	California	Texas	Texas	Colorado	Illinois	Kansas	Iowa
Test criteria	1. 1.25-inch (31.5-mm) Maximum Per Table 3 2. Minimum 45 psi (310 kPa) 3. Minimum 1,250 lb (5,560 N) g 4. Minimum 0.70	Bituminous Stabilized Material (BMS) Class 1—More than 3 million ESALs 1. ITS Dry > 225 kPa. 2. ITS Soak >100 kPa.	Bituminous Stabilized Material (BMS) Class 1- More than 3 million ESALs 1. ITS Dry > 225 kPa. 2. ITS Soak >100 kPa.	1. 5.56 kN min at 40 °C 2. 70% min at 40°C after V.S. and 24 h soak 3. 2% max, 20-gyr,cured at 21 °C for 4 h	1. 120 psi min. 2. 50 psi min. 3. 80% min.	1. Min 45 psi. 2. Min 30 psi. 3. Min 120 psi.	Highest emulsion content providing the highest stability, with the highest TSR (Tensile Strength Ratio) from Lottman testing, and voids between 6% and 12% in the compacted sample	1. 1250 lb (567 kg) minimum. 2. 70% minimum. 3. 2% maximum at 50 ° F (10oC)	1. 5.56 kN, min at 104o F (40o C) 2. 70% min, at vacuum sat. of 55 to 75%, water bath 770 F (25o C) @ 23 hours, last hour at 1040 F (400 C) water bath. 3. 2 % max at ambient temperature.	1. 1000 lb min. at 100ºF (40ºC) after 2 hour temperature conditioning in a forced draft oven 2. 70% min at saturate to 55% to 75%, soak in a 75ºF (25ºC) water bath for 23 hours, followed by a 1 hour soak at 100ºF (40ºC) 3. -20oC max. 4. 2% Max.

III.4. Life-Cycle Cost Analysis

Scarce funds and limited budgets prompt state agency officials to choose the most cost-effective pavement maintenance and rehabilitation strategies while still providing a high quality of service to the traveling public. LCCA is an essential economic evaluation tool that provides valuable guidance to state agency officials in this process (Braham, 2016). As defined by FHWA, LCCA is an analysis technique that builds on the well-founded principles of economic analysis to evaluate the long-term economic efficiency between alternative investment options (FHWA, 1998).

Besides being used as a decision support tool when selecting pavement type, LCCA is also employed to assess different rehabilitation strategies within the same pavement type. The end result of a successful LCCA is not simply the selection of one alternative over the other, but also the selection of the most cost-effective design strategy for a given situation that provides a greater understanding of the factors that influence cost effectiveness. LCCA considers both short- and long-term activities. Specifically, when it has been decided that a project will be implemented, LCCA will assist in determining the best lowest-cost way to accomplish the project. The LCCA approach enables the total cost comparison of competing design (or preservation) alternatives.

The concept of LCCA in pavement investment decisions has matured over the past 4 decades, and most states have embraced the application of LCCA concepts in their decision-making processes. Over the past few decades, various agencies and institutions have developed methodologies for pavement LCCA, and some of these organizations have gone a step further to develop computer software for their LCCA methodologies to facilitate the analysis. Organizations that have supported the development of LCCA for pavement design and management include the Asphalt Institute, the American Concrete Paving Association, the Asphalt Pavement Alliance, the American Association of State Highway and Transportation Officials, FHWA, and many DOTs (Curry and Anderson, 1972; Darter et al., 1987; Markow 1991; Witczak and Mirza, 1992; AASHTO, 1993; FHWA, 1998; Lamptey et al., 2005).

The cost and savings associated with recycling are usually dependent on the amount of RAP included in the mixture. A recent LCCA coupled with a life-cycle assessment over a 45-year analysis period, as recommended by the Illinois DOT, indicated cost savings on only the binder course of 15 percent, 22 percent, and 28 percent for recycled mixtures with 30 percent, 40 percent, and 50 percent RAP, respectively (Aurangzeb and Al-Qadi, 2014). The analysis also demonstrated savings in terms of energy use and reduction of greenhouse gas emissions of 28 percent.

There are some limitations associated with the use of the majority of the existing LCCA models. For example, user costs, preventive maintenance treatments, and uncertainty of input parameters are often excluded in most LCCA methods. Compared to other LCCA analysis methods, the FHWA RealCost software is widely used by several state agencies because of its comprehensive treatment of different input parameters (Lamptey et al., 2005). Further, FHWA has been instrumental in providing support to customize the RealCost software to meet individual state DOT needs.

IV. EXPERIMENTAL PLAN

IV.1. Material Selection

To evaluate the performance of the hot and cold recycled asphalt mixtures, two types of virgin aggregate—limestone and granite— were selected. The binder used in the case of the hot recycled mixtures was a PG 52-28 in accordance with FDOT specifications, Section 334-2.3.5., which prescribes the binder PG for mixtures with various percentages of RAP. For the cold recycled mixtures, a PG 67-22 was used in the foamed binder case as well as an emulsion commercially available in Florida. Two sources of RAP were also included: limestone and a mix of granite/limestone.

In regard to the recycling agents, two petroleum-based recycling agents (one that FDOT has successfully used in past projects and a separate commercially available product) and two organic-based products (a modified vegetable oil and a bio-based oil) were selected. After an initial evaluation, the best from each category (one petroleum-based and one organic-based) were used for mixture preparation. Lime and Portland cement were included in cases where poor moisture susceptibility or strength was observed to assess improvements in the recycled mixture performance.

IV.2. Test Procedures

To characterize the virgin aggregate, binder, and RAP, the standard laboratory tests listed in Table 16 were employed.

Table 16. Experimental Plan Selected Material Properties

Material Type	Material Property	Standard Test Method
Virgin Aggregate	Gradation Specific Gravity & Absorption	AASHTO T 27 FM 1-T084 & FM 1-T085
Binder	PG, ΔT_c Master Curve, Glover-Rowe (G-R) parameter	AASHTO M 320
RAP	Binder Content Gradation PG, ΔT_c, master curve, and G-R parameter of the extracted binder	FM 5-563 AASHTO T 255 FM 1-T030 AASHTO M 320
Recycling Agent	High Temperature PG*	AASHTO M 320

* Test performed on binder blends: virgin binder + extracted RAP binder + recycling agent.

The specific gravity and absorption per FM 1-T084 and FM 1-T085 of the limestone and granite aggregates were provided by FDOT, while the gradation was measured following AASHTO T 27.

To characterize the binders, AASHTO M 320 was followed, including measurements of stiffness and phase angle before and after RTFO and PAV in the DSR and stiffness and relaxation after RTFO and PAV in the BBR. The information obtained from the BBR was also used to determine the ΔT_c parameter, which was calculated as the difference between low temperatures where the binder reaches the thresholds for stiffness and relaxation: S = 300 MPa and m-value = 0.30. This parameter is used as an indicator of the quality of the binder in regard to its ability to be ductile, be in a state of relaxed stress, and therefore be more resistant to cracking.

In addition, a master curve before and after RTFO and PAV aging was developed using a range of temperatures (i.e., 41–77°F [5–25°C]) and frequencies (i.e., 0.01–16 Hz) at each temperature in the DSR. The information was processed using RHEA^{TM} software to estimate the G-R parameter, observe the evolution of this value with binder aging, and compare against the damage zone thresholds in the Black space diagram that define the onset and propagation of cracking, as previously shown in Figure 4.

The RAP from the proposed limestone and granite/limestone sources was characterized by determining binder content per FM 5-563 and gradation per FM 1-T030 after and before burning the binder in the ignition oven. The binder from the RAP was extracted and recovered following FM 5-524 and FM 3-D5404, respectively. The extracted binder was characterized using the same test methods employed to test the virgin binders, including PG, ΔTc, and master curve.

IV.3. Recycling Agent

IV.3.1. Selection and Dose

As previously mentioned, four types of recycling agents were initially evaluated, two petroleum-based and two organic-based. These recycling agents are henceforth labeled P1, P2, O1, and O2 according to their type. The recycling agent evaluation consisted of blending the virgin binder, the extracted and recovered RAP binder, and the recycling agent and measuring the PGH of the binder blend before and after 40-hr PAV aging.

The recycling agent used in the binder blend from each category that registered the least change with aging in PGH was selected for mixture preparation. The initial and optimum recycling agent doses were estimated following the methodology developed in NCHRP Project 09-58 and previously discussed in Chapter III.

The optimum recycling agent dose was verified by preparing binder blends with 0, 2, and 10 percent recycling agent and measuring the PGH. The validation procedure utilized the PGH of the recycled blend to estimate the maximum dose that could be incorporated without causing a rutting problem. This procedure was done by limiting the dose to match the PGH_{Blend} to that of the PGH_{Target}.

IV.3.2. Addition Method

For mixture preparation, two recycling agent addition methods were initially explored: (a) adding the recycling agent to the binder (as it is traditionally done in the laboratory and most asphalt plants), and (b) adding it directly to the RAP and letting it marinate before the mixing process. To evaluate the most effective addition method, the workability of a selected mixture during compaction and its coatability after compaction were measured.

The plan was to select the addition method that yielded better workability and/or coatability for preparation of all the recycled mixtures. However, as will be detailed in Chapter V, no significant differences between the two addition methods were observed, and the traditional option of adding the recycling agent to the binder was pursued. The techniques followed to measure workability and coatability are described next.

Workability is a property that describes how easy it is to place and compact a mixture, and it is a function of several factors, such as the temperature of the mixture, characteristics of the binder (e.g., viscosity, PG, polymer modification), and properties of the aggregate (e.g., size, angularity), among others. The proposed method to evaluate workability is based on work done by De Sombre et al. (1998) in quantifying the workability of mixtures with various aggregate gradations and binders to define optimum compaction temperatures and employs the SGC shear stress data. The principle is that resistance to shear stress in the mixture is provided by internal friction from a combination of the angularity and hardness of the aggregate and the cohesion provided by the binder, as shown in Figure 30 (De Sombre et al., 1998). Mixtures with lower SGC maximum shear stress and not exceeding 200 SGC gyrations are considered workable.

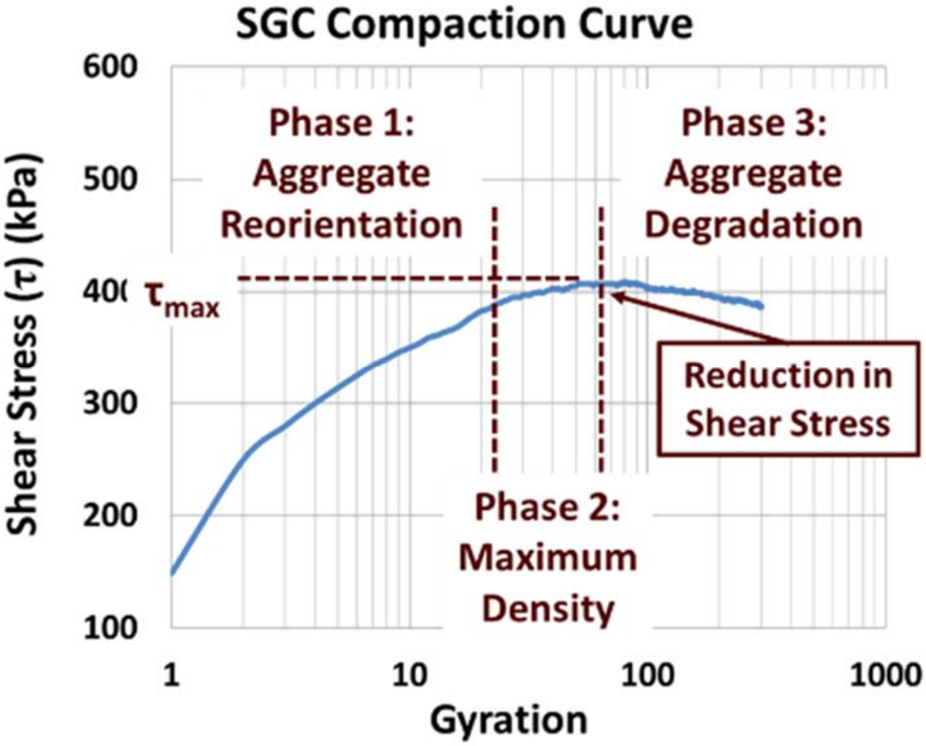


Figure 30. Example of Shear Stress vs. Number of Gyrations in the SGC

Coatability of mixtures is a measure of how well the binder distributes itself over the surface of the aggregate particles in the mixture. This parameter is important to the performance of mixtures since well coated aggregates are likely to have a stronger bond between the particle and the binder and thus have a better resistance to moisture damage and other distresses. The proposed method to evaluate the coatability index (CI) is based on work done at the University of Wisconsin (Velasquez et al., 2012) and further refined as part of NCHRP Project 09-53 *Properties of Foamed binders for Warm Mix Asphalt Applications* (Newcomb et al., 2015) and uses the relative difference in measurement of water absorption of bare coarse aggregate versus the water absorption of coated coarse aggregate. The assumption is that a completely coated aggregate submerged in water for a short period (e.g., 1 hour) cannot absorb water because water cannot penetrate through the film of binder surrounding the surface of the aggregate, while a partially coated aggregate is expected to have detectable water absorption since water is able to penetrate and be absorbed by the uncoated particle.

To quantify the CI, the coarse portion of the aggregate gradation (adjusting for the change in surface area with respect to the full aggregate gradation) was mixed with the binder for 60 seconds and the resulting coated aggregate sample was conditioned for 2 hours at 275°F (the temperature can be reduced to 240°F if warm-mix additives are used). Both the coated and uncoated aggregate samples are weighed to obtain their oven-dry weights. Samples of uncoated coarse aggregate and coated coarse aggregate are soaked in water for a period of 1 hour. The samples are then brought to a saturated surface dry (SSD) condition and weighed again. The relative difference in water absorption between the two samples is the CI. A threshold value of 70 percent for the CI was established by Newcomb et al. (2015).

IV.4. Mixture Characterization

The selected combinations to evaluate the performance of the hot and cold recycled mixtures as well as the performance tests employed are described next.

IV.4.1. Hot Recycled Mixtures

IV.4.1.1. Mixture Types

The selected material combinations for hot recycled mixtures are listed in Table 17. The RAP and aggregate were proportioned in accordance to FDOT specifications, Section 334, that requires following AASHTO M 323 for the combined aggregate gradation. Depending on the gradation of the RAP, a NMAS of 9.5 mm or 12.5 mm was used.

Table 17. Hot Recycled Mixture Types

Mixture ID	RAP Type and Amount (%)		Aggregate Type		Recycling Agent Type		Additive
	Limestone	Granite/ Limestone	Limestone	Granite	Petroleum -Based	Organic-Based	Lime
H-60L-L	60	–	×	–	–	–	–
H-60G-G	–	60	–	×	–	–	–
H-60L-LP	60	–	×	–	×	–	–
H-60L-LO	60	–	×	–	–	×	–
H-60L-GP	60	–	–	×	×	–	–
H-60L-GO	60	–	–	×	–	×	–
H-60G-GP	–	60	–	×	×	–	–
H-60G-GO	–	60	–	×	–	×	–

× Combination selected for the experimental plan.
– Combination not included in the experimental plan.

The OBC was determined for virgin mixtures fabricated with limestone and granite aggregate. No RAP content was included. Three binder contents were selected to estimate the OBC. After mixing, the loose mix was conditioned in the oven for 2 hours at 275°F (135°C) to simulate the asphalt plant production process. After this period, all specimens were molded in the SGC to N_{Design} = 50 gyrations, as established in FDOT specifications, Section 334-3.2.4, for a traffic level of less than 0.3×10^6 ESALs, and in accordance with AASHTO T 312. The selected OBC that satisfied density, voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and dust-to-binder ratio requirements, as specified in AASHTO M323-12, Table 6, and required by FDOT specifications, Section 334-3.2.5, was then assigned to the recycled mixtures listed in Table 17 according to their virgin aggregate type.

IV.4.1.2. Performance Testing

Specimens at the selected OBC and recycling agent dose were prepared and tested to verify adequate performance using the test methods listed in Table 18. The aggregate was heated overnight at the mixing temperature, while the binder and the RAP were introduced in the oven about 2 hours prior to mixing. The recycling agent was blended with the binder roughly 30 minutes before mixing. The loose mix was conditioned in the oven for 2 hours at 275°F (135°C) and further compacted to a target density of 7.0 percent ± 0.5 percent in the SGC for performance testing. The specimen dimensions varied according to the type of test to be conducted. A minimum of three replicates were produced for each test. A brief description of the test methods is provided next.

Table 18. Hot Recycled Mixtures Performance Tests

Mixture Property	Test Method	Test Standard	Test Parameter
Intermediate Temperature Cracking	Semicircular Bending (SCB)	AASHTO TP 124	Flexibility Index (FI), Cracking Resistance Index (CRI)
Rutting & Moisture Susceptibility	Hamburg Wheel Tracking Test (HWTT)	AASHTO T 324	Rut Depth, Stripping Slope, Stripping Inflection Point (SIP), Rutting Resistance Parameter ($\Delta\varepsilon_{SN}^{vp}$)
Moisture Susceptibility	Modified Lottman	FM 1-T 283	Indirect Tensile (IDT) Strength, TSR

Semicircular Bending Test

The Illinois Center for Transportation (ICT) recently developed the Illinois flexibility index test (I-FIT) to assess the intermediate temperature cracking resistance of mixtures (Al Qadi et al., 2015). AASHTO TP 124 was used to conduct the test, and an automated software tool developed by the ICT was employed to process the test data. Specimens with a diameter of 6.0 inches (152.4 mm) and a thickness of 2.0 inches (50.8 mm) were cut in half, and a notch 0.6 inches (15 mm) deep by 0.06 inches (1.5 mm) wide was introduced along the axis of symmetry. The semicircular specimen was placed in a three-point bending configuration, as shown in Figure 31, and a monotonic load at a rate of 2.0 inches/min applied until failure. The test was performed at 77°F (25°C).

The load-displacement curve was plotted and the area under the curve determined (i.e., work of fracture), as well as the slope of the fitted curve post-peak load (m). The FI is the output parameter, which was calculated by dividing the fracture energy by the slope of the post-peak load versus displacement curve, as shown in Figure 32. High FI values are desired for mixtures to provide good cracking resistance.

Figure 31. Semicircular Bending Test: (a) Notched Specimen before Failure, (b) Notched Specimen after Failure, and (c) Test Setup

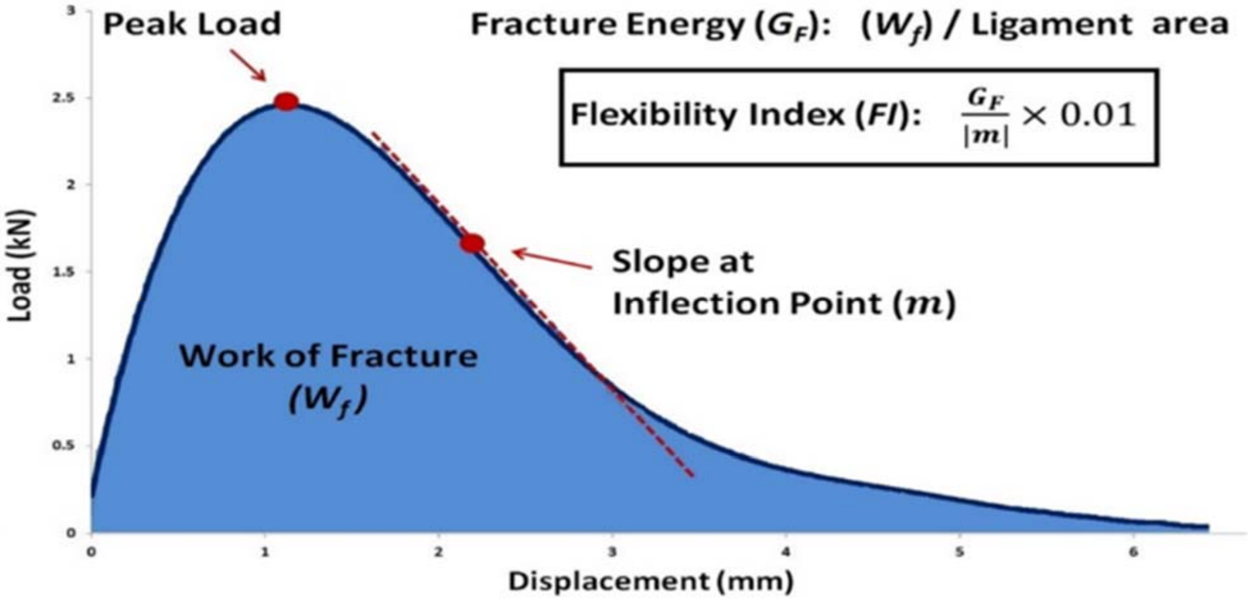


Figure 32. Typical Load-Displacement Curve for a Virgin Mixture Tested in the I-FIT

One of the shortcomings of the FI is that it is not always able to characterize brittle mixtures, especially the ones with high quantities of recycled materials. This shortcoming occurs because no displacement data after the peak load are usually detected on this type of specimen, as shown in Figure 33. Therefore, the slope of the post-peak load versus displacement curve cannot be determined. NCHRP Project 09-58 has proposed an alternative parameter, the CRI, to characterize these types of specimens by taking the fracture energy up to the peak load and dividing it by the magnitude of the peak load measured during the test, as expressed in Equation 3.

$$CRI = \frac{G_f}{P_{max}} \qquad \text{Equation 3}$$

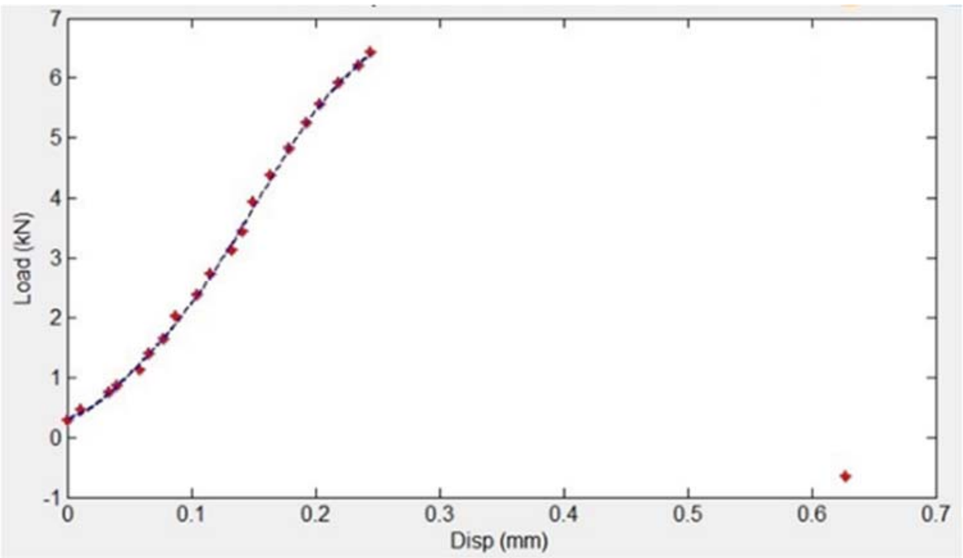


Figure 33. Typical Load-Displacement Curve for a Brittle Mixture Tested in the I-FIT

Hamburg Wheel Tracking Test

HWTT is a common test procedure used to determine susceptibility to rutting and moisture damage. The standard test method is AASHTO T 324. The HWTT utilizes repetitive loading in the presence of water and measures the resulting rut depth with increasing load cycles. Typically, two SGC-compacted specimens with a diameter of 6.0 inches (152.4 mm) and a thickness of 2.4 inches (61 mm) are trimmed and placed side by side in high-density polyethylene molds, as shown in Figure 34a. The specimens are submerged in water at a temperature of 122°F (50ºC), left to saturate for about 30 minutes, and subjected to 52 passes of a steel wheel per minute (Figure 34b). During testing, the equipment records the number of passes and the rut depth along the path of the steel wheel. Each set of specimens was continuously loaded up to a certain number of load cycles or until the center of the specimen deforms by 0.5 inch (12.5 mm). The number of load cycles required for satisfactory performance (i.e., rut depth less than 0.5 inch) usually depends on the PG of the binder used to prepare the mixtures being tested.

Traditional analysis of HWTT data divides the output average rut depth versus load cycles curve into three phases: post-compaction phase, creep phase, and stripping phase (Solaimanian et al., 2003). The post-compaction phase corresponds to the initial consolidation of the specimen; the deformation in the creep phase is assigned to the viscous flow of the mixture; and the stripping phase is considered to have started once the bond between the binder and the aggregate degrades, causing visible damage such as stripping or raveling with additional load cycles. The SIP represents the number of load cycles at which a sudden increase in rut depth occurs, and it is graphically represented as the intersection of the fitted lines that characterize the creep phase and the stripping phase, as shown in Figure 35. This traditional analysis assumes that the consolidation phase of the specimen occurs within the first 1,000 load cycles. Then, the creep slope is fitted by assuming a 0.04-inch (1-mm) rut depth increase due to viscous flow, and the stripping slope quantified as the number of passes required to create a 0.04-inch (1-mm) rut depth after stripping begins.


(a) (b)

Figure 34. HWTT: (a) View of Loaded Specimens, (b) View of Apparatus

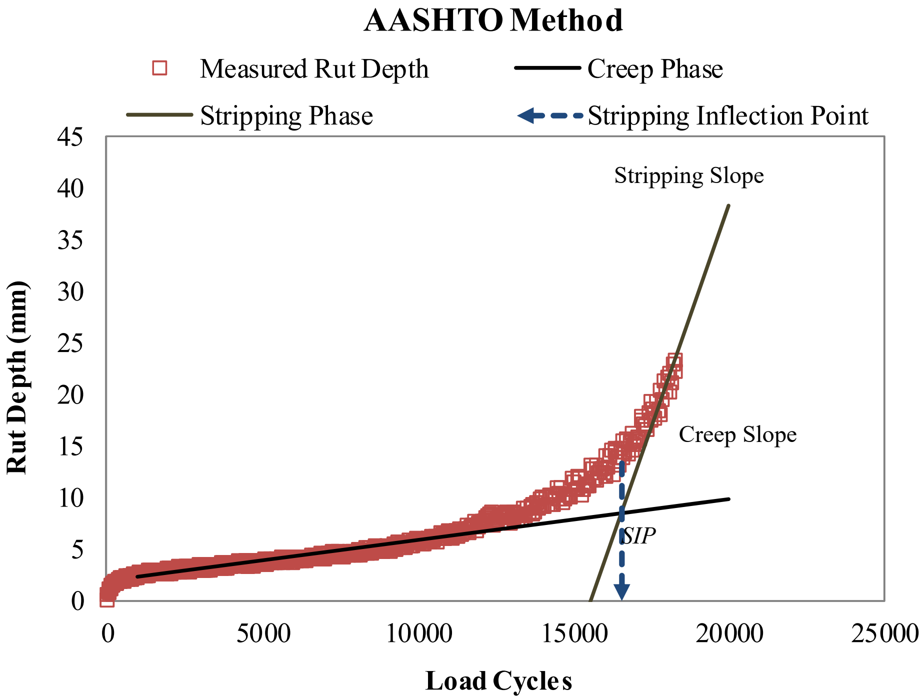


Figure 35. Traditional HWTT Analysis Parameters

Currently, the SIP and average rut depth at a certain number of load cycles are the traditional output parameters used to evaluate moisture sensitivity and rutting resistance of mixtures, respectively. Mixtures with higher SIP values and lower rut depths are considered to have better performance. The downside of the traditional HWTT analysis is that it is based on multiple arbitrary assumptions, and it is highly dependent on the ending point of the test. Therefore, besides the traditional HWTT analysis, a recently developed method by Yin et al. (2014) was used to analyze the HWTT output. This novel method offers several advantages over the traditional analysis, such as not needing to make assumptions about the consolidation, creep, or stripping phases of the mixture. This novel method is based on fitting a curve to the entire rut depth versus load cycles HWTT output using Equation 4.

$$RD_{(LC)} = \rho * \left[\ln\left(\frac{LC_{ult}}{LC}\right)\right]^{-\frac{1}{\beta}} \qquad \text{Equation 4}$$

Where:

LC = load cycles at a certain rut depth,
LC_{ult} = maximum load cycle,
$RD_{(LC)}$ = rut depth of the HWTT specimen at a certain number of load cycles (mm),
ρ and β = regression coefficients.

The fitted curve has a negative curvature at the beginning of the test, followed by a positive curvature after the onset of stripping. If the mixture is moisture susceptible (like Mixture B in Figure 36), the inflection point of the curve (where the curvature changes from negative to positive) will occur earlier than in the case of mixtures that are less affected by moisture. The inflection point is labeled the stripping number (SN), and the number of load cycles to this point, or LC_{SN}, is used as an indicator of moisture susceptibility before stripping (Equation 5). Mixtures with no apparent stripping (like Mixture A in Figure 36) have LC_{SN} values that are larger than the number of load cycles applied during the test.

$$LC_{SN} = LC_{ult}\exp\left(-\frac{\beta+1}{\beta}\right) \qquad \text{Equation 5}$$

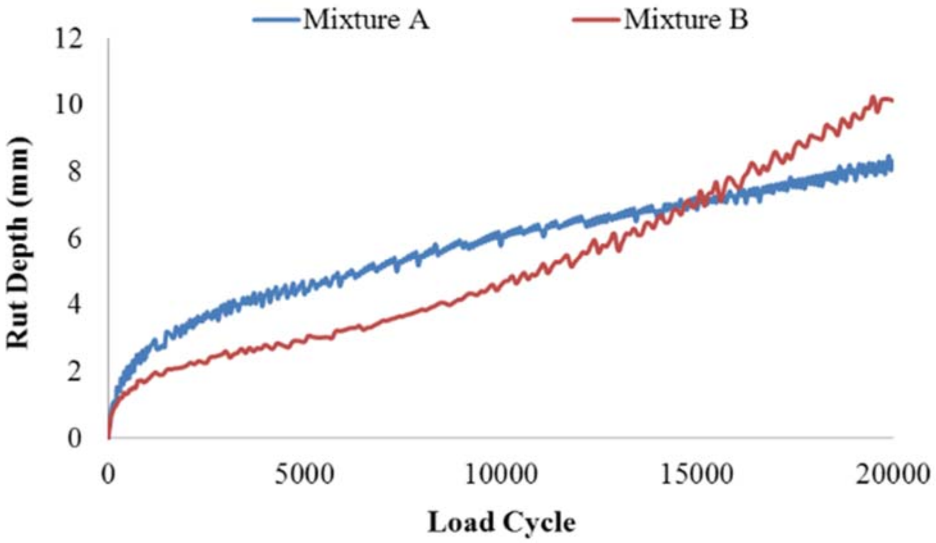


Figure 36. Typical HWTT Rut Depth Trends for Mixtures with No Apparent Stripping (Mixture A) and Mixtures with Rapid Increase in Rut Depth Due to Stripping (Mixture B)

Further, the Tseng-Lytton model (Tseng and Lytton, 1989) is employed to fit the viscoplastic strain before stripping, and the slope at the SN ($\Delta\varepsilon_{SN}^{vp}$) is proposed as a rutting resistance parameter (RRP). Mixtures with lower $\Delta\varepsilon_{SN}^{vp}$ values were expected to have better resistance to moisture damage and rutting.

Modified Lottman Test

In addition to the HWTT output parameters described above that are used to estimate the moisture susceptibility of mixtures, the modified Lottman test—as outlined in Florida test method FM 1-T 283—was conducted to evaluate moisture susceptibility. This test measures the change in IDT strength resulting from the effects of accelerated moisture conditioning: 70–80 percent vacuum saturation, freezing at -18°C for 16 hours, and thawing in a water bath at 60°C for 24 hours. Usually, six to eight specimens are divided in two subsets: three to four specimens to be tested without conditioning (i.e., dry), and three to four specimens to be tested after moisture conditioning. The IDT strength test is performed at room temperature (77°F [25°C]) under a monotonic load applied at a rate of 2.0 inches/minute (50 mm/min). The peak load and specimen dimensions are used to estimate the IDT strength. The ratio of conditioned to dry IDT strength is labeled TSR.

IV.4.2. Cold Recycled Mixtures

IV.4.2.1. Mixture Types

The selected material combinations for cold recycled mixtures are listed in Table 19. The RAP and aggregate proportions were in accordance to FDOT specification, Section 234. To compare against the results of the hot recycled mixtures, a RAP content of 60 percent was selected. For the recycled mixtures with 60 percent granite/limestone RAP, only the emulsion was employed. Additional mixtures prepared with 80 percent limestone and granite/limestone RAP and 100 percent limestone RAP were evaluated. Furthermore, lime as an anti-stripping agent for mixtures with emulsion and Portland cement for mixtures with foamed binder was included in cases with poor moisture susceptibility or strength.

Table 19. Selected Material Combinations for Cold Recycled Mixtures

Mix ID	RAP Type and Amount (%)		Aggregate Type		Binder Type	
	Limestone	Granite/ Limestone	Limestone	Granite	PG 67-22 (Foaming)	Engineered Emulsion
C-60L-LF	60	–	×	–	×	–
C-60L-LE	60	–	×	–	–	×
C-60L-GF	60	–	–	×	×	–
C-60L-GE	60	–	–	×	–	×
C-60G-GE	–	60	–	×	–	×
C-80L-LF	80	–	×	–	–	×
C-80L-LE	80	–	×	–	×	–
C-80G-GE	–	80	–	×	–	×
C-100L-F	100	–	–	–	×	–
C-100L-E	100	–	–	–	–	×

IV.4.2.2. Emulsion Specimens

To estimate the optimum emulsion content, at least three emulsion contents between 2.0 and 8.0 percent were selected to prepare six to eight specimens 6 inches (152.4 mm) in diameter by approximately 1.5 inches (38.1 mm) in height for IDT strength testing. Specimens were compacted in the SGC using 30 gyrations, as currently recommended by ARRA Standard CR201.

Curing of the emulsion specimens was done after compaction in a forced draft oven at 140°F (60°C) to constant weight, which was determined as a maximum of 0.05 percent weight loss in 2 hours. A curing period of 16 hours as a minimum and 48 hours as a maximum are usually recommended (TxDOT, 2004). To establish the curing time, an initial experiment was conducted on two mixtures, C-100L-E and C-60L-LE, periodically measuring the weight. The period required for the mass of the specimen to plateau was selected as the curing time.

IV.4.2.3. Foamed Binder Specimens

The optimum foaming water content for the PG 67-22 binder was determined via expansion ratio (ER) and half-life (H-L). ER is defined as the volume of a foamed liquid at any point relative to its unfoamed volume, while H-L is the period between the maximum ER (i.e., the maximum volume increase experienced by a foamed liquid) to one-half of its value. To measure ER and HL, a novel laser-based non-contact method developed in NCHRP Project 09-53 was employed (Newcomb et al., 2015).

The laser-based sensor known as a laser distance meter (LDM) comprises an emitter and detector. The LDM is set up on a tripod above a standard one-gallon can with a sample of foamed binder at a selected foaming water content (Figure 37a). The LDM measures the height of the foamed binder surface by reflecting light of different wavelengths over a very small circular spot of about 1 mm in diameter. The laser sensor collects data at a frequency of 1 Hz. An exponential equation is then fitted to the recorded data, and with the known weight of the dispensed binder sample, the final height it occupied in the container, and the container size, ER and H-L are determined (Newcomb et al., 2015). An example of the measured and fitted data for a binder foamed with 3 percent water content is shown in Figure 37b.

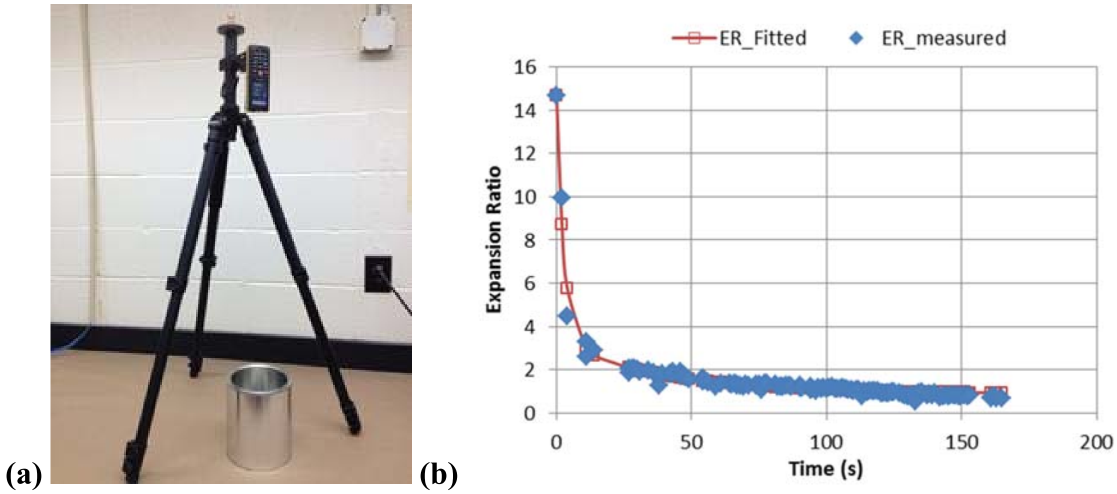


Figure 37. Optimum Foaming Water Content Determination: (a) LDM Equipment Setup, (b) Example of ER Curve Measured with the LDM

At least three foaming water contents were tested, including 1.5 percent, 3.0 percent, and 4.5 percent, and the resulting ER and H-L values were plotted in a graph like the one illustrated in Figure 38. By using the recommended ER and H-L limits put forth by the Wirtgen Group in their Cold Recycling Technology manual (Wirtgen Group, 2012), the optimum foaming water content was established for the PG 67-22 binder.

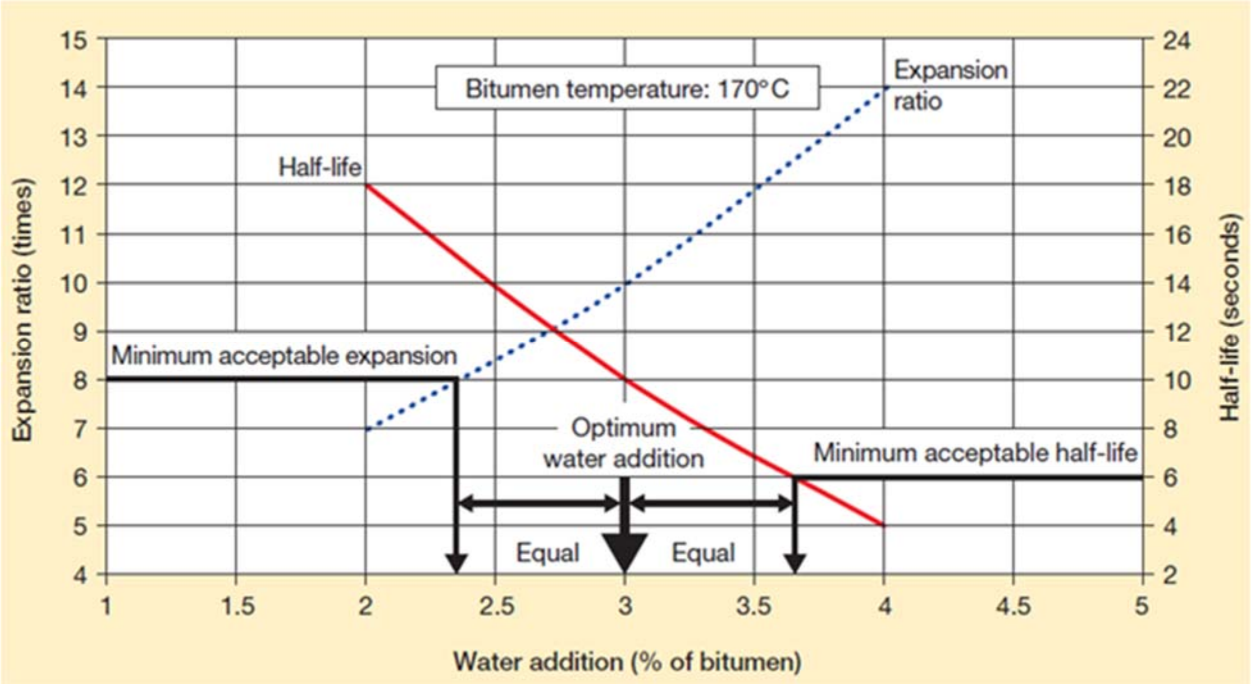


Figure 38. Optimum Foaming Water Content per ER and H-L Limits (Wirtgen Group, 2012)

As was done for the emulsion specimens, three binder contents were selected for the foamed binder specimens to establish the optimum foamed binder content, and six to eight specimens 4.0 inches (101.6 mm) in diameter by 2.8 inches (71.1 mm) tall were prepared for IDT strength testing. Specimens were compacted in the SGC using 30 gyrations.

IV.4.2.4. Performance Testing

After compaction and curing, the specimens were allowed to cool for a minimum of 12 hours before testing. Rice specific gravity per AASHTO T 209 and bulk specific gravity per AASHTO T 166 were determined for all specimens. The specimens were then divided in two subsets with equivalent AV content; three specimens were subjected to IDT strength tests in dry conditions, and the other three were subjected to moisture conditioning by soaking for 24 hours at room temperature (~77°F [25°C]). Then, an optimum emulsion and foamed binder content was selected based on the recommended minimum IDT strength of 45 psi (310 kPa) (ARRA CR201).

Specimens at the selected optimum emulsion/foamed binder content were prepared and tested to verify adequate performance using the methods listed in Table 20 and current thresholds for cold mixtures, when available. The specimen dimensions varied according to the type of test. A minimum of three replicates were considered for each test.

Table 20. Selected Performance Tests for Cold Recycled Mixtures

Mixture Property	Test Method/ Apparatus	Test Standard	Test Parameter
Rutting & Moisture Susceptibility	HWTT	AASHTO T 324	Rut Depth, Stripping Slope, *SIP*, $\Delta\varepsilon_{SN}^{vp}$
Moisture Susceptibility	Modified Lottman with no freeze/thaw cycle	FM 1-T 283	Wet IDT Strength
Raveling	Cantabro Abrasion Loss Test	AASHTO TP 108	Abrasion Loss

Some of the tests listed in Table 20 were also selected for the hot recycled mixtures and were described previously. For HWTT performed on cold recycled mixtures, some researchers have proposed having a minimum of 5,000 passes prior to reaching a 0.5-inch rut depth, and a maximum of 15,000 passes to reach the threshold of a 0.5-inch rut depth (TxDOT, 2004). For moisture susceptibility, FM 1-T 283 was considered but without the freeze/thaw cycle. Only a minimum of 45 psi (310 kPa) for IDT strength was considered for the cold recycled mixtures, as recommended by ARRA CR201.

Raveling

To measure the performance of the mixtures with respect to raveling, the Cantabro abrasion loss test was used. The Cantabro abrasion loss test is used to determine the durability of a mixture in relation to the binder content and grade. It is primarily used for evaluating durability of open-graded friction courses but has recently been used to evaluate other types of mixtures. AASHTO TP 108 and ASTM D7064 are the standard test methods. The procedure consists of preparing compacted specimens and placing them in the Los Angeles abrasion machine (Figure 39a) without the steel balls and turning the drum at a rate of 30 to 33 revolutions per minute for a total of 300 revolutions. At the end of the test, the loose material is discarded, and the final weight of the specimen is used to estimate the abrasion loss using Equation 6. Figure 39b and Figure 39c illustrate a set of specimens before and after the Cantabro abrasion loss test.

(a) **(b)** **(c)**

Figure 39. Cantabro Abrasion Loss Test: (a) Apparatus, (b) Specimens before Test, (c) Specimens after Test

For dense and open-graded mixtures, AASHTO TP 108 recommends a maximum abrasion loss of 15 percent–20 percent, while ASTM D7064 recommends a threshold of 20 percent loss for unaged specimens, 30 percent for aged specimens, and no more than 50 percent loss on an individual specimen.

$$Abrasion\ Loss = \frac{W_1 - W_2}{W_1} \times 100 \qquad \text{Equation 6}$$

Where:

W_1 = initial mass of the specimen.
W_2 = final mass of the specimen.

Resilient Modulus (M_R)

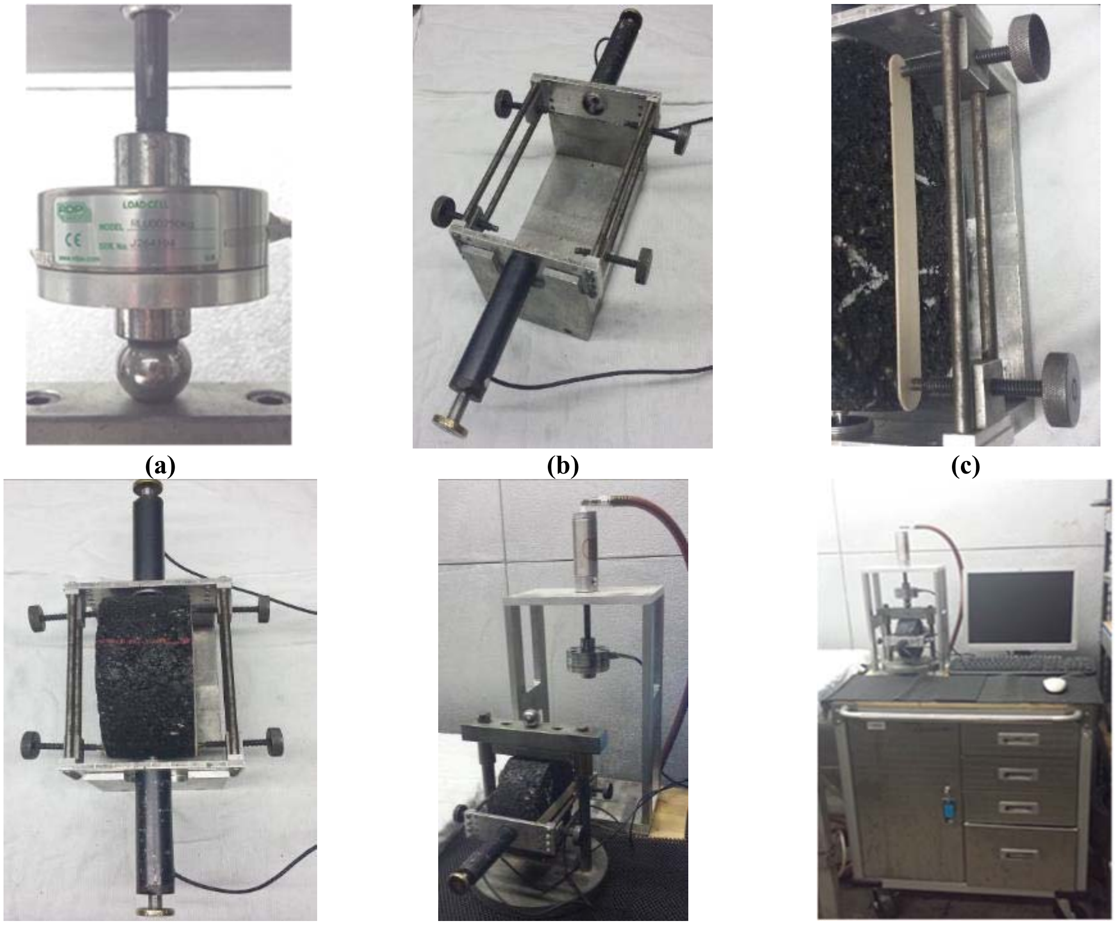
The mixture resilient modulus (M_R) test was conducted in accordance with ASTM D7369. The original test method was developed by Schmidt (1972) and published as ASTM D4123, which was later revised and replaced by ASTM D7369. The equipment used in this study is presented in Figure 40. The test consists of applying a repetitive haversine compressive load pulse of 75 lbf every 0.1 second with a 0.9-second rest period. The load is applied in the vertical diametral plane of the cylindrical specimen (Figure 40e and Figure 40f). The Poisson's ratio is assumed to be constant between 0.25 and 0.45 depending on the testing temperature. Therefore, a Poisson's ratio of 0.35 was selected based on the test temperature of 77°F (25ºC). The horizontal deformation occurring in the specimen due to the repeated load is registered through a set of two linear variable differential transducers (LVDTs) aligned in the diametral plane, perpendicular to the load, as depicted in Figure 40b and Figure 40d. The deformation is registered in the computer attached to the device (Figure 40f).

In accordance with ASTM D7369, M_R is calculated using the assumed Poisson's ratio and the recoverable horizontal deformation registered by the LVDTs as noted by Equation 7.

$$M_R = \frac{P_{cyclic}}{t * \delta_h}(I_1 - I_2 * \mu) \qquad \text{Equation 7}$$

Where:

M_R = instantaneous or total resilient modulus of elasticity, MPa (psi).
P_{cyclic} = cyclic load applied to the specimen, N (lb).
t = thickness of the specimen, mm (in.).
δ_h = recoverable horizontal (instantaneous or total) deformation, mm (in.).
I_1, I_2 = constant values; for gauge length as fraction of specimen diameter = 1.
I_1 = 0.27 and I_2 = −1.00.
μ = instantaneous or total Poisson's ratio.



(a) (b) (c)

(d) (e) (f)

Figure 40. M_R Apparatus: (a) Load Cell, (b) Mounting Support for the Specimen, (c) Detailed View of Support Pins, (d) Specimen on Mounting Support, (e) Mounting Support and Load Cell Assembly, and (f) Final Test Setup

V. HOT RECYCLED MIXTURE RESULTS

This chapter describes the results from the laboratory testing of the hot recycled mixtures, including raw material characterization, recycling agent selection, development of the mix design, specimen fabrication, and performance testing. The materials employed for the production of hot recycled mixtures with 60 percent RAP are shown in Table 21.

Table 21. Recycled Mixture Materials

Material	Type	Product Description	Product Code	Product Name	Plant/Pit Number
Aggregates	Limestone	S1A Stone	C-41	#78 Stone	87339
		Screenings	F-22	W-10 Screenings	
	Granite	S1A Stone	C-47	#78 Stone	GA-553
		Screenings	F-22	W-10 Screenings	
RAP	Stockpile 1-09	Limestone	STK 09		
	Stockpile 1-16	Granite/limestone	STK 16		
Binder	—	PG 52-28	916-52		

V.1. Material Characterization

To understand the performance of the hot recycled mixtures, it was important to characterize the individual mixture components—aggregate, binder, and RAP—by means of the standard laboratory tests described in Chapter IV.

V.1.1. Aggregates

Two aggregate sizes were used for each aggregate type: intermediate size stone (#78) and fine screenings (W-10). The particle size distribution for each of these materials was provided by FDOT and verified employing the *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates* per AASHTO T-27 (AASHTO, 2018). The results showed minimal differences between gradations provided by FDOT and the ones obtained by the Texas A&M Transportation Institute (TTI) research team. These gradations can be found in Appendix C.

Table 22 presents the oven-dry bulk specific gravity ($Gs_{(OD)}$) of the aggregates provided by FDOT. Other physical properties of the aggregates are presented in Appendix D.

Table 22. Aggregates Oven-Dry Bulk Specific Gravity (GS $_{(OD)}$)

Aggregate Type	Product Name	$G_{sb\,(OD)}$ (−)
Limestone	#78 Stone	2.407
	W-10 Screenings	2.520
Granite	#78 Stone	2.775
	W-10 Screenings	2.740

V.1.2. Binder

The binder used corresponds to a PG 58-28 in accordance to FDOT specifications, Section 334-2.3.5, which identifies this binder grade as the one required for the production of mixtures with high RAP content.

Following the methodology defined in AASHTO M 320, *Standard Specification for Performance-Graded Asphalt Binder* (AASHTO, 2017a), measurements of stiffness and phase angle were conducted before and after RTFO and PAV in the DSR. Binder stiffness and relaxation after RTFO and PAV were also investigated at low temperatures in the BBR. Table 23 displays the determined continuous high and low temperatures PG of the binder. Appendix E presents detailed results of the binder PG determination.

Table 23. Binder PG 52-28 Continuous Grade

Binder Type	**Continuous Grade**	
	High-Temp PG (ºC)	**Low-Temp PG (ºC)**
Virgin Binder PG 52-28	56.9	−31.3

Using the information obtained from the BBR, the ΔT_c parameter was estimated as 0.8°C for the PG 52-28 binder (See Figure 41). This parameter is an indicator of binder quality with regard to its resistance to low temperature cracking. A less negative or even positive ΔT_c value indicates good binder quality (i.e., better ductility).

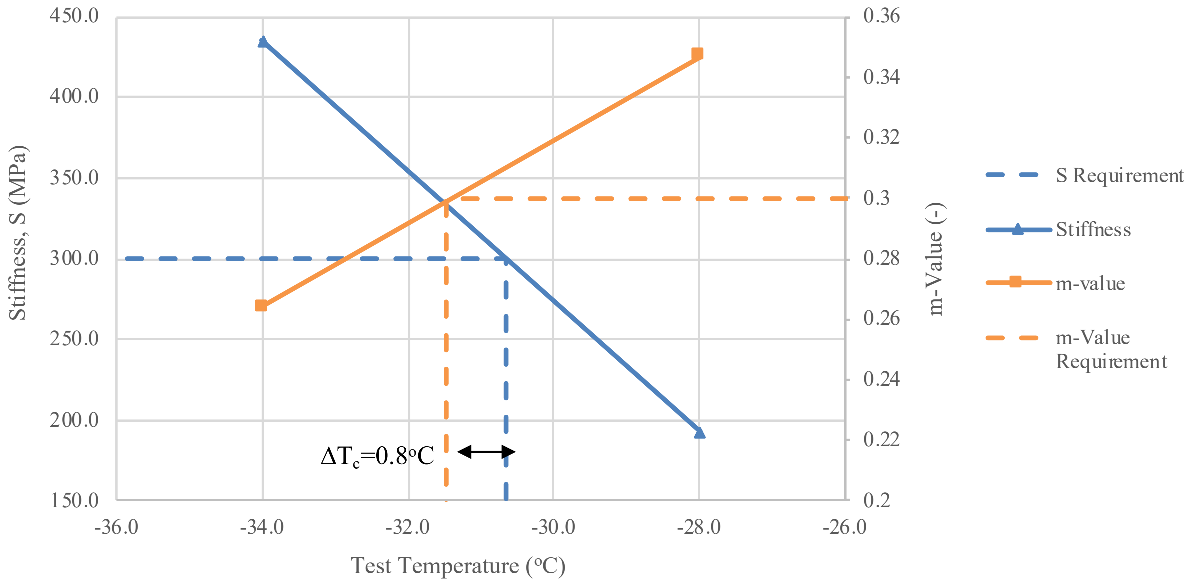


Figure 41. PG 52-28 ΔT_c Parameter Estimation

The binder aging process was characterized employing the G-R parameter. Master curves before and after RTFO plus 20-hour, 40-hour, and 60-hour PAV aging were developed in the DSR. Using the RHEA™ software, complex modulus (G*), phase angle (δ) at a temperature of 59ºF (15ºC), and load application frequency of 0.005 rad/s were estimated and later employed in the determination of the G-R parameter by means of Equation 8.

$$GR = \frac{G'}{\eta'/G'} = \frac{G^{*}Cos^{2}(\delta)}{\sin(\delta)} \qquad \text{Equation 8}$$

The G-R parameter was plotted in a Black space diagram and compared with the damage thresholds that define the onset and propagation of cracking (see Figure 42). The limits are 26 psi (180kPa) for damage onset and 87 psi (600 kPa) for significant damage and correlate to low asphalt ductility values of 2.0 inches (5.0 cm) and 1.2 inches (3 cm), respectively, for field sections located in a PG 58-28 climate (Kandhal, 1977, Glover et al., 2005).

The results evidenced a quick deterioration of the binder with aging. After short-term aging (i.e., RTFO) the binder reaches the damage onset curve, and after RTFO plus 40-hour and 60-hour PAV, the G-R parameters are far beyond the significant damage threshold curve, with magnitudes of modulus and phase angle similar to those observed in aged binders extracted and recovered from RAP Stockpile 1-09 and 1-16, respectively, that are also shown in Figure 42.

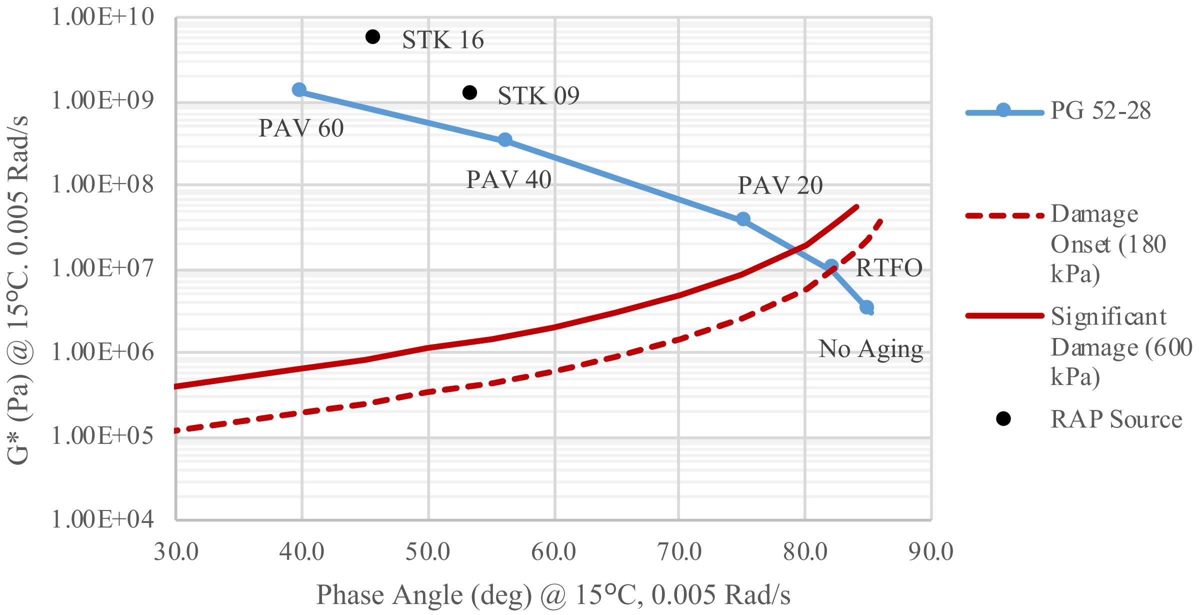


Figure 42. Aging Evaluation of Binder PG 52-28 in Black Space Diagram

V.1.3. Recycled Asphalt Pavement

Two RAP sources, Stockpile 1-09 (limestone) and Stockpile 1-16 (granite/limestone), were used in the fabrication of the hot recycled mixtures. Binder content and calibration factors were determined for each RAP source following the Florida test method FM 5-563, *Quantitative Determination of Asphalt Content from Asphalt Paving Mixtures by the Ignition Method* (FDOT, 2015). Table 24 summarizes the results for each RAP source, and Appendix F provides the detailed calculations.

Following the methodology defined in AASHTO M 320, measurements of stiffness and phase angle in the DSR and BBR were conducted on samples of binder extracted and recovered from each RAP source. The RAP binder extraction was performed following FDOT test methods FM 5-524: *Reflux Extraction of Bitumen from Bituminous Paving Mixtures* and FM 3-D5404*: Recovery of Asphalt from Solution Using the Rotovapor Apparatus*. Due to a pre-existing advanced aging level, the characterization of the RAP binders did not include RTFO and PAV tests. Table 24 presents the high and low temperature of the PG determined for each RAP binder.

Table 24. RAP Characteristics

RAP Type	RAP Aggregate Type	Binder Content	RAP Binder Continuous Grade		PG
			High-Temp PG (ºC)	Low-Temp PG (ºC)	
RAP Stockpile 1-09	Limestone	5.4%	96.3	−15.6	94-10
RAP Stockpile 1-16	Granite/Limestone	4.8%	99.0	−19.2	94-16

The particle size distribution after binder extraction by means of the ignition oven were provided by FDOT for each RAP source and verified by the TTI research team employing the standard test method, AASHTO T-27. The results showed minimal differences between the gradations provided by FDOT and the ones obtained by TTI. These gradations can be found in Appendix C.

V.2. Recycling Agent Selection and Dose

This section details the (a) selection, (b) dose estimation, and (c) addition method of recycling agents used in the fabrication of the hot recycled mixtures. A total of four recycling agents were initially evaluated, two classified as petroleum-based (generically labeled P1 and P2) and two classified as organic-based (generically labeled O1 and O2).

These four types of recycling agents were evaluated to select the most suitable products to be used in the performance testing of hot recycled high RAP mixtures. As detailed in Chapter IV, one petroleum-based and one organic-based product were selected for mixture preparation. The selection of the recycling agents was conducted employing blends of virgin binder PG 52-28, extracted and recovered RAP binder, and recycling agents. The virgin and RAP aggregates were excluded from the blends in order to evaluate only the interaction of the recycling agents with the binders. A total of eight blends were evaluated as result of the combination of two RAP binder sources and four recycling agents.

The research team defined as criteria for the recycling agent selection the aging susceptibility of the blend, quantified by the change in the PGH and carbonyl area (CA) after aging. The blends were subjected to RTFO aging per AASHTO T 240, *Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)*, followed by 40 hours in the PAV per AASHTO R 28, *Standard Test Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)* (AASHTO, 2016; AASHTO, 2017b).

V.2.1. Initial Recycling Agent Dose

Initial recycling agent doses were estimated using the methodology developed in NCHRP Project 09-58, where the PGH of the blend without the addition of recycling agents (PGH_{Blend}) and the PGH for the specific location where the recycled mixture will be used (PGH_{Target}) are input parameters (Kaseer et al., 2018). After studying multiple sources and grades of virgin binders, recycled materials and types of recycling agents, NCHRP Project 09-58 established Equation 2.

Per FDOT specifications, Section 334-2.2—*Superpave Asphalt Binder,* a PG 67-22 binder is required for the production of HMA in the state of Florida ($PGH_{Target} = 67^oC$). To estimate the PGH_{Blend}, NCHRP Project 09-58 developed a blending chart in the form of Equation 9 (Kaseer et al., 2018). It requires the determination of the PGH for the virgin binder ($PGH_{V.Binder}$) and RAP source (PGH_{RAP}) employed in the fabrication of the recycled mixture. The recycled binder ratio (RBR) represents the RAP content in terms of replacement of the virgin binder and was computed according to Equation 10.

$$PGH_{Blend} = PGH_{V.Binder} + (PGH_{RAP} - PGH_{V.Binder}) \cdot RBR \qquad \text{Equation 9}$$

The binder content of the RAP source (BC_{RAP}) and the OBC of the virgin mixture (i.e., with no RAP) were estimated beforehand to compute the RBR of the recycled mixture. The OBC are presented with the mix designs results.

$$RBR = \frac{\%RAP \cdot BC_{RAP}}{100 \cdot OBC} \qquad \text{Equation 10}$$

Table 23 and Table 24 contain the information of $PGH_{V.Binder}$, PGH_{RAP}, and BC_{RAP} used to compute the initial dose of the recycling agents. A RAP content (%RAP) of 60 percent was assumed in the calculations. The detailed estimation can be found in Appendix G.

Table 25 presents the resulting PGH_{Blend} and recycling agent doses for each RAP source. These doses were considered as initial estimates and only used in the initial evaluation of the recycling agents. These values were also later verified to guarantee that all blends reached the target PGH.

Table 25. PGH_{Blend} and Recycling Agent Dose Estimate

RAP Source	PGH_{Blend} (°C)	RBR (@ %RAP = 60%)	Dose by Total Mass of Binder (%)
Stockpile 1-09	75.7	0.47	5.1
Stockpile 1-16	77.1	0.48	5.9

V.2.2. Rheological Characterization

PGH was the rheological parameter used to quantify aging susceptibility of the blends. Following the methodology defined in AASHTO M 320, two replicate measurements of stiffness were conducted in the DSR before and after RTFO plus 40-hour PAV. These measurements were performed at increasing temperatures until a minimum blend stiffness of 1.0 kPa was obtained.

Figure 43 and Figure 44 present the average change in PGH (i.e., ΔPGH) after RTFO plus 40-hour PAV aging for RAP stockpiles 1-09 and 1-16. Detailed results obtained, including the continuous PGH for all blends, are shown in Appendix H.

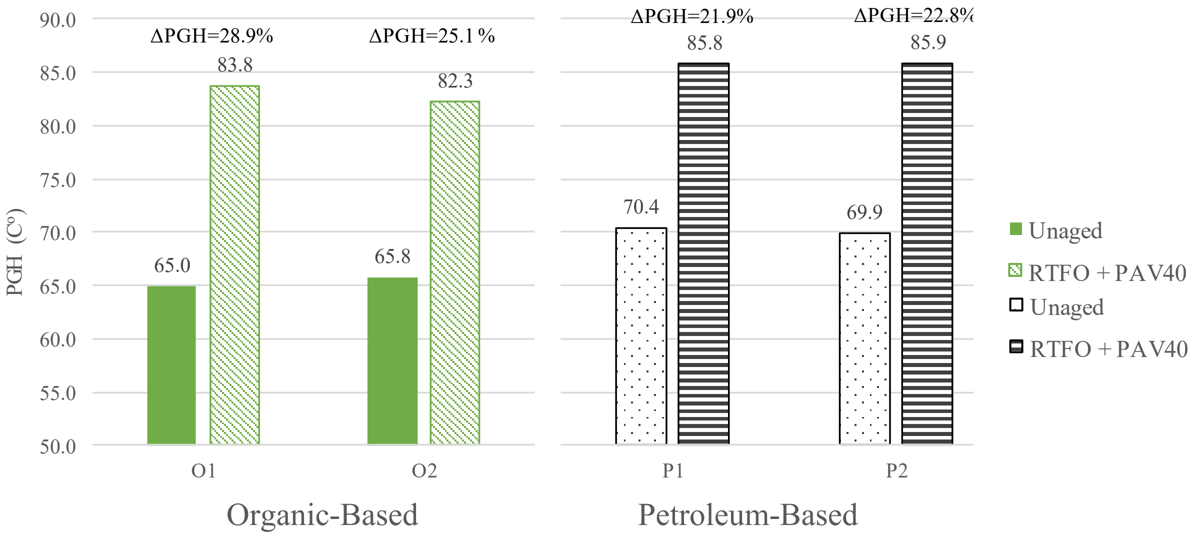


Figure 43. Change in PGH with Aging for Blends with PG 52-28 Virgin Binder + Extracted and Recovered RAP from Stockpile 1-09

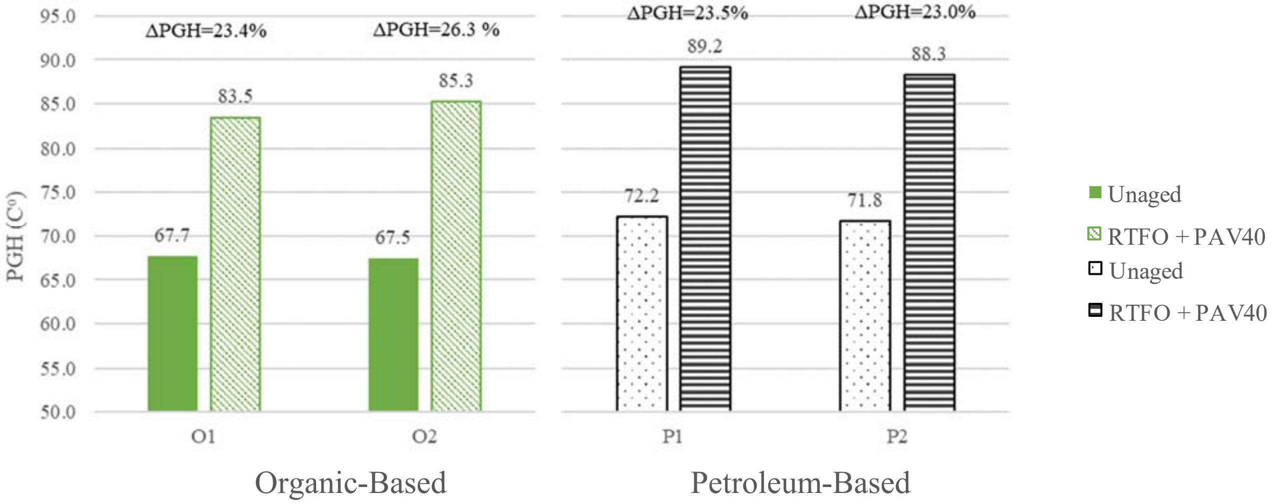


Figure 44. Change in PGH with Aging for Blends with PG 52-28 Virgin Binder + Extracted and Recovered RAP from Stockpile 1-16

According to the information shown in Figure 43 and Figure 44, blends prepared with extracted and recovered RAP from both sources presented changes in PGH after aging between 23.4 percent and 28.9 percent for organic-based recycling agents O1 and O2 and between 21.9 percent and 23.5 percent for petroleum-based recycling agents P1 and P2. These changes indicate the contribution of the recycling agents to improving the performance of the blends after aging. In addition, the results seem to demonstrate that petroleum-based recycling agents are equally or more effective than organic-based recycled agents at minimizing the effect of aging since a smaller change in PGH was observed in the former. However, it is useful to note that the PGH of the blends prepared with petroleum-based products are about 2–6°C higher than their organic-based counterparts.

The influence of the recycling agents in the change in PGH of the blends after aging differed for each RAP source. Within a recycling agent category, a particular agent generated the largest change in PGH for one RAP source and the lowest change for the other source. This change was the case for both recycling agent categories, which led to inconclusive results and to not determining a definite way to select the most effective recycling agent.

V.2.3. Chemical Characterization

Considering the inconclusive rheology results, the research team approached the evaluation of the blends employing CA, which is a parameter that quantifies the formation of carbonyl functional groups (C = O bonds) in the binder due to aging. This parameter was determined by employing Fourier Transform Infrared Spectroscopy (FT-IR), a method proven effective at evaluating the molecular structure of binders and its change with oxidation. The procedure is based on the premise that different types of chemical bonds absorb light with dissimilar infrared intensity and absorption behavior (Yin et al., 2017). The CA is defined as the area, in arbitrary units, under the frequency-absorbance curve within the frequency band from 1,820 to 1,650 cm^{-1}. Binders with higher CA are expected to have greater aging susceptibility than those with lower CA. The CA values were estimated using the equations proposed by Jemison et al. (1992).

Figure 45 and Figure 46 present the change in CA after RTFO plus 40–hour PAV aging for blends prepared with extracted and recovered RAP from stockpiles 1-09 and 1-16. Detailed results for the change in CA estimation are shown in Appendix H. According to the information presented in the figures, O2 and P2 presented a lower change in CA within the organic-based and petroleum-based recycling agent categories, respectively, for both RAP sources. One should note that the changes in CA were approximately the same for the petroleum-based recycling agent products.

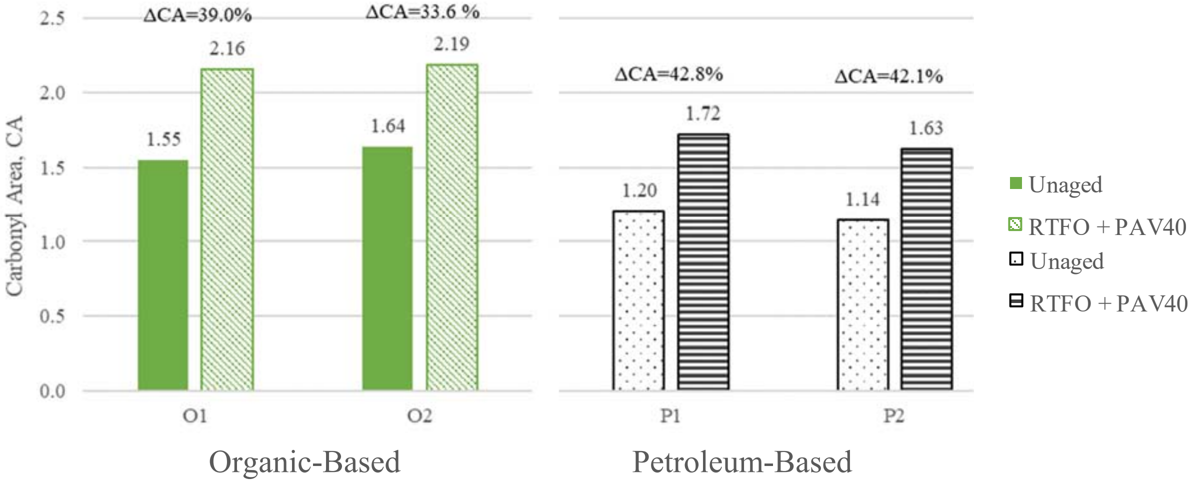


Figure 45. Change in CA with Aging for Blends with PG 52-28 Virgin Binder + Extracted and Recovered RAP from Stockpile 1-09

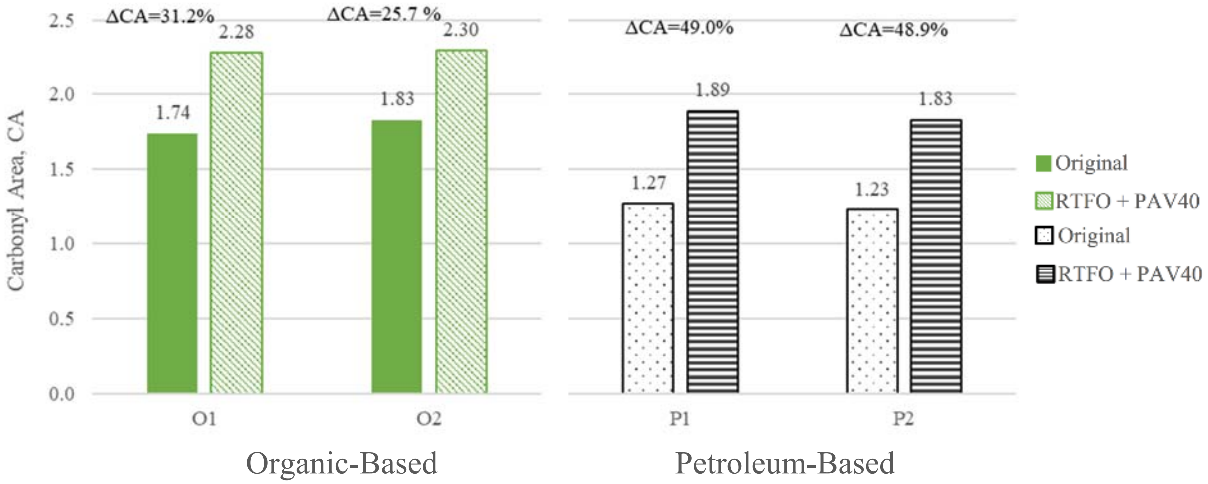


Figure 46. Change in CA with Aging for Blends with PG 52-28 Virgin Binder + Extracted and Recovered RAP from Stockpile 1-16

Considering the information gathered from the rheological and chemical characterization, O2 and P2 were selected for further preparation and evaluation of the hot recycled high RAP mixtures. These recycling agents were selected by taking into account their equivalent rheological response to the other two products and their lower CA changes within their recycling agent category for each RAP source. In addition, even though the petroleum-based recycling agents presented similar change in CA, FDOT has used P2 successfully in the past, which was a decisive factor in the selection.

V.2.4. Recycling Agent Dose Verification

The initial recycling agent dose estimated using Equation 2 was verified by preparing blends of virgin binder, extracted and recovered RAP binder, and 0 percent, 2 percent, and 8 percent recycling agents and measuring the unaged and RTFO-aged PGH in the DSR. The validation procedure aimed to match the PGH of the blend to the PGH of the target binder; this procedure is done to avoid rutting problems but provide sufficient cracking resistance (Arámbula-Mercado et al., 2018). Therefore, the minimum dose (using the unaged or RTFO-aged PGH curves) was selected to avoid over softening of the binder blend. As mentioned before, a PG 67-22 is used in Florida to meet climate and traffic demands; thus PGH_{Target} = 67°C.

Figure 47 through Figure 50 present the results of the dose verification. The recycling agent doses are reported in percent by mass of total weight of binder and represent the amount of virgin binder replaced by the recycling agent. A total of four blends resulting from the combination of two recycling agents (O2 and P2) and two RAP binder sources (Stockpiles 1-09 and 1-16) were evaluated. For the case of the blend with P2 and extracted and recovered RAP binder from Stockpile 1-16 (Figure 50), an additional recycling agent dose of 14 percent was included to avoid extrapolating the test data to achieve PGH_{Target} = 67°C. Detailed results obtained in the dose verification tests are shown in Appendix I.

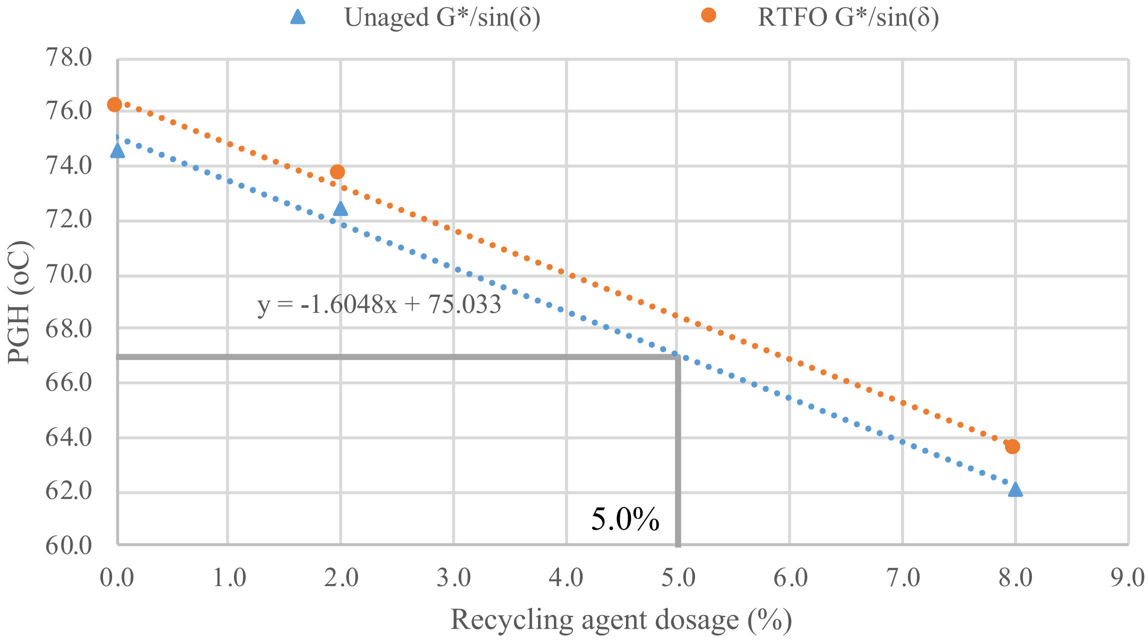


Figure 47. Recycling Agent Dose Verification for Blends with PG 52-28 Virgin Binder + O2 + Extracted and Recovered RAP from Stockpile 1-09

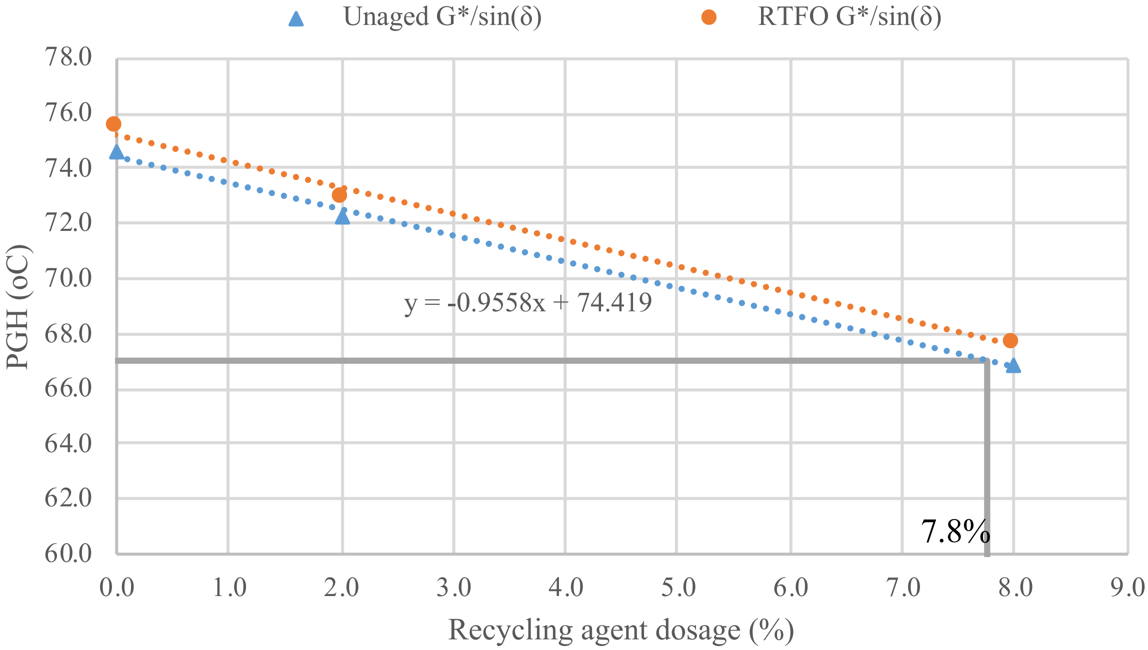


Figure 48. Recycling Agent Dose Verification for Blends with PG 52-28 Virgin Binder + P2 + Extracted and Recovered RAP from Stockpile 1-09

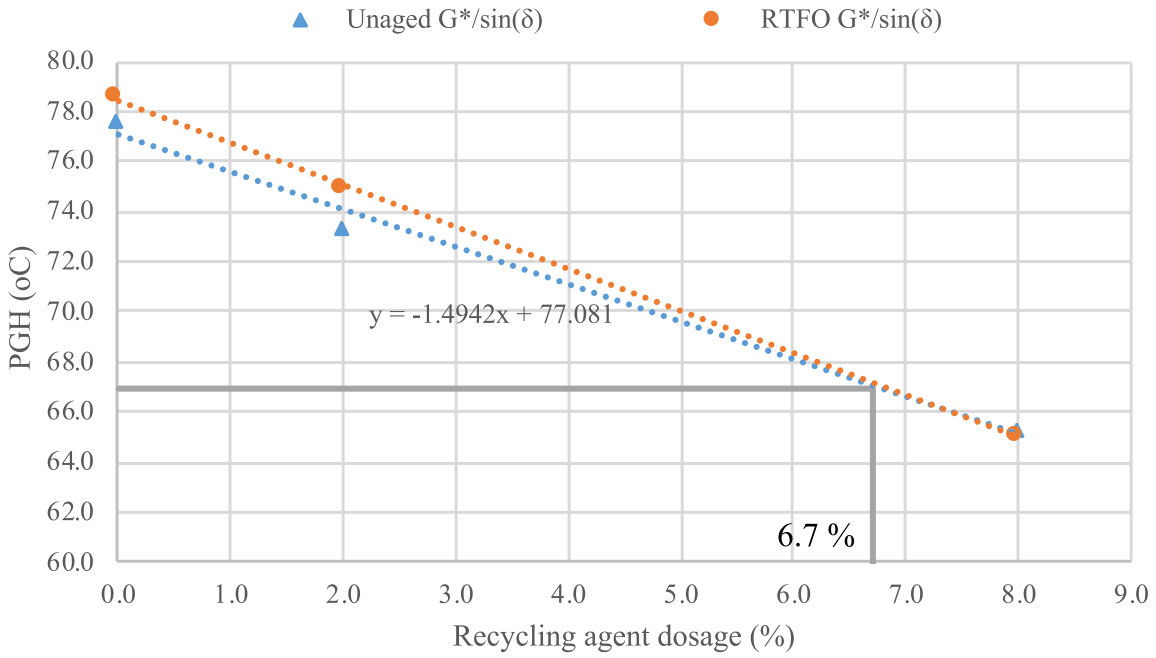


Figure 49. Recycling Agent Dose Verification for Blends with PG 52-28 Virgin Binder + O2 + Extracted and Recovered RAP from Stockpile 1-16

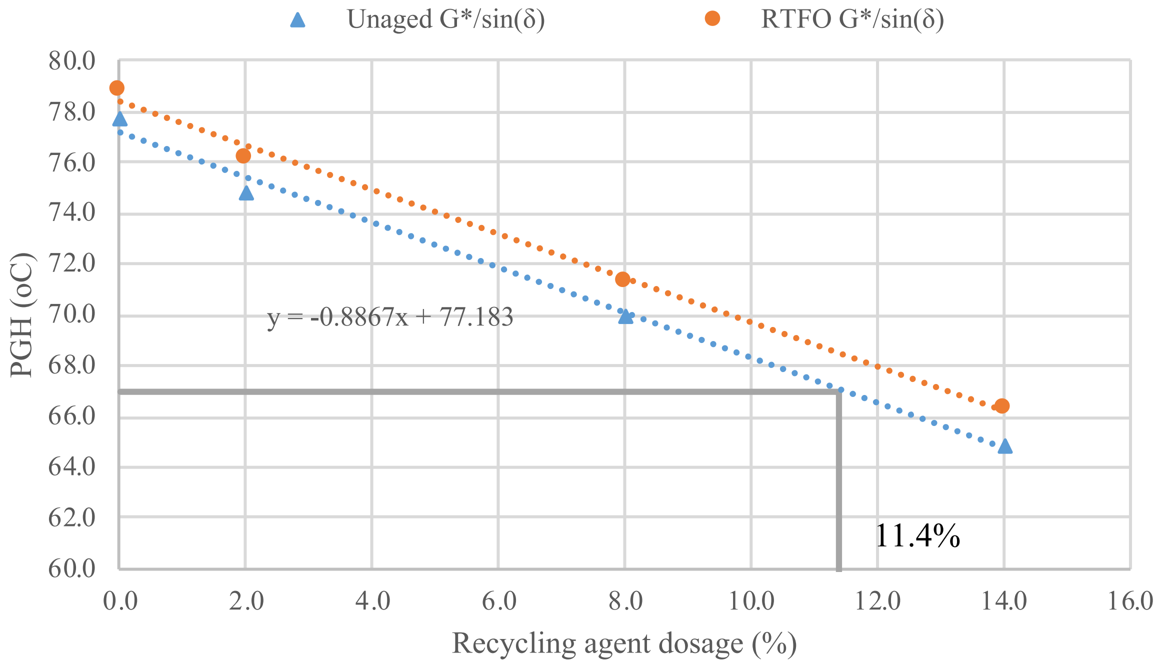


Figure 50. Recycling Agent Dose Verification for Blends with PG 52-28 Virgin Binder + P2 + Extracted and Recovered RAP Stockpile 1-16

Table 26 presents the recycling agent doses obtained through the verification process for each blend. The results from the initial recycling agent dose estimates were close for O2 but not for

P2. The resulting values listed in Table 26 were employed in the fabrication of the hot recycled mixtures for performance testing.

Table 26. Recycling Agent Dose for Hot Recycled High RAP Mixtures Evaluation

RAP Source	Recycling Agent Type	Dose by Mass of Total Binder (%)
Stockpile 1-09	O2	5.0
	P2	7.8
Stockpile 1-16	O2	6.7
	P2	11.4

V.2.5. Recycling Agent Addition Method

To determine the best method for adding the recycling agent to the mixture, workability and coatability tests were conducted on specimens produced with the selected recycling agents (O2 and P2) and the RAP from Stockpile 1-16.

As mentioned in Chapter IV, the assessment considered two addition methods: (a) adding the recycling agent at the selected dose to the virgin binder (VB + recycling agent, as it is traditionally done in the laboratory and most asphalt plants); and (b) adding the recycling agent at the selected dose directly to the RAP and letting it marinate (RAP + recycling agent). A total of four mixtures resulting from the combination of two recycling agents (O2 and P2) and two addition methods were evaluated.

V.2.5.1. Workability

Workability is a property of the mixture that describes how easy it is to place and compact it. The method requires measurement of the shear stress and sample height at each gyration during compaction in the SGC. Specimens 6 inches (152.4 mm) in diameter by approximately 4 inches (101.6 mm) in height were fabricated employing the mixture H-60G-G (Table 17).

For the RAP + recycling agent addition method, the research team defined a marination period of 2 minutes to let the recycling agent react with the heated RAP, after which both materials were put back into the oven at mixing temperature (275°F) for no more than 8 minutes to allow the RAP to recover lost heat. The pre-heated virgin aggregates and virgin binder at mixing temperature were then added to the marinated RAP to produce the mixture.

The G_{mm} of the mixtures was estimated following Florida's standard test method FM 1-T 209, *Maximum Specific Gravity of Asphalt Paving Mixtures*. The results are listed in Appendix J.

The criteria used to evaluate workability included the maximum shear stress (τ_{max}), gyration number to τ_{max}, and density energy. All parameters were estimated from the data collected in the SGC. The density energy is a parameter of arbitrary units understood as the required energy for compaction and is calculated as the area under the %G_{mm}-N curve from the initial (N_{ini}) to the maximum (N_{Max}) number of gyrations. In this study, $N_{ini} = 6$, according to AASHTO M 323, *Standard Specification for Superpave Volumetric Mix Design*, and $N_{Max} = 300$, as recommended in Appendix C of NCHRP Report 807 (Newcomb et al., 2015). Mixtures with higher energy densities are expected to present lower workability when compared to those with lower energy densities. Table 27 and Table 28 present the values determined for the mixtures with the O2 and P2 recycling agents, respectively.

Table 27. Workability Test Results for the Recycled Mixtures with Recycling Agent O2

Addition Method	Max Shear, τ_{max} (kPa)	No. of Gyrations to τ_{max}	Density Energy (-)
VB + recycling agent	413.0	13.0	28,059.7
RAP + recycling agent	408.0	13.0	28,044.8
Relative Difference (%)	−1.2	—	−0.05

Table 28. Workability Test Results for the Recycled Mixtures with Recycling Agent P2

Addition Method	Max Shear, τ_{max} (kPa)	No. of Gyrations to τ_{max}	Density Energy (-)
VB + recycling agent	383.0	9.0	28,086.9
RAP + recycling agent	396.0	16.0	28,043.8
Relative Difference (%)	3.4	77.8	−0.15

The information presented in the previous tables show that the recycling agent addition method had no impact in the mixture workability since very small to negligible changes were observed in the selected parameters for both recycling agents. P2 presented a high relative change of 77.8 percent in the number of gyrations to the maximum shear stress. However, considering that the net measured difference between addition methods is only seven gyrations, the two values can be considered practically equivalent, especially when compared to the 300 gyrations employed for specimen preparation.

V.2.5.2. Coatability

The coatability test procedure is based on the premise that aggregates completely coated with binder will present zero water absorption when submerged in it for a short period (i.e., 1 hour) since the asphalt film covering the aggregate particles will not allow water permeation. However, partially coated aggregates are expected to absorb water when submerged in it, and thus will have a lower CI.

Based on the test protocol outlined in NCHRP Report 807 (Newcomb et al., 2015), 8.8 lb (4,000 g) from the coarse portion of the Granite + RAP mixture were employed as sample mass to conduct the test. The mixtures were produced following the procedure described and employed for the workability tests. However, compaction was not conducted, since the test requires loose mixture specimens. Table 29 presents the resulting CI values estimated for each recycling agent and addition method. Detailed calculations of CI are shown in Appendix J.

Table 29. Coatability Test Results

Recycling Agent Addition Method	CI	
	O2	P2
Virgin Binder + Recycling Agent	93.1	90.6
RAP + Recycling Agent	84.0	75.6
% Change	−9.9%	−16.5%

The information presented in the previous table shows that the recycling agent addition method has an impact on the mixture coatability since reductions of the CI were observed for both O2 and P2 when the recycling agent was added to the RAP.

Considering the information gathered from the workability and coatability tests, researchers decided to follow the traditional procedure of adding the recycling agent to the virgin binder for preparation and evaluation of the hot recycled mixtures. This recycling agent addition method was selected after taking into account that no negative effect on workability was observed and that better CI values were obtained.

V.3. Mix Design

The hot recycled mixtures were designed employing the Superpave methodology outlined in FDOT specifications, Section 334, and AASHTO M 323. A virgin mixture for each type of aggregate was designed first in order to find the aggregate gradation and OBC that satisfied all volumetric property requirements. After the virgin mix design was established, the RAP material was introduced, and adjustments to the aggregate gradation and amount of virgin binder were made by taking into account the gradation of the RAP, its binder content, and the RAP content in the mixture.

It is noteworthy that the RAP could have been incorporated in the mixture when conducting the mix design per FDOT specifications, Section 334 (instead of developing a virgin mix design and then modifying it). An alternative mix design method similar to the one followed for cold recycled mixtures can also be applied to hot recycled mixtures. These two methods are outlined in Appendix K.

V.3.1. Virgin Mix Design

V.3.1.1. Aggregate Gradation

For each aggregate type (e.g., limestone and granite), the #78 intermediate size stone and W-10 fine screenings were blended to meet the aggregate gradation requirements established in FDOT specifications in *Superpave Asphalt Concrete*, *S*ection 334-1.3. Three mixtures are defined based on AASHTO M 323: mixtures with NMAS of 9.5 (SP-9.5), 12.5 (SP-12.5), and 19 mm (SP-19.0).

The combined aggregate blend's proportions of the #78 stone and W-10 screenings that met the gradation requirements are shown in Table 30. Figure 51 and Figure 52 show these gradations for limestone and granite blends, respectively. It is noteworthy that the limestone aggregate blend had a NMAS of 19.0 mm, whereas the granite aggregate blend had a NMAS of 12.5 mm. Therefore, the produced mix and verified requirements for the limestone mixture corresponded to SP-19 and for the granite mixture corresponded to SP-12.5. Detailed aggregate blend calculations are shown in Appendix L.

Table 30. Aggregate Proportions for the Hot Recycled Virgin Mixture

Aggregate's Blend	Proportioning		NMAS (mm)	Superpave Mixture
	#78 Stone	W-10 Screenings		
Limestone	50%	50%	19.00	SP-19.0
Granite	40%	60%	12.50	SP-12.5

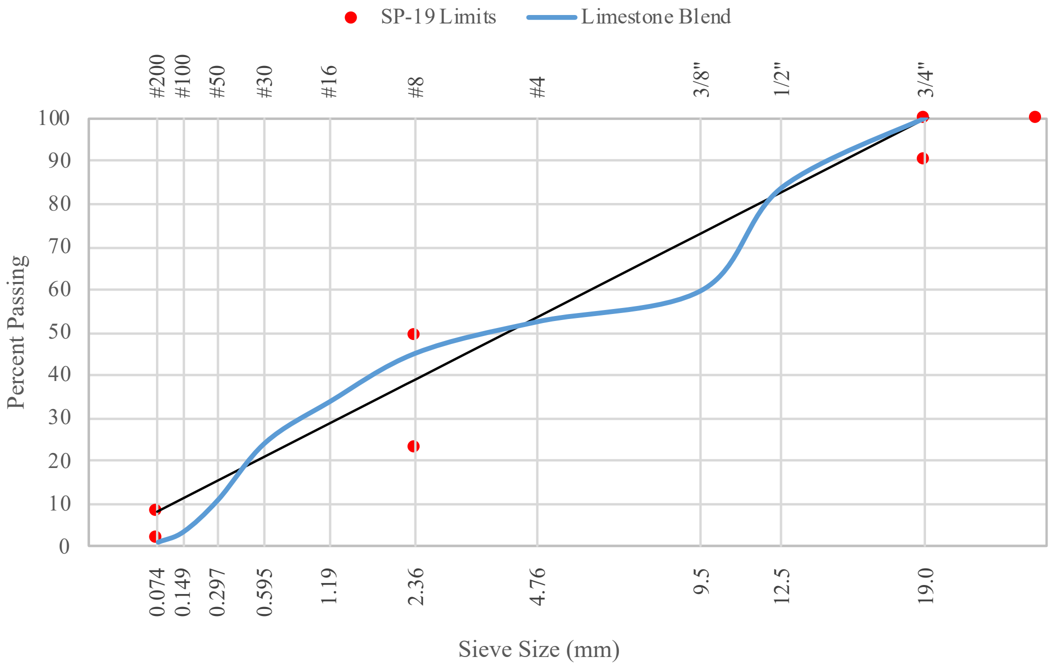


Figure 51. Limestone Aggregate Blend Gradation Curve

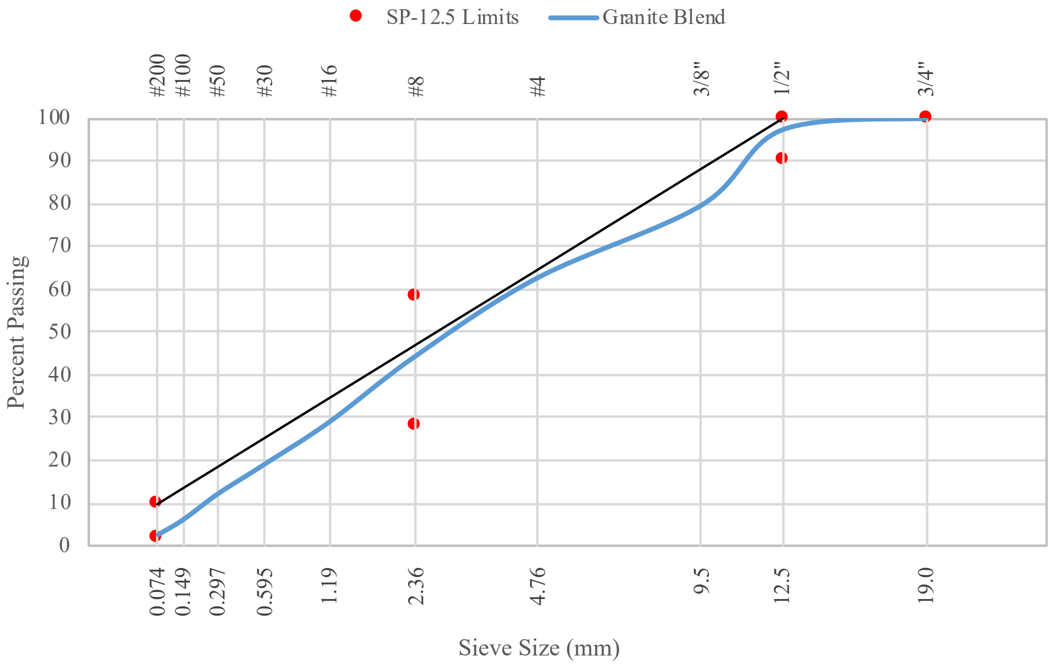


Figure 52. Granite Aggregate Blend Gradation Curve

A washed sieve analysis procedure was also performed on each aggregate blend by following FDOT standard test method FM 1-T 011. The material finer than sieve size #200 was adjusted for each aggregate blend considered in the washed sieve analysis results displayed in Table 31.

Table 31. Washed Sieve Analysis Test Results

Aggregate's blend	Mass change, ΔW (%)	Mass retained at pan (%)*	Mass < #200 adhered to larger aggregates (%)
Limestone	1.9	1.1	0.8
Granite	3.5	2.7	0.8

* Mass determined at ordinary sieve analysis AASHTO T-27.

V.3.1.2. Specimen Fabrication for Virgin Mix Design

Mixtures with four binder contents were fabricated for each aggregate blend shown in Table 30 in order to find the OBC that satisfies volumetric requirements specified in AASHTO M323, Table 6, as required by FDOT specifications, Section 334-3.2.5.

Before mixing, the aggregate blends were placed in an oven at 230ºF (100ºC) and left overnight. A mechanical mixer was then employed to combine the materials at 275ºF (135ºC) until uniform aggregate coating was observed or a maximum of 2 minutes of mixing was reached.

Once mixing was complete, the loose mix was conditioned in the oven for 2 hours at 275ºF (135ºC) to simulate the asphalt plant production process. After this period, two specimens 6 inches (150 mm) in diameter by 4.5 inches (115 mm) in height were compacted per each asphalt content in the SGC to $N_{Design} = 50$ gyrations as established in FDOT specifications, Section 334-3.2.4, for a traffic level of less than 0.3×10^6 ESALs.

After compacting, the specimens were placed on a flat surface and allowed to cool down for at least 24 hours. After this period, the mass of the specimen in air, mass of the specimen soaked in water, and SSD mass of each specimen was determined as required by Florida standard test method FM 1-T 166, *Bulk Specific Gravity of Compacted Asphalt Specimens*. Appendix M presents the bulk specific gravity (G_{sb}), effective specific gravity (G_{se}), and volumetric properties for each aggregate type and binder content.

Two additional samples at one of the binder contents were fabricated for each aggregate blend and allowed to cool down at ambient temperature in loose conditions. The G_{mm} of the mixtures was estimated following Florida's standard test method FM 1-T 209, *Maximum Specific Gravity of Asphalt Paving Mixtures*. These results are also listed in Appendix M.

V.3.1.3. Volumetric Properties of the Virgin Mixtures

Table 32 presents the G_{se} values for each mixture type from the estimated G_{mm} values.

Table 32. Effective Specific Gravity of the Hot Virgin Mixtures

Virgin Mixture Type	Average G_{se} (-)
Limestone Mix	2.604
Granite Mix	2.818

Figure 53 and Figure 54 show the relationship between the AV content and binder content of the limestone and granite mixtures, respectively. Plots for the trends of other volumetric properties are presented in Appendix M.

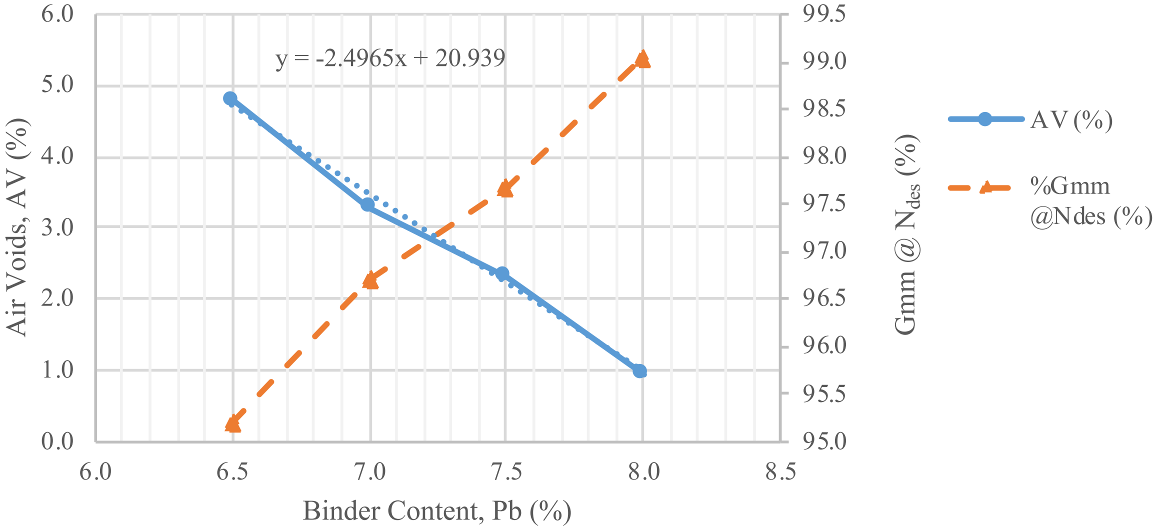


Figure 53. AV Content to Binder Content for the Limestone Virgin Mixture

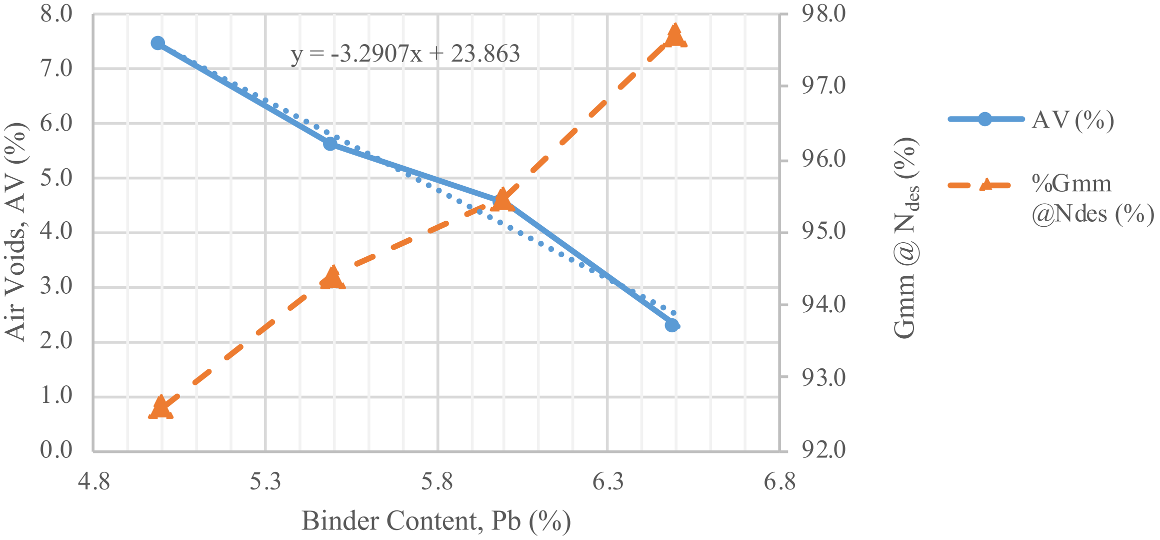


Figure 54. AV Content to Binder Content for the Granite Virgin Mixture

Table 33 and Table 34 present the OBC for the limestone and granite virgin mixtures determined using the linear equations presented in Figure 53 and Figure 54. According to these relationships, the OBC for the limestone mixture corresponds to 6.8 percent and for the granite mixture corresponds to 6.0 percent. VMA, VFA and dust proportion (DP) calculated at the selected OBC are also listed in Table 33 and Table 34. The DP for the limestone mixture is slightly lower (i.e., 0.4) than the limit prescribed in FDOT specifications (i.e., 0.6–1.2). All other volumetric properties are within the specification limits.

Table 33. Limestone Virgin Mixture Volumetric Properties at OBC

Property	FDOT Spec. 334 SP-19	Mix Design
OBC (%)	—	6.8
AV (%)	—	3.9
VMA (%)	> 13.0	14.6
VFA (%)	70–80	73.1
DP (%)	0.6–1.2	0.4

Table 34. Granite Virgin Mixture Volumetric Properties at the OBC

Property	FDOT Spec. 334 SP-12.5	Mix Design
OBC (%)	—	6.0
AV (%)	—	4.4
VMA (%)	> 14.0	17.1
VFA (%)	70–80	74.6
DP (%)	0.6–1.2	0.7

It is worth mentioning that the volumetric properties (VMA, VFA, and DP) at the OBC of 6.0 percent for the granite mixture (see Table 34) are not exactly the same as the ones obtained from the laboratory measurements at 6.0 percent P_b. This is because the linear equation in Figure 54 was employed to obtain the values listed in Table 34. The final mix design in FDOT format is presented in Appendix N.

V.3.2. Recycled Mix Design

The hot recycled mixtures with high RAP content were designed by modifying the virgin mix design to take into account the after-ignition oven gradation and binder content of the RAP, while maintaining the OBC established for the virgin mixtures (Table 33 and Table 34). As previously mentioned, two RAP sources, Stockpile 1-09 (limestone) and Stockpile 1-16 (granite/limestone), were used in combination with the virgin limestone and granite aggregates.

The binder content and calibration factors were determined for each RAP source following the Florida test method FM 5-563, as described previously in the material characterization section (see Table 24 and Appendix F).

Three combinations of aggregate type and RAP source, hereafter referred to as aggregate blends, were selected for the design of hot recycled mixtures, following the experimental plan (see Table 35). Therefore, the RAP, #78 stone, and W-10 screenings were blended to meet the aggregate gradation requirements established in FDOT specifications, *Superpave Asphalt Concrete*, Section 334-1.3. The resulting blends' proportions are shown in Table 35.

In Table 35 and henceforth in this report, the aggregate blends will be denoted by AB, followed by the nomenclature shown in Figure 55 and explained below.

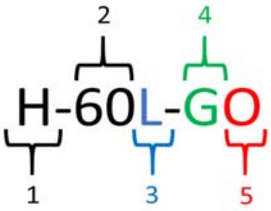


Figure 55. Nomenclature for Aggregate Blend and Mixture Identification

1. Recycling Methodology: H = Hot Recycling
   C = Cold Recycling
2. RAP Content (%): 60
   80
   100
3. RAP Type: L = Limestone
   G = Granite
4. Virgin Aggregate Type: L = Limestone
   G = Granite
5. Recycling Agent Type: O = Organic-Based (O2)
   P = Petroleum-Based (P2)
   Cold Recycling Type: E = Emulsion (CSS-1H)
   F = Foamed Binder (PG 67-22)

Table 35. Aggregate Blends' Proportions for Hot Recycled Mixtures

Aggregate Blend	RAP			Virgin Aggregate		
	Source	Aggregate Type	Amount (%)	Type	#78 Stone (%)	W-10 Screenings (%)
ABH-60L-L	Stockpile 1-09	Limestone	60	Limestone	35	5
ABH-60G-G	Stockpile 1-16	Limestone/ Granite	60	Granite	20	20
ABH-60L-G	Stockpile 1-09	Limestone	60	Granite	35	5

Figure 56 through Figure 58 show the resulting aggregate gradation curves for the aggregate blends presented in Table 35.

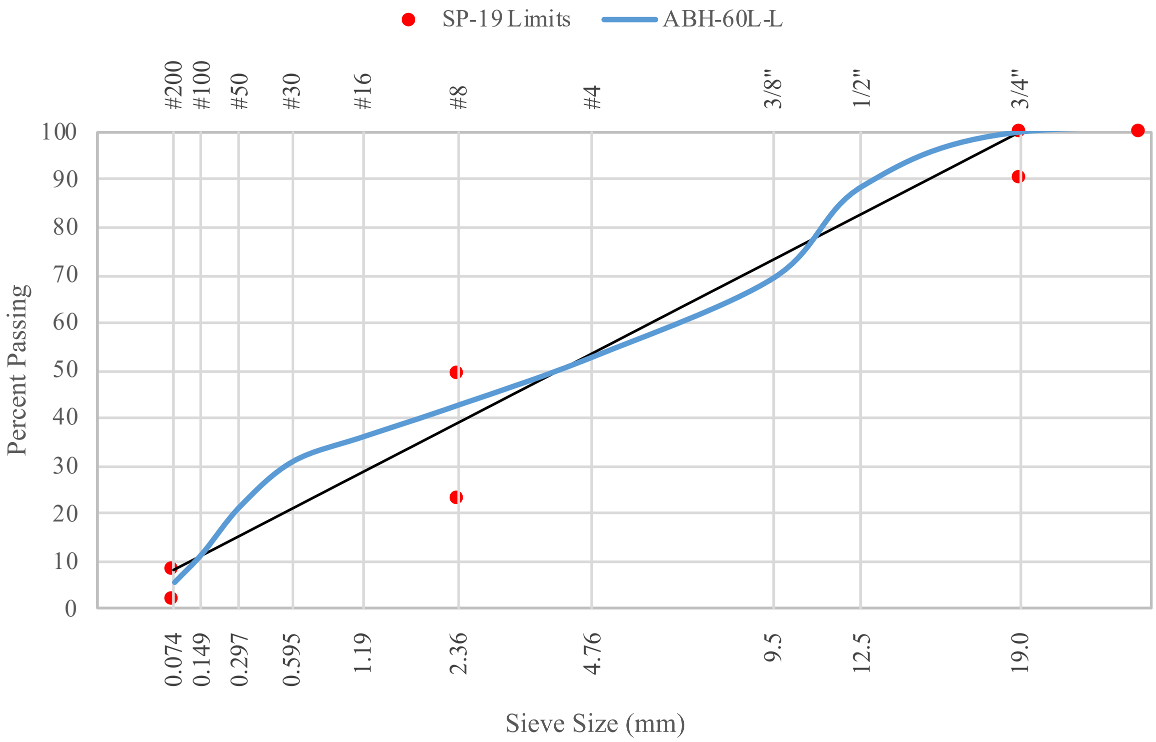


Figure 56. ABH-60L-L Aggregate Blend Gradation Curve

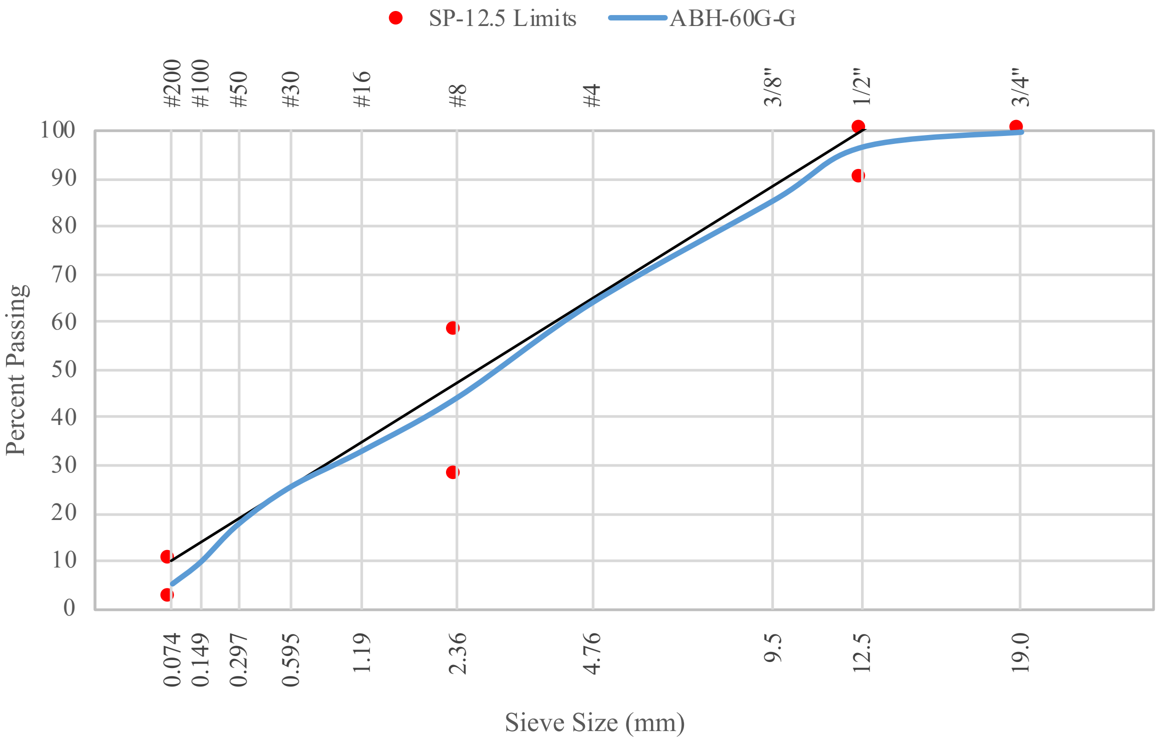


Figure 57. ABH-60G-G Aggregate Blend Gradation Curve

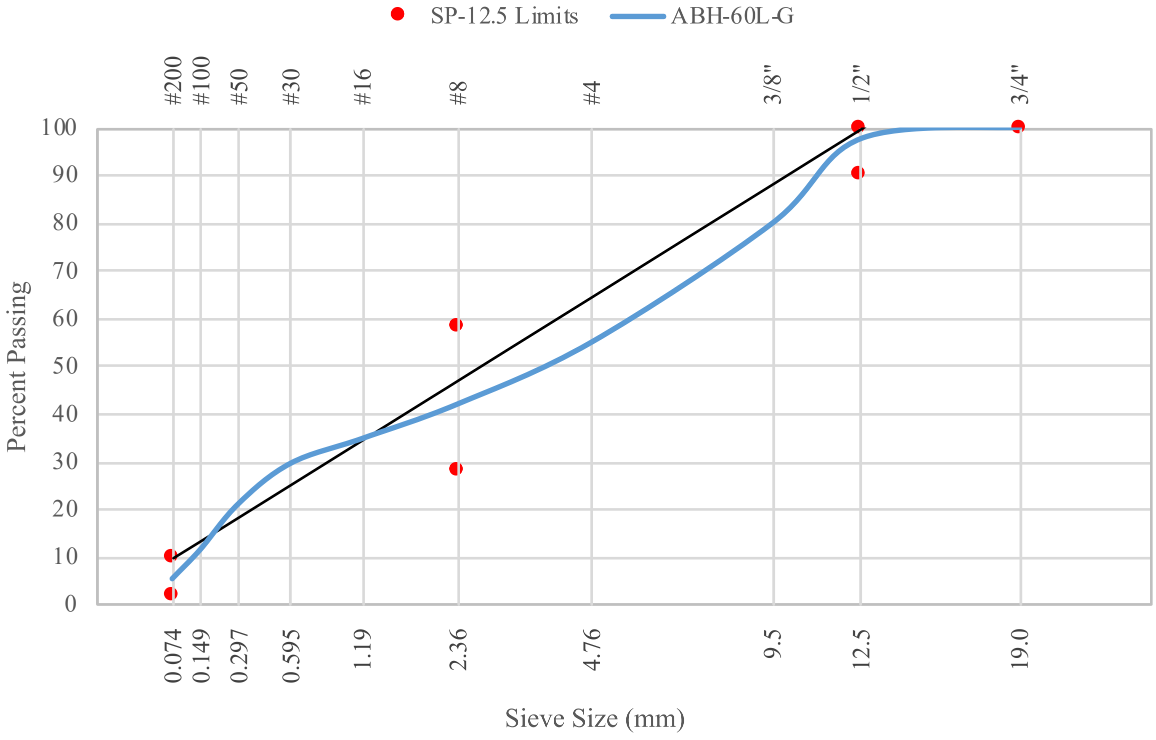


Figure 58. ABH-60L-G Aggregate Blend Gradation Curve

As before, the ABH-60L-L aggregate blend resulted in a NMAS of 19.0 mm, whereas the ABH-60G-G and ABH-60L-G aggregate blends presented a NMAS of 12.5 mm. Therefore, the produced mixture and verified requirements for the ABH-60L-L aggregate blend corresponded to SP-19, and the ABH-60G-G and ABH-60L-G aggregate blends corresponded to SP-12.5. Detailed virgin aggregate and RAP combined aggregate blend calculations are shown in Appendix C.

Table 36 shows the amount of virgin asphalt (PG 52-28) required for the fabrication of the hot recycled mixtures according to the proportioning of RAP and virgin aggregates previously defined and to the OBC determined from the virgin mix design. These reported doses were estimated assuming that all the asphalt present in the RAP is activated and contributes to the OBC required in the mixture. The mix design in FDOT format is presented in Appendix N, and measured volumetric properties of the mixtures is presented in Appendix M.

Table 36. Virgin Binder (PG 52-28) Content for Hot Recycled Mixtures

Hot Recycled Mixture	Aggregate Blend	OBC (%)	RAP		PG 52-28 Virgin Binder	
			% by Weight of Aggregates	Binder Content (%)	% by Weight of Aggregates	Binder Content (%)
H-60L-L	ABH-60L-L	6.8%	60.0%	5.3%	40.0%	3.6%
H-60G-G	ABH-60G-G	6.0%	60.0%	4.8%	40.0%	3.1%
H-60L-G	ABH-60L-G	6.0%	60.0%	5.3%	40.0%	2.8%

V.4. Specimen Fabrication

Specimens required for performance testing of hot recycled mixtures were fabricated for the eight mixture types presented in Table 17. The proportioning of aggregate and RAP determined to meet FDOT specification Section 234 are presented in Table 37. The OBC employed in the mixtures was defined by pairing the virgin aggregate of the mix designs presented in Table 36 with the type of virgin aggregate used in each recycled mixture (see Table 37). Therefore, limestone virgin aggregate mixtures were assigned an OBC of 6.8 percent, while granite virgin aggregate mixtures were assigned an OBC of 6.0 percent.

Table 37. Hot Recycled Mixture Types

Mixture ID	RAP Type and Amount		Virgin Aggregate Type Proportioning				OBC	Recycling Agent		
	Limestone (Stockpile 1-09)	Limestone /Granite (Stockpile 1-16)	Limestone		Granite			Product	Type	Dose by Mass of Binder (%)
			#78 Stone	W-10 Screenings	#78 Stone	W-10 Screenings				
H-60G-G	–	60.0%	–	–	20.0%	20.0%	6.0%	–	–	–
H-60G-GO	–	60.0%	–	–	20.0%	20.0%	6.0%	O2	Organic	6.7%
H-60G-GP	–	60.0%	–	–	20.0%	20.0%	6.0%	P2	Petroleum	11.4%
H-60L-L	60.0%	–	35.0%	5.0%	–	–	6.8%	–	–	–
H-60L-LO	60.0%	–	35.0%	5.0%	–	–	6.8%	O2	Organic	5.0%
H-60L-LP	60.0%	–	35.0%	5.0%	–	–	6.8%	P2	Petroleum	7.8%
H-60L-GO	60.0%	–	–	–	35.0%	5.0%	6.0%	O2	Organic	5.0%
H-60L-GP	60.0%	–	–	–	35.0%	5.0%	6.0%	P2	Petroleum	7.8%

Specimens were fabricated for each performance test included in the experimental plan. Table 38 provides a list of tests and their corresponding specimen characteristics and replicates. A total of 96 specimens were fabricated.

Table 38. Hot Recycled Specimen Characteristics and Quantities

Mixture Property	Test	Standard	Diameter in (mm)	Compaction Criteria	Number of Samples per Mixture Type	Total Number of Samples
Moisture Susceptibility	Modified Lottman, IDT	FM 1-T 283	6 (152.4)	Height: 1.5 in. (38.1 mm)	6	48
Rutting & Moisture Susceptibility	HWTT	AASHTO T 324	6 (152.4)	Height: 2.5 in. (63.5 mm)	4	32
Intermediate Temperature Cracking	SCB	AASHTO TP 124	6 (152.4)	Height: 2.0 in (50.8 mm)	2	16
Stiffness	M_R	ASTM D7369	6 (152.4)	Height: 2.0 in (50.8 mm)	1*	8*

* The M_R test was conducted on specimens fabricated for intermediate temperature cracking before that evaluation. One additional specimen was fabricated to have a total of three replicates in the M_R test.

Before mixing, the blends of virgin aggregate (#78 stone and W-10 screenings) were placed in an oven at 230ºF (100ºC) and left overnight. Two hours before mixing, RAP, asphalt (PG 52-28), and aggregate blends were placed together in an oven at a mixing temperature of

275ºF (135ºC). A mechanical mixer was then employed to combine the materials until uniform aggregate coating was observed or a maximum of 2 minutes of mixing was reached.

Once mixing was complete, the loose mixture was conditioned in the oven for 2 hours at 275ºF (135ºC) to simulate the plant production process. After this period, the set of specimens defined in Table 38 was compacted in the SGC to the compaction criteria specified for each specimen type in the same table (see Table 38).

After compacting, the specimens were placed on a flat surface and allowed to cool down for at least 24 hours. After this period, the mass of the specimen in air, mass of the specimen soaked in water, and SSD mass of each specimen was determined as required by Florida standard test method FM 1-T 166, *Bulk Specific Gravity of Compacted Asphalt Specimens*. Appendix O presents the G_{sb} and estimated AV content for each specimen and mixture defined in Table 37 and Table 38.

Two additional samples were fabricated for each hot recycled mixture displayed in Table 36 and allowed to cool down at ambient temperature in loose condition. The G_{mm} of the mixtures was estimated following Florida standard test method FM 1-T 209. The results are also listed in Appendix O.

V.5. Performance Results

Moisture susceptibility, stiffness, and resistance to cracking and rutting of high RAP hot recycled mixtures were evaluated to verify adequate performance based on current thresholds for HMA mixtures.

V.5.1. Moisture Susceptibility

The moisture susceptibility of hot recycled mixtures was evaluated by means of the modified Lottman test as outlined in FDOT test method FM 1-T 283, *Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage.*

Due to limitations of the SGC equipment to achieve target heights below 1.96 inches (50 mm), three samples of 6-inch diameter were compacted, per hot recycled mix type, to a target height of 3.1 inches (78.2 mm) and cut in half along the thickness in order to produce six specimens 1.5 inches (38.1 mm) thick.

The six specimens were divided in two subsets of three specimens each according to their AV content. One subset of specimens was subjected to the standard moisture conditioning thorough vacuum saturation followed by freezing at −18°C for 16 hours and thawing in a water bath at 140°F (60°C) for 24 hours. Ten Hg-inches of partial pressure were applied to each specimen of the subset to vacuum saturate. After this period, the vacuum was removed, and the specimens were left submerged for 5 minutes. The other specimen subset was air-conditioned at room temperature during the time required to moisture condition the other subset (approximately 42 hours). Appendix O presents the volumetric properties of the specimens and their degree of saturation.

Both subsets (i.e., unconditioned and moisture conditioned) were tested at the same time after completing the freeze-thaw conditioning. IDT strength measurements were conducted at room temperature of about 77°F (25°C) under a monotonic load applied at a rate of 2.0 inches/minute (50 mm/min), as required by FDOT test method FM 1-T 283. It is noteworthy that the moisture conditioned specimens were allowed to reach ambient temperature in a water bath for 2 hours before testing.

Figure 59 and Figure 60 present the results of IDT strength and TSR obtained for the hot recycled mixtures, respectively. n the figures, the bars and numbers in them correspond to the average value and the error bars ± one standard deviation from the average value. Minimum requirements of IDT strength recommended by TxDOT Specification Item 358 (*Hot In-Place Recycling of Asphalt Concrete Surfaces*) and ARRA Standard CR201 (*Recommended Mix Design Guidelines for Cold Recycling Using Emulsified Asphalt Recycling Agent*) are displayed in Figure 59. Likewise, minimum requirements for TSR according to ARRA CR201 are presented in Figure 60.

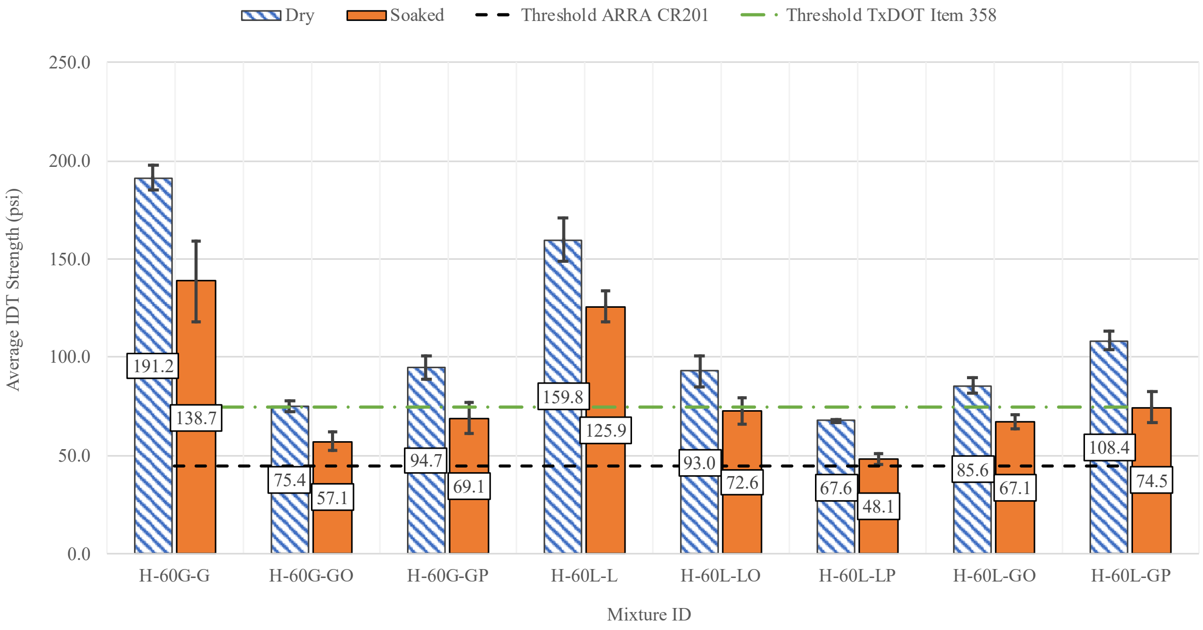


Figure 59. Hot Recycled Mixtures' Unconditioned and Moisture Conditioned IDT Strength

The results presented in Figure 59 show a general reduction of the mixture IDT strength with the inclusion of recycling agents (both organic and petroleum-based types). This decrease in strength ranges from 32 percent to 61 percent for specimens in dry condition and from 41 percent to 62 percent for the moisture conditioned specimens. Furthermore, the hot recycled mixtures that incorporated granite virgin aggregate and a petroleum-based recycling agent (i.e., H-60G-GP and H-60G-GP) developed greater IDT strengths than their counterparts that employed the organic recycling agent. Conversely, the hot recycled mixtures fabricated with limestone virgin aggregate had a larger IDT strength when the organic recycling agent was used.

Although the IDT strength of the hot recycled mixtures that included recycling agents was lower than the mixtures without them, the average IDT strength was still above the minimum threshold recommended by ARRA, indicating good performance. On the other hand, according to the requirements defined by TxDOT Specification Item 358, only the mixtures with no recycling agent (i.e., H-60G-G and H-60L-L) met the minimum dry and moisture conditioned IDT strength requirement. Moreover, of the mixtures including recycling agents, all but H-60L-LP met the threshold in dry conditions, but none passed it after moisture conditioning.

Considering that the hot and cold recycled mixtures evaluated in this research project were intended for the same purpose, that is, as surface layers for low volume roads, it was decided to employ hereafter in the design and assessment of the recycled mixtures the same IDT strength threshold for both hot and cold recycled mixtures. A single value allows a direct comparison between mixtures types and recycling methodologies (i.e., hot and cold). Therefore, a minimum IDT strength of 45 psi (310 kPa) was established as recommended by ARRA Standard CR201, taking into consideration that cold recycled projects normally incorporate higher RAP contents.

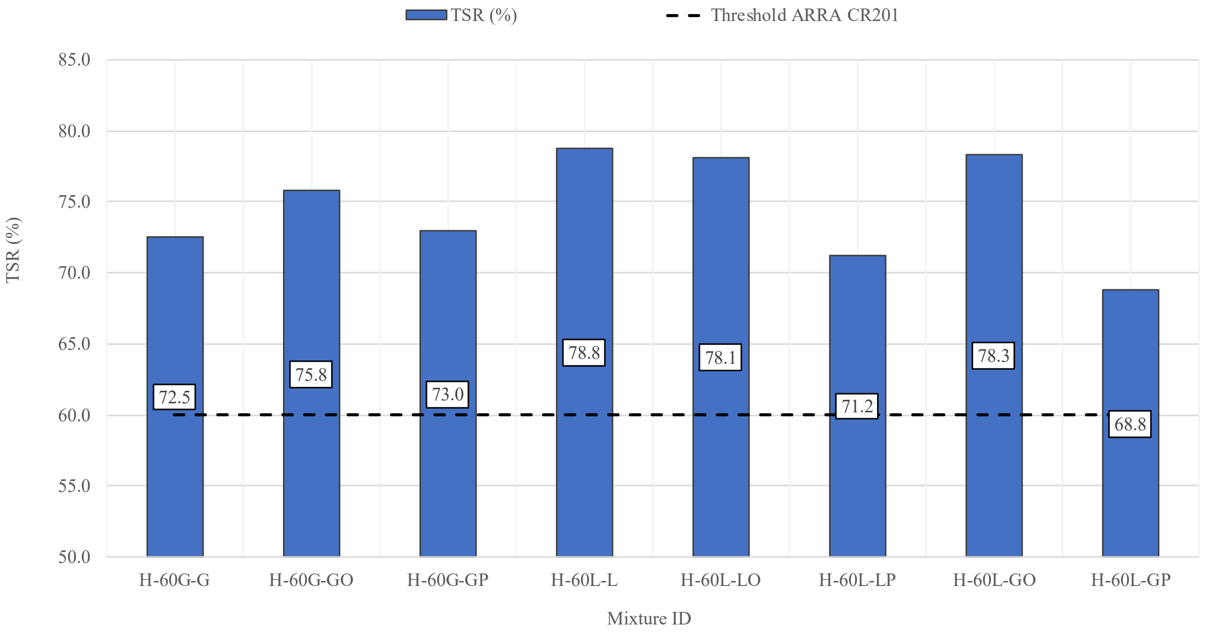


Figure 60. Hot Recycled Mixtures' Tensile Strength Ratio

The TSR results presented in Figure 60 are quite homogeneous, ranging from 68.8 percent to 78.8 percent. Although all TSR results were above the minimum of 60 percent recommended by ARRA (given the moisture conditioned IDT strength exceeds the minimum dry strength/stability requirement of 45 psi), suggesting low moisture susceptibility, the effect of the inclusion of a recycling agent, the RAP source, or a virgin aggregate type were not apparent in the results. However, the results did identify lower moisture susceptibility on the order of 3.7 percent to 12.2 percent in the recycled mixtures that included the organic-based recycling agent when compared to recycled mixtures with the petroleum-based recycling agent.

A statistical multi-factor analysis of covariance (ANCOVA) was conducted to determine the influence of factors, including RAP type, virgin aggregate type, recycling agent type, and moisture conditioning type, on the IDT strength of the high RAP hot recycled mixtures. The AV content was also included in the analysis. Appendix R contains the analysis output obtained by the JMP statistical package. The results showed that recycling agent type and moisture conditioning were statistically significant at $\alpha = 0.05$, meaning that these factors have a statistically significant effect on the IDT strength. The IDT strength "dry" results were significantly higher than the ones after moisture conditioning, as expected. For recycling agent type, the conclusion was that mixtures with no recycling agent had significantly higher IDT strength value than when either the organic or petroleum-based recycling agents were incorporated.

V.5.2. Rutting and Moisture Susceptibility

The moisture susceptibility of hot recycled mixtures was evaluated by means of the HWTT in accordance to AASHTO T324, *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA).*As defined by that AASHTO standard, the SIP and rut depth at a certain number of load cycles were determined for each mixture type in order to evaluate moisture susceptibility and rutting resistance, respectively. Two test replicates were performed simultaneously per mixture type employing both wheels of the HWTT equipment (i.e., left and right). Figure 61 and Figure 62 present the SIP obtained on each wheel and the average rut depth versus load cycle, respectively.

According to the results shown in Figure 61, the determination of the SIP parameter was not possible for most of the hot recycled mixtures in either one or both wheels, indicating that the specimens were resistant to stripping throughout the test.

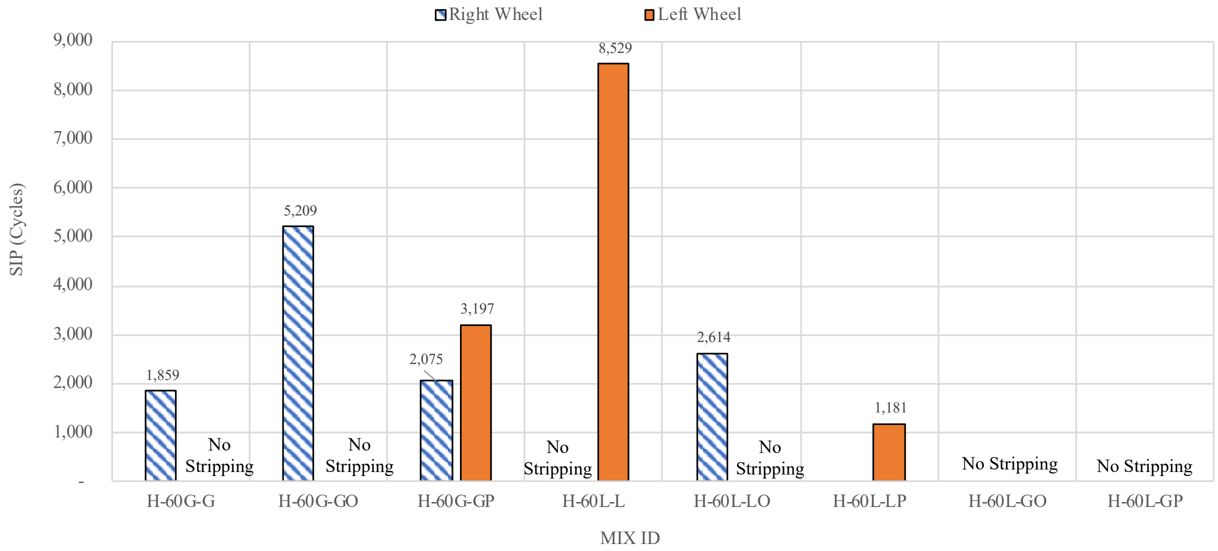


Figure 61. Hot Recycled Mixtures' SIP

From Figure 61, it was observed that the addition of recycling agents to the mixtures fabricated with granite/limestone RAP and granite virgin aggregate resulted in larger SIP values and thus had greater moisture susceptibility. Likewise, the inclusion of recycling agents on the mixtures fabricated with limestone RAP lowered the SIP and hence increased the moisture susceptibility by about 78 percent.

Figure 62 presents the average rut depth for each hot recycled mixture type. Most mixtures experienced accelerated rutting at early load cycle stages. The assigned rut depth failure criteria of ½ inch (12.5 mm) was reached in less than 5,000 load cycles by every mixture fabricated with limestone RAP regardless of the presence or absence of the recycling agent. The mixtures including only virgin aggregate and RAP (i.e., H-60G-G and H-60L-L) exhibited better rutting resistance when compared to equivalent mixtures that included recycling agents.

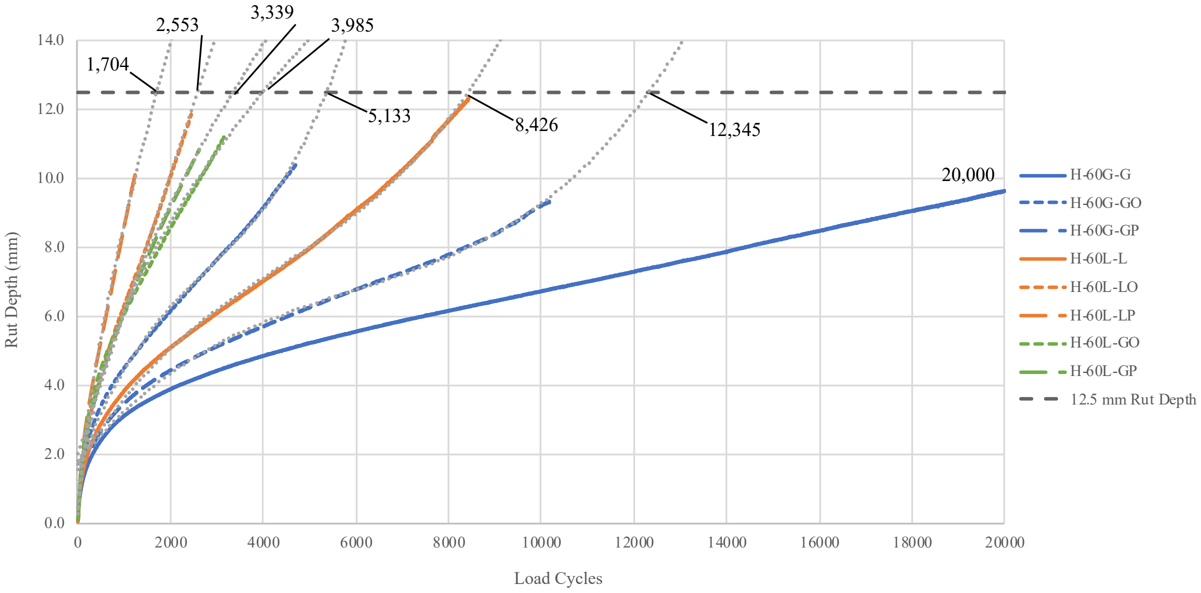


Figure 62. Hot Recycled Mixtures Rut Depth vs. Load Cycles

In addition to the parameters defined in the AASHTO standard, the rutting resistance of the mixtures were evaluated by means of a parameter proposed by Yin et al. (2014). This novel methodology to analyze HWTT output fits a curve of double concavity to rut depth versus load cycles data, assumes that stripping starts at the inflexion point of the fitted curve, and labels this point as the SN. Then, the slope of the fitted curve at the SN ($\Delta\varepsilon^{vp}_{SN}$) is the RRP; higher values represent more susceptibility to rutting. Figure 63 presents the $\Delta\varepsilon^{vp}_{SN}$ values for each hot recycled mixture. According to the results, the mixtures prepared with granite virgin aggregate, regardless of the inclusion of recycling agents, exhibited better rutting resistance than the mixtures with limestone virgin aggregate and recycling agents. The rutting susceptibility for mixtures with organic recycling agents exhibited an increase of 3.8 times and 6.0 times for limestone and granite aggregates, respectively as compared to equivalent mixtures without recycling agents. In the case of mixtures with petroleum-based recycling agents, the increase in rutting susceptibility for granite mixtures was 2.0 times and for limestone mixtures was 7.2 times as compared to equivalent mixtures without recycling agents.

A multi-factor ANCOVA was conducted to assess the effect of RAP type, virgin aggregate type, recycling agent type, and AV content in the rutting behavior of the hot recycled mixtures. The selected HWTT response variables—(a) rut depth at 1,000 cycles, (b) SIP, and (c) $\Delta\varepsilon^{vp}_{SN}$—were analyzed separately. Appendix R contains the analysis output obtained by the JMP statistical package. The results for the rut depth at 1,000 load cycles showed that AV content was statistically significant at $\alpha = 0.05$, with increasing rut depth as AV content increased. For the SIP data, since there were only seven observations available, the multi-factor ANCOVA excluded virgin aggregate type. None of the remaining factors had a significant effect on SIP. Regarding the RRP, an initial multi-factor analysis of variance (ANOVA) suggested that RAP type was a statistically insignificant factor, with a p-value of 0.9268. Therefore, after excluding this variable, it was observed that virgin aggregate type and AV content were statistically significant at $\alpha = 0.05$. The granite mixtures yielded larger $\Delta\varepsilon^{vp}_{SN}$ values, and as AV increased, the RRP decreased.

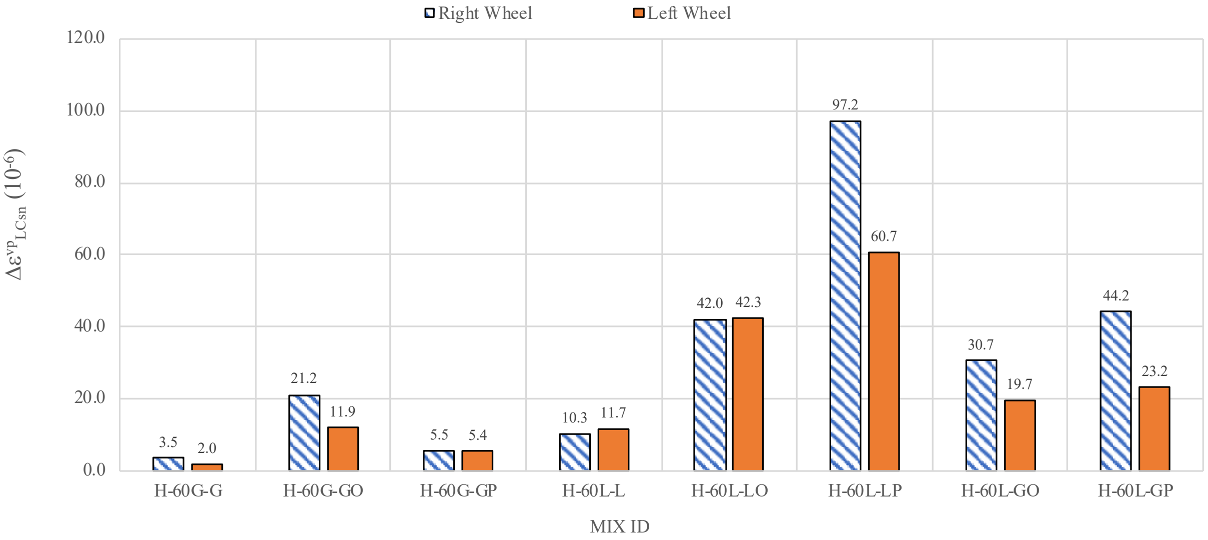


Figure 63. Hot Recycled Mixtures Rutting Resistance Parameter ($\Delta\varepsilon^{vp}_{SN}$)

V.5.3. Intermediate Temperature Cracking

The intermediate temperature cracking resistance of the hot recycled mixtures was assessed in accordance with the standard method AASHTO TP 124, *Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature.*

Two replicate specimens 6 inches (152.4 mm) in diameter were compacted in the SGC to a target height of 1.96 inches (50 mm). As required by the standard test method, each specimen was cut in half and a notch was introduced along the axis of symmetry of the resulting semicircular specimens. Monotonic load was applied until failure at the top of the specimens in a three-point bending arrangement while load and vertical displacement data were recorded during the test.

The cracking resistance of the hot recycled mixtures was characterized by means of the Flexibility Index (FI, as previously shown in Figure 32) and the Cracking Resistance Index (CRI, as expressed in Equation 3). High FI values suggest better cracking resistance of the mixture. Figure 64 and Figure 65 present the FI and CRI results, respectively, for the hot recycled mixtures. In the figures, the bars and numbers in them correspond to the average value and the error bars ± one standard deviation from the average value. Both FI and CRI seemed to agree in the characterization of the cracking behavior of the hot recycled mixtures, since both parameters displayed quite similar trends when varying the recycling agent and virgin aggregate type. Although discrepancies are observed for the H-60L-LO and H-60L-LP mixtures, where CRI suggests a better cracking performance for the latter, the differences were negligible.

The mixtures with no recycling agent (i.e., H-60G-G and H-60L-L) showed the lowest cracking indices, which confirms the IDT strength results (see Figure 59) and suggests stiffer less ductile binders in these mixtures. Conversely, the mixtures in which the rheology of the recycled binder was intended to be restored by recycling agents displayed improved intermediate cracking behavior (i.e., greater FI and CRI values).

The mixtures that included recycling agents improved their FI with respect to equivalent mixtures without recycling agents, from 45 percent to 145 percent for granite virgin aggregate mixtures, and around 160 percent for limestone virgin aggregate mixtures. Likewise, the improvement in the CRI ranges, from 28 percent to 61 percent for the granite virgin aggregate mixtures, and around 50 percent for the limestone virgin aggregate mixtures.

The results also show that the mixtures including limestone RAP, regardless of the recycling agent type or virgin aggregate type, reached approximately the same FI and CRI values, whereas the mixtures including granite/limestone RAP and granite virgin aggregate had better cracking performance (i.e., greater FI and CRI) when including the petroleum-based recycling agent.

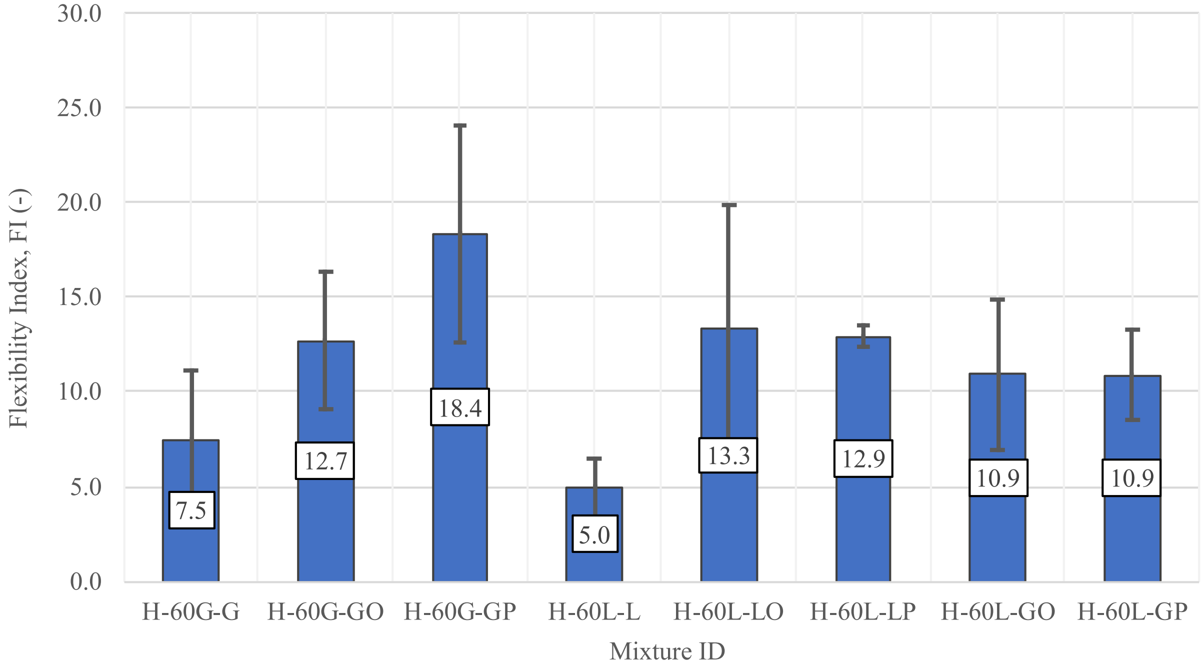


Figure 64. Hot Recycled Mixtures' FI

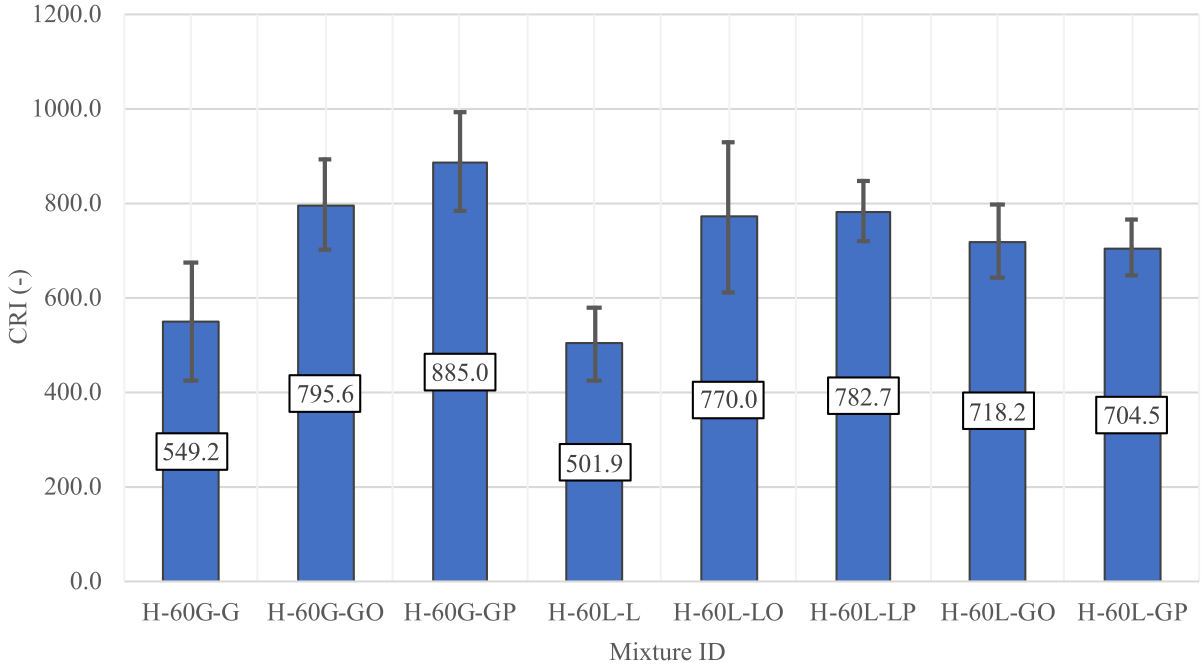


Figure 65. Hot Recycled Mixtures' CRI

A multi-factor ANCOVA was conducted to determine the influence of factors, including RAP type, virgin aggregate type, recycling agent type, and AV content, on the FI of the high RAP hot recycled mixtures. Appendix R contains the analysis output obtained by the JMP statistical package. The results of the model fitted to the FI and CRI data showed that the effect of recycling agent type was statistically significant at $\alpha = 0.05$, meaning that this factor had a statistically significant effect on the resulting FI and CRI values. Tukey's multiple comparison test (Tukey's HSD test) indicated that for recycling agent type, the petroleum and organic-based recycling agents yielded significantly higher results than the mixtures with no recycling agent, but there was not a statistically significant difference between the two types of products. A multi-factor ANOVA was also conducted for the FI data normalized by the AV content to 7 percent. The output of the analysis was with regard to the recycling agent type factor, but with the normalized data, the virgin aggregate type was statistically significant at $\alpha = 0.05$. In addition, the goodness of fit (e.g., R-square) improved when the multi-factor ANOVA models used the normalized data by AV content. Also, the effect of virgin aggregate type was estimated more precisely with the normalized data (i.e., the standard errors for virgin aggregate type were smaller for the normalized data).

V.5.4. Stiffness

The stiffness of the hot recycled mixtures was evaluated employing the M_R test determined in accordance to ASTM D7369, *Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension Test.* Given the nondestructive nature of the test, M_R measurements were conducted on specimens destined to conduct the intermediate temperature cracking evaluation (i.e., SCB) prior to cutting and notching of the samples. Therefore, M_R measurements per hot recycled mix type were conducted on three specimens 6 inches (152.4 mm) in diameter by 1.96 inches (50 mm) in height.

Figure 66 presents the average values in the bars and numbers in them, and ± one standard deviation from the average value in the error bars. average and standard deviation of the M_R measurements for each type of hot recycled mixture. Similar to the IDT strength result, the M_R values for the mixtures with recycling agents were compared to the mixtures with no recycling agents. The reduction in stiffness between these two groups of mixtures was between 36 percent and 57 percent for the granite virgin aggregate mixtures and between 46 percent and 60 percent for the limestone virgin aggregate mixtures. Furthermore, the mixtures including granite virgin aggregate and the petroleum-based recycling agent developed slightly higher levels of stiffness than equivalent mixtures prepared with the organic recycling agent. This result was the case for the H-60G-GP and H-60L-GP mixtures. Conversely, the mixture fabricated with limestone virgin aggregate and the organic recycling agent presented a larger M_R value than its counterpart prepared with the petroleum-based recycling agent.

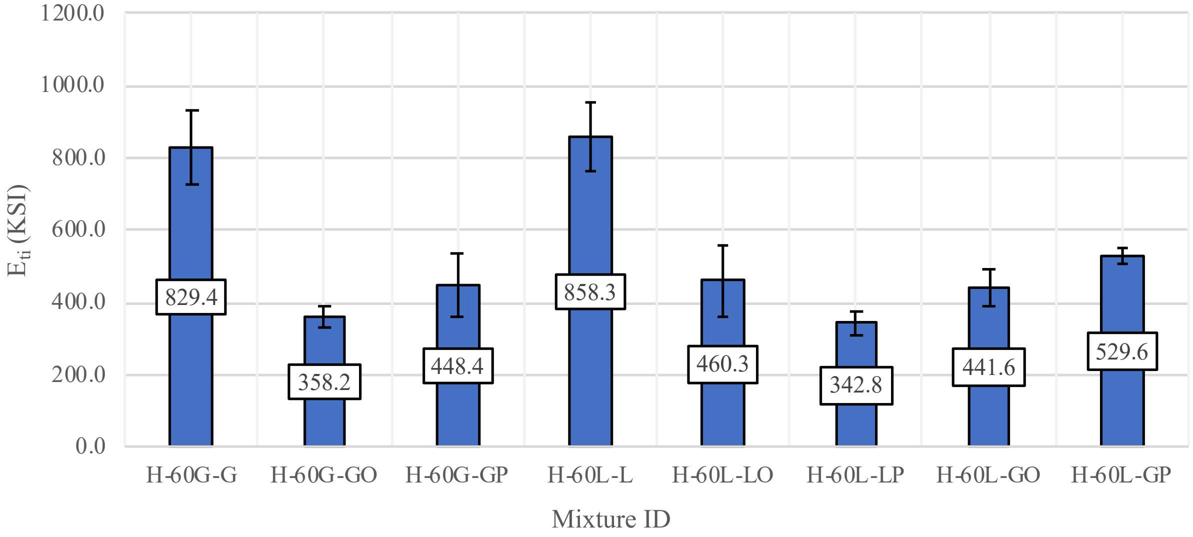


Figure 66. Hot Recycled M_R

A multi-factor ANCOVA was conducted to determine the influence of factors, including RAP type, virgin aggregate type, recycling agent type, and AV content, on stiffness measured via M_R. Appendix R contains the analysis output obtained by the JMP statistical package. The results of the model showed that RAP type and recycling agent type were statistically significant at $\alpha = 0.05$, which means that these factors have a statistically significant effect on the mixture stiffness. With regard to RAP type, the limestone type yielded significantly larger M_R values than the granite/limestone type. For recycling agent type, Tukey's HSD test indicated that the recycled mixtures with no recycling agent had significantly larger M_R values than the mixtures that incorporated either kind of recycling agent.

VI. EMULSIFIED COLD RECYCLED MIXTURE RESULTS

The materials employed in the production of the emulsified cold recycled mixtures correspond to the RAP sources (Stockpile 1-09 and Stockpile 1-16) and virgin aggregates types (limestone and granite) previously listed in Table 21.

Additionally, in lieu of binder PG 52-28, a slow-setting cationic emulsion of low viscosity and hard asphalt residue coded CSS-1H (TxDOT, 2015) was employed for the design and production of the recycled mixtures. The selection of the emulsion product was based on input from industry representatives when consulted about the type of emulsions used for cold recycling in the state of Florida. Table 39 presents the emulsion properties as reported in the Materials Safety Data Sheet.

Table 39. CSS-1H Emulsion Properties

Chemical Name	%
Asphalt	50–70
Water	30 –< 40
Hydrochloric Acid	< 2

This chapter describes the procedure followed for the design of the emulsified cold recycled mixtures, specimen preparation, and performance results.

VI.1. Mix Design

The three combinations of aggregate type and RAP source, hereafter referred to as aggregate blends listed in Table 40 , were selected for the design of emulsified cold recycled mixtures.

VI.1.1. Material Proportioning

Considering the nature of cold recycled mixtures, FDOT base material specification was used rather than FDOT HMA specification (i.e., Section 334) in order to establish the design aggregate gradations. Therefore, FDOT specifications, Section 234, *Superpave Asphalt Base*, was employed to determine the aggregate blend proportioning.

For each aggregate blend, #78 intermediate size stone and W-10 fine screenings were blended with RAP to meet the aggregate gradation requirements established in FDOT specifications, Section 234-1. For the design of the cold recycled mixtures, the researchers considered the RAP as a black rock; that is, it was assumed that the binder coating the RAP particles did not activate during mixing. Therefore, the gradations of the RAP before the ignition oven (i.e., including the asphalt coating the rock) were determined following the standard test method, AASHTO T-27, and were employed to meet the gradation requirements as shown in Appendix L.

Only one type of asphalt base is defined in FDOT specifications, Section 234: base with NMAS of ½ inch (12.5 mm) (i.e., B-12.5). The base types were extended to include a NMAS of ¾ inch (19.0 mm) (i.e., B-19.0), making an allowance to accommodate the larger particle sizes observed in the limestone intermediate stone (C-41) and granite/limestone RAP (Stockpile 1-16). Gradation requirements for each NMAS gradation are shown in Appendix L.

The aggregate blends' proportions of the #78 stone, W-10 screenings, and RAP that met the gradation requirements are shown in Table 40. Figure 67 through Figure 69 show the resulting aggregate gradation curves for each aggregate blend.

Table 40. Emulsified Cold Recycled Aggregate Blends' Proportions

Aggregate's Blend	RAP			Virgin Aggregate		
	Source	Aggregate Type	Amount (%)	Type	#78 Stone (%)	W-10 Screenings (%)
ABC-100L-E	Stockpile 1-09	Limestone	100	—	—	—
ABC-60L-LE	Stockpile 1-09	Limestone	60	Limestone	25	15
ABC-60G-GE	Stockpile 1-16	Limestone /Granite	60	Granite	5	35

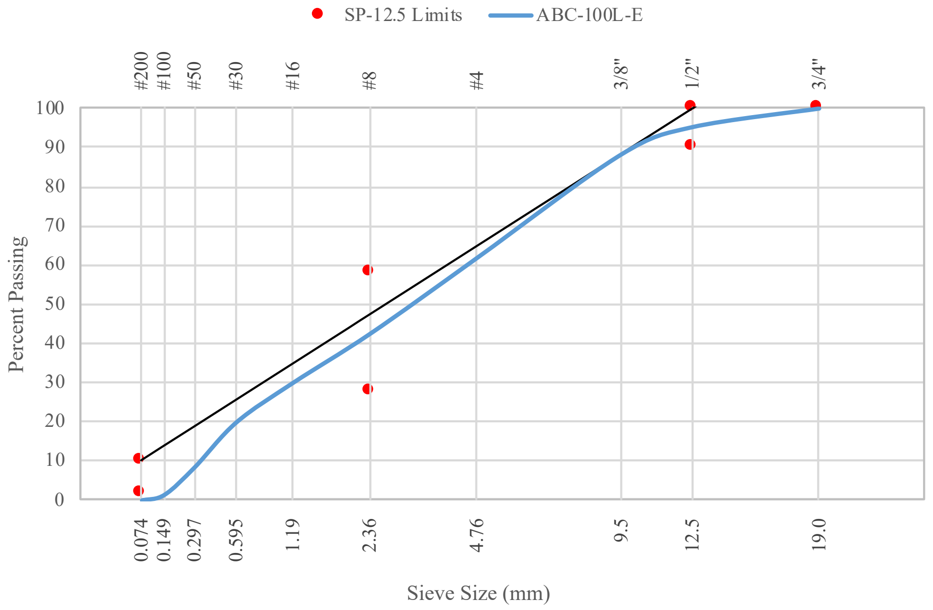


Figure 67. Emulsified Cold Recycled Mixtures ABC-100L-E Aggregate Blend Gradation Curve

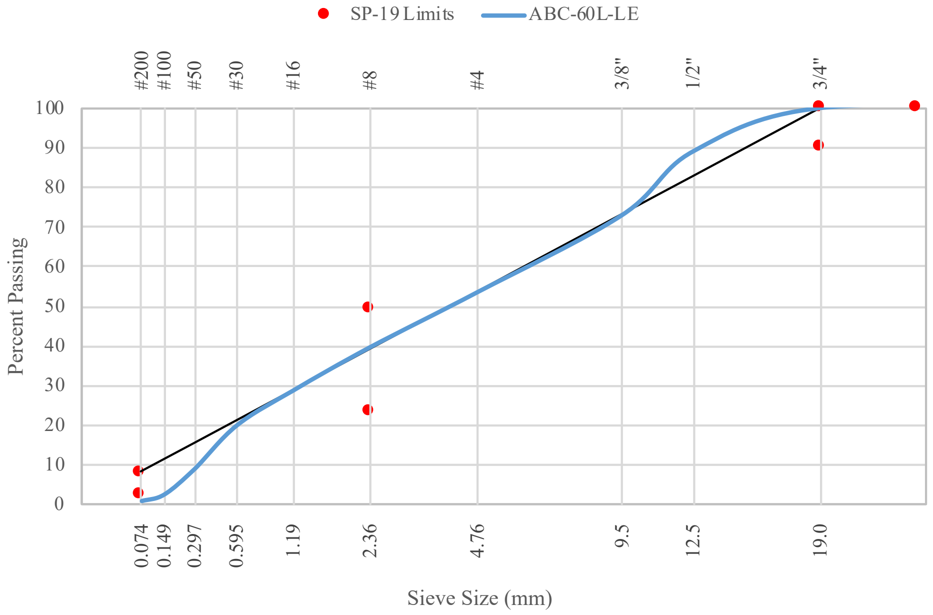


Figure 68. Emulsified Cold Recycled Mixtures ABC-60L-LE Aggregate Blend Gradation Curve

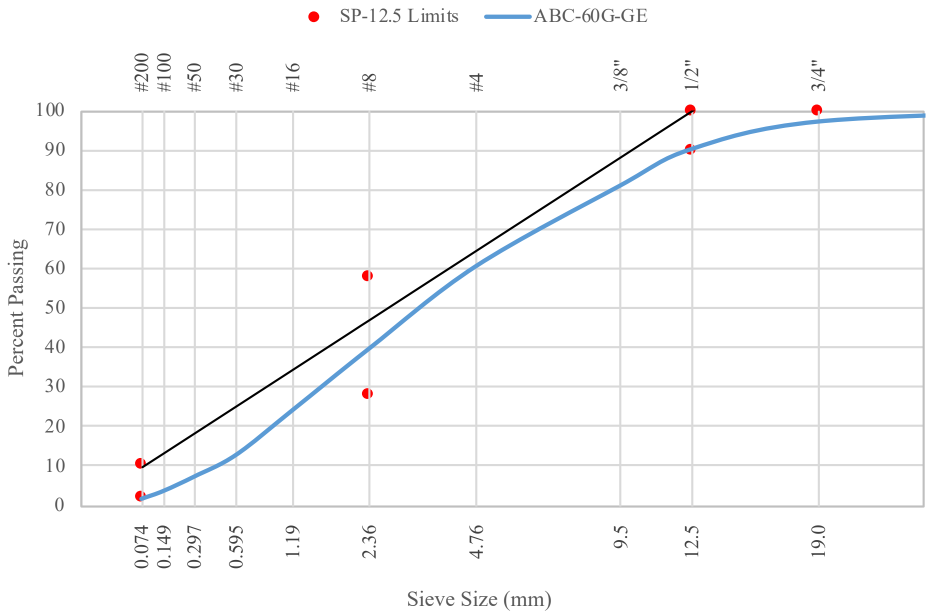


Figure 69. Emulsified Cold Recycled Mixture ABC-60G-GE Aggregate Blend Gradation Curve

The aggregate blend of the ABC-100L-E and ABC-60G-GE blends resulted in a NMAS of ½ inch (12.5 mm), whereas the ABC-60L-LE blend presented a NMAS of ¾ inch (19.0 mm). Therefore, the produced mixtures and verified requirements for the ABC-100L-E and ABC-60G-GE aggregate blends corresponded to B-12.5 and for the ABC-60L-LE aggregate blend corresponded to B-19.0. Detailed aggregate blend calculations are shown in Appendix L.

VI.1.2. Optimum Moisture Content Determination

The OMC for the aggregate blends presented in Table 40 was defined as the required added moisture for the production of the emulsified cold recycled mixtures. Moisture-density curves were established for the ABC-100L-E and ABC-60L-LE blends following Florida test method FM 1-T 180, *Moisture-density relations of soils using a 4.54-kg [10-lb] rammer and a 457-mm [18-inch] drop*. Figure 70 shows the results.

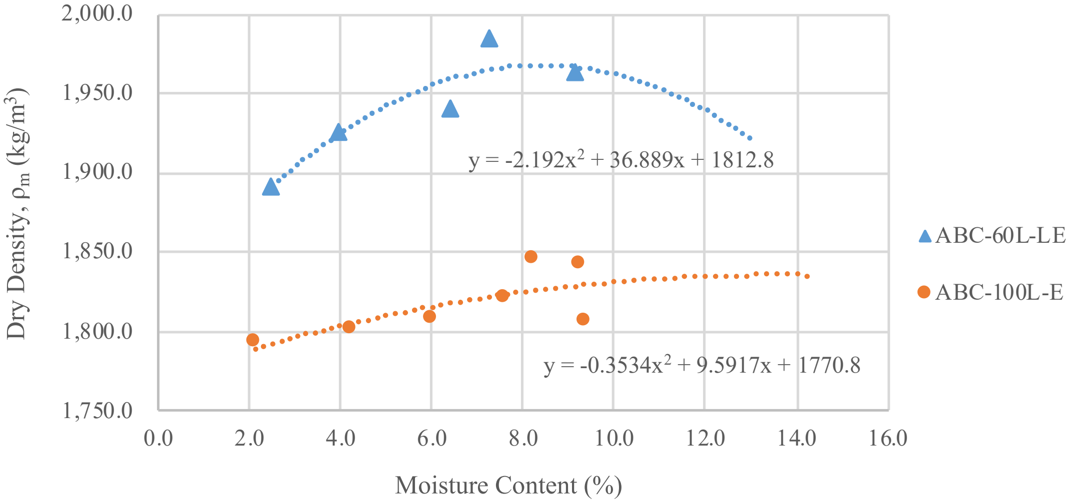


Figure 70. Aggregate Blends Moisture-Density Curves

The OMC was obtained from the moisture-density curves as the point of maximum density. Using the regression curves, the resulting OMC was 13.6 percent for the ABC-100L-E blend and 8.4 percent for the ABC-60L-LE blend. However, after attempting to fabricate specimens using these OMC values, the resulting specimens had excessive water, as can be observed in Figure 71.

(a) (b)

Figure 71. Cold Recycled Mixtures: (a) Loose Mixture OMC = 8%, (b) Compacted Specimen OMC = 8%

Multiple methods have been proposed and investigated for determining the OMC of recycled mixtures. Conventional soil methodologies, such as proctor, have been identified to determine considerably high moisture contents on the order of 8 percent and above (Cox and Howard, 2015). Marshall Design is recommended by some agencies since density and strength information is provided. Kim et al. (2007) attributed the difficulty of finding sound values of OMC for CIR aggregate blends to the RAP coarseness and lack of fines.

Some of the current DOT standards and special provisions for CIR provide OMC intervals that usually range between 1 percent to 3 percent (ARRA CR201, CalTrans LP-8, Colorado DOT CP-L 5111, Kansas DOT C.M. Part V—5.3.4). Mamlouk and Ayoub (1983), Scholz et al. (1991), and Khosla and Bienvenu (1996) fabricated cold recycled mixtures stabilized with emulsion employing arbitrary fixed values of moisture ranging from 1 percent to 5 percent. Babei and Walter (1989) and Kim et al. (2011) in a more recent investigation defined an MC limit of 4 percent in order to achieve proper compaction.

Figure 72 presents a histogram put together by Cox and Howard (2015) displaying the mixing moisture contents employed in 43 references of CIR. The results show an average moisture content of 3.5 percent and a mode of 4 percent with a frequency around 40.

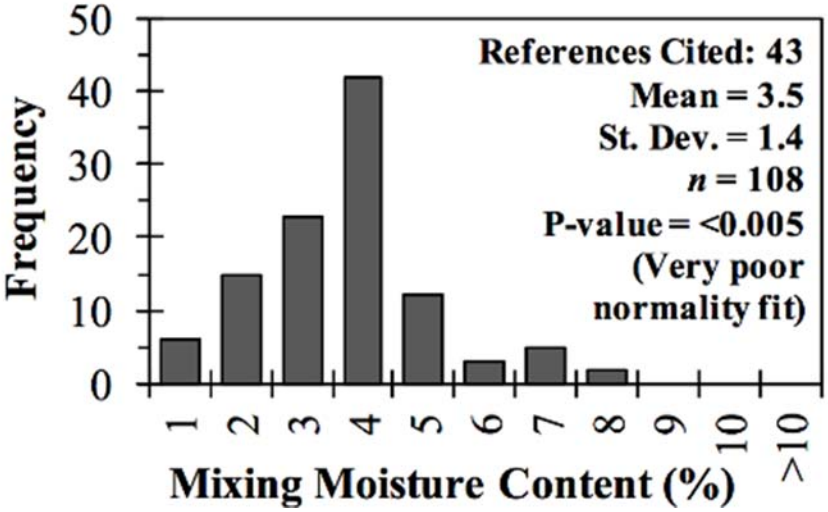


Figure 72. Cold In-Place Mixing Moisture Contents (Cox and Howard, 2015)

Consequently, the OMC was reduced to 4 percent after considering the research results, reported practices in the literature, and DOT standards.

VI.1.3. Optimum Emulsion Content

Cold recycled mixtures with three emulsion contents were fabricated for each aggregate blend shown in Table 40 in order to find the optimum emulsion content (OEC) that satisfied the minimum indirect tensile strength requirement specified in ARRA Standard CR201. The three emulsion contents for mixtures C-100L-E and C-60L-LE were 5.0 percenet (3.0 percent RBC), 6.5 percent (3.9 percent RBC), and 8.0 percent (4.8 percent RBC) while for mixture C-60G-GE the emulsion contents used included 3.3 percent (2.0 percent RBC), 5.0 percent (3.0 percent RBC), and 6.7 percent (4.0 percent RBC).

According to Table 39, the asphalt proportion (AP) of the CSS-1H emulsion is 60 percent. Thus, the actual amount of binder added to the emulsified cold recycled mixture, also known as residual binder content (RBC), was estimated through Equation 11.

$$RBC = \frac{EC}{AP_{Emulsion}} \qquad \text{Equation 11}$$

Before mixing, the aggregates (#78 and W-10) and RAP were dried overnight and for 4 hours, respectively, in an oven at 230ºF (110°C). The materials were allowed to cool down to room temperature and then mixed in a mechanical mixer with the 4 percent OMC and the target EC.

Once mixing was complete, four specimens of 6-inch (152.4-mm) diameter by approximately 1.5-inch (38.1-mm) height were compacted, per each EC in the SGC to N_{Design} = 30 gyrations, as established in ARRA Standard CR201.

VI.1.3.1. Curing Protocol

The curing time of the compacted cold recycled mixture specimens was determined prior to production. As outlined in the ARRA Standard CR201, test specimens were cured in a force-draft oven at 140ºF (60°C) until constant weight was achieved (i.e., 0.05 percent max change in weight in 2 hours).

The effect of RAP and EC in the curing time was evaluated in the protocol experiment. Four 6-inch (152.4-mm) diameter by approximately 1.5-inch (38.1-mm) tall specimens of the ABC-100L-E and ABC-60L-LE aggregate blends were fabricated with an EC of 6.5 percent (3.9 percent RBC). An additional four specimens of ABC-100L-E blend were fabricated with an EC of 8.0 percent (4.8 percent RBC). These were the intermediate and high ECs used to select the OEC. All mixtures were fabricated employing the defined OMC of 4 percent.

Figure 73 presents the evolution in time of the average weight change for each of the test mixtures produced. The results showed that both of the C-100L-E mixtures (6.5 percent and 8.0 percent EC) presented a weight stabilization after approximately 25 hours of curing, and the C-60L-LE mixture stabilizes after 20 hours. Detailed measurements of weight loss for every specimen and mixture are presented in Appendix P. Based on the experiment results, a curing period of 24 hours at a temperature of 140°F (60°C) was selected for all aggregate blends. After curing, the specimens were allowed to cool down for at least 12 hours on a flat surface.

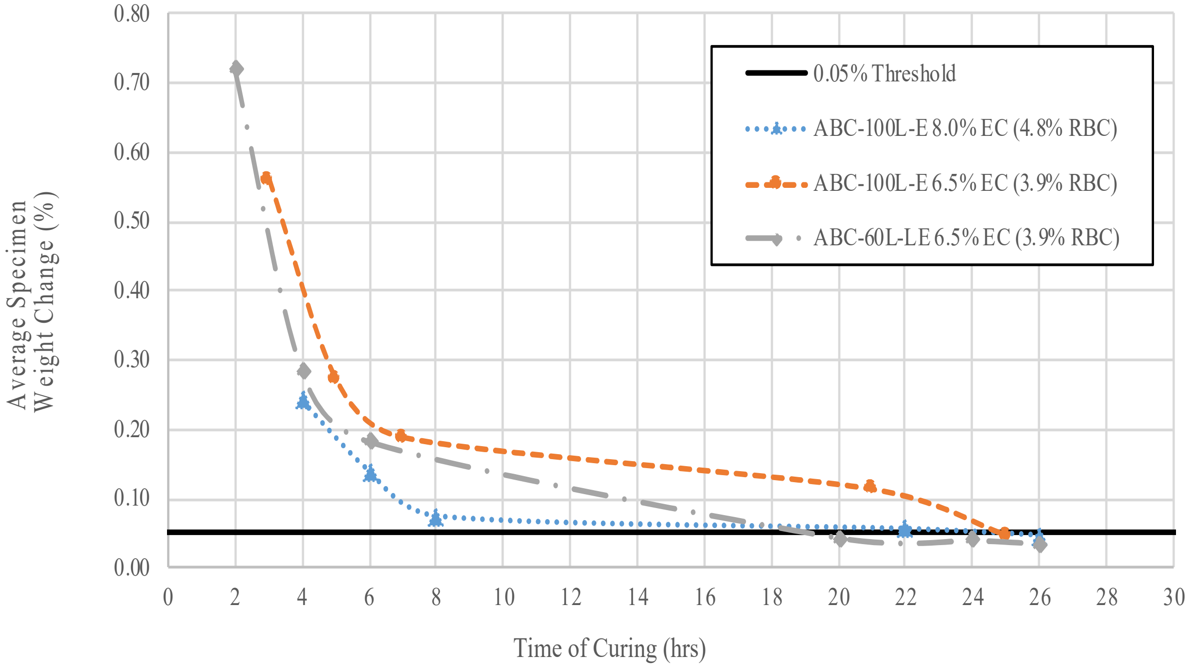


Figure 73. Curing Protocol Experiment Average Specimen Weight Loss

Table 41 summarizes the emulsified cold recycled mixtures' OMC and selected curing time determined using the aggregate blends listed in Table 40.

Table 41. Emulsified Cold Recycled Mixtures' OMC and Curing Time

Cold Recycled Mixture ID	Aggregate Blend	OMC	Curing Time @ 60ºC
C-100L-E	ABC-100L-E	4%	24 h
C-60L-LE	ABC-60L-LE		
C-60G-GE	ABC-60G-GE		

VI.1.3.2. IDT Strength Results

Two specimens per EC were moisture conditioned in a water bath at room temperature for 24 hours. Two other compacted specimens of the same EC were tested without conditioning. The IDT strength was determined in accordance with FM 1-T 283, *Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage* for both dry and moisture conditioned specimens.

Figure 74 through Figure 76 present the unconditioned and moisture conditioned IDT strength. A minimum indirect tensile strength threshold of 45 psi (310 kPa) for cured and conditioned test specimens is indicated for by ARRA in Standard CR201, Table 1. This value was used to select the OEC using the critical IDT strength i.e., the curve with the lowest IDT strength regardless of conditioning. In the case of C-100L-E and C-60L-LE the dry IDT was critical, while in the case of C-60G-GE the soaked curved was critical.

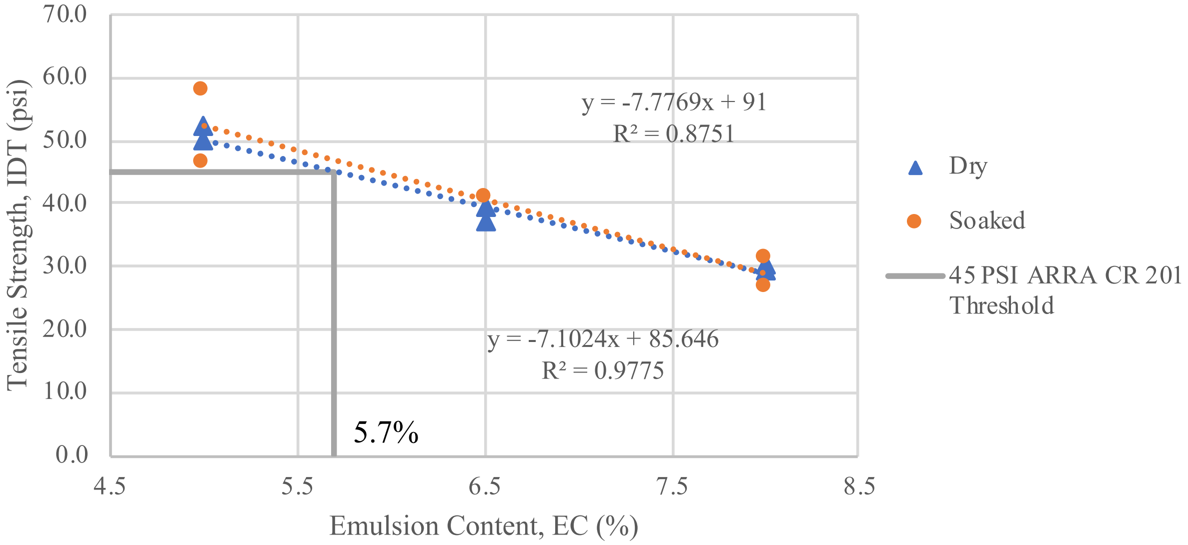


Figure 74. C-100L-E Emulsified Cold Recycled Mixture IDT Strength

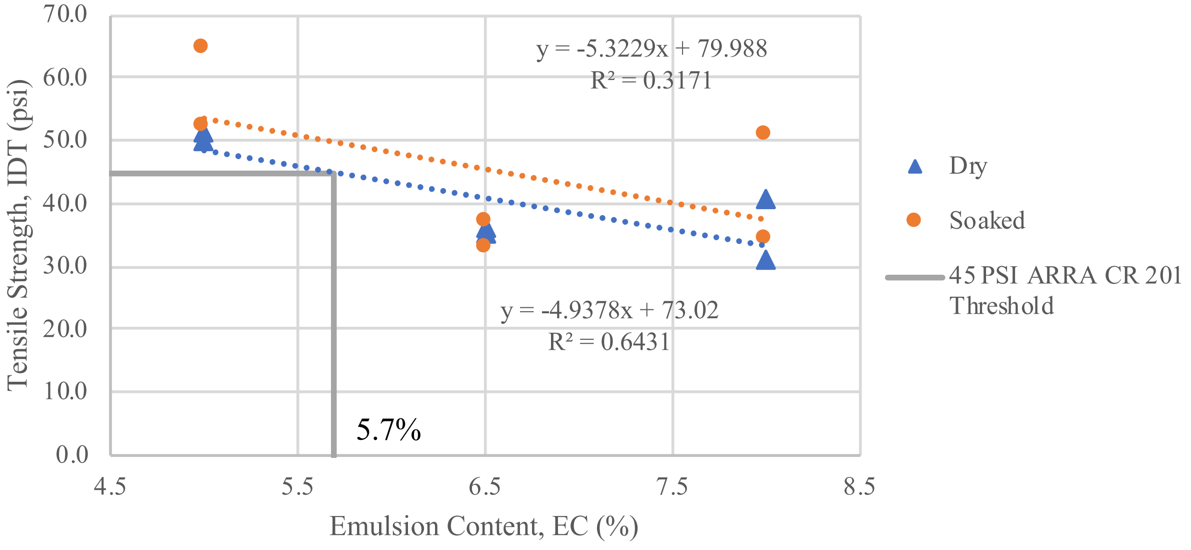


Figure 75. C-60L-LE Emulsified Cold Recycled Mixture IDT Strength

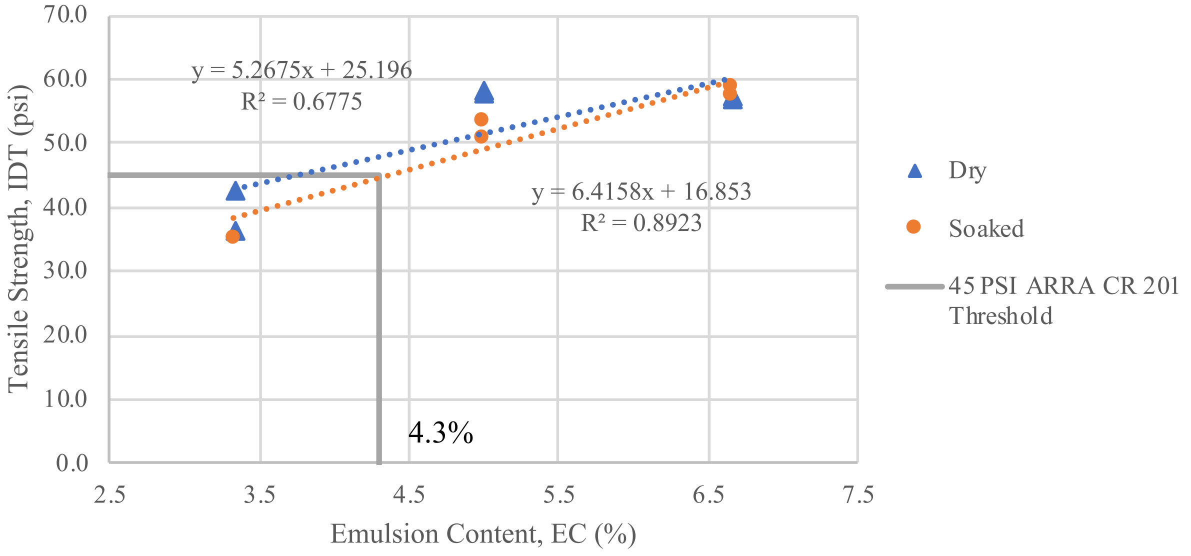


Figure 76. C-60G-GE Emulsified Cold Recycled Mixture IDT Strength

Table 42 and Table 43 present the TSR for each mixture and EC. A minimum TSR of 70 percent is defined in the ARRA Standard CR201, Table 1, for mixtures that incorporate RAP, with a provision to reduce TSR to 60 percent if the IDT strength of the moisture conditioned specimens exceeds the minimum dry strength/stability requirement of 45 psi.

Table 42. C-100L-E and C-60L-LE Mixtures TSR Results

EC (RBC) (%)	TSR (%)	
	C-100L-E	C-60L-LE
5.0 (3.0)	100	120
6.5 (3.9)	110	100
8.0 (4.8)	100	120

Table 43. C-60G-GE Mixture TSR Results

EC (RBC) (%)	TSR (%)
	C-60G-GE
3.3 (2.0)	90
5.0 (3.0)	90
6.7 (4.0)	100

Table 44 presents the OEC and corresponding TSR interpolated from the data presented in Table 42 and Table 43. Based on the obtained TSR values, the mixtures did not exhibit moisture susceptibility; thus, no stabilization by means of addition of lime was considered necessary.

Table 44. Optimum Emulsion Content

Cold Recycled Mixture	OEC (ORBC) (%)	TSR (%)
C-100L-E	5.7 (3.4)	100
C-60L-LE	5.7 (3.4)	110
C-60G-GE	4.3 (2.6)	90

VI.2. Specimen Fabrication

Following the approved experimental plan, specimens for six types of emulsified cold recycled mixtures were fabricated. The proportion of aggregate and RAP determined to meet FDOT specifications, Section 234, are presented in Table 45. The OEC employed in the mixtures production was defined by pairing the virgin aggregate type of the mix designs presented in Table 44 with the type of virgin aggregate in each mix (see Table 45). The OEC was defined the same for every mixture with the same virgin aggregate type regardless of the RAP content. Therefore, mixtures with limestone virgin aggregate were assigned an OEC of 5.7 percent (3.4 percent ORBC), while mixtures with granite virgin aggregate were assigned an OEC of 4.3 percent (2.6 percent ORBC).

Table 45. Emulsified Cold Recycled Mixtures' Material Proportions

Mixture Type	RAP Type and Amount		Virgin Aggregate Type Proportioning				OEC (ORBC) (%)	OMC (%)
	Limestone (Stockpile 1-09)	Limestone/ Granite (Stockpile 1-16)	Limestone		Granite			
			#78 Stone	W-10 Screenings	#78 Stone	W-10 Screenings		
C-60L-LE	60.0%	–	25.0%	15.0%	–	–	5.7 (3.4)	4.0
C-80L-LE	80.0%	–	20.0%	0.0%	–	–	5.7 (3.4)	4.0
C-100L-E	100.0%	–	–	–	–	–	5.7 (3.4)	4.0
C-60G-GE	–	60.0%	–	–	5.0%	35.0%	4.3 (2.6)	4.0
C-80G-GE	–	80.0%	–	–	0.0%	20.0%	4.3 (2.6)	4.0
C-60L-GE	60.0%	–	–	–	20.0%	20.0%	4.3 (2.6)	4.0

Specimens were fabricated for each performance test included in the experimental plan. Table 46 presents the type of tests that were conducted, the specimen characteristics, and number of specimens. A total of 78 specimens were fabricated.

Table 46. Emulsified Cold Recycled Mixture Specimen Characteristics and Quantities

Mixture Property	Test	Standard	Diameter, in (mm)	Compaction Criteria	Number of Replicates per Mix Type	Total Number of Specimens
Moisture Susceptibility	IDT	FM 1-T283	6 (152.4)	N_{design} = 30 gyrations	6	36
Rutting & Moisture Susceptibility	HWTT	AASHTO T 324	6 (152.4)	Height: 2.5 in. (63.5 mm)	4	24
Stiffness	M_R	ASTM D7369	6 (152.4)	Height: 2.5 in. (63.5 mm)	*	*
Durability	Cantabro Abrasion Loss Test	AASHTO TP 108	6 (152.4)	Height: 4.5 in. (115.0 mm)	3	18

*The M_R test was conducted on three of the four specimens fabricated for rutting and moisture susceptibility evaluation.

Before mixing, the virgin aggregates (#78 and W-10) and RAP were oven dried overnight and for 4 hours, respectively, at 230ºF (110°C). The materials were allowed to cool down to room temperature and then mixed with the 4 percent OMC and the OEC by a mechanical mixer.

Once mixing was complete, the specimen replicates listed in Table 46 were compacted in the SGC using the compaction criteria that are also listed in Table 46. After compacting, the specimens cured for 24 hours in a forced draft oven at 140ºF (60ºC). Next, the specimens were taken out of the oven and placed on a flat surface to cool down for at least 24 hours before testing. After the cooldown period, the mass of the specimen in air, mass of the specimen soaked in water, and mass in SSD condition were determined as required by Florida's standard test method FM 1-T 166, *Bulk Specific Gravity of Compacted Asphalt Specimens*. Appendix O presents the G_{sb} and AV content for each specimen and mixture defined in Table 45 and Table 46.

Two additional samples were fabricated for each cold recycled mixture displayed in Table 44 and allowed to cool down at ambient temperature in loose condition. The G_{mm} of the mixtures was estimated using Florida's standard test method FM 1-T 209. The results are listed in Appendix O.

VI.3. Performance Results

Moisture susceptibility, rutting, durability, and stiffness of the emulsified cold recycled mixtures were evaluated to verify adequate performance based on current thresholds for cold recycled mixtures.

VI.3.1. Moisture Susceptibility

The moisture susceptibility of cold recycled mixtures with emulsion was evaluated by means of the modified Lottman test as outlined in FDOT test method FM 1-T 283, *Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage.*

Prior to the moisture susceptibility evaluation, moisture conditioning trials were performed on compacted specimens subjected to the standard and a reduced moisture conditioning protocols. The standard protocol as prescribed in FM 1-T 283 consisted of vacuum saturation, freezing at 0°F (−18°C) for 16 hours, and thawing in a water bath at 140°F (60°C) for 24 hours. The reduced moisture conditioning protocol consisted of vacuum saturation followed by a 24-hour water bath at room temperature. The latter procedure corresponds to the moisture conditioning procedure recommended by ARRA Standard CR201 plus vacuum saturation. Figure 77 compares the IDT strengths resulting from both conditionings. No error bars are shown in Figure 77 because only two replicates per condition were tested.

The results show that the standard moisture conditioning protocol resulted in significantly lower IDT strengths as compared to the specimens subjected to the reduced moisture conditioning protocol. The difference in IDT strengths was between 16 percent and 73 percent. Therefore, the moisture conditioning protocol currently prescribed for HMA mixtures in FM 1-T 283 was considered too severe for the emulsified cold recycled mixtures, and vacuum saturation plus a 24-hour water bath at room temperature was used instead for the moisture susceptibility evaluation.

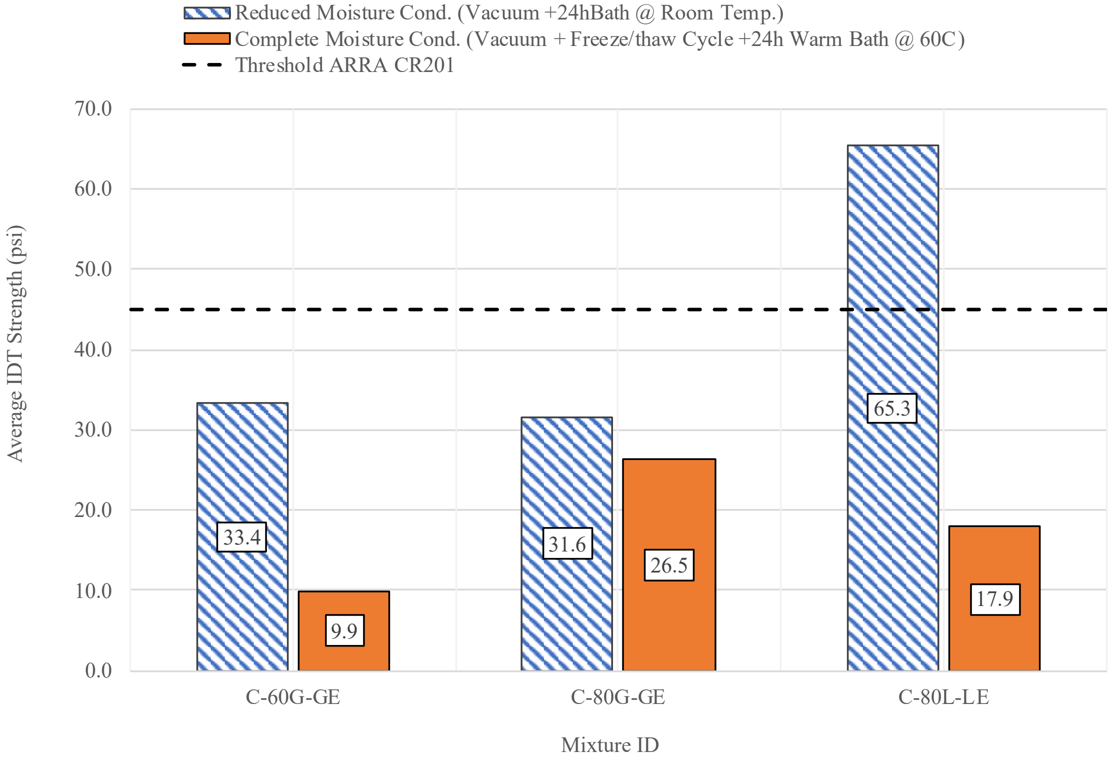


Figure 77. Emulsified Cold Recycled Mixtures' IDT Strength for Specimens Subjected to Different Moisture Conditioning Protocols

The six replicate specimens per emulsified cold recycled mixture type were divided into two subsets of three specimens each according to their AV content. One subset was moisture conditioned using the reduced moisture conditioning protocol described above. The other subset was air-conditioned at room temperature throughout the time required to moisture condition the other subset. Appendix O presents the specimens' volumetric properties and the vacuum saturation level achieved. Both subsets were tested at the same time after the moisture conditioning was completed. IDT strength measurements were conducted at room temperature (77°F [25°]) under a monotonic load applied at a rate of 2.0 inches/min (50 mm/min), as required by FM 1-T 283.

Figure 78 and Figure 79 present the IDT strength and TSR results obtained for the emulsified cold recycled mixtures. Minimum requirements of IDT strength and TSR according to ARRA Standard CR201 are also displayed in the figures.

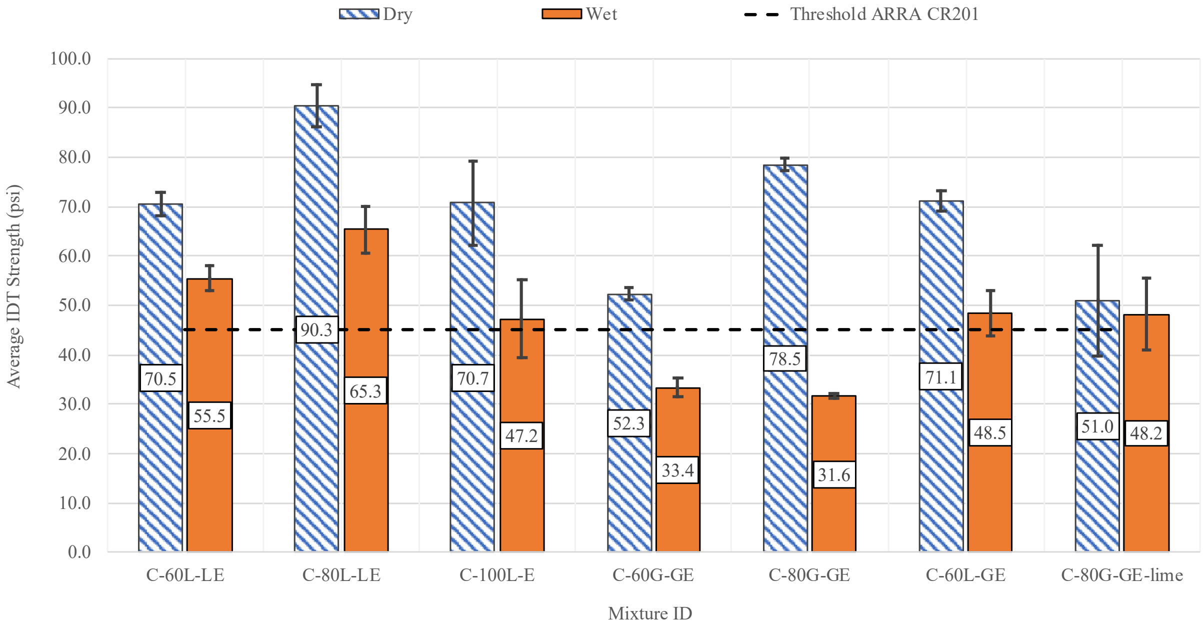


Figure 78. Emulsified Cold Recycled Mixtures' IDT Strength Results

According to Figure 78, the emulsified cold recycled mixtures fabricated with limestone RAP evidenced a good IDT strength performance. Regardless of the RAP content, the average IDT strength of these mixtures was found to meet the minimum IDT strength requirement recommended by ARRA. In contrast, the unconditioned specimens fabricated with granite/limestone RAP had adequate performance but failed to pass the minimum IDT strength threshold after moisture conditioning. The largest unconditioned IDT strength was achieved by the emulsified cold recycled mixtures with 80 percent RAP content.

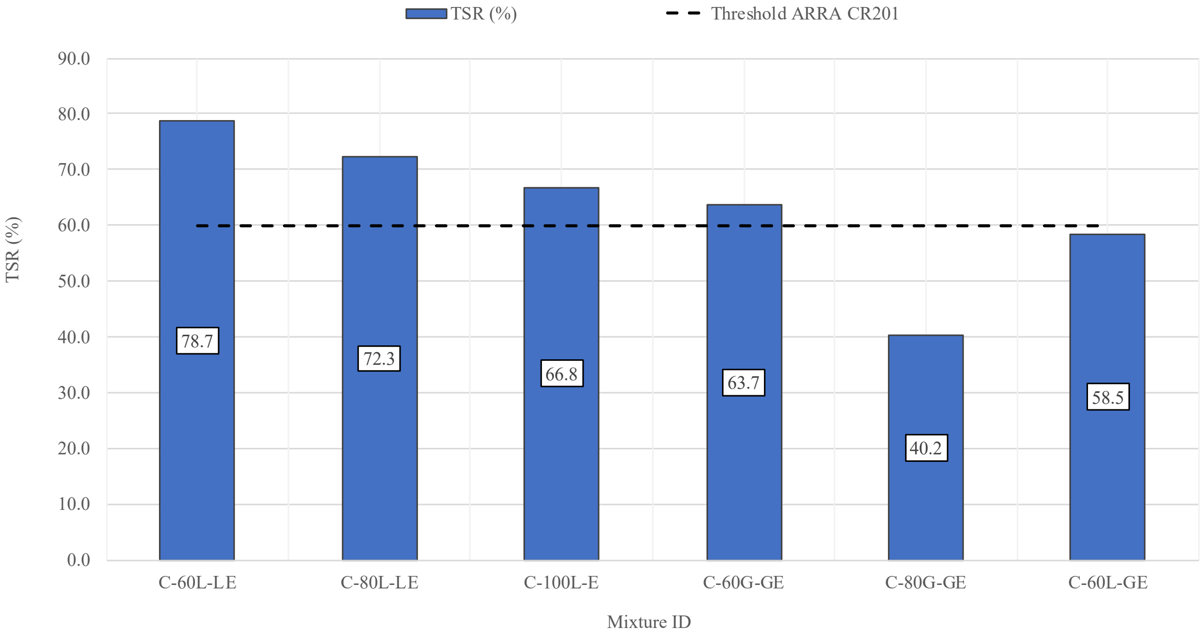
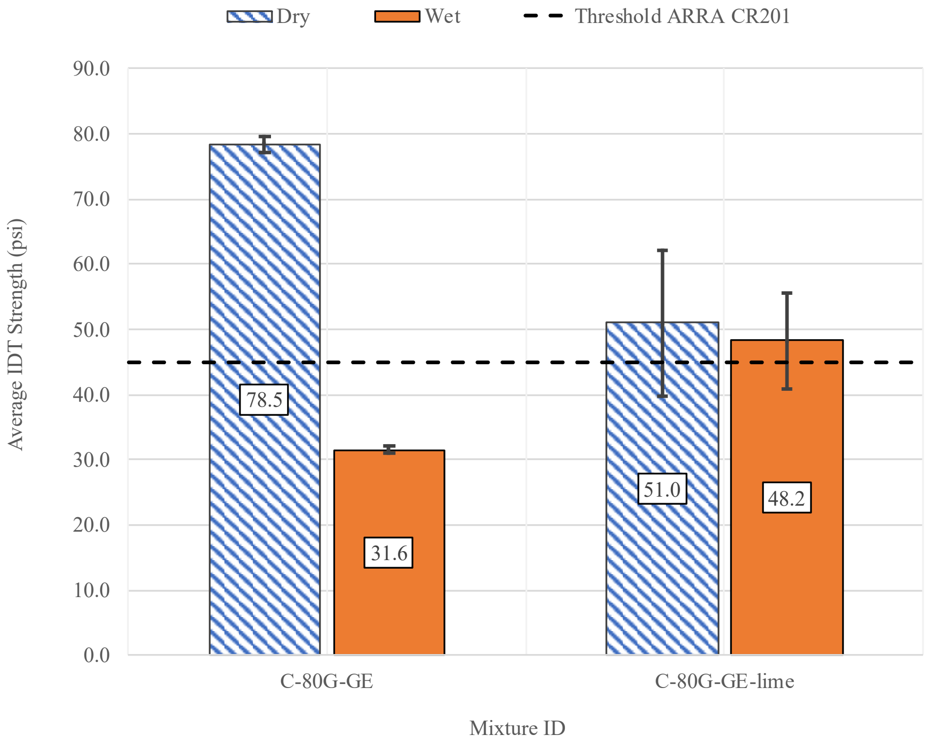


Figure 79. Emulsified Cold Recycled Mixtures' TSR Results

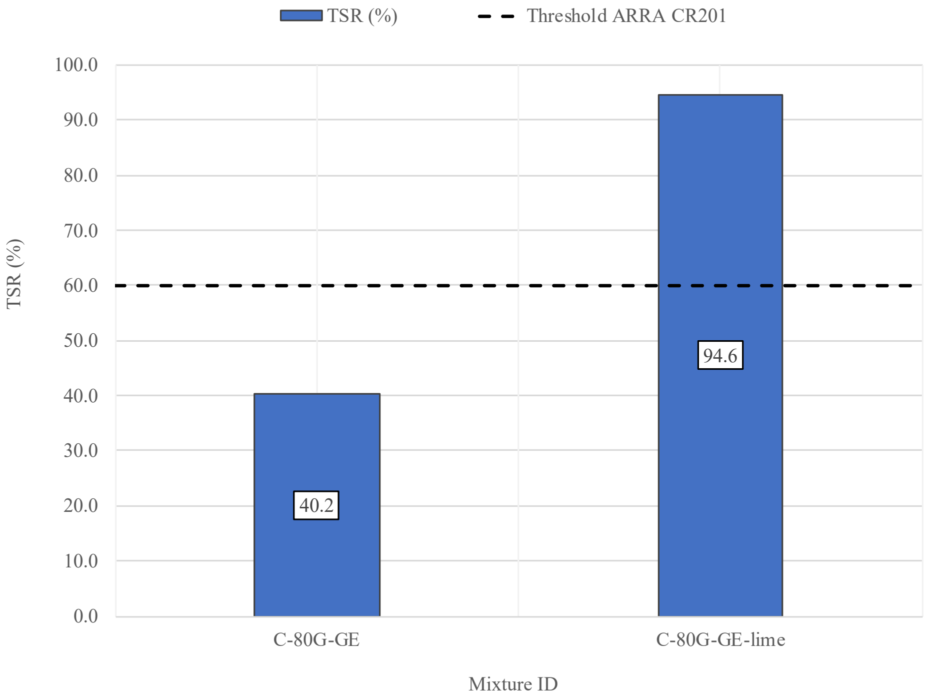
As determined from the information in Figure 79, the TSR results of the mixtures developed an inverse relationship with respect to the RAP content, meaning that mixtures with higher RAP content developed lower IDT strengths after moisture conditioning, and thus were more susceptible to moisture damage. The moisture susceptibility performance of mixtures that included limestone RAP and limestone virgin aggregate could be considered adequate since the minimum TSR requirement was met. However, the mixtures fabricated with more than 60 percent granite/limestone RAP and granite virgin aggregate failed to meet the minimum TSR requirements due to considerable reduction of the tensile strength after moisture conditioning the specimens.

The inclusion of anti-strip agents such as hydrated lime in emulsified cold recycled mixtures is common to improve resistance to moisture damage. To assess the improvement in the IDT strength and TSR on these types of mixtures, 1 percent hydrated lime (by mass of mixture solids) was added to the worst performing mixture, C-80G-GE, which had the lowest IDT strength and TSR, as shown in Figure 78 and Figure 79, respectively.

Four compacted specimens of the C-80G-GE recycled mixture with the hydrated lime were fabricated and cured following the procedure previously described. The specimens were divided into two subsets, one that tested dry and the other that was subjected to moisture conditioning. Figure 80(a) and (b) compare the IDT strength and TSR results of the C-80-G-GE mixture with and without hydrated lime.



(a)



(b)

Figure 80. C-80G-GE Mixture Results with and without Hydrated Lime: (a) IDT Strength, and (b) TSR

The results indicated that the dry IDT strength of the C-80G-GE mixture reduced after incorporating the hydrated lime, but the wet IDT strength improved significantly, about 52 percent (Figure 80[a]), resulting also in a larger TSR (Figure 80[b]). Nevertheless, although the dry IDT strength reduced for the mixture with the hydrated lime, both dry and wet IDT strengths were above the minimum threshold of 45 psi recommended by ARRA Standard CR201. Therefore, the addition of hydrated lime to emulsified cold recycled mixtures appears to be a feasible option to preclude moisture susceptibility.

A multi-factor ANCOVA followed by Tukey's HSD test was conducted to determine the influence of factors, including RAP content, RAP type, virgin aggregate type, and moisture conditioning type, on the IDT strength of the emulsified cold recycled mixtures. The AV content was also included in the analysis. Appendix R contains the analysis output obtained by the JMP statistical package. The results showed that RAP content and moisture conditioning were statistically significant at $\alpha = 0.05$, meaning that these factors had a significant effect on IDT strength. Conversely, virgin aggregate type was statistically insignificant.

VI.3.2. Rutting and Moisture Susceptibility

The moisture susceptibility of the emulsified cold recycled mixtures was evaluated by means of the HWTT in accordance to AASHTO T 324. As defined by that AASHTO standard, the SIP and rut depth at a certain number of load cycles were determined for each mixture in order to evaluate moisture susceptibility and rutting resistance, respectively. Two test replicates were simultaneously tested per mixture type by employing both wheels of the HWTT equipment (i.e., left and right). Figure 81 and Figure 82 present the SIP obtained on each wheel and the average rut depth versus load cycles, respectively.

According to the results shown in Figure 81, the determination of the SIP parameter was not feasible for two of the emulsified cold recycled mixtures in either one or both wheels, which indicated that the test specimens did not evidence stripping throughout the test.

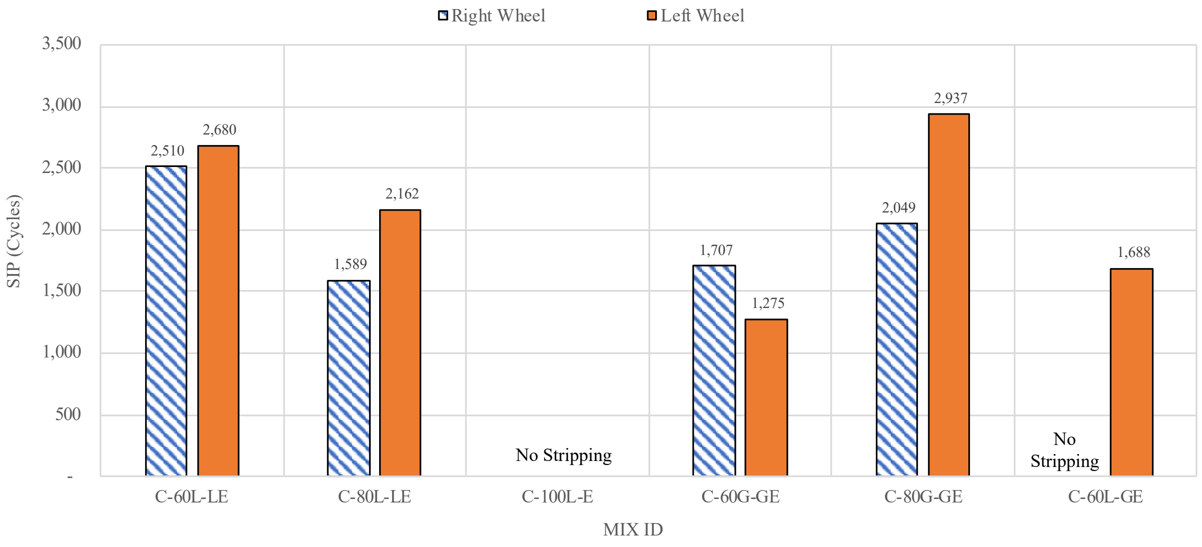


Figure 81. Emulsified Cold Recycled Mixtures' SIP

Based on the data in Figure 81, it is possible to observe that increasing the limestone RAP content of mixtures fabricated with limestone virgin aggregate resulted in a reduction of the SIP and thus an increase in moisture susceptibility. Conversely, increasing the granite/limestone RAP content of mixtures fabricated with granite virgin aggregate increased the SIP, resulting in improved moisture susceptibility. Mixture C-100L-E and C-60L-GE did not present strong evidence of stripping.

Figure 82 presents the average rut depth of each emulsified cold recycled mixture. All specimens experienced accelerated rutting at early test stages. The assigned rut depth failure criteria of ½ inch (12.5 mm) was reached in less than 5,000 load cycles by all mixtures regardless of the RAP and virgin aggregate type and content. Mixtures C-60L-LE and C-80L-LE exhibited better rutting performance.

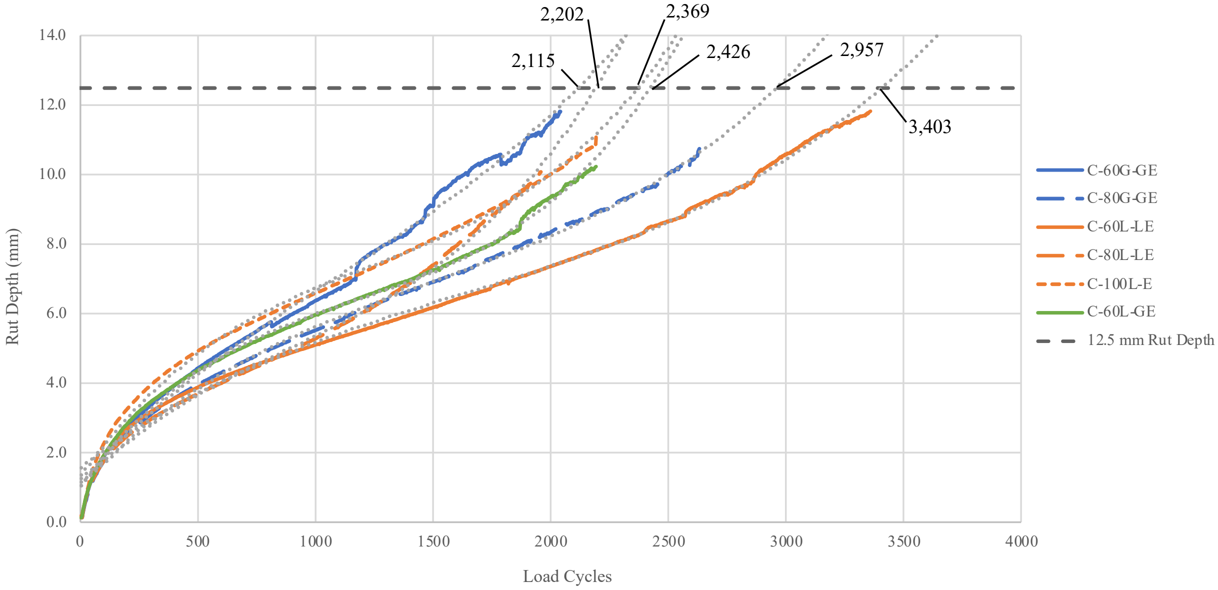


Figure 82. Emulsified Cold Recycled Mixtures' Rut Depth vs. Load Cycles

Figure 83 presents the $\Delta\varepsilon^{vp}_{SN}$ values for each emulsified cold recycled mixture. Mixtures with limestone virgin aggregate with limestone RAP exhibited lower RRP values at RAP contents of 60 percent and 100 percent. Conversely, mixtures with granite/limestone RAP presented better RRP values at a RAP content of 80 percent. However, it is noteworthy that there is a significant amount of variability between replicates, yielding a wide range of RRP values ranging from 23.5 to 59.8.

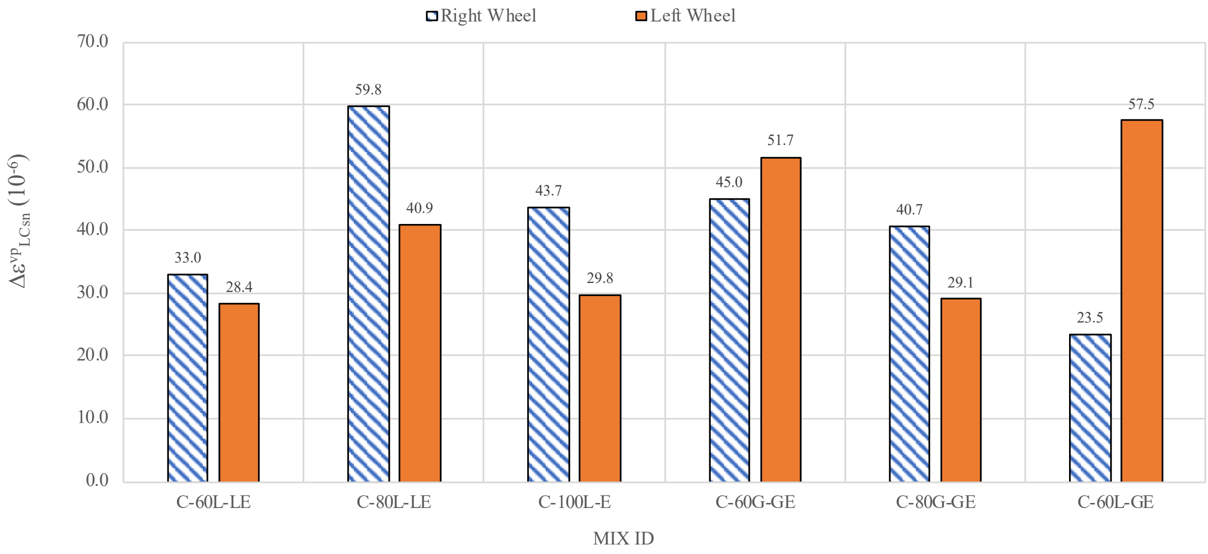


Figure 83. Emulsified Cold Recycled Mixtures' Rutting Resistance Parameter ($\Delta\varepsilon^{vp}_{SN}$)

A multi-factor ANCOVA was conducted to assess the effect of RAP content, RAP type, virgin aggregate type, and AV content on the HWTT response variables: (a) rut depth at 1,000 cycles, (b) SIP, and (c) $\Delta\varepsilon^{vp}_{SN}$. The analysis was performed for each response variable separately. Appendix R presents the results of the analysis obtained with the JMP statistical package. With regard to the rut depth at 1,000 load cycles, the effect of RAP content and virgin aggregate type was partially confounded. Therefore, virgin aggregate type was excluded from the multi-factor ANCOVA. The results showed that none of the factors (i.e., RAP content, RAP type, or AV content) were statistically significant at $\alpha = 0.05$. For the SIP, the multi-factor ANCOVA included RAP content, RAP type, and virgin aggregate type (AV content was excluded because it was statistically very insignificant, with a p-value of 0.9905). As with the rut depth, none of the factors were statistically significant at $\alpha = 0.05$. Finally, for the RRP, the effect of RAP type was statistically very insignificant, with a p-value greater than 0.9, and thus was excluded from the multi-factor ANCOVA. As with the other two HWTT response variables, none of the effects were statistically significant at $\alpha = 0.05$. In general, the RRP was negatively related to AV content, and the granite mixtures yielded larger $\Delta\varepsilon^{vp}_{SN}$ values than the limestone mixtures.

VI.3.3. Durability

The durability of the emulsified cold recycled mixtures was assessed with the Cantabro abrasion loss test in accordance to AASHTO TP 108, *Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens.* As previously mentioned, this test is primarily used for evaluating durability of open graded friction courses but has recently been employed to evaluate the durability other types of mixtures.

Figure 84 presents the average mass loss of compacted specimens after conducting the test. Three replicates per emulsified cold recycled mixture type were conducted. A maximum threshold of 20 percent that is specified for adequate durability of open graded friction course mixtures in AASHTO PP 77 is also displayed in the figure.

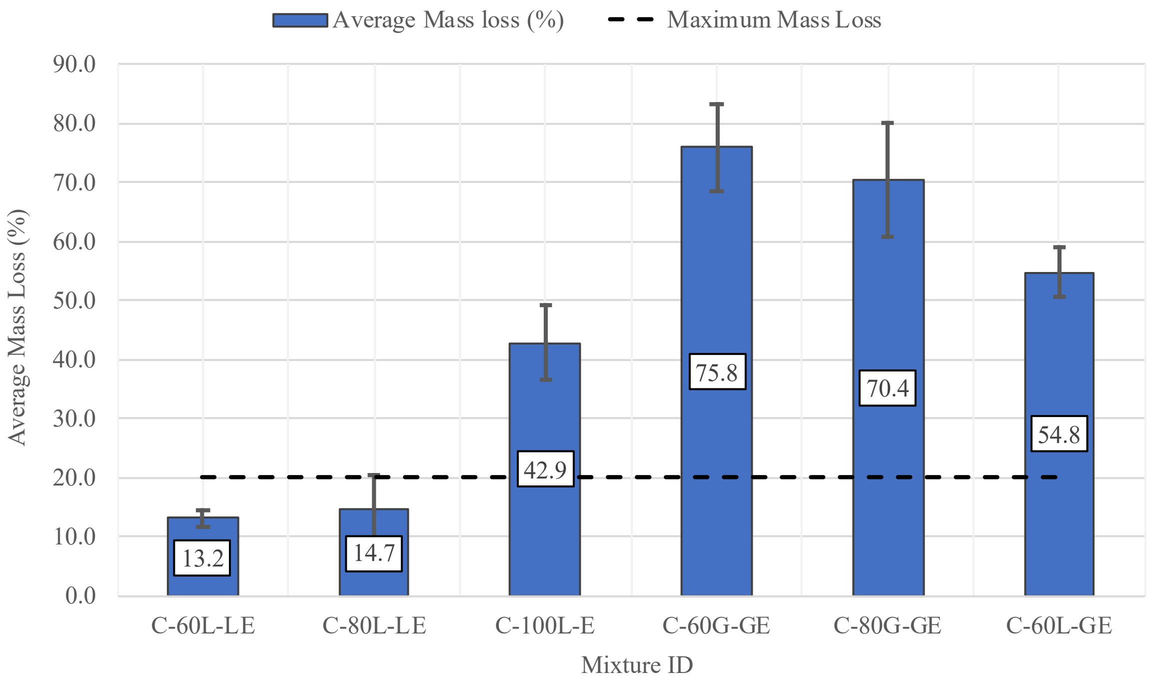


Figure 84. Emulsified Cold Recycled Mixtures' Cantabro Abrasion Mass Loss

The mixtures fabricated with granite virgin aggregate, regardless of the RAP content and type, presented considerably high mass loss, from 55 percent up to 76 percent. Conversely, mixtures fabricated with limestone RAP and limestone virgin aggregate presented—for RAP contents up to 80 percent—good durability, with mass loss values of 15 percent or less. However, the mixture with only limestone RAP, when compared to the other specimens that also had 60 percent and 80 percent limestone RAP contents, presented a much larger mass loss of 43 percent. Figure 85 shows how the test specimens looked before and after conducting the Cantabro abrasion loss test.

(a) **(b)**

Figure 85. Cantabro Abrasion Loss Specimens: (a) Mixture C-60L-LE before (right) and after (left) Testing, and (b) Mixture C-60L-LE after Testing (left) and Mixture C-60G-GE after Testing (right)

A multi-factor ANCOVA was conducted to determine the influence of factors, including RAP content, RAP type, virgin aggregate type, and AV content, on durability measured in terms of the Cantabro abrasion mass loss. Appendix R contains the analysis output obtained by the JMP statistical package. The results show that the factors of RAP type and virgin aggregate type were statistically significant at α = 0.05, meaning those factors had a significant effect on the durability of the mixtures. It was observed that the granite/limestone RAP type resulted in a significantly higher Cantabro abrasion mass loss than the limestone RAP type.

VI.3.4. Stiffness

The stiffness of the cold recycled mixtures with emulsion was evaluated employing M_R in accordance to ASTM D7369. Given the nondestructive nature of the test, the M_R measurements were conducted on HWTT specimens before performing that test. Therefore, the M_R measurements per emulsified cold recycled mix type were conducted on three specimens 6 inches (152.4 mm) in diameter by 2.5 inches (63.5 mm) in height. As with the hot recycled mixtures, a Poisson's ratio of 0.35 was selected to calculate M_R based on the test temperature (77°F [25°C]). After conditioning, a repetitive haversine compressive load pulse was applied in the vertical diametral plane of the specimens, and the horizontal deformation was registered through a set of two LVDTs aligned along the diametral plane.

Figure 86 presents the average and standard deviation of the M_R measurements for each emulsified cold recycled mixture. The results show that the mixtures fabricated with RAP contents of 60 percent, regardless of the RAP and virgin aggregate type, developed not only the greatest but quite similar magnitudes of stiffness of around 650 ksi. Likewise, the mixtures with RAP contents of 80 percent and 100 percent, again independent of the RAP and virgin aggregate type, developed similar but lower M_R values of around 480 ksi. A reduction of about 26 percent was observed in the M_R values after incrementing the RAP content from 60 percent to 80 percent and 100 percent.

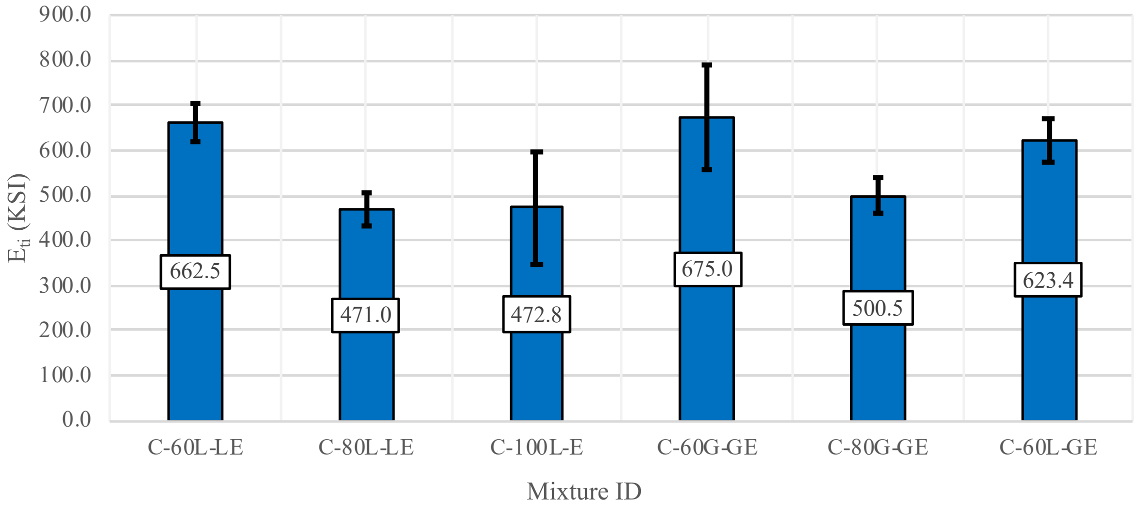


Figure 86. Emulsified Cold Recycled M_R Results

A multi-factor ANCOVA was conducted to determine the influence of factors, including RAP content, RAP type, virgin aggregate type, and AV content, on M_R stiffness. Appendix R contains the analysis output obtained by the JMP statistical package. The results show that the effect of RAP content was statistically significant at α = 0.05, meaning that this factor had a significant effect on the stiffness of the mixtures. It was also observed that 60 percent RAP yielded a statistically significantly higher M_R value than the 80 percent or 100 percent RAP contents.

VII. FOAMED COLD RECYCLED MIXTURE RESULTS

The materials employed in the production of the foamed cold recycled mixtures correspond to the RAP sources (Stockpile 1-09 and Stockpile 1-16) and virgin aggregates types (limestone and granite) listed in Table 21. Additionally, as required per FDOT specifications, Section 334-2.2, *Superpave Asphalt Binder*, a PG 67-22 binder was employed in the design and production of the foamed cold recycled mixtures. The binder rheology was characterized following the methodology defined in AASHTO M 320 in order to verify the continuous high and low temperature PG. Appendix E presents detailed results for the binder PG determination.

This chapter describes the procedure followed for the mix design of the cold recycled mixtures stabilized with foamed binder, the specimen preparation, and the performance results.

VII.1. Mix Design

VII.1.2. Optimum Foaming Water Content

In order to achieve proper foaming performance of the PG 67-22 binder, the optimum foaming water content was determined employing ER and H-L measurements. As mentioned in Chapter IV, ER is defined as the ratio between the volume of a specific mass of fluid before and after foaming, while H-L is the period of time that the same fluid takes to transit from its maximum ER to one-half of that value.

The foaming characteristics (i.e., ER and H-L) of the PG 67-22 binder were determined using a novel methodology developed in NCHRP Project 09-53 (Newcomb et al., 2015) in which non-contact measurements of the foamed binder height by means of a laser sensor replace the traditional dipstick method. This approach removes the subjectivity associated with the conventional method because measurements done with the dipstick are generally highly dependent on the visual judgement of the operator.

The LDM was set up on a tripod above a standard one-gallon can (see Figure 87[a]) in which a sample of foamed binder employing various foaming water contents was dispensed by the Wirtgen WLB 10S. The LDM measured the height of the foamed binder surface by reflecting a laser beam over a very small circular spot (see Figure 87[b]) at a frequency of 1 Hz. If the mass of the dispensed binder sample and the container size is known, the volume of the sample before foaming can be calculated, and the LDM recorded data converted into ER values. An exponential equation was then fitted to the ER versus time data in order to calculate the H-L parameter.


(a) (b)

Figure 87. Foamed Binder Measurements: (a) LDM Equipment Setup and (b) LDM Point Measurement

Figure 88 presents the ER and H-L results of four foaming water contents at a binder foaming temperature of 320ºF (160ºC). The minimum ER and H-L limits recommended by the Wirtgen Group in their cold recycling technology manual (Wirtgen Group, 2012) are also included in the figure and were used to select the optimum foaming water content. Based on both ER and H-L, the results suggested optimum foaming water contents quite apart and outside the investigated range of selected foaming water contents (see Figure 88); therefore the procedure was repeated at a higher binder foaming temperature of 338ºF (170ºC) (see Figure 89).

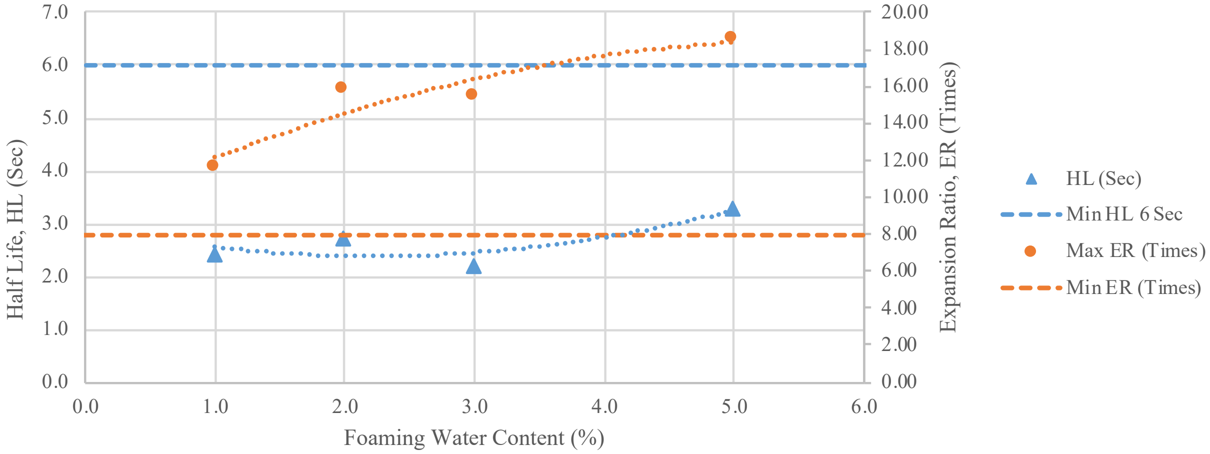


Figure 88. Optimum Foaming Water Content Determination at 320ºF (160ºC)

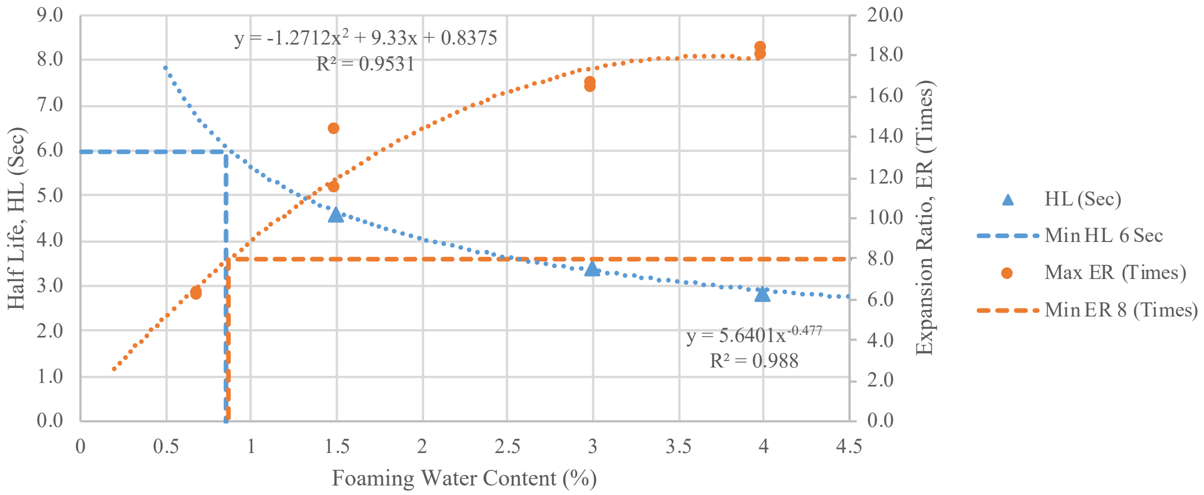


Figure 89. Optimum Foaming Water Content Determination at 338ºF (170ºC)

The results presented in Figure 89 suggest an optimum foaming water content of 0.85 percent based on both ER and H-L. However, due to practicality and ease of use of the Wirtgen WLB 10S foamer, a water content of 1.0 percent was selected as optimum. Appendix Q presents detailed ER and H-L test results.

VII.1.3. Material Proportioning

Two combinations of aggregate type and RAP source (aggregate blends) were selected for the design of the foamed cold recycled mixtures following the experimental plan (see Table 47).

As defined for the emulsified cold recycled mixtures, the design of foamed cold recycled mixtures was conducted following FDOT base material specifications. For each aggregate blend, #78 intermediate size stone and W-10 fine screenings were blended with RAP to meet FDOT aggregate gradation requirements established in Section 234-1, *Superpave Asphalt Base*. As was done for the emulsified cold recycled mixtures, the RAP was considered as a black rock. Therefore, the gradations of the RAP before the ignition oven (including the binder coating the RAP material) were employed to meet FDOT specification requirements.

The aggregate blends proportions of #78 stone, W-10 screenings, and RAP that met the gradation requirements are shown in Table 47. Figure 90 and Figure 91 show the resulting aggregate gradation curves for each aggregate blend.

Table 47. Foamed Cold Recycled Mixtures Aggregate Blends' Proportions

Aggregate's Blend	RAP			Virgin Aggregate		
	Source	Aggregate Type	Amount (%)	Type	#78 Stone (%)	W-10 Screenings (%)
ABC-60L-LF	Stockpile 1-09	Limestone	60	Limestone	25	15
ABC-60L-GF	Stockpile 1-09	Limestone	60	Granite	20	20

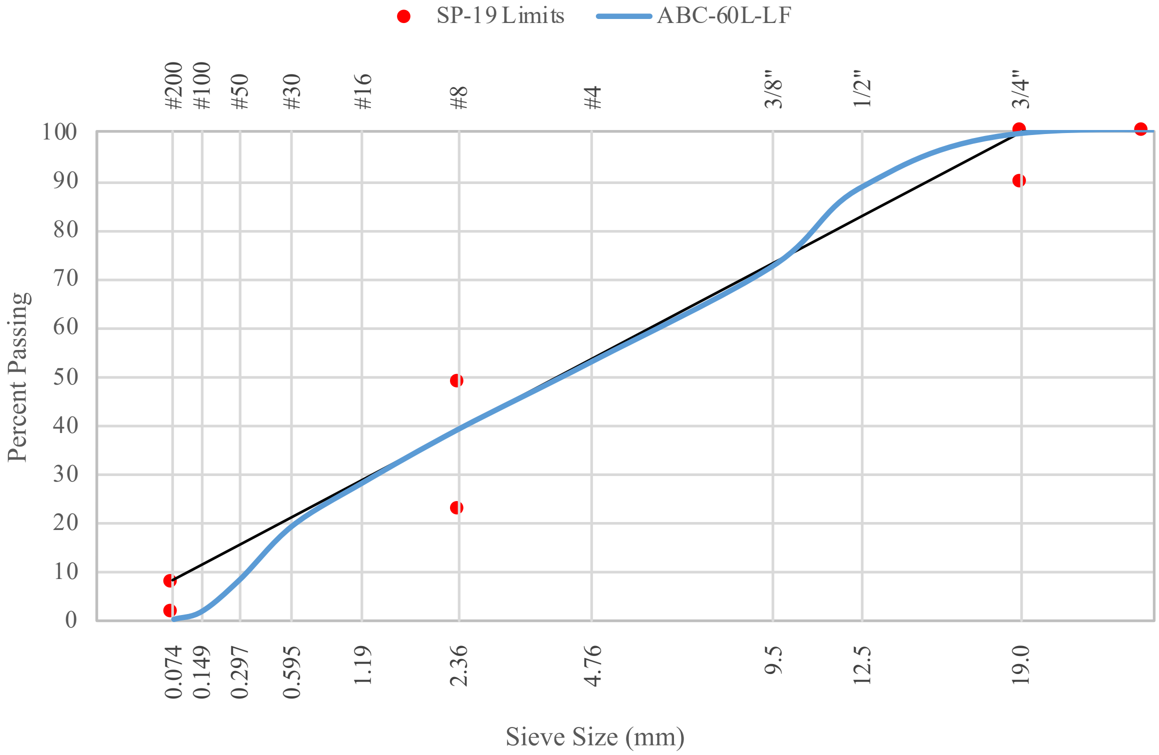


Figure 90. Foamed Cold Recycled Mixtures ABC-60L-LF Aggregate Blend Gradation Curve

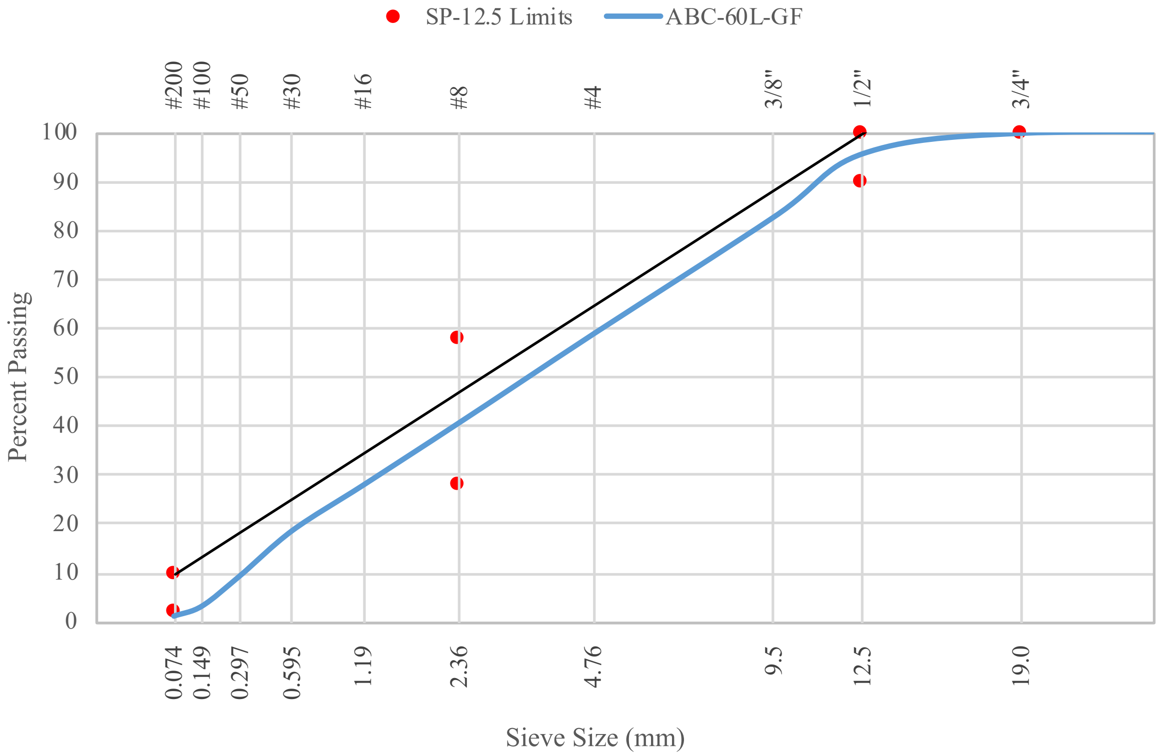


Figure 91. Foamed Cold Recycled Mixtures ABC-60L-GF Aggregate Blend Gradation Curve

The aggregate blend for the ABC-60L-GE mixture resulted in a NMAS of ½ inch (12.5 mm), whereas the aggregate blend for the ABC-60L-LE mixture presented a NMAS of ¾ inches (19.0 mm). Therefore, the produced mixtures and verified requirements for the ABC-60L-GE aggregate blend corresponded to B-12.5 and corresponded to B-19.0 for the ABC-60L-LE aggregate blend. Detailed aggregate blend calculations and gradation requirements for each NMAS are shown in Appendix L.

VII.1.4. Moisture Content and Curing Protocol

In order to determine the need for moisture inclusion and curing of foamed cold recycled mixtures, trial mixtures with three binder contents were fabricated employing the ABC-60L-LF aggregate blend listed in Table 47 and moisture contents of 0 percent and OMC = 4 percent as determined for the emulsified cold recycled mixtures. Trial specimens were produced and tested for moisture susceptibility as outlined in ARRA Standard CR201.

Four specimens 4 inches (101.6 mm) in diameter by about 2.8 inches (70.0 mm) in height were fabricated with foamed binder contents of 3 percent and 5 percent, employing no water other (i.e., OMC = 0 percent) than that required to foam the binder (i.e., dry aggregates). The mixing and compaction procedures detailed in the next section were followed for the fabrication of the specimens. Four additional specimens of the same dimensions were fabricated with a foamed binder content of 4 percent, but 4 percent water (i.e., OMC = 4 percent) was added to the aggregate blend before dispensing the foamed binder. It is important to note that no curing time was provided to these trial specimens.

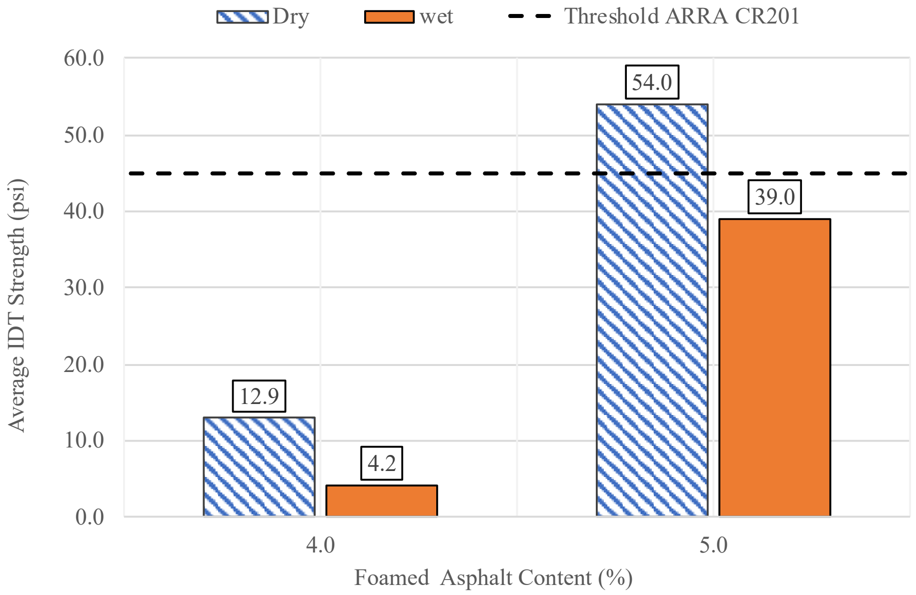
The trial mixtures at 3 percent and 5 percent foamed binder content and OMC = 0 had poor workability when mixing and compacting. Moreover, the trial specimens at 3 percent binder content did not reach enough stability for testing. After compacting, the samples crumbled when ejected from the compaction mold, losing most of their cross section. Figure 92 shows the resulting mixture after dispensing the foamed binder and mixing with the aggregate blend. Uncoated aggregate particles and binder lumps covered with fine material were apparent after mixing.

Figure 92. Appearance of Foamed Cold Recycled Mixture with 3% Foamed Binder and No MC after Mixing

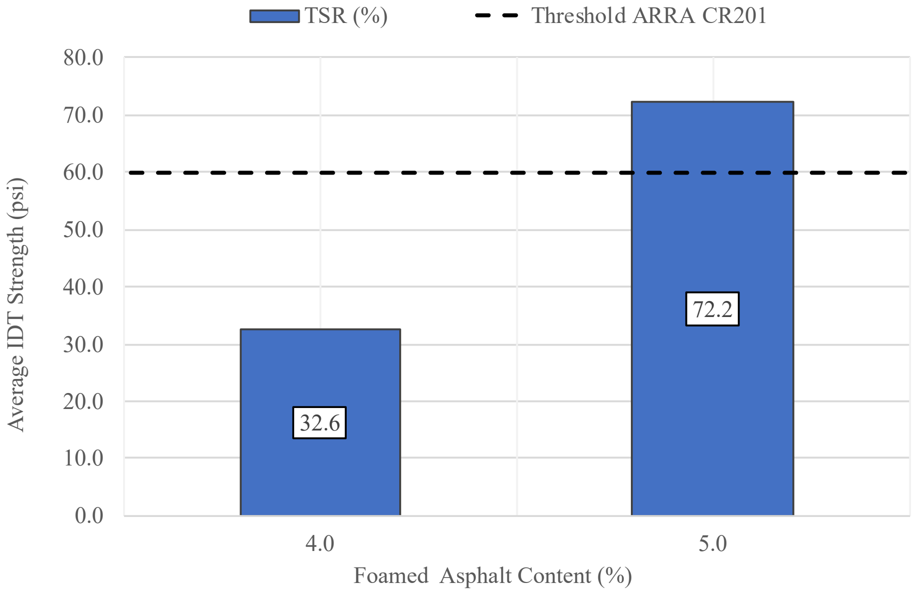
The specimens with 5 percent foamed binder content and OMC = 0 and the specimens with 4 percent foamed binder content and OMC = 4 percent were placed on a flat surface and allowed to sit for at least 3 hours after compaction. After this period, the AV content was determined following FDOT standard test method FM 1-T 166, *Bulk Specific Gravity of Compacted Asphalt Specimens* and FM 1-T 209, *Maximum Specific Gravity of Asphalt Paving Mixtures*. Appendix M presents the G_{sb} and volumetric properties for each foamed binder content.

Subsets of two specimens per foamed binder content were moisture conditioned in a water bath at room temperature for 24 hours. Two other compacted specimens at the same foamed binder content were tested without conditioning. The IDT strength was determined in accordance with FM 1-T 283, *Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage*, for both unconditioned and moisture conditioned specimens.

Figure 93 presents the IDT strength and TSR results. The minimum recommended IDT strength and TSR values according to ARRA CR201 are also displayed in the figure.



(a)



(b)

Figure 93. Foamed Cold Recycled Mixture Trial Results: (a) IDT Strength and (b) TSR

The results showed that the foamed cold recycled mixtures with a foamed binder content of 5 percent and OMC = 0 met the minimum IDT strength requirement. However, it was difficult to mix and compact these specimens because the mixture was not workable. When an MC of 4 percent was added to the foamed cold recycled mixtures with 4 percent foamed binder content, workability improved significantly, but the IDT strength reduced to the point of not meeting the ARRA requirement. In addition, after failing these specimens with added MC, a significant amount of moisture was observed inside the specimens, as shown in Figure 94.

Figure 94. Cross-section of Foamed Cold Recycled Mixture Trial Specimen with 4% Foamed Binder Content and 4% MC

Based on these results, it was decided to produce the foamed binder cold recycled mixtures employing an MC of 4 percent but curing the compacted specimens for 24 hours at a temperature of 140ºF (60ºC), as was done for the emulsified cold recycled mixtures. This option was selected in order to avoid workability issues during mixing and compaction and to also improve the IDT strength of the compacted specimens.

Table 48 summarizes the foamed cold recycled mixtures' selected MC and curing protocol for the aggregate blends listed in Table 47.

Table 48. Foamed Cold Recycled Mixtures' OMC and Curing Time

Cold Recycled Mixture ID	Aggregate's Blend	OMC	Curing Time @ 60ºC
C-60L-LF	ABC-60L-LF	4%	24h
C-60L-GF	ABC-60L-GF		

VII.1.5. Optimum Foamed Binder Content

Mixtures with three foamed binder contents were fabricated for each aggregate blend shown in Table 47 in order to find the optimum foamed binder content that could satisfy the minimum IDT strength requirement specified in ARRA Standard CR201.

Before mixing, the aggregates (#78 and W-10) and RAP were oven dried overnight and for 4 hours, respectively, at 230ºF (110°C). The materials were allowed to cool down to room temperature and then mixed with the 4 percent MC. After no more than 5 minutes after adding the water, the binder at the selected amount was foamed using the optimum foaming water content in the Wirtgen WLB 10S (see Figure 95) and mixed with the aggregate blend by employing a mechanical mixer.

Figure 95. Wirtgen WLB 10S Foaming Unit

Once mixing was complete, four specimens 4 inches (100 mm) in diameter by about 2.8 inches (70 mm) in height were compacted for each foamed binder content in the SGC to N_{Design} = 30 gyrations, as established in ARRA Standard CR201. After compaction, the specimens were cured in an oven at 140ºF (60°C) for 24 hours and then allowed to cool down for at least 3 hours on a flat surface.

After this period, the AV content of the specimens was determined following FDOT standard test method FM 1-T 166, *Bulk Specific Gravity of Compacted Asphalt Specimens*, and FM 1-T 209, *Maximum Specific Gravity of Asphalt Paving Mixtures*. Appendix M presents the G_{sb} and volumetric properties for each foamed binder content.

Two specimens per foamed binder content were moisture conditioned in a water bath at room temperature for 24 hours. Two other specimens prepared at the same foamed binder content were left unconditioned. IDT strength was determined in accordance with FM 1-T 283, *Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage*, for both unconditioned and moisture conditioned specimens.

Figure 96 and Figure 97 present the IDT strength of the unconditioned and moisture conditioned specimens. Wirtgen recommended minimum IDT strengths of 32.6 psi (225 kPa) and 14.4 psi (100 kPa) for unconditioned and moisture conditioned specimens, respectively (Wirtgen Group, 2012). However, the IDT strength levels developed by the foamed cold recycled mixtures surpassed these thresholds with foamed binder contents as low as 2 percent. Therefore, a higher and sole threshold of 45 psi as prescribed for cured and conditioned specimens in ARRA Standard CR201, Table 1, was employed to estimate the optimum foamed binder content. Although this threshold is prescribed for cured and conditioned specimens, it was applied to select the optimum foamed binder content using the critical IDT strength i.e., the curve with the lowest IDT strength regardless of conditioning.

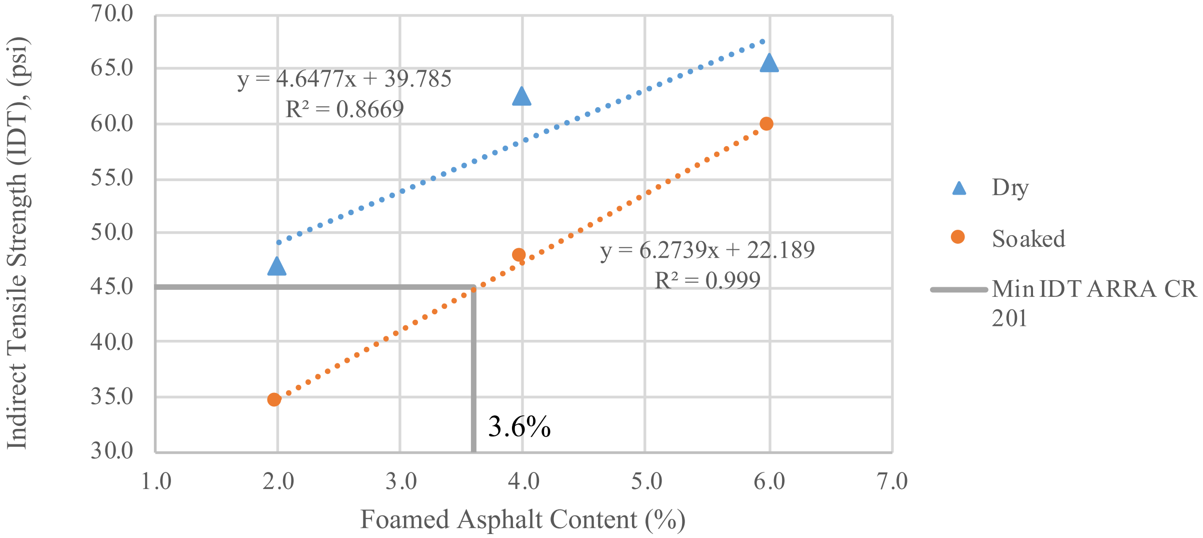


Figure 96. Foamed Cold Recycled Mixture C-60L-LF IDT Strength

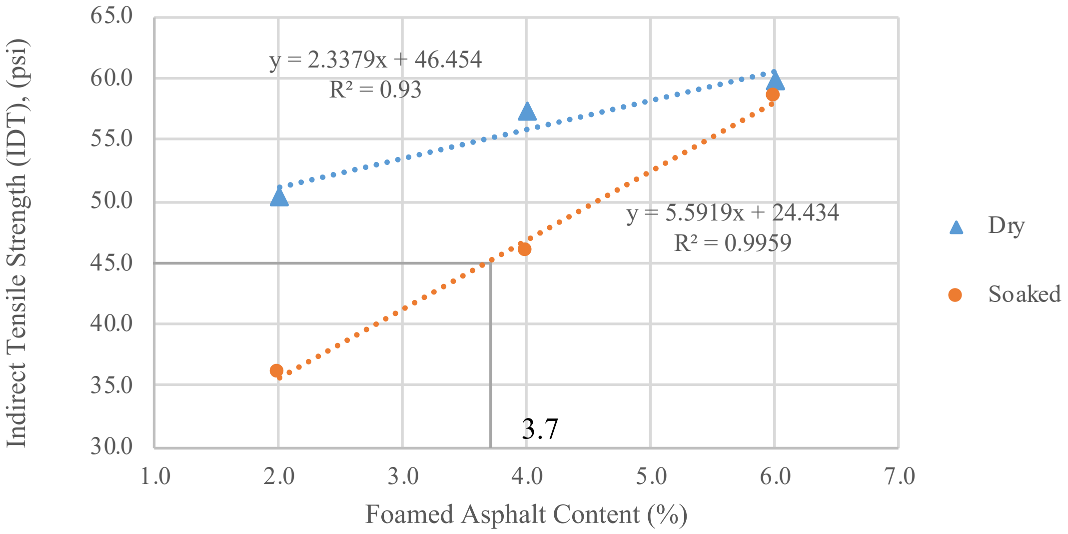


Figure 97. Foamed Cold Recycled Mixture C-60L-GF IDT Strength

Table 49 presents the TSR for each mixture type and foamed binder content. A minimum TSR of 60 percent is established in the ARRA Standard CR201 for mixtures that incorporate RAP and for when the moisture conditioned IDT strength exceeds the minimum dry strength/stability requirement of 45 psi.

Table 49. Foamed Cold Recycled Mixtures TSR Results

Foamed Binder Content (%)	TSR (%)	
	C-60L-LF	C-60L-GF
2.0	73	72
4.0	76	80
6.0	91	98

Table 50 presents the optimum foamed binder content for each mixture and the corresponding TSR interpolated from the data presented in Table 49. Based on the resulting TSR values, the mixtures had low moisture susceptibility; therefore, no stabilization by means of addition of lime was considered necessary.

Table 50. Foamed Cold Recycled Mixtures Optimum Foamed Binder Content

Cold Recycled Mixture	Optimum Foamed Binder Content (%)	TSR (%)
C-60L-LF	3.6	79
C-60L-GF	3.7	81

VII.2. Specimen Fabrication

In following the experimental plan, the specimens required for performance testing of foamed cold recycled mixtures are listed in Table 51. The proportion of aggregate and RAP determined to meet FDOT specifications, Section 234, was presented in Table 47. The optimum foamed binder content was assigned by pairing the virgin aggregate type of the mix designs presented in

Table 50 with the type of virgin aggregate in each mix (see Table 51). Therefore, limestone virgin aggregate mixtures were assigned an optimum foamed binder content of 3.6 percent, while granite virgin aggregate mixtures were assigned an optimum foamed binder content of 3.7 percent.

Table 51. Foamed Cold Recycled Mixtures Material Proportions

Mixture Type	RAP Type and Amount		Virgin Aggregate Type Proportioning				Optimum Foamed Binder content (%)	MC (%)
			Limestone		Granite			
	Limestone (Stockpile 1-09)	Granite/Limestone (Stockpile 1-16)	#78 Stone	W-10 Screenings	#78 Stone	W-10 Screenings		
C-60L-LF	60.0%	–	25.0%	15.0%	–	–	3.6	4.0
C-80L-LF	80.0%	–	20.0%	0.0%	–	–	3.6	4.0
C-100L-F	100.00%	–	–	–	–	–	3.6	4.0
C-60L-GF	60.0%	–	–	–	20.0%	20.0%	3.7	4.0

The specimens were fabricated for each performance test included in the experimental plan. Table 52 presents a list of the tests and the specimen characteristics and quantities. A total of 50 foamed cold recycled mixture specimens were fabricated.

Before mixing, the aggregates (#78 and W-10) and RAP were dried overnight and for 4 hours, respectively, in an oven at 230ºF (110°C). The materials were allowed to cool down to room temperature and then mixed with the 4 percent OMC by employing the mixing chamber of the Wirtgen WLB 10S foaming unit. No more than 2 minutes after, and with the mixing chamber operating, the optimum foamed binder content was dispensed and mixed with the aggregate blend for one minute using the Wirtgen WLB 10S configured to foam the binder at the optimum foaming water content.

Table 52. Foamed Cold Recycled Mixtures Specimen Characteristics and Quantities

Mixture Property	Test	Standard	Diameter, in (mm)	Compaction Criteria	Number of Samples per Mix Type	Total Number of Samples
Moisture Susceptibility	Modified Lottman, IDT	FM 1-T283	6 (152.4)	N_{design} = 30 gyrations	6	24
Rutting & Moisture Susceptibility	HWTT	AASHTO T 324	6 (152.4)	Height: 2.5 in. (63.5 mm)	4	14
Stiffness	M_R	ASTM D7369	6 (152.4)	Height: 2.5 in. (63.5 mm)	*	*
Durability	Cantabro Abrasion Loss Test	AASHTO TP 108	6 (152.4)	Height: 4.5 in. (115.0 mm)	3	12

*The M_R test was conducted on three of the four specimens fabricated for rutting and moisture susceptibility evaluation.

Once mixing was complete, the specimens shown in Table 52 were compacted in the SGC to the compaction criteria specified for each specimen type in the same table.

After compacting, the specimens were placed to cure for 24 hours in a forced draft oven at 140ºF (60ºC). Next, the specimens were taken out of the oven and placed on a flat surface to cool down for at least 24 hours before testing. After this period, the mass of the specimen in air, mass of the specimen soaked in water, and SSD mass of each specimen was determined as required by

Florida standard test method FM 1-T 166, *Bulk Specific Gravity of Compacted Asphalt Specimens*. Appendix O presents the G_{sb} and estimated AV content for each specimen and mixture defined in Table 51 and Table 52.

One additional sample was fabricated for each hot recycled mixture displayed in Table 44 and allowed to cool down at ambient temperature in loose condition. The G_{mm} of the mixtures was estimated following Florida's standard test method FM 1-T 209. The results are also listed in Appendix O.

VII.3. Performance Results

VII.3.1. Moisture Susceptibility

The moisture susceptibility of the foamed cold recycled mixtures was evaluated by means of the modified Lottman test as outlined in FDOT test method FM 1-T 283, *Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage.*

Due to limitations of the SGC equipment to achieve a compaction height below 1.96 inches (50 mm), three samples 6 inches (152.4 mm) in diameter per foamed cold recycled mixture type were compacted in the SGC using $N_{Design} = 30$ gyrations as established in ARRA Standard CR201 and cut in half in order to produce six specimens 1.5 inches (38.1 mm) thick.

The six replicate specimens were divided into two subsets of three specimens each according to their AV content. One subset was moisture conditioned using vacuum saturation plus a 24-hour water bath at room temperature as was done in the case of the emulsified cold recycled mixtures. Ten Hg-inches of partial pressure were applied to each specimen of the subset to achieve vacuum saturation.

After this period, the vacuum was removed, and the specimens were left submerged for 5 minutes. The other subset of specimens was stored at room temperature throughout the time required to moisture condition the compaction specimen subset. Appendix O presents the volumetric properties and saturation for each specimen.

Both subsets were tested at the same time after moisture conditioning was completed. IDT strength measurements were conducted at room temperature (77°F [25°C]) under a monotonic load applied at a rate of 2.0 inches/min (50 mm/min), as required by FDOT test method FM 1-T 283.

Figure 98 and Figure 99 present the IDT strength and TSR results for the foamed cold recycled mixtures. The minimum IDT strength and TSR requirements according to ARRA Standard CR201 are also displayed in the figures.

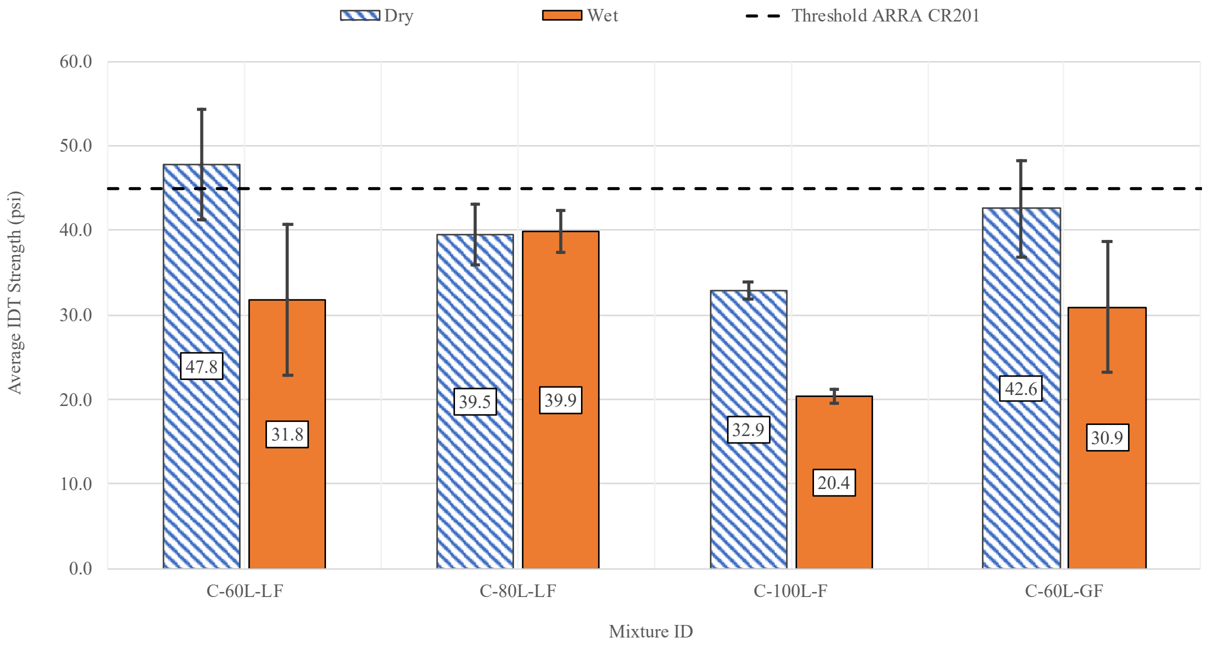


Figure 98. Indirect Tensile Strength of Foamed Cold Recycled Mixtures

According to Figure 98, the foamed cold recycled mixtures evidenced unconditioned IDT strengths that did not meet the minimum ARRA requirement. The mixture with 60 percent limestone RAP and limestone virgin aggregate was the only one that developed IDT strengths above the threshold. Regardless of the RAP content and virgin aggregate type, no mixture met the minimum IDT strength requirement after moisture conditioning.

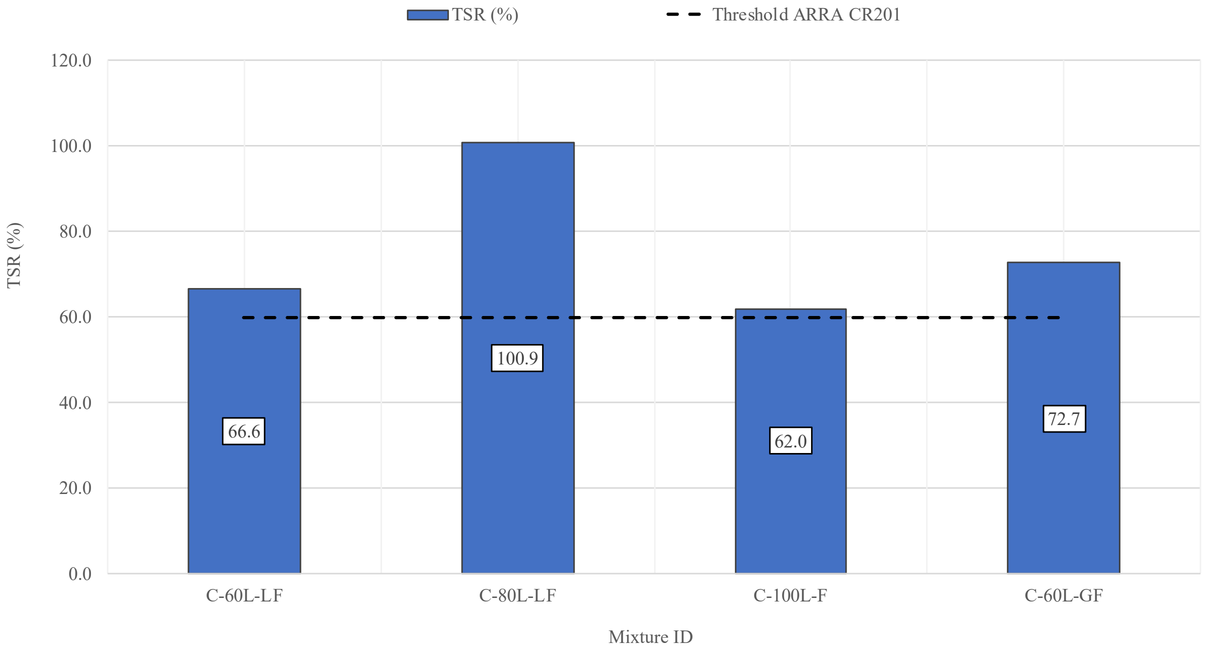


Figure 99. Tensile Strength Ratio of Foamed Cold Recycled Mixtures

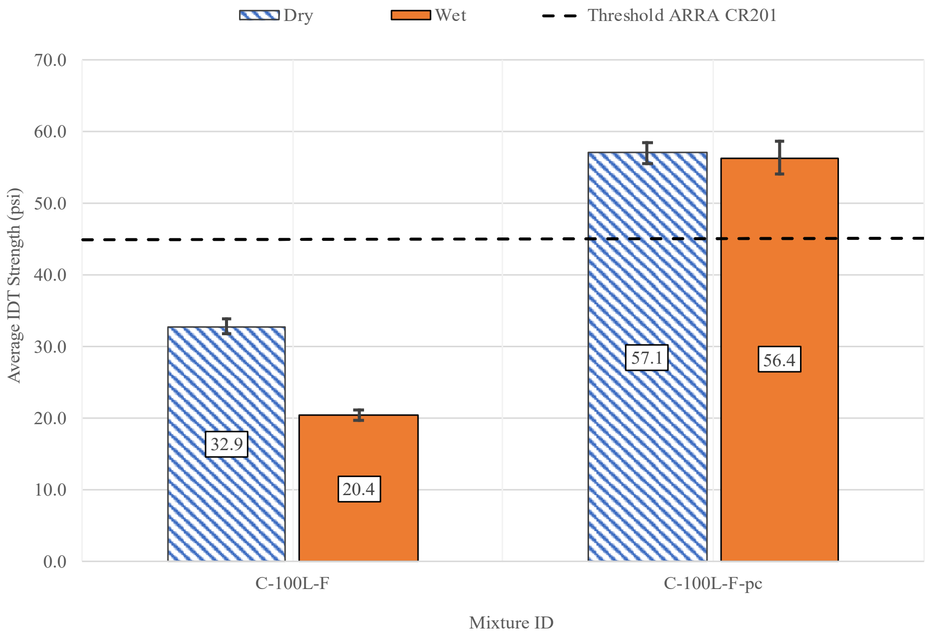
As shown in Figure 99, the TSR presented acceptable performance for all the mixtures. However, the mixture with limestone RAP content of 100 percent barely met the TSR requirement due to a considerable reduction of the tensile strength after moisture conditioning. The results of the mixtures fabricated with limestone virgin aggregate seemed to have a better TSR at a RAP content of 80 percent. Moreover, the IDT strengths and TSR results were similar to each other for mixtures with 60 percent limestone RAP regardless of the virgin aggregate type.

The inclusion of fillers such as Portland cement in foamed cold recycled mixtures is common to improve the strength of base-type materials like the ones employed in FDR. To assess the effect of Portland cement on the IDT strength and TSR of the foamed recycled mixtures, 1 percent of the filler (by mass of mixture solids) was added to the worst performing mixture, C-100L-F.

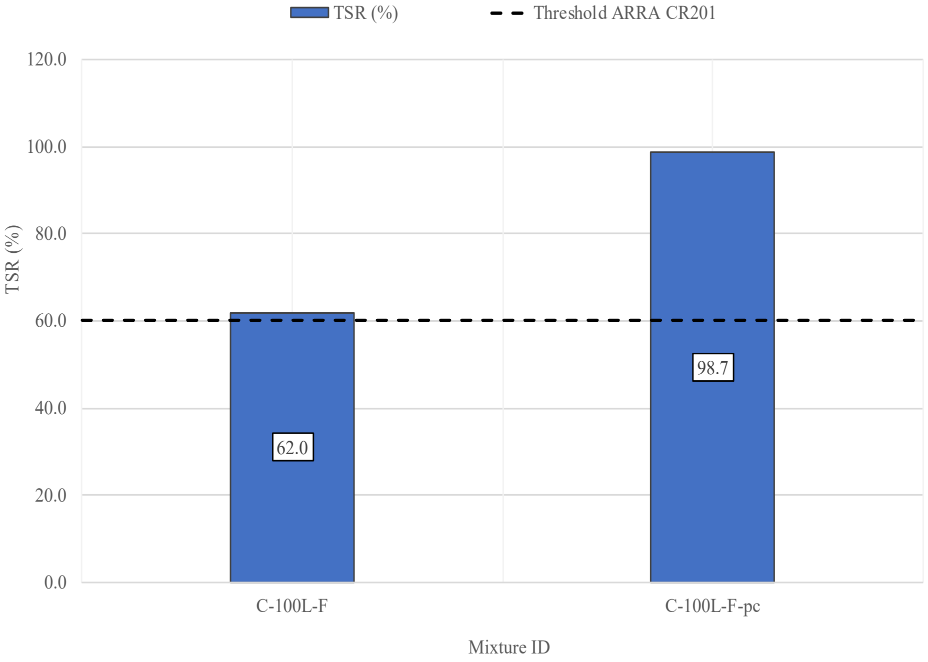
Four compacted specimens of the C-100L-F mixture with Portland cement were fabricated and cured following the procedure previously described. The specimens were divided into two subsets, one that was tested dry and the other that was subjected to moisture conditioning. Figure 100a and Figure 100b compare the IDT strengths and TSR results of the foamed cold recycled mixtures with (labeled C-100L-F-pc) and without Portland cement.

The results show a significant improvement in IDT strength after adding the Portland cement for both dry and conditioned specimens of about 74 percent and 176 percent, respectively. The TSR also improved significantly for the mixtures with Portland cement, with an increase of about 60 percent. These results underscore the importance of incorporating fillers such as Portland cement to improve the performance of foamed cold recycled mixtures.

A multi-factor ANCOVA was conducted to determine the influence of factors, including RAP content, virgin aggregate type, and moisture conditioning type, on the IDT strength of the high RAP cold recycled mixtures with foamed binder. The AV content was also included in the analysis. Appendix R contains the analysis output obtained by the JMP statistical package. The results showed that moisture conditioning was statistically significant at $\alpha = 0.05$, meaning that this factor has a significant effect on IDT strength. In addition, as expected, the statistical analysis proved that the specimens in dry condition had statistically higher IDT strengths than specimens after moisture conditioning.



(a)



(b)

Figure 100. C-100L-F with and without Portland Cement: (a) IDT Strength and (b) TSR.

VII.3.2. Rutting and Moisture Susceptibility

Rutting and moisture susceptibility of the foamed cold recycled mixtures was evaluated with the HWTT in accordance to AASHTO T324, *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA).* As defined by that AASHTO standard, the

SIP and rut depth at a certain number of load cycles were determined for each mixture type in order to evaluate moisture susceptibility and rutting resistance, respectively. Two test replicates were concurrently conducted per mixture type employing both wheels of the HWTT equipment (i.e., left and right).

Figure 101 and Figure 102 present the SIP obtained on each wheel and the average rut depth versus load cycle, respectively. According to the results shown in Figure 101, the determination of the SIP parameter was not possible for two of the foamed cold recycled mixtures in either one or both wheels, which indicates that the test specimens did not evidence stripping throughout the test.

The data in Figure 101 demonstrate that increasing the limestone RAP content of mixtures fabricated with limestone virgin aggregate had no impact on moisture susceptibility, since both mixtures, C-60L-LF and C-80L-LF, presented approximately the same SIP. With regard to mixture C-60L-GF, the relative lower SIP value (about 1,000 cycles) indicated that moisture susceptibility was also likely an issue.

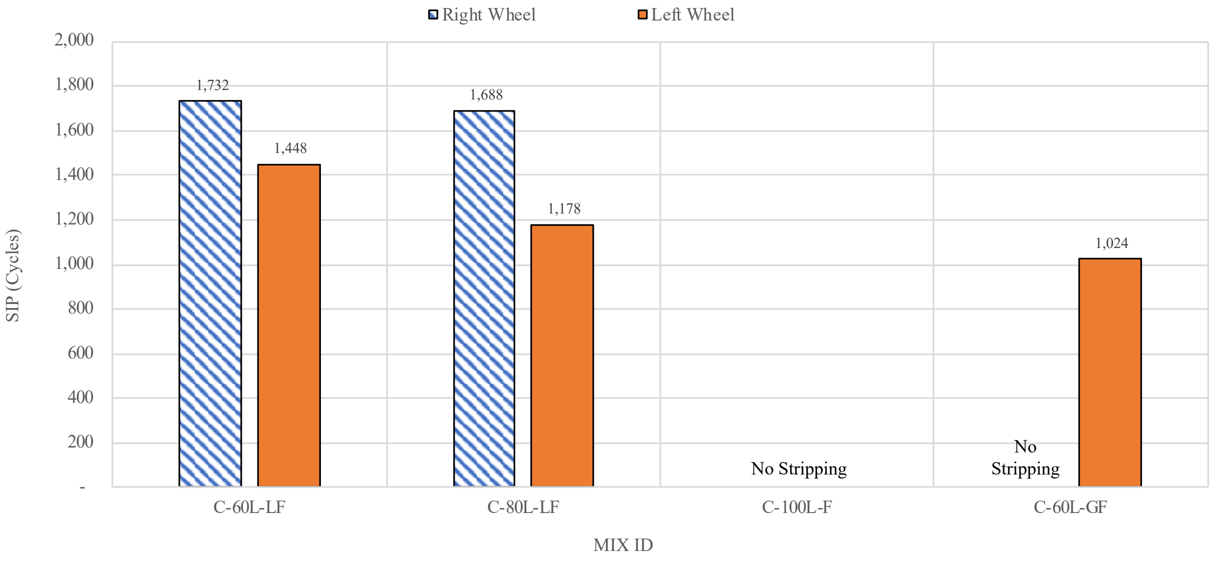


Figure 101. Foamed Cold Recycled Mixtures' SIP

Figure 102 presents the average rut depth of each cold recycled mixture with foamed binder. All mixtures experienced accelerated rutting at early load cycles. The assigned rut depth failure criteria of ½ inch (12.5 mm) was reached in less than 2,500 load cycles by all mixtures except C-80L-LF, which reached failure in less than 5,000 cycles.

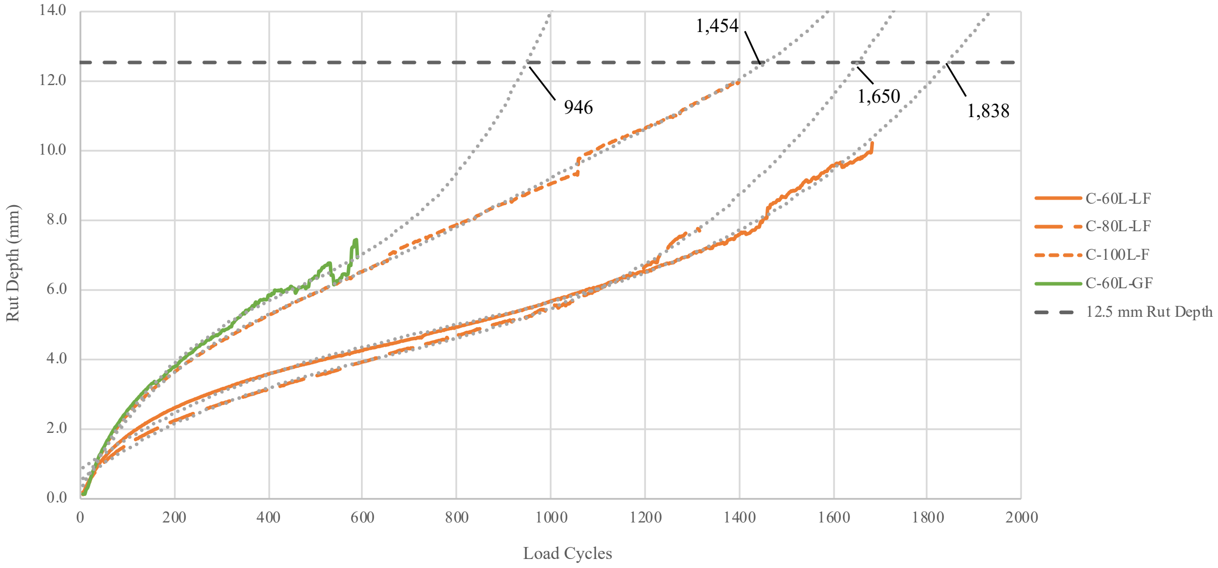


Figure 102. Foamed Cold Recycled Mixtures' Rut Depth vs. Load Cycles

Figure 103 presents the RRP ($\Delta\varepsilon^{vp}_{SN}$) values for each foamed cold recycled mixture. Mixtures with limestone virgin aggregate have considerably similar rutting resistance, considering that the average of the mixtures ranges from 59.4 to 64.3. However, replacing the limestone virgin aggregate with granite virgin aggregate in mixtures with 60 percent limestone RAP content seems to increase the RRP (i.e., mixtures are more prone to rutting) by about 40 percent.

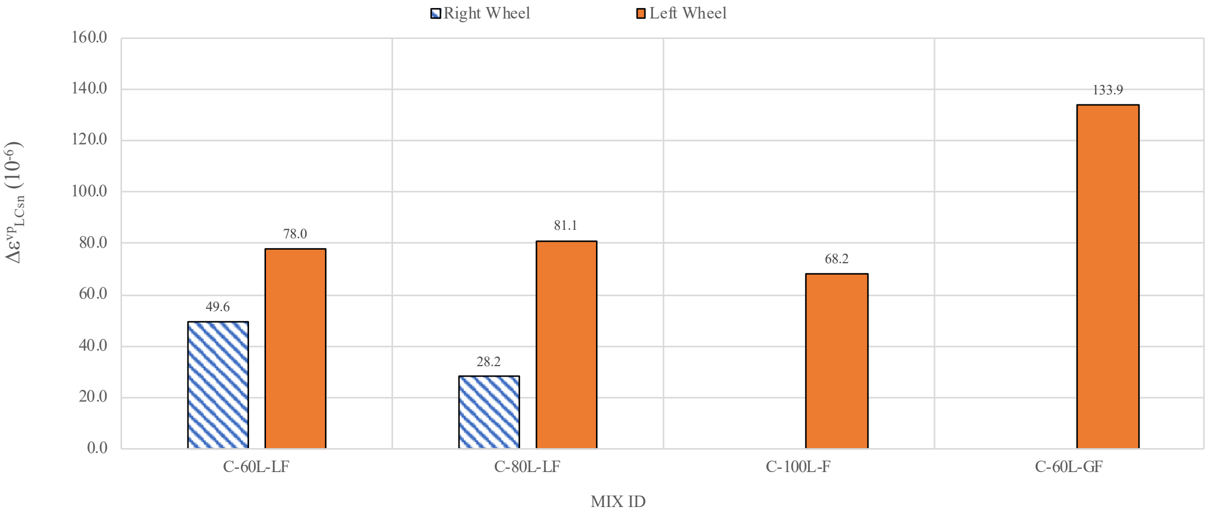


Figure 103. Foamed Cold Recycled Mixtures' Rutting Resistance Parameter ($\Delta\varepsilon^{vp}_{SN}$)

A multi-factor ANCOVA was conducted to assess the effects of RAP content, virgin aggregate type, and AV content on the HWTT response variables: (a) rut depth at 1,000 load cycles, (b) SIP, and (c) $\Delta\varepsilon^{vp}_{SN}$. Note that RAP type and recycling agent type (i.e., foaming) were fixed factors. The multi-factor ANCOVA was performed separately for each of the response variables. Appendix R presents the results of the analysis obtained with the JMP statistical package. For the rut depth at 1,000 cycles, the effects of RAP content and virgin aggregate type were confounded, and thus the analysis was performed using virgin aggregate type since it yielded a better goodness of fit for the data. The results showed that the effect of virgin aggregate type was statistically significant at $\alpha = 0.05$. For the SIP, the multi-factor ANCOVA model, including RAP content, virgin aggregate type, and AV content, showed that none of the factors were statistically significant at $\alpha = 0.05$. This result could partially be due to the fact that there were only six SIP observations. For the RRP, the multi-factor ANCOVA included virgin aggregate type and AV content. In this case, virgin aggregate type was statistically significant at $\alpha = 0.05$.

VII.3.3. Durability

The durability of the foamed cold recycled mixtures was conducted employing the Cantabro abrasion loss test in accordance to AASHTO TP 108, *Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens.* Figure 104 presents the average mass loss of compacted specimens after conducting the test. Three replicates per recycled mixture type were tested.

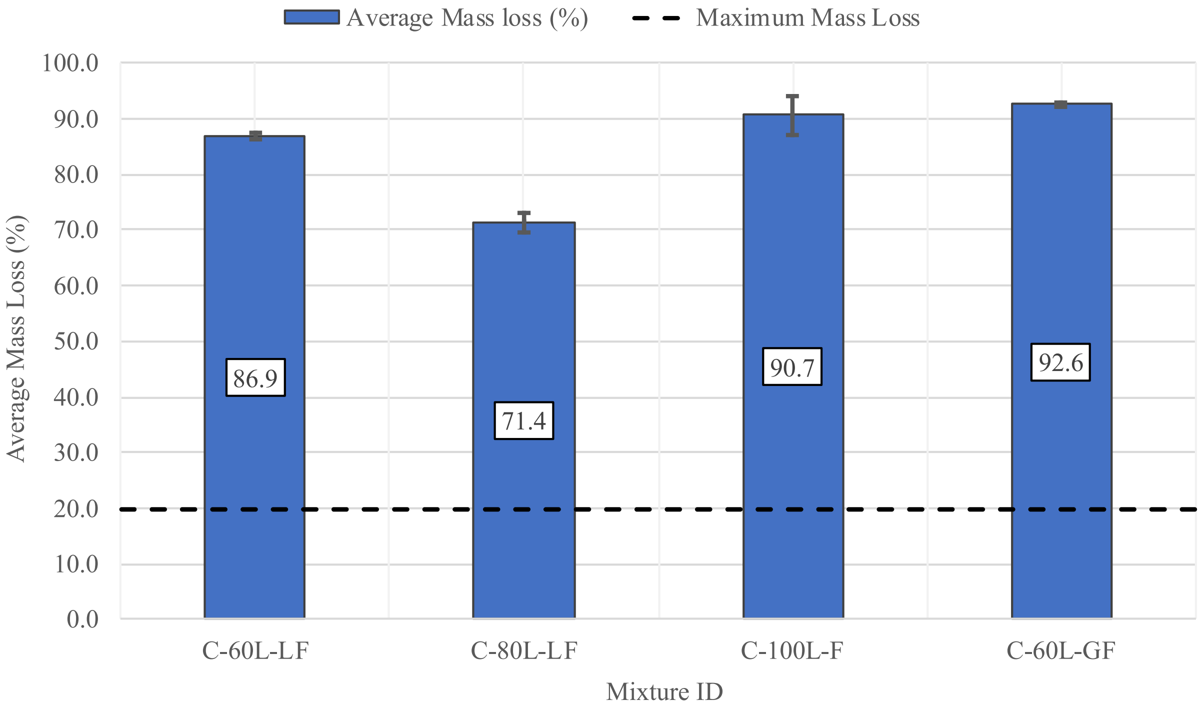


Figure 104. Mass Loss of Foamed Cold Recycled Mixtures after Cantabro Abrasion Loss Test

All foamed cold recycled mixtures exhibited poor durability, with abrasion mass losses ranging from 71 percent to 92 percent. Regardless of the RAP content and virgin aggregate type, the foamed cold recycled mixtures developed considerably high mass loss after testing, which indicates poor cementation between aggregate particles and thus low abrasion resistance. Figure 105 illustrates how the test specimens looked before and after conducting the Cantabro abrasion loss test.

(a) (b)

Figure 105. Specimens before and after Cantabro Abrasion Loss Test: (a) Mixture C-80L-LF and (b) Mixture C-60L-GF

It was previously demonstrated that the inclusion of Portland cement in foamed cold mixtures was effective at improving the IDT strength. Thus, it was also of interest to assess if introducing this type of additive could also improve the durability in terms of Cantabro abrasion loss. To quantify the difference in performance, 1 percent Portland cement (by mass of mixture solids) was added to the foamed cold recycled mixture C-100L-F, which, based on the results shown in Figure 104, had poor durability with a 90.7 percent Cantabro mass loss.

Two compacted specimens of the foamed cold recycled mixture with Portland cement were fabricated and cured following the procedure previously described. Figure 106 compares the Cantabro mass loss of the mixture with (labeled C-100L-F-pc) and without Portland cement.

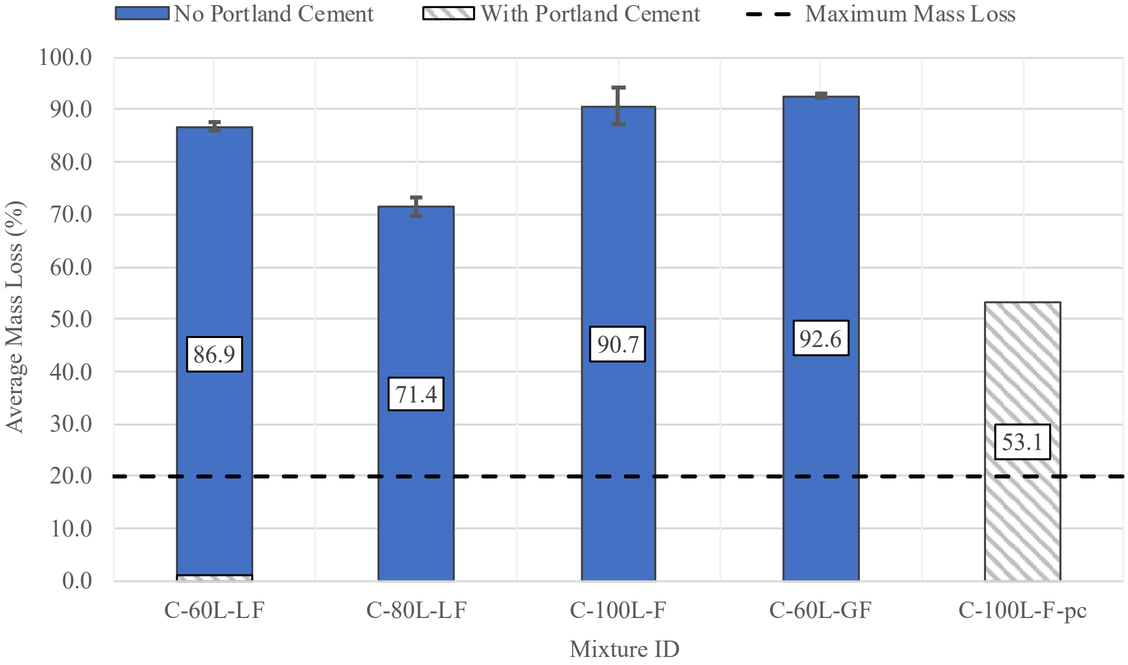


Figure 106. Comparison of Mass Loss of Foamed Cold Recycled Mixtures with and without Portland Cement

In Figure 106, it can be observed that the inclusion of Portland cement led to increased durability with a reduction in the Cantabro mass loss of about 41 percent. However, the Cantabro mass loss was still substantial (i.e., larger than 50 percent). Nevertheless, the recycled mixture with Portland cement (i.e., C-100L-F-pc) registered the lowest Cantabro mass loss for all foamed cold recycled mixtures.

A multi-factor ANCOVA was conducted to determine the influence of factors, including RAP content, virgin aggregate type, and AV content, on the durability of the foamed recycled mixtures. Appendix R contains the detailed analysis output obtained by the JMP statistical package. The results showed that RAP Content and AV content were statistically significant at $\alpha = 0.05$, meaning that these factors had a significant effect on Cantabro abrasion mass loss.

VII.3.4. Stiffness

The M_R stiffness of the foamed cold recycled mixtures was evaluated in accordance to ASTM D7369, *Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension Test.* Given the nondestructive nature of the test, the M_R measurements were conducted on HWTT specimens prior to testing. The M_R measurements were conducted on three replicate 6-inch (152.4-mm) diameter by 2.5-inch (63.5-mm) tall specimens per mixture type. To calculate the M_R value, a Poisson's ratio of 0.35 was assumed based on the test temperature (i.e., 77°F [25°C]). After conditioning, a repetitive haversine compressive load pulse was applied along the vertical diametral plane of the specimens and the horizontal deformation registered through a set of two LVDTs aligned along the diametral plane.

Figure 107 presents the average and standard deviation of the M_R measurements per mixture type. The results show that the maximum stiffness was achieved by the mixture fabricated with 80 percent limestone RAP content. Moreover, the results seem to evidence an impact of the virgin aggregate type in the foamed cold recycled mixture stiffness. A reduction of about 25 percent was observed in the M_R value of the C-60L-LF mixture when granite was used instead of limestone as virgin aggregate (C-60L-LG).

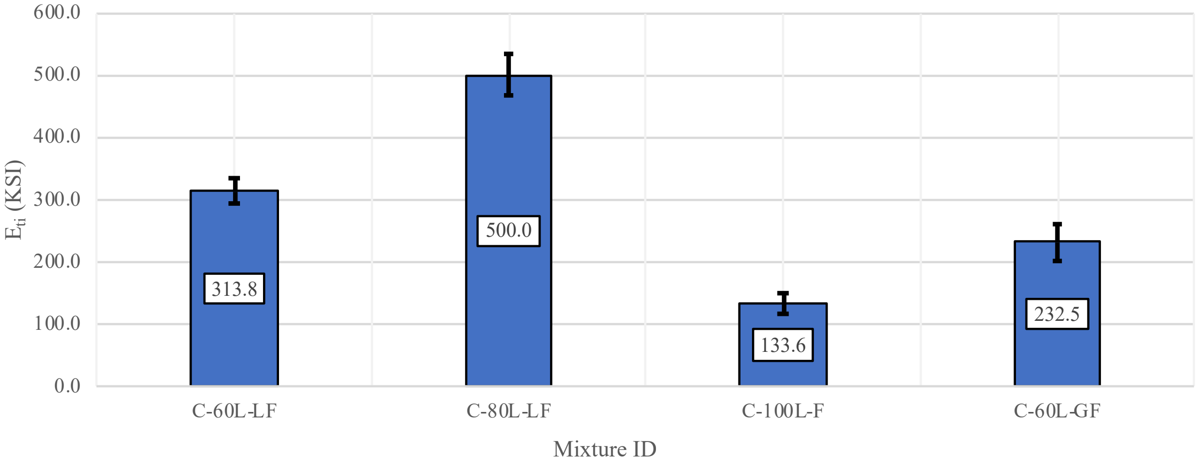


Figure 107. Foamed Cold Recycled M_R Results

A multi-factor ANCOVA was conducted to determine the influence of factors including RAP content, virgin aggregate type, and AV content on M_R stiffness. Appendix R contains the analysis output obtained by the JMP statistical package. The results show that RAP content, AV content, and virgin aggregate type were statistically significant at $\alpha = 0.05$, meaning that these factors had a significant effect on the stiffness of the mixtures.

VIII. LIFE-CYCLE COST ANALYSIS

An economic time-based evaluation during the recycling methodologies was conducted to assess the cost-effectiveness of hot recycled mixtures with 60 percent RAP and cold mixtures with 60 percent, 80 percent, and 100 percent RAP. Three steps were taken to perform the analysis:

1. Multilayer linear elastic and finite element analyses were performed to compare the stress/strain distribution and stress intensity factors (SIFs) for different pavement structures and different mixtures.
2. The performance models were incorporated to predict the cracking and rutting life expectancy for a typical pavement structure based on selected weather stations in Florida.
3. The LCCA was performed based on the life expectancy prediction results and the cost data provided by FDOT.

In the analysis, a typical three-layer pavement structure (surface layer, base layer, and subgrade) was considered. First, the Shell Bitumen Stress Analysis in Roads (BISAR) program was used to determine the horizontal tensile strain at the bottom of the surface layer and the vertical compressive strain at the surface of the subgrade under different combinations of layer moduli and thicknesses. Second, the allowable axle load repetitions were determined according to the Asphalt Institute equations and corresponding fatigue cracking and rutting criteria. Third, the SIFs were determined using a pavement finite element (FE) program specifically developed for that purpose. A sensitivity analysis was then performed based on these results. Further, the laboratory test results for the hot and cold mixtures with different RAP contents were incorporated in a mechanistic-empirical (ME) analysis program to predict the pavement service life based on Florida weather conditions and traffic for low volume roads. Finally, with the combined life expectancy and cost data, a summary and conclusions were provided.

VIII.1. Pavement Structure

The pavement structure and layer properties considered for the stress/strain and SIF analysis are listed in Table 53.

Table 53. Pavement Structure and Layer Properties

Layers	Thickness (in.)	Modulus (ksi)	Poisson Ratio
Surface layer	2, 3, 4	100, 500, 1,000	0.35
Base	4, 6, 8	50, 100, 150	0.35
Subgrade	—	4, 8, 20	0.4

Note that for the strain analysis, a full factorial experiment of the variables listed in Table 53 was considered, with 3 × 3 × 3 × 3 × 3 × 3 = 243 combinations, for the SIF analysis. Because the crack length is also a key factor, the number of combinations is larger.

VIII.2. Strain Analysis Based on Multilayer Elastic Theory

Two types of strains have frequently been considered the most critical for the design of asphalt pavements. One is the horizontal tensile strain at the bottom of the asphalt layer, which causes fatigue cracking; the other is the vertical compressive strain on the surface of the subgrade, which causes permanent deformation or rutting. These two strains are used as failure criteria in the Asphalt Institute method.

VIII.2.1. BISAR Calculation

The BISAR program was used to perform the strain calculation (Shell Group, 1998; Strickland, 2000). To carry out the BISAR analysis, simplifications of both the pavement structure and loading conditions were required. The pavement was considered as an elastic multilayered system. Figure 108 illustrates the pavement structure with a standard vertical dual-tire load. The red star and blue circle icons in the figure represent the strain calculation points.

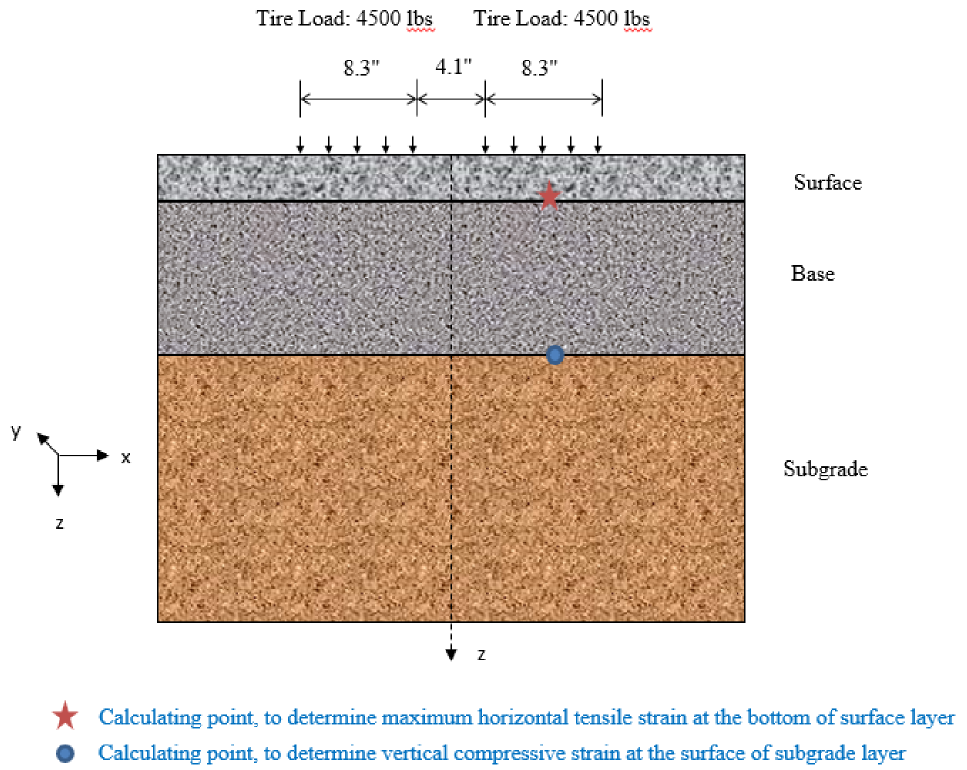


Figure 108. Schematic of the Pavement Structure under Dual-Tire Loading for Multilayer Elastic Analysis Using the BISAR Program

<u>Asphalt Institute Method for Predicting Fatigue Life</u>

The Asphalt Institute equation for fatigue cracking life determination is as follows:

$$N_f = 0.0796(\varepsilon_t)^{-3.291}|E^*|^{-0.854} \qquad \text{Equation 12}$$

Where:

N_f = allowable number of standard axle load repetitions to control fatigue cracking.
ε_t = tensile strain at the bottom of AC layer.
$|E^*|$ = dynamic modulus of the mixture.

The use of the above equation would result in fatigue cracking of 20 percent of the total pavement area (45 percent of the wheel path area) as observed on selected sections of the

American Association of State Highway and Transportation Officials Road Test (Asphalt Institute, 1982).

Asphalt Institute Method for Predicting Rutting Life

The Asphalt Institute equation for rutting life determination is as follows:

$$N_d = 1.365 \times 10^{-9}(\varepsilon_c)^{-4.477} \qquad \text{Equation 13}$$

Where:

N_d = allowable number of standard axle load repetitions to control permanent deformation (rutting).

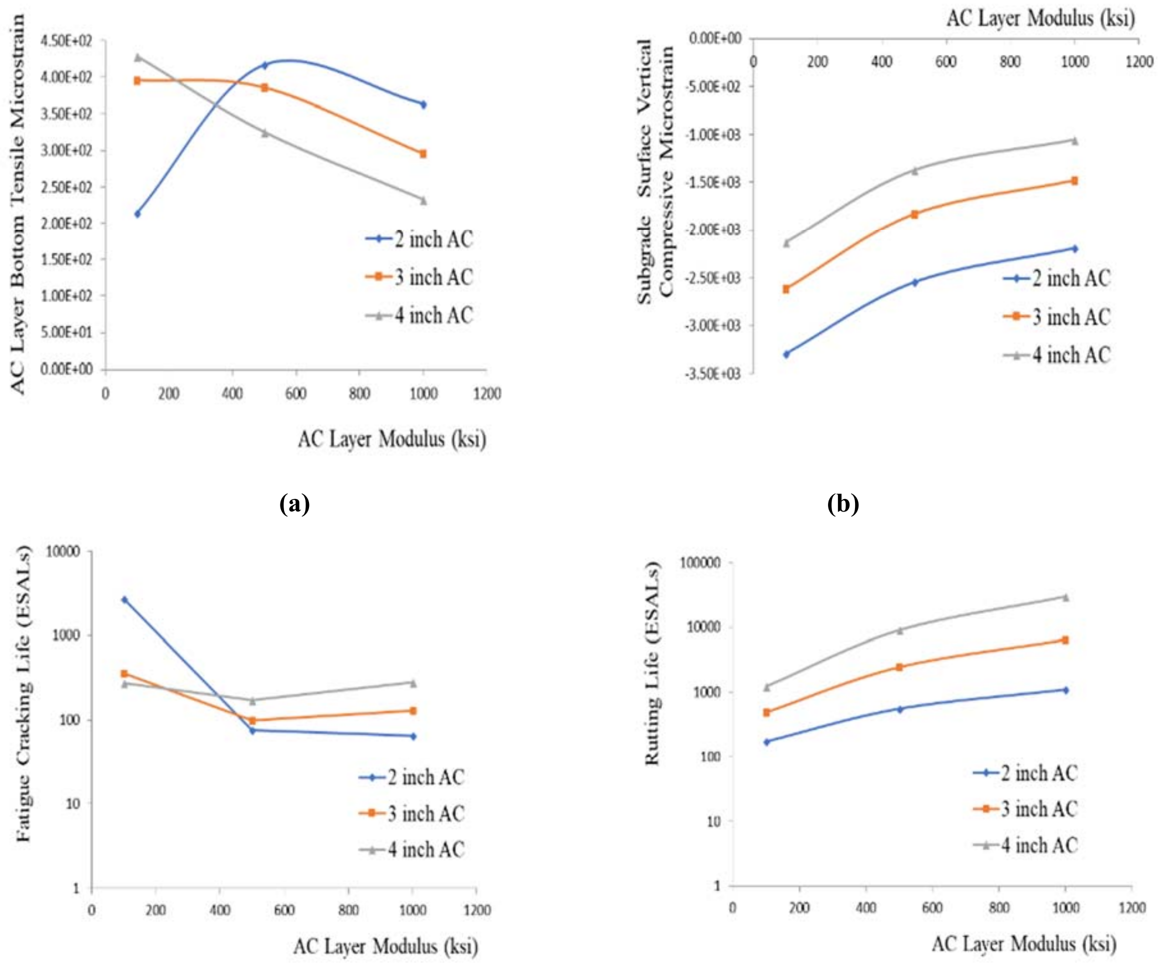
ε_c = vertical compressive strain on the surface of subgrade.

As long as good compaction of the pavement is achieved and the mixture is well designed, Equation 13 should result in rut depth smaller than 0.5 inch (12.5 mm) for the intended traffic level (Huang, 2004).

VIII.2.2. Strain Analysis Result

As previously mentioned, the horizontal tensile strain at the bottom of the surface layer and the vertical compressive strain at the surface of the subgrade layer were calculated for the strain analysis. Figure 109 through Figure 112 show the strain results and the corresponding fatigue cracking life and rutting life results for the different variables listed in Table 53. A positive strain value means the strain is in tension, while a negative strain value means it is in compression.

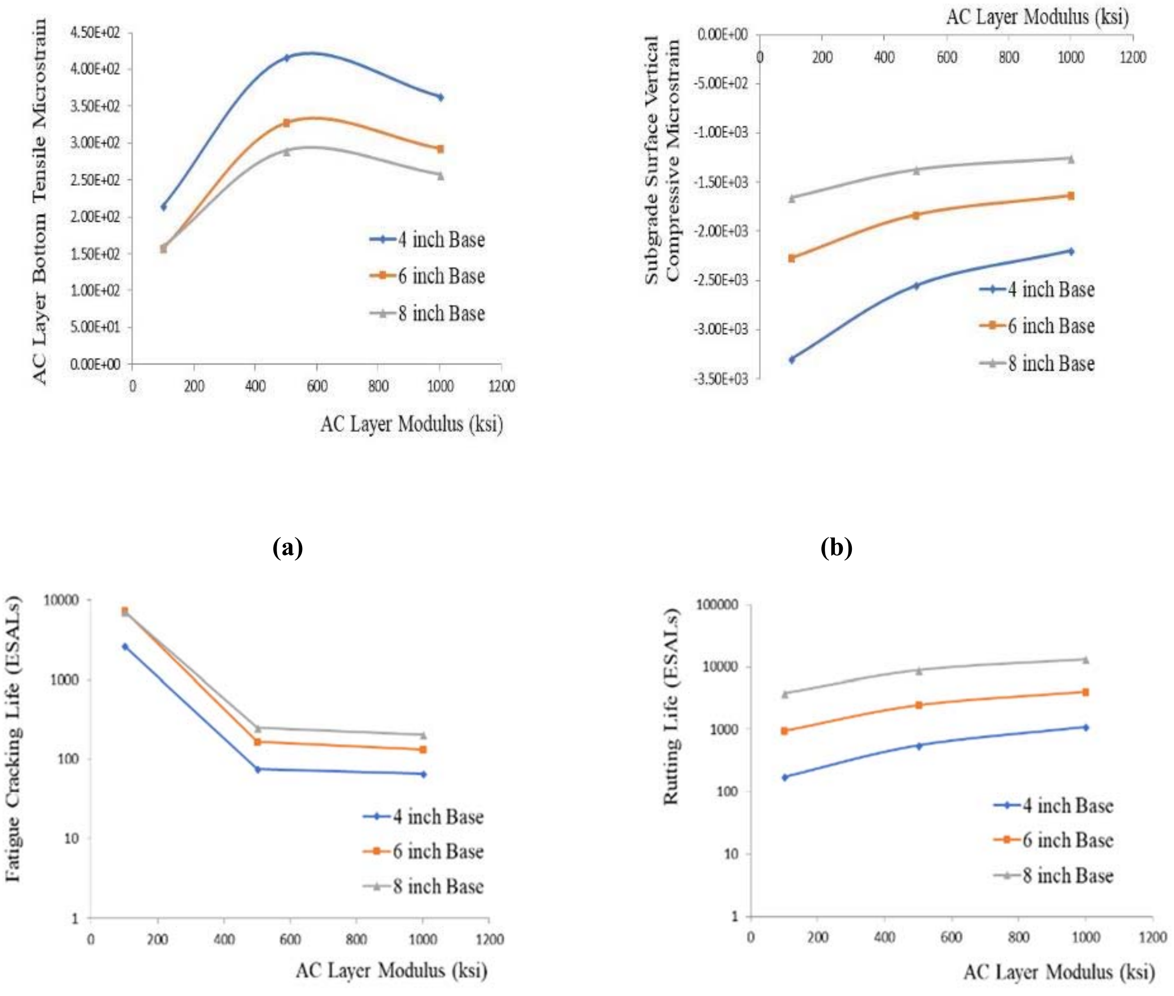
Since the objective of this task was to determine benefit-to-cost differences between hot and cold recycled mixtures as well as between cold recycled mixtures with various RAP contents, the x-axis in all the figures is the modulus of the mixture (i.e., AC layer), which is usually the variable that differentiates mixture type and RAP content. With that variable fixed, Figure 109 through Figure 112 show the influence of the AC layer thickness, base layer thickness, base layer modulus, and subgrade layer modulus, respectively. The resulting fatigue cracking life N_f and rutting life N_d can be easily converted to time (e.g., months) given the traffic information for a test section. For example, if a test section has 0.24 million ESALs in 20 years, the average standard axle load repetitions in each month would be 1,000; thus, the N_f or N_d divided by 1,000 would be the expected life in months.



(a) **(b)**

(c) **(d)**

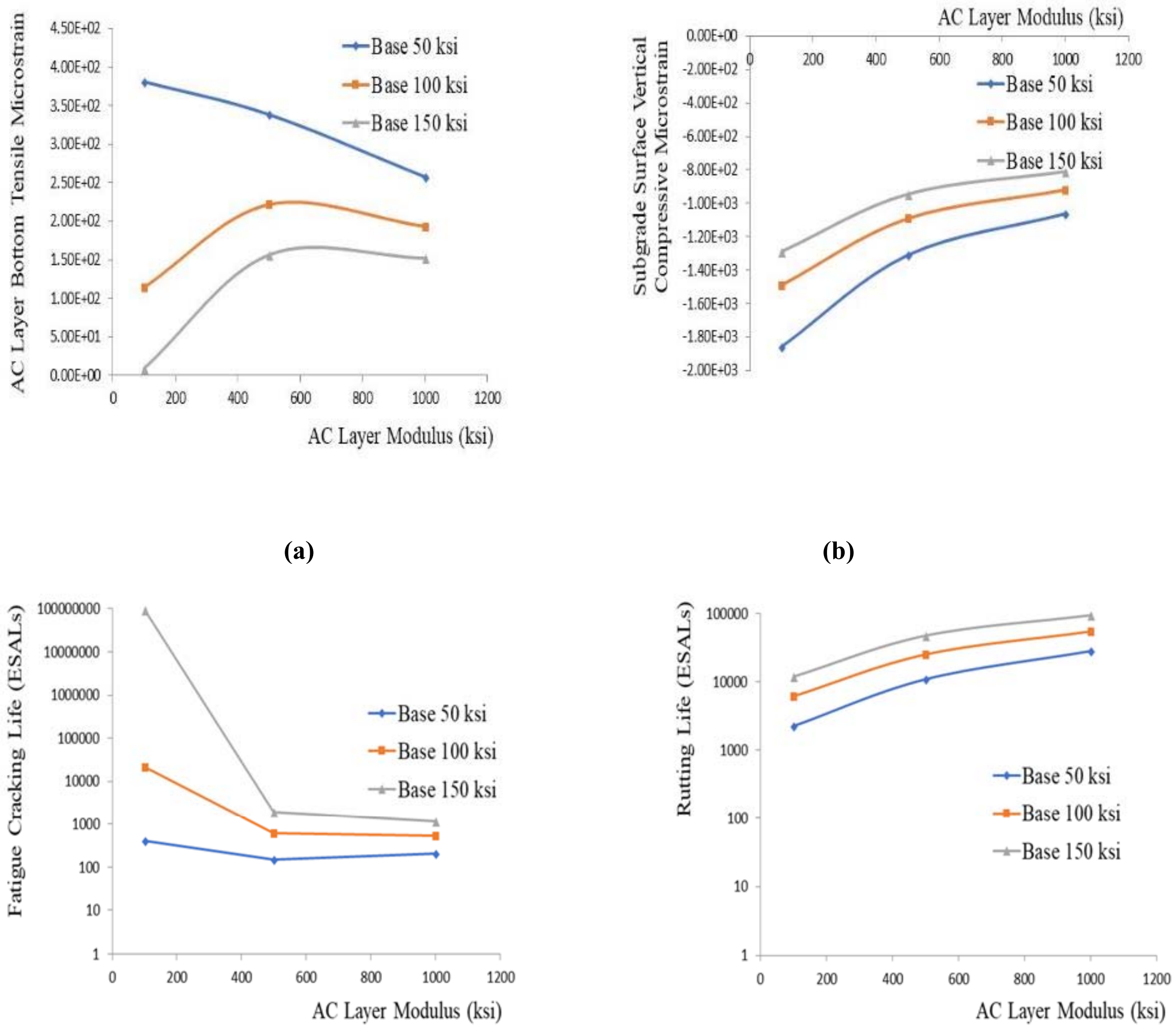
Figure 109. Strain, Fatigue Cracking, and Rutting Life Results for Different AC Layer Thicknesses: (a) AC Bottom Horizontal Strain, (b) Subgrade Surface Vertical Strain, (c) Fatigue Cracking Life, and (d) Rutting Life



(a) **(b)**

(c) **(d)**

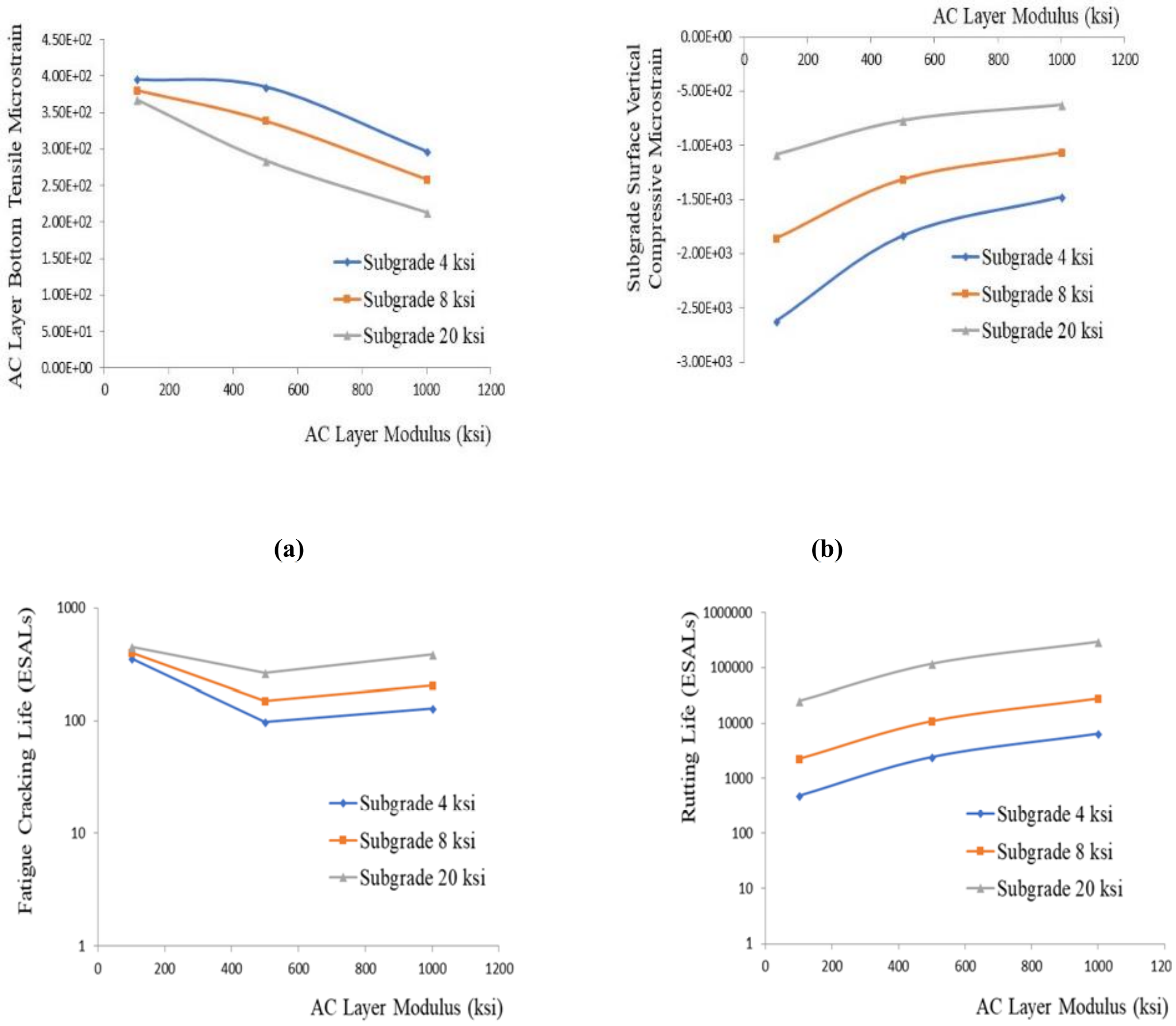
Figure 110. Strain, Fatigue Cracking, and Rutting Life Results for Different Base Layer Thicknesses: (a) AC Bottom Horizontal Strain, (b) Subgrade Surface Vertical Strain, (c) Fatigue Cracking Life, and (d) Rutting Life



(a) **(b)**

(c) **(d)**

Figure 111. Strain, Fatigue Cracking, and Rutting Life Results for Different Base Layer Modulus: (a) AC Bottom Horizontal Strain, (b) Subgrade Surface Vertical Strain, (c) Fatigue Cracking Life, and (d) Rutting Life



(a) (b)

(c) (d)

Figure 112. Strain, Fatigue Cracking, and Rutting Life Results for Different Subgrade Layer Modulus: (a) AC Bottom Horizontal Strain, (b) Subgrade Surface Vertical Strain, (c) Fatigue Cracking Life, and (d) Rutting Life

The following observations can be drawn based on Figure 109 through Figure 112:

- The higher the surface layer (i.e., AC layer) modulus, the smaller the vertical compressive subgrade surface strain and the better the rutting life.
- Usually, the higher the AC layer modulus, the lower the AC bottom horizontal strain. However, the modulus itself also influences the fatigue cracking life, as shown in Equation 12. Thus, a higher AC layer modulus does not always lead to better fatigue cracking life, as shown in Figure 109, Figure 110, and Figure 111. In most cases, a softer material (lower modulus) has better fatigue cracking life.
- In most situations, the thicker the AC layer, the smaller the horizontal tensile strain at the bottom of the AC layer and the smaller the vertical compressive strain at the top of the subgrade; therefore, there is better fatigue cracking life and rutting life.

- The thicker the base layer, the smaller the horizontal tensile strain at the bottom of the AC layer and the smaller the vertical compressive strain at the top of the subgrade; therefore, there is better fatigue cracking life and rutting life.
- The higher the base layer or subgrade layer moduli, the smaller the horizontal tensile strain at the bottom of the AC layer and the smaller the vertical compressive strain at the top of the subgrade; therefore, there is better fatigue cracking life and rutting life.

VIII.3. Finite Element Analysis

An FE analysis was performed to determine the SIFs by applying fracture mechanics and Paris' Law (Paris and Erdogan, 1963) to predict the crack propagation in the pavement.

VIII.3.1. Pavement and Loading Simulation

Figure 113 shows the three different crack modes and their associated SIFs. For pavement cracking analysis, usually only K_I (K_1) and K_{II} (K_2) exist and need to be analyzed (Ingraffea and Wawrzynek, 2003). Generally, the higher SIF value (positive value), the faster the crack propagates.

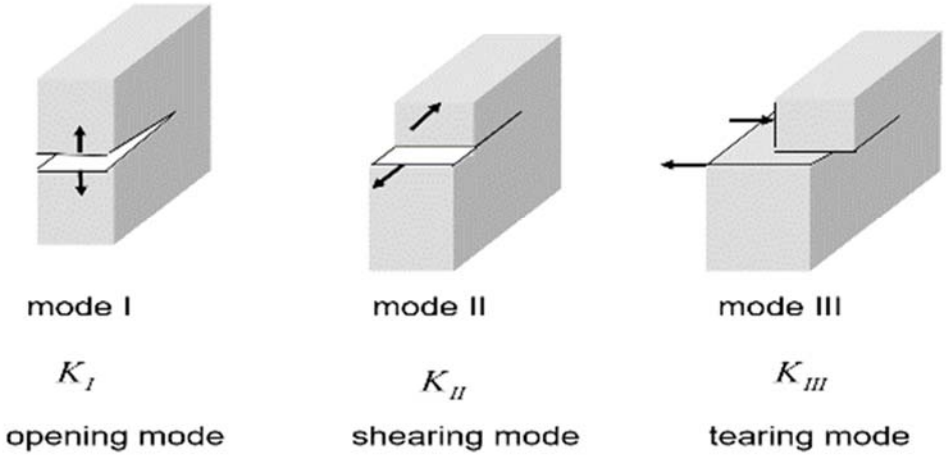
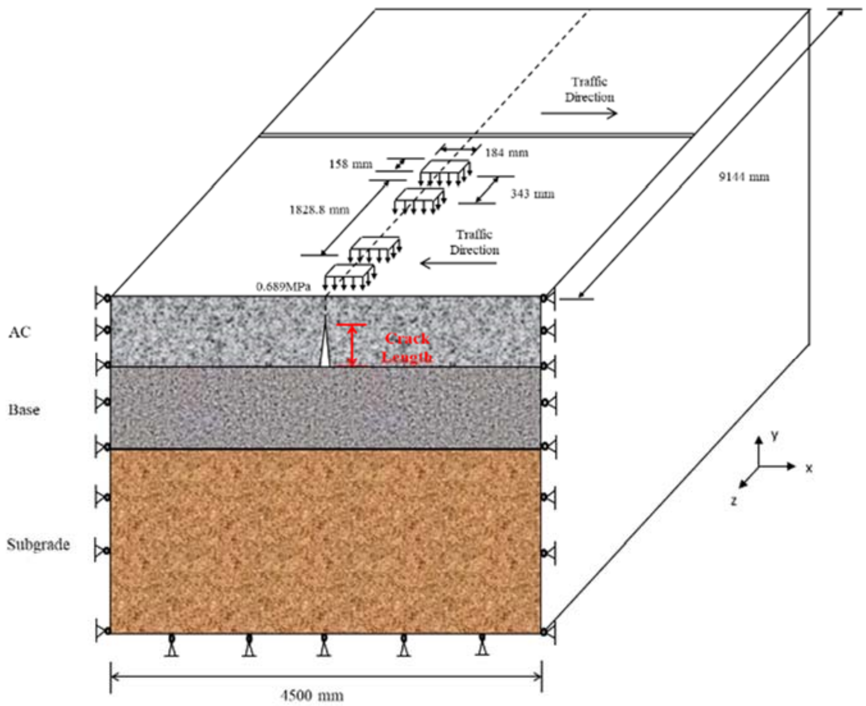
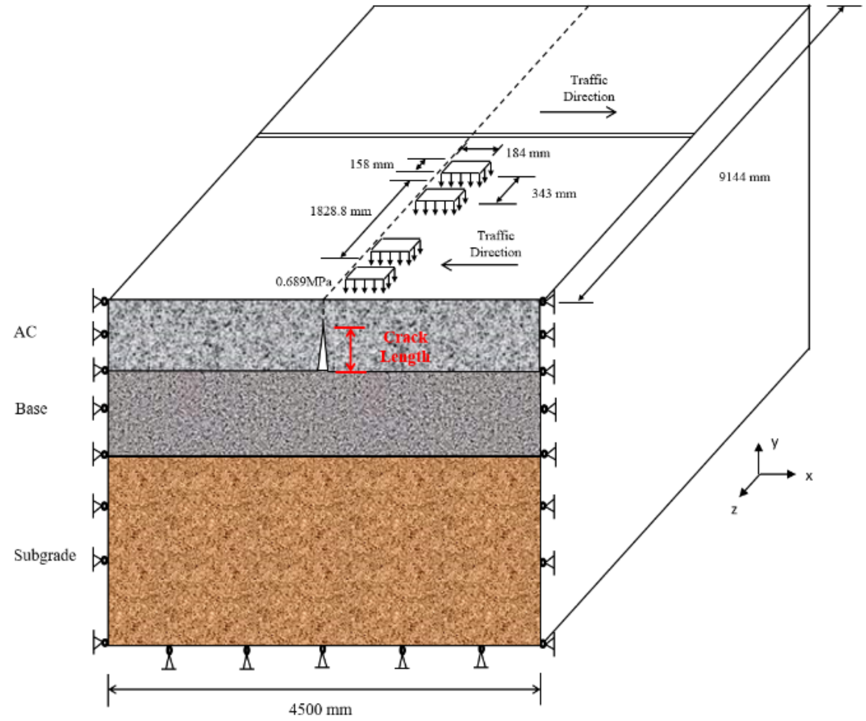


Figure 113. Cracking Modes and Corresponding SIFs

Figure 114 shows the schematics of the pavement structures and loading parameters used for the FE analysis of bending SIF (K_1) and shearing SIF (K_2). The crack length in the AC layer is considered from the bottom of the surface layer to the crack tip. The load is a standard 18-kip (80 kN) axle load (single axle, dual-tire), and the tire pressure is 100 psi (0.689 MPa). The tire-pavement contact area shape is assumed rectangular, with a size as indicated in Figure 114. Note that the bending SIF and the shearing SIF require a 3D analysis due to the traffic axle loading feature. The difference between Figure 114a and Figure 114b is the axle load location; one is covering the crack line (causing a bending effect) and the other is at the side of the crack line (causing a shearing effect). A specifically developed FE program was employed to perform these SIF calculations (Hu et al., 2008).



(a)

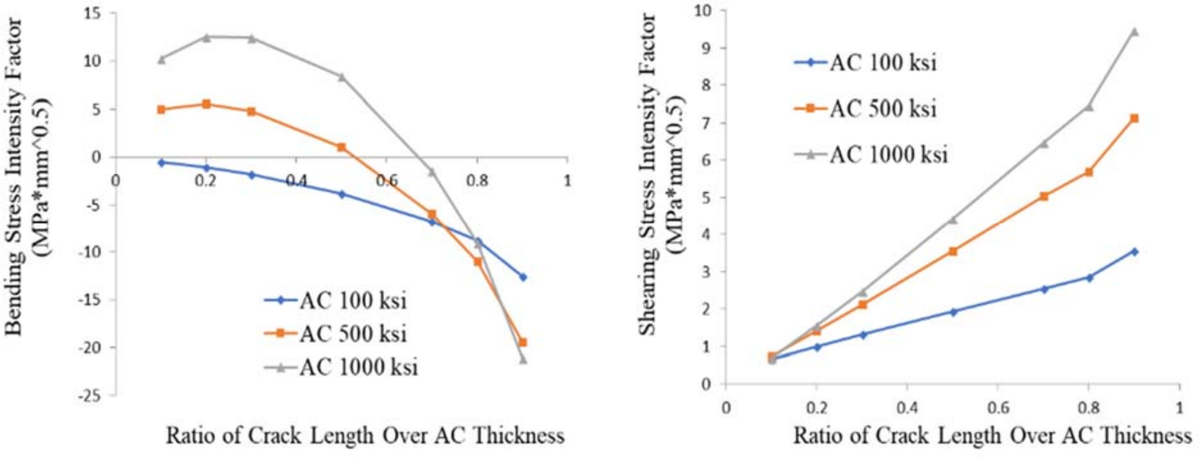


(b)

Figure 114. Pavement Structure and Loading Schematic for SIF Analysis at (a) Bending Mode (K_1) and (b) Shearing Mode (K_2)

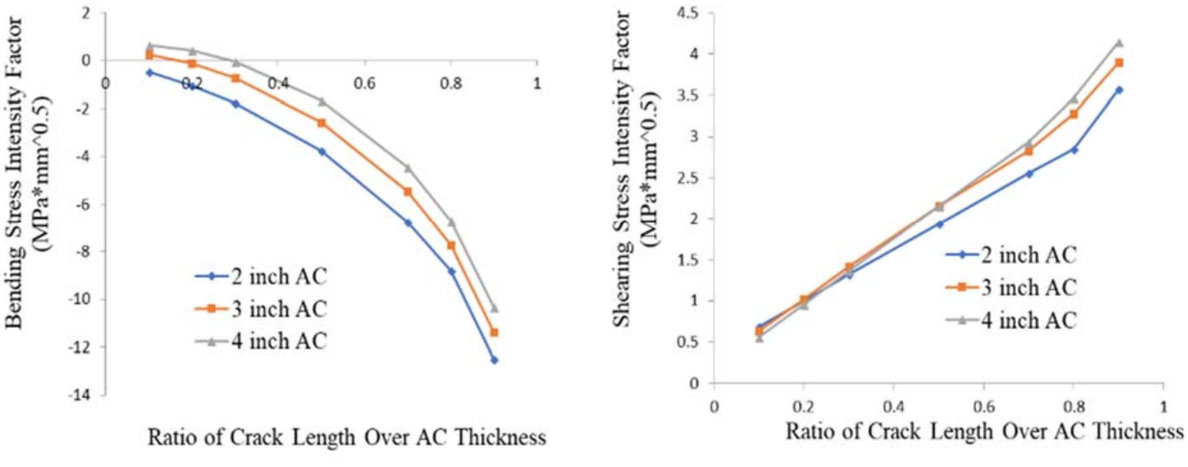
VIII.3.2. SIF Analysis Result

Since the SIF significantly depends on the crack length, different values that represented the ratio of the crack length to the AC layer thickness, including 0.1, 0.2, 0.3, 0.5, 0.7, 0.8, and 0.9 were selected for the analysis. Thus, 243 × 7 × 2 = 3402 SIFs were calculated in this study. Figure 115 through to Figure 119 summarize the results and show the influence of the AC layer thickness, AC layer modulus, base layer thickness, base layer modulus, and subgrade modulus, respectively.



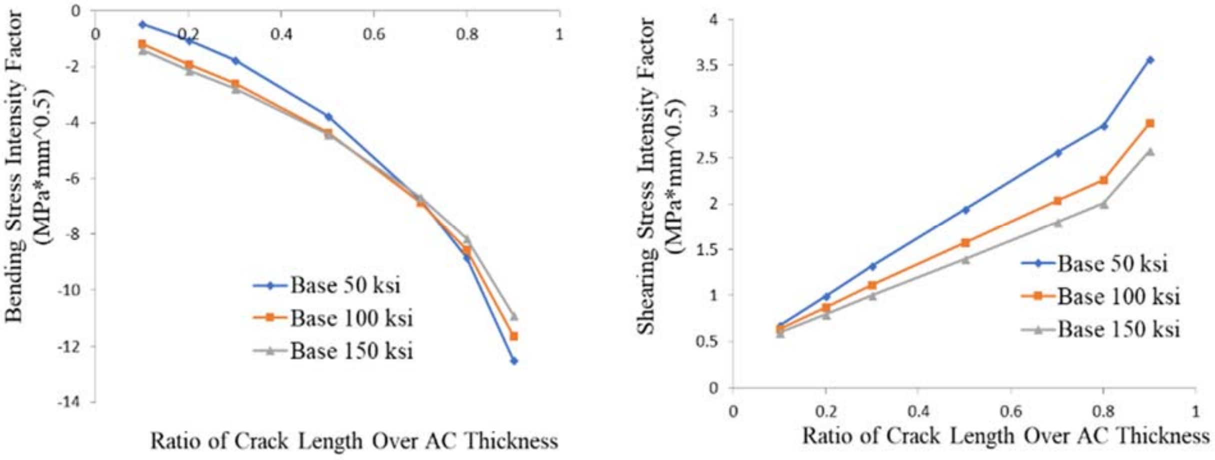
(a) (b)

Figure 115. SIF Results for Different AC Layer Moduli: (a) Bending Mode and (b) Shearing Mode



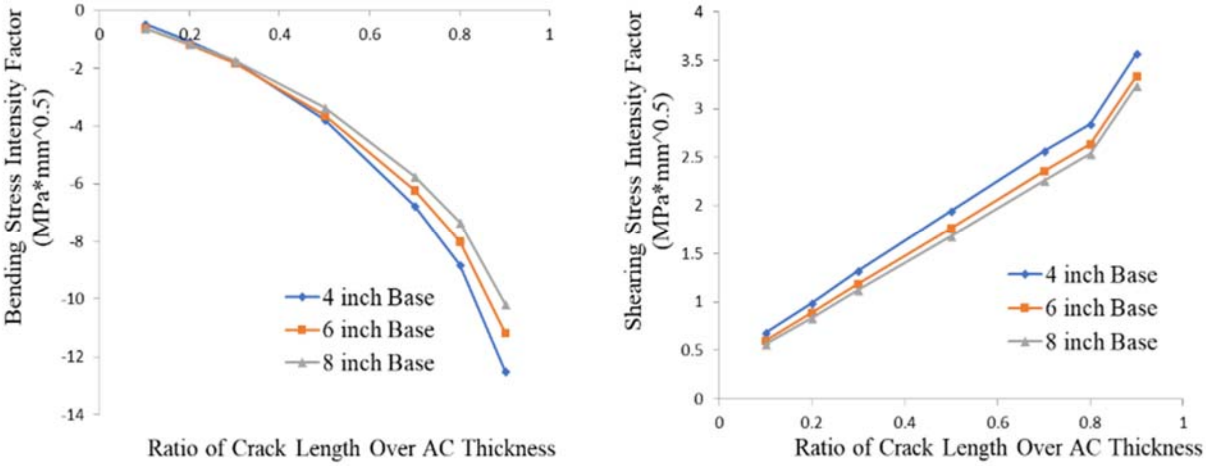
(a) (b)

Figure 116. SIF Results for Different AC Layer Thicknesses: (a) Bending Mode and (b) Shearing Mode



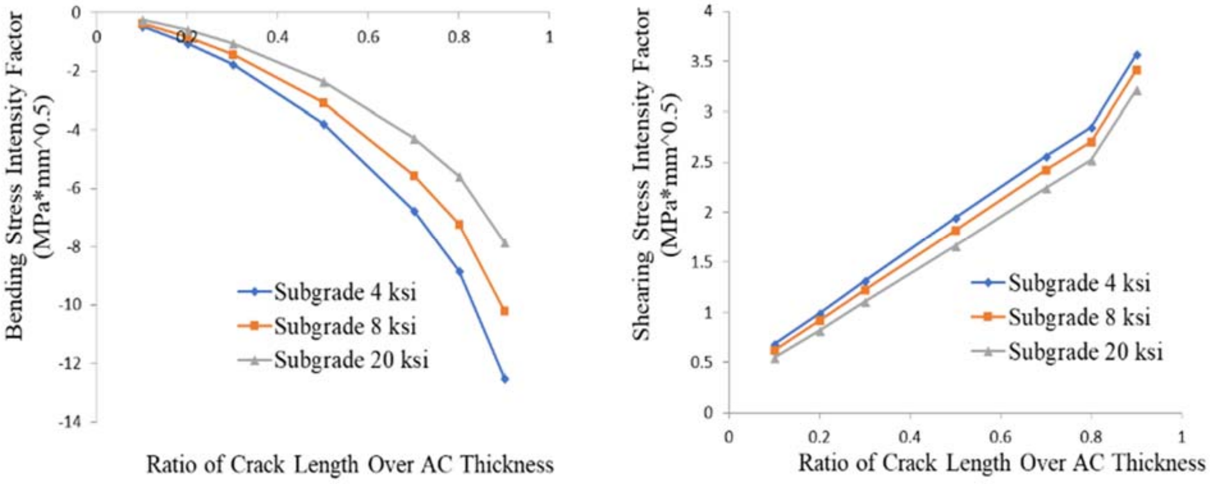
(a) **(b)**

Figure 117. SIF Results for Different Base Layer Moduli: (a) Bending Mode and (b) Shearing Mode



(a) **(b)**

Figure 118. SIF Results for Different Base Layer Thicknesses: (a) Bending Mode and (b) Shearing Mode



(a) (b)

Figure 119. SIF Results for Different Subgrade Layer Moduli: (a) Bending Mode and (b) Shearing Mode

The following observations can be drawn based on Figure 115 through to Figure 119:

- The longer the crack length, the larger the shearing SIF value and the smaller (from positive to negative) bending SIF value. This result is likely because when the crack length is short, the opening mode (K_1) is dominant, while when the crack length is long, the shearing mode (K_2) is dominant. Negative bending SIF value means the crack tip area is subjected to compression rather than tension.
- In most situations, the higher the AC layer or base layer or subgrade layer moduli, the smaller the shearing SIF value.
- The thicker the AC layer or the base layer, the smaller the shearing SIF value.

VIII.4. Laboratory Test Data Analysis and Performance Prediction

The strain and SIF analyses provide an estimate of how the various types of mixtures (represented by a dissimilar mixture modulus) will affect the pavement response and subsequent performance. However, although the relative trends of the calculated fatigue cracking life N_f and rutting life N_d are reasonable, the range is wide and may not be comparable to actual field performance. In order to more accurately predict field performance and conduct a cost-benefit analysis based on specific climate and traffic conditions, laboratory tests of the hot recycled mixture with 60 percent limestone RAP and limestone virgin aggregate (i.e., H-60L-L) and of the foamed cold recycled mixtures with 60 percent, 80 percent, and 100 percent limestone RAP and limestone virgin aggregate (i.e., C-60L-LF, C-80L-LF, and C-100L-F) were conducted. The laboratory tests included dynamic modulus (stiffness), OT (fracture), and flow number (rutting). These test results were used as input in the Texas Mechanistic-Empirical (TxME) analysis software to predict performance.

VIII.4.1. Background of TxME and Performance Models

VIII.4.1.1. TxME Software

TxME is a flexible pavement design and analysis program that incorporates ME performance models to generate incremental distress predictions (Hu et al., 2012). Figure 120 shows the main screen of the TxME software.

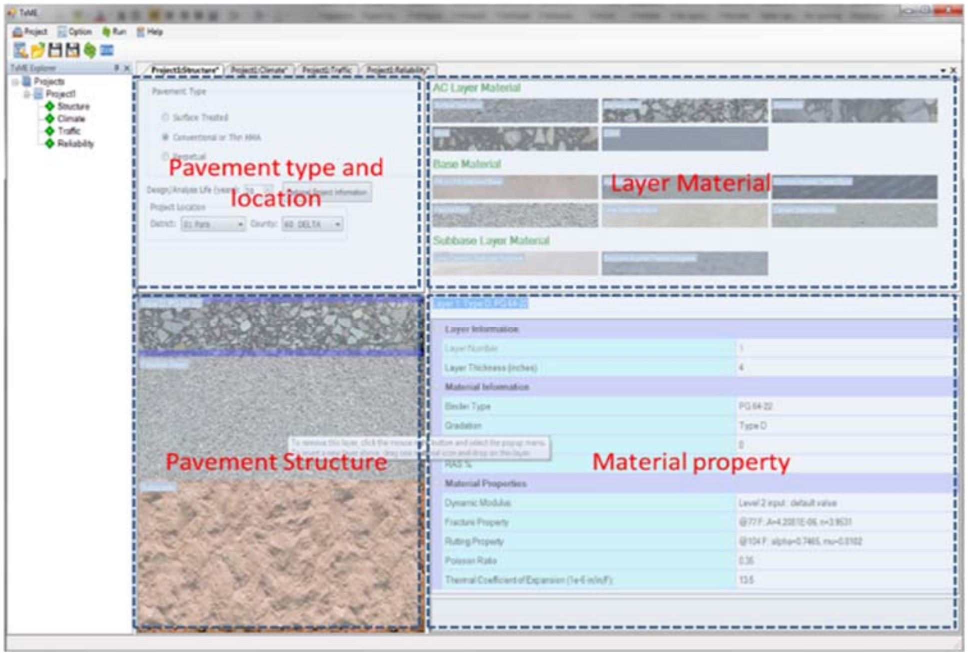


Figure 120. Main Screen of TxME Software

VIII.4.1.2. Fatigue Cracking Model

In the TxME software, the AC layer fatigue cracking model is composed of three parts: (a) fatigue life model, (b) fatigue damage model, and (c) fatigue area model (Zhou et al., 2007).

The fatigue life model includes the following equations:

$$N_f = k_i N_i + k_p N_p \qquad \text{Equation 14}$$

$$N_i = k_1 \left(\frac{1}{\varepsilon}\right)^{k_2} \qquad \text{Equation 15}$$

$$k_1 = 10^{6.97001 - 3.20145 k_2 - 0.83661 logE} \qquad \text{Equation 16}$$

$$k_2 = n \qquad \text{Equation 17}$$

$$N_p = \int_{c_0}^{h} \frac{1}{k_b A K_I^n + k_s A K_{II}^n} dc \qquad \text{Equation 18}$$

Where:

N_f = fatigue life.
N_i = crack initiation life.
N_p = crack propagation life.
K_i, k_p, k_b, k_s = calibration factors.

ε = maximum tensile strain at the bottom of asphalt layer.
E = dynamic modulus.
A, n = fracture properties, determined from overlay testing.
K_I, K_{II} = SIFs caused by bending and shearing stresses.

The fatigue damage model is estimated using Miner's law:

$$D = \sum \frac{N}{N_f} \qquad \text{Equation 19}$$

Where:

D = accumulated fatigue damage.
N = applied load repetitions.

The fatigue area model is proposed as a sigmoidal function:

$$fatigued_{area}(\%) = \frac{100}{1+e^{ClogD}} \qquad \text{Equation 20}$$

Where:

C = field calibration factor.

Note that in each month, the properties (i.e., modulus) of the pavement layers change due to the variation in the environmental temperature and moisture content. Thus, the N_i and N_p of each month are different.

To determine the crack initiation life N_i for a given month, the maximum tensile strain at the bottom of AC layer ε needs to be determined based on the multilayer elastic program. Then, Equation 15 through Equation 17 can be used to calculate the N_i.

To determine the crack propagation life N_p for a given month, the SIFs K_I and K_{II} need to be determined for each crack length, and Equation 18 has to be expanded to achieve accumulation incrementally.

VIII.4.1.3. Rutting Model

The VESYS layer rutting model, originally developed by FHWA in the 1970s (Kenis, 1978; Kenis and Wang, 1997), is used in TxME as a layer rutting model:

$$RD = k \int \Delta U \mu N^{-\alpha} \qquad \text{Equation 21}$$

Where:

RD = rut depth in the layer.
k = calibration factor.
ΔU = deflection difference between the layer top and layer bottom.
N = load repetitions.
α, μ = rutting properties of the layer, determined in the laboratory.

VIII.4.2. Laboratory Test Results

To compare the performance of the mixtures, the dynamic modulus (stiffness), overlay (fracture), and flow number (rutting) properties measured in the laboratory were input in the TxME software. The laboratory test results are summarized below. As previously mentioned, the hot recycled mixture with 60 percent limestone RAP and limestone virgin aggregate is labeled

H-60L-L; the foamed cold recycled mixtures with 60 percent, 80 percent and 100 percent limestone RAP and limestone virgin aggregate are labeled C-60L-LF, C-80L-LF, and C-100L-F, respectively.

Dynamic Modulus Test

The dynamic modulus test was conducted using the Asphalt Mixture Performance Tester (AMPT) machine and following the procedure in AASHTO T 378 (AASHTO, 2017c). The moduli were determined at various temperatures and frequencies. With that input, TxME developed a dynamic modulus master curve and obtained modulus values using actual pavement temperature and traffic conditions. For each mixture, two replicates were tested. Table 54 shows the dynamic test results that have been averaged between replicates and processed into the 5-temperature and 6-frequency format.

Table 54. Dynamic Modulus Test Results

Mixture Type	Temperature (°F)	Frequency (Hz)					
		25	10	5	1	0.5	0.1
C-60L-LF	14	1671.3	1577.9	1502.6	1314.8	1229.5	1026.8
	40	1244.9	1130.2	1042.5	841.2	757.8	578.2
	70	758.2	653.2	578.6	425.3	368.7	259.7
	100	402.5	332.0	285.3	198.2	168.9	116.5
	130	202.1	163.5	139.3	96.5	82.9	59.2
C-80L-LF	14	1553.7	1479.0	1417.4	1258.3	1183.6	1000.5
	40	1192.0	1089.4	1009.4	821.0	741.2	566.4
	70	736.0	634.4	561.7	411.2	355.5	248.7
	100	385.2	316.3	271.0	187.1	159.3	110.2
	130	189.1	152.8	130.2	91.0	78.6	57.4
C-100L-F	14	1311.2	1243.2	1188.2	1049.7	986.2	833.0
	40	955.4	868.2	801.3	647.1	583.0	443.9
	70	541.3	462.7	407.3	294.4	253.1	174.3
	100	253.4	205.6	174.6	117.7	99.0	66.3
	130	109.5	87.1	73.3	49.5	42.0	29.4
H-60L-L	14	2064.6	1984.8	1917.5	1737.5	1650.1	1427.6
	40	1663.8	1541.1	1442.9	1202.9	1097.4	858.2
	70	1095.0	957.1	856.0	640.0	557.7	396.4
	100	604.9	501.9	433.0	303.1	259.3	181.6
	130	307.9	250.5	214.6	151.7	131.8	97.7

Flow Number Test

The rutting parameters α and μ from the VESYS layer rutting model are determined from a RLPD test (Hu et al., 2011). In this case, laboratory-prepared specimens were subjected to the flow number test in the AMPT machine. The specimen dimensions for the flow number test were the same as the specimens used in the dynamic modulus test. During testing, the specimen deformed under loading, and α and μ were determined with the resulting permanent deformation curve. These two parameters were then used to determine the AC layer rut depth under traffic loading. Table 55 shows the resulting rutting parameters.

Table 55. Flow Number Rutting Parameters

Mixture Type	α	μ
C-60L-LF	0.698	0.186
C-80L-LF	0.6865	0.1866
C-100L-F	0.6653	0.206
H-60L-L	0.6718	0.1457

Overlay Test

The parameters A and n from the fatigue cracking model were determined by subjecting laboratory test specimens to the Texas OT (TxDOT, 2017). A laboratory-prepared specimen was glued with epoxy onto two metal plates; one of these plates was able to move horizontally a fixed amount during testing, while the other one was fixed in the test equipment. After several cycles, the vertical crack in the specimen propagated from the bottom to the top of the specimen. The fracture properties indicate the crack propagation speed (Zhou et al., 2007). Table 56 shows the resulting fracture parameters for all mixtures.

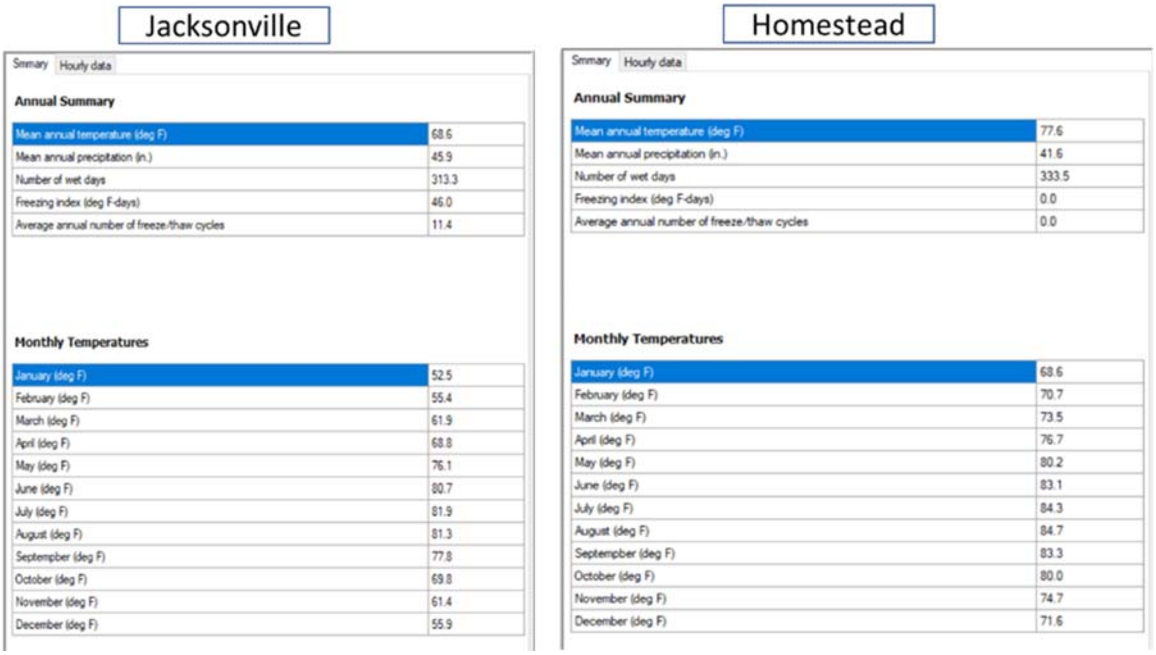
Table 56. OT Test Results and Fracture Properties

Mixture Type	A	n
C-60L-LF	7.0443E-6	3.8115
C-80L-LF	3.2621E-5	3.391
C-100L-F	2.8315E-5	3.4299
H-60L-L	8.2469E-5	3.1366

VIII.4.3. Weather Input

To determine the effect of weather in the cost-benefit analysis, the state of Florida was divided into north and south. The city of Jacksonville in the north and the city of Homestead in the south were selected to represent those portions of the state, and hourly climatic data information on each location were obtained from www.infopave.com. The location of the cities is shown in Figure 121. After processing the weather data in the TxME software, the annual and monthly average air temperatures for each city is shown in Figure 122.

Figure 121. Map Showing the Selected Locations: Jacksonville, FL, in the North and Homestead, FL, in the South



Jacksonville

Annual Summary

Mean annual temperature (deg F)	68.6
Mean annual precipitation (in.)	45.9
Number of wet days	313.3
Freezing index (deg F-days)	46.0
Average annual number of freeze/thaw cycles	11.4

Monthly Temperatures

January (deg F)	52.5
February (deg F)	55.4
March (deg F)	61.9
April (deg F)	68.8
May (deg F)	76.1
June (deg F)	80.7
July (deg F)	81.9
August (deg F)	81.3
Septempber (deg F)	77.8
October (deg F)	69.8
November (deg F)	61.4
December (deg F)	55.9

(a)

Homestead

Annual Summary

Mean annual temperature (deg F)	77.6
Mean annual precipitation (in.)	41.6
Number of wet days	333.5
Freezing index (deg F-days)	0.0
Average annual number of freeze/thaw cycles	0.0

Monthly Temperatures

January (deg F)	68.6
February (deg F)	70.7
March (deg F)	73.5
April (deg F)	76.7
May (deg F)	80.2
June (deg F)	83.1
July (deg F)	84.3
August (deg F)	84.7
Septempber (deg F)	83.3
October (deg F)	80.0
November (deg F)	74.7
December (deg F)	71.6

(b)

Figure 122. Annual and Monthly Average Air Temperature Information: (a) Jacksonville, FL, in the North and (b) Homestead, FL, in the South

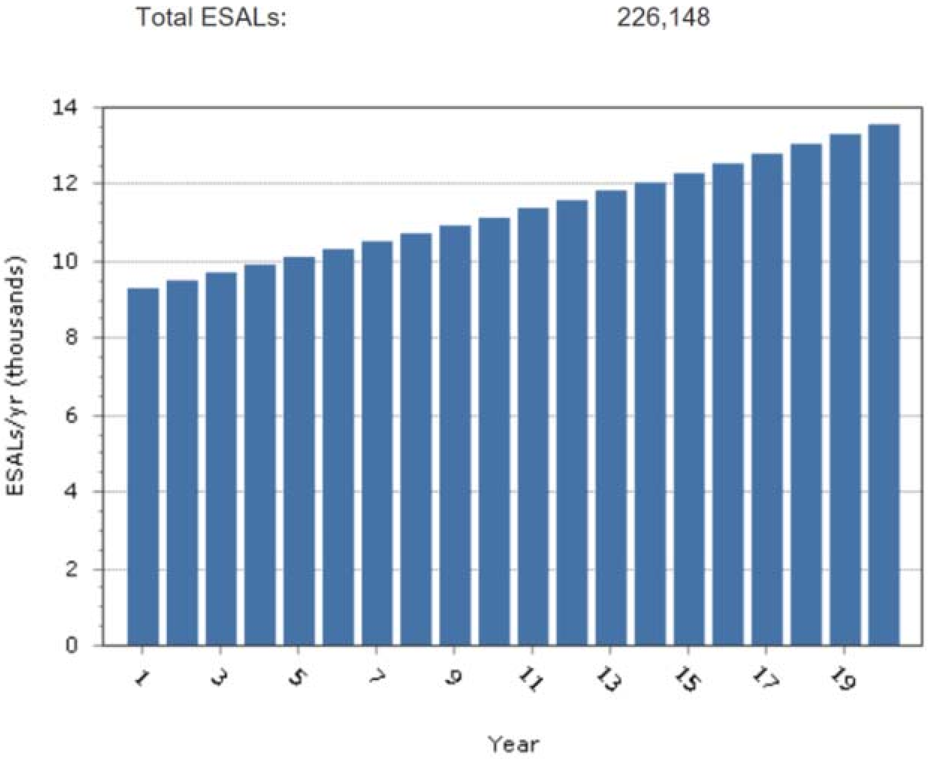
VIII.4.4 Traffic Input

The TxME software accepts total 20-year ESALs as traffic input. To determine the total ESALs, the following parameters were assumed representative of a low volume road:

- Annual ADT (AADT): 750 vehicles.
- Trucks: 2 percent.
- Traffic growth rate: 2 percent.
- Truck factor: 1.7.

The resulting total ESALs were 226,148 (i.e., 0.23 million), as seen in Figure 123.

The TxME software distributes the total ESALs into monthly ESALs based on the yearly growth rate and number of days in each month. These distributed monthly ESALs are then incorporated into the fatigue cracking and rutting models to determine the monthly distress accumulation.



Total ESALs: 226,148

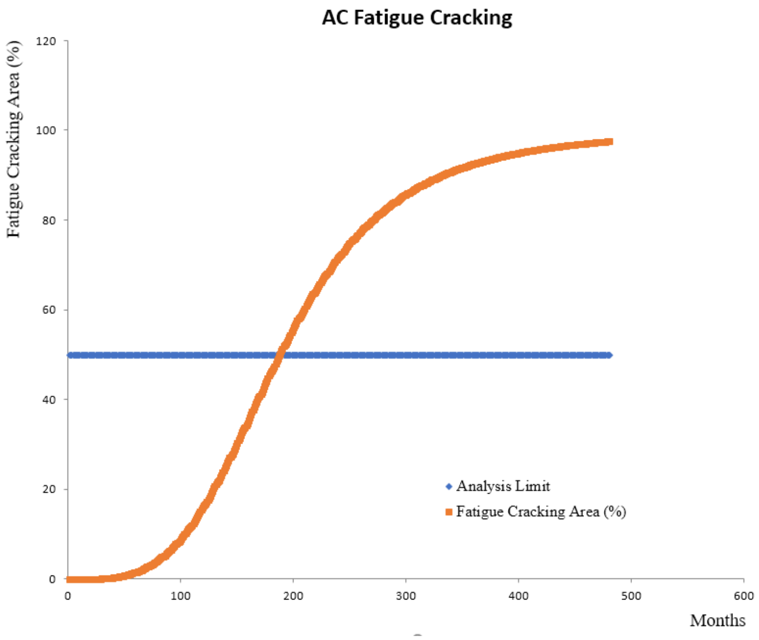
Figure 123. Total ESALs Calculation

VIII.4.5. Performance Prediction Results

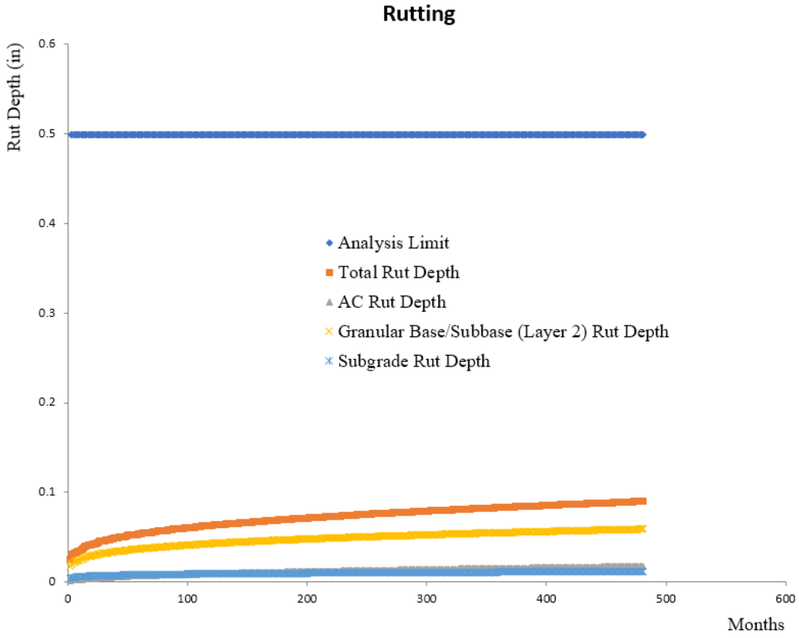
A three-layer pavement structure (2-inch AC layer, 4-inch flexible base layer, and subgrade layer) was selected to perform the TxME performance predictions. With the above input, the following eight cases were analyzed:

- **Case 1:** Climate: Jacksonville weather station; Material: C-60L-LF.
- **Case 2:** Climate: Jacksonville weather station; Material: C-80L-LF.
- **Case 3:** Climate: Jacksonville weather station; Material: C-100L-F.
- **Case 4:** Climate: Jacksonville weather station; Material: H-60L-L.
- **Case 5:** Climate: Homestead weather station; Material: C-60L-LF.
- **Case 6:** Climate: Homestead weather station; Material: C-80L-LF.
- **Case 7:** Climate: Homestead weather station; Material: C-100L-F.
- **Case 8:** Climate: Homestead weather station; Material: H-60L-L.

As an example of the TxME software output, Figure 124 shows the monthly fatigue cracking and rutting model prediction results for Case 1.



(a)



(b)

Figure 124. TxME Output for Case 1: (a) Fatigue Cracking Model Prediction Result and (b) Rutting Model Prediction Result

Note that for Case 1, at the 188th month, the fatigue cracking area reaches the limit (50 percent of the wheel path area); thus, the fatigue cracking life is 188 months. The predicted rut depth is far less than the limit (0.5 inch) even after more than 40 years, so rutting is not a concern for this case.

Table 57 provides a summary of the performance prediction for all eight cases. It is noteworthy that in Jacksonville, the rut depth was always higher than in Homestead, although

Jacksonville is colder in terms of monthly average temperature. The reason is that during summer, Jacksonville experiences many hours at a higher air temperature (and pavement temperature) than Homestead, and rutting accumulation mainly occurs during summer when the pavement temperature is high. In comparison, Homestead has more evenly distributed air temperatures during the day.

Table 57. Summary of Performance Prediction

Case No.	Weather Station	Mixture Type	Months @ Fatigue Cracking = 50% Wheel Path Area	Total Rut Depth @ 20 Years (inch)
1	Jacksonville	C-60L-LF	188	0.0755
2	Jacksonville	C-80L-LF	169	0.0794
3	Jacksonville	C-100L-F	235	0.1250
4	Jacksonville	H-60L-L	150	0.0667
5	Homestead	C-60L-LF	169	0.0716
6	Homestead	C-80L-LF	159	0.0743
7	Homestead	C-100L-F	219	0.1080
8	Homestead	H-60L-L	149	0.0635

VIII.5. Life-Cycle Cost Analysis

Based on the results of the performance prediction, the pavement LCCA was conducted to evaluate the financial benefits of the different mixture types. FHWA's RealCost (FHWA, 2002; Lamptey et al., 2005) software was considered a more versatile package than other available LCCA software. RealCost was developed based on a Microsoft Excel macro and has both spreadsheet and screen input interfaces. In this study, researchers used RealCost as a tool to compare the total user and agency costs of project implementation alternatives (hot recycled mixture with 60 percent RAP and cold recycled mixtures with 60 percent, 80 percent, and 100 percent RAP).

The following sections provide an overview of the RealCost software, then describe the input information of the alternatives, and finally describe the analysis results and present summaries.

VIII.5.1. Overview of FHWA RealCost Software

FHWA RealCost software is founded on the technical guidance and recommendations on good practices in conducting an LCCA for pavement design provided in an interim technical bulletin (Walls and Smith, 1998). It also incorporates risk analysis, a probabilistic approach to describe and account for the uncertainties inherent in the decision process. It deals specifically with the technical aspects of long-term economic efficiency implications of alternative pavement designs. The technical bulletin was intended for state highway agency personnel responsible for conducting and/or reviewing pavement design LCCAs. The LCCA steps are:

1. Establish design alternatives.
2. Determine activity timing.
3. Estimate costs (agency and user).

4. Compute life-cycle costs.
5. Analyze the results.

The RealCost software interface requires the user to enter inputs in various screens, as shown in Figure 125, and then it applies a series of algorithms to determine which of the given alternatives is the superior choice based on the inputs. To be most accurate, an LCCA requires precise information pertaining to the specific job being assessed. However, for the purposes of this research, some scenarios had to be hypothesized.

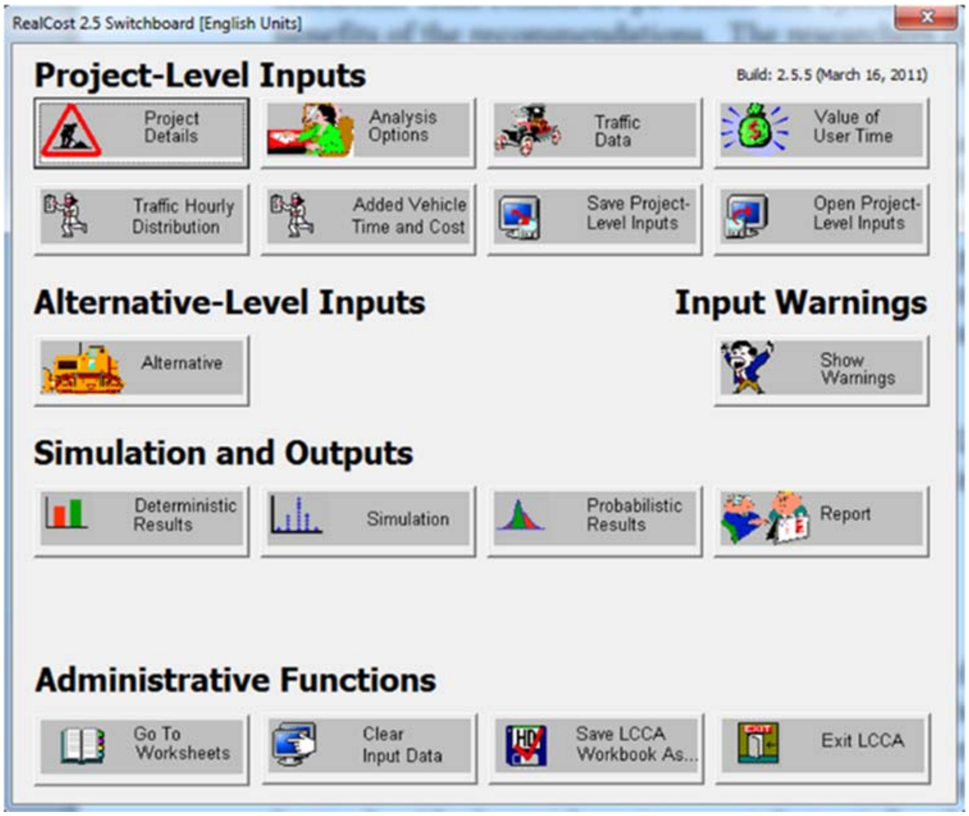


Figure 125. Interface of FHWA RealCost Software

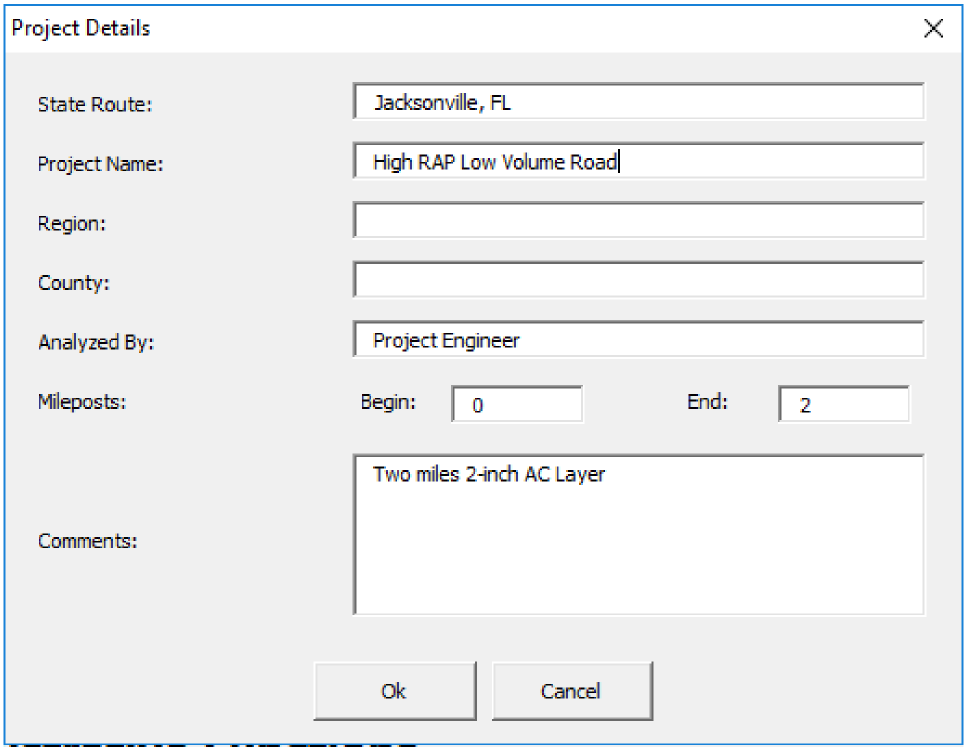
VIII.5.2. Inputs to FHWA RealCost Software

Due to the complex nature of the inputs required, and in order to obtain the best representative numbers, researchers gathered inputs from several sources to perform the LCCA. The inputs are discussed in the order in which they appear in the RealCost software. After the general discussion of inputs that apply to all cases, the specific inputs are discussed for different mixtures and RAP contents.

In this study, a 2-mile long section with a 2-inch thick AC layer pavement was considered for all analyses; the traffic was assumed to be 0.23 million ESALs for one lane in one direction.

VIII.5.2.1. Project Details Input

The project details consist of the general information of the pavement section. Figure 126 shows an example of the project details screen.


Project Details

State Route: Jacksonville, FL

Project Name: High RAP Low Volume Road

Region:

County:

Analyzed By: Project Engineer

Mileposts: Begin: 0 End: 2

Comments: Two miles 2-inch AC Layer

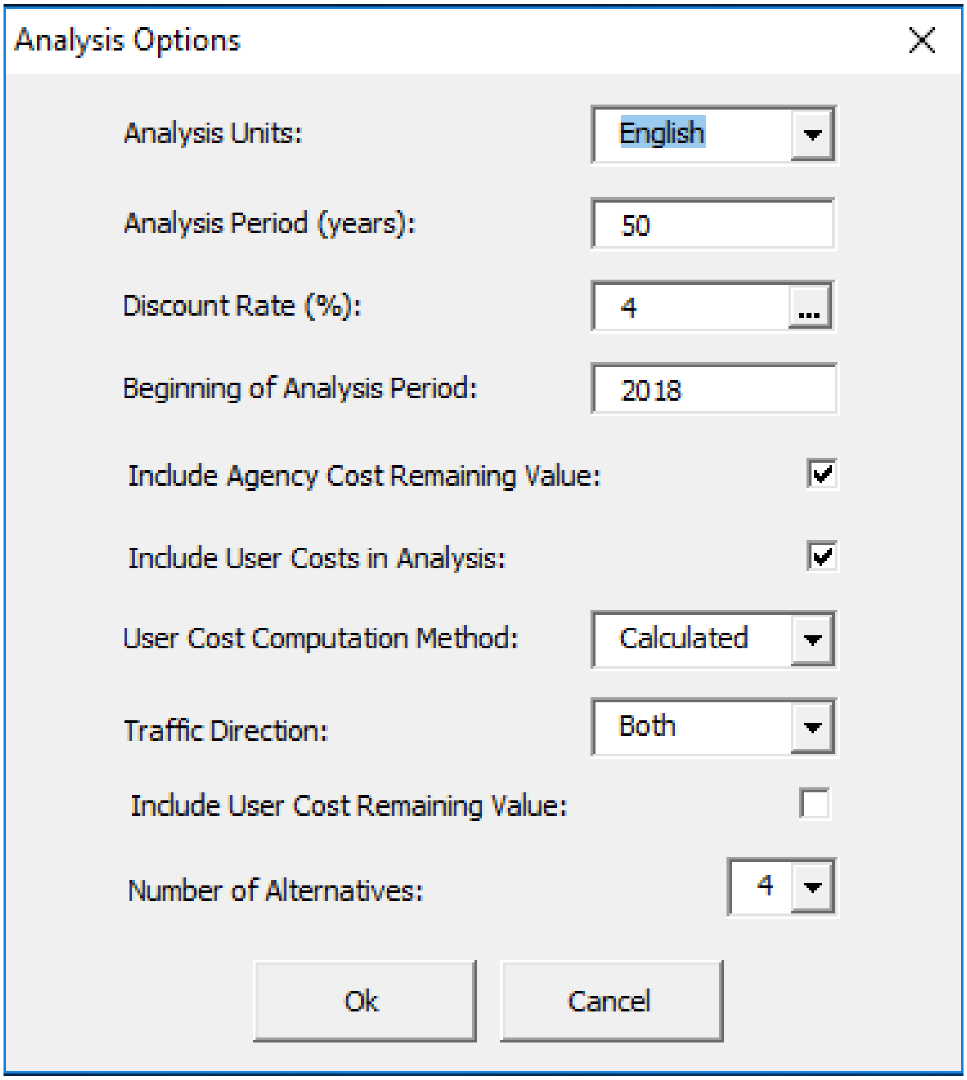
Figure 126. Example of Project Details Screen

VIII.5.2.2. Analysis Options Input

The analysis options input include:

- Analysis Units—English or metric. All LCCAs in this study used English units.
- Analysis period (years)—The number of years for which the program will run the analysis.
- Discount Rate (percent)—The discount rate in the program applies to the costs for the analysis period. This number is generally between 2 percent–4 percent nationally. A discount rate of 4 percent was used on all LCCAs.
- Beginning of Analysis Period—The year the user wants the analysis to begin. All LCCAs in this study were run beginning in 2018.
- Include Agency Cost Remaining Service Life Value (check box)—This box was left checked for all LCCAs.
- Include User Costs in Analysis (check box)—This box was left checked for all LCCAs.
- User Cost Computation Method—Users choose “calculated” or “specified.” “Calculated” was selected for all LCCAs.
- Traffic Direction—Users select “one-way” or “both.” “Both” was specified for all LCCAs.
- Include User Cost Remaining Value (check box)—This box was left checked for all LCCAs.
- Number of Alternatives—Researchers selected four since the alternatives in this study included one hot recycled mixture with 60 percent RAP and three cold recycled mixtures with 60 percent, 80 percent, and 100 percent RAP.

Figure 127 shows an example of the analysis options screen.



Analysis Units: English

Analysis Period (years): 50

Discount Rate (%): 4

Beginning of Analysis Period: 2018

Include Agency Cost Remaining Value: ☑

Include User Costs in Analysis: ☑

User Cost Computation Method: Calculated

Traffic Direction: Both

Include User Cost Remaining Value: ☐

Number of Alternatives: 4

Figure 127. Example of Analysis Options Screen

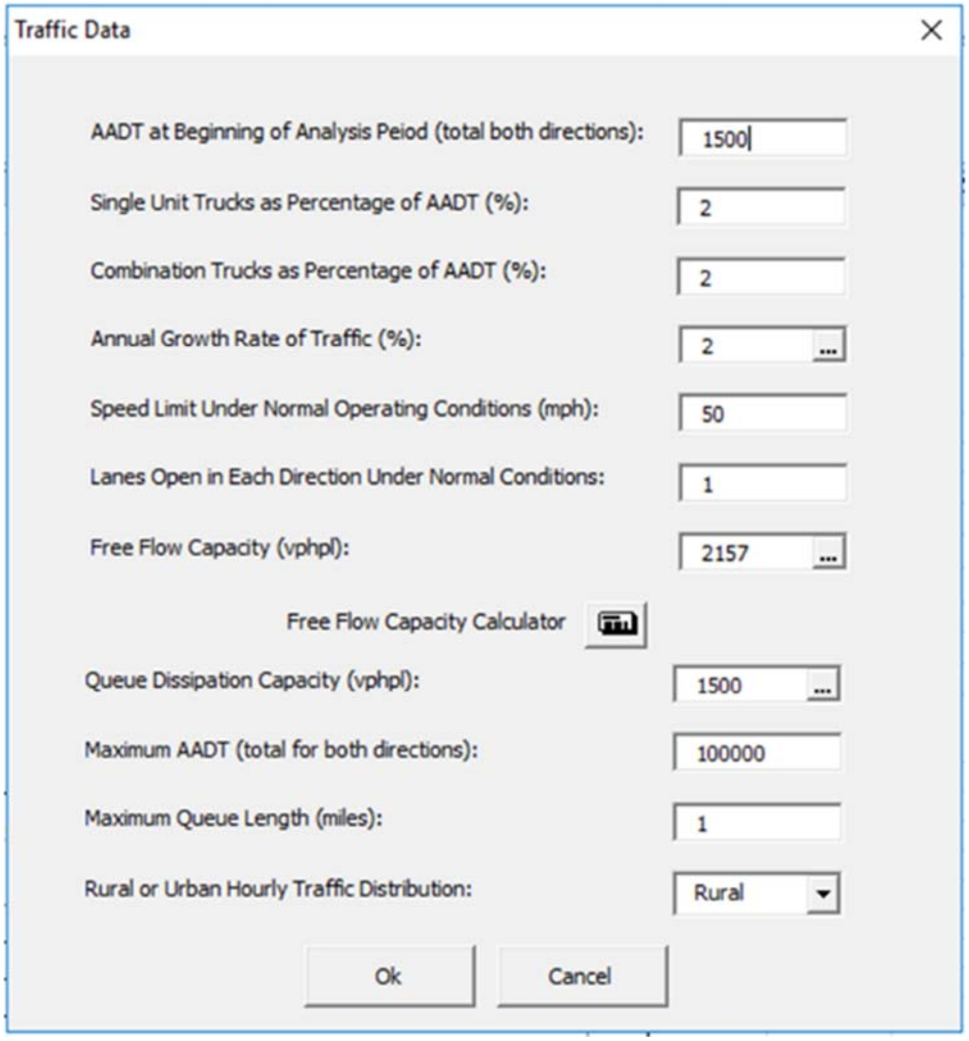
VIII.5.2.3. Traffic Data Input

To calculate user costs, the program uses work zone traffic data. The inputs include:

- AADT at Beginning of Analysis Period (total both directions)—The AADT level for the year in which the analysis period is set to begin. An AADT of 1500 was used for this study since it is a two-way AADT.
- Single Unit Trucks as percentage of AADT—Set at 2 percent for this study.
- Combination Trucks as percentage of AADT—Set at 2 percent for this study.
- Annual Growth Rate of Traffic—An average annual growth rate of 2 percent was assumed for this analysis.
- Speed Limit under Normal Operating Conditions—This input was defined as 50 mph.
- Lanes Open in Each Direction under Normal Conditions—The input used was 1.
- Free Flow Capacity (vphpl)—RealCost has a built-in, free flow capacity calculator that was used to calculate the free flow capacity.

- Queue Dissipation Capacity (QC)—A value of 1,500 passenger cars per hour per lane (pcphpl) was used, which represented a good physical feature of the road.
- Maximum AADT (both directions)—A default value of 100,000 was used.
- Maximum Queue Length—1 milw is suggested to be the maximum acceptable queue length.
- Rural or Urban Hourly Traffic Distribution—“Rural” was assumed for this study.

Figure 128 shows an example of the traffic data input screen. Note that traffic data have no impact on the agency cost; thus, this input was not as critical.



AADT at Beginning of Analysis Peiod (total both directions): 1500
Single Unit Trucks as Percentage of AADT (%): 2
Combination Trucks as Percentage of AADT (%): 2
Annual Growth Rate of Traffic (%): 2
Speed Limit Under Normal Operating Conditions (mph): 50
Lanes Open in Each Direction Under Normal Conditions: 1
Free Flow Capacity (vphpl): 2157
Queue Dissipation Capacity (vphpl): 1500
Maximum AADT (total for both directions): 100000
Maximum Queue Length (miles): 1
Rural or Urban Hourly Traffic Distribution: Rural

Figure 128. Example of Traffic Data Screen

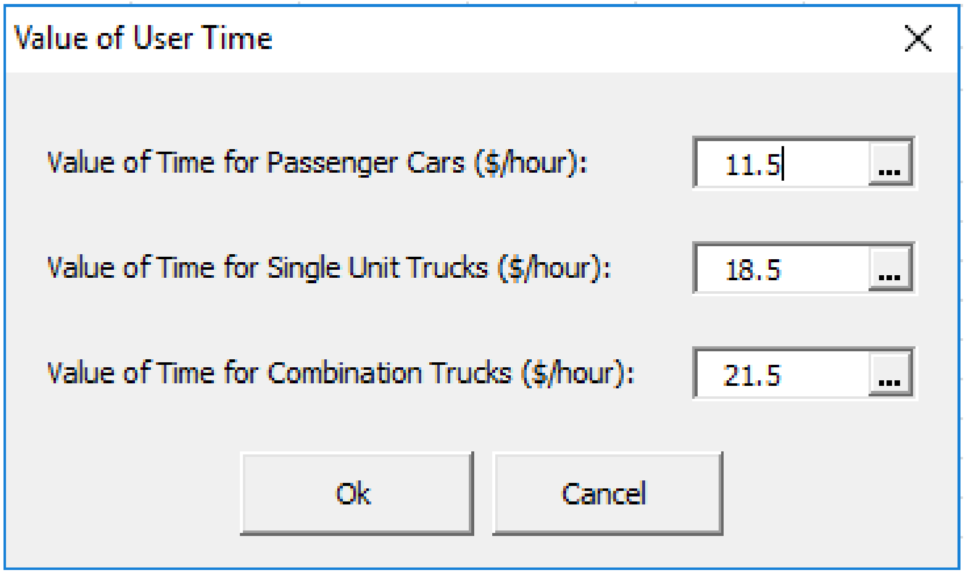
VIII.5.2.4. Value of User Time Input

The value of user time is used to calculate user costs. There are many factors to consider when calculating user cost, and the process can be very complicated. In this study, the calculations were based on predetermined average highway user cost, and the default values in the RealCost software were accepted:

- Value of Time for Passenger Cars ($/hour)—$11.50.
- Value of Time for Single Unit Trucks ($/hour)—$18.50.

- Value of Time for Combination Trucks ($/hour)—$21.50.

Figure 129 shows an example of the value of user time screen.



Value of Time for Passenger Cars ($/hour): 11.5

Value of Time for Single Unit Trucks ($/hour): 18.5

Value of Time for Combination Trucks ($/hour): 21.5

Figure 129. Example of Value of User Time Screen

VIII.5.2.5. Mixture-Level Input

The type of mixtures considered for the LCCA included one hot recycled mixture with 60 percent RAP and three cold recycled mixtures with various RAP contents. For each type of mixture, the initial agency construction cost was calculated as shown below.

According to Copeland (2011), there are four cost categories for asphalt production: materials, plant production, trucking, and lay down. Among them, the most expensive production cost category is materials, comprising 70 percent of the total cost to produce the mixture. Table 58 shows the construction cost for each type of mixture. The asphalt prices were selected and averaged from Argus Asphalt Report (Argus, 2018). The calculation was performed based on the following assumptions:

- Section length: 2 miles.
- AC layer thickness: 2 inches.
- Virgin asphalt content: 3.6 percent.
- Mixture density after compaction: 145 lb per cubic ft (CF).
- Virgin aggregate price: $30/ton.
- RAP price: $10/ton.

Table 58. Initial Construction Agency Cost Calculation

Mixture Type	Binder Price ($/ton)	RAP Content (%)	Mixture Price ($/ton)	Material and Construction Cost ($/CF)	Agency Construction Cost ($)
	A	B	C = (A × 0.036 + 30 × 0.964 × (1 − B/100) + 10 × 0.964 × B/100)	D = C/0.7 × 145/2000	E = D × 2/12 × 5280 × 24 × 2
C-60L-LF	380	60	31.0	3.21	135,761
C-80L-LF	380	80	27.2	2.81	118,891
C-100L-F	380	100	23.3	2.42	102,022
H-60L-L	380	60	31.0	3.21	135,761

For each mixture type, rehabilitation activities were provided. To determine the rehabilitation activity timing, the previous predicted AC fatigue cracking life was used, as seen in Table 59.

Table 59. Predicted Cracking Life for Each Mixture Type

Mixture Type	Cracking Life (Months)	
	Jacksonville	Homestead
C-60L-LF	188	169
C-80L-LF	169	159
C-100L-F	235	219
H-60L-L	150	149

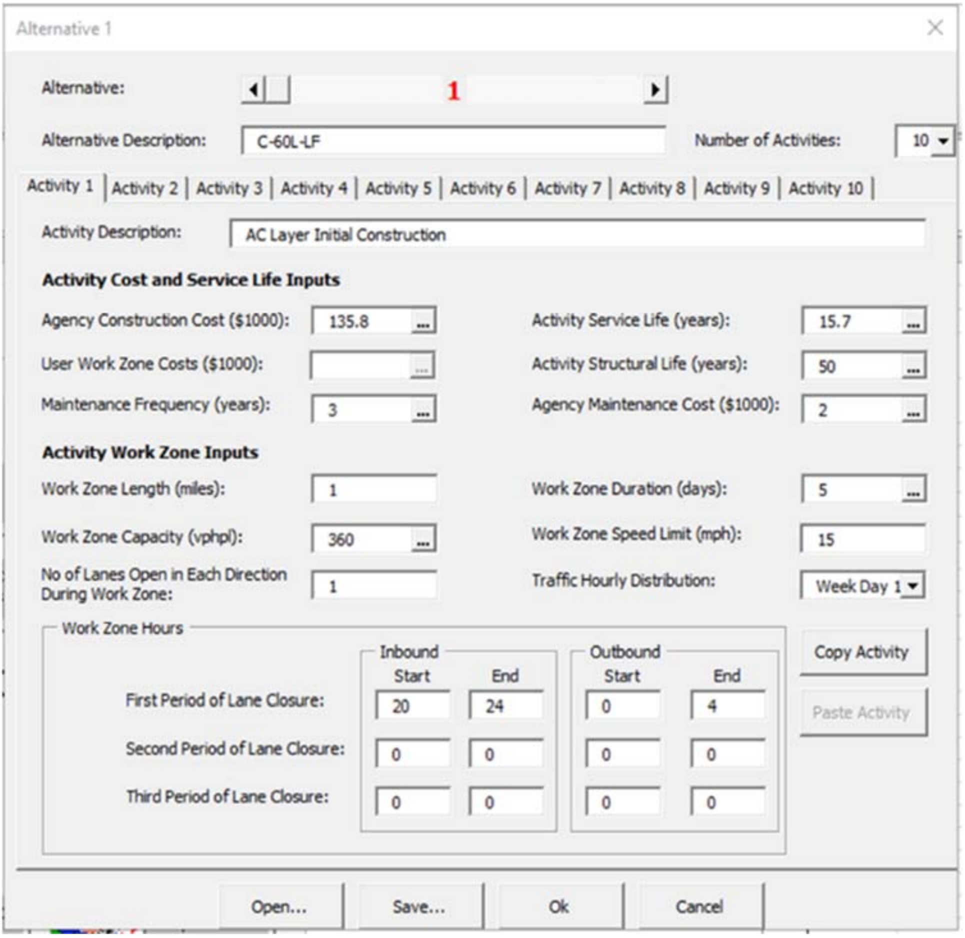
Since the fatigue cracking life was defined as the number of months needed for the cracking area to reach 50 percent of the wheel path area, the rehabilitation activity hypothesized that at the end of the cracking life, half of the wheel path cracked area (i.e., 25 percent of the total pavement area) needed to be replaced. Thus, both the activity timing and cost were estimated under those assumptions.

The other activity inputs were determined based on various factors, as discussed below.

- User Work Zone Costs—this was left as "Calculated" in the analysis options screen, so the user was not able to input a value in this box.
- Work Zone Duration—this was the number of days lanes would be closed; it was assigned a value of "0" for initial construction and then 5 days for the other maintenance activities.
- Number of Lanes Open in Each Direction during Work Zone—one lane was assumed to be open in each direction, whether by diversion to a frontage road or other means.
- Activity Service Life—this was the amount of time the activity was intended to survive with minimal maintenance until another activity was needed. The predicted cracking life for each alternative was provided here. For example, 15.7 years (188 months) was the input for the case of the cold recycled mixture with 60 percent RAP in Jacksonville.
- Activity Structural Life—the anticipated pavement life was assumed to be 50 years.
- Maintenance Frequency—the number of years maintenance has to be performed. It was assumed that maintenance would be conducted every 3 years, and the cost was fixed at $2,000.

- Work Zone Length (mi)—the work zone length is the length of the lane closure. This was assumed to be 1 mile.
- Work Zone Speed Limit (mph)—the researchers used "15" as the input here.
- Work Zone Capacity (WC)—360 was assumed here.
- Traffic Hourly Distribution—"Weekday 1" was chosen for all LCCAs run in this study.

Figure 130 shows an example of activity input under Alternative 1 (cold recycled mixture with 60 percent RAP) in Jacksonville. It was assumed that 25 percent of the section pavement needs to be rehabilitated during the 25 percent time of the pavement predicted cracking life. Thus, in this case, 10 activities were assigned to cover the analysis period of 50 years. In this input screen, the agency cost of Activity 1 was the initial construction cost, $135,761. The agency cost of other activities was the rehabilitation cost, which was 25 percent of the initial construction cost. The milling cost was assumed to be included in this rehabilitation cost. Thus, the agency cost of each activity (starting from Activity 2) for the mixture types C-60L-LF, C-80L-LF, C-100L-F, and H-60L-L were equal to $33,940, $29,723, $25,505, and $33,940, respectively.



Alternative: 1

Alternative Description: C-60L-LF

Number of Activities: 10

Activity Description: AC Layer Initial Construction

Agency Construction Cost ($1000): 135.8

Activity Service Life (years): 15.7

User Work Zone Costs ($1000):

Activity Structural Life (years): 50

Maintenance Frequency (years): 3

Agency Maintenance Cost ($1000): 2

Work Zone Length (miles): 1

Work Zone Duration (days): 5

Work Zone Capacity (vphpl): 360

Work Zone Speed Limit (mph): 15

No of Lanes Open in Each Direction During Work Zone: 1

Traffic Hourly Distribution: Week Day 1

	Inbound Start	Inbound End	Outbound Start	Outbound End
First Period of Lane Closure:	20	24	0	4
Second Period of Lane Closure:	0	0	0	0
Third Period of Lane Closure:	0	0	0	0

Figure 130. Example of Alternative and Activity Input Screen

After researchers inputted the necessary information for each mixture type, the FHWA RealCost software was ready to perform the calculation. The next section describes the LCCA results.

VIII.5.3. Output

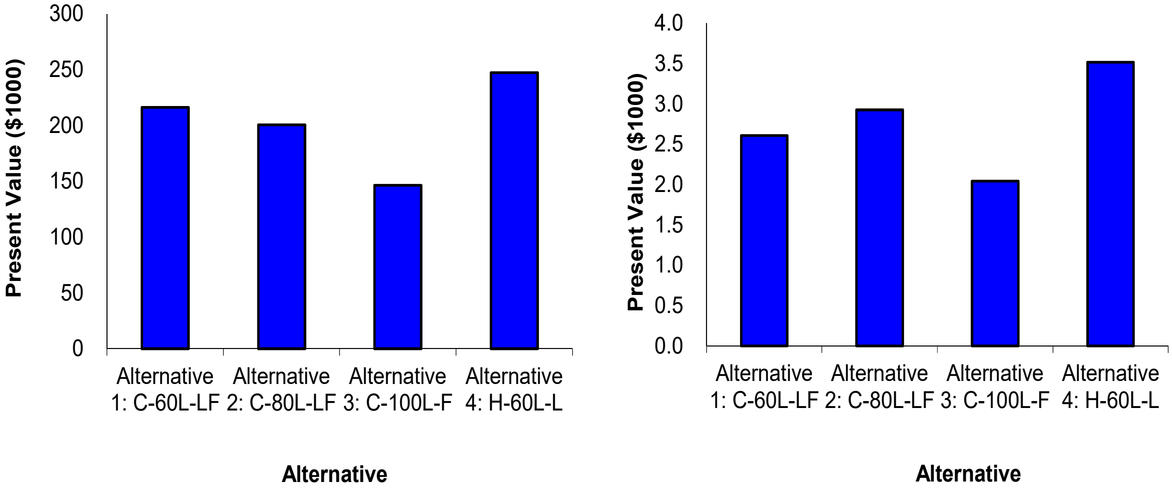
Below is the comparison of the output for the different mixture types. It is important to understand that LCCA is a concept of the time value of money. A given amount of money received one day has a higher value than the same amount received later. One way to understand this concept is to think about how funds received today may be invested and immediately begin to earn interest. A number of techniques based on the concept of discounting are available (FHWA, 2002). In the RealCost software, costs incurred at different times are converted to present value (also known as present worth), and the equivalent uniform annual cost (EUAC) is also provided.

Jacksonville, Florida

Table 60 and Figure 131 show the LCCA results for the Jacksonville weather station. According to these results, the cold recycled mixture with 100 percent RAP had the lowest agency and user costs and was identified as the best option. This finding is consistent with the laboratory test results and performance prediction results since this mixture (i.e., C-100L-F) showed a significantly lower modulus and longer fatigue cracking life in a comparison of the two mixture types.

Table 60. LCCA Results for Jacksonville, FL

Output Variables	**Mixture Type**							
	C-60L-LF		**C-60L-LF**		**C-100L-F**		**H-60L-L**	
	Agency Cost ($1,000)	User Cost ($1,000)	Agency Cost ($1,000)	User Cost ($1,000)	Agency Cost ($1,000)	User Cost ($1,000)	Agency Cost ($1,000)	User Cost ($1,000)
Undiscounted Sum	$273.91	$7.90	$254.73	$8.77	$182.05	$6.59	$310.38	$10.84
Present Value	$216.21	$2.61	$200.46	$2.93	$146.38	$2.04	$247.33	$3.52
EUAC	$10.06	$0.12	$9.33	$0.14	$6.81	$0.10	$11.51	$0.16
Lowest Present Value Agency Cost:				**C-100L-F**				
Lowest Present Value User Cost:				**C-100L-F**				



(a) (b)

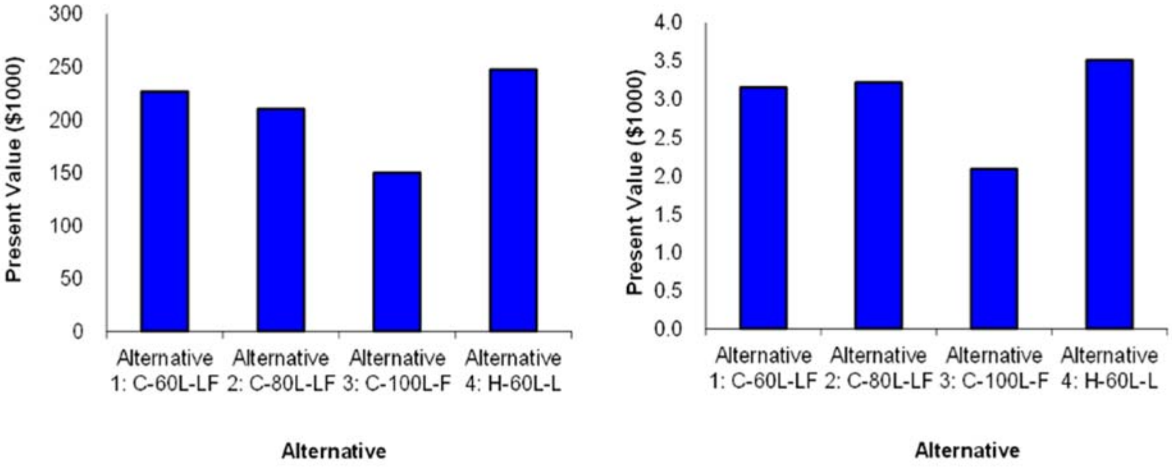
Figure 131. LCCA Present Value Results for Jacksonville, FL: (a) Agency Cost and (b) User Cost

Homestead, Florida

Table 61 and Figure 132 show the LCCA results for the Homestead weather station. Again, the cold recycled mixture with 100 percent RAP (i.e., C-100L-F) had both the lowest agency and user costs and was identified as the best option. The difference in the LCCA output between the Jacksonville and Homestead locations was not significant, although the costs for the Homestead location were slightly higher in terms of present values.

Table 61. LCCA Results of Homestead

Total Cost	**Mixture Type**							
	C-60L-LF		**C-60L-LF**		**C-100L-F**		**H-60L-L**	
	Agency Cost ($1,000)	User Cost ($1,000)	Agency Cost ($1,000)	User Cost ($1,000)	Agency Cost ($1,000)	User Cost ($1,000)	Agency Cost ($1,000)	User Cost ($1,000)
Undiscounted Sum	$281.03	$10.03	$267.12	$9.91	$189.90	$6.35	$310.38	$10.84
Present Value	$226.53	$3.16	$210.49	$3.22	$150.77	$2.10	$247.33	$3.52
EUAC	$10.54	$0.15	$9.80	$0.15	$7.02	$0.10	$11.51	$0.16
Lowest Present Value Agency Cost:				**C-100L-F**				
Lowest Present Value User Cost:				**C-100L-F**				



(a) (b)

Figure 132. LCCA Present Value Results for Homestead, FL: (a) Agency Cost and (b) User Cost

IX. SUMMARY AND COMPARISON OF RESULTS

IX.1. Moisture Susceptibility

Figure 133 and Figure 134 compare the IDT strength and TSR results of the hot, emulsified, and foamed recycled mixtures. The results presented in Figure 133 show that the unconditioned IDT strength of all recycled mixtures, with the exception of C-80L-LF, C-100L-F, and C-60L-GF, met the minimum requirement. However, several cold recycled mixtures failed to meet the IDT strength requirement after moisture conditioning. With regard to the TSR results shown in Figure 134; with the exception of C-80G-GE and C-60L-GE, all mixtures had TSR values above the minimum threshold. Note that a threshold of 60 percent is being applied in the case of TSR, which is allowed by the ARRA specification as long as the conditioned IDT strength complies with the minimum IDT criteria. Otherwise, a value of 70 percent is recommended.

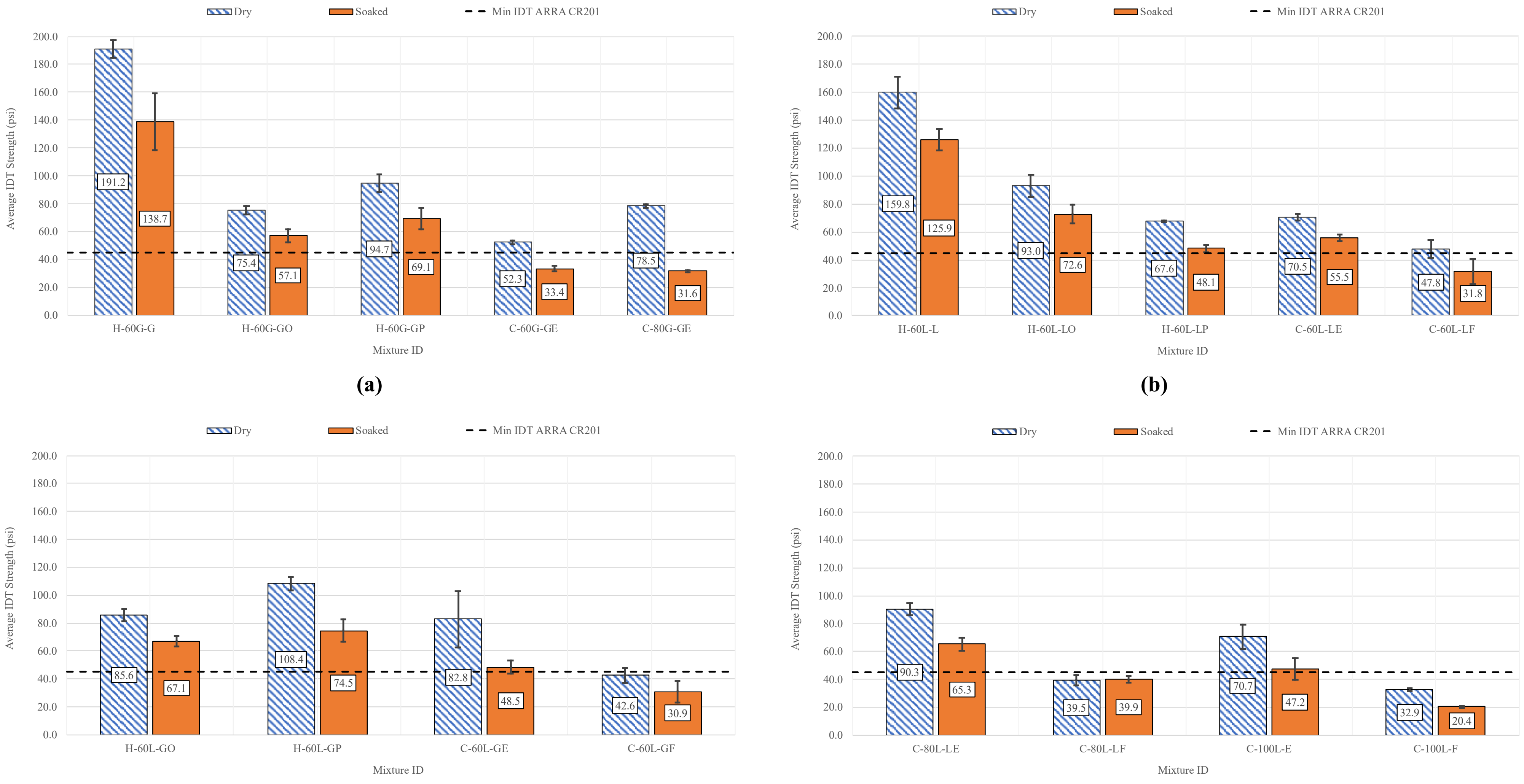
The hot recycled mixtures with no recycling agents (H-60L-L and H-60G-G) developed the largest IDT strengths for both granite and limestone virgin aggregates. As noted before, the addition of recycling agents to the hot recycled mixtures presented a reduction of the IDT strength. In the case of mixtures fabricated with granite/limestone RAP and granite virgin aggregate, regardless of the recycling agents type (i.e., organic or petroleum-based), the IDT strength reduction led to strengths barely 30 percent greater than emulsified cold recycled mixtures.

For mixtures fabricated with limestone RAP and limestone virgin aggregate, the IDT strength reduction experienced when adding petroleum-based recycling agents was severe to the point of reaching IDT strength levels equivalent to the emulsified or foamed cold recycled mixtures. Although the reduction in IDT strength was not as critical when adding organic-based agents, the resulting IDT strength was barely 24 percent greater than the one obtained for foamed cold recycled mixtures.

Mixtures with limestone RAP with granite virgin aggregate simulated, to a certain extent, the aggregate blend of RAP Stockpile 1-16 (granite/limestone). The IDT strengths of these mixtures fabricated with RAP contents of 60 percent, developed the largest IDT strength when fabricated with hot recycling methodologies even when petroleum-based recycling agents were incorporated. The IDT strengths reached by the emulsified cold recycled mixtures were just 23 percent lower than their HMA counterparts.

Mixtures with higher RAP contents (i.e., 80 percent and 100 percent) are more common in cold recycling applications, and thus these RAP contents were evaluated in emulsified and foamed cold recycled mixtures. According to Figure 133d, only C-80L-LE met the IDT strength requirement for unconditioned and moisture conditioned specimens. Mixtures with RAP contents of 100 percent could achieve the IDT strength requirement by adding hydrated lime or cement.

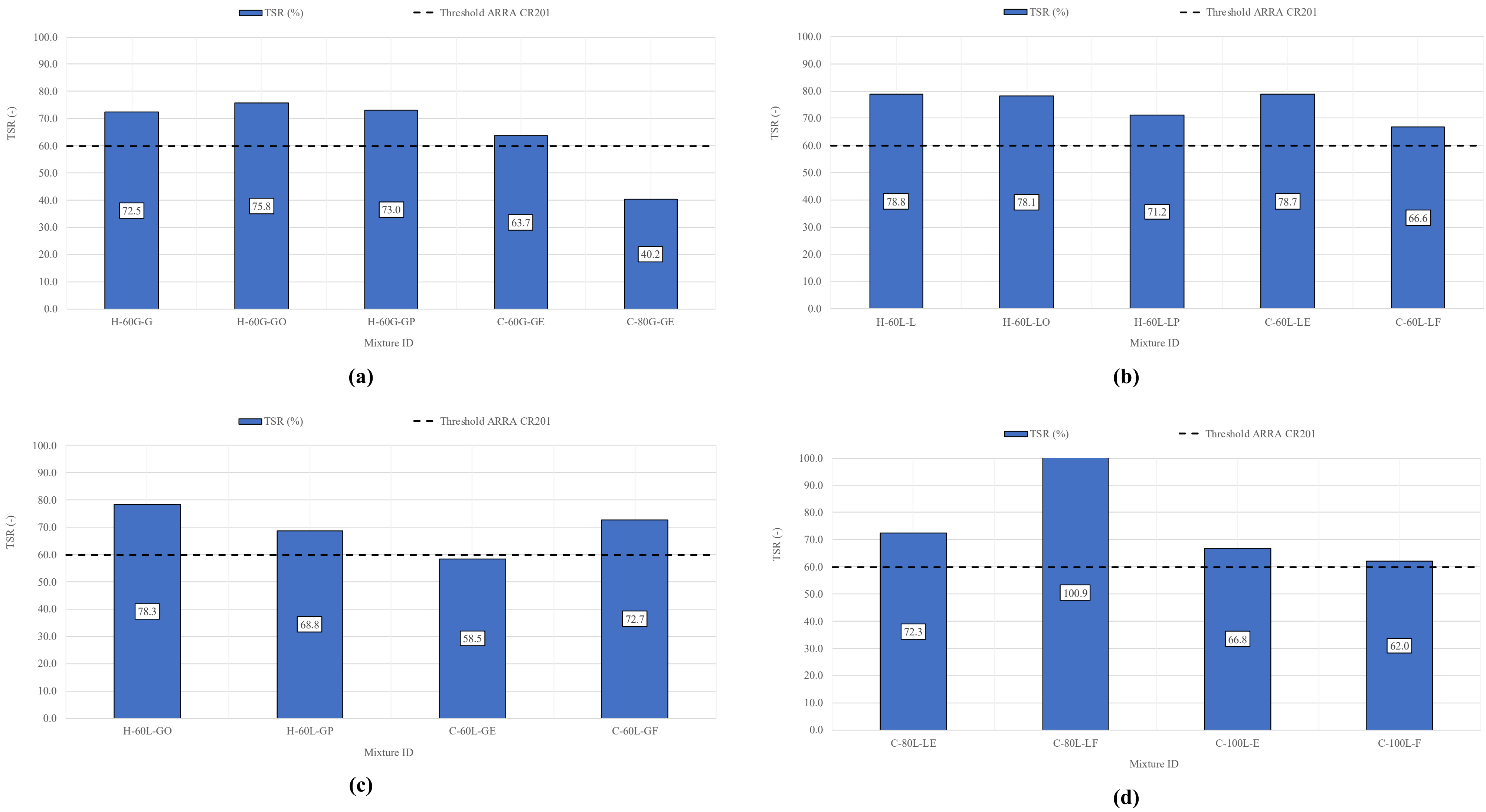
The IDT strength results evidenced better performance of the hot recycling mixtures that combine granite aggregate (either virgin or present in the RAP) with petroleum-based recycling agent. Moreover, an overall assessment of the IDT strength results shows that cold recycling with foamed binder yielded the lowest IDT strengths as compared to the other two methodologies.



(a) **(b)**

(c) **(d)**

Figure 133. IDT Strength Comparison



(a) **(b)**

(c) **(d)**

Figure 134. TSR Comparison

IX.2. Rutting and Moisture Susceptibility

In order to evaluate moisture susceptibility, Figure 135 compares the SIP results of recycled mixtures with similar characteristics produced by means of the three different recycling methodologies.

Based on Figure 135a, some replicates of mixtures with 60 percent granite/limestone RAP and granite virgin aggregate did exhibit stripping. The results demonstrate that these mixtures, regardless of the recycling methodology, present relative high moisture susceptibility with low SIP values of around 2,000 cycles. The SIP of the H-60G-GO mixture was the best among all mixtures.

In general, cold recycled mixtures fabricated with limestone RAP and limestone virgin aggregate using emulsified or foamed binder exhibited stripping (see Figure 135[b]).

The SIP results showed absence of stripping in hot recycled mixtures fabricated with limestone RAP and granite virgin aggregate (see Figure 135[c]). The moisture susceptibility of cold recycled mixtures with 60 percent and 80 percent RAP was similar (see Figure 135[a], [b], and [c]), with SIP values between about 1,000 and 3,000 load cycles. Thus, in the cold recycling case, the inclusion of 60 percent or 80 percent RAP seemed to have little influence on the moisture susceptibility of the mixtures. However, the recycled mixtures with 100 percent limestone RAP using emulsified or foamed binder showed no stripping (see Figure 135[d]).

Figure 136 compares the results of the $\Delta\varepsilon^{vp}_{SN}$ parameter to evaluate rutting resistance of recycled mixtures with similar characteristics produced by means of the three different recycling methodologies.

Among the mixtures fabricated with 60 percent granite/limestone RAP and granite virgin aggregate (see Figure 136[a]), the hot recycled mixtures presented the lowest $\Delta\varepsilon^{vp}_{SN}$ values, ranging from 2.0 to 21.1, and thus demonstrated the best rutting resistance. The opposite occurs for mixtures fabricated with 60 percent limestone RAP and limestone virgin aggregate (see Figure 136[b]), where rutting resistance similar to the hot recycling mixtures can be achieved though emulsified cold recycling, as shown by the C-60L-LE mixture.

With regard to the mixtures combining 60 percent limestone RAP and granite virgin aggregate, poor rutting performance was observed with relatively high $\Delta\varepsilon^{vp}_{SN}$ values (see Figure 136[c]). Finally, the mixtures with higher RAP contents of 80 percent and 100 percent values (see Figure 136[d]) fabricated with emulsified or foamed cold recycled techniques presented the lowest rutting resistance of all the recycled mixtures, with $\Delta\varepsilon^{vp}_{SN}$ values up to 81.1.

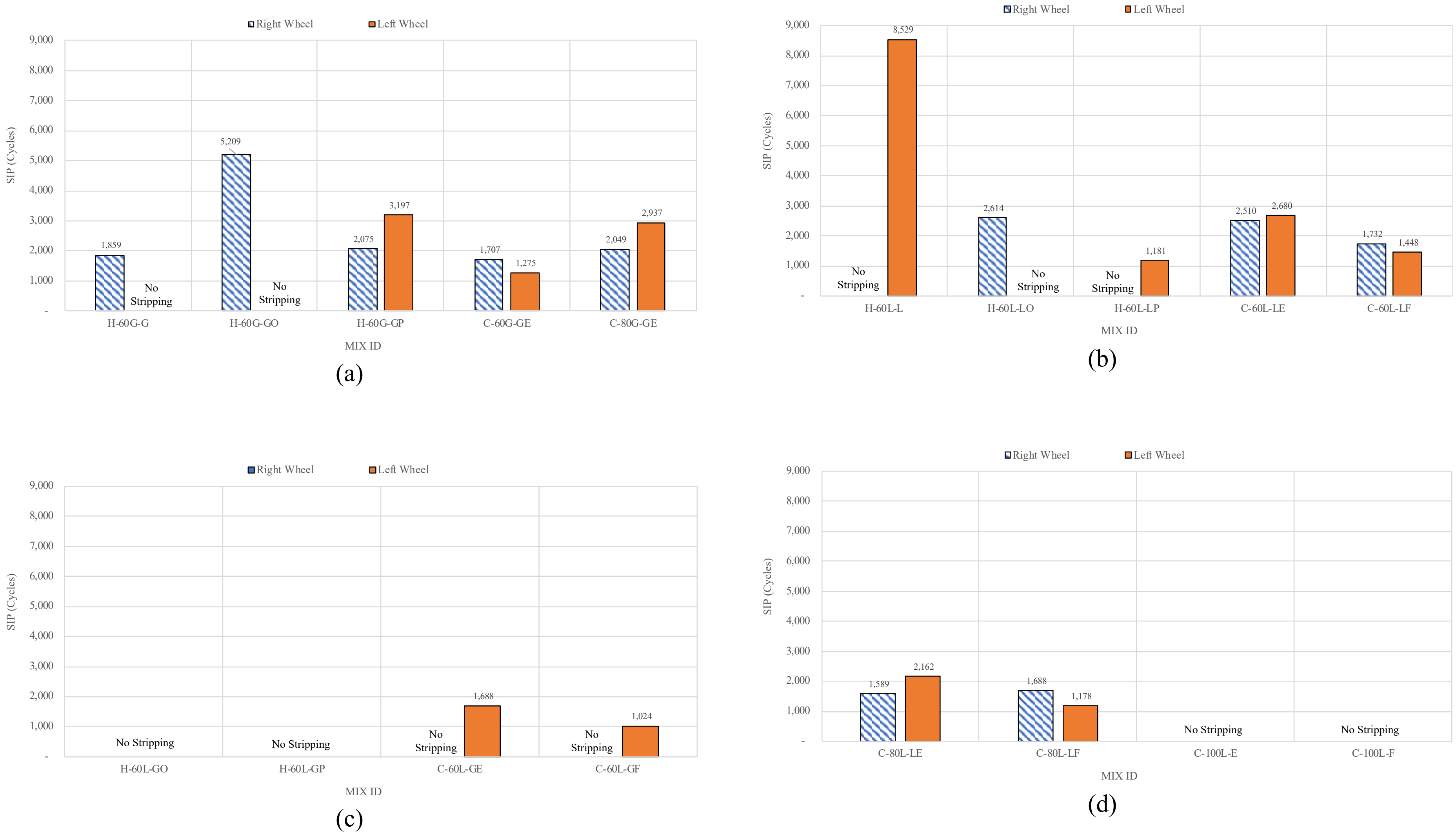
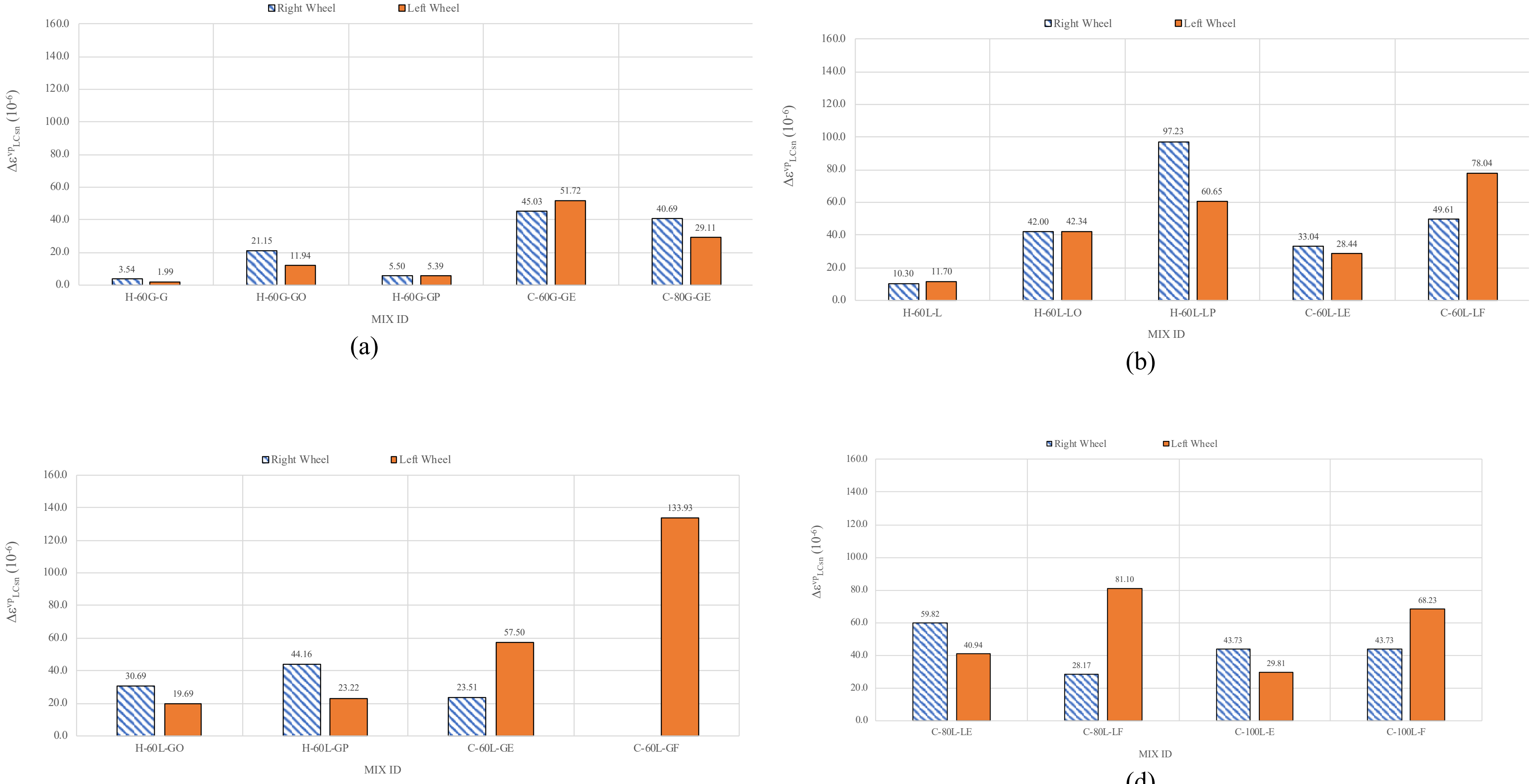


Figure 135. SIP Comparison



(a)

(b)

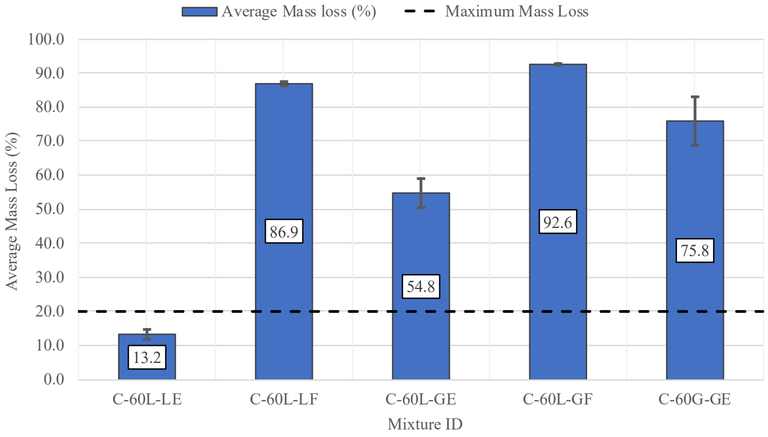
(c)

(d)

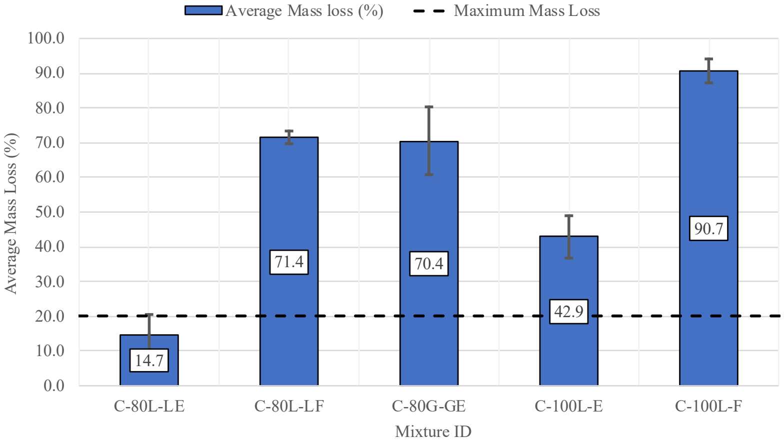
Figure 136. Rutting Resistance Parameter ($\Delta\varepsilon^{vp}_{SN}$) Comparison

IX.3. Durability

Figure 137 compares the mass loss of cold recycled mixtures' specimens subjected to the Cantabro abrasion loss test. Most cold recycled mixtures fabricated with 60 percent RAP, regardless of the RAP type and recycling technique, register high mass loss values of up to 92.6 percent after the test. The C-60L-LE mixture presented the best raveling performance, with 13.2 percent mass loss (see Figure 137[a]). Likewise, for cold recycled mixtures with higher RAP contents of 80 percent and 100 percent, it was observed that the C-80L-LE mixture lost 14.7 percent of mass after the test (see Figure 137[b]).



(a)



(b)

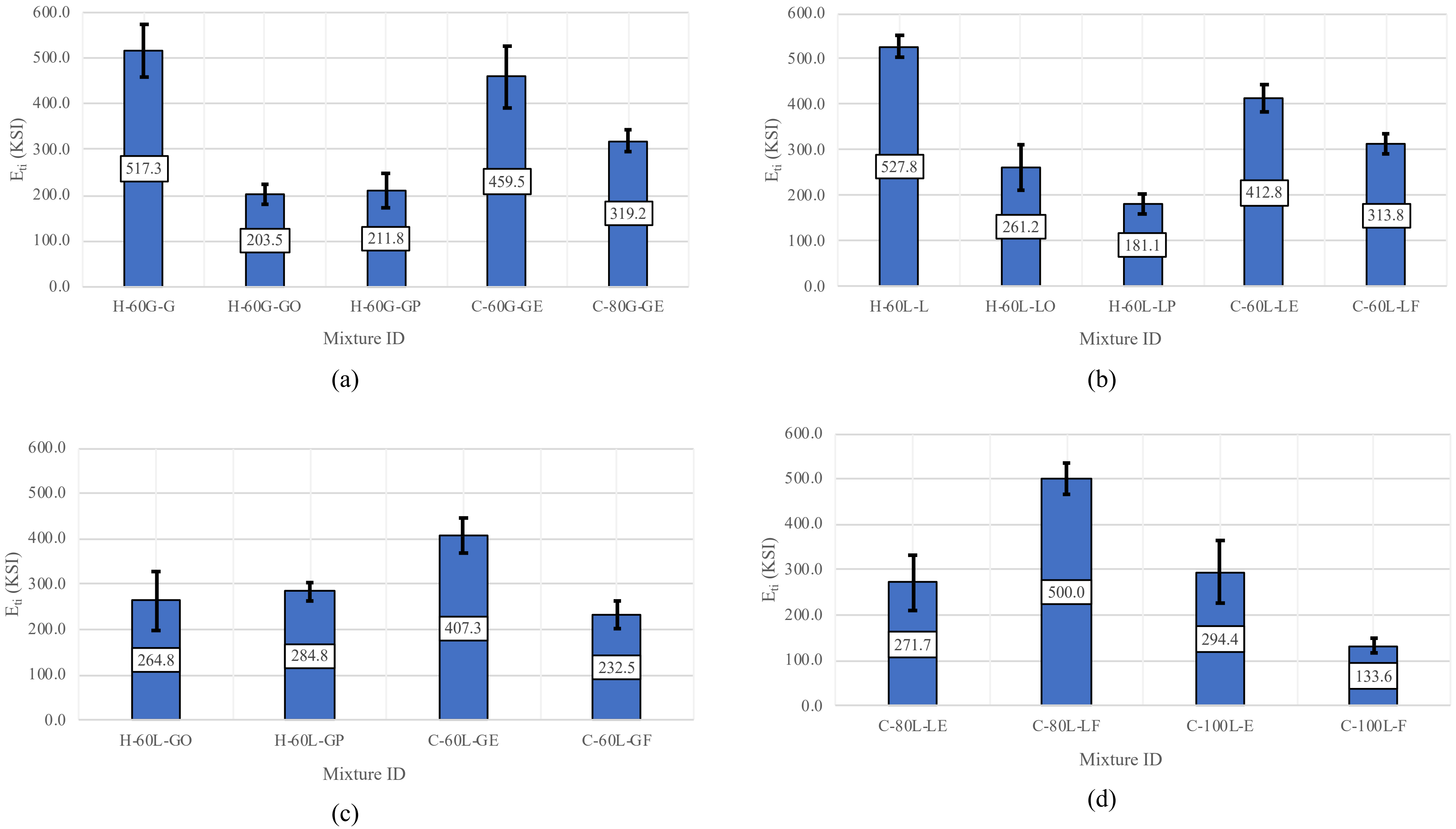
Figure 137. Cantabro Abrasion Mass Loss Comparison

This durability evaluation shows that the mixtures fabricated with limestone RAP and limestone virgin aggregate through emulsified cold recycling seem to develop a stronger, better quality bonding that provides the mixture with improved durability. Conversely, the other types of cold mixtures that were produced with different material combinations or recycling methodologies tended to exhibit poor bonding and durability.

IX.4. Stiffness

Figure 138 compares the M_R results of recycled mixtures with similar characteristics produced by means of three different recycling methodologies. The results show that the stiffness of the hot recycled mixtures with recycling agents of any type tended to be similar regardless of the RAP or virgin aggregate type. The M_R values for the hot recycled mixtures with recycling agents ranged from 181.1 to 284.8 ksi, resulting in the lowest stiffness of all the recycled mixtures.

According to Figure 138a through c, the emulsified cold recycled mixtures registered in many cases larger stiffness values when excluding the mixtures without recycling agents. In the case of RAP contents of 80 percent (see Figure 138[d]), the foamed recycled mixtures had almost double the stiffness of the emulsified recycled mixtures. For the 100 percent RAP content mixtures, the trend was opposite, with almost double the stiffness for the emulsified recycled mixture as its foamed counterpart. For the emulsified recycled mixture, the stiffness is practically the same regardless of the increase in RAP content from 80 percent to 100 percent.



(a)

(b)

(c)

(d)

Figure 138. Resilient Modulus (M_R) Comparison

IX.5. Combined Performance

Figure 139 to Figure 141 present the interaction of IDT, TSR, and FI results with respect to load cycles until failure in the HWTT for the hot recycled mixtures in order to assess their combined performance. Regions of performance compliance are highlighted and delimited by the performance thresholds for each test. The minimum load cycles before failure due to rutting was defined as 10,000, as recommended by TxDOT specifications, Item 358, *Hot In-Place Recycling of Asphalt Concrete Surfaces*.

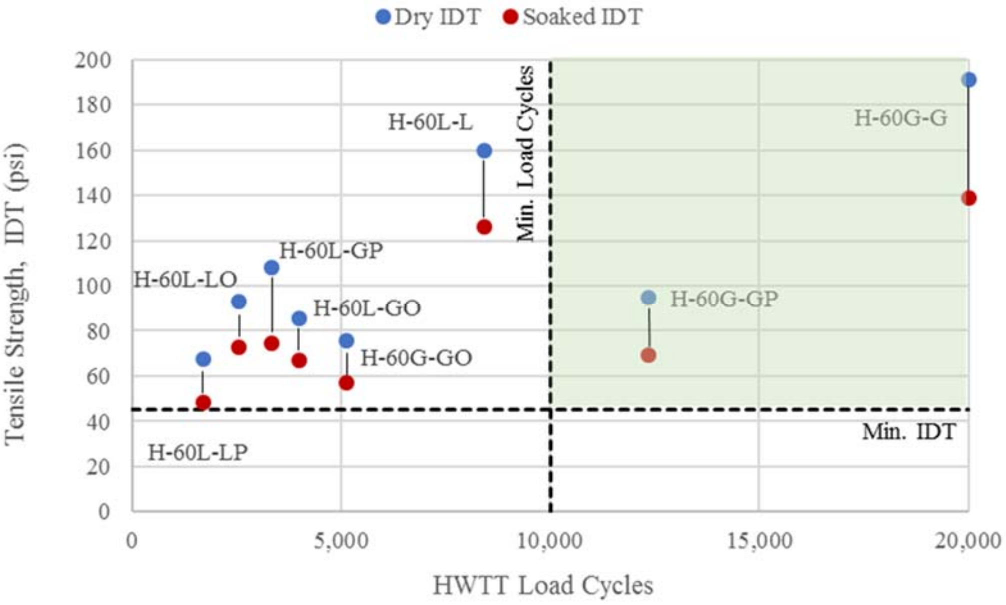


Figure 139. HWTT Load Cycles to Failure and IDT, Hot Recycling

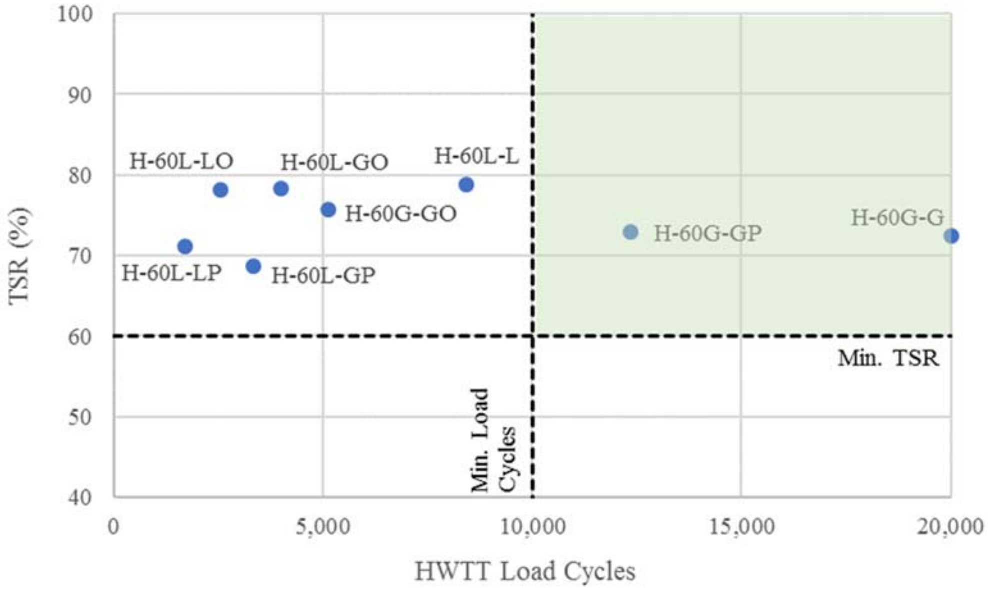


Figure 140. HWTT Load Cycles to Failure and TSR, Hot Recycling

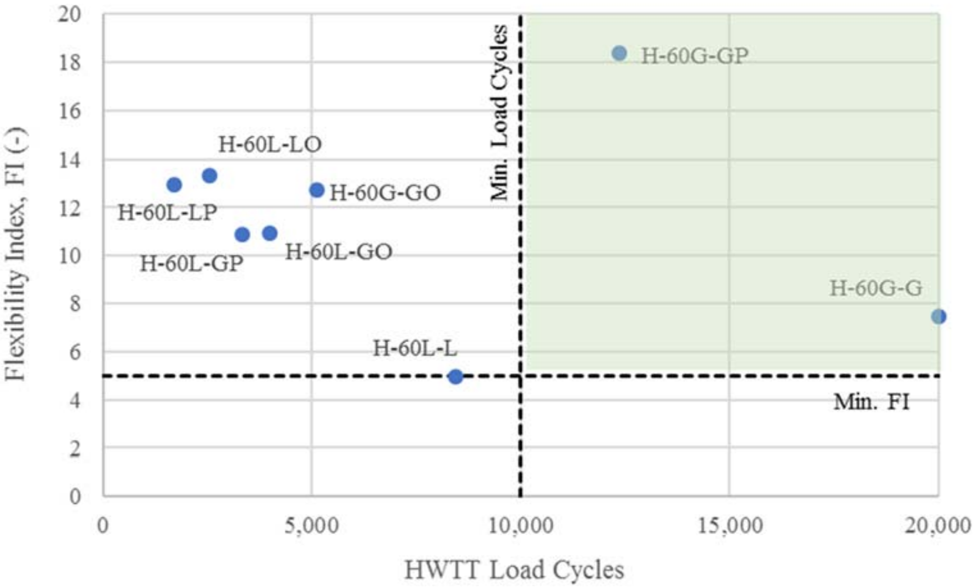


Figure 141. HWTT Load Cycles to Failure and FI, Hot Recycling

According to Figure 139 to Figure 141, resistance to rutting by means of HWTT controls the performance of high RAP hot recycled mixtures, since 75 percent (six mixtures) of the evaluated mixtures failed to pass rutting requirements. However, considering that the performance of most mixtures was adequate in every other test (IDT, TSR, and FI), the conventional protocol for rutting evaluation through HWTT is likely too severe for the assessment of high RAP mixtures, or the threshold may be too demanding for low volume roads.

However, the mixtures H-60G-G and H-60G-GP met all the requirements, including rutting resistance. With the exception of moisture susceptibility, these two mixtures display considerable differences in the performance evaluation. The mixture with no recycling agent (H-60G-G) developed very high IDT strength and rutting resistance but an FI notably close to the minimum threshold, while the mixture including the petroleum-based recycling agent (H-60G-GP) presented better cracking behavior with a higher FI and still very good tensile strength and rutting resistance. These mixtures support the importance of incorporating intermediate temperature cracking tests like SCB in the performance assessment of hot recycled mixtures and at the same time support the capability of hot recycling methodologies to produce high RAP hot recycled mixtures with adequate overall performance.

Figure 142 presents the interaction between IDT results and load cycles until failure in the HWTT for the emulsified cold recycled mixtures. The requirement for load cycles before failure due to rutting was defined to be no less than 5,000 but no more than 15,000, as recommended by TxDOT Special Standard S.S. 3254, *Cold In-Place Recycling of Asphalt Concrete Pavement*.

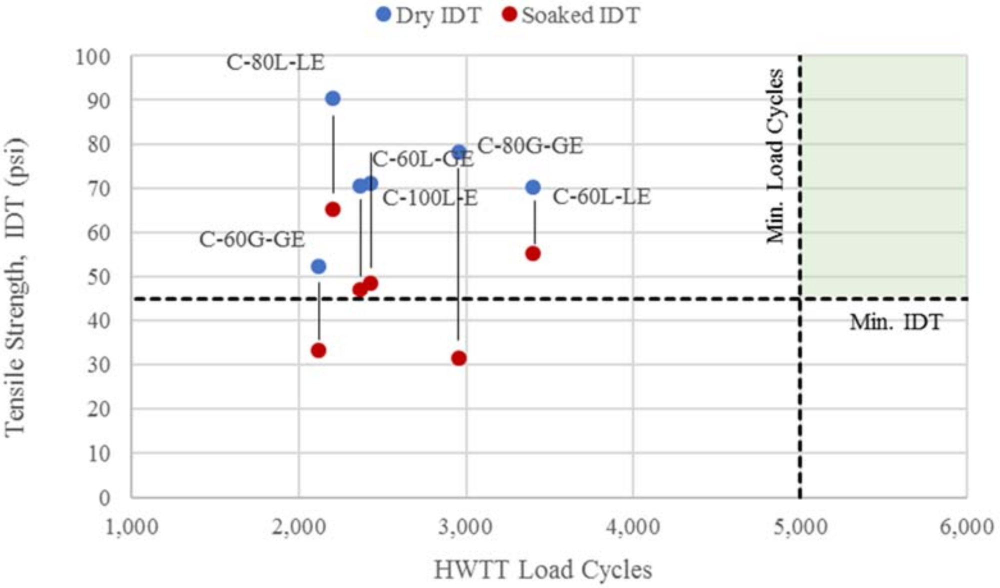


Figure 142. HWTT Load Cycles to Failure and IDT, Cold Recycling—Emulsion

According to Figure 142, none of the high RAP mixtures with emulsion met the minimum requirement of 5,000 load cycles before failure in the HWTT. The mixture C-60L-LE presented the maximum resistance to rutting, with approximately 2/3 of the minimum threshold (i.e., 3,400 cycles). Moreover, most of the mixtures presented a more critical performance developing cycles to failure below one-half of the minimum threshold (i.e., 2,500 cycles). Therefore, the conventional protocol for rutting evaluation through HWTT is likely too severe for the assessment of high RAP cold recycled mixtures.

Since HWTT does not facilitate the global performance assessment of cold recycled mixtures with emulsion and the base-material nature of cold recycled mixtures, Figure 143 and Figure 144 present the interaction of IDT and TSR results with respect to Cantabro abrasion mass loss. Only mixtures C-60L-LE and C-80L-LE met the performance requirements, including IDT strength, moisture susceptibility, and durability.

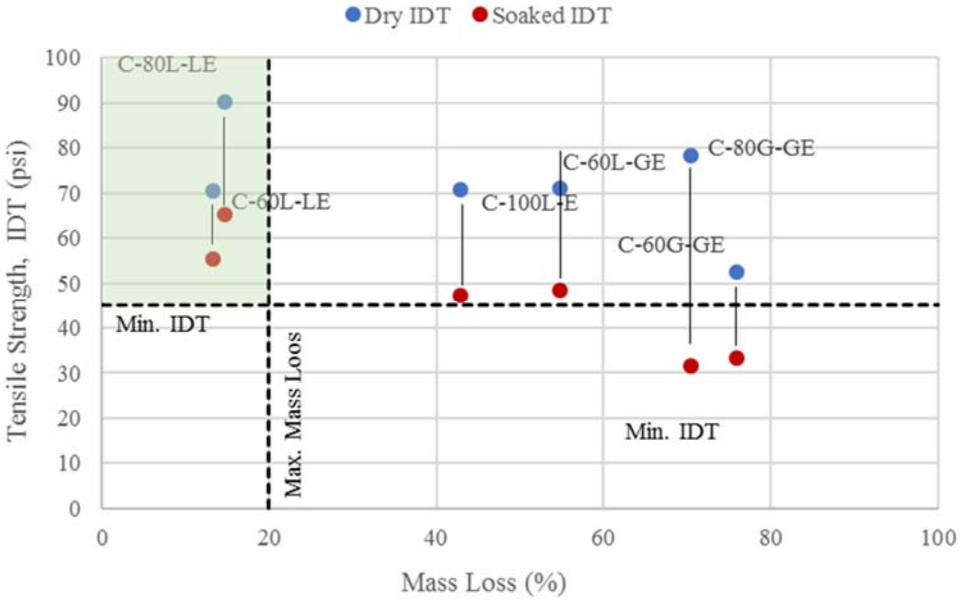


Figure 143. Cantabro Mass Loss and IDT, Cold Recycling—Emulsion

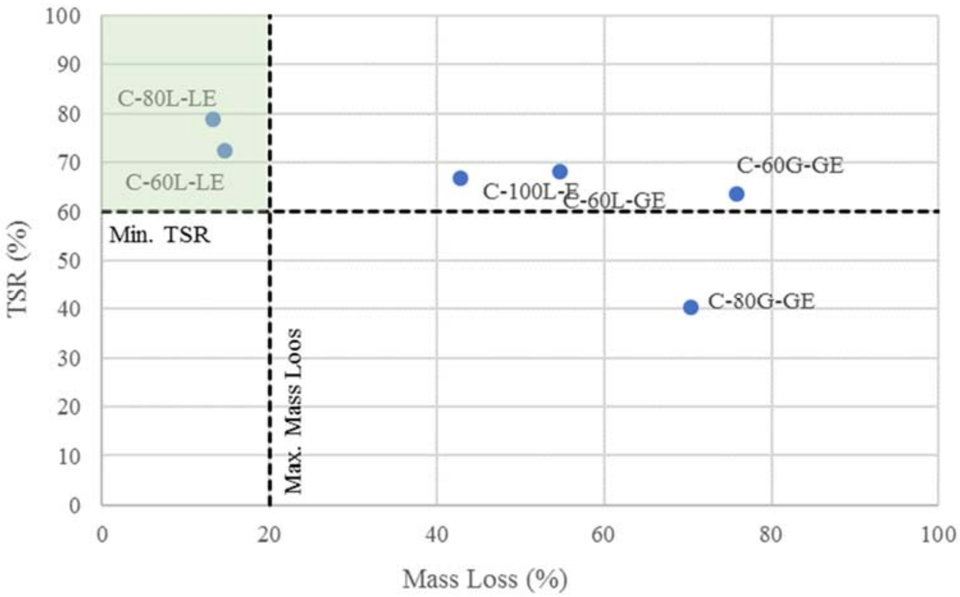


Figure 144. Cantabro Mass Loss and TSR, Cold Recycling—Emulsion

These two mixtures (C-60L-LE and C-80L-LE) support the need of incorporating durability tests such as Cantabro into the performance assessment of cold recycled mixtures, and at the same time support the ability of cold recycling methodologies with emulsion to produce mixtures with adequate overall performance.

X. CONCLUSIONS

The following summary of observations and conclusions was generated after conducting the laboratory tests and analyzing the obtained results for the performance evaluation of high RAP content mixtures.

X.1. Hot Recycled Mixtures

For the hot recycled mixtures, the following observations were gathered:

- The organic and petroleum-based recycling agents O2 and P2 displayed the lowest susceptibility to laboratory aging.
- Workability and CI tests displayed no significant difference between adding the recycling agent to the virgin binder and the alternative of letting the recycling agent marinate the RAP before mixing.
- All unconditioned and moisture conditioned hot recycled mixtures evaluated had adequate moisture susceptibility performance with respect to the minimum IDT strength and TSR requirements.
- The IDT strength reduced for the hot recycled mixtures after the inclusion of recycling agents (both organic and petroleum-based types). This decrease in IDT strength ranged from 32 percent to 61 percent for unconditioned specimens and from 41 percent to 62 percent for the moisture conditioned specimens. Despite the reduction, all specimens were above the minimum IDT strength threshold.
- All TSR results were above the minimum recommended by ARRA of 60 percent, suggesting low moisture susceptibility.
- Most of the hot recycled mixtures fabricated with limestone RAP and granite virgin aggregate did not show stripping in the HWTT.
- Most HWTT replicates experienced accelerated rutting at early load cycles. The rut depth failure criteria of ½ inch (12.5 mm) was reached in less than 5,000 load cycles by half of the hot recycled mixtures.
- The mixtures with recycling agents improved their FI with respect to those without recycling agents, from 46 percent to 145 percent for granite virgin aggregate mixtures and to around 160 percent for limestone virgin aggregate mixtures. All hot recycled mixtures showed acceptable performance, with FI values of 5.0 or above.
- The reduction in stiffness in the mixture with recycling agents was in the range of 36 percent to 57 percent for the granite virgin aggregate and from 38 percent to 60 percent for the limestone virgin aggregate.

X.2. Cold Recycled Mixtures

For the cold recycled mixtures, the following observations were gathered:

- The OMC obtained from moisture-density curves resulted in elevated water contents that reduced the stability of compacted specimens.
- The OMC was set at 4 percent after considering the results and approach conducted by Kim et al. (2011) in a study related to base stabilization.
- The moisture conditioning protocol defined in FM 1-T 283 led to IDT strengths below the requirements. Therefore, it was considered too aggressive for the cold recycled mixtures

and replaced by a reduced moisture conditioning protocol consisting of vacuum saturation plus a 24-hour water bath at room temperature.

- Based on results of mass stabilization of compacted specimens, a curing protocol in a forced draft oven for 24 hours at a temperature of 140°F (60°C) was applied to all cold recycled mixtures.
- Two of the evaluated cold recycled mixtures (C-100L-E and C-100L-F) did not show evidence of stripping in the HWTT.
- Mixtures with better rutting performance (C-60L-LE and C-80L-LE) also had the best durability.

X.2.1. Emulsion

- When accounting for the variability in the IDT strength exhibited by some of the emulsified cold recycled mixtures, the largest IDT strength was achieved by mixtures with 80 percent RAP content.
- Mixtures fabricated with higher RAP contents developed lower IDT strengths after moisture conditioning, and thus were more moisture susceptible. The moisture susceptibility performance of mixtures including limestone RAP and limestone virgin aggregate was adequate since the minimum TSR requirement was met. However, the mixtures fabricated with granite/limestone RAP at contents over 60 percent did not meet the TSR requirement due to considerable reduction of the tensile strength after moisture conditioning.
- Mixtures with limestone RAP and virgin aggregate showed a general and improved moisture susceptibility compared to mixtures with granite/limestone RAP with granite virgin aggregate mixtures according to SIP parameter.
- Adding 1 percent hydrated lime to the worst performing mixture (C-80G-GE) in terms of IDT strength and TSR improved significantly the wet IDT strength, resulting also in a larger TSR. Therefore, the addition of hydrated lime to emulsified cold recycled mixtures appears to be a feasible option to preclude moisture susceptibility.
- All mixtures experienced accelerated rutting at early load cycles. The rut depth failure criteria of ½ inch (12.5 mm) was reached in less than 5,000 load cycles in all cases.
- Considerably high Cantabro mass loss was registered for mixtures with granite virgin aggregate, ranging from 55 percent up to 76 percent.
- A reduction of about 26 percent in the mixtures' stiffness was detected after increasing the RAP content from 60 percent to 80 percent or 100 percent. This reduction in stiffness seemed significant based on the poor rutting and durability results.

X.2.2. Foamed Binder

- In order to provide adequate workability, the mixtures required the addition of water to the aggregate blend before adding the foamed binder.
- The unconditioned specimens yielded IDT strengths that barely met the minimum requirement. None of the mixtures met the minimum requirement after moisture conditioning.
- One of the mixtures (C-100L-F) did not show evidence of stripping throughout the HWTT test.

- Adding 1 percent Portland cement to the worst performing mixture (C-100L-F) resulted in a significant improvement in IDT strength for both dry and conditioned specimens, and TSR TSR also improved significantly. Therefore, incorporating fillers such as Portland cement could improve the moisture resistance of foamed cold recycled mixtures.
- All mixtures experienced accelerated rutting at early load cycles. The rut depth failure criteria of ½ inch (12.5 mm) was reached in less than 2,500 load cycles by all mixtures except C-80L-LF, which reached failure criteria in less than 5,000 load cycles.
- The mixtures presented poor durability with considerable high Cantabro mass loss, ranging from 71 percent to 92 percent, leading to the conclusion that poor adhesion between aggregate particles was prevalent.
- Maximum M_R stiffness was achieved by the mixture with limestone RAP content of 80 percent.

X.3. Life-Cycle Cost Analysis

In this study, the pavement response analysis, performance prediction, and cost-benefit analysis were conducted to assess the most feasible high RAP mixture for low volume roads. A typical 3-layer pavement structure (AC layer, base layer, and subgrade) was simulated for both multilayer linear analysis and FE analysis.

The BISAR program was used to determine the horizontal strain at the bottom of the surface, or AC layer, and the vertical strain at the surface of the subgrade under different combinations of layer moduli and thicknesses. Then, the allowable axle load repetitions (cracking life and rutting life) were determined according to the Asphalt Institute equations. Next, the SIFs were determined using a specifically developed pavement FE software. A sensitivity analysis was performed based on these calculations.

Laboratory tests, including dynamic modulus, flow number, and Texas overlay for one hot recycled mixture with 60 percent RAP and three foamed cold recycled mixtures with 60, 80, and 100 percent RAP, were conducted. This information was inputted into the TxME software to predict pavement performance for these mixtures. Two cities in the north and south portion of the state of Florida (i.e., Jacksonville and Homestead) were selected to gather weather data, which was also used for the performance prediction.

Using the performance prediction results, the FHWA RealCost software was employed to conduct the LCCA. The foamed cold recycled mixture with 100 percent RAP resulted in the lowest agency and user costs option when compared to the other three mixtures included in the LCCA.

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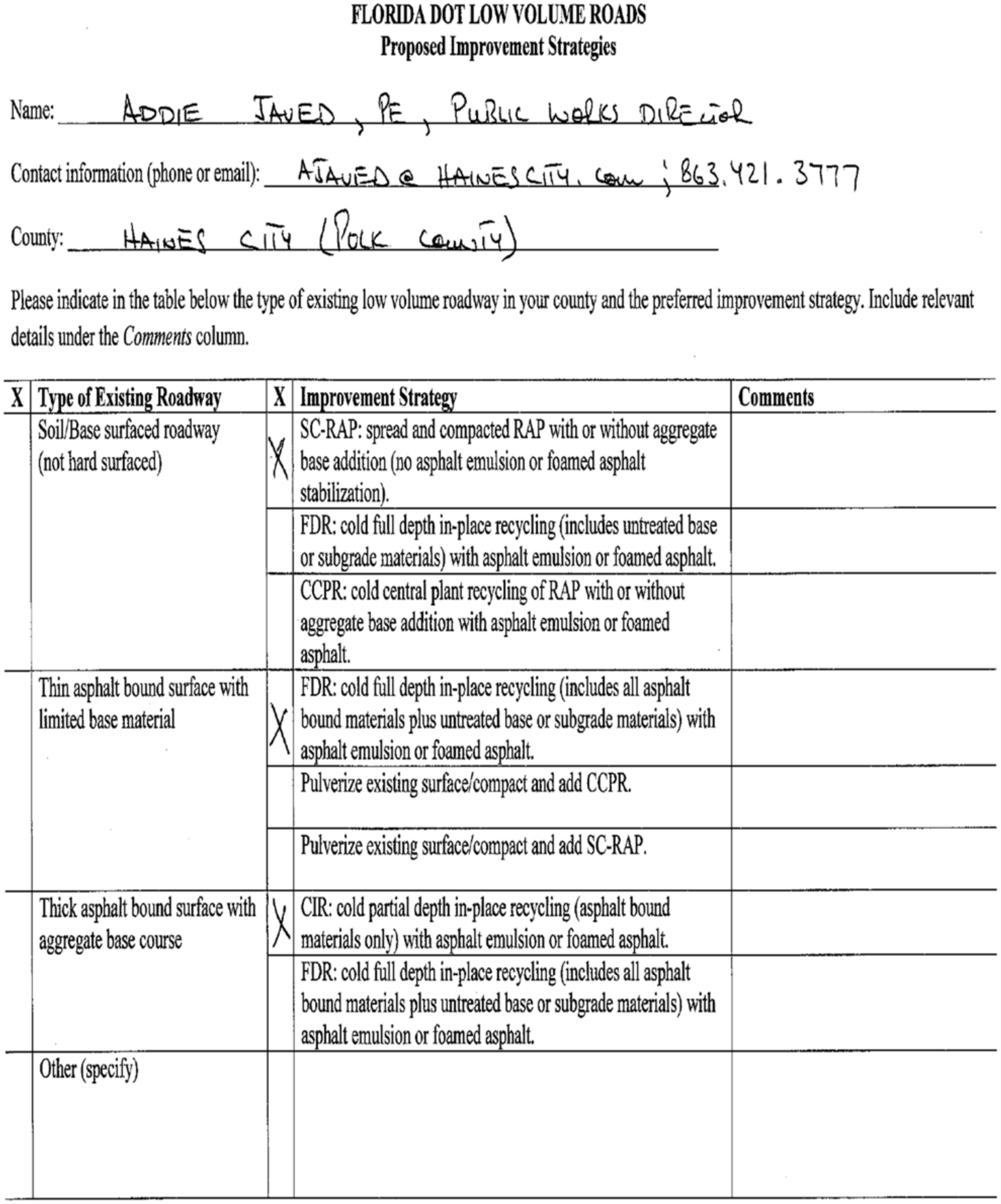
APPENDIX A.
COUNTY REPRESENTATIVES SURVEY RESULTS



FLORIDA DOT LOW VOLUME ROADS
Proposed Improvement Strategies

Name: ADDIE JAVED, PE, PUBLIC WORKS DIRECTOR

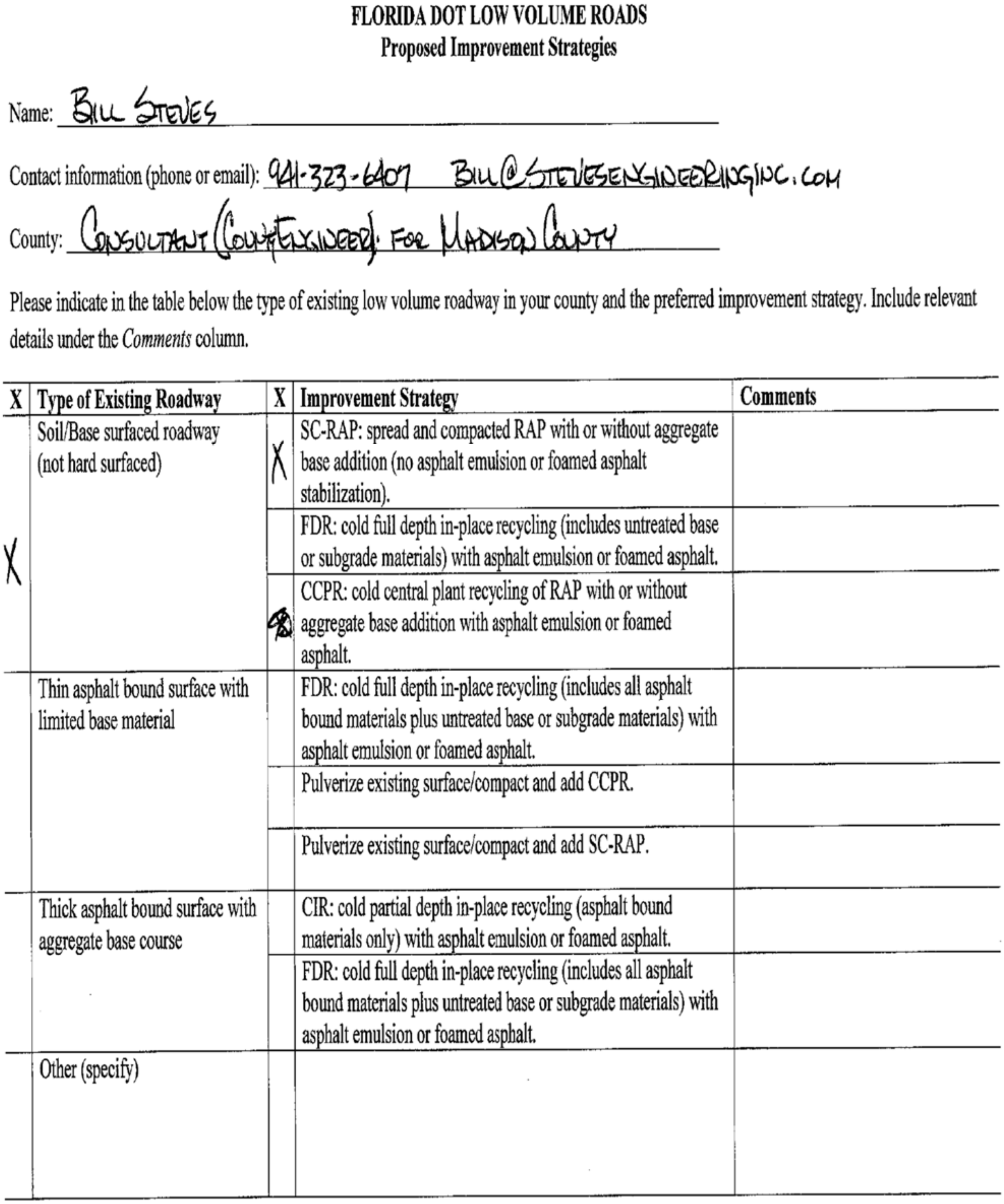
Contact information (phone or email): AJAVED@HAINESCITY.COM; 863.421.3777

County: HAINES CITY (POLK COUNTY)

Please indicate in the table below the type of existing low volume roadway in your county and the preferred improvement strategy. Include relevant details under the *Comments* column.

X	Type of Existing Roadway	X	Improvement Strategy	Comments
	Soil/Base surfaced roadway (not hard surfaced)	X	SC-RAP: spread and compacted RAP with or without aggregate base addition (no asphalt emulsion or foamed asphalt stabilization).	
			FDR: cold full depth in-place recycling (includes untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			CCPR: cold central plant recycling of RAP with or without aggregate base addition with asphalt emulsion or foamed asphalt.	
	Thin asphalt bound surface with limited base material	X	FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			Pulverize existing surface/compact and add CCPR.	
			Pulverize existing surface/compact and add SC-RAP.	
	Thick asphalt bound surface with aggregate base course	X	CIR: cold partial depth in-place recycling (asphalt bound materials only) with asphalt emulsion or foamed asphalt.	
			FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
	Other (specify)			

Figure A.1. Survey Response: Polk County



FLORIDA DOT LOW VOLUME ROADS
Proposed Improvement Strategies

Name: BILL STEVES

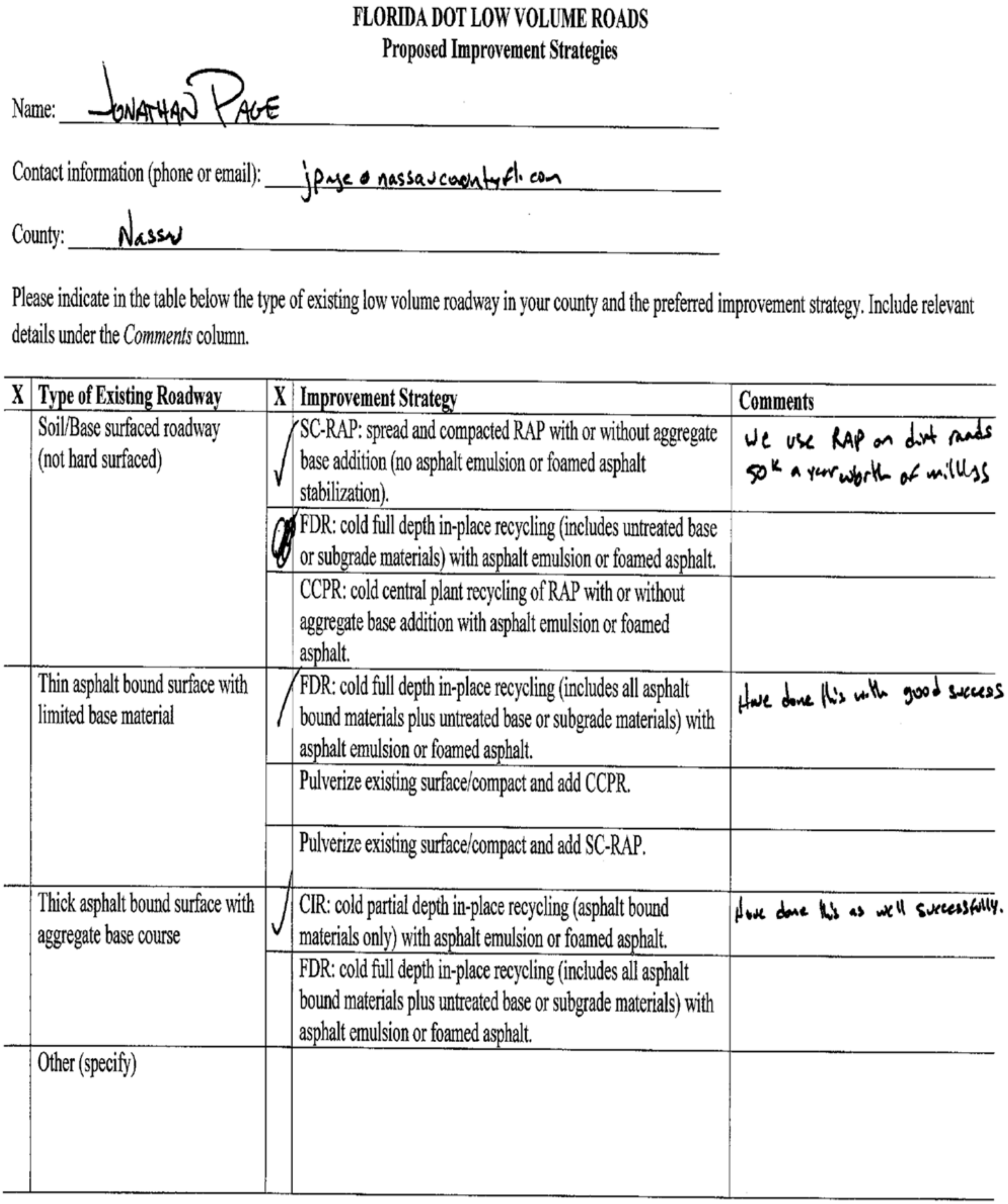
Contact information (phone or email): 941-323-6407 BILL@STEVESENGINEERINGINC.COM

County: CONSULTANT (COUNTY ENGINEER) FOR MADISON COUNTY

Please indicate in the table below the type of existing low volume roadway in your county and the preferred improvement strategy. Include relevant details under the *Comments* column.

X	Type of Existing Roadway	X	Improvement Strategy	Comments
X	Soil/Base surfaced roadway (not hard surfaced)	X	SC-RAP: spread and compacted RAP with or without aggregate base addition (no asphalt emulsion or foamed asphalt stabilization).	
			FDR: cold full depth in-place recycling (includes untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			CCPR: cold central plant recycling of RAP with or without aggregate base addition with asphalt emulsion or foamed asphalt.	
	Thin asphalt bound surface with limited base material		FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			Pulverize existing surface/compact and add CCPR.	
			Pulverize existing surface/compact and add SC-RAP.	
	Thick asphalt bound surface with aggregate base course		CIR: cold partial depth in-place recycling (asphalt bound materials only) with asphalt emulsion or foamed asphalt.	
			FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
	Other (specify)			

Figure A.2. Survey Response: Madison County



FLORIDA DOT LOW VOLUME ROADS

Proposed Improvement Strategies

Name: Jonathan Page

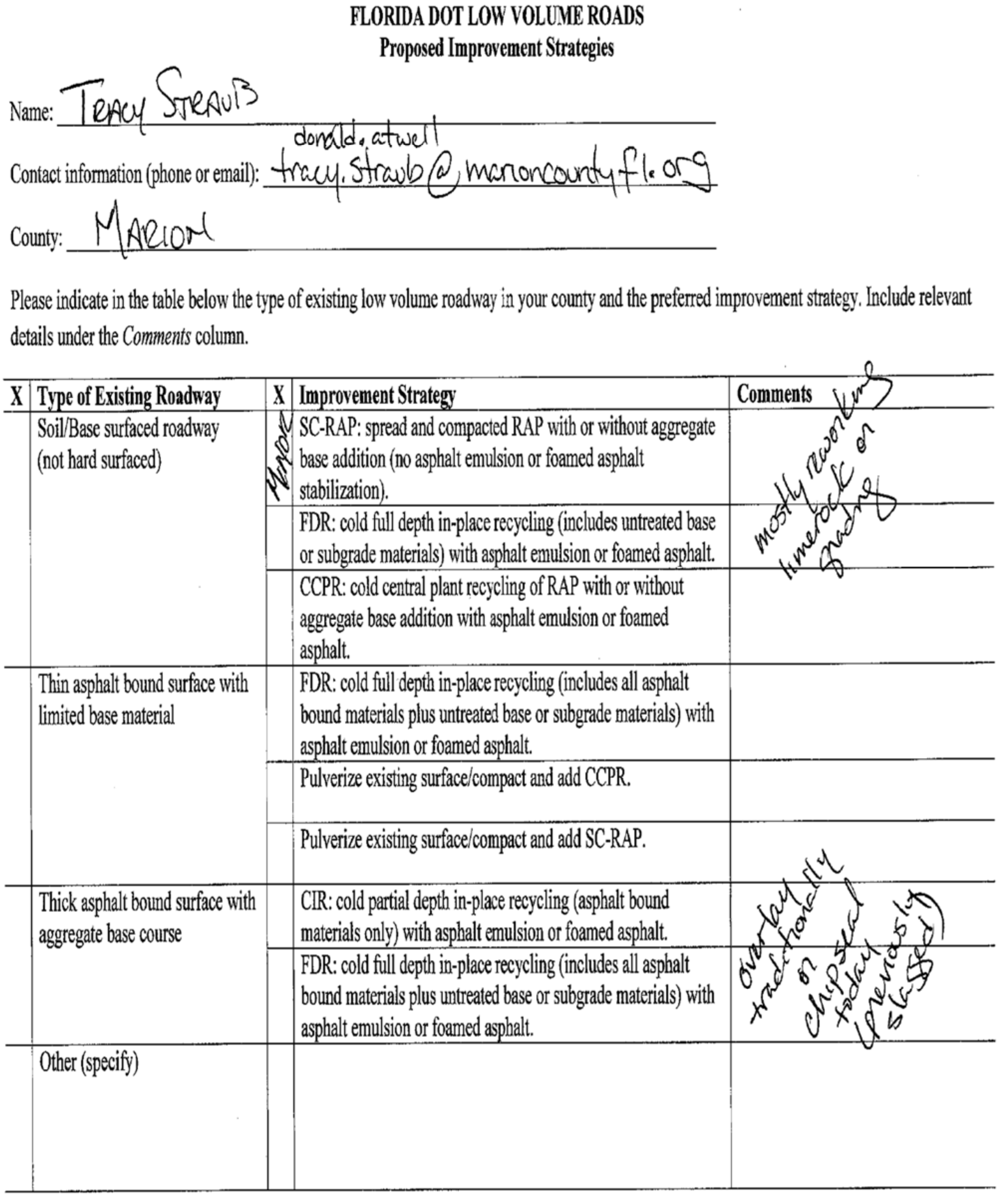
Contact information (phone or email): jpage@nassaucountyfl.com

County: Nassau

Please indicate in the table below the type of existing low volume roadway in your county and the preferred improvement strategy. Include relevant details under the *Comments* column.

X	Type of Existing Roadway	X	Improvement Strategy	Comments
	Soil/Base surfaced roadway (not hard surfaced)	✓	SC-RAP: spread and compacted RAP with or without aggregate base addition (no asphalt emulsion or foamed asphalt stabilization).	We use RAP on dirt roads 50k a year worth of millings
			FDR: cold full depth in-place recycling (includes untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			CCPR: cold central plant recycling of RAP with or without aggregate base addition with asphalt emulsion or foamed asphalt.	
	Thin asphalt bound surface with limited base material	✓	FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	Have done this with good success
			Pulverize existing surface/compact and add CCPR.	
			Pulverize existing surface/compact and add SC-RAP.	
	Thick asphalt bound surface with aggregate base course	✓	CIR: cold partial depth in-place recycling (asphalt bound materials only) with asphalt emulsion or foamed asphalt.	Have done this as well successfully.
			FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
	Other (specify)			

Figure A.3. Survey Response: Nassau County



FLORIDA DOT LOW VOLUME ROADS
Proposed Improvement Strategies

Name: TRACY STRAUB

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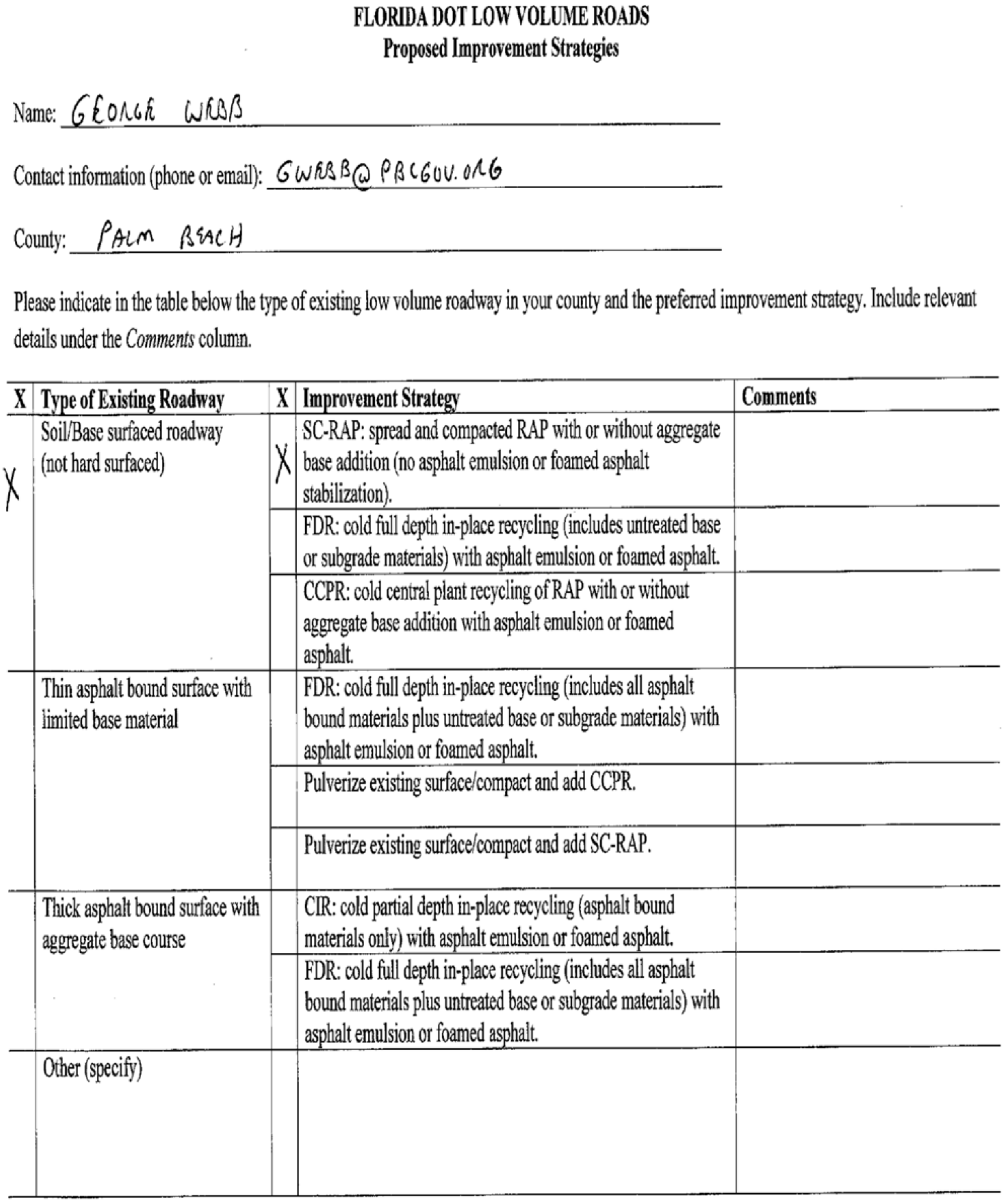
County: MARION

Please indicate in the table below the type of existing low volume roadway in your county and the preferred improvement strategy. Include relevant details under the *Comments* column.

X	Type of Existing Roadway	X	Improvement Strategy	Comments
	Soil/Base surfaced roadway (not hard surfaced)	Minor	SC-RAP: spread and compacted RAP with or without aggregate base addition (no asphalt emulsion or foamed asphalt stabilization).	mostly reworking limerock on grading
			FDR: cold full depth in-place recycling (includes untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			CCPR: cold central plant recycling of RAP with or without aggregate base addition with asphalt emulsion or foamed asphalt.	
	Thin asphalt bound surface with limited base material		FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			Pulverize existing surface/compact and add CCPR.	
			Pulverize existing surface/compact and add SC-RAP.	
	Thick asphalt bound surface with aggregate base course		CIR: cold partial depth in-place recycling (asphalt bound materials only) with asphalt emulsion or foamed asphalt.	overlay traditionally on chipseal today (previously slagged)
			FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
	Other (specify)			

Figure A.4. Survey Response: Marion County



FLORIDA DOT LOW VOLUME ROADS
Proposed Improvement Strategies

Name: GEORGE WEBB

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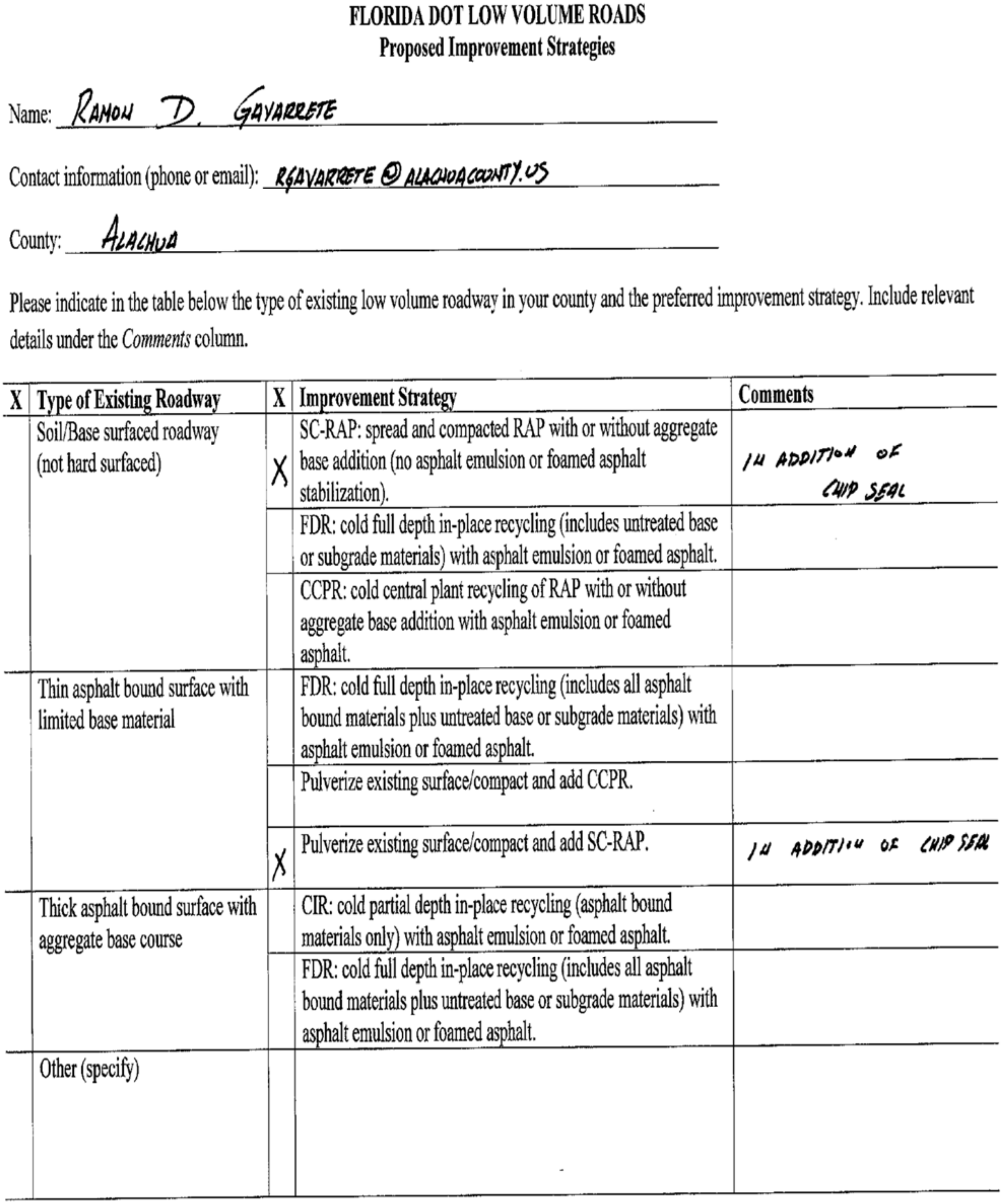
County: PALM BEACH

Please indicate in the table below the type of existing low volume roadway in your county and the preferred improvement strategy. Include relevant details under the *Comments* column.

X	Type of Existing Roadway	X	Improvement Strategy	Comments
X	Soil/Base surfaced roadway (not hard surfaced)	X	SC-RAP: spread and compacted RAP with or without aggregate base addition (no asphalt emulsion or foamed asphalt stabilization).	
			FDR: cold full depth in-place recycling (includes untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			CCPR: cold central plant recycling of RAP with or without aggregate base addition with asphalt emulsion or foamed asphalt.	
	Thin asphalt bound surface with limited base material		FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			Pulverize existing surface/compact and add CCPR.	
			Pulverize existing surface/compact and add SC-RAP.	
	Thick asphalt bound surface with aggregate base course		CIR: cold partial depth in-place recycling (asphalt bound materials only) with asphalt emulsion or foamed asphalt.	
			FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
	Other (specify)			

Figure A.5. Survey Response: Palm Beach County



FLORIDA DOT LOW VOLUME ROADS
Proposed Improvement Strategies

Name: RAMON D. GAYARRETE

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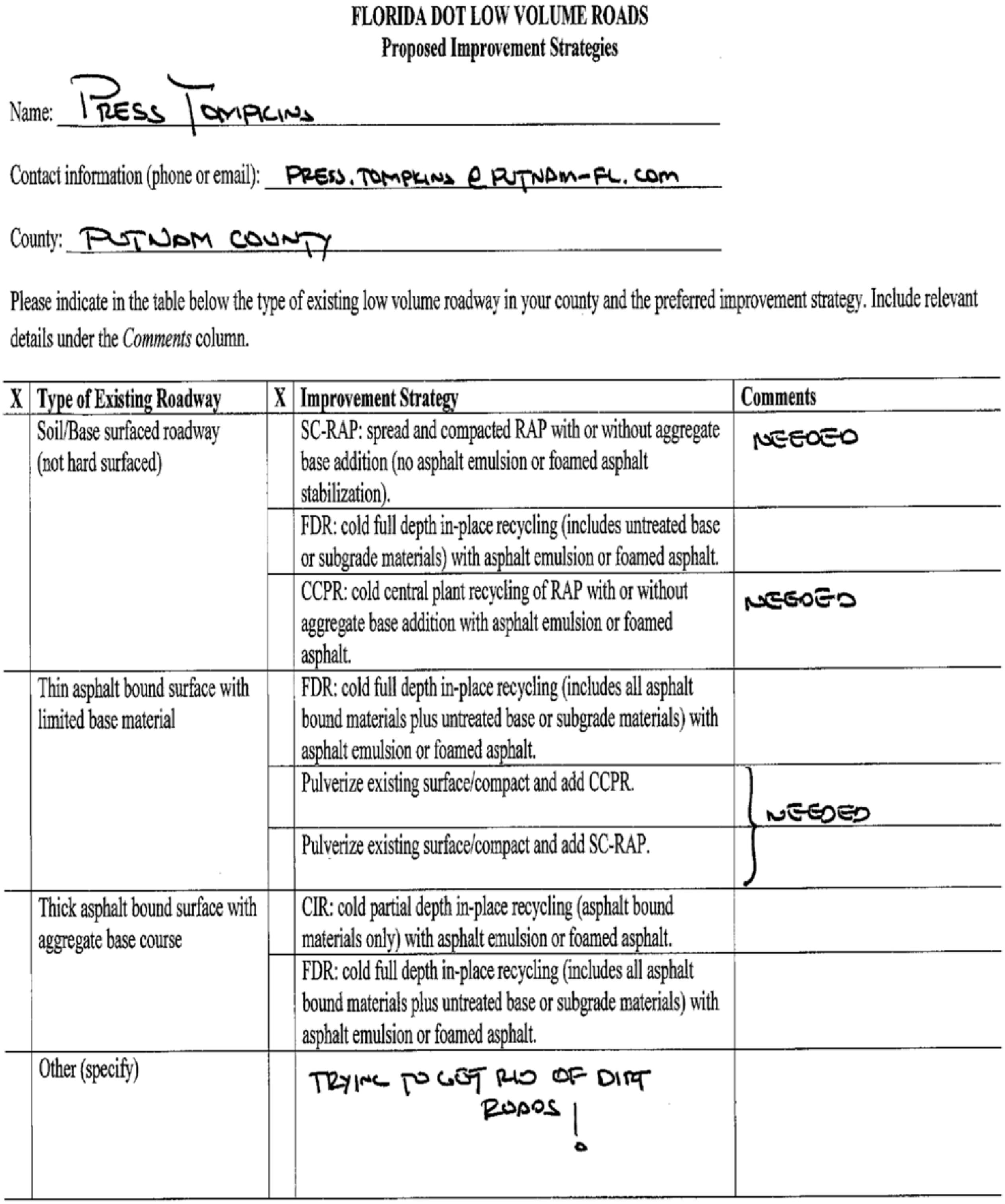
County: ALACHUA

Please indicate in the table below the type of existing low volume roadway in your county and the preferred improvement strategy. Include relevant details under the *Comments* column.

X	Type of Existing Roadway	X	Improvement Strategy	Comments
	Soil/Base surfaced roadway (not hard surfaced)	X	SC-RAP: spread and compacted RAP with or without aggregate base addition (no asphalt emulsion or foamed asphalt stabilization).	IN ADDITION OF CHIP SEAL
			FDR: cold full depth in-place recycling (includes untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			CCPR: cold central plant recycling of RAP with or without aggregate base addition with asphalt emulsion or foamed asphalt.	
	Thin asphalt bound surface with limited base material		FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			Pulverize existing surface/compact and add CCPR.	
		X	Pulverize existing surface/compact and add SC-RAP.	IN ADDITION OF CHIP SEAL
	Thick asphalt bound surface with aggregate base course		CIR: cold partial depth in-place recycling (asphalt bound materials only) with asphalt emulsion or foamed asphalt.	
			FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
	Other (specify)			

Figure A.6. Survey Response: Alachua County



FLORIDA DOT LOW VOLUME ROADS
Proposed Improvement Strategies

Name: PRESS TOMPKINS

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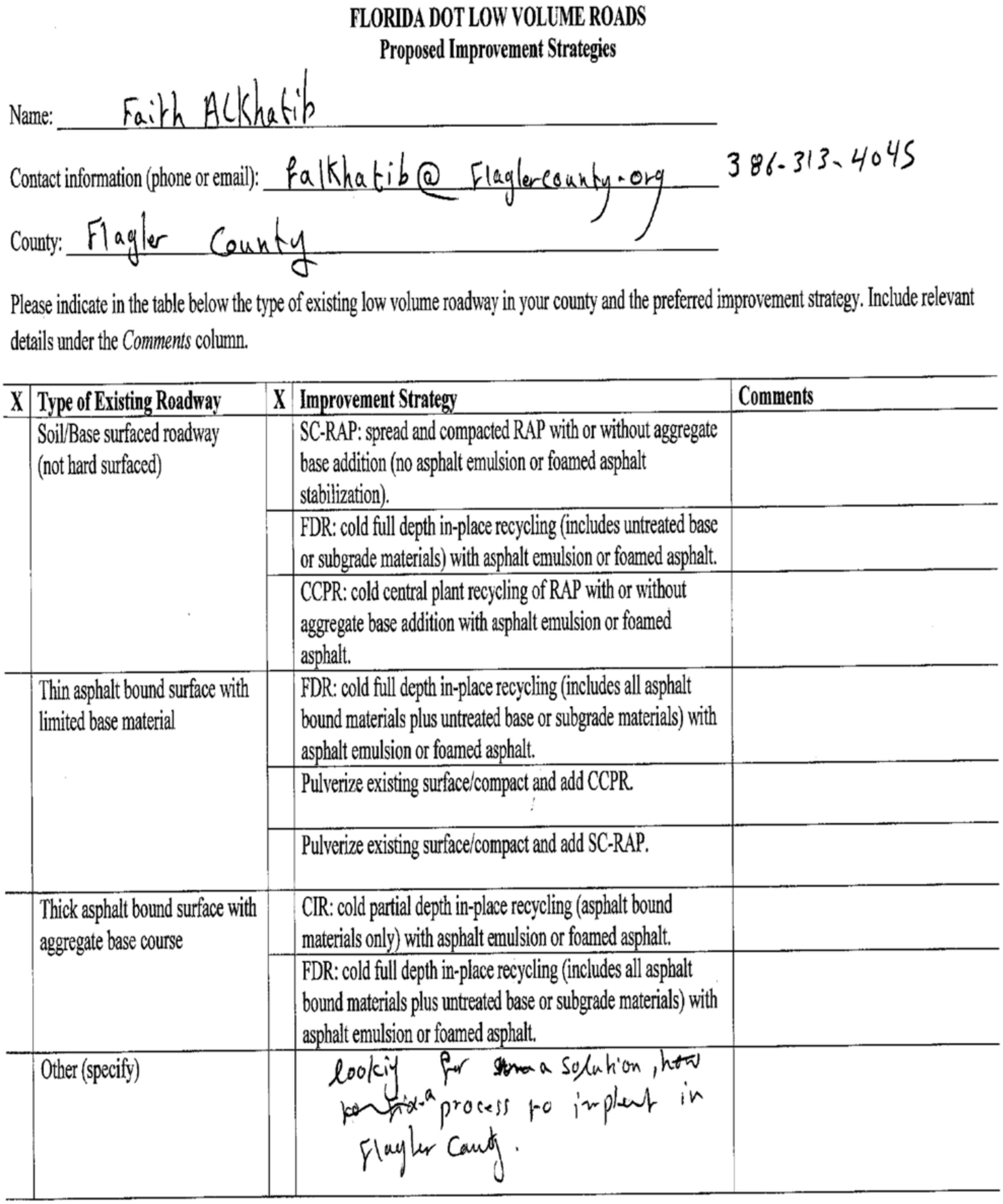
County: PUTNAM COUNTY

Please indicate in the table below the type of existing low volume roadway in your county and the preferred improvement strategy. Include relevant details under the *Comments* column.

X	Type of Existing Roadway	X	Improvement Strategy	Comments
	Soil/Base surfaced roadway (not hard surfaced)		SC-RAP: spread and compacted RAP with or without aggregate base addition (no asphalt emulsion or foamed asphalt stabilization).	NEEDED
			FDR: cold full depth in-place recycling (includes untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			CCPR: cold central plant recycling of RAP with or without aggregate base addition with asphalt emulsion or foamed asphalt.	NEEDED
	Thin asphalt bound surface with limited base material		FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			Pulverize existing surface/compact and add CCPR.	NEEDED
			Pulverize existing surface/compact and add SC-RAP.	
	Thick asphalt bound surface with aggregate base course		CIR: cold partial depth in-place recycling (asphalt bound materials only) with asphalt emulsion or foamed asphalt.	
			FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
	Other (specify)		TRYING TO GET RID OF DIRT ROADS!	

Figure A.7. Survey Response: Putnam County



FLORIDA DOT LOW VOLUME ROADS

Proposed Improvement Strategies

Name: Faith AlKhatib

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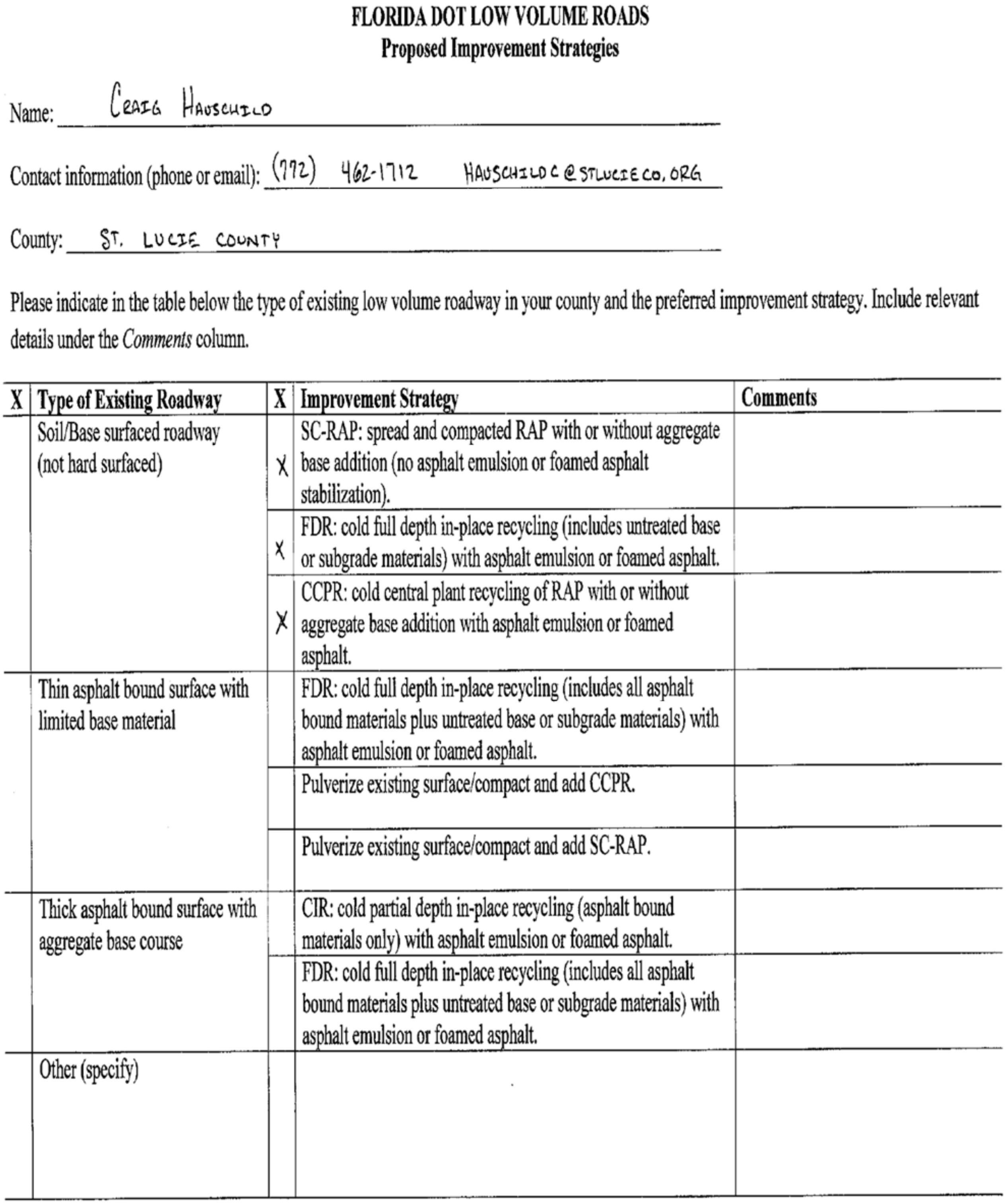
County: Flagler County

Please indicate in the table below the type of existing low volume roadway in your county and the preferred improvement strategy. Include relevant details under the *Comments* column.

X	Type of Existing Roadway	X	Improvement Strategy	Comments
	Soil/Base surfaced roadway (not hard surfaced)		SC-RAP: spread and compacted RAP with or without aggregate base addition (no asphalt emulsion or foamed asphalt stabilization).	
			FDR: cold full depth in-place recycling (includes untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			CCPR: cold central plant recycling of RAP with or without aggregate base addition with asphalt emulsion or foamed asphalt.	
	Thin asphalt bound surface with limited base material		FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			Pulverize existing surface/compact and add CCPR.	
			Pulverize existing surface/compact and add SC-RAP.	
	Thick asphalt bound surface with aggregate base course		CIR: cold partial depth in-place recycling (asphalt bound materials only) with asphalt emulsion or foamed asphalt.	
			FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
	Other (specify)		lookig for a Solution, ~~how~~ a process to implent in Flagler County.	

Figure A.8. Survey Response: Flagler County



FLORIDA DOT LOW VOLUME ROADS
Proposed Improvement Strategies

Name: CRAIG HAUSCHILD

Contact information (phone or email): (772) 462-1712 HAUSCHILDC@STLUCIECO.ORG

County: ST. LUCIE COUNTY

Please indicate in the table below the type of existing low volume roadway in your county and the preferred improvement strategy. Include relevant details under the *Comments* column.

X	Type of Existing Roadway	X	Improvement Strategy	Comments
	Soil/Base surfaced roadway (not hard surfaced)	X	SC-RAP: spread and compacted RAP with or without aggregate base addition (no asphalt emulsion or foamed asphalt stabilization).	
		X	FDR: cold full depth in-place recycling (includes untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
		X	CCPR: cold central plant recycling of RAP with or without aggregate base addition with asphalt emulsion or foamed asphalt.	
	Thin asphalt bound surface with limited base material		FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
			Pulverize existing surface/compact and add CCPR.	
			Pulverize existing surface/compact and add SC-RAP.	
	Thick asphalt bound surface with aggregate base course		CIR: cold partial depth in-place recycling (asphalt bound materials only) with asphalt emulsion or foamed asphalt.	
			FDR: cold full depth in-place recycling (includes all asphalt bound materials plus untreated base or subgrade materials) with asphalt emulsion or foamed asphalt.	
	Other (specify)			

Figure A.9. Survey Response: St. Lucie County

APPENDIX B.

FIRST-COST ASSESSMENT

Hot Recycling

The information below identifies cost savings associated with increasing RAP contents in HMA mixtures. For this analysis, it is assumed that the recycled mixtures with high RAP will yield the same pavement life as non-RAP mixtures, and thus savings will be reflected in first costs.

To determine the economic advantages, cost information is required for material transportation, virgin binders, recycling agents, virgin aggregates, RAP, and HMA components. Assumptions associated with costs for transportation, materials, HMA production, laydown, and mix design are provided below. Economic comparisons are provided based on these assumptions. Representative cost for the various materials are shown in Table B.1.

Table B.1. Representative Costs

Item	Unit	Cost (dollars)	
		Representative Range	Representative Value
Transportation	Per ton-mile	0.12 to 0.18	0.15
Virgin Binder	Per ton	400 to 800	450
Recycling Agent	Per ton	500 to 700	550
Virgin Aggregate	Per ton	12.00 to 15.00	13.00
RAP	Per ton	5.00 to 8.00	6.00

MIX DESIGN CONSIDERATIONS

Several mix design considerations are important when determining the value of RAP use in HMA. The amount of RAP utilized, the available binder in the RAP, the amount of virgin binder used, and the amount of recycling agent used are among the more important variables that contribute to the cost of recycled HMA.

Amount of RAP in Mixture

The amount of RAP in an HMA mixture is typically 15 percent to 20 percent by weight of the total mixture. There is an economical incentive to increase the RAP contents. Presently available HMA construction equipment limits the high RAP contents to about 40 percent.

Available Binder in RAP

The amount of binder available in the RAP is dependent on a number of factors. Typical ranges for available RAP binder used by industry are between 4.0 and 4.75 percent by weight of RAP.

Amount of Virgin Binder in Mixture

The amount of virgin binder used in an HMA mixture will depend on the asphalt demand for a mixture without RAP, the amount of available binder in the RAP, and the amount of recycling agent. For the purposes of this economic analysis, it has been assumed that the total binder content (virgin binder plus binder available from the RAP plus the recycling agent) is on the order of 5.5 percent by total weight of the mixture.

Amount of Recycling Agent

Recycling agent contents vary considerable depending on product type. If soft binder is used as a recycling agent and the price is the same as a conventional virgin binder, the virgin binder and the recycling agent (soft binder) are identical. When aromatic type recycling agents and other specialty materials are utilized, the price of the recycling agent may range from $500 to $700/ton or greater. Typical recycling agent contents range from 2 percent to 10 percent by weight of the total binder. Total binder is the sum of the RAP binder, virgin binder, and the recycling agent.

HOT-MIX ASPHALT COST/PRICE

The calculations summarized are for material costs only in the HMA mixture. Costs for the mixing plant and equipment at the plant location, transportation to the job site, laydown and compaction, quality control/quality assurance, overhead, and margins or profits are not included. Cost differences associated with material costs are summarized.

The costs savings for materials are nearly identical to those for the savings in the produced mixture. Production plant costs, equipment, transportation, laydown and compaction, quality control/quality assurance, overhead, and margins are not very affected by the use of RAP. For reference purposes, the price of a ton of HMA materials is typically in the range of $55 to $85, with a representative value of approximately $70/ton. Material costs are typically in the range of 45 percent to 55 percent of total in-place price of the HMA mixture. Asphalt plant production prices, including materials and equipment, are on the order of 80 percent to 85 percent ($55 to $60 per ton) of the in-place price of the HMA mixture. Haul, laydown, and compaction of the HMA mixture are typically on the order of 15 percent to 20 percent ($10 to $15 per ton) of the in-place price.

ECONOMIC SCENARIOS

The estimate of material costs associated with HMA production assumes that no recycling agent has been used for mixtures with 0 percent and 10 percent RAP, 2 percent recycling agent has been used for mixtures with 20 percent RAP, 5 percent recycling agent has been used for mixtures with 30 percent RAP and 10 percent recycling agent has been used for mixtures with 40 percent RAP.

Low-Cost Economic Incentive Scenario

In this scenario, the virgin binder and aggregate prices were assumed low, and the recycling agent and RAP costs were assumed relatively high, with the amount of binder from the RAP at a relatively low level. The assumptions are provided below:

- Virgin Binder: $400/ton.
- Recycling Agent: $700/ton.
- Virgin Aggregate: $12/ton.
- RAP: $8/ton.
- Binder in RAP: 4 percent.

Table B.2. indicates that cost savings are on the order of $0.16 to $0.20 for the various RAP percentages used in the mixture. For 40 percent RAP mixtures the cost savings is approximately 12 percent of the production costs and 9 percent of the total in-place costs. The cost savings by increasing the RAP content from 20 percent to 40 percent is $2.68, or 4.9 percent of the production costs and 3.8 percent of the total in-place cost.

Table B.2. Cost Associated with Low Economic Incentive Scenario

RAP (%)	Recycling Agent (%)	Material Costs ($/ton)	Cost Difference of HMA ($/ton)	$/% RAP
0	0	33.34	—	—
10	0	31.34	2.00	0.20
20	2	29.67	3.67	0.184
30	5	28.17	5.17	0.172
40	10	26.99	6.35	0.159

High-Cost Economic Incentive Scenario

For this scenario, the virgin binder and aggregate prices were assumed high and the recycling agent and RAP costs were assumed relatively low, with the amount of binder from the RAP at a relatively high level. The assumptions are provided below:

- Virgin Binder: $800/ton.
- Recycling Agent: $700/ton.
- Virgin Aggregate: $15/ton.
- RAP: $5/ton.
- Binder in RAP: 4.75 percent.

Note that the cost of the recycling agent is below that of the virgin binder. This anomaly is not usually the case for aromatic recycling agents. This lower costs assumes that a non-petroleum base recycling agent is available at a lower cost.

Table B.3. indicates that cost savings are on the order of $0.49 for the various RAP percentages used in the mixture. For 40 percent RAP mixtures, the cost savings is approximately 35 percent of the production costs and 20 percent of the total in-place costs. The cost savings by increasing the RAP content from 20 percent to 40 percent is $10.04, or 17 percent of the production costs and 11 percent of the total in-place cost. Considerable cost savings are evident when virgin material costs are relatively high and recycling agent and RAP costs are relatively low. This finding supports the observed interest in recycling when virgin material costs and in particular binder costs are high.

Table B.3. Cost Associated with High Economic Incentive Scenario

RAP (%)	Recycling Agent (%)	Material Costs ($/ton)	Cost Difference of HMA ($/ton)	$/% RAP
0	0	58.18	—	—
10	0	53.34	4.84	0.484
20	2	48.47	9.71	0.485
30	5	43.50	14.68	0.489
40	10	38.43	19.75	0.494

SUMMARY

The cost savings associated with the use of RAP is dependent on the cost of the virgin binder and, to a lesser extent, on the costs of the recycling agent, virgin aggregate, RAP, and the amount of binder available in the RAP.

The low-cost economic incentive scenario (low virgin material prices [binder and aggregates] and high RAP and recycling agent prices) yielded an economic incentive on the order of $0.15 to $0.20 per percent RAP utilized in the mixture. A mixture with 40 percent RAP will have a savings of about $6.25/ton while a mixture with 20 percent RAP will have a savings of about $3.65/ton. The additional saving associated with increasing the RAP content from 20 to 40 percent is about $3.00/ton of HMA, or about 5 percent of the production cost of HMA.

The high-price economic incentive scenario (high virgin material prices [binder and aggregates] and low RAP and recycling agent prices) yielded an economic incentive on the order of $0.45 to $0.50 per percent RAP utilized in the mixture. A mixture with 40 percent RAP will have a savings of about $20.00/ton while a mixture with 20 percent RAP will have a savings of about $10.00/ton. The additional savings associated with increasing the RAP content from 20 to 40 percent is about $10.00/ton of HMA, or about 15 percent of the production cost of HMA.

During periods of high material costs (virgin binder and aggregates), savings associated with the use of higher RAP contents and recycling agents (20 percent to 40 percent RAP) will be on the order of $6.00 to $8.00 per ton, or from $0.30 to $0.40 per percent RAP.

The magnitude of the potential cost savings is large enough to support technology improvements to support increased RAP usage in selected projects. This magnitude of cost savings is significant for the contractor and public agency. If 5 million tons of HMA were produced with 40 percent versus 20 percent RAP, the savings would be within the range of $20 to $50 million per year, depending primarily on the price of virgin materials (binder and aggregate).

Cold Recycling

Prices of pavement layers produced from cold recycled operations are of interest to determine comparative first costs and life-cycle costs associated with various rehabilitation alternatives. This document provides information on first costs and not life-cycle costs and is based on phone interviews with cold recycling contractors and a review of cost information from a state DOT.

Cost information is based on medium-sized projects on the order of 50,000 to 100,000 sq yd. Mobilization costs have been included, as well as traffic control costs for the recycling operation only. Cold recycling contractors are often hired as sub-contractors on projects. The cost information includes material costs, pulverization and mixing costs, and laydown and compaction costs. Mobilization and traffic control for the recycling operation are also included in the cost information.

Note that the costs associated with cold recycling operations vary by individual project. The size of the project, mobilization, material prices, quantity of materials (stabilizers), and the cost of pulverization, mixing, laydown, and compaction are all significant variables on a project. Thus, representative costs and ranges are determined and shown below. Note that the cost information is ultimately reduced to units of dollars per square yard of surface area per inch of pavement thickness ($/sq yd-inch).

Costs of interest for determining prices for these cold recycling operations include mobilization, traffic control, materials, transportation, material processing, and laydown and compaction. Assumptions associated with costs are provided below. Economic comparisons are provided based on these assumptions. Representative costs for the various materials are shown in Table B.4..

Table B.4. Representative Costs

Item	Unit	Cost (dollars)	
		Representative Value	Representative Range
Transportation	Per ton-mile	0.15	0.12 to 0.18
Virgin Binder	Per ton	425.00	400.00 to 475.00
Emulsion	Per ton	425.00	400.00 to 450.00
Emulsion (Engineered)	Per ton	450.00	425.00 to 500.00
Portland Cement	Per ton	140.00	125.00 to 175.00
Hydrated Lime	Per ton	150.00	125.00 to 200.00
Virgin Aggregate	Per ton	15.00	12.00 to 25.00
RAP	Per ton	6.00	5.00 to 8.00

ECONOMIC CONSIDERATIONS

Representative costs and representative ranges of costs for the various bid line items for cold recycling operations are shown in Table B.5. and Table B.6. for CIR process.

Table B.5. Representative Costs for CIR Operations

Item	Representative Cost, $/sq yd-in.	Representative Cost Range, $/sq yd-in.
Processing	1.25	0.75 to 2.00
Emulsion	0.55	0.45 to 0.75
Portland Cement	0.07	0.07 to 0.15
Lime	0.07	0.07 to 0.17
Mobilization	0.10	0.05 to 0.15

Table B.6. In-Place Representative Costs for CIR, $/sq yd-in.

Operation					
Processing	Emulsion	Portland Cement	Lime	Mobilization	Total
1.25 (0.75–2.00)*	0.55 (0.45–0.75)	—	—	0.10 (0.05–0.15)	1.90 (1.25–2.90)
1.25 (0.75–2.00)	0.55 (0.45–0.75)	0.07 (0.07–0.15)	—	0.10 (0.05–0.15)	1.97 (1.32–3.05)
1.25 (0.75–2.00)	0.55 (0.45–0.75)	—	0.07 (0.07–0.17)	0.10 (0.05–0.15)	1.97 (1.32–3.07)

* Representative value and range ( ).

Considering the information presented in Table B.5. and Table B.6., representative costs and representative cost ranges for in-place recycling operations are shown in Table B.7..

Table B.7. Representative Costs for Various Types of Pavement Materials, $/sq yd-in.

Operation	Representative Cost, $/sq yd-in.	Representative Cost Range, $/sq yd-in.
CIR	2.10	1.50–2.75
CCPR	2.40	1.60–3.25
HMA	4.00	3.25–4.25
Chip Seal (Surface Treatment)	2.50 (sq yd)	2.10–2.75 (sq yd)

Aggregate Base	1.20	0.90–1.50

Limited information was available on CCPR operations. The cost of process, binders, mobilization, and traffic control are nearly equal to those for in-place recycling operations. Depending on how the price of RAP is assigned to the project, a cost of $5 to $8 per ton, or about $0.25 to $0.40 sq yd-inch, can be added to the price of the in-place costs of cold recycling. An additional cost is the cost of haul. For a 10-mile haul, an additional $0.07 per sq yd-inch can be added to the in-place costs of cold recycling. These two costs will increase the cost of CCPR to about $2.30 to 2.50 per sq yd-inch.

The use of foamed binder rather than emulsion has been used in a number of locations in the United States and the world. The amount of residual binder is typically slightly lower with the use of foamed binder, and 1.0 percent Portland cement is often incorporated as an additive. Usually, traffic is allowed on the recycled pavement sooner when foamed binder is utilized instead of emulsion. An assumption is made that the cost of CIR with emulsion and foamed binder are approximately the same.

ECONOMIC SCENARIOS

The scenarios shown below are to illustrate typical cost ranges. Costs should always be determined on a project basis with local materials and contractors. For the examples shown below, a traffic volume of 500,000 ESALs over a 20-year design period was assumed (about 30 legally loaded, 18-wheel trucks per day) together with a subgrade with moderate to low supporting capability. According to the AASHTO pavement design method, the pavement requires a Structural Number of about 3.0. Layer coefficients for different cold recycled materials were assumed based on a general knowledge. Note that changes in the structural coefficients will have a significant effect on the structural section requirements and cost estimates. Structural layer coefficients should be adjusted depending on local experience.

Information has been developed for new construction and rehabilitation/maintenance alternatives for three typical existing roadway structures. Costs are based on representative costs shown on Table B.7.. The representative ranges in costs should be considered to determine the cost sensitivity of the various pavement sections.

New Construction

The costs of new pavement sections are shown in Table B.8.. The cost of removal of the existing pavement was not included. The cost of removal of the existing pavement is about $0.40 to $ 0.50 per sq yd-inch. If a 20-mile haul is assumed for transportation of the removed material, an additional cost of about $0.15 per ton-mile of haul is incurred. The cost of reworking the subgrade is about $0.50 to $0.60 per sq yd of surface area. Thus, the cost of removal and reworking of the existing pavement will be on the order of $4.00 to $5.50 per sq yd of surface area for 6- and 8-inch pavement removals.

The estimated costs per sq yd for removal and replacement is $30 to $35 per sq yd of pavement surface depending on what materials are used for the structural section. If traffic volumes are less and the subgrade strength is higher, the structural section can be reduced.

Table B.8. provides three new pavement section alternatives:

A. Conventional pavement-aggregate base and HMA surface.

B. CCPR with chip seal.
C. Full-depth HMA pavement.

The use of CCPR offers potential cost savings of approximately 18 percent.

Table B.8. New Pavement Construction Representative Costs

Alternative	Layer	Description	AASHTO Coefficient	Thickness (in.)	Costs ($/sq yd-in.)	Costs ($/sq yd)
A	1	HMA	0.44	3.5	4.00	14.00
	2	Aggregate Base	0.12	12	1.20	14.40
	subtotal					**28.40**
B	1	Chip Seal	0.00	1/2	2.50	2.50
	2	CCPR	0.35	8.5	2.40	20.40
	subtotal					**22.90**
C	1	HMA	0.44	7	4.00	28.00
	subtotal					**28.00**

Rehabilitation—Scenario 1

Two rehabilitation scenarios are discussed below. Existing roadways are described, and various rehabilitation/maintenance alternatives are provided. Recall that many cold recycling projects are associated with lower traffic volume roadways. The three scenarios are based on low volume roads.

Scenario 1 involves the repair of an existing roadway that is unsurfaced and has a 6-inch aggregate base. Traffic has been using the unsurfaced roadway for a number of years. The traffic volume has increased, and the dusting due to traffic has become a more serious problem. The repair strategies provide for both strengthening of the roadway and the placement of an all-weather/dust-free surface.

For Scenario 1 (Table B9), Alternative A applies 6 inches of additional aggregate base (either on top of the existing base or mixed with the existing base), plus CCPR and a chip seal. Alternative B retains the existing aggregate base and adds HMA as the surfacing material. Recycling options are economical. This is a conventional HMA overlay alternative.

Table B.9. Rehabilitation Scenario 1 Representative Costs

Alternative	Layer	Description	AASHTO Coefficient	Thickness (in.)	Costs ($/sq yd-in.)	Costs ($/sq yd)
A	1	Chip Seal	0.00	1/2	2.50	2.50
	2	CCPR	0.35	5	2.40	12.00
	3	Aggregate base	0.12	6	1.20	7.20
	4	Existing aggregate base	0.10	6	0.00	
	subtotal					**21.70**
B	1	HMA	0.44	5.5	4.00	22.00
	2	Existing aggregate base	0.10	6	0.00	0.00
	Subtotal					**22.00**

Rehabilitation—Scenario 2

Scenario 2 involves the repair of an existing roadway that has a surface of 4 inches of asphalt-bound materials (chips seals and/or hot-mix and/or cold-mix build-up over the years) on top of 6 inches of aggregate base. The asphalt surface has numerous types of distress and needs repair. In addition, the traffic volume is forecast to increase over the next 20 years.

For Scenario 2 (Table B10), Alternative A uses the CIR process to recycle the top 3 inches of the existing pavement and places a 3-inch HMA layer as the surface. Alternative B is a typical HMA overlay placed to a depth of 3.75 inches. The existing pavement remains in place without major repair prior to overlay. The life of this pavement may be less than predicted from a pavement structural design standpoint.

Table B.10. Rehabilitation Scenario 2 Representative Costs

Alternative	Layer	Description	AASHTO Coefficient	Thickness (in.)	Costs ($/sq yd-in.)	Costs ($/sq yd)
A	1	HMA	0.44	3	4.00	12.00
	2	CIR	0.35	3	2.10	6.30
	3	Existing aggregate base	0.10	7	0.00	0.00
	Subtotal					**18.30**
B	1	HMA	0.44	3.75	4.00	15.00
	2	Existing HMA	0.20	4.00	0.00	0.00
	3	Existing aggregate base	0.10	6.00	0.00	0.00
	Subtotal					**15.00**

SUMMARY

Cost information from the contracting community and a state DOT official was obtained and summarized. Representative costs and representative ranges of costs for several construction materials and construction operations for cold recycling operations were listed. As noted, these costs vary over a large range due to a number of variables.

First-cost economics were summarized for pavement rehabilitation alternatives for low traffic volume roadways. These first-cost alternatives were based on providing pavement structural sections of equal traffic-carrying capability based on the AASHTO design method. This design method does not precisely consider the pavement performance, which can be affected by a number of factors, including the condition of the existing pavement, reflection cracking, and load-carrying ability of materials. Pavement alternative sections provided for each of the economic scenarios may not achieve the same pavement performance life.

Table B.11. provides first-cost comparison among pavement cold recycling options utilizing either existing HMA in the pavement as RAP or using RAP in CCPR operations.

Table B.11. First-Cost Comparison for Pavement Recycling Alternatives

Alternative	Remove/Replace, $/sq yd	Recycle Mixture with Chip Seal or HMA Surface, $/sq yd
New Construction	30–35	23–28
Rehabilitation Scenario 1	30–35	22
Rehabilitation Scenario 2	30–35	15–18

Based on the information shown in Table B.11., economic savings on the order of about 20 to 50 percent are possible when cold recycling is compared with removal and replacement of pavement. Recall that these are first-cost savings based on equivalent structural pavement sections. Under these assumptions, the proposed recycling alternatives are cost competitive.

APPENDIX C.
AGGREGATE AND RAP GRADATIONS

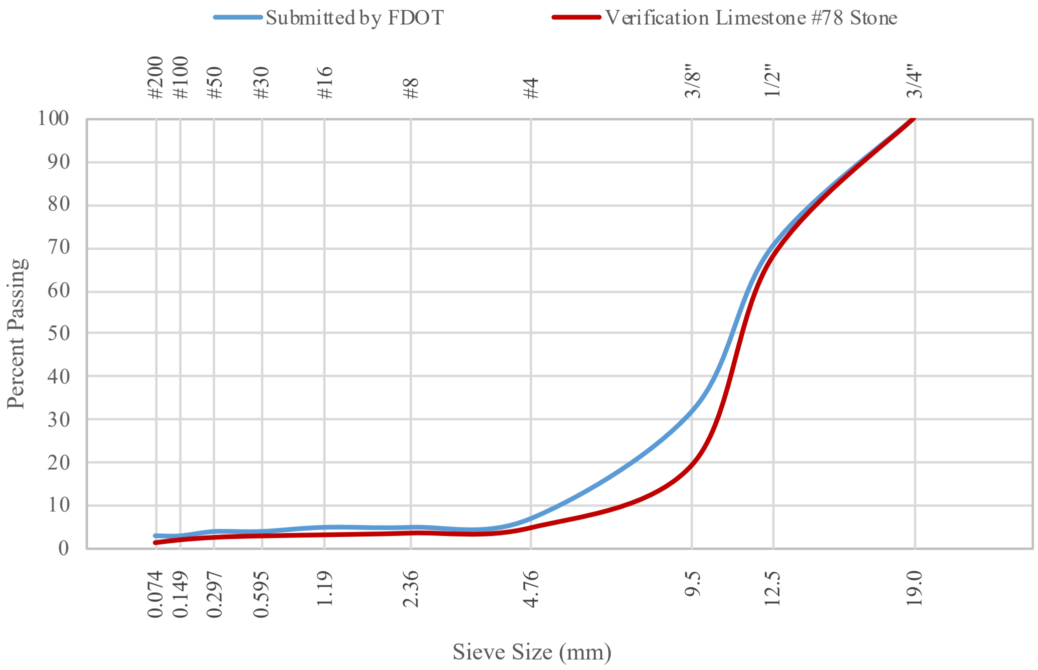


Figure C.1. Gradation Curve, #78 Stone of Limestone

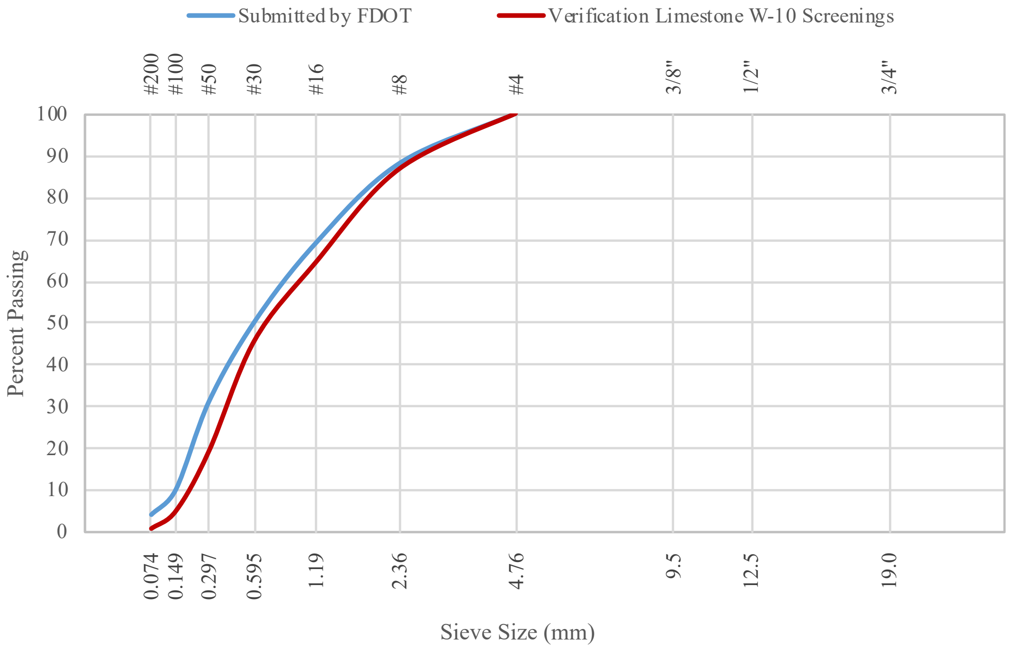


Figure C.2. Gradation Curve, W-10 Screenings of Limestone

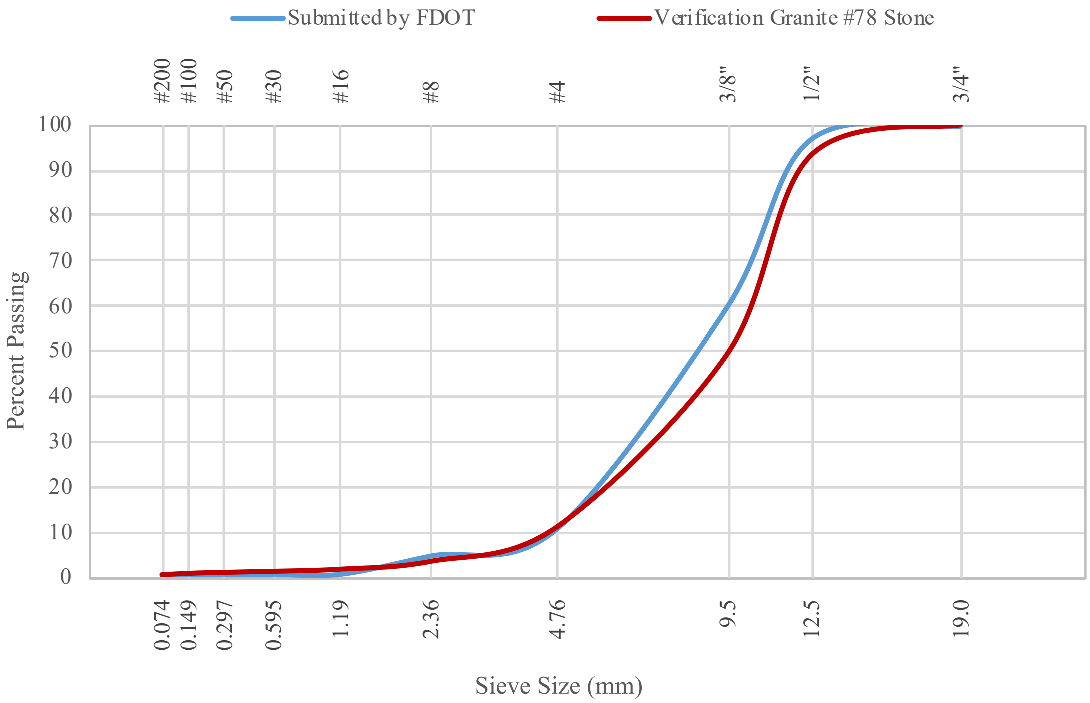


Figure C.3. Gradation Curve, #78 Stone of Granite

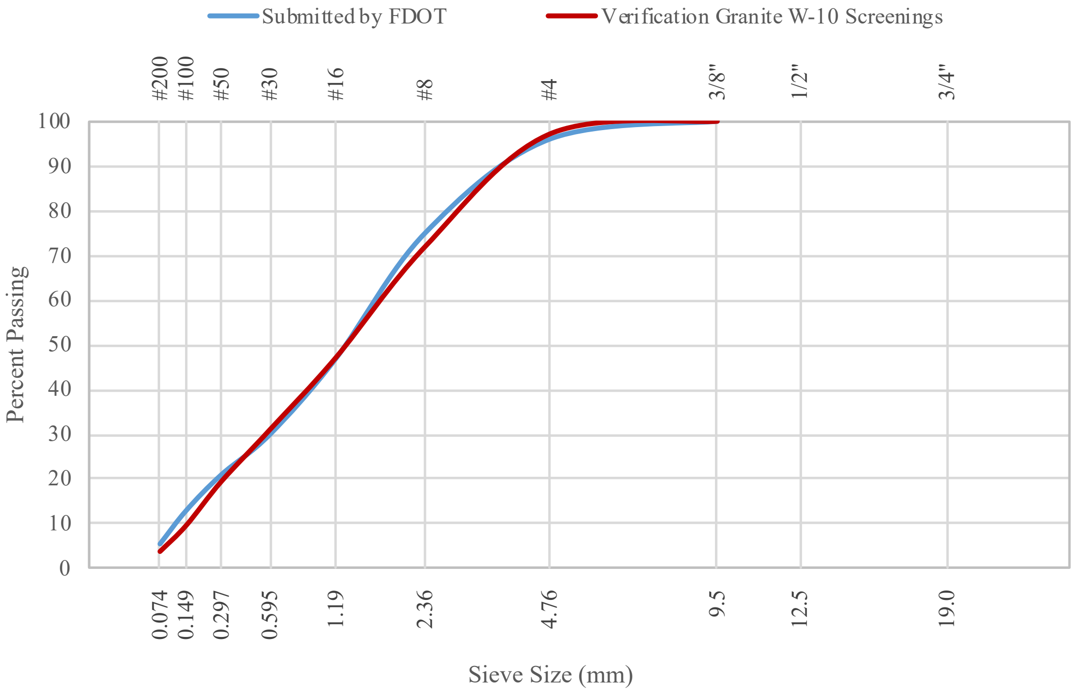


Figure C.4. Gradation Curve, W-10 Screenings of Granite

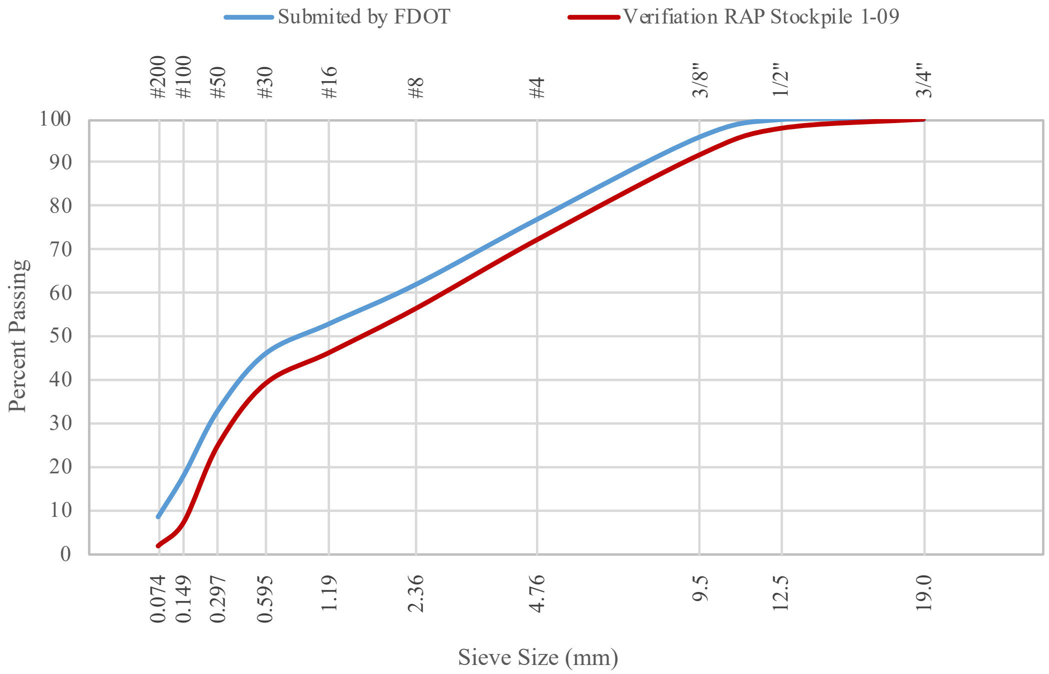


Figure C.5. Gradation Curve after Ignition Oven, RAP Stockpile 1-09 Limestone

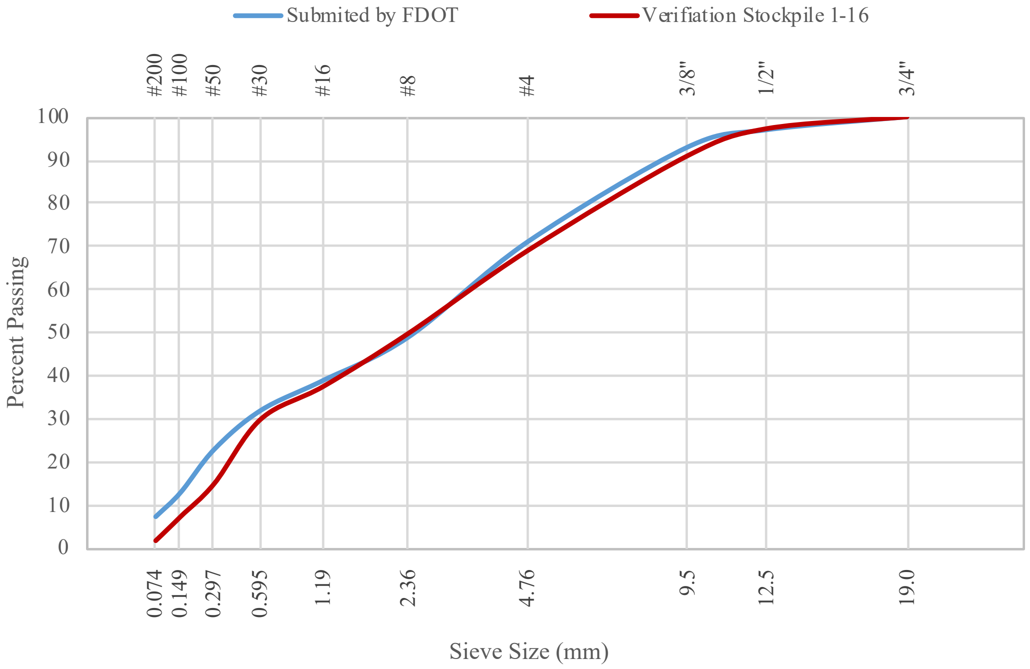


Figure C.6. Gradation Curve after Ignition Oven, RAP Stockpile 1-16 Granite/Limestone

APPENDIX D.
AGGREGATE PROPERTIES

Table D.1. Specific Gravity, #78 Stone Limestone

Geographic District	Managing District	Mine	Terminal	Facility Type	Product	Process	Description	Depleted?	Gsb
DISTRICT 6	DISTRICT 6	87339		Mine	C41	1	S1A Stone		2.775
DISTRICT 6	DISTRICT 6	87339	TM 427	Terminal	C41	1	S1A Stone		2.775

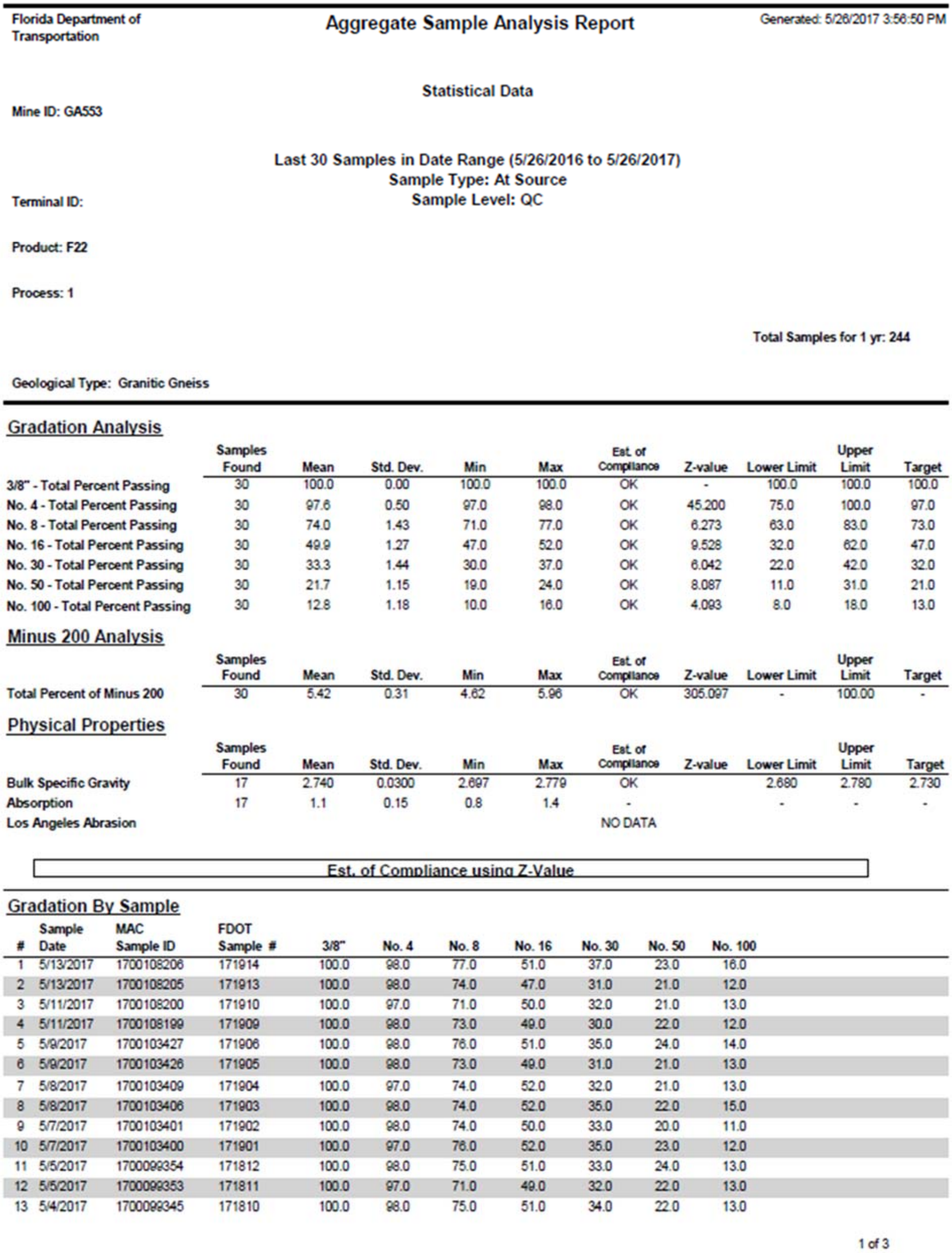
Note: Data provided by FDOT on June 5, 2017.

Table D.2. Specific Gravity, #78 Stone Granite

Geographic District	Managing District	Mine	Terminal	Facility Type	Product	Process	Description	Depleted?	Gsb
DISTRICT 2	DISTRICT 2	GA553	TM561	Terminal	C47	1	S1A Stone		2.775
DISTRICT 2	DISTRICT 2	GA553	TM759	Terminal	C47	1	S1A Stone		2.775

Note: Data provided by FDOT on June 5, 2017.

Table D.3. Aggregate Sample Analysis Report: Granite W-10 Screenings



Florida Department of
Transportation

Aggregate Sample Analysis Report

Generated: 5/26/2017 3:56:50 PM

Statistical Data

Mine ID: GA553

Last 30 Samples in Date Range (5/26/2016 to 5/26/2017)
Sample Type: At Source
Sample Level: QC

Terminal ID:

Product: F22

Process: 1

Total Samples for 1 yr: 244

Geological Type: Granitic Gneiss

Gradation Analysis

	Samples Found	Mean	Std. Dev.	Min	Max	Est. of Compliance	Z-value	Lower Limit	Upper Limit	Target
3/8" - Total Percent Passing	30	100.0	0.00	100.0	100.0	OK	-	100.0	100.0	100.0
No. 4 - Total Percent Passing	30	97.6	0.50	97.0	98.0	OK	45.200	75.0	100.0	97.0
No. 8 - Total Percent Passing	30	74.0	1.43	71.0	77.0	OK	6.273	63.0	83.0	73.0
No. 16 - Total Percent Passing	30	49.9	1.27	47.0	52.0	OK	9.528	32.0	62.0	47.0
No. 30 - Total Percent Passing	30	33.3	1.44	30.0	37.0	OK	6.042	22.0	42.0	32.0
No. 50 - Total Percent Passing	30	21.7	1.15	19.0	24.0	OK	8.087	11.0	31.0	21.0
No. 100 - Total Percent Passing	30	12.8	1.18	10.0	16.0	OK	4.093	8.0	18.0	13.0

Minus 200 Analysis

	Samples Found	Mean	Std. Dev.	Min	Max	Est. of Compliance	Z-value	Lower Limit	Upper Limit	Target
Total Percent of Minus 200	30	5.42	0.31	4.62	5.96	OK	305.097	-	100.00	-

Physical Properties

	Samples Found	Mean	Std. Dev.	Min	Max	Est. of Compliance	Z-value	Lower Limit	Upper Limit	Target
Bulk Specific Gravity	17	2.740	0.0300	2.697	2.779	OK		2.680	2.780	2.730
Absorption	17	1.1	0.15	0.8	1.4	-		-	-	-
Los Angeles Abrasion						NO DATA				

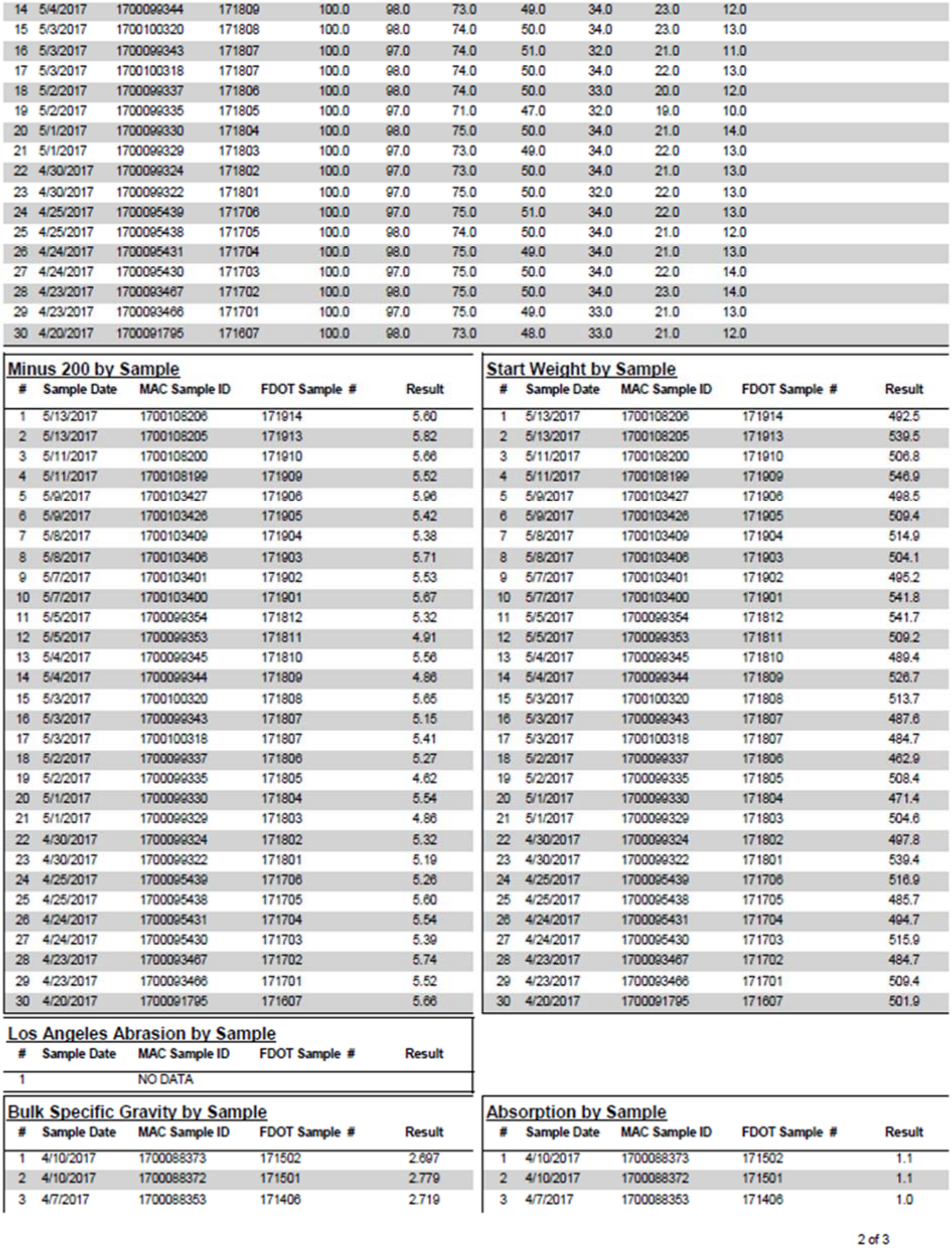
Est. of Compliance using Z-Value

Gradation By Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100
1	5/13/2017	1700108206	171914	100.0	98.0	77.0	51.0	37.0	23.0	16.0
2	5/13/2017	1700108205	171913	100.0	98.0	74.0	47.0	31.0	21.0	12.0
3	5/11/2017	1700108200	171910	100.0	97.0	71.0	50.0	32.0	21.0	13.0
4	5/11/2017	1700108199	171909	100.0	98.0	73.0	49.0	30.0	22.0	12.0
5	5/9/2017	1700103427	171906	100.0	98.0	76.0	51.0	35.0	24.0	14.0
6	5/9/2017	1700103426	171905	100.0	98.0	73.0	49.0	31.0	21.0	13.0
7	5/8/2017	1700103409	171904	100.0	97.0	74.0	52.0	32.0	21.0	13.0
8	5/8/2017	1700103406	171903	100.0	98.0	74.0	52.0	35.0	22.0	15.0
9	5/7/2017	1700103401	171902	100.0	98.0	74.0	50.0	33.0	20.0	11.0
10	5/7/2017	1700103400	171901	100.0	97.0	76.0	52.0	35.0	23.0	12.0
11	5/5/2017	1700099354	171812	100.0	98.0	75.0	51.0	33.0	24.0	13.0
12	5/5/2017	1700099353	171811	100.0	97.0	71.0	49.0	32.0	22.0	13.0
13	5/4/2017	1700099345	171810	100.0	98.0	75.0	51.0	34.0	22.0	13.0

1 of 3

Table D.3 (Continued). Aggregate Sample Analysis Report: Granite W-10 Screenings



14	5/4/2017	1700099344	171809	100.0	98.0	73.0	49.0	34.0	23.0	12.0
15	5/3/2017	1700100320	171808	100.0	98.0	74.0	50.0	34.0	23.0	13.0
16	5/3/2017	1700099343	171807	100.0	97.0	74.0	51.0	32.0	21.0	11.0
17	5/3/2017	1700100318	171807	100.0	98.0	74.0	50.0	34.0	22.0	13.0
18	5/2/2017	1700099337	171806	100.0	98.0	74.0	50.0	33.0	20.0	12.0
19	5/2/2017	1700099335	171805	100.0	97.0	71.0	47.0	32.0	19.0	10.0
20	5/1/2017	1700099330	171804	100.0	98.0	75.0	50.0	34.0	21.0	14.0
21	5/1/2017	1700099329	171803	100.0	97.0	73.0	49.0	34.0	22.0	13.0
22	4/30/2017	1700099324	171802	100.0	97.0	73.0	50.0	34.0	21.0	13.0
23	4/30/2017	1700099322	171801	100.0	97.0	75.0	50.0	32.0	22.0	13.0
24	4/25/2017	1700095439	171706	100.0	97.0	75.0	51.0	34.0	22.0	13.0
25	4/25/2017	1700095438	171705	100.0	98.0	74.0	50.0	34.0	21.0	12.0
26	4/24/2017	1700095431	171704	100.0	98.0	75.0	49.0	34.0	21.0	13.0
27	4/24/2017	1700095430	171703	100.0	97.0	75.0	50.0	34.0	22.0	14.0
28	4/23/2017	1700093467	171702	100.0	98.0	75.0	50.0	34.0	23.0	14.0
29	4/23/2017	1700093466	171701	100.0	97.0	75.0	49.0	33.0	21.0	13.0
30	4/20/2017	1700091795	171607	100.0	98.0	73.0	48.0	33.0	21.0	12.0

Minus 200 by Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	Result
1	5/13/2017	1700108206	171914	5.60
2	5/13/2017	1700108205	171913	5.82
3	5/11/2017	1700108200	171910	5.66
4	5/11/2017	1700108199	171909	5.52
5	5/9/2017	1700103427	171906	5.96
6	5/9/2017	1700103426	171905	5.42
7	5/8/2017	1700103409	171904	5.38
8	5/8/2017	1700103406	171903	5.71
9	5/7/2017	1700103401	171902	5.53
10	5/7/2017	1700103400	171901	5.67
11	5/5/2017	1700099354	171812	5.32
12	5/5/2017	1700099353	171811	4.91
13	5/4/2017	1700099345	171810	5.56
14	5/4/2017	1700099344	171809	4.86
15	5/3/2017	1700100320	171808	5.65
16	5/3/2017	1700099343	171807	5.15
17	5/3/2017	1700100318	171807	5.41
18	5/2/2017	1700099337	171806	5.27
19	5/2/2017	1700099335	171805	4.62
20	5/1/2017	1700099330	171804	5.54
21	5/1/2017	1700099329	171803	4.86
22	4/30/2017	1700099324	171802	5.32
23	4/30/2017	1700099322	171801	5.19
24	4/25/2017	1700095439	171706	5.26
25	4/25/2017	1700095438	171705	5.60
26	4/24/2017	1700095431	171704	5.54
27	4/24/2017	1700095430	171703	5.39
28	4/23/2017	1700093467	171702	5.74
29	4/23/2017	1700093466	171701	5.52
30	4/20/2017	1700091795	171607	5.66

Start Weight by Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	Result
1	5/13/2017	1700108206	171914	492.5
2	5/13/2017	1700108205	171913	539.5
3	5/11/2017	1700108200	171910	506.8
4	5/11/2017	1700108199	171909	546.9
5	5/9/2017	1700103427	171906	498.5
6	5/9/2017	1700103426	171905	509.4
7	5/8/2017	1700103409	171904	514.9
8	5/8/2017	1700103406	171903	504.1
9	5/7/2017	1700103401	171902	495.2
10	5/7/2017	1700103400	171901	541.8
11	5/5/2017	1700099354	171812	541.7
12	5/5/2017	1700099353	171811	509.2
13	5/4/2017	1700099345	171810	489.4
14	5/4/2017	1700099344	171809	526.7
15	5/3/2017	1700100320	171808	513.7
16	5/3/2017	1700099343	171807	487.6
17	5/3/2017	1700100318	171807	484.7
18	5/2/2017	1700099337	171806	462.9
19	5/2/2017	1700099335	171805	508.4
20	5/1/2017	1700099330	171804	471.4
21	5/1/2017	1700099329	171803	504.6
22	4/30/2017	1700099324	171802	497.8
23	4/30/2017	1700099322	171801	539.4
24	4/25/2017	1700095439	171706	516.9
25	4/25/2017	1700095438	171705	485.7
26	4/24/2017	1700095431	171704	494.7
27	4/24/2017	1700095430	171703	515.9
28	4/23/2017	1700093467	171702	484.7
29	4/23/2017	1700093466	171701	509.4
30	4/20/2017	1700091795	171607	501.9

Los Angeles Abrasion by Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	Result
1		NO DATA		

Bulk Specific Gravity by Sample

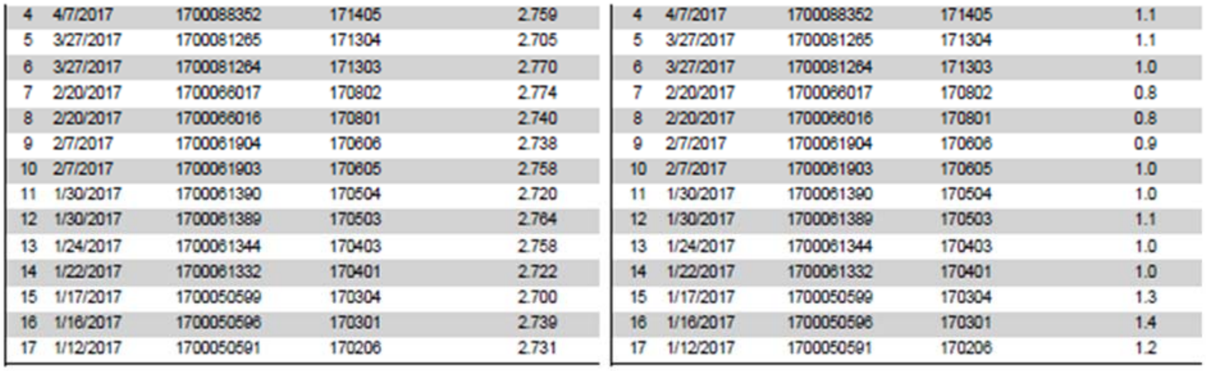
#	Sample Date	MAC Sample ID	FDOT Sample #	Result
1	4/10/2017	1700088373	171502	2.697
2	4/10/2017	1700088372	171501	2.779
3	4/7/2017	1700088353	171406	2.719

Absorption by Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	Result
1	4/10/2017	1700088373	171502	1.1
2	4/10/2017	1700088372	171501	1.1
3	4/7/2017	1700088353	171406	1.0

2 of 3

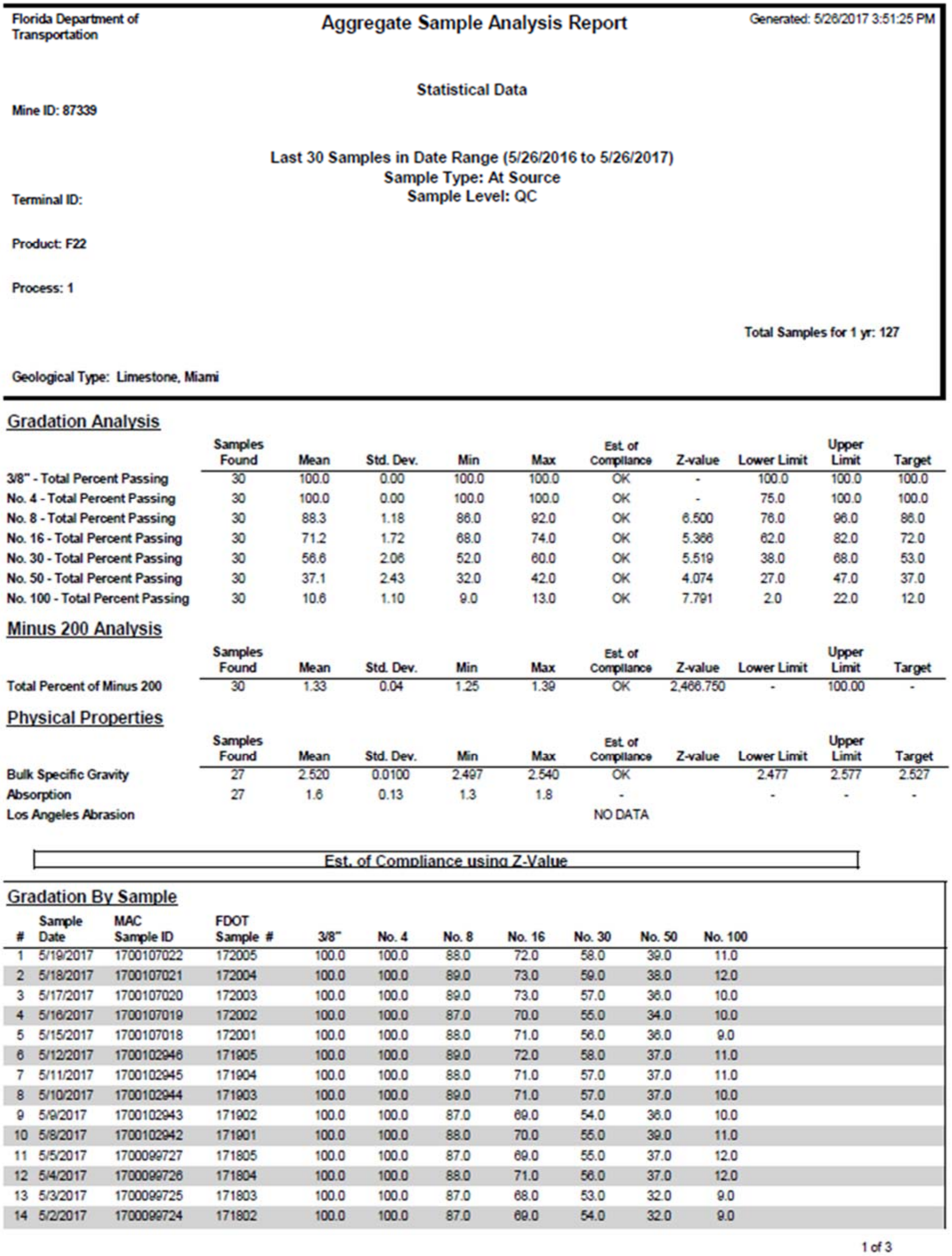
Table D.3 (Continued). Aggregate Sample Analysis Report: Granite W-10 Screenings



4	4/7/2017	1700088352	171405	2.759
5	3/27/2017	1700081265	171304	2.705
6	3/27/2017	1700081264	171303	2.770
7	2/20/2017	1700066017	170802	2.774
8	2/20/2017	1700066016	170801	2.740
9	2/7/2017	1700061904	170606	2.738
10	2/7/2017	1700061903	170605	2.758
11	1/30/2017	1700061390	170504	2.720
12	1/30/2017	1700061389	170503	2.764
13	1/24/2017	1700061344	170403	2.758
14	1/22/2017	1700061332	170401	2.722
15	1/17/2017	1700050599	170304	2.700
16	1/16/2017	1700050596	170301	2.739
17	1/12/2017	1700050591	170206	2.731

4	4/7/2017	1700088352	171405	1.1
5	3/27/2017	1700081265	171304	1.1
6	3/27/2017	1700081264	171303	1.0
7	2/20/2017	1700066017	170802	0.8
8	2/20/2017	1700066016	170801	0.8
9	2/7/2017	1700061904	170606	0.9
10	2/7/2017	1700061903	170605	1.0
11	1/30/2017	1700061390	170504	1.0
12	1/30/2017	1700061389	170503	1.1
13	1/24/2017	1700061344	170403	1.0
14	1/22/2017	1700061332	170401	1.0
15	1/17/2017	1700050599	170304	1.3
16	1/16/2017	1700050596	170301	1.4
17	1/12/2017	1700050591	170206	1.2

Table D.4. Aggregate Sample Analysis Report: Limestone W-10 Screenings



Florida Department of Transportation

Aggregate Sample Analysis Report

Generated: 5/26/2017 3:51:25 PM

Statistical Data

Mine ID: 87339

Last 30 Samples in Date Range (5/26/2016 to 5/26/2017)
Sample Type: At Source
Sample Level: QC

Terminal ID:

Product: F22

Process: 1

Total Samples for 1 yr: 127

Geological Type: Limestone, Miami

Gradation Analysis

	Samples Found	Mean	Std. Dev.	Min	Max	Est. of Compliance	Z-value	Lower Limit	Upper Limit	Target
3/8" - Total Percent Passing	30	100.0	0.00	100.0	100.0	OK	-	100.0	100.0	100.0
No. 4 - Total Percent Passing	30	100.0	0.00	100.0	100.0	OK	-	75.0	100.0	100.0
No. 8 - Total Percent Passing	30	88.3	1.18	86.0	92.0	OK	6.500	76.0	96.0	86.0
No. 16 - Total Percent Passing	30	71.2	1.72	68.0	74.0	OK	5.366	62.0	82.0	72.0
No. 30 - Total Percent Passing	30	56.6	2.06	52.0	60.0	OK	5.519	38.0	68.0	53.0
No. 50 - Total Percent Passing	30	37.1	2.43	32.0	42.0	OK	4.074	27.0	47.0	37.0
No. 100 - Total Percent Passing	30	10.6	1.10	9.0	13.0	OK	7.791	2.0	22.0	12.0

Minus 200 Analysis

	Samples Found	Mean	Std. Dev.	Min	Max	Est. of Compliance	Z-value	Lower Limit	Upper Limit	Target
Total Percent of Minus 200	30	1.33	0.04	1.25	1.39	OK	2,466.750	-	100.00	-

Physical Properties

	Samples Found	Mean	Std. Dev.	Min	Max	Est. of Compliance	Z-value	Lower Limit	Upper Limit	Target
Bulk Specific Gravity	27	2.520	0.0100	2.497	2.540	OK		2.477	2.577	2.527
Absorption	27	1.6	0.13	1.3	1.8	-		-	-	-
Los Angeles Abrasion						NO DATA				

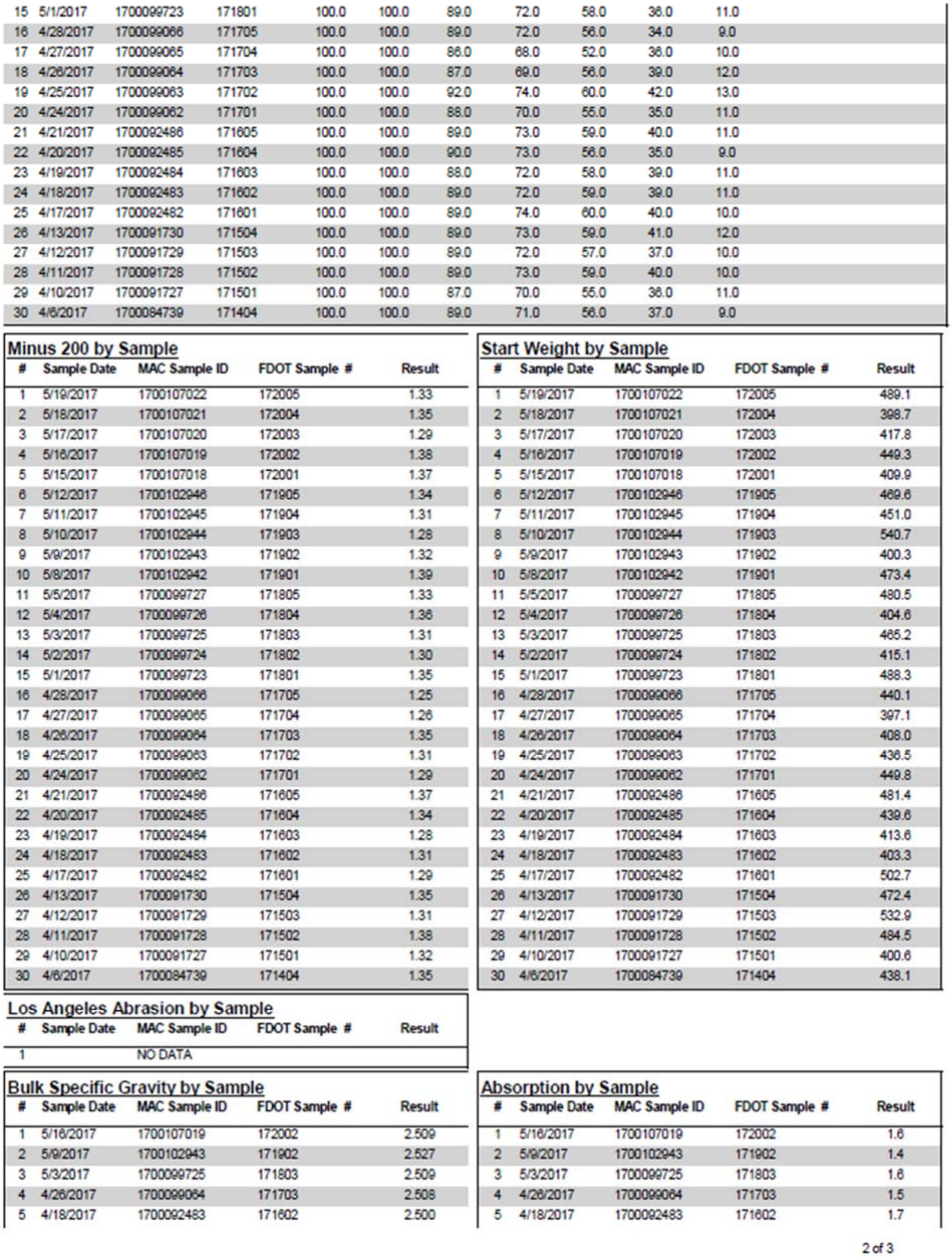
Est. of Compliance using Z-Value

Gradation By Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	3/8"	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100
1	5/19/2017	1700107022	172005	100.0	100.0	88.0	72.0	58.0	39.0	11.0
2	5/18/2017	1700107021	172004	100.0	100.0	89.0	73.0	59.0	38.0	12.0
3	5/17/2017	1700107020	172003	100.0	100.0	89.0	73.0	57.0	36.0	10.0
4	5/16/2017	1700107019	172002	100.0	100.0	87.0	70.0	55.0	34.0	10.0
5	5/15/2017	1700107018	172001	100.0	100.0	88.0	71.0	56.0	36.0	9.0
6	5/12/2017	1700102946	171905	100.0	100.0	89.0	72.0	58.0	37.0	11.0
7	5/11/2017	1700102945	171904	100.0	100.0	88.0	71.0	57.0	37.0	11.0
8	5/10/2017	1700102944	171903	100.0	100.0	89.0	71.0	57.0	37.0	10.0
9	5/9/2017	1700102943	171902	100.0	100.0	87.0	69.0	54.0	36.0	10.0
10	5/8/2017	1700102942	171901	100.0	100.0	88.0	70.0	55.0	39.0	11.0
11	5/5/2017	1700099727	171805	100.0	100.0	87.0	69.0	55.0	37.0	12.0
12	5/4/2017	1700099726	171804	100.0	100.0	88.0	71.0	56.0	37.0	12.0
13	5/3/2017	1700099725	171803	100.0	100.0	87.0	68.0	53.0	32.0	9.0
14	5/2/2017	1700099724	171802	100.0	100.0	87.0	69.0	54.0	32.0	9.0

1 of 3

Table D.4 (Continued). Aggregate Sample Analysis Report: Limestone W-10 Screenings



15	5/1/2017	1700099723	171801	100.0	100.0	89.0	72.0	58.0	36.0	11.0
16	4/28/2017	1700099066	171705	100.0	100.0	89.0	72.0	56.0	34.0	9.0
17	4/27/2017	1700099065	171704	100.0	100.0	86.0	68.0	52.0	36.0	10.0
18	4/26/2017	1700099064	171703	100.0	100.0	87.0	69.0	56.0	39.0	12.0
19	4/25/2017	1700099063	171702	100.0	100.0	92.0	74.0	60.0	42.0	13.0
20	4/24/2017	1700099062	171701	100.0	100.0	88.0	70.0	55.0	35.0	11.0
21	4/21/2017	1700092486	171605	100.0	100.0	89.0	73.0	59.0	40.0	11.0
22	4/20/2017	1700092485	171604	100.0	100.0	90.0	73.0	56.0	35.0	9.0
23	4/19/2017	1700092484	171603	100.0	100.0	88.0	72.0	58.0	39.0	11.0
24	4/18/2017	1700092483	171602	100.0	100.0	89.0	72.0	59.0	39.0	11.0
25	4/17/2017	1700092482	171601	100.0	100.0	89.0	74.0	60.0	40.0	10.0
26	4/13/2017	1700091730	171504	100.0	100.0	89.0	73.0	59.0	41.0	12.0
27	4/12/2017	1700091729	171503	100.0	100.0	89.0	72.0	57.0	37.0	10.0
28	4/11/2017	1700091728	171502	100.0	100.0	89.0	73.0	59.0	40.0	10.0
29	4/10/2017	1700091727	171501	100.0	100.0	87.0	70.0	55.0	36.0	11.0
30	4/6/2017	1700084739	171404	100.0	100.0	89.0	71.0	56.0	37.0	9.0

Minus 200 by Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	Result
1	5/19/2017	1700107022	172005	1.33
2	5/18/2017	1700107021	172004	1.35
3	5/17/2017	1700107020	172003	1.29
4	5/16/2017	1700107019	172002	1.38
5	5/15/2017	1700107018	172001	1.37
6	5/12/2017	1700102946	171905	1.34
7	5/11/2017	1700102945	171904	1.31
8	5/10/2017	1700102944	171903	1.28
9	5/9/2017	1700102943	171902	1.32
10	5/8/2017	1700102942	171901	1.39
11	5/5/2017	1700099727	171805	1.33
12	5/4/2017	1700099726	171804	1.36
13	5/3/2017	1700099725	171803	1.31
14	5/2/2017	1700099724	171802	1.30
15	5/1/2017	1700099723	171801	1.35
16	4/28/2017	1700099066	171705	1.25
17	4/27/2017	1700099065	171704	1.26
18	4/26/2017	1700099064	171703	1.35
19	4/25/2017	1700099063	171702	1.31
20	4/24/2017	1700099062	171701	1.29
21	4/21/2017	1700092486	171605	1.37
22	4/20/2017	1700092485	171604	1.34
23	4/19/2017	1700092484	171603	1.28
24	4/18/2017	1700092483	171602	1.31
25	4/17/2017	1700092482	171601	1.29
26	4/13/2017	1700091730	171504	1.35
27	4/12/2017	1700091729	171503	1.31
28	4/11/2017	1700091728	171502	1.38
29	4/10/2017	1700091727	171501	1.32
30	4/6/2017	1700084739	171404	1.35

Start Weight by Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	Result
1	5/19/2017	1700107022	172005	489.1
2	5/18/2017	1700107021	172004	398.7
3	5/17/2017	1700107020	172003	417.8
4	5/16/2017	1700107019	172002	449.3
5	5/15/2017	1700107018	172001	409.9
6	5/12/2017	1700102946	171905	469.6
7	5/11/2017	1700102945	171904	451.0
8	5/10/2017	1700102944	171903	540.7
9	5/9/2017	1700102943	171902	400.3
10	5/8/2017	1700102942	171901	473.4
11	5/5/2017	1700099727	171805	480.5
12	5/4/2017	1700099726	171804	404.6
13	5/3/2017	1700099725	171803	465.2
14	5/2/2017	1700099724	171802	415.1
15	5/1/2017	1700099723	171801	488.3
16	4/28/2017	1700099066	171705	440.1
17	4/27/2017	1700099065	171704	397.1
18	4/26/2017	1700099064	171703	408.0
19	4/25/2017	1700099063	171702	436.5
20	4/24/2017	1700099062	171701	449.8
21	4/21/2017	1700092486	171605	481.4
22	4/20/2017	1700092485	171604	439.6
23	4/19/2017	1700092484	171603	413.6
24	4/18/2017	1700092483	171602	403.3
25	4/17/2017	1700092482	171601	502.7
26	4/13/2017	1700091730	171504	472.4
27	4/12/2017	1700091729	171503	532.9
28	4/11/2017	1700091728	171502	484.5
29	4/10/2017	1700091727	171501	400.6
30	4/6/2017	1700084739	171404	438.1

Los Angeles Abrasion by Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	Result
1		NO DATA		

Bulk Specific Gravity by Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	Result
1	5/16/2017	1700107019	172002	2.509
2	5/9/2017	1700102943	171902	2.527
3	5/3/2017	1700099725	171803	2.509
4	4/26/2017	1700099064	171703	2.508
5	4/18/2017	1700092483	171602	2.500

Absorption by Sample

#	Sample Date	MAC Sample ID	FDOT Sample #	Result
1	5/16/2017	1700107019	172002	1.6
2	5/9/2017	1700102943	171902	1.4
3	5/3/2017	1700099725	171803	1.6
4	4/26/2017	1700099064	171703	1.5
5	4/18/2017	1700092483	171602	1.7

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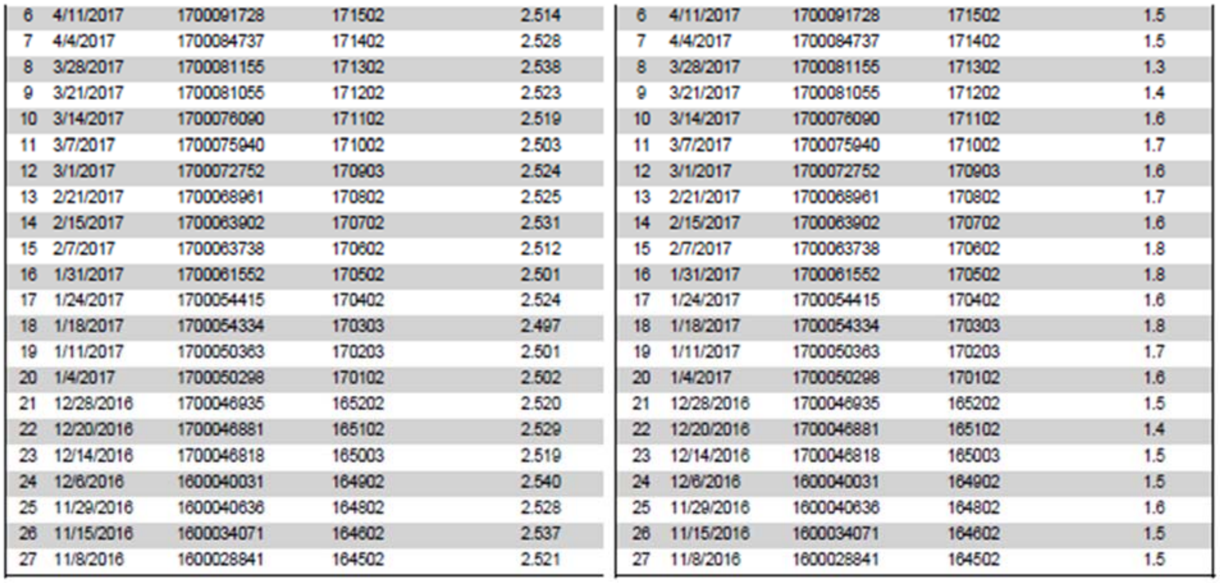
Table D.4 (Continued). Aggregate Sample Analysis Report: Limestone W-10 Screenings



6	4/11/2017	1700091728	171502	2.514
7	4/4/2017	1700084737	171402	2.528
8	3/28/2017	1700081155	171302	2.538
9	3/21/2017	1700081055	171202	2.523
10	3/14/2017	1700076090	171102	2.519
11	3/7/2017	1700075940	171002	2.503
12	3/1/2017	1700072752	170903	2.524
13	2/21/2017	1700068961	170802	2.525
14	2/15/2017	1700063902	170702	2.531
15	2/7/2017	1700063738	170602	2.512
16	1/31/2017	1700061552	170502	2.501
17	1/24/2017	1700054415	170402	2.524
18	1/18/2017	1700054334	170303	2.497
19	1/11/2017	1700050363	170203	2.501
20	1/4/2017	1700050298	170102	2.502
21	12/28/2016	1700046935	165202	2.520
22	12/20/2016	1700046881	165102	2.529
23	12/14/2016	1700046818	165003	2.519
24	12/6/2016	1600040031	164902	2.540
25	11/29/2016	1600040636	164802	2.528
26	11/15/2016	1600034071	164602	2.537
27	11/8/2016	1600028841	164502	2.521

6	4/11/2017	1700091728	171502	1.5
7	4/4/2017	1700084737	171402	1.5
8	3/28/2017	1700081155	171302	1.3
9	3/21/2017	1700081055	171202	1.4
10	3/14/2017	1700076090	171102	1.6
11	3/7/2017	1700075940	171002	1.7
12	3/1/2017	1700072752	170903	1.6
13	2/21/2017	1700068961	170802	1.7
14	2/15/2017	1700063902	170702	1.6
15	2/7/2017	1700063738	170602	1.8
16	1/31/2017	1700061552	170502	1.8
17	1/24/2017	1700054415	170402	1.6
18	1/18/2017	1700054334	170303	1.8
19	1/11/2017	1700050363	170203	1.7
20	1/4/2017	1700050298	170102	1.6
21	12/28/2016	1700046935	165202	1.5
22	12/20/2016	1700046881	165102	1.4
23	12/14/2016	1700046818	165003	1.5
24	12/6/2016	1600040031	164902	1.5
25	11/29/2016	1600040636	164802	1.6
26	11/15/2016	1600034071	164602	1.5
27	11/8/2016	1600028841	164502	1.5

APPENDIX E.
BINDER PG GRADE TEST RESULTS

Table E.1. PG 52-28 Replicate 1

Property	**PG 52-28**		
Original Properties			
Dynamic Shear			
Min. 1.0 kPa	G*/sinδ at 52°C	1.98	kPa
	G*/ sinδ at 58°C	0.86	kPa
RTFO Aged Binder			
Dynamic Shear			
Min. 2.2 kPa	G*/ sinδ at 52°C	4.84	kPa
	G*/ sinδ at 58°C	1.98	kPa
RTFO and PAV Aged Binder			
Dynamic Shear			
Max. 5000 kPa	G* sinδ at 13°C	7345	kPa
	G* sinδ at 16°C	4779	kPa
Creep Stiffness			
S. Max. 300 MPa	**Temperature**	**S (MPa)**	**m-Value (-)**
m-Value Min. 0.3	−18°C	211	0.345
	−24°C	400	0.268

Table E.2. PG 52-28 Replicate 2

Property	**PG 52-28**		
Original Properties			
Dynamic Shear			
Min. 1.0 kPa	G*/ sinδ at 52°C	1.98	kPa
	G*/ sinδ at 58°C	0.85	kPa
RTFO Aged Binder			
Dynamic Shear			
Min. 2.2 kPa	G*/ sinδ at 52°C	4.84	kPa
	G*/ sinδ at 58°C		kPa
RTFO and PAV Aged Binder			
Dynamic Shear			
Max. 5000 kPa	G* sinδ at 13°C	7234	kPa
	G* sinδ at 16°C	4701	kPa
Creep Stiffness			
S. Max. 300 MPa	**Temperature**	**S (MPa)**	**m-Value (-)**
m-Value Min. 0.3	−18°C	193	0.347
	−24°C	435	0.264

Table E.3. PG 67-22 Replicate 1

Property	PG 67-22		
Original Properties			
Dynamic Shear			
Min. 1.0 kPa	G*/sinδ at 64°C	1.82	kPa
	G*/ sinδ at 70°C	0.85	kPa
	G*/ sinδ at 68.7°C	1.00	kPa
RTFO Aged Binder			
Dynamic Shear			
Min. 2.2 kPa	G*/ sinδ at 64°C	3.93	kPa
	G*/ sinδ at 70°C	1.78	kPa
RTFO and PAV Aged Binder			
Dynamic Shear			
Max. 5000 kPa	G* sinδ at 25°C	3951	kPa
	G* sinδ at 22°C	5848	kPa
Creep Stiffness			
S. Max. 300 MPa	**Temperature**	**S (MPa)**	**m-Value (-)**
m-Value Min. 0.3	−12°C	199	0.302
	−18°C	518	0.227

Table E.4. PG 67-22 Replicate 2

Property	PG 67-22		
Original Properties			
Dynamic Shear			
Min. 1.0 kPa	G*/ sinδ at 64°C	1.83	kPa
	G*/ sinδ at 70°C	0.84	kPa
	G*/ sinδ at 68.7°C	1.00	kPa
RTFO Aged Binder			
Dynamic Shear			
Min. 2.2 kPa	G*/ sinδ at 64°C	3.98	kPa
	G*/ sinδ at 70°C	1.81	kPa
RTFO and PAV Aged Binder			
Dynamic Shear			
Max. 5000 kPa	G* sinδ at 25°C	5543	kPa
	G* sinδ at 22°C	8560	kPa
Creep Stiffness			
S. Max. 300 MPa	**Temperature**	**S (MPa)**	**m-Value (-)**
m-Value Min. 0.3	−12°C	199	0.302
	−18°C	518	0.227

APPENDIX F.
BINDER CONTENT OF RAP SOURCES

Table F.1. RAP Calibration Factors

	Limestone Mixture			Granite Mixture	
Sample	**1**	**2**	**3**	**1**	**2**
AC_{Actual} (%)	4.5%	4.5%	7.0%	4.5%	4.5%
Basket Mass (g)	3046.5	3050.7	3045.0	3043.7	3045.2
Basket + Sample Mass (g)	5348.7	5272.2	5032.5	5199.7	5372.6
Initial Sample Mass (g)	2302.2	2221.5	1987.5	2156.0	2327.4
Basket + Sample Mass (g) − After	5240.5	5166.4	4888.1	5096.7	5261.4
Final Sample Mass (g)	2194.0	2115.7	1843.1	2053.0	2216.2
Mass Loss (g)	108.2	105.8	144.4	103.0	111.2
$AC_{Measured}$ (%)	4.70%	4.76%	7.27%	4.78%	4.78%
W_L (%)	−0.20%	−0.26%	−0.27%	−0.28%	−0.28%
CF[AC]	−0.24%			−0.28%	

Table F.2. RAP Binder Content

	Stockpile 1-09: Limestone Aggregate		Stockpile 1-16: Granite/Limestone Aggregate	
Sample	**1**	**2**	**1**	**2**
Basket Mass (g)	3042.0	2850.4	2852.0	2850.5
Basket + Sample Mass (g)	5078.5	5999.9	5347.3	6060.1
Initial Sample Mass (g)	2036.5	3149.5	2495.3	3209.6
Basket + Sample Mass (g) - After	4963.5	5825.6	5222.2	5897.5
Final Sample Mass (g)	1921.5	2975.2	2370.2	3047.0
Mass Loss (g)	115.0	174.3	125.1	162.6
$AC_{Measured}$ (%)	5.65%	5.53%	5.01%	5.07%
CF[AC]	−0.24%		−0.28%	
$AC_{Calibrated}$ (%)	5.40%	5.29%	4.74%	4.79%
Average $AC_{Calibrated}$ (%)	5.35%		4.76%	

APPENDIX G.
RBR ESTIMATION

$$RBR = \frac{RAP_{Content} * RAP_{Binder\ Content}}{OBC}$$ Equation G.1

Table G.1. Limestone + RAP Mixture

MIX	
Virgin Aggregate	Limestone (C-41)

RAP	
RAP Source	STK 09 Limestone RAP
RAP Content of The Mix (%)	60
Binder Content of RAP (%)	5.4

Virgin Binder	
Binder	PG 52-28
OBC (%)	6.8

$$RBR = \frac{60.0\% * 5.4\%}{6.8\%} = 0.48$$ Equation G.2

Table G.2. Granite + RAP Mixture

MIX	
Virgin Aggregate	Granite (C-47)

RAP	
RAP Source	STK 16 Granite/limestone RAP
RAP Content of The Mix (%)	60
Binder Content of RAP (%)	4.8

Virgin Binder	
Binder	PG 52-28
OBC (%)	6

$$RBR = \frac{60.0\% * 4.8\%}{6.0\%} = 0.48$$ Equation G.3

APPENDIX H.
RECYCLING AGENT SELECTION TEST RESULTS

Table H.1. Rheological Characterization of RAP Stockpile 1-09

RAP	Recycling Agent	Recycling Agent Dose (%)	High Temperature PG						PGH Change %
			Unaged			RTFO + PAV40			
			Rep. 1	Rep. 2	Average	Rep. 1	Rep. 2	Average	
Stockpile 1-09	O1	5.1	65.4	64.5	64.95	83.6	83.9	83.75	28.95
	O2		65.7	65.8	65.75	82.2	82.3	82.25	25.10
	P1		70.5	70.3	70.40	85.8	85.8	85.80	21.88
	P2		70	69.8	69.90	85.9	85.8	85.85	22.82

Table H.2. Rheological Characterization of RAP Stockpile 1-16

RAP	Recycling Agent	Recycling Agent Dose (%)	High Temperature PG						PGH Change %
			Original			RTFO + PAV40			
			Rep. 1	Rep. 2	Average	Rep. 1	Rep. 2	Average	
Stockpile 1-16	O1	5.9	67.6	67.7	67.65	83.6	83.4	83.50	23.43
	O2		67.5	67.5	67.50	85.2	85.3	85.25	26.30
	P1		72.3	72.1	72.20	89.3	89.1	89.20	23.55
	P2		71.7	71.8	71.75	88.4	88.1	88.25	23.00

Table H.3. Chemical Characterization of RAP Stockpile 1-09

Recycling Agent	RAP	CA (-)								CA Change%
		Unaged				RTFO + PAV40				
		Rep. 1	Rep. 2	Rep. 3	Average	Rep. 1	Rep. 2	Rep. 3	Average	
O1	Stockpile 1-09	1.63	1.51	1.52	1.55	2.19	2.20	2.08	2.16	39.0
O2		1.63	1.67	1.61	1.64	2.20	2.16	2.20	2.19	33.6
P1		1.21	1.22	1.19	1.20	1.72	1.72	1.72	1.72	42.8
P2		1.13	1.16	1.14	1.14	1.61	1.65	1.62	1.63	42.1

Table H.4. Chemical Characterization of RAP Stockpile 1-16

Recycling Agent	RAP	CA (-)											CA Change %
		Unaged					RTFO + PAV40						
		R. 1	R. 2	R. 3	R. 4	Average	R. 1	R. 2	R. 3	R. 4	R. 5	Average	
O1	Stockpile 1-16	1.69	1.74	1.75	1.78	1.74	2.35	2.20	2.29	—	—	2.28	31.2
O2		1.86	1.85	1.78	—	1.83	2.44	2.41	1.65	2.49	2.49	2.30	25.7
P1		1.28	1.29	1.24	—	1.27	1.90	1.91	1.87	—	—	1.89	49.0
P2		1.28	1.18	1.23	—	1.23	1.80	1.81	1.88	—	—	1.83	48.9

APPENDIX I.
RECYCLING AGENT DOSE VERIFICATION RESULTS

Table I.1. RAP Binder Stockpile 1-09 Blends: Replicate Results

Recycling Agent Dose (%)	High Temperature PG							
	O2				P2			
	Unaged G*/sin(δ)		RTFO G*/sin(δ)		Unaged G*/sin(δ)		RTFO G*/sin(δ)	
0.0	74.8	74.4	76	76.3	74.8	74.5	75.4	75.6
2.0	72.6	72.2	73.6	73.8	72.3	72.1	72.9	73
8.0	62	62.1	63.2	63.9	66.9	66.8	67.8	67.6

Table I.2. RAP Binder Stockpile 1-09 Blends: Average Results

Recycling Agent Dose (%)	High Temperature PG			
	O2		P2	
	Average Unaged G*/sin(δ)	Average RTFO G*/sin(δ)	Average Unaged G*/sin(δ)	Average RTFO G*/sin(δ)
	OB	RTFO	OB	RTFO
0.0	74.6	76.2	74.7	75.5
2.0	72.4	73.7	72.2	73.0
8.0	62.1	63.6	66.9	67.7

Table I.3. RAP Binder Stockpile 1-16 Blends: Replicate Results

Recycling Agent Dose (%)	High Temperature PG Grade							
	O2				P2			
	Unaged G*/sin(δ)		RTFO G*/sin(δ)		Unaged G*/sin(δ)		RTFO G*/sin(δ)	
0.0	77.5	77.7	78.5	78.6	77.5	77.9	78.8	78.9
2.0	73.4	73.4	74.9	74.9	74.9	74.8	76.3	76.1
8.0	65.2	65.4	65.2	64.9	70.1	69.9	71.2	71.4
14.0	—		—		65.1	64.7	66.3	66.4

Table I.4. RAP Binder Stockpile 1-16 Blends: Average Results

Recycling Agent Dose (%)	High Temperature PG Grade			
	O2		P2	
	Average Unaged G*/sin(δ)	Average RTFO G*/sin(δ)	Average Unaged G*/sin(δ)	Average RTFO G*/sin(δ)
	OB	RTFO	OB	RTFO
0.0	77.6	78.6	77.7	78.9
2.0	73.4	74.9	74.9	76.2
8.0	65.3	65.1	70.0	71.3
14.0	—	—	64.9	66.4

APPENDIX J.
RECYCLING AGENT ADDITION METHOD TEST RESULTS

WORKABILITY

Organic-Based Recycling Agent: O2

Table J.1. Recycling Agent O2 Workability Test Results—Maximum Specific Gravity (G_{mm})

Aggregates	Sample	P_b (%)	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)
Granite	1	5.9	1848.3	1569.7	2676.8	2.494
	2	5.9	1844.8	1571.7	2669.3	2.469
					Average	**2.481**

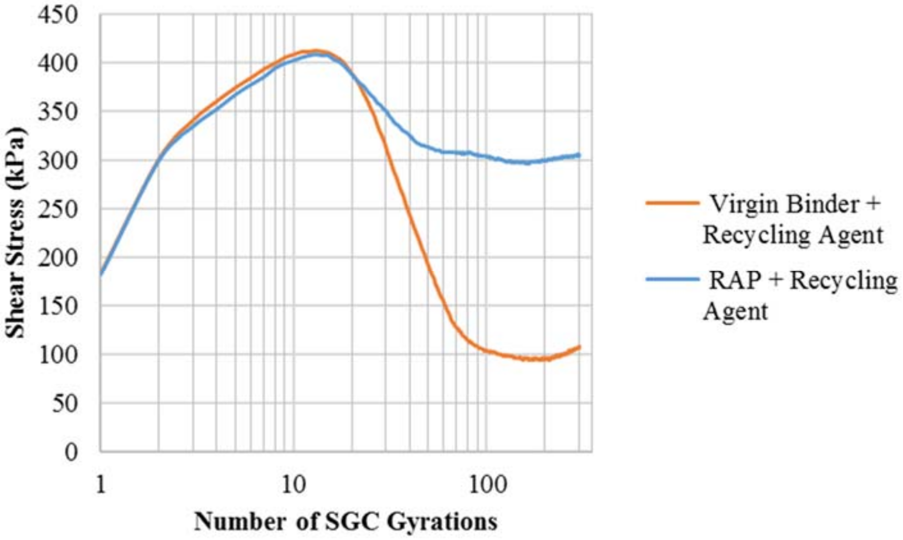


Figure J.1. Recycling Agent O2 Workability Test Results—Shear Stress Evolution

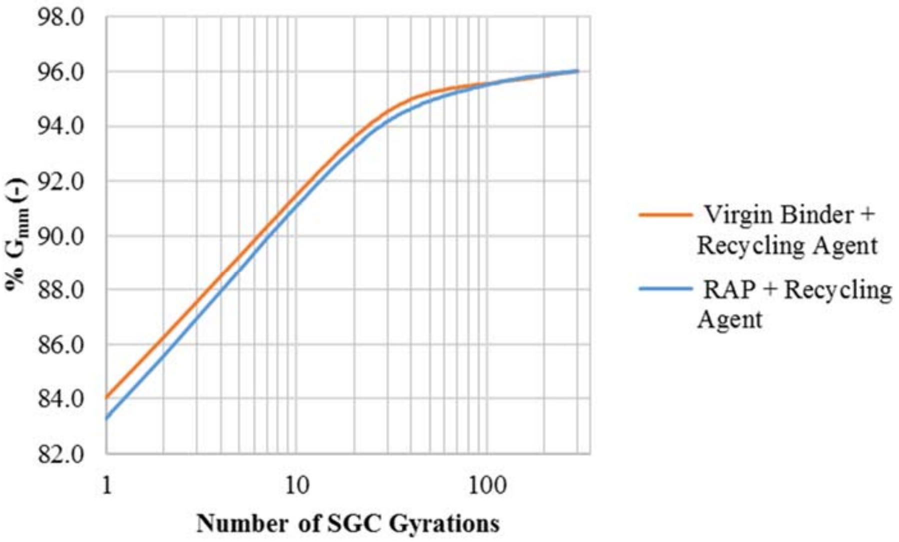


Figure J.2. Recycling Agent O2 Workability Test Results—G_{mm} Evolution

Petroleum-Based Recycling Agent: P2

Table J.2. Recycling Agent P2 Workability Test Results—Maximum Specific Gravity (G_{mm})

Aggregates	Sample	P_b (%)	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)
Granite	1	5.9	1862.8	1569.7	2673.1	2.453
	2	5.9	1829.1	1571.7	2660.5	2.471
					Average	**2.462**

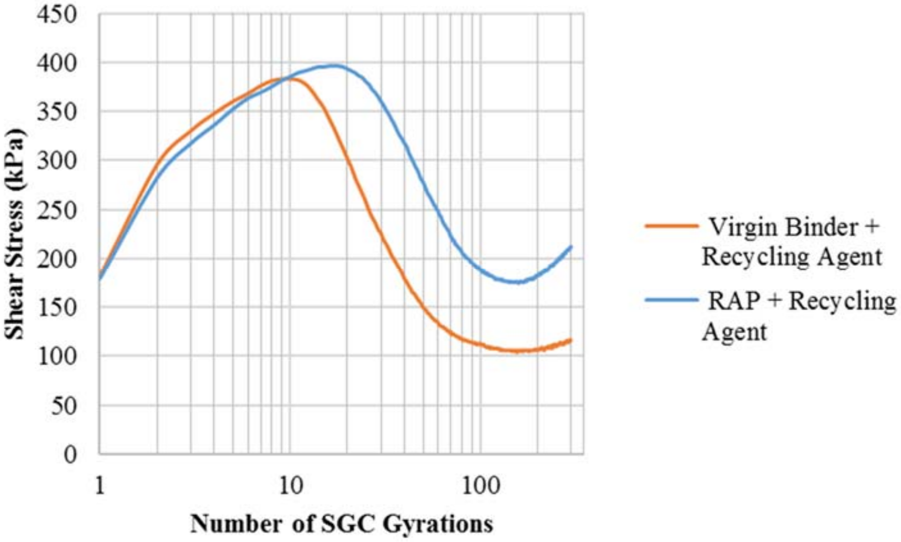


Figure J.3. Recycling Agent P2 Workability Test Results—Shear Stress Evolution

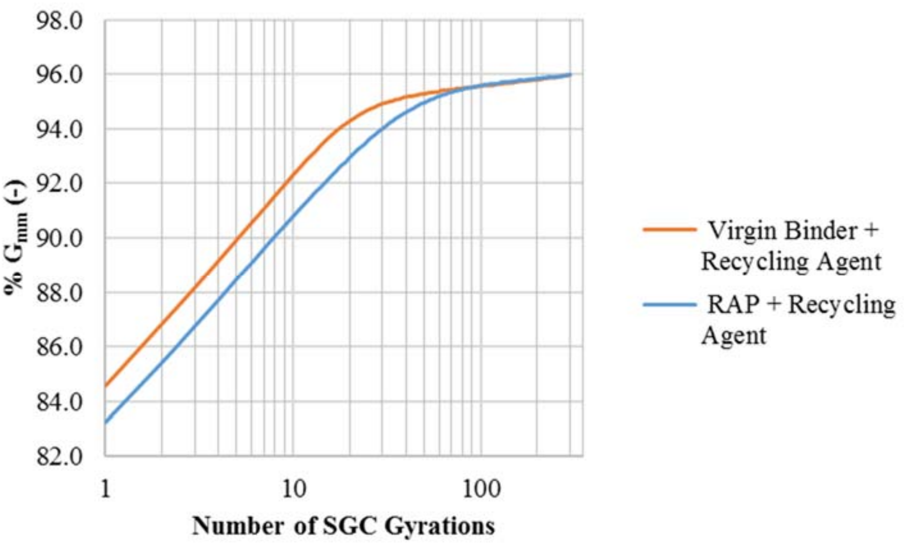


Figure J.4. Recycling Agent P2 Workability Test Results—G_{mm} Evolution

COATABILITY

Organic-Based Recycling Agent: O2

Table J.3. Recycling Agent O2 Coatability Test Results—Virgin Binder + Recycling Agent

W_{agg} OD-1 (g)	2000.0	W_{loose} OD-1 (g)	986.1	W_{loose} SSD-1 (g)	986.5
		W_{loose} OD-2(g)	985.3	W_{loose} SSD-2 (g)	985.4
W_{agg} OD-2 (g)	2001.6			W_{agg} SSD-2 (g)	2009.0

Absorption_{Agg} (%)	0.37
$\text{Absorption}_{Loose\text{-}1}$ (%)	0.04
$\text{Absorption}_{Loose\text{-}2}$ (%)	0.01
$\text{Absorption}_{Loose\text{-}average}$ (%)	0.03

CI (%)	93.1

Table J.4. Recycling Agent O2 Coatability Test Results—RAP + Recycling Agent

W_{agg} OD-1 (g)	2000.0	W_{loose} OD-1 (g)	975.5	W_{loose} SSD-1 (g)	976.1
		W_{loose} OD-2(g)	973.7	W_{loose} SSD-2 (g)	974.4
W_{agg} OD-2 (g)	1997.0			W_{agg} SSD-2 (g)	2005.3

Absorption$_{Agg}$ (%)	0.42
Absorption$_{Loose-1}$ (%)	0.06
Absorption$_{Loose-2}$ (%)	0.07
Absorption$_{Loose-average}$ (%)	0.07

CI (%)	84.0

Petroleum-Based Recycling Agent: P2

Table J.5. Recycling Agent P2 Coatability Test Results—Virgin Binder + Recycling Agent

W_{agg} OD-1 (g)	2000.0	W_{loose} OD-1 (g)	977.3	W_{loose} SSD-1 (g)	978.2
		W_{loose} OD-2(g)	974.2	W_{loose} SSD-2 (g)	974.2
W_{agg} OD-2 (g)	2002.0			W_{agg} SSD-2 (g)	2011.8

Absorption$_{Agg}$ (%)	0.5
Absorption$_{Loose-1}$ (%)	0.1
Absorption$_{Loose-2}$ (%)	0.0
Absorption$_{Loose-average}$ (%)	0.0

CI (%)	90.6

Table J.6. Recycling Agent P2 Coatability Test Results—RAP + Recycling Agent

W_{agg} OD-1 (g)	2000.0	W_{loose} OD-1 (g)	974.6	W_{loose} SSD-1 (g)	975.6
		W_{loose} OD-2(g)	975.8	W_{loose} SSD-2 (g)	976.4
W_{agg} OD-2 (g)	1990.4			W_{agg} SSD-2 (g)	1997.1

Absorption$_{Agg}$ (%)	0.3
Absorption$_{Loose-1}$ (%)	0.1
Absorption$_{Loose-2}$ (%)	0.1
Absorption$_{Loose-average}$ (%)	0.1
CI (%)	75.6

APPENDIX K.
MIX DESIGN GUIDELINES

GUIDELINES FOR THE MIX DESIGN OF HOT RECYCLED MIXTURES WITH LARGE QUANTITIES OF RECLAIMED ASPHALT PAVEMENT (RAP) - METHODS A & B

I. Description

This document provides two methods that can be used for mix design of hot recycled mixtures with large quantities of RAP (i.e., 60 to 100%). **Method A** follows FDOT Specification, Section 334: *Superpave Asphalt Concrete* but provides guidance on how to handle and incorporate the RAP in the recycled mixture. **Method B** is as an alternative to FDOT Specification 334, and it is similar to the proposed mix design methodologies for cold recycled mixtures in the sense that it is based on indirect tensile (IDT) strength rather than mixture volumetrics.

Both methods are applicable for asphalt mixtures fabricated through either Hot In-place Recycling (HIR) or central plant recycling, and employed as surface layers on low volume roads (i.e., less than 750 vehicles per day). Hot recycled asphalt mixtures may be designed employing Method A or Method B based on preference or specific project requirements.

The methodology for both methods includes:

- Testing for the characterization of the mixture components: RAP, virgin aggregate, binder, and recycled agent.
- Mix design procedure for hot recycled mixtures with recycling agents.
- List of variables and test results to be included in the mix design report.

II. Standard Test Methods

AASHTO M-320	Standard Specification for Performance-Graded Binder
AASHTO M 323-12	Standard Specification for Superpave Mix Design
FM 1-T 030	Florida Method of Test for Mechanical Analysis of Extracted Aggregate
FDOT Spec. 334	Superpave Asphalt Concrete
FM 3-D5404	Florida Method of Test for Recovery of Asphalt from Solution Using the Rotavapor Apparatus
FM 5-524	Florida Method of Test for Reflux Extraction of Bitumen from Bituminous Paving Mixtures
FM 5-563	Florida Method of Test for Quantitative Determination of Asphalt Content from Asphalt Paving Mixtures by the Ignition Method

III. Definitions

BBR = Bending beam rheometer

DSR = Dynamic shear rheometer

m_{BB} = Total binder blend mass (g)

m_{BB-RA} = Mass of recycling agent in the binder blend (g)

$m_{BB\text{-}RAP}$ = Mass of RAP binder in the binder blend (g)
$m_{BB\text{-}vb}$ = Mass of virgin binder in the binder blend (g)
m_{mix} = Mass of the recycled mixture (g)
m_{RA} = Mass of the recycled agent in the recycled mixture (g)
m_{vb} = Mass of virgin binder in the recycled mixture (g)
NCHRP = National Cooperative Highway Research Program
NMAS = Nominal maximum aggregate size
OBC = Optimum binder content in the recycled mixture (%)
P_b = Virgin binder content in the recycled mixture (%)
$P_{b\ RAP}$ = RAP binder content (%)
PG = Binder performance grade
PGH = High-temperature PG (°)
PGH_{Blend} = PGH of the blend of virgin and RAP binders in the recycled mixture (°)
PGH_{RAP} = PGH of the RAP binder (°)
PGH_{Target} = PGH required for a specific project location (°)
PGH_{vb} = PGH of the virgin binder (°)
PGL = Low-temperature PG (°)
P_{RA} = Recycling agent dose (%)
P_{RAP} = RAP content in the recycled mixture (%)
RAP = Reclaimed asphalt pavement
RBR = Recycled binder ratio (-)
RTFO = Rolling-thin film oven
TBC = Total binder content in the recycled mixture (%)

IV. Mixture Components and Characterization

IV.1. Reclaimed Asphalt Pavement (RAP)

IV.1.1. Binder Content

Follow FDOT's standard test method FM 5-563 to determine the binder content for each RAP source by means of the ignition oven. This value is referred to as $P_{b\ RAP}$ in this document.

> ***Note:*** *As part of FDOT's standard test method FM 5-563, report the calibrated asphalt content, calibration factors, total percent mass loss and test temperature.*

IV.1.2. Aggregate Gradation

For each RAP source to be employed in the recycled mixture, follow FDOT's standard test method FM 5-563, Section 8 to determine the binder content in the RAP.

Collect the required sample of the resulting RAP aggregate particles and follow the standard test method FM 1-T 030 to determine their particle size distribution.

IV.1.3. RAP Binder PG

Follow FDOT's standard test method FM 5-524 for binder extraction and FM 3-D5404 for binder recovery using the rotovapor apparatus to extract and recover the RAP binder.

Follow the standard test method in AASHTO M 320 to determine the performance grade (PG) of the RAP binder for each RAP source. Report the continuous high-temperature PG (PGH) and continuous low-temperature (PGL) for each RAP source.

> ***Note**: No aging through rolling-thin film oven (RTFO) and/or pressure aging vessel (PAV) shall be done on the RAP binder prior to determining the PGH and PGL. A value of* $G^*/\sin\delta$ *of 1.0 should be used to determine the PGH of the RAP binder.*

IV.2. Virgin Aggregate

Follow the standard test method in AASHTO T-27 to determine the particle size distribution for the virgin aggregate source(s) to be employed in the recycled mixture.

IV.3. Virgin Binder

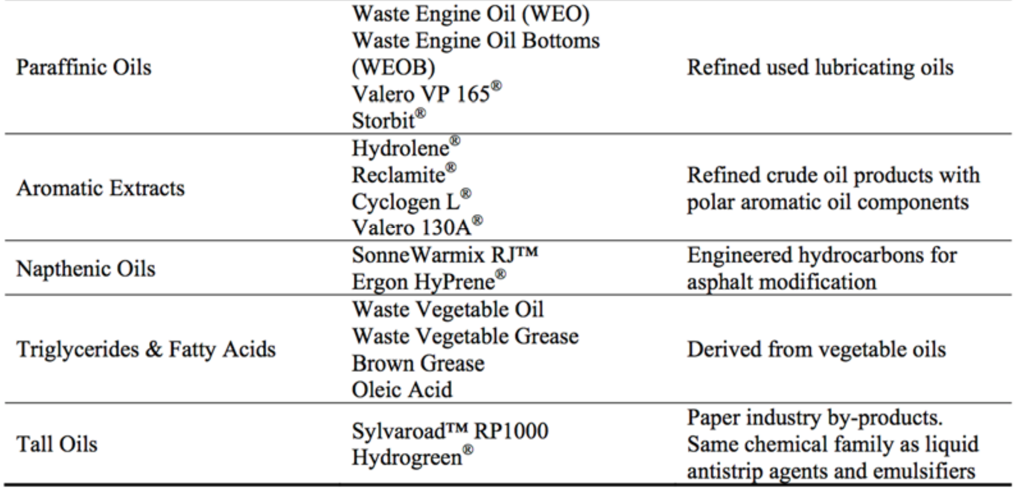
Select the virgin binder PG required for the production of the hot recycled mixture in accordance to FDOT Standard Specification, Section 334-2.3.5: Binder for Mixes with RAP, Table 334-1, which currently indicates a PG 52-28 binder.

Follow the standard test method in AASHTO M 320 to verify the PG of the virgin binder, and report the continuous PGH and continuous PGL.

IV.4. Recycling Agent

Error! Reference source not found. presents common types of recycling agents that according to the National Center for Asphalt Technology (NCAT) satisfy criteria for safety, compatibility, and commercial availability.

Table K.1. Common Types of Recycling Agents (NCAT, 2014)



Category	Types	Description
Paraffinic Oils	Waste Engine Oil (WEO) Waste Engine Oil Bottoms (WEOB) Valero VP 165® Storbit®	Refined used lubricating oils
Aromatic Extracts	Hydrolene® Reclamite® Cyclogen L® Valero 130A®	Refined crude oil products with polar aromatic oil components
Napthenic Oils	SonneWarmix RJ™ Ergon HyPrene®	Engineered hydrocarbons for asphalt modification
Triglycerides & Fatty Acids	Waste Vegetable Oil Waste Vegetable Grease Brown Grease Oleic Acid	Derived from vegetable oils
Tall Oils	Sylvaroad™ RP1000 Hydrogreen®	Paper industry by-products. Same chemical family as liquid antistrip agents and emulsifiers

The type of recycling agent to use in the production of the hot recycled mixtures shall be selected based on availability.

V. Mixture Components Preparation

1. All sources of virgin aggregate and RAP shall be dried prior to conducting the mix design by spreading the materials in flat, shallow pans, avoiding layers thicker than 2.0 inches (5.0 cm).
2. Place the virgin aggregates overnight and RAP source(s) the necessary time until dry in an oven at 230°F (110°C). Allow the materials to cool down and reach room temperature.

__Note__: The RAP can be fan dried overnight first to minimize the time in the oven to complete drying. Immediately after removing the RAP from the oven, stir it periodically by hand to avoid the formation of clumps, until it reaches room temperature.

3. Remove from the virgin aggregates and RAP sources any particle exceeding the nominal maximum aggregate size (NMAS) of the virgin aggregate/RAP blend by sieving.

VI. Recycling Agent Dose

There are two methods available to determine the recycling agent dose for the production of the hot recycled mixtures. The first or fast method uses a set of equations developed in NCHRP project 09-58 and requires minimal laboratory work (Kaseer, 2018). The second or detailed method requires preparing binder blends and measuring their stiffness in the DSR.

VI.1. Fast Dose Selection Method

The fast recycling agent dose selection method requires following FDOT's standard test method FM 5-524 for binder extraction and FM 3-D5404 for binder recovery using the rotovapor apparatus to extract and recover the RAP binder, in addition to the standard test method in AASHTO M 320 to determine the continuous high-temperature PG (PGH) of the RAP binder. The PGH of the RAP binder is used along with the amount of RAP to be introduced in the hot recycled asphalt mixture to estimate the PGH of the blend of virgin and RAP binders.

With these values, Equation 22 and Equation 9 are applied to estimate the recycling agent dose. These equations were developed in NCHRP project 09-58 using multiple sources and grades of virgin binders, RAP materials, and types of recycling agents.

$$P_{RA} = \frac{PGH_{Blend} - PGH_{Target}}{1.82}$$

Equation 22

Where:

P_{RA} = Recycling agent dose (%)

PGH_{Blend} = PGH of the blend of virgin and RAP binders (°)

PGH_{Target} = PGH required for a specific project location. FDOT Specifications, Section 334-2.2, Superpave Binder, states that a PG 67-22 binder is required for the production of hot mix asphalt in the state of Florida. Thus, a PGH_{Target} in the case of Florida will be equal to 67°. A different binder grade could be considered for durability or economic purposes.

***Note**: Equation 1 provides a universal recycling agent dose selection method using 1.82 as a rate of reduction in PGH per 1% recycling agent dose. For petroleum-based aromatic extracts, a rate of reduction in PGH per 1% recycling agent dose of 1.38 is recommended.*

$$PGH_{Blend} = PG_{vb} + (PGH_{RAP} - PGH_{vb}) \cdot RBR$$

Equation 23

Where:

PGH_{vb} = Continuous PGH of the virgin binder (º)

PGH_{RAP} = Continuous PGH of the RAP binder (º)

RBR = Recycled binder ratio (-)

The recycled binder ratio (RBR) corresponds to the RAP binder content in terms of replacement of the total binder content in the recycled mixture, and is computed according to Equation 10:

$$RBR = \frac{P_{RAP} \cdot P_{b\ RAP}}{TBC}$$

Equation 24

Where:

P_{RAP} = RAP content in the recycled mixture (%)

$P_{b\ RAP}$ = RAP binder content (%)

TBC = Total binder content in the recycled mixture (%) —see section VII.2

VI.2. Detailed Dose Selection Method

The detailed recycling agent dose selection method requires, besides the extraction and recovery of the RAP binder, preparation of binder blends (virgin binder + RAP binder + recycled agent), and measurements of their PGH.

The detailed method provides a more certain estimate of the recycling agent dose and should be used when added accuracy is needed based on specific project requirements, or to verify the results of the fast method if considered necessary.

The steps of the detailed recycling agent dose selection method for hot recycled asphalt mixtures are:

1. Prepare binder blends by combining the virgin binder, RAP binder, and recycling agent at doses of 0, 2, and 8% by weight of total binder.

Determine the mass of RAP binder to use in the binder blend as follows:

$$m_{BB-RAP} = m_{BB} \cdot RBR$$

Equation 25

Where:

m_{BB-RAP} = Mass of RAP binder in the binder blend (g)

m_{BB} = Total binder blend mass (g)

RBR = Recycled binder ratio (-)

Determine the mass of virgin binder to use in the binder blend as follows:

$$m_{BB-vb} = m_{BB} \cdot (1 - RBR - P_{RA})$$

Equation 26

Where:

m_{BB-vb} = Mass of virgin binder in the binder blend (g)

m_{BB} = Total binder blend mass (g)

RBR = Recycled binder ratio

P_{RA} = Recycling agent dose

Determine the mass of recycling agent to use in the binder blend as follows:

$$m_{BB-RA} = m_{BB} \cdot (P_{RA})$$

Equation 27

Where:

m_{BB-RA} = Mass of recycling agent in the binder blend (g)

m_{BB} = Total binder blend mass (g)

P_{RA} = Recycling agent dose

***Notes**:*

i. *Avoid overheating the virgin binder by warming it up during the same time and at the same temperature of the RAP binder.*
ii. *Consider that the RAP binder might require a higher temperature and longer heating time than the virgin asphalt to be fluid enough prior to mixing.*
iii. *Thoroughly blend the RAP binder and virgin binder prior to adding the recycling agent to the binder blend.*
iv. *After adding the recycling agent to the binder blend, mix for no more than 30 seconds and place the blend back in the oven for 5 minutes. Repeat the procedure of mixing for no more than 30 seconds and placing the blend back in the oven for 5 minutes a maximum of three times and let the binder blend cool down to room temperature.*
v. *Avoid hot streams of air contact directly the surface of the virgin and RAP binders while heating in the oven by placing a lid on top of the containers.*

2. Follow the standard test method in AASHTO M 320 to determine the continuous PGH of each binder blend.
3. Plot the continuous PGH with respect to the recycling agent dose as shown in **Error! Reference source not found.**.

4. Short-term-age the binder blends using the RTFO per the standard test method in AASHTO M320, and determine the continuous PGH of each short-term aged binder blend.
5. Plot in a separate curve the continuous PGH of the short-term aged binder blends with respect to the recycling agent dose as shown in **Error! Reference source not found.**.
6. Determine the dose of recycling agent (P_{RA}) that matches $\mathrm{PGH}_{\mathrm{Target}}$ using the lower of the unaged and RTFO lines as also shown in **Error! Reference source not found.**

***Notes**:*

i. Lineal interpolation shall be used to estimate the P_{RA} that matches PGH_{Target}.

ii. The P_{RA} that matches the PGH_{Target} should be within the range of recycling agent employed in the production of the binder blends. Extrapolation of the PGH values to determine P_{RA} is not recommended.

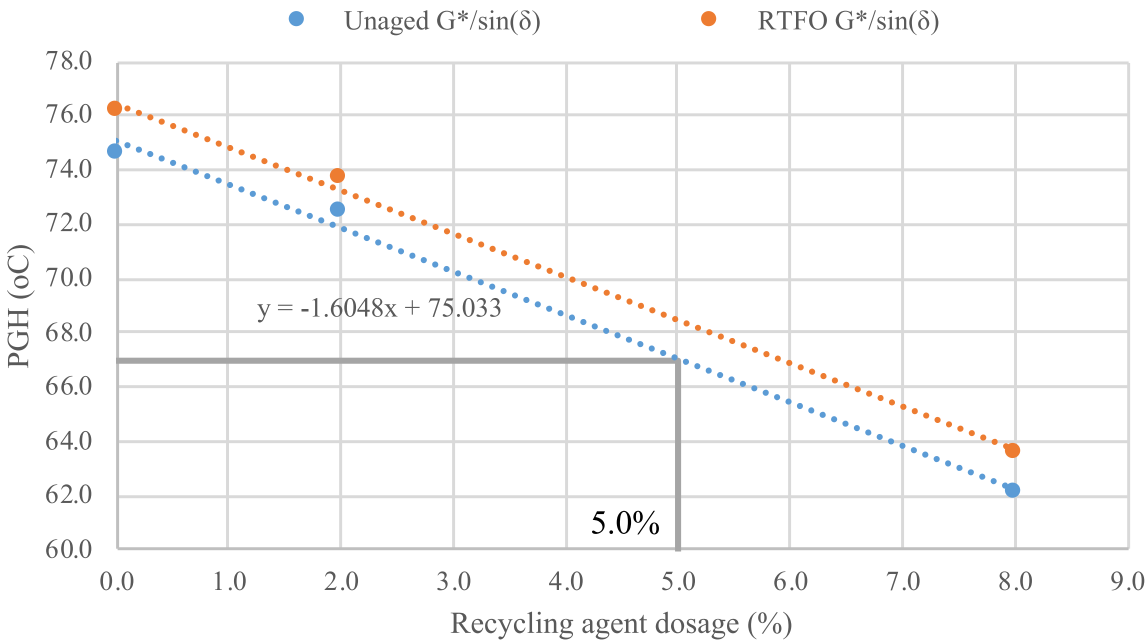


Figure K.1. Example of Recycling Agent Dose Determination – Detailed Method

VII. Mix Design Procedure – Method A

VII.1. Optimum Virgin Binder Content

Follow FDOT Specification, Section 334 (Superpave methodology AASHTO M 323-12) to perform the mix design of the hot recycled mixture with the following considerations:

1. The combination of virgin aggregate and RAP sources, hereafter referred to as aggregate blend, is required to meet the gradation limits. The proportioning of the aggregate blend shall be determined employing the gradation of the RAP after ignition oven test determined in section IV.1.2. Aggregates from various sources may be combined. Plot the gradation of the resulting aggregate blend on an FHWA 0.45 Power Gradation Chart including the limits (i.e., control points) from FDOT Specification, Section 334.

Notes:

i. *Mixtures with various NMAS are defined in FDOT Specification, Section 334: 9.5 (SP-9.5), 12.5 (SP-12.5) and 19 mm (SP-19.0).*

ii. *The RAP can be sieved before combining with the virgin aggregate or can be used without sieving. If the RAP is not sieved, avoid obtaining samples from only one section of the RAP container or stockpile. A representative RAP sample must be obtained before combining with the virgin aggregate.*

iii. *The mass of RAP binder shall be taken into consideration when calculating the RAP amount to be batched for the aggregate blend.*

2. Test specimens shall be fabricated employing the aggregate blend proportions and various virgin binder contents (P_b).
3. Determine and report the optimum virgin binder content (OBC) as the P_b meeting relative density, VMA, VFA, and dust-to-binder ratio as specified in AASHTO M 323-12, Table 6 at N_{Design} = 50 gyrations (Traffic Level A). $N_{initial}$ and $N_{maximum}$ requirements are not applicable. Additionally, report the aggregate blend proportion and gradation chart. Finally, for each compacted test specimen present the bulk specific gravity, maximum specific gravity and air void content.

Note: *The OBC shall be within the range of virgin binder contents employed in the production of the test specimens. Extrapolation of volumetric properties to determine the OBC is not recommended.*

VII.2. Total Binder Content

Calculate the total content of binder in the recycled mixture as follows:

$$TBC = \mathrm{OBC} + P_{b\,RAP} \cdot P_{RAP}$$

Equation 28

Where:

TBC = Total binder content in the recycled mixture (%)

OBC = Optimum binder content in the recycled mixture (%)

$P_{b\,RAP}$ = RAP binder content (%)

P_{RAP} = RAP content in the recycled mixture (%)

VII.3. Job Mix Formula

The mass of recycling agent to add to the recycled mixture shall be calculated as follows:

$$m_{RA} = m_{mix}\, TBC \cdot P_{RA}$$

Equation 29

Where:

m_{RA} = Mass of recycling agent in the recycled mixture (g)

m_{mix} = Mass of the recycled mixture (g)

P_{RA} = Recycling agent dose (%)

The mass of virgin binder to be added to the hot recycled mixture shall consider the recycling agent dose (see Section VI). The mass of virgin binder is reduced to take into account the contribution of the recycling agent as follows:

$$m_{vb} = m_{mix}(\mathrm{OBC} - \mathrm{TBC} \cdot P_{RA})$$

Equation 30

Where:

m_{vb} = Mass of virgin binder in the recycled mixture (g)

m_{mix} = Mass of the recycled mixture (g)

OBC = Optimum binder content in the recycled mixture (%)

TBC = Total binder content in the recycled mixture (%)

P_{RA} = Recycling agent dose (%)

VIII. Mix Design Procedure – Method B

VIII.1. Aggregate Blend Proportions

The combination of aggregate and RAP sources, hereafter referred to as aggregate blend, are required to meet the gradation limits defined in FDOT Specification, Section 334. The proportioning of the aggregate blend shall be determined employing the gradation of the RAP after ignition oven test determined in section IV.1.2. Aggregates from various sources may be combined.

Plot the gradation of the resulting aggregate blend on an FHWA 0.45 Power Gradation Chart including the limits (i.e., control points) from FDOT Specification, Section 334.

Notes:

i. Mixtures with various NMAS are defined in FDOT Specification, Section 334: 9.5 (SP-9.5), 12.5 (SP-12.5) and 19 mm (SP-19.0).

ii. The RAP can be sieved before combining with the virgin aggregate or can be used without sieving. If the RAP is not sieved, avoid obtaining samples from only one section of the RAP container or stockpile. A representative RAP sample must be obtained before combining with the virgin aggregate.

iii. The mass of RAP binder shall be taken into consideration when calculating the RAP amount to be batched for the aggregate blend.

VIII.2. Specimen Preparation

Test specimens shall be fabricated employing the aggregate blend proportions determined in section VIII.1 and at least three virgin binder contents (P_b). The recycling agent shall not be included as part of the mix design procedure. A minimum of six compacted test specimens and two loose specimens shall be fabricated per virgin binder content.

Notes:

i. Preparation of the test specimens shall be performed employing a mechanical mixer and must not exceed 60 seconds.

ii. *After mixing, specimens 6-inch (152.4 mm) diameter by approximately 1.5-inch (38.1 mm) shall be compacted in the Superpave Gyratory Compactor (SGC) to* N_{Design} *= 30 gyrations following procedure described in AASHTO T 312.*

iii. *Loose specimens of the recycled mixtures shall meet requirements defined in FDOT's standard test method FM 1-T 209 for determining maximum specific gravity.*

iv. *After compaction in the SGC, specimens shall be allowed to cool down at room temperature a minimum of 12 hours.*

VIII.3. Specimen Testing

1. Bulk Specific Gravity (G_{mb}) and Maximum Specific Gravity (G_{mm})

Measure and report the bulk specific gravity of every compacted test specimen according to FDOT's standard test method FM 1-T 166. In addition, the loose specimens shall be used to determine the maximum specific gravity following FDOT's standard test method FM 1-T 209.

Calculate and report the air void content of each compacted test specimen and report the average maximum specific gravity for each binder content.

2. Moisture Conditioning

Randomly divide the compacted test specimens into two subsets of at least three specimens each. Moisture condition one of the subsets using vacuum saturation plus a 24-hour water bath at room temperature. The other subset should be left undisturbed at room temperature throughout the time needed to moisture condition the companion subset.

Notes:

i. *Vacuum saturation of the conditioned subset shall follow the procedure and requirements stated in FDOT's standard test method FM 1-T 283 Section 9.3 through 9.8.*

ii. *Calculate and report for each conditioned specimen the volume of absorbed water and percent vacuum saturation as described in the FDOT's standard test method FM 1-T 283 Section 9.3 through 9.8.*

3. Indirect Tensile Strength

Determine the IDT strength of the unconditioned and moisture conditioned specimens following the procedure detailed in FDOT's standard test method FM 1-T 283, Section 10.

Calculate and report the average IDT strength of the unconditioned and moisture conditioned specimens along with their standard deviation and coefficient of variation (CV).

Note: *The CV of the unconditioned or moisture conditioned specimen subsets shall not exceed a value of 15%.*

4. Tensile Strength Ratio

Calculate the resistance of the recycled mixture to moisture induced damage as the ratio of the conditioned to unconditioned IDT strength as follows:

$$TSR = \frac{S_2}{S_1} \cdot 100$$

Equation 31

Where:

TSR = Tensile strength ratio (%)

S_1 = Average IDT strength of the unconditioned specimens subset (psi)

S_2 = Average IDT strength of the moisture conditioned specimens subset (psi)

VIII.4. Optimum Virgin Binder Content

Plot the average IDT strength results (psi [kPa]) with respect the virgin binder content (*P_b*) used in the recycled mixture and fit a linear trend line. Employ separate curves for the unconditioned and moisture conditioned specimen subsets as shown in Figure K.2..

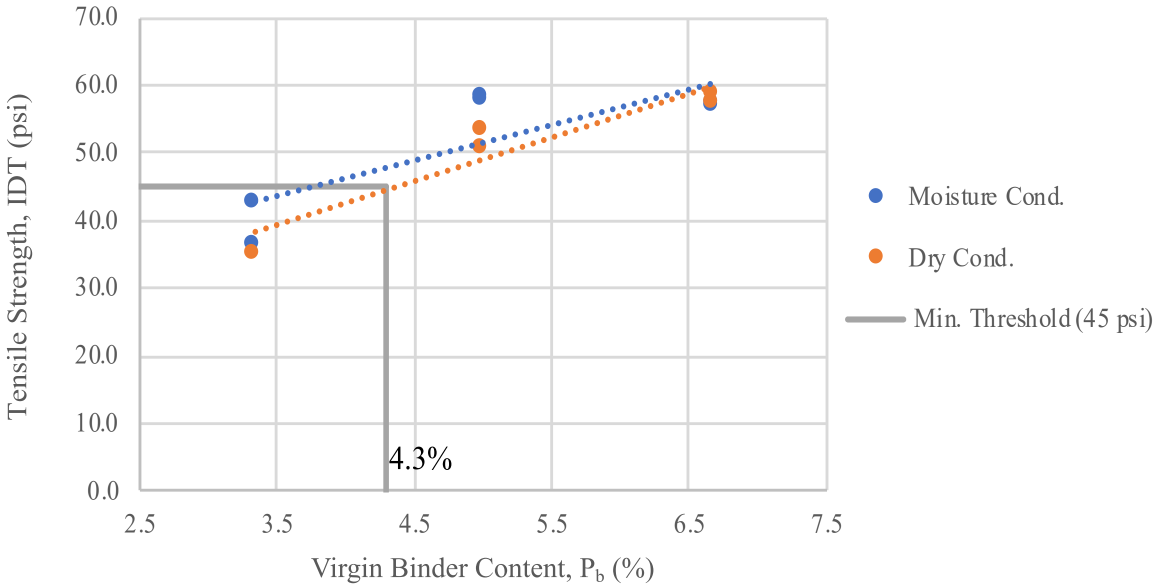


Figure K.2. Example of IDT strength vs. Virgin Binder Content (P_b)

Determine the optimum virgin binder content (OBC) as the largest virgin binder content (P_b) value (using either the unconditioned or moisture conditioned trend line) that meets a minimum IDT strength of 45 psi (310 kPa).

Verify that at the selected OBC the unconditioned and moisture conditioned IDT strengths (obtained either by measured values or using the linear trend lines) yield a minimum TSR value of 60%.

> ***Note:*** *The selected OBC shall be within the range of virgin binder contents employed in the production of the test specimens. Extrapolation of IDT strength values to determine the OBC is not recommended.*

VIII.5. Total Binder Content

Determine the total content of binder in the recycled mixture as follows:

$$TBC = \mathrm{OBC} + P_{b\,RAP} \cdot P_{RAP}$$

Equation 32

Where:

OBC = Optimum virgin binder content (%)

TBC = Total binder content in the recycled mixture (%)

$P_{b\,RAP}$ = RAP binder (%)

P_{RAP} = RAP content in the recycled mixture (%)

VIII.6. Job Mix Formula

The Mass of recycling agent to add to the recycled mixture shall be calculated as follows:

$$m_{RA} = m_{mix}\,TBC \cdot P_{RA}$$

Equation 33

Where:

m_{RA} = Mass of recycling agent in the recycled mixture (g)

m_{mix} = Mass of the recycled mixture (g)

TBC = Total binder content in the recycled mixture (%)

P_{RA} = Recycling agent dose (%)

The mass of virgin binder to be added to the hot recycled mixture shall consider the recycling agent dose (see Section VI). The mass of virgin binder is reduced to take into account the contribution of the recycling agent as follows:

$$m_{vb} = m_{mix}(\mathrm{OBC} - \mathrm{TBC} \cdot P_{RA})$$

Equation 34

Where:

m_{vb} = Mass of virgin binder in the recycled mixture (g)

m_{mix} = Mass of the recycled mixture (g)

OBC = Optimum binder content in the recycled mixture (%)

TBC = Total binder content in the recycled mixture (%)

P_{RA} = Recycling agent dose (%)

IX. Mix Design Report

Provide a report with the resulting mix design information. A report template for Method B is illustrated in and available in electronic (spreadsheet) format from FDOT's State Materials Office. The use of the electronic format will help the user input all test data and obtain automated calculations and plots.

IX.1. Virgin Asphalt Properties

1. Binder Supplier
2. Binder grade
3. Continuous PGH and PGL

IX.2. RAP

1. Stockpile source ID
2. Mineral aggregate type
3. Mineral aggregate gradation
4. Binder content
5. Continuous PGH and PGL of the RAP binder

IX.3. Virgin Aggregate

1. Supplier
2. Stockpile source ID
3. Type
4. Gradation

IX.4. Recycling Agent

1. Commercial name
2. Manufacturer
3. Type
4. Dose selection method
5. Dose

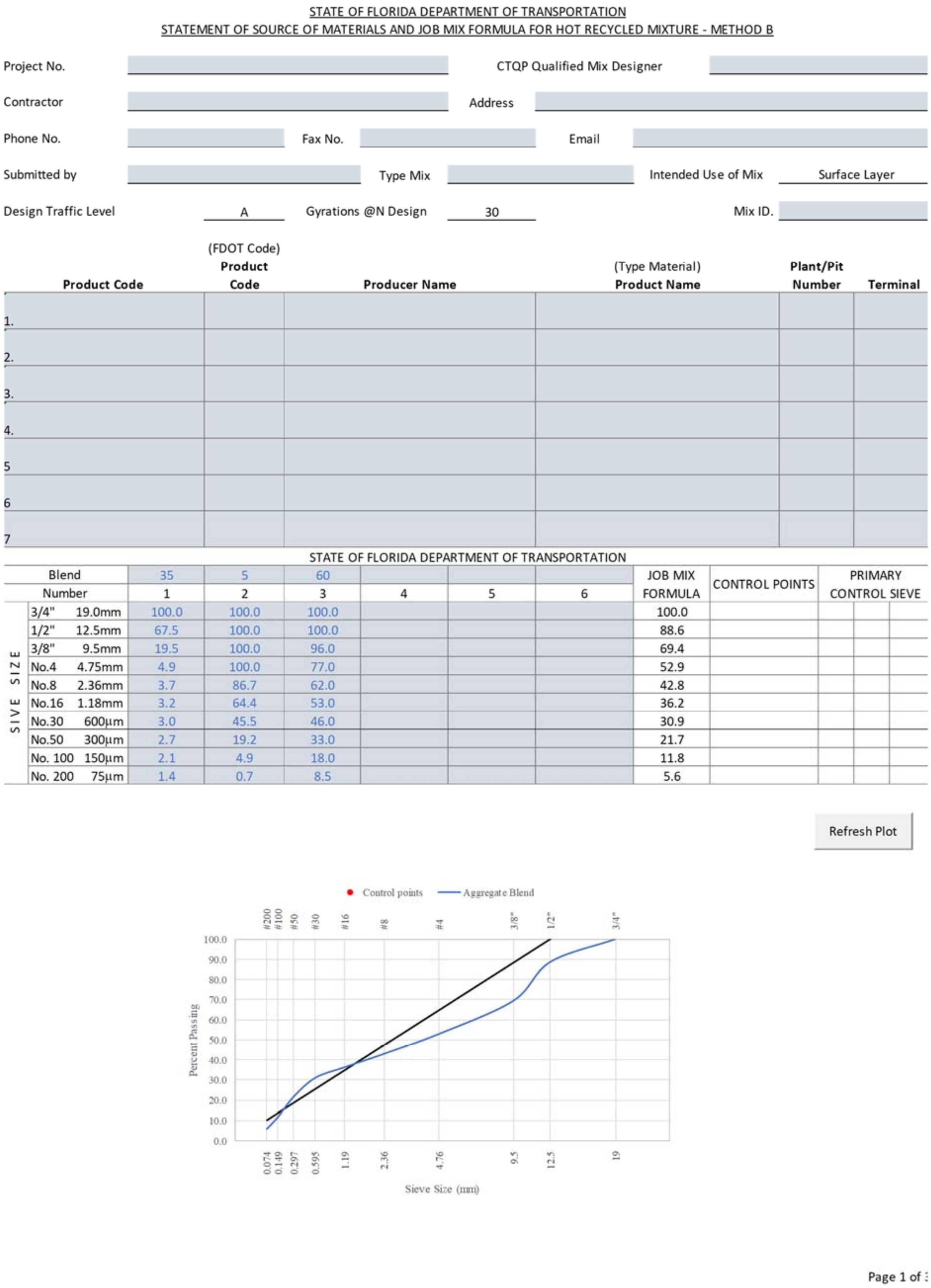
IX.5. Mixture Design

1. Aggregate blend proportion
2. FHWA 0.45 power gradation chart with the aggregate blend including control points from FDOT Specification, Section 334.
3. Mixture NMAS
4. Bulk specific gravity (G_{mb}) of the compacted specimens
5. Air void content of the compacted specimens

6. Average specific gravity (G_{mm}) of each mixture with different virgin binder contents (P_b)
7. (Method B only) Individual unconditioned and moisture conditioned IDT strength of the compacted specimens
8. (Method B only) Average unconditioned and moisture conditioned IDT strengths of each recycled mixture with different P_b
9. (Method B only) Standard deviation and CV of unconditioned and moisture conditioned IDT strength results for each recycled mixture with different P_b
10. (Method B only) Percent vacuum saturation of each moisture conditioned compacted specimen
11. (Method B only) TSR of each recycled mixture with different P_b
12. Optimum virgin binder content of the recycled mixture (OBC)
13. Total binder content of the recycled mixture (TBC)
14. (Method A only) Volumetric properties at OBC
15. (Method B only) Unconditioned and moisture conditioned IDT strengths at OBC
16. (Method B only) TSR at OBC

X. References

- Kaseer, F., Garcia Cucalon, L., Arámbula-Mercado, E., Epps Martin, A. and J. Epps. (2018) "Practical Tools for Optimizing Recycled Materials Content and Recycling Agent Dose for Improved Short- and Long-Term Performance of Rejuvenated Binder Blends and Mixtures". Journal of the Association of Asphalt Paving Technologists, In press.
- NCAT (2014) "NCAT Researchers Explore Multiple Uses of Rejuvenators." Asphalt Technology News, Vol. 26, No. 1 (Spring), http://www.ncat.us/info-pubs/newsletters/spring- 2014/rejuvenators.html. (Accessed April 2016).



STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR HOT RECYCLED MIXTURE - METHOD B

Project No. CTQP Qualified Mix Designer

Contractor Address

Phone No. Fax No. Email

Submitted by Type Mix Intended Use of Mix Surface Layer

Design Traffic Level A Gyrations @N Design 30 Mix ID.

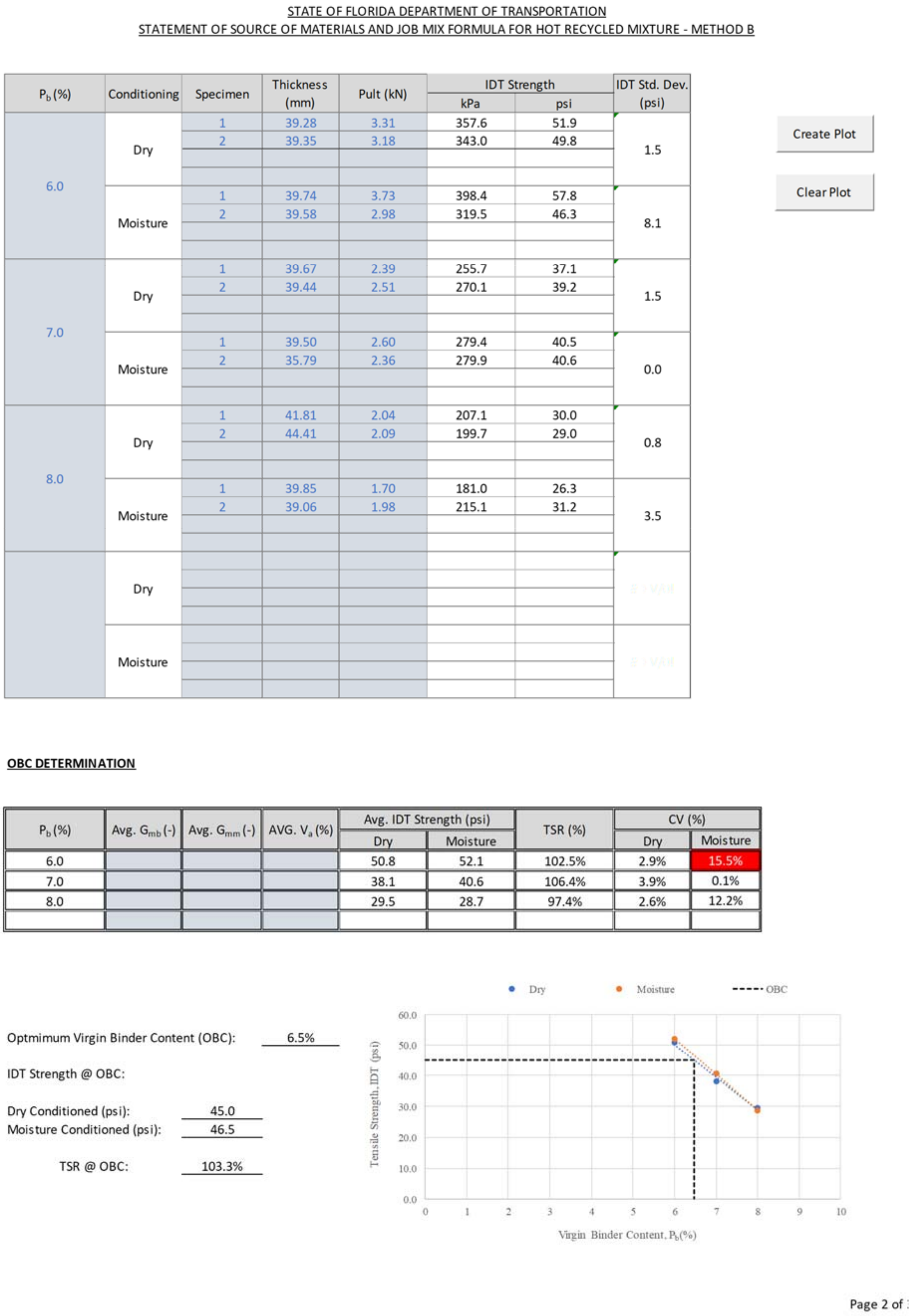
Product Code	(FDOT Code) Product Code	Producer Name	(Type Material) Product Name	Plant/Pit Number	Terminal
1.					
2.					
3.					
4.					
5					
6					
7					

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

	Blend	35	5	60				JOB MIX FORMULA	CONTROL POINTS	PRIMARY CONTROL SIEVE		
	Number	1	2	3	4	5	6					
SIVE SIZE	3/4" 19.0mm	100.0	100.0	100.0				100.0				
	1/2" 12.5mm	67.5	100.0	100.0				88.6				
	3/8" 9.5mm	19.5	100.0	96.0				69.4				
	No.4 4.75mm	4.9	100.0	77.0				52.9				
	No.8 2.36mm	3.7	86.7	62.0				42.8				
	No.16 1.18mm	3.2	64.4	53.0				36.2				
	No.30 600µm	3.0	45.5	46.0				30.9				
	No.50 300µm	2.7	19.2	33.0				21.7				
	No. 100 150µm	2.1	4.9	18.0				11.8				
	No. 200 75µm	1.4	0.7	8.5				5.6				

Page 1 of

(a)



STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR HOT RECYCLED MIXTURE - METHOD B

P_b (%)	Conditioning	Specimen	Thickness (mm)	Pult (kN)	IDT Strength		IDT Std. Dev. (psi)
					kPa	psi	
6.0	Dry	1	39.28	3.31	357.6	51.9	1.5
		2	39.35	3.18	343.0	49.8	
	Moisture	1	39.74	3.73	398.4	57.8	8.1
		2	39.58	2.98	319.5	46.3	
7.0	Dry	1	39.67	2.39	255.7	37.1	1.5
		2	39.44	2.51	270.1	39.2	
	Moisture	1	39.50	2.60	279.4	40.5	0.0
		2	35.79	2.36	279.9	40.6	
8.0	Dry	1	41.81	2.04	207.1	30.0	0.8
		2	44.41	2.09	199.7	29.0	
	Moisture	1	39.85	1.70	181.0	26.3	3.5
		2	39.06	1.98	215.1	31.2	
	Dry						#DIV/0!
	Moisture						#DIV/0!

OBC DETERMINATION

P_b (%)	Avg. G_{mb} (-)	Avg. G_{mm} (-)	AVG. V_a (%)	Avg. IDT Strength (psi)		TSR (%)	CV (%)	
				Dry	Moisture		Dry	Moisture
6.0				50.8	52.1	102.5%	2.9%	15.5%
7.0				38.1	40.6	106.4%	3.9%	0.1%
8.0				29.5	28.7	97.4%	2.6%	12.2%

Optmimum Virgin Binder Content (OBC): 6.5%

IDT Strength @ OBC:

Dry Conditioned (psi): 45.0
Moisture Conditioned (psi): 46.5

TSR @ OBC: 103.3%

Page 2 of

(b)

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR HOT RECYCLED MIXTURE - METHOD B

RECYCLING AGENT DOSE DETERMINATION

RAP content in the recycled mixture (%), P_{RAP}= 60

Binder content of the RAP source (%), $P_{b\ RAP}$= 5.1

Optimum Viging Binder Content (%), OBC= 6.5

Total Binder Content (%), TBC= 9.5

PGH_{Target} (^{o}C)= 67

Binder	PGH (^{o}C)	Continous PGH (^{o}C)
Virgin Asphalt	58	59.2
RAP Binder	98	101.5

Fast Method

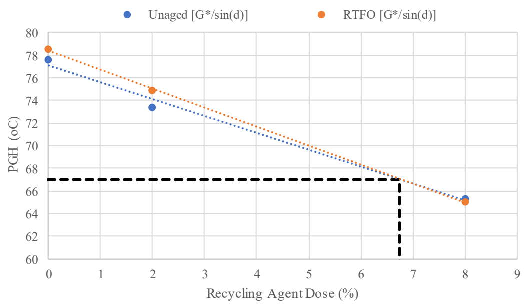
Recycled Binder Ratio (%), RBR= 0.32

PGHBlend (^{o}C)= 72.77

Recycling Agent Dosage (%), P_{RA}= 3.4

Detailed Methd

P_{RA} (%)	Continous PGH (^{o}C) of Binder Blends	
	Unaged [G*/sin(δ)]	RTFO [G*/sin(δ)]
0	77.6	78.55
2	73.4	74.9
8	65.3	65.05



Recycling Agent Dose (%), P_{RA}= 6.7

Page 3 of

(c)

Figure K.3. Example of Mix Design Report Template; (a) Pg. 1/3, (b) Pg. 2/3, (c) Pg. 3/3

GUIDELINES FOR THE MIX DESIGN OF COLD RECYCLED MIXTURES WITH EMULSION AND LARGE QUANTITIES OF RECLAIMED ASPHALT PAVEMENT (RAP)

I. Description

This document provides a performance-based methodology for the design of cold recycled asphalt mixtures with emulsion, large quantities of RAP (i.e., 60 to 100%) and fabricated through either Cold In-place Recycling (CIR) or Cold Central Plant Recycling (CCPR). The methodology is applicable to recycled asphalt mixtures to be employed as surface layers on low volume roads (i.e., less than 750 vehicles per day).

This methodology includes:

- Testing for the characterization of the mixture components: RAP, virgin aggregate and emulsion.
- Mix design procedure for cold recycled mixtures stabilized with emulsion.
- List of variables and test results to be included in the mix design report.

II. Standard Test Methods

AASHTO M 323-12	Standard Specification for Superpave Mix Design
AASHTO T-27	Standard Specification for Sieve Analysis of Fine and Coarse Aggregates
AASHTO T-312	Standard Method of Test for Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor
FDOT Spec. 234	Superpave Asphalt Base
FM 1-T 166	Florida Method of Test for Bulk Specific Gravity of Compacted Asphalt Specimens
FM 1-T 209	Florida Method of test for Maximum Specific Gravity of Asphalt Paving Mixtures
FM 1-T 283	Florida Method of Test for Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage

III. Definitions

CV = Coefficient of variation

G_{mm} = Maximum specific gravity (-)

G_{sb} = Bulk specific gravity (-)

IDT = Indirect tensile strength (kPa)

MC = Mixing water content (%)

M_{mw} = Mass of mixing water (g)

m_{sa} = Mass of anti-strip agent (g)

m_{Solids} = Mass of solids in the mixture (g)

OEC = Optimum emulsion content (%)

P_b = Emulsion content (%)

$P_{b\ Emulsion}$ = Asphalt content in the emulsion (%)

RAP = Reclaimed asphalt pavement
S_1 = Average IDT strength of unconditioned specimen subset (psi)
S_2 = Average IDT strength of moisture conditioned specimen subset (psi)
TSR = Tensile strength ratio (%)

IV. Mixture Components and Characterization

IV.1. Reclaimed Asphalt Pavement (RAP)

Follow the standard test method in AASHTO T-27 to determine the particle size distribution for each RAP source to be employed in the fabrication of the recycled mixture.

> ***Note**: The gradation of the RAP sources shall be determined on the material including the binder coating the mineral aggregate. Binder extraction shall not be performed.*

IV.2. Virgin Aggregate

Follow the standard test method in AASHTO T-27 to determine the particle size distribution for the virgin aggregate source(s) to be employed in the fabrication of the recycled mixture.

IV.3. Emulsion

Report the emulsion composition provided by the manufacturer. Specifically, the water ($MC_{Emulsion}$) and binder ($P_{b\ Emulsion}$) content. In the case where a range is provided for the water and asphalt contents, report both: the information provided by the manufacturer and value selected to perform the mix design.

IV.4. Anti-strip Agent

Use of hydrated lime is recommended as anti-strip agent in the design of recycled mixtures with emulsion. The inclusion of hydrated lime enhances the resistance to moisture susceptibility by improving the recycled mixture IDT strength and TSR.

V. Mixture Components Preparation

1. All sources of virgin aggregate and RAP shall be dried prior to conducting the mix design by spreading the materials in flat, shallow pans, avoiding layers thicker than 2.0 inches (5.0 cm).
2. Place the virgin aggregates overnight and RAP source(s) the necessary time until dry in an oven at 230ºF (110°C). Allow the materials to cool down and reach room temperature.

> ***Note**: The RAP can be fan dried overnight first to minimize the time in the oven to complete drying. Immediately after removing the RAP from the oven, stir periodically by hand to avoid the formation of clumps, until it reaches room temperature.*

3. Remove from the virgin aggregate and RAP materials any particle exceeding the nominal maximum aggregate size (NMAS) of the virgin aggregate/RAP blend by sieving.

4. Employing a mechanical mixer, stir the emulsion thoroughly until and the material appears homogeneous.

__Note__: In case of prolonged storage/resting of the emulsion, verify for settlement prior to use. If the settled material is soft, place the emulsion in a force draft oven at 140°F (60°C) for one hour and proceed to stir it with a mechanical mixer until no sediment is detected in the bottom of the container after suspending the mixer, and the material appears homogeneous. Figure K.4 shows an example of an emulsion sediment in good condition before stirring. If hard or packed settlement is detected, the emulsion should be discarded.

Figure K.4. Emulsion Sediment in Good Condition

VI. Mix Design Procedure

VI.1. Aggregate Blend Proportions

The combination of virgin aggregate and RAP sources, hereafter referred to as aggregate blends, shall meet the gradation requirements defined in FDOT Specifications, Section 334. Aggregates from various sources may be combined.

Plot the gradation of the resulting aggregate blend on an FHWA 0.45 Power Gradation Chart including the Control Points from FDOT Specification Section 334.

VI.2. Optimum Mixing Water Content

The production of cold recycled mixtures with emulsion requires the addition of moisture. Experience demonstrates adequate results are obtained with mixing water contents (MC) ranging from 1.0 to 4.0% (by mass of mixture's solids).

To select the optimum MC, prepare a trial mixture and compact specimens with an initial 4.0% MC. Using visual judgment, assess the mixture fluidity and specimen stability. Avoid too fluid or too dry mixtures. If the trial specimen is too wet and low stability is observed, reduce the MC by 1.0% and repeat the procedure until good fluidity and stability are observed. Figure 71a and Figure 71b illustrate a loose mixture and compacted specimen with excessive MC, respectively.

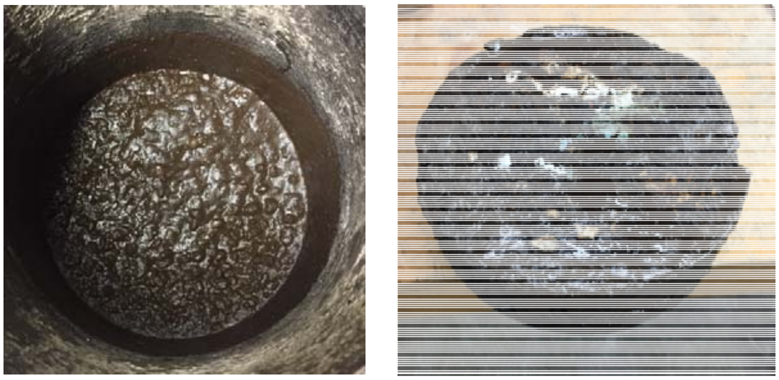

(a) (b)

Figure K.5. Cold Recycled Asphalt Mixtures; (a) Loose Mixture With 8% MC, (b) Compacted Specimen With 8% MC

The mass of mixing water to add to the mixture must take into account the water included in the emulsion and shall be calculated as follows:

$$M_{mw} = m_{solids} \cdot MC - m_{solids} \cdot P_b\left(1 - P_{b_{Emulsion}}\right)$$

Equation 1

Where:

M_{mw} = Mass of mixing water (g)

m_{solids} = Mass of solids in the mixture (g)

MC = Mixing water content (%)

P_b = Emulsion content (%)

$P_{b_{Emulsion}}$ = Asphalt content in the emulsion (%)

VI.3. Anti-Strip Agent

A mass of hydrated lime equivalent to 1.0% of the recycled mixture's solids shall be used as anti-strip agent. The mass of hydrated lime shall be calculated as follows:

$$m_{sa} = 0.01 \cdot m_{solids}$$

Equation 2

Where:

m_{sa} = Mass of anti-strip agent (g)

m_{solids} = Mass of solids in the mixture (g)

VI.4. Specimen Preparation

Test specimens shall be fabricated employing the aggregate blend proportions determined in section VI.1 and at least three emulsion contents (P_b). A minimum of six compacted test specimens and two loose specimens shall be fabricated per emulsion content.

***Notes**:*

1. *The RAP, virgin aggregates, and anti-strip agent shall be thoroughly mixed with the mixing water at ambient temperature before adding the emulsion.*
2. *Preparation of the test specimens shall be performed employing a mechanical mixer and mixing must not exceed two minutes.*
3. *After mixing, avoid loss of moisture in the recycled mixture by covering the top of the container with aluminum foil.*
4. *Specimens 6-inch (152.4 mm) diameter by approximately 1.5-inch (38.1 mm) shall be compacted in the Superpave Gyratory Compactor (SGC) to* N_{Design} *= 30 gyrations following procedure described in AASHTO T 312.*
5. *Loose specimens of the recycled mixtures shall meet requirements defined in FDOT's standard test method FM 1-T 209 for determining maximum specific gravity.*

VI.5. Specimen Curing

After compaction in the SGC, the test specimens shall be cured in a force draft oven at 140°F (60°C) until constant weight is achieved (i.e., 0.05% max change in weight in two hours). Test specimens shall be cured a minimum of 16 hours but not more than 48 hours.

Periodically during the curing process, measure the mass of the test specimen, and report the time required for mass stabilization for each emulsion content.

***Notes**:*

1. *Periodic mass measurement is not required for all test specimens, but should be measured for at least one test specimen per emulsion content.*
2. *After curing, specimens shall be allowed to cool down at room temperature a minimum of 12 hours.*

VI.6. Specimen Testing

1. Bulk Specific Gravity (G_{mb}) and Maximum Specific Gravity (G_{mm})

Measure and report the bulk specific gravity of every compacted test specimen according to FDOT's standard test method FM 1-T 166. In addition, the loose specimens shall be used to determine the maximum specific gravity following FDOT's standard test method FM 1-T 209.

Calculate and report the air void content of each compacted test specimen and report the average maximum specific gravity for each emulsion content.

2. Moisture Conditioning

Divide the compacted test specimens into two subsets of at least three specimens each having an average air void content as close as possible from one another. Moisture condition one of the subsets using vacuum saturation to a level between 55 and 75% plus a 24-hour water bath at room temperature (77±2°F [25±1.1°C]). The other subset should be left undisturbed at room temperature throughout the time needed to moisture condition the companion subset.

***Notes**:*

i. *Vacuum saturation of the conditioned subset shall follow the procedure and requirements stated in FDOT's standard test method FM 1-T 283 Section 9.3 through 9.8.*
ii. *Calculate and report for each conditioned specimen the volume of absorbed water and percent vacuum saturation as described in the FDOT's standard test method FM 1-T 283 Section 9.3 through 9.8.*

3. Indirect Tensile Strength

Determine the IDT strength of the unconditioned and moisture conditioned specimens following the procedure detailed in FDOT's standard test method FM 1-T 283, Section 10.

Calculate and report the average IDT strength of the unconditioned and moisture conditioned specimens along with their standard deviation and coefficient of variation (CV).

***Note**: The CV of the unconditioned or moisture conditioned specimen subsets shall not exceed a value of 15%.*

4. Tensile Strength Ratio

Calculate the resistance of the recycled mixture to moisture induced damage as the ratio of the conditioned to unconditioned IDT strength as follows:

$$TSR = \frac{S_2}{S_1} \cdot 100$$

Equation 3

Where:

TSR = Tensile strength ratio (%)

S_1 = Average IDT strength of the unconditioned specimens subset (psi)

S_2 = Average IDT strength of the moisture conditioned specimens subset (psi)

VI.7. Optimum Emulsion Content

Plot the average IDT strength results (psi [kPa]) with respect the emulsion content (P_b) used in the recycled mixture and fit a linear trend line. Employ separate curves for the unconditioned and moisture conditioned specimen subsets as shown in Figure K.6..

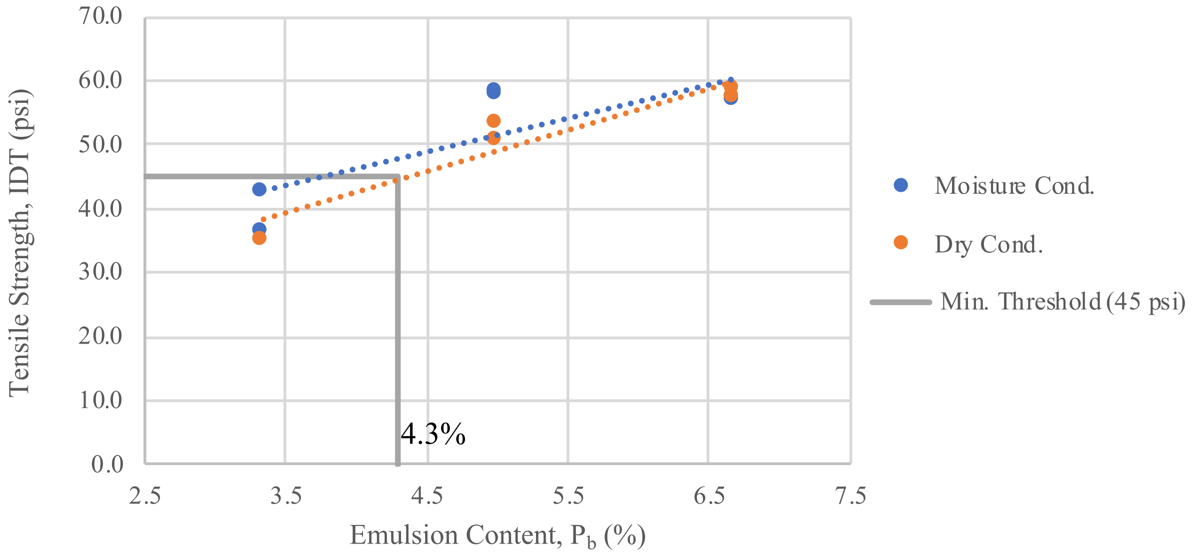


Figure K.6. Example of IDT strength vs. Emulsion Content (P_b)

Determine the optimum emulsion content (OEC) as the largest emulsion content (P_b) value (using either the unconditioned or moisture conditioned trend line) that meets a minimum IDT strength of 45 psi (310 kPa).

Verify that at the selected OEC the unconditioned and moisture conditioned IDT strengths (obtained either by measured values or using the linear trend lines) yield a minimum TSR value of 60%.

> ***Note***: *The selected OEC shall be within the range of emulsion contents employed in the production of the test specimens. Extrapolation of IDT strength values to determine the OEC is not recommended.*

VII. Mix Design Report

Provide a report with the resulting mix design information. A report template is illustrated in Figure K.7.. The use of the electronic format will help the user input all test data and obtain automated calculations and plots.

VII.1. Emulsion Properties

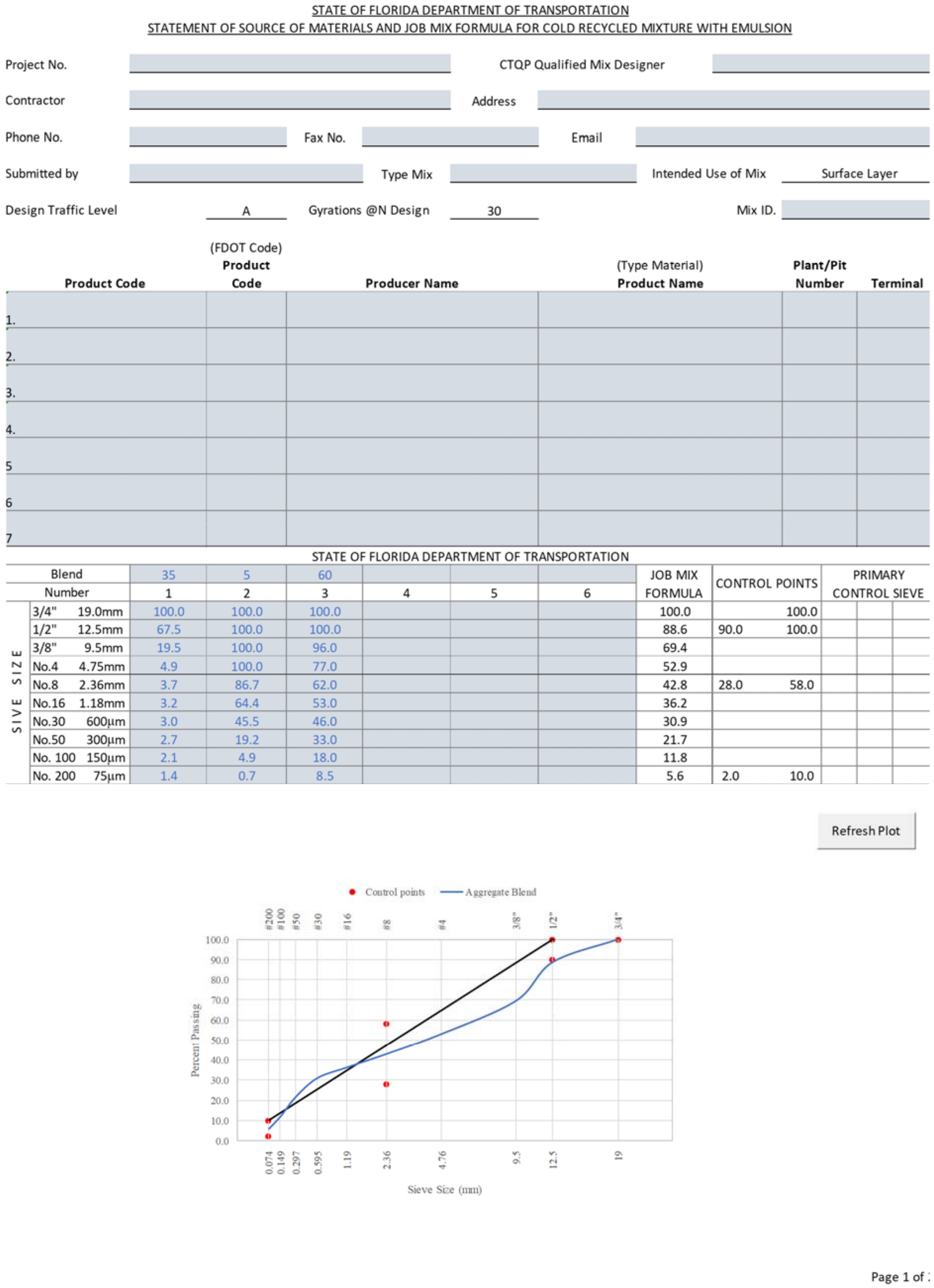
1. Manufacturer
2. Type
3. Water/asphalt content provided by the manufacturer
4. Water/asphalt content selected for mix design

VII.2. Aggregate Blend Properties

1. Gradation of the RAP source(s)
2. Gradation of the virgin aggregate source(s)
3. Virgin aggregate and RAP sources proportioning
4. FHWA 0.45 power gradation chart with the aggregate blend including control points from FDOT Specification, Section 234

VII.3. Recycled Mix Design Parameters

1. Bulk specific gravity (G_{mb}) of the compacted specimens
2. Air void content of the compacted specimens
3. Average specific gravity (G_{mm}) of each recycled mixture with different emulsion contents (P_b)
4. Curing time of the compacted specimens
5. Individual unconditioned and moisture conditioned IDT strength of the compacted specimens
6. Average unconditioned and moisture conditioned IDT strengths of each recycled mixture with different P_b
7. Standard deviation and CV of unconditioned and moisture conditioned IDT strength results for each recycled mixture with different P_b
8. Percent vacuum saturation of each moisture conditioned compacted specimen
9. TSR of each recycled mixture with different P_b
10. Optimum emulsion content
11. Unconditioned and moisture conditioned IDT strengths at OEC
12. TSR at OEC



STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR COLD RECYCLED MIXTURE WITH EMULSION

Project No. CTQP Qualified Mix Designer
Contractor Address
Phone No. Fax No. Email
Submitted by Type Mix Intended Use of Mix Surface Layer
Design Traffic Level A Gyrations @N Design 30 Mix ID.

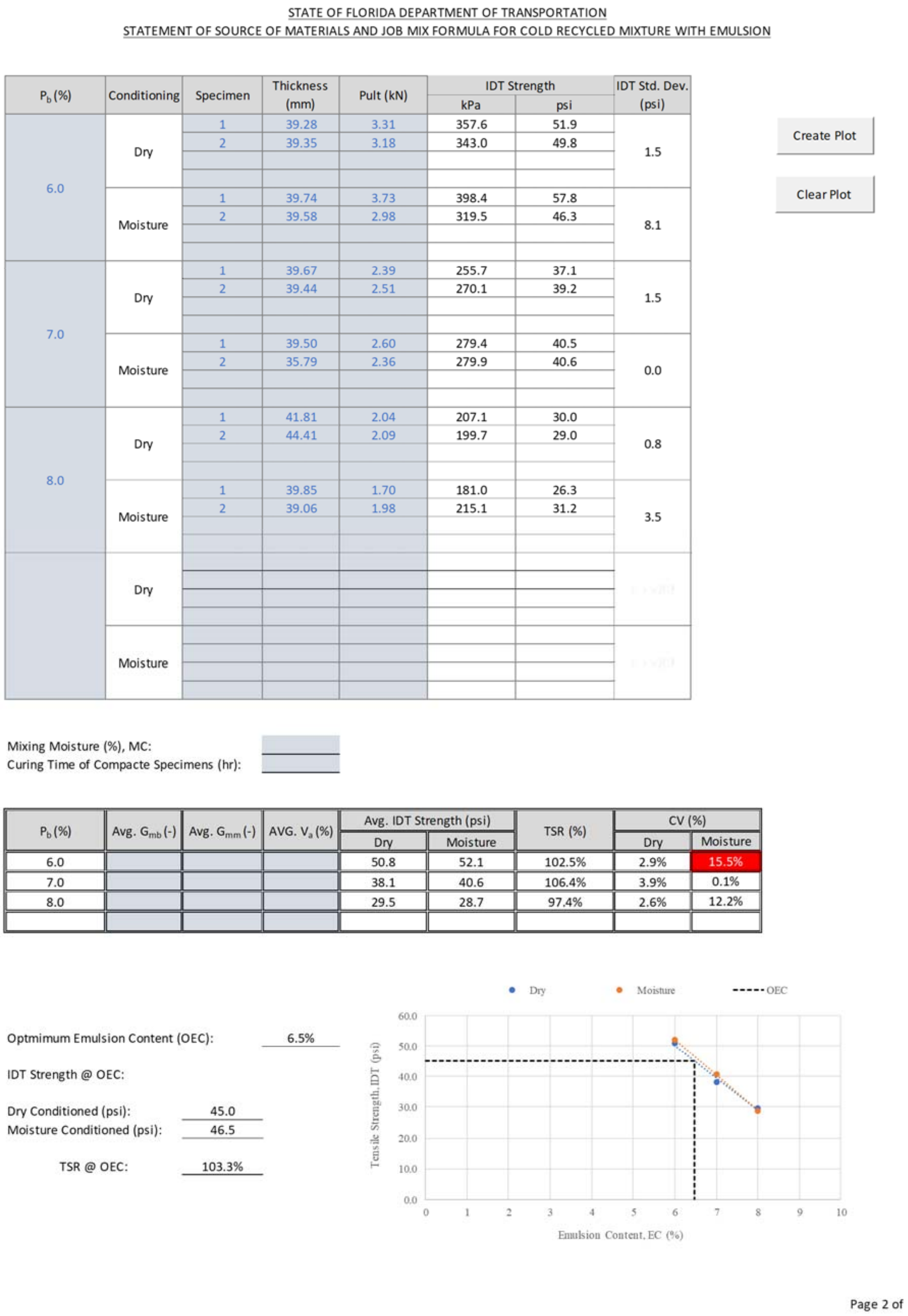
Product Code	(FDOT Code) Product Code	Producer Name	(Type Material) Product Name	Plant/Pit Number	Terminal
1.					
2.					
3.					
4.					
5					
6					
7					

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

Blend		35	5	60				JOB MIX FORMULA	CONTROL POINTS		PRIMARY CONTROL SIEVE		
Number		1	2	3	4	5	6						
SIVE SIZE	3/4" 19.0mm	100.0	100.0	100.0				100.0		100.0			
	1/2" 12.5mm	67.5	100.0	100.0				88.6	90.0	100.0			
	3/8" 9.5mm	19.5	100.0	96.0				69.4					
	No.4 4.75mm	4.9	100.0	77.0				52.9					
	No.8 2.36mm	3.7	86.7	62.0				42.8	28.0	58.0			
	No.16 1.18mm	3.2	64.4	53.0				36.2					
	No.30 600µm	3.0	45.5	46.0				30.9					
	No.50 300µm	2.7	19.2	33.0				21.7					
	No. 100 150µm	2.1	4.9	18.0				11.8					
	No. 200 75µm	1.4	0.7	8.5				5.6	2.0	10.0			

Page 1 of

(a)



STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR COLD RECYCLED MIXTURE WITH EMULSION

P_b (%)	Conditioning	Specimen	Thickness (mm)	Pult (kN)	IDT Strength kPa	IDT Strength psi	IDT Std. Dev. (psi)
6.0	Dry	1	39.28	3.31	357.6	51.9	1.5
		2	39.35	3.18	343.0	49.8	
	Moisture	1	39.74	3.73	398.4	57.8	8.1
		2	39.58	2.98	319.5	46.3	
7.0	Dry	1	39.67	2.39	255.7	37.1	1.5
		2	39.44	2.51	270.1	39.2	
	Moisture	1	39.50	2.60	279.4	40.5	0.0
		2	35.79	2.36	279.9	40.6	
8.0	Dry	1	41.81	2.04	207.1	30.0	0.8
		2	44.41	2.09	199.7	29.0	
	Moisture	1	39.85	1.70	181.0	26.3	3.5
		2	39.06	1.98	215.1	31.2	
	Dry						#DIV/0!
	Moisture						#DIV/0!

Mixing Moisture (%), MC:

Curing Time of Compacte Specimens (hr):

P_b (%)	Avg. G_{mb} (-)	Avg. G_{mm} (-)	AVG. V_a (%)	Avg. IDT Strength (psi)		TSR (%)	CV (%)	
				Dry	Moisture		Dry	Moisture
6.0				50.8	52.1	102.5%	2.9%	15.5%
7.0				38.1	40.6	106.4%	3.9%	0.1%
8.0				29.5	28.7	97.4%	2.6%	12.2%

Optmimum Emulsion Content (OEC): 6.5%

IDT Strength @ OEC:

Dry Conditioned (psi): 45.0

Moisture Conditioned (psi): 46.5

TSR @ OEC: 103.3%

Page 2 of

(b)

Figure K.7. Example of Mix Design Report Template; (a) Pg. 1 of 2, (b) Pg. 2 of 2

GUIDELINES FOR THE MIX DESIGN OF COLD RECYCLED MIXTURES WITH FOAMED BINDER AND LARGE QUANTITIES OF RECLAIMED ASPHALT PAVEMENT (RAP)

I. Description

This document provides a performance-based methodology for the design of cold recycled asphalt mixtures with foamed binder, large quantities of RAP (i.e., 60 to 100%) and fabricated through either Cold In-place Recycling (CIR) or Cold Central Plant Recycling (CCPR). The methodology is applicable to recycled asphalt mixtures to be employed as surface layers of low volume roads (i.e., less than 750 vehicles per day).

This methodology includes:

- Testing for the characterization of the mixture components: RAP, virgin aggregate and foamed binder.
- Mix design procedure for cold recycled mixture stabilized with foamed binder.
- List of variables and test results to report after conducting the mixture design

II. Standard Test Methods

AASHTO M 323-12	Standard Specification for Superpave Mix Design
AASHTO T-27	Standard Specification for Sieve Analysis of Fine and Coarse Aggregates
AASHTO T-312	Standard Method of Test for Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor
FDOT Spec. 234	Superpave Asphalt Base
FM 1-T 166	Florida Method of Test for Bulk Specific Gravity of Compacted Asphalt Specimens
FM 1-T 209	Florida Method of test for Maximum Specific Gravity of Asphalt Paving Mixtures
FM 1-T 283	Florida Method of Test for Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage

III. Definitions

CV = Coefficient of variation

G_{mm} = Maximum specific gravity (-)

G_{sb} = Bulk specific gravity (-)

IDT = Indirect tensile strength (kPa)

m_{af} = Mass of active filler (g)

MC = Mixing water content (%)

M_{mw} = Mass of mixing water (g)

m_{Solids} = Mass of solids in the mixture (g)

OFC = Optimum foamed binder content (%)

P_b = Foamed binder content (%)
RAP = Reclaimed asphalt pavement
S_1 = Average IDT strength of unconditioned specimen subset (psi)
S_2 = Average IDT strength of moisture conditioned specimen subset (psi)
TSR = Tensile strength ratio (%)

IV. Mixture Components and Characterization

IV.1. Reclaimed Asphalt Pavement (RAP)

Follow the standard test method in AASHTO T-27 to determine the particle size distribution for each RAP source to be employed in the fabrication of the recycled mixture.

Note*: The gradation of the RAP sources shall be determined on the material including the binder coating the mineral aggregate. Binder extraction shall not be performed.*

IV.2. Virgin Aggregate

Follow the standard test method in AASHTO T-27 to determine the particle size distribution for the virgin aggregate source(s) to be employed in the fabrication of the recycled mixture.

IV.3. Binder

A binder PG 67-22 shall be employed in the production of the foamed cold recycled mixtures. A different binder grade could be allowed when considered beneficial.

IV.4. Active Filler

Portland cement shall be used as active filler and included in the design of the foamed recycled mixtures. The inclusion of Portland cement improves the recycled mixture IDT strength and TSR.

V. Mixture Components Preparation

1. All sources of virgin aggregate and RAP shall be dried prior to conducting the mix design by spreading the materials in flat, shallow pans, avoiding layers thicker than 2.0 inches (5.0 cm).
2. Place the virgin aggregates overnight and RAP source(s) the necessary time until dry in an oven at 230°F (110°C). Allow the materials to cool down and reach room temperature.

Note*: The RAP can be fan dried overnight first to minimize the time in the oven to complete drying. Immediately after removing the RAP from the oven, stir it periodically by hand to avoid the formation of clumps, until it reaches room temperature.*

3. Remove from the virgin aggregates and RAP materials any particle exceeding the nominal maximum aggregate size (NMAS) of the virgin aggregate/RAP blend.

VI. Mixture Design Procedure

VI.1. Aggregate Blend Proportions

The combination of virgin aggregate and RAP sources, hereafter referred to as aggregate blends, shall meet gradation requirements defined in FDOT Specifications Section 334. Aggregates from various sources may be combined.

Plot the gradation of the resulting aggregate blend on an FHWA 0.45 Power Gradation Chart including the Control Points from FDOT Specification Section 334.

VI.2. Optimum Foaming Water Content

The production of foamed binder requires combining binder heated at elevated temperature with small quantities of water at room temperature. This induces the formation of bubbles in the binder, lowering its viscosity and facilitating its dispersion for mixing. Proper foamed binder performance is achieved by optimizing the amount of water injected to the heated binder.

The optimum foaming water content (OFWC) shall be determined by measuring the expansion ratio (ER) and half-life (H-L) properties of the foamed binder. ER is defined as the ratio between the volume of a specific mass of fluid before and after foaming, while H-L is the period that the same fluid takes to transit from its maximum ER to one-half of that value.

ER and H-L shall be measured for at least four foaming water contents at a foamed binder temperature of 338°F (170°C). A minimum ER and H-L of 8-times and 6 seconds, respectively, shall be achieved by the foamed binder. The OFWC shall be established as the average of the foaming water contents at which minimum ER and H-L requirements are met as shown in Figure K.8..

Note: *The OFWC that meets the ER and H-L requirements shall be within the range of measured foaming water contents. Extrapolation of ER and H-L results to determine the OFWC is not recommended.*

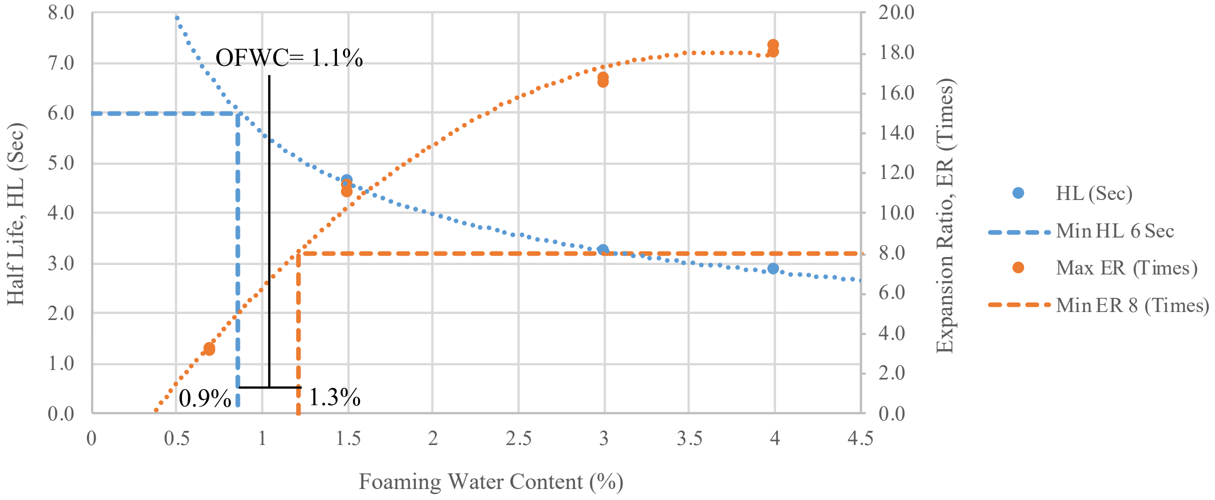


Figure K.8. Example of Optimum Foaming Water Content Determination

VI.3. Optimum Mixing Water Content

The production of cold recycled mixtures with emulsified asphalt requires the addition of moisture. Experience demonstrates adequate results are obtained with mixing water contents (MC) ranging from 1.0 to 4.0% (by mass of mixture's solids).

To select the optimum MC, prepare a trial mixture and compact specimens with an initial 4.0% MC. Using visual judgment, assess the mixture fluidity and specimen stability. Avoid too fluid or too dry mixtures. If the trial specimen is too wet and low stability is observed, reduce the MC by 1.0% and repeat the procedure until good fluidity and stability are observed. Figure 71 (a) and Figure 71(b) illustrate a loose mix and compacted specimen with excessive MC, respectively.

The mass of mixing water to add to the mixture shall be calculated as follows:

$$M_{mw} = m_{solids} \cdot MC$$

Equation 1

Where:

M_{mw} = Mass of mixing water (g)

m_{solids} = Mass of solids in the mixture (g)

MC = Mixing water content (%)

VI.4. Active Filler

A mass of Portland cement equivalent to 1.0% of the recycle mixture's solids shall be used as active filler. The mass of Portland cement shall be calculated as follows:

$$m_{sa} = 0.01 \cdot m_{solids}$$

Equation 2

Where:

m_{sa} = Mass of active filler (g)

m_{solids} = Mass of solids in the mixture (g)

VI.5. Specimen Preparation

Test specimens shall be fabricated employing the aggregate blend proportions determined in section VI.1 and at least three foamed binder contents (P_b). A minimum of six compacted test specimens and two loose specimens shall be fabricated per foamed binder content.

Notes:

i. *The RAP, virgin aggregates, and active filler agent shall be thoroughly mixed with the mixing water at ambient temperature and before adding the foamed binder.*

ii. *Preparation of the test specimens shall be performed employing a mechanical mixer and mixing must not exceed two minutes.*

iii. *After mixing, avoid loss of moisture in the recycled mixture by covering the top of the container with aluminum foil.*

iv. *Specimens 6-inch (152.4 mm) diameter by approximately 1.5-inch (38.1 mm) shall be compacted in the Superpave Gyratory Compactor (SGC) to* N_{Design} *= 30 gyrations following the procedure described in AASHTO T 312.*

v. *Loose specimens of the recycled mixtures shall meet requirements defined in FDOT's standard test method FM 1-T 209 for determining maximum specific gravity.*

VI.6. Specimen Curing

After compaction in the SGC, the test specimens shall be cured in a force draft oven at 140°F (60°C) until constant weight is achieved (i.e., 0.05% max change in weight in two hours). Test Specimens must be cured a minimum of 16 hours but not more than 48 hours.

Periodically during the curing process, measure the mass of the test specimen, and report the time required for mass stabilization of each foamed binder content.

Notes:

i. *Periodic mass measurement is not required for all test specimens, but should be measured for at least one test specimen per foamed binder content.*

ii. *After curing, specimens shall be allowed to cool down at room temperature a minimum of 12 hours.*

VI.7. Specimen Testing

1. Bulk Specific Gravity (G_{mb}) and Maximum Specific Gravity (G_{mm})

Measure and report the Bulk specific gravity of every compacted specimen according to FDOT's standard test method FM 1-T 166. In addition, the loose specimens shall be used to determine the maximum specific gravity following Florida's standard test method FM 1-T 209.

Calculate and report the air void content of each compacted test specimen and report the average maximum specific gravity for each foamed binder content.

2. Moisture Conditioning

Randomly divide the compacted test specimens into two subsets of at least three specimens each. Moisture condition one of the subsets using vacuum saturation plus a 24-hour water bath at room temperature (77±2ºF [25±1.1ºC]). The other subset should be left undisturbed at room temperature throughout the time needed to moisture condition the companion subset.

Notes:

i. *Vacuum saturation of the conditioned subset shall follow the procedure and requirements stated in FDOT's standard test method FM 1-T 283 Section 9.3 through 9.8.*

ii. *Calculate and report for each conditioned specimen the volume of absorbed water and percent vacuum saturation as described in FDOT's standard test method FM 1-T 283 Section 9.3 through 9.8.*

3. Indirect Tensile Strength

Determine the IDT strength of the unconditioned and moisture conditioned specimens following the procedure detailed in FDOT's standard test method FM 1-T 283, Section 10.

Calculate and report the average IDT strength of the unconditioned and moisture conditioned specimens along their standard deviation and coefficient of variation (CV).

> ***Note***: The CV of the unconditioned or moisture conditioned specimen subsets shall not exceed a value of 15%

4. Tensile Strength Ratio

Calculate the resistance of the recycled mixture to moisture induced damage as the ratio of the conditioned to unconditioned IDT strength as follows:

$$TSR = \frac{S_2}{S_1} \cdot 100$$

Equation 3

Where:

TSR = Tensile strength ratio (%)

S_1 = Average IDT strength of the unconditioned specimen (psi)

S_2 = Average IDT strength of the moisture conditioned specimen subset (psi)

VI.8. Optimum Foamed binder Content

Plot the average IDT strength results (psi [kPa]) with respect the foamed binder content (*P_b*) used in the recycled mixture and fit a linear trend. Employ separate curves for the unconditioned and moisture conditioned specimen subsets as shown in Figure K.9..

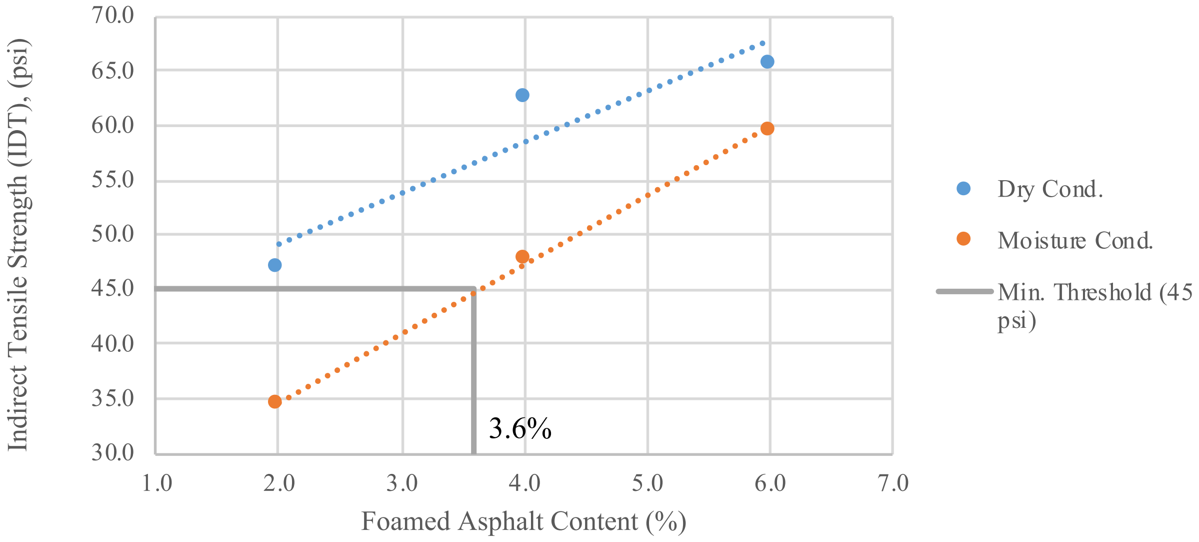


Figure K.9. Example of IDT Strength vs. Foamed binder Content (*P_b*)

Determine the optimum foamed binder content (OFC) as the largest foamed binder content (P_b) value (using either the unconditioned or moisture conditioned trend line) that meets a minimum IDT strength of 45 psi (310 kPa).

Verify that at the selected OFC the unconditioned and moisture conditioned IDT strengths (obtained either by measured values or using the linear trend lines) yield a minimum TSR value of 60%.

> ***Note:*** *The selected OFC shall be within the range of foamed binder contents employed in the production of the test specimens. Extrapolation of IDT strength values to determine the OFC is not recommended.*

VII. Mix Design Report

Provide a report with the resulting mix design information. A report template is illustrated in Figure K.10.. The use of the electronic format will help the user input all test data and obtain automated calculations and plots.

VII.1. Foamed binder Properties

1. Binder supplier
2. Binder grade
3. ER and H-L curves vs foaming water content
4. Optimum foaming water content

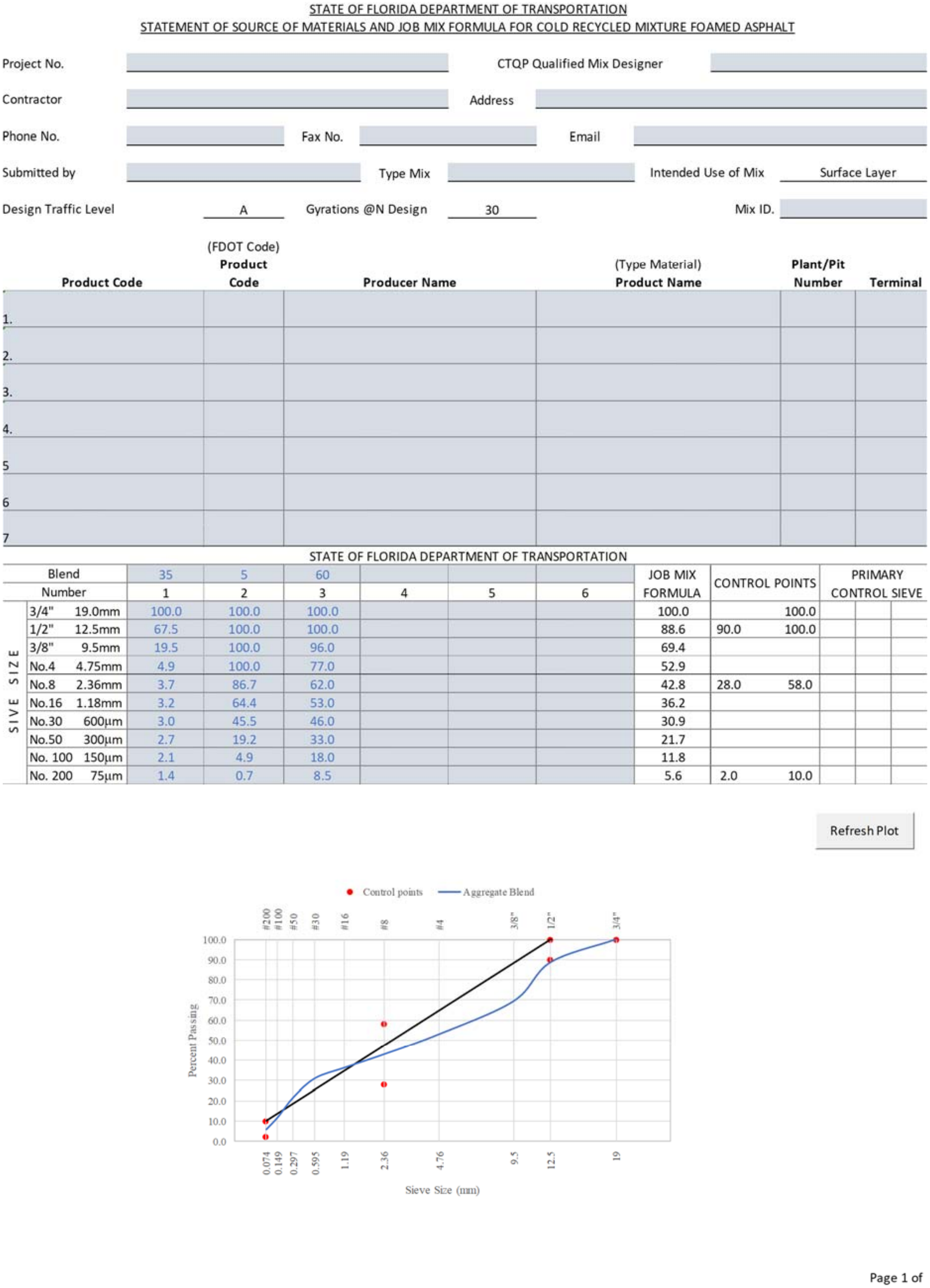
VII.2. Aggregate Blend Properties

1. Gradation of the RAP source(s)
2. Gradation of the virgin aggregate source(s)
3. Virgin aggregate and RAP sources proportioning
4. FHWA 0.45 power gradation chart with the aggregate blend including control points from FDOT Specification, Section 234.

VII.3. Recycled Mix Design Parameters

1. Bulk specific gravity (G_{mb}) of the compacted specimens
2. Air void content of compacted specimens
3. Average specific gravity (G_{mm}) of each recycled mixture with different foamed binder contents (P_b).
4. Curing time of the compacted specimens

5. Individual unconditioned and moisture conditioned IDT strength of the compacted specimens
6. Average unconditioned and moisture conditioned IDT strength of each recycled mixture with different P_b.
7. Standard deviation and CV of unconditioned and moisture conditioned IDT strength results for each recycled mixture with different P_b.
8. Percent vacuum saturation of each moisture conditioned specimen
9. TSR of each recycled mixture with different P_b.
10. Optimum foamed binder content
11. Unconditioned and moisture conditioned IDT strengths at OFC
12. TSR at OFC



STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR COLD RECYCLED MIXTURE FOAMED ASPHALT

Project No.
CTQP Qualified Mix Designer
Contractor
Address
Phone No.
Fax No.
Email
Submitted by
Type Mix
Intended Use of Mix: Surface Layer
Design Traffic Level: A
Gyrations @N Design: 30
Mix ID.

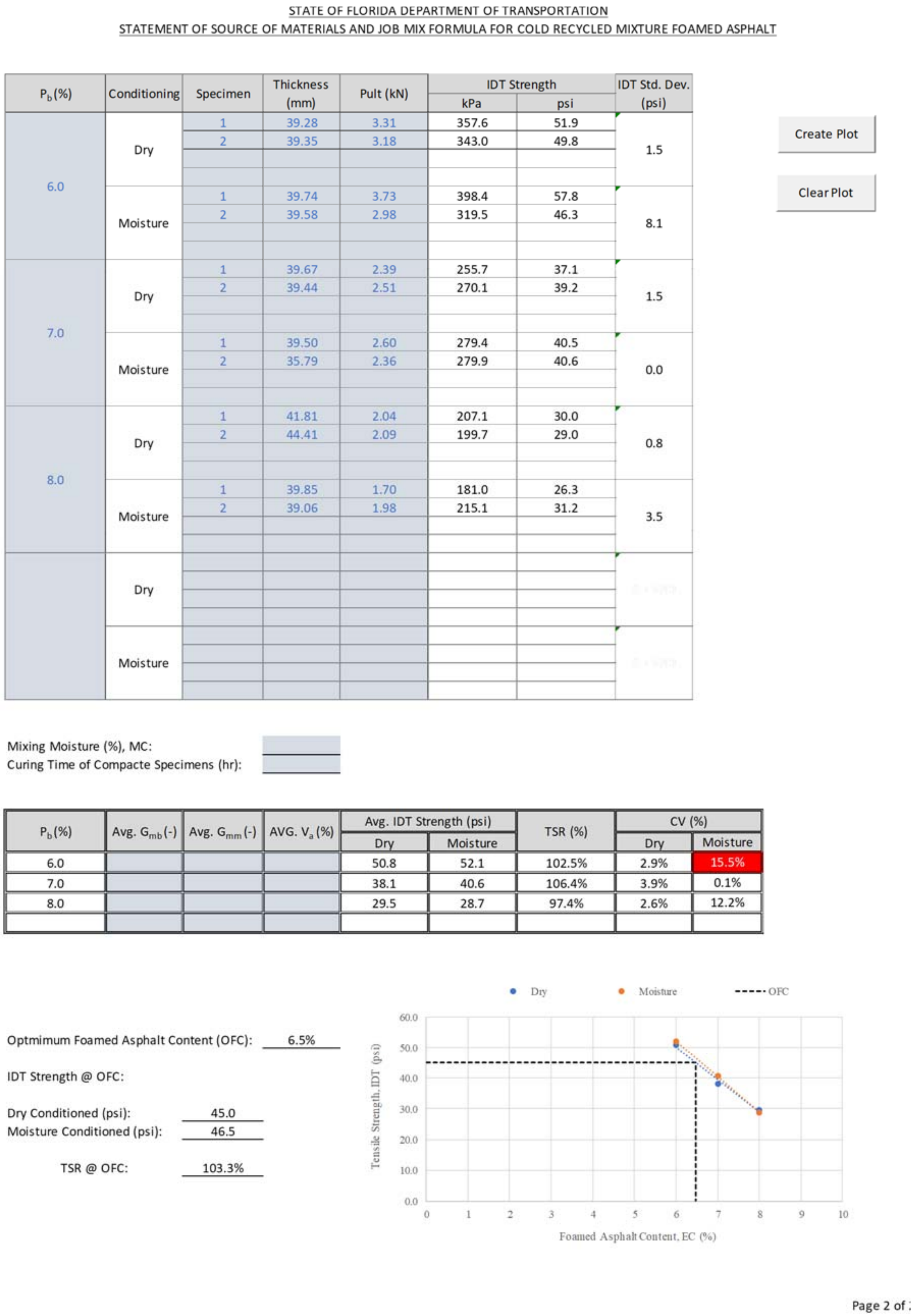
Product Code	(FDOT Code) Product Code	Producer Name	(Type Material) Product Name	Plant/Pit Number	Terminal
1.					
2.					
3.					
4.					
5					
6					
7					

STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

	Blend	35	5	60				JOB MIX FORMULA	CONTROL POINTS		PRIMARY CONTROL SIEVE		
	Number	1	2	3	4	5	6						
SIVE SIZE	3/4" 19.0mm	100.0	100.0	100.0				100.0		100.0			
	1/2" 12.5mm	67.5	100.0	100.0				88.6	90.0	100.0			
	3/8" 9.5mm	19.5	100.0	96.0				69.4					
	No.4 4.75mm	4.9	100.0	77.0				52.9					
	No.8 2.36mm	3.7	86.7	62.0				42.8	28.0	58.0			
	No.16 1.18mm	3.2	64.4	53.0				36.2					
	No.30 600µm	3.0	45.5	46.0				30.9					
	No.50 300µm	2.7	19.2	33.0				21.7					
	No. 100 150µm	2.1	4.9	18.0				11.8					
	No. 200 75µm	1.4	0.7	8.5				5.6	2.0	10.0			

Page 1 of

(a)



STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION

STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR COLD RECYCLED MIXTURE FOAMED ASPHALT

P_b (%)	Conditioning	Specimen	Thickness (mm)	Pult (kN)	IDT Strength		IDT Std. Dev. (psi)
					kPa	psi	
6.0	Dry	1	39.28	3.31	357.6	51.9	1.5
		2	39.35	3.18	343.0	49.8	
	Moisture	1	39.74	3.73	398.4	57.8	8.1
		2	39.58	2.98	319.5	46.3	
7.0	Dry	1	39.67	2.39	255.7	37.1	1.5
		2	39.44	2.51	270.1	39.2	
	Moisture	1	39.50	2.60	279.4	40.5	0.0
		2	35.79	2.36	279.9	40.6	
8.0	Dry	1	41.81	2.04	207.1	30.0	0.8
		2	44.41	2.09	199.7	29.0	
	Moisture	1	39.85	1.70	181.0	26.3	3.5
		2	39.06	1.98	215.1	31.2	
	Dry						
	Moisture						

Create Plot

Clear Plot

Mixing Moisture (%), MC:

Curing Time of Compacte Specimens (hr):

P_b (%)	Avg. G_{mb} (-)	Avg. G_{mm} (-)	AVG. V_a (%)	Avg. IDT Strength (psi)		TSR (%)	CV (%)	
				Dry	Moisture		Dry	Moisture
6.0				50.8	52.1	102.5%	2.9%	15.5%
7.0				38.1	40.6	106.4%	3.9%	0.1%
8.0				29.5	28.7	97.4%	2.6%	12.2%

Optmimum Foamed Asphalt Content (OFC): 6.5%

IDT Strength @ OFC:

Dry Conditioned (psi): 45.0

Moisture Conditioned (psi): 46.5

TSR @ OFC: 103.3%

Page 2 of :

(b)

Figure K.10. Example of Mix Design Report Template; (a) Pg. 1 of 2, (b) Pg. 2 of 2

APPENDIX L.
PROPORTIONING OF AGGREGATE BLENDS

Hot Recycling

Table L.2. Limestone Virgin Aggregate Blend

Sieve Size			#78 Stone		W-10 Screenings		A + B	Limestone Blend	
			A (%)	50	B (%)	50	100	SP-19.0	
(in)	(mm)	^0.45	% Passing	A(%) * %Pass	% Passing	B(%) * %Pass	% Passing	Lower	Upper
1.5"	37.5	5.1	100.0	50.0	100.0	50.0	100.0		100
3/4"	19	3.8	100.0	50.0	100.0	50.0	100.0	90	100
1/2"	12.5	3.1	67.5	33.8	100.0	50.0	83.8		
3/8"	9.5	2.8	19.5	9.8	100.0	50.0	59.8		
#4	4.76	2	4.9	2.4	100.0	50.0	52.4		
#8	2.36	1.5	3.7	1.8	86.7	43.4	45.2	23	49
#16	1.19	1.1	3.2	1.6	64.4	32.2	33.8		
#30	0.595	0.8	3.0	1.5	45.5	22.8	24.3		
#50	0.297	0.6	2.7	1.3	19.2	9.6	10.9		
#100	0.149	0.4	2.1	1.0	4.9	2.5	3.5		
#200	0.074	0.3	1.4	0.7	0.7	0.4	1.1	2	8

Table L.3. Granite Virgin Aggregate Blend

Sieve Size			#78 Stone		W-10 Screenings		A + B	Granite Blend	
			A (%)	40	B (%)	60	100	SP-12.5	
(in)	(mm)	^0.45	% Passing	A(%) * %Pass	% Passing	B(%) * %Pass	% Passing	Lower	Upper
3/4"	19	3.8	100.0	40.0	100.0	60.0	100.0		100
1/2"	12.5	3.1	93.3	37.3	100.0	60.0	97.3	90	100
3/8"	9.5	2.8	49.4	19.8	100.0	60.0	79.8		
#4	4.76	2	11.3	4.5	97.2	58.3	62.8		
#8	2.36	1.5	3.7	1.5	72.0	43.2	44.7	28	58
#16	1.19	1.1	2.0	0.8	47.3	28.4	29.2		
#30	0.595	0.8	1.5	0.6	31.2	18.7	19.3		
#50	0.297	0.6	1.3	0.5	19.7	11.8	12.3		
#100	0.149	0.4	1.1	0.4	9.9	5.9	6.4		
#200	0.074	0.3	0.7	0.3	4.1	2.4	2.7	2	10

Table L.4. Aggregate Blend ABH-60L-L

Sieve Size			Limestone #78 Stone (C-41)		Limestone W-10 Screenings (F22)		Limestone RAP		A + B + C	SP-19	
			A (%)	35	B (%)	5	C (%)	60	100		
In	mm	^0.45	% Passing	A (%) * %Pass	% Passing	B (%) * %Pass	% Passing	C (%) * %Pass	% Passing	Lower	Upper
1.5"	37.5	5.1	100.0	35.0	100.0	5.0	100.0	60.0	100.0		100.0
3/4"	19	3.8	100.0	35.0	100.0	5.0	100.0	60.0	100.0	90.0	100.0
1/2"	12.5	3.1	70.0	24.5	100.0	5.0	100.0	60.0	88.6		
3/8"	9.5	2.8	32.0	11.2	100.0	5.0	96.0	57.6	69.4		
#4	4.76	2	7.0	2.5	100.0	5.0	77.0	46.2	52.9		
#8	2.36	1.5	5.0	1.8	86.7	4.3	62.0	37.2	42.8	23.0	49.0
#16	1.19	1.1	5.0	1.8	64.4	3.2	53.0	31.8	36.2		
#30	0.595	0.8	4.0	1.4	45.5	2.3	46.0	27.6	30.9		
#50	0.297	0.6	4.0	1.4	19.2	1.0	33.0	19.8	21.7		
#100	0.149	0.4	3.0	1.1	4.9	0.2	18.0	10.8	11.8		
#200	0.074	0.3	3.0	1.1	0.7	0.0	8.5	5.1	5.6	2.0	8.0

Table L.5. Aggregate Blend ABH-60G-G

Sieve Size			Granite #78 Stone (C-47)		Granite W-10 Screenings (F22)		Granite/Limestone RAP		A + B + C	SP-12.5	
			A (%)	20	B (%)	20	C (%)	60	100%		
In	mm	^0.45	% Passing	A (%) * %Pass	% Passing	B (%) * %Pass	% Passing	C (%) * %Pass	% Passing	Lower	Upper
1.5"	37.5	5.1	100.0	20.0	100.0	20.0	100.0	60.0	100.0		100.0
3/4"	19	3.8	100.0	20.0	100.0	20.0	100.0	60.0	100.0	90.0	100.0
1/2"	12.5	3.1	93.3	18.7	100.0	20.0	97.0	58.2	88.6		
3/8"	9.5	2.8	49.4	9.9	100.0	20.0	93.0	55.8	69.4		
#4	4.76	2	11.3	2.3	97.2	19.4	71.0	42.6	52.9		
#8	2.36	1.5	3.7	0.7	72.0	14.4	49.0	29.4	42.8	23.0	49.0
#16	1.19	1.1	2.0	0.4	47.3	9.5	39.0	23.4	36.2		
#30	0.595	0.8	1.5	0.3	31.2	6.2	32.0	19.2	30.9		
#50	0.297	0.6	1.3	0.3	19.7	3.9	23.0	13.8	21.7		
#100	0.149	0.4	1.1	0.2	9.9	2.0	13.0	7.8	11.8		
#200	0.074	0.3	0.7	0.1	4.1	0.8	7.4	4.4	5.6	2.0	8.0

Table L.6. Aggregate Blend ABH-60L-G

Sieve Size			Granite #78 Stone (C-47)		Granite W-10 Screenings (F22)		Limestone RAP		A + B + C	SP-12.5	
			A (%)	35	B (%)	5	C (%)	60	100%		
In	mm	^0.45	% Passing	A (%) * %Pass	% Passing	B (%) * %Pass	% Passing	C (%) * %Pass	% Passing	Lower	Upper
1.5"	37.5	5.1	100.0	35.0	100.0	5.0	100.0	60.0	100.0		
3/4"	19	3.8	100.0	35.0	100.0	5.0	100.0	60.0	100.0		100.0
1/2"	12.5	3.1	93.3	32.6	100.0	5.0	100.0	60.0	97.6	90.0	100.0
3/8"	9.5	2.8	49.4	17.3	100.0	5.0	96.0	57.6	79.9		
#4	4.76	2	11.3	4.0	97.2	4.9	77.0	46.2	55.0		
#8	2.36	1.5	3.7	1.3	72.0	3.6	62.0	37.2	42.1	28.0	58.0
#16	1.19	1.1	2.0	0.7	47.3	2.4	53.0	31.8	34.9		
#30	0.595	0.8	1.5	0.5	31.2	1.6	46.0	27.6	29.7		
#50	0.297	0.6	1.3	0.4	19.7	1.0	33.0	19.8	21.2		
#100	0.149	0.4	1.1	0.4	9.9	0.5	18.0	10.8	11.7		
#200	0.074	0.3	0.7	0.3	4.1	0.2	8.5	5.1	5.6	2.0	8.0

Cold Recycling

Table L.7. Aggregate Blend ABC-60L-LE or ABC-60L-LF

Sieve Size			Limestone #78 Stone (C-41)		Limestone W-10 Screenings (F22)		Limestone RAP		A + B + C	SP-19	
			A (%)	25	B (%)	15	C (%)	60	100%		
In	mm	^0.45	% Passing	A (%) * %Pass	% Passing	B (%) * %Pass	% Passing	C (%) * %Pass	% Passing	Lower	Upper
1.5"	37.5	5.1	100.0	25.0	100.0	15.0	100.0	60.0	100.0		100.0
3/4"	19	3.8	100.0	25.0	100.0	15.0	100.0	60.0	100.0	90.0	100.0
1/2"	12.5	3.1	67.5	16.9	100.0	15.0	95.3	57.2	89.0		
3/8"	9.5	2.8	19.5	4.9	100.0	15.0	88.3	53.0	72.9		
#4	4.76	2	4.9	1.2	100.0	15.0	61.9	37.2	53.4		
#8	2.36	1.5	3.7	0.9	86.7	13.0	42.6	25.5	39.5	23.0	49.0
#16	1.19	1.1	3.2	0.8	64.4	9.7	30.1	18.1	28.6		
#30	0.595	0.8	3.0	0.7	45.5	6.8	20.1	12.0	19.6		
#50	0.297	0.6	2.7	0.7	19.2	2.9	8.6	5.2	8.7		
#100	0.149	0.4	2.1	0.5	4.9	0.7	1.6	0.9	2.2		
#200	0.074	0.3	1.4	0.3	0.7	0.1	0.2	0.1	0.6	2.0	8.0

Table L.8. Aggregate Blend ABC-60G-GE

Sieve Size			Granite #78 Stone (C-47)		Granite W-10 Screenings (F22)		Limestone RAP		A + B + C	SP-12.5	
			A (%)	5	B (%)	35	C (%)	60	100%		
In	mm	^0.45	% Passing	A (%) * %Pass	% Passing	B (%) * %Pass	% Passing	C (%) * %Pass	% Passing	Lower	Upper
1.5"	37.5	5.1	100.0	5.0	100.0	35.0	100.0	60.0	100.0		
3/4"	19	3.8	100.0	5.0	100.0	35.0	95.4	57.2	97.2		100.0
1/2"	12.5	3.1	93.3	4.7	100.0	35.0	84.3	50.6	90.2	90.0	100.0
3/8"	9.5	2.8	49.4	2.5	100.0	35.0	72.5	43.5	81.0		
#4	4.76	2	11.3	0.6	97.2	34.0	43.3	26.0	60.5		
#8	2.36	1.5	3.7	0.2	72.0	25.2	23.7	14.2	39.6	28.0	58.0
#16	1.19	1.1	2.0	0.1	47.3	16.6	12.2	7.3	24.0		
#30	0.595	0.8	1.5	0.1	31.2	10.9	2.7	1.6	12.6		
#50	0.297	0.6	1.3	0.1	19.7	6.9	0.3	0.2	7.1		
#100	0.149	0.4	1.1	0.1	9.9	3.5	0.0	0.0	3.5		
#200	0.074	0.3	0.7	0.0	4.1	1.4	0.0	0.0	1.5	2.0	8.0

Table L.9. Aggregate Blend ABC-60L-GF

Sieve Size			Granite #78 Stone (C-47)		Granite W-10 Screenings (F22)		Limestone RAP		A + B + C	SP-12.5	
			A (%)	20	B (%)	20	C (%)	60	100%		
In	mm	^0.45	% Passing	A (%) * %Pass	% Passing	B (%) * %Pass	% Passing	C (%) * %Pass	% Passing	Lower	Upper
1.5"	37.5	5.1	100.0	20.0	100.0	20.0	100.0	60.0	100.0		
3/4"	19	3.8	100.0	20.0	100.0	20.0	100.0	60.0	100.0		100.0
1/2"	12.5	3.1	93.3	18.7	100.0	20.0	95.3	57.2	95.8	90.0	100.0
3/8"	9.5	2.8	49.4	9.9	100.0	20.0	88.3	53.0	82.9		
#4	4.76	2	11.3	2.3	97.2	19.4	61.9	37.2	58.9		
#8	2.36	1.5	3.7	0.7	72.0	14.4	42.6	25.5	40.7	28.0	58.0
#16	1.19	1.1	2.0	0.4	47.3	9.5	30.1	18.1	27.9		
#30	0.595	0.8	1.5	0.3	31.2	6.2	20.1	12.0	18.6		
#50	0.297	0.6	1.3	0.3	19.7	3.9	8.6	5.2	9.4		
#100	0.149	0.4	1.1	0.2	9.9	2.0	1.6	0.9	3.1		
#200	0.074	0.3	0.7	0.1	4.1	0.8	0.2	0.1	1.1	2.0	8.0

APPENDIX M.
MIX DESIGN VOLUMETRIC CALCULATIONS

Hot Recycling

Limestone Virgin Mixture

Table M.1. Bulk Specific Gravity (G_{mb}), Limestone Mixture

$P_{b\text{-}Wagg}$ (%)	6.9
P_b (%)	6.5

Sample	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	H @ N_{Ini} (mm)	H @ N_{des} (mm)
1	4528.00	2533.30	4537.00	2.260	2.358	123.0	115.4
2	4507.30	2500.70	4522.90	2.229		123.8	116.0
			Average	2.245		123.4	115.7

$P_{b\text{-}Wagg}$ (%)	7.5
P_b (%)	7.0

Sample	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	H @ N_{Ini} (mm)	H @ N_{des} (mm)
1	4504.80	2517.60	4508.80	2.262	2.341	122.5	114.6
2	4483.80	2513.30	4492.20	2.266		122.9	114.9
			Average	2.264		122.7	114.8

$P_{b\text{-}Wagg}$ (%)	8.1
P_b (%)	7.5

Sample	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	H @ N_{Ini} (mm)	H @ N_{des} (mm)
1	4506.60	2517.30	4509.00	2.263	2.324	122.3	114.6
2	4506.80	2529.50	4508.90	2.277		122.4	114.4
			Average	2.270		122.3	114.5

$P_{b\text{-}Wagg}$ (%)	8.7
P_b (%)	8.0

Sample	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	H @ N_{Ini} (mm)	H @ N_{des} (mm)
1	4504.30	2528.10	4505.70	2.278	2.308	122.2	113.8
2	4512.60	2546.10	4513.90	2.293		121.5	113.2
			Average	2.286		121.9	113.5

Table M.2. Maximum Specific Gravity (G_{mm}) and Effective Specific Gravity (G_{se}), Limestone Mixture

Aggregates	Sample	P_b (%)	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)	G_{se} (-)
Limestone	1	7.5	1829.4	1571.9	2616.9	2.3322	2.615
	2	7.5	1831.1	1570.0	2610.4	2.3158	2.592

Table M.3. Volumetric Properties, Limestone Mixture

P_b (%)	G_{mb} (-)	G_{mm} (-)	$P_{0.075}$ (%)	P_{ba} (%)	P_{be} (%)	AV (%)	VMA (%)	VFA (%)	DP (%)	$\%G_{mm}$ @N_{ini} (%)	$\%G_{mm}$ @N_{des} (%)
6.5	2.245	2.358	1.9	2.2	4.4	4.8	14.7	67.5	0.4	89.3	95.2
7.0	2.264	2.341	1.9	2.2	4.9	3.3	14.5	77.3	0.4	90.5	96.7
7.5	2.270	2.324	1.9	2.2	5.5	2.3	14.7	84.2	0.3	91.4	97.7
8.0	2.286	2.308	1.9	2.2	6.0	1.0	14.6	93.5	0.3	92.3	99.0

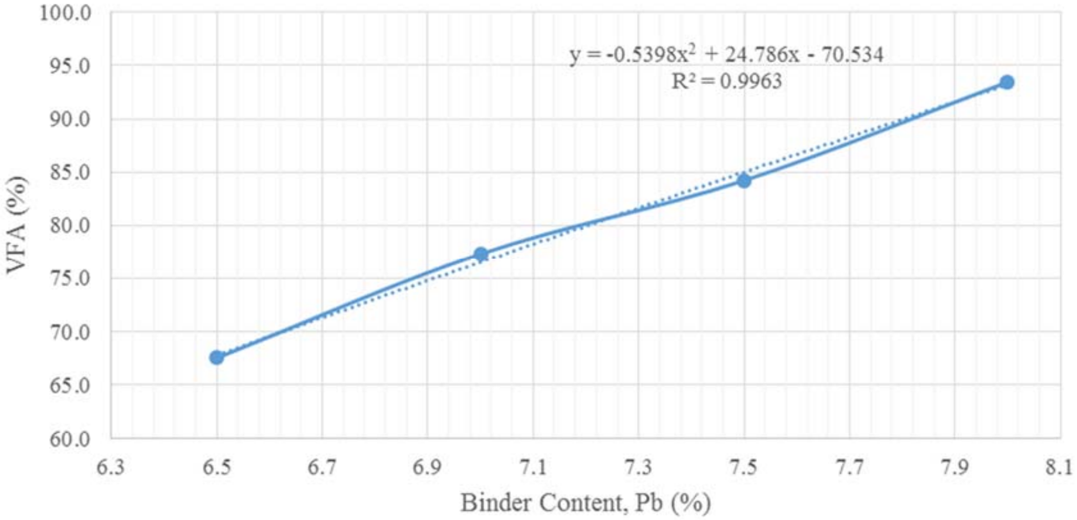


Figure M.1. VFA Results, Limestone Mixture

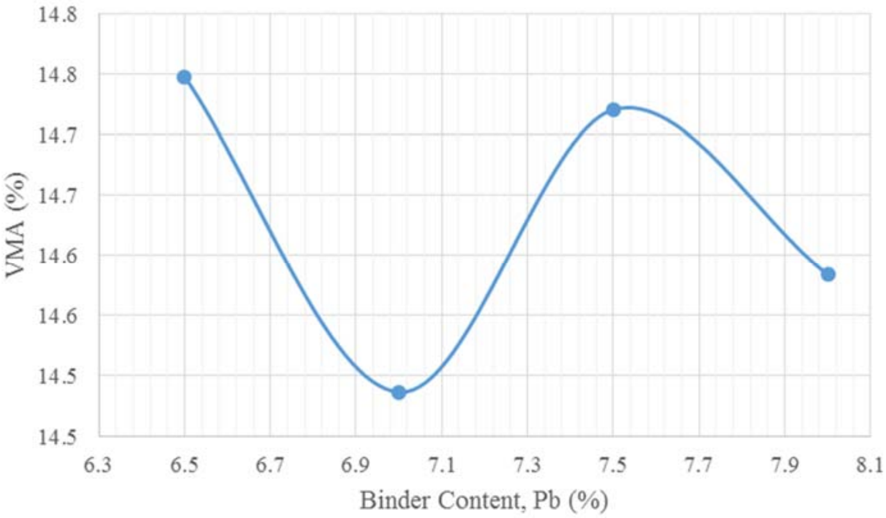


Figure M.2. VMA Results, Limestone Mixture

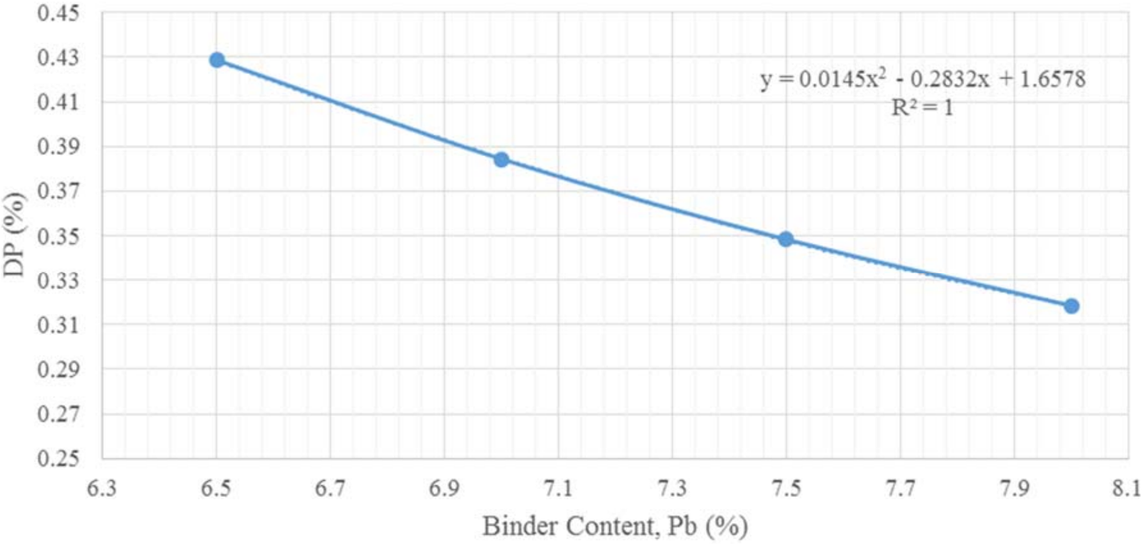


Figure M.3. DP Results, Limestone Mixture

Granite Virgin Mixture

Table M.4. Bulk Specific Gravity (G_{mb}), Granite Mixture

$P_{b\text{-}Wagg}$ (%)	4.4
P_b (%)	5.0

Sample	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	H @ N_{Ini} (mm)	H @ N_{des} (mm)
1	4518.40	2645.50	4541.70	2.383	2.583	118.0	108.9
2	4512.40	2653.90	4533.70	2.400		117.1	108.3
			Average	2.392		117.5	108.6

$P_{b\text{-}Wagg}$ (%)	4.9
P_b (%)	5.5

Sample	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	H @ N_{Ini} (mm)	H @ N_{des} (mm)
1	4521.40	2657.30	4531.20	2.413	2.562	117.6	108.3
2	4512.30	2660.90	4522.20	2.424		116.8	107.7
			Average	2.419		117.2	108.0

$P_{b\text{-}Wagg}$ (%)	6.4
P_b (%)	6.0

Sample	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	H @ N_{Ini} (mm)	H @ N_{des} (mm)
1	4519.10	2658.60	4525.30	2.421	2.541	117.4	107.9
2	4513.00	2662.60	4518.70	2.431		117.0	107.4
			Average	2.426		117.2	107.6

$P_{b\text{-}Wagg}$ (%)	7.0
P_b (%)	6.5

Sample	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	H @ N_{Ini} (mm)	H @ N_{des} (mm)
1	4512.20	2680.90	4514.10	2.461	2.520	115.1	105.8
2	4519.40	2686.60	4521.00	2.464		115.9	106.1
			Average	2.463		115.5	106.0

Table M.5. Maximum Specific Gravity (G_{mm}) and Effective Specific Gravity (G_{se}), Granite Mixture

Aggregates	Sample	P_b (%)	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)	G_{se} (-)
Granite	1	5.0	1831.4	1572	2694.7	2.5842	2.819
	2	5.0	1815.6	1569.8	2682.4	2.5826	2.817

Table M.6. Volumetric Properties, Granite Mixture

P_b (%)	G_{mb} (-)	G_{mm} (-)	$P_{0.075}$ (%)	P_{ba} (%)	P_{be} (%)	AV (%)	VMA (%)	VFA (%)	DP (%)	%G_{mm} @N_{ini} (%)	%G_{mm} @N_{des} (%)
5.0	2.392	2.583	3.5	0.8	4.2	7.4	17.5	57.7	0.8	85.6	92.6
5.5	2.419	2.562	3.5	0.8	4.7	5.6	17.0	67.2	0.7	87.0	94.4
6.0	2.426	2.541	3.5	0.8	5.2	4.5	17.2	73.7	0.7	87.7	95.5
6.5	2.463	2.520	3.5	0.8	5.7	2.3	16.4	86.2	0.6	89.7	97.7

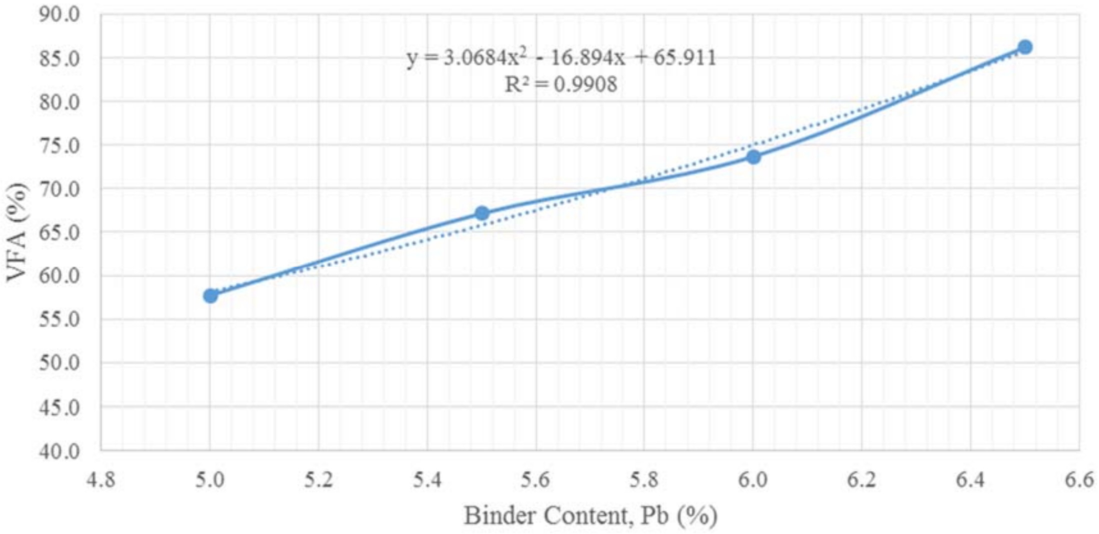


Figure M.4. VFA Results, Granite Mixture

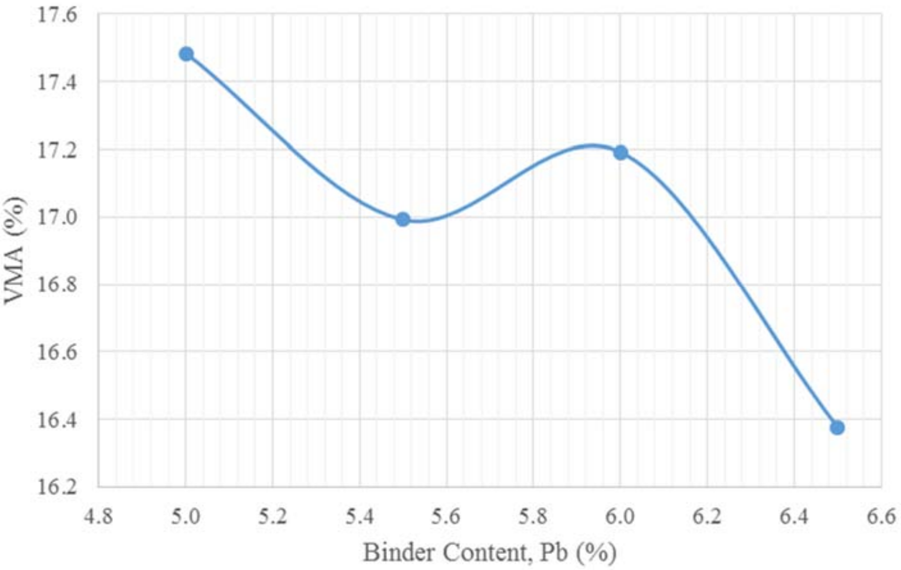


Figure M.5. VMA Results, Granite Mixture

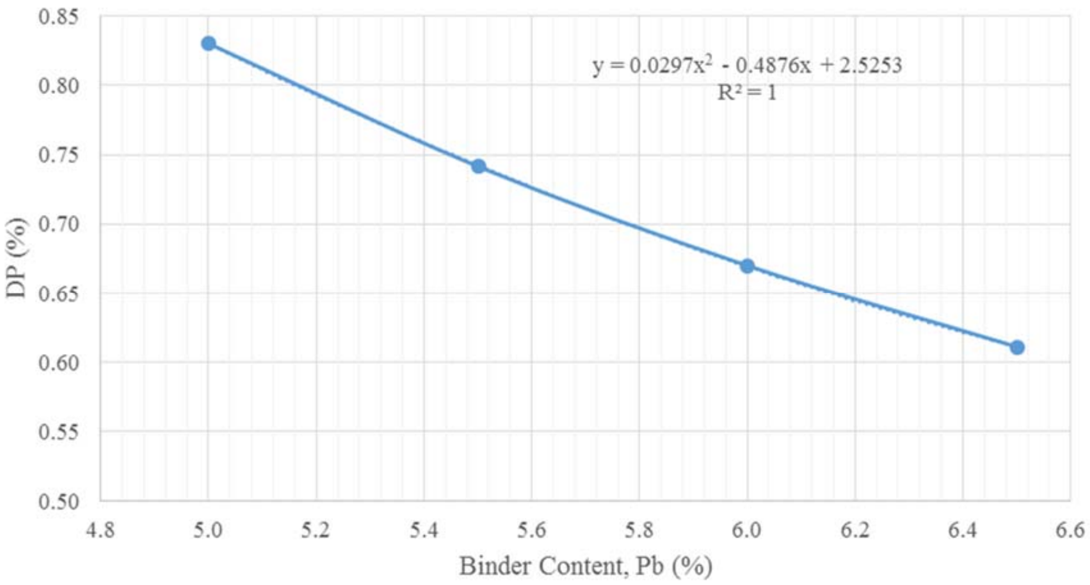


Figure M.6. DP Results, Granite Mixture

Recycled Mixtures

Table M.7. Maximum Specific Gravity (G_{mm}) and Effective Specific Gravity (G_{se}), RAP Sources

RAP	Sample	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)	$G_{mm\ avg}$ (-)
STK 09	1	2208.2	1512.1	2810.9	2.428	2.427
	2	1993.4	1488.6	2660.1	2.425	
STK 16	1	2203.8	1512.1	2835.8	2.504	2.509
	2	2196.8	1488.6	2811.9	2.515	

RAP	$G_{mm\ avg}$ (-)	P_b (%)	P_{ba} (%)	G_{se} (-)	G_{sb} (-)
STK 09	2.427	5.4	1.75	2.642	2.525
STK 16	2.509	4.8	1.5	2.716	2.610

Table M.8. Bulk Specific Gravity (G_{mb}), Recycled Mixtures

			P_w (%)	$P_w/G_{sb\ i}$
H-60L-L	$G_{sb\text{ (OD) W-10}}$	2.520	5	1.98
	$G_{sb\text{ (OD) C-41}}$	2.407	35	14.54
	$G_{sb\text{ (OD) RAP STK 09}}$	2.525	60	23.76
			G_{mb} (-)	2.482

			P_w (%)	$P_w/G_{sb\ i}$
H-60G-G	$G_{sb\text{ (OD) W-10}}$	2.740	20	7.30
	$G_{sb\text{ (OD) C-47}}$	2.775	20	7.21
	$G_{sb\text{ (OD) RAP STK 16}}$	2.610	60	22.99
			G_{mb} (-)	2.667

			P_w (%)	$P_w/G_{sb\ i}$
H-60L-G	$G_{sb\text{ (OD) W-10}}$	2.740	5	1.82
	$G_{sb\text{ (OD) C-47}}$	2.775	35	12.61
	$G_{sb\text{ (OD) RAP STK 09}}$	2.525	60	23.76
			G_{mb} (-)	2.618

Table M.9. Maximum Specific Gravity (G_{mm}), Recycled Mixtures

Mix ID	$W_{mix\text{-}loose}$ (g)	$W_{pyc\text{ (soak)}}$ (g)	$W_{spyc+mix\text{ (soak)}}$ (g)	G_{mm} (-)	G_{mm} (-)
H-60L-L	1816.9	1512.8	2549.9	2.330	2.343
	1849.9	1489.6	2554.1	2.355	
H-60L-G	1375.9	1512.8	2328.8	2.457	2.460
	1380.1	1489.6	2309.3	2.463	
H-60G-G	1834.1	1512.8	2610.4	2.490	2.493
	1859.8	1489.6	2604.2	2.496	

Table M.10. Effective Specific Gravity (G_{se}), Recycled Mixtures

Mix ID	P_b (%)	G_{mm} (-)	G_{se} (-)	$G_{sb\text{ (OD)}}$
H-60L-L	6.8	2.343	2.598	2.482
H-60G-G	6.0	2.493	2.756	2.667
H-60L-G	6.0	2.460	2.713	2.618

Table M.11. Volumetric Properties, Recycled Mixtures

Mixture	NMAS	P_b (%)	G_{mb} (-)	G_{se} (-)	G_{mm} (-)	$P_{0.075}$ (%)	P_{ba} (%)	P_{be} (%)	AV (%)	VMA (%)	VFA (%)	%G_{mm} @N_{ini} (%)	%G_{mm} @N_{des} (%)	DP (%)
H-60L-L	SP-19.0	6.8	2.340	2.598	2.343	5.6	1.8	5.1	0.1	12.1	98.9	95.1	99.9	1.1
H-60G-G	SP-12.5	6.0	2.455	2.756	2.493	5.4	1.2	4.9	1.5	7.0	78.3	90.8	98.5	1.1
H-60L-G	SP-12.5	6.0	2.438	2.713	2.460	5.6	1.3	4.7	0.9	7.7	88.4	92.6	99.1	1.2

Cold Recycling with Emulsion

Table M.12. Tensile Strength, C-100L-E Mixture

Conditioning	Residual Binder Content (%)	Sample	Height (mm)					Peak Load (kN)	Tensile Strength, S_t (kPa)
			1	2	3	4	Average		
Dry	3.0	2	39.24	39.36	39.30	39.23	39.28	3.31	357.6
		4	39.45	39.33	39.24	39.36	39.35	3.18	343.0
	3.9	3	39.64	39.68	39.79	39.56	39.67	2.39	255.7
		5	39.64	39.45	39.30	39.38	39.44	2.51	270.1
	4.8	1	41.85	42.08	41.71	41.59	41.81	2.04	207.1
		3	39.15	59.87	39.49	39.13	44.41	2.09	199.7
Soaked	3.0	1	39.97	39.72	39.95	39.31	39.74	3.73	398.4
		3	39.82	39.47	39.58	39.46	39.58	2.98	319.5
	3.9	2	39.63	39.23	39.45	39.67	39.50	2.60	279.4
		4	35.65	35.61	36.38	35.51	35.79	2.36	279.9
	4.8	2	39.92	39.71	39.62	40.16	39.85	1.70	181.0
		4	39.10	39.12	39.14	38.88	39.06	1.98	215.1

Table M.13. Tensile Strength, C-60L-LE Mixture

Conditioning	Residual Binder Content (%)	Sample	Height (mm)					Peak Load (kN)	Tensile Strength, S_t (kPa)
			1	2	3	4	Average		
Dry	3.0	4	42.74	42.54	42.38	42.21	42.47	3.47	346.8
		5	41.04	40.68	40.77	40.76	40.81	3.4	353.6
	3.9	2	41.34	41.42	41.50	41.37	41.41	2.45	251.1
		3	41.19	41.34	41.09	41.01	41.16	2.38	245.4
	4.8	3	41.12	41.26	41.30	41.28	41.24	2.74	282.0
		5	40.70	41.05	40.96	40.63	40.84	2.06	214.1
Soaked	3.0	2	41.72	41.77	41.52	41.63	41.66	3.53	359.6
		3	41.86	41.66	41.68	41.63	41.71	4.40	447.7
	3.9	1	40.57	40.74	41.00	41.12	40.86	2.47	256.6
		4	41.06	41.15	40.88	40.98	41.02	2.19	226.6
	4.8	1	40.85	40.43	40.10	40.35	40.43	3.34	350.6
		5	40.80	40.64	40.53	40.93	40.73	2.27	236.6

Table M.14. Tensile Strength, C-60G-GE Mixture

Specimen Conditioning	Residual Binder Content (%)	Sample	Height (mm)					Peak Load (kN)	Tensile Strength, S_t (kPa)
			1	2	3	4	Average		
Dry	2.0	2	43.57	43.14	43.42	43.52	43.41	2.56	250.3
		3	43.14	43.13	42.98	43.03	43.07	2.99	294.6
	3.0	3	41.67	41.42	41.51	41.87	41.62	3.94	401.8
		4	41.46	41.80	41.75	41.72	41.68	3.91	398.1
	4.0	3	41.87	42.00	41.95	41.70	41.88	3.9	395.2
		4	42.36	42.48	42.64	42.37	42.46	3.92	391.8
Soaked	2.0	1	43.62	43.06	43.03	43.18	43.22	2.47	242.5
	3.0	1	42.08	41.53	41.31	41.67	41.65	3.62	368.9
		2	41.80	41.53	41.31	41.67	41.58	3.41	348.1
	4.0	1	41.78	41.83	41.59	41.63	41.71	3.99	406.0
		2	40.87	40.62	40.82	40.98	40.82	3.80	395.1

Cold Recycling With Foamed Binder

Trial Mixtures ABC-60L-LF Aggregate blend, P_b= 5%, No MC

Table M.15. Maximum Specific Gravity (G_{mm}), ABC-60L-LF Mixture

Sample	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)
1	2288.4	1512.9	2826.5	2.348

Table M.16. Bulk Specific Gravity (G_{mb}), ABC-60L-LF Mixture

P_b (%)	5.0

Sample	Height (mm)					W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV%
	1	2	3	4	Average						
1	69.92	69.97	70.38	69.87	70.04	1099.50	612.00	1139.00	2.086	2.348	11.1
2	65.78	70.78	70.59	67.47	68.66	1054.80	580.70	1089.50	2.073	2.348	11.7
3	68.42	69.02	68.75	68.21	68.60	1102.20	609.30	1129.00	2.121	2.348	9.7
4	67.94	68.1	68.37	68.55	68.24	1068.40	598.00	1104.50	2.109	2.348	10.2
								Average	2.097		

C-60L-GF Mixture

Table M.17. Maximum Specific Gravity (G_{mm}), C-60L-GF Mixture

P_b (%)	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)
2.0	2126.5	1488.4	2753.1	2.468
4.0	2154.1	1488.4	2743.2	2.395
6.0	2166.8	1488.4	2727.3	2.335

Table M.18. Bulk Specific Gravity (G_{mb}), C-60L-GF Mixture

C-60L-GF	
P_b (%)	2.0

Sample	**Height (mm)**					**W_{Dry} (g)**	**W_{soak} (g)**	**W_{SSD} (g)**	**G_{mb} (-)**	**G_{mm} (-)**	**AV%**
	1	**2**	**3**	**4**	**Average**						
1	69.53	69.36	68.01	68.87	68.94	1066.10	563.10	1079.10	2.066	2.468	16.3
2	70.12	70.21	70.29	70.29	70.23	1074.10	567.90	1088.40	2.064	2.468	16.4
3	70.35	70.31	70.64	70.36	70.42	1075.30	565.90	1093.20	2.039	2.468	17.4
4	70.14	70.42	71.11	69.17	70.21	1094.90	583.80	1112.40	2.071	2.468	16.1
								Average	2.060		

C-60L-GF	
P_b (%)	4.0

Sample	**Height (mm)**					**W_{Dry} (g)**	**W_{soak} (g)**	**W_{SSD} (g)**	**G_{mb} (-)**	**G_{mm} (-)**	**AV%**
	1	**2**	**3**	**4**	**Average**						
1	70.2	70.42	70.33	70.32	70.32	1080.00	562.50	1094.40	2.030	2.395	15.3
2	70.79	70.79	70.44	70.28	70.58	1087.70	567.20	1101.80	2.035	2.395	15.0
3	70.223	69.78	70.13	70.34	70.12	1083.00	565.90	1097.20	2.038	2.395	14.9
4	69.84	69.42	69.53	69.46	69.56	1075.80	563.70	1090.30	2.043	2.395	14.7
								Average	2.037		

C-60L-GF	
P_b (%)	6.0

Sample	**Height (mm)**					**W_{Dry} (g)**	**W_{soak} (g)**	**W_{SSD} (g)**	**G_{mb} (-)**	**G_{mm} (-)**	**AV%**
	1	**2**	**3**	**4**	**Average**						
1	69.62	69.78	70.9	69.43	69.93	1085.50	567.60	1096.80	2.051	2.335	12.2
2	70.04	70.41	70.25	70.05	70.19	1084.60	568.40	1098.60	2.046	2.335	12.4
3	70.36	70.31	70.58	70.59	70.46	1100.10	572.10	1110.80	2.042	2.335	12.6
4	70.41	70.42	69.99	71.04	70.47	1095.20	575.00	1108.20	2.054	2.335	12.0
								Average	2.048		

C-60L-LF Mixture

Table M.19. Maximum Specific Gravity (G_{mm}), C-60L-LF Mixture

P_b (%)	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)
2.0	2126	1512.5	2761.2	2.423
4.0	2063.6	1512.5	2700.3	2.356
6.0	2187	1512.5	2740	2.279

Table M.20. Bulk Specific Gravity (G_{mb}), C-60L-LF Mixture

C-60L-LF	
P_b (%)	2.0

Sample	Height (mm)					W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV%
	1	2	3	4	Average						
1	71.35	71.48	71.41	71.14	71.35	1082.00	556.10	1096.50	2.002	2.423	17.4
2	70.17	71.05	71.37	71.23	70.96	1075.70	554.90	1093.40	1.998	2.423	17.6
3	71.51	71.63	71.55	71.67	71.59	1080.30	558.40	1102.90	1.984	2.423	18.1
4	69.64	71.33	71.42	71.15	70.89	1067.70	553.00	1088.10	1.995	2.423	17.7
								Average	1.995		

C-60L-LF	
P_b (%)	4.0

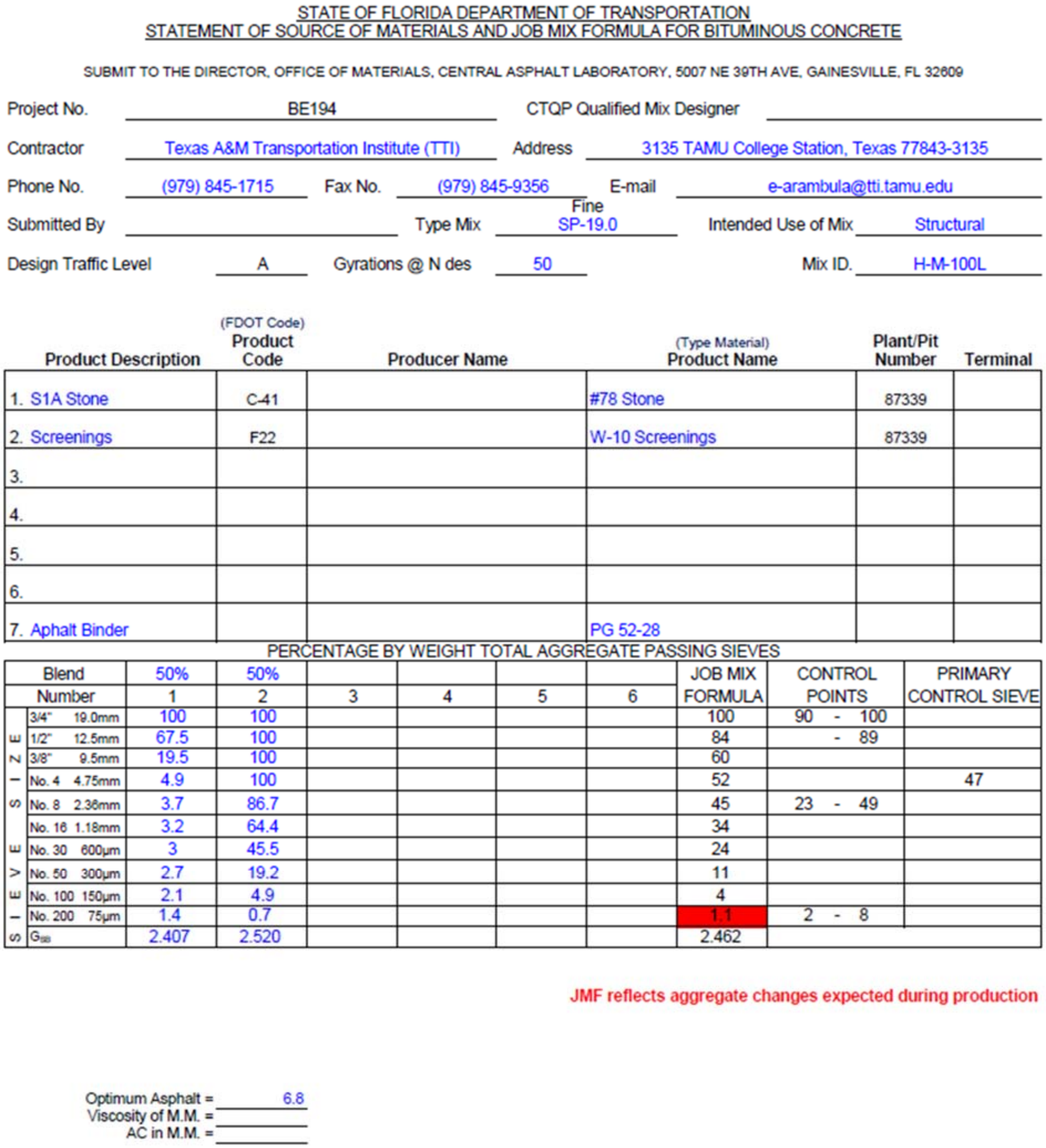
Sample	Height (mm)					W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV%
	1	2	3	4	Average						
1	71.76	71.75	71.16	70.92	71.40	1067.80	545.50	1082.60	1.988	2.356	15.6
2	72	70.83	70.7	71.16	71.17	1055.40	543.30	1072.70	1.994	2.356	15.4
3	71.22	71.91	72.49	72.22	71.96	1077.30	547.90	1089.60	1.989	2.356	15.6
4	73.33	73.03	72.67	71.61	72.66	1086.50	556.80	1103.50	1.987	2.356	15.7
								Average	1.990		

C-60L-LF	
P_b (%)	6.0

Sample	Height (mm)					W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV%
	1	2	3	4	Average						
1	72.95	73.13	72.37	72.39	72.71	1105.50	556.60	1113.20	1.986	2.279	12.9
2	72.76	72.55	72.62	72.8	72.68	1100.70	555.50	1109.60	1.986	2.279	12.9
3	71.94	71.48	71.66	72.02	71.78	1095.50	552.70	1102.80	1.991	2.279	12.6
4	72.25	72.41	72.45	71.91	72.26	1090.50	551.70	1102.00	1.982	2.279	13.0
								Average	1.986		

APPENDIX N.
HOT-MIX DESIGN RESULTS—FDOT FORMAT

Limestone Virgin Mixture



STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR BITUMINOUS CONCRETE

SUBMIT TO THE DIRECTOR, OFFICE OF MATERIALS, CENTRAL ASPHALT LABORATORY, 5007 NE 39TH AVE, GAINESVILLE, FL 32609

Project No. BE194
CTQP Qualified Mix Designer
Contractor Texas A&M Transportation Institute (TTI)
Address 3135 TAMU College Station, Texas 77843-3135
Phone No. (979) 845-1715
Fax No. (979) 845-9356
E-mail e-arambula@tti.tamu.edu
Submitted By
Type Mix Fine SP-19.0
Intended Use of Mix Structural
Design Traffic Level A
Gyrations @ N des 50
Mix ID. H-M-100L

Product Description	(FDOT Code) Product Code	Producer Name	(Type Material) Product Name	Plant/Pit Number	Terminal
1. S1A Stone	C-41		#78 Stone	87339	
2. Screenings	F22		W-10 Screenings	87339	
3.					
4.					
5.					
6.					
7. Aphalt Binder			PG 52-28		

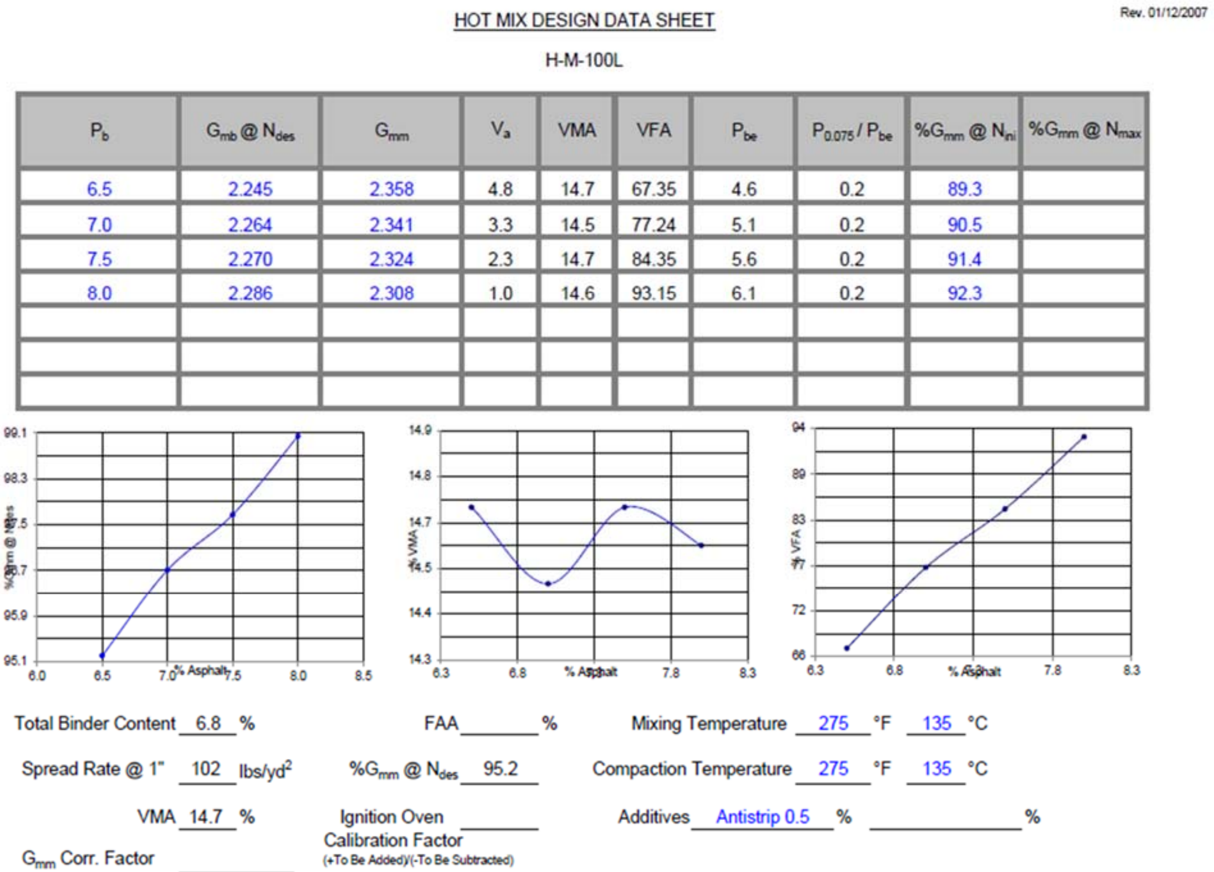
PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

	Blend	50%	50%					JOB MIX	CONTROL	PRIMARY
	Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
SIEVE SIZE	3/4" 19.0mm	100	100					100	90 - 100	
	1/2" 12.5mm	67.5	100					84	- 89	
	3/8" 9.5mm	19.5	100					60		
	No. 4 4.75mm	4.9	100					52		47
	No. 8 2.36mm	3.7	86.7					45	23 - 49	
	No. 16 1.18mm	3.2	64.4					34		
	No. 30 600µm	3	45.5					24		
	No. 50 300µm	2.7	19.2					11		
	No. 100 150µm	2.1	4.9					4		
	No. 200 75µm	1.4	0.7					1.1	2 - 8	
	G_{SB}	2.407	2.520					2.462		

JMF reflects aggregate changes expected during production

Optimum Asphalt = 6.8
Viscosity of M.M. =
AC in M.M. =

Figure N.1. Mix Design FDOT Format Page 1, Limestone Mixture



Rev. 01/12/2007

HOT MIX DESIGN DATA SHEET

H-M-100L

P_b	G_{mb} @ N_{des}	G_{mm}	V_a	VMA	VFA	P_{be}	$P_{0.075}$ / P_{be}	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}
6.5	2.245	2.358	4.8	14.7	67.35	4.6	0.2	89.3	
7.0	2.264	2.341	3.3	14.5	77.24	5.1	0.2	90.5	
7.5	2.270	2.324	2.3	14.7	84.35	5.6	0.2	91.4	
8.0	2.286	2.308	1.0	14.6	93.15	6.1	0.2	92.3	

Total Binder Content 6.8 %

FAA ________ %

Mixing Temperature 275 °F 135 °C

Spread Rate @ 1" 102 lbs/yd^2

%G_{mm} @ N_{des} 95.2

Compaction Temperature 275 °F 135 °C

VMA 14.7 %

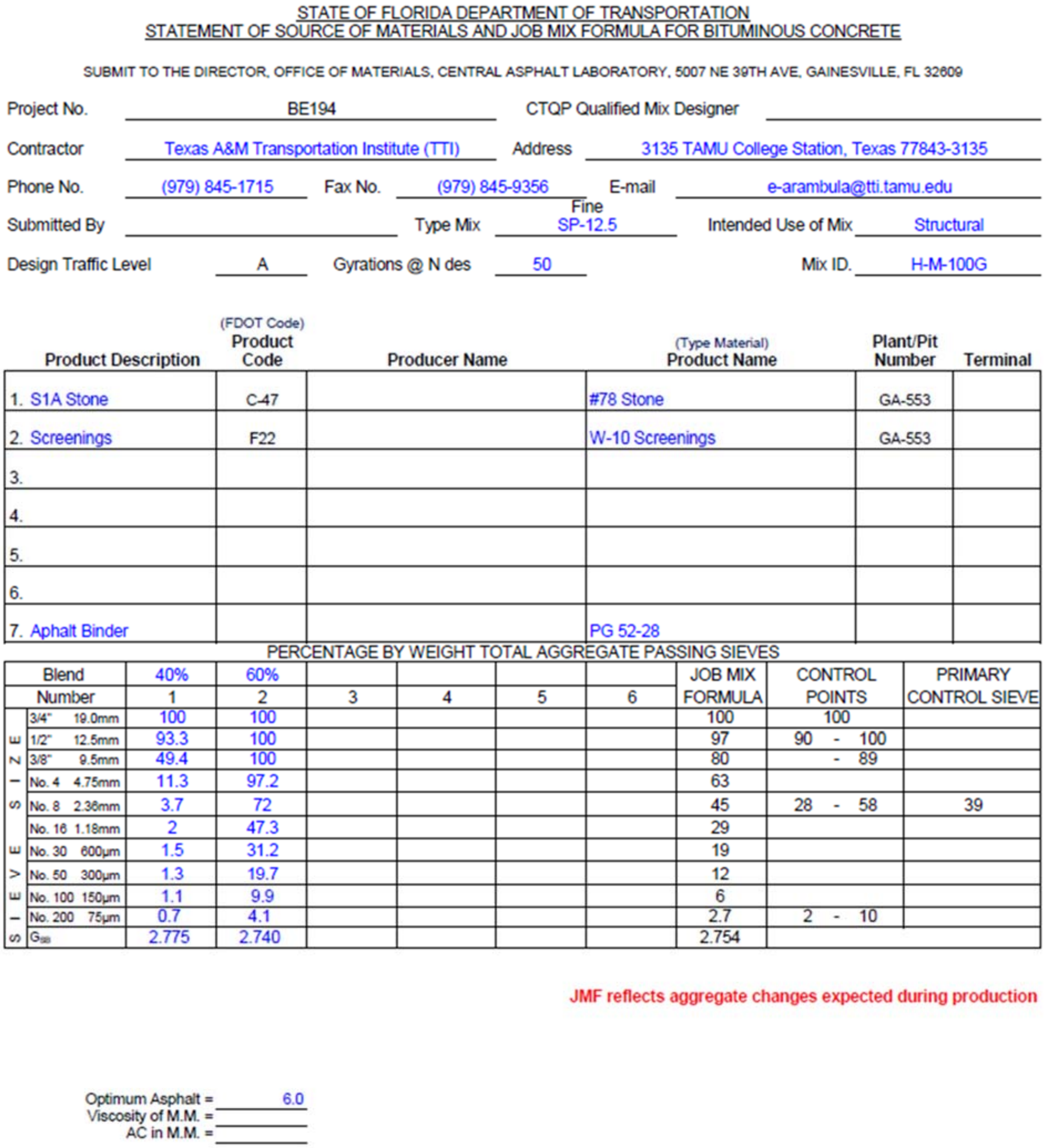
Ignition Oven Calibration Factor ________
(+To Be Added)/(-To Be Subtracted)

Additives Antistrip 0.5 % ______________ %

G_{mm} Corr. Factor ___________

Figure N.2. Mix Design FDOT Format Page 2, Limestone Mixture

Granite Virgin Mixture



STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR BITUMINOUS CONCRETE

SUBMIT TO THE DIRECTOR, OFFICE OF MATERIALS, CENTRAL ASPHALT LABORATORY, 5007 NE 39TH AVE, GAINESVILLE, FL 32609

Project No. BE194
CTQP Qualified Mix Designer
Contractor Texas A&M Transportation Institute (TTI)
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E-mail e-arambula@tti.tamu.edu
Submitted By
Type Mix Fine SP-12.5
Intended Use of Mix Structural
Design Traffic Level A
Gyrations @ N des 50
Mix ID. H-M-100G

Product Description	(FDOT Code) Product Code	Producer Name	(Type Material) Product Name	Plant/Pit Number	Terminal
1. S1A Stone	C-47		#78 Stone	GA-553	
2. Screenings	F22		W-10 Screenings	GA-553	
3.					
4.					
5.					
6.					
7. Aphalt Binder			PG 52-28		

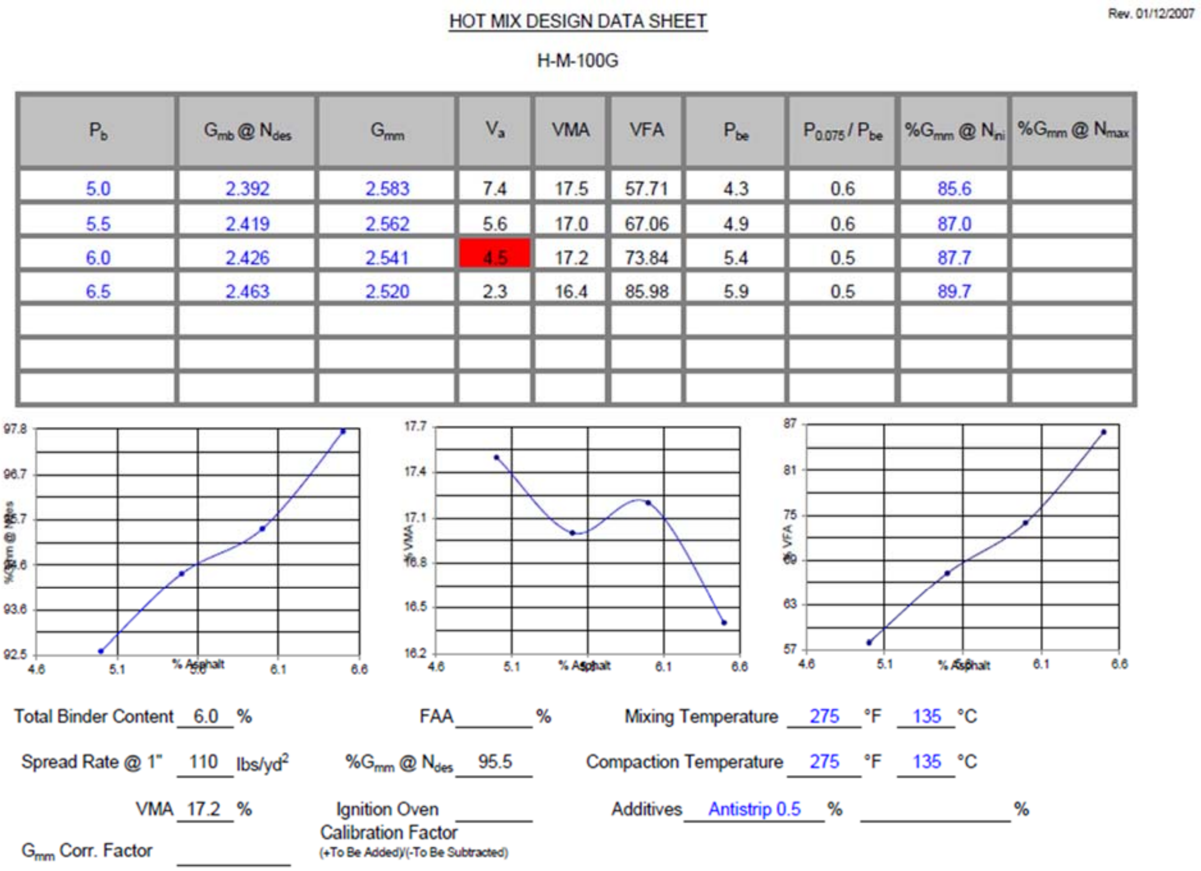
PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

	Blend	40%	60%					JOB MIX	CONTROL	PRIMARY
	Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
SIEVE SIZE	3/4" 19.0mm	100	100					100	100	
	1/2" 12.5mm	93.3	100					97	90 - 100	
	3/8" 9.5mm	49.4	100					80	- 89	
	No. 4 4.75mm	11.3	97.2					63		
	No. 8 2.36mm	3.7	72					45	28 - 58	39
	No. 16 1.18mm	2	47.3					29		
	No. 30 600μm	1.5	31.2					19		
	No. 50 300μm	1.3	19.7					12		
	No. 100 150μm	1.1	9.9					6		
	No. 200 75μm	0.7	4.1					2.7	2 - 10	
	G_{sb}	2.775	2.740					2.754		

JMF reflects aggregate changes expected during production

Optimum Asphalt = 6.0
Viscosity of M.M. =
AC in M.M. =

Figure N.3. Mix Design FDOT Format Page 1, Granite Mixture



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HOT MIX DESIGN DATA SHEET

H-M-100G

P_b	G_{mb} @ N_{des}	G_{mm}	V_a	VMA	VFA	P_{be}	$P_{0.075}$ / P_{be}	%G_{mm} @ N_{ini}	%G_{mm} @ N_{max}
5.0	2.392	2.583	7.4	17.5	57.71	4.3	0.6	85.6	
5.5	2.419	2.562	5.6	17.0	67.06	4.9	0.6	87.0	
6.0	2.426	2.541	4.5	17.2	73.84	5.4	0.5	87.7	
6.5	2.463	2.520	2.3	16.4	85.98	5.9	0.5	89.7	

Total Binder Content 6.0 %

FAA ______ %

Mixing Temperature 275 °F 135 °C

Spread Rate @ 1" 110 lbs/yd^2

%G_{mm} @ N_{des} 95.5

Compaction Temperature 275 °F 135 °C

VMA 17.2 %

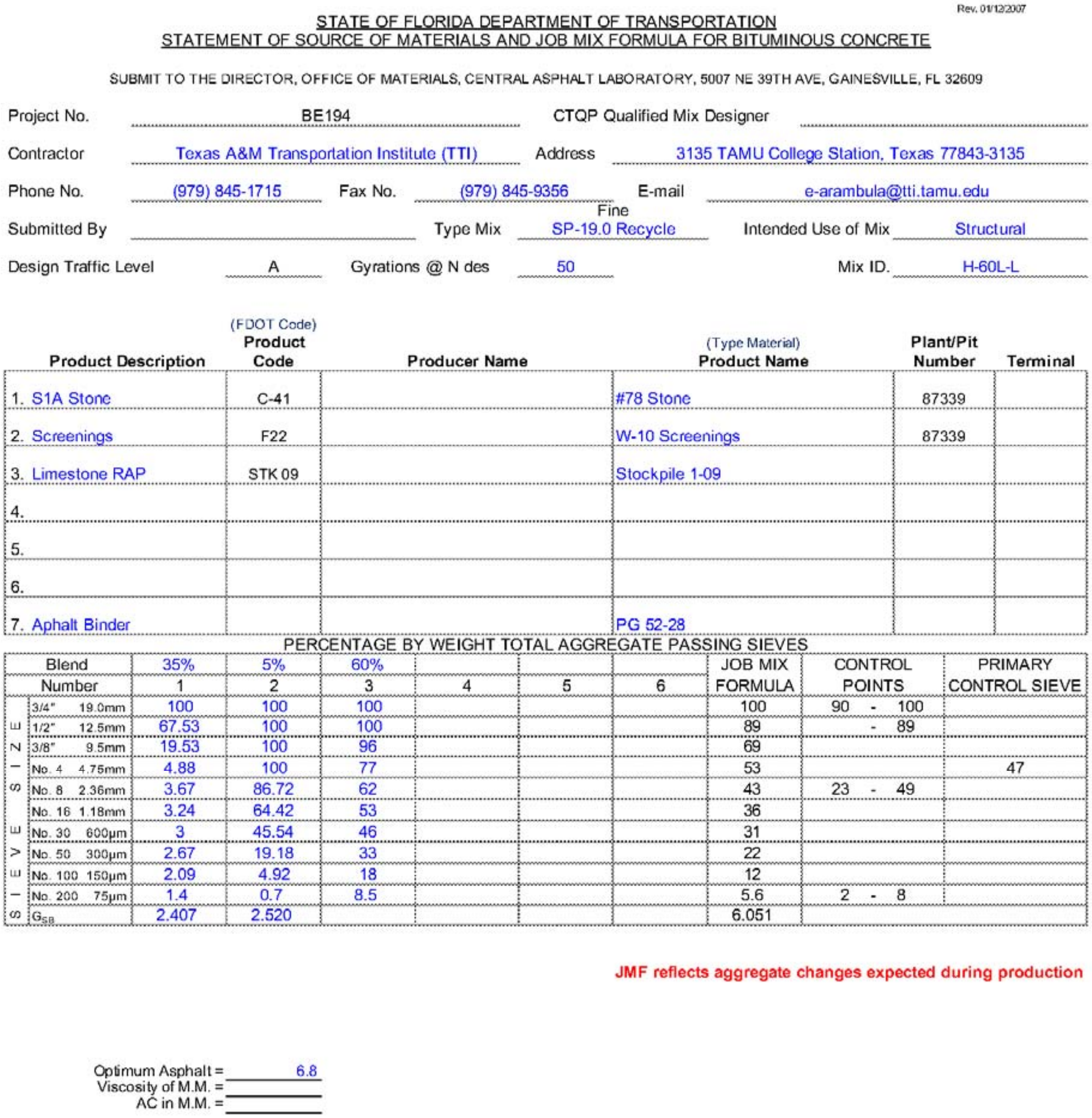
Ignition Oven Calibration Factor ______
(+To Be Added)/(-To Be Subtracted)

Additives Antistrip 0.5 % ______ %

G_{mm} Corr. Factor ______

Figure N.4. Mix Design FDOT Format Page 2, Granite Mixture

Recycled Limestone Mixture with Limestone RAP



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STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR BITUMINOUS CONCRETE

SUBMIT TO THE DIRECTOR, OFFICE OF MATERIALS, CENTRAL ASPHALT LABORATORY, 5007 NE 39TH AVE, GAINESVILLE, FL 32609

Project No. BE194 CTQP Qualified Mix Designer

Contractor Texas A&M Transportation Institute (TTI) Address 3135 TAMU College Station, Texas 77843-3135

Phone No. (979) 845-1715 Fax No. (979) 845-9356 E-mail e-arambula@tti.tamu.edu

Submitted By Type Mix Fine SP-19.0 Recycle Intended Use of Mix Structural

Design Traffic Level A Gyrations @ N des 50 Mix ID. H-60L-L

Product Description	(FDOT Code) Product Code	Producer Name	(Type Material) Product Name	Plant/Pit Number	Terminal
1. S1A Stone	C-41		#78 Stone	87339	
2. Screenings	F22		W-10 Screenings	87339	
3. Limestone RAP	STK 09		Stockpile 1-09		
4.					
5.					
6.					
7. Aphalt Binder			PG 52-28		

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

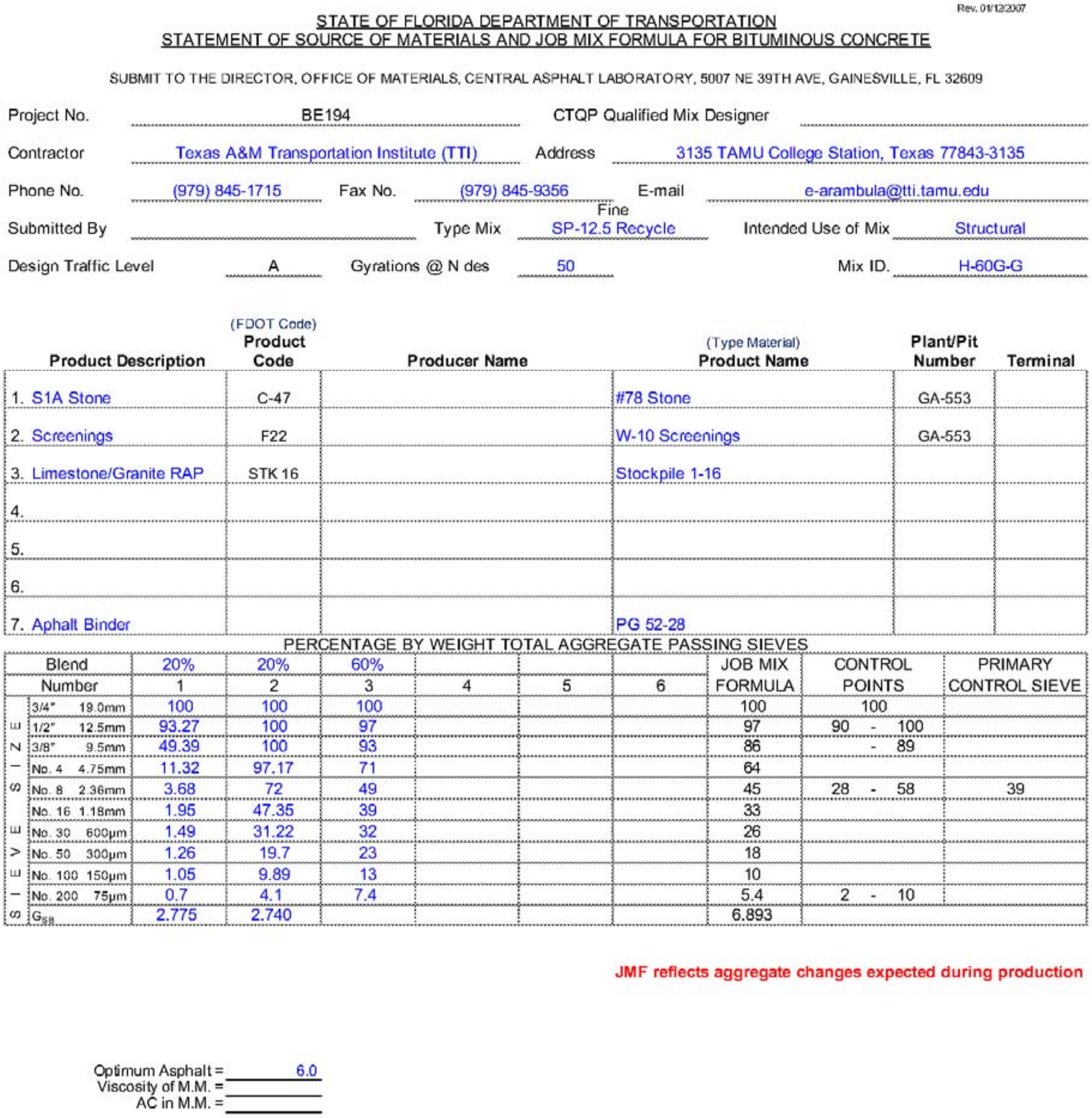
Blend	35%	5%	60%				JOB MIX	CONTROL	PRIMARY
Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
SIEVE SIZE 3/4" 19.0mm	100	100	100				100	90 - 100	
1/2" 12.5mm	67.53	100	100				89	- 89	
3/8" 9.5mm	19.53	100	96				69		
No. 4 4.75mm	4.88	100	77				53		47
No. 8 2.36mm	3.67	86.72	62				43	23 - 49	
No. 16 1.18mm	3.24	64.42	53				36		
No. 30 600μm	3	45.54	46				31		
No. 50 300μm	2.67	19.18	33				22		
No. 100 150μm	2.09	4.92	18				12		
No. 200 75μm	1.4	0.7	8.5				5.6	2 - 8	
G_{SB}	2.407	2.520					6.051		

JMF reflects aggregate changes expected during production

Optimum Asphalt = 6.8
Viscosity of M.M. =
AC in M.M. =

Figure N.5. Mix Design FDOT Format, Recycled Limestone Mixture with Limestone RAP

Recycled Granite Mixture with Granite/limestone RAP



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STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR BITUMINOUS CONCRETE

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CTQP Qualified Mix Designer
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E-mail e-arambula@tti.tamu.edu
Submitted By
Type Mix Fine SP-12.5 Recycle
Intended Use of Mix Structural
Design Traffic Level A
Gyrations @ N des 50
Mix ID. H-60G-G

Product Description	(FDOT Code) Product Code	Producer Name	(Type Material) Product Name	Plant/Pit Number	Terminal
1. S1A Stone	C-47		#78 Stone	GA-553	
2. Screenings	F22		W-10 Screenings	GA-553	
3. Limestone/Granite RAP	STK 16		Stockpile 1-16		
4.					
5.					
6.					
7. Aphalt Binder			PG 52-28		

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

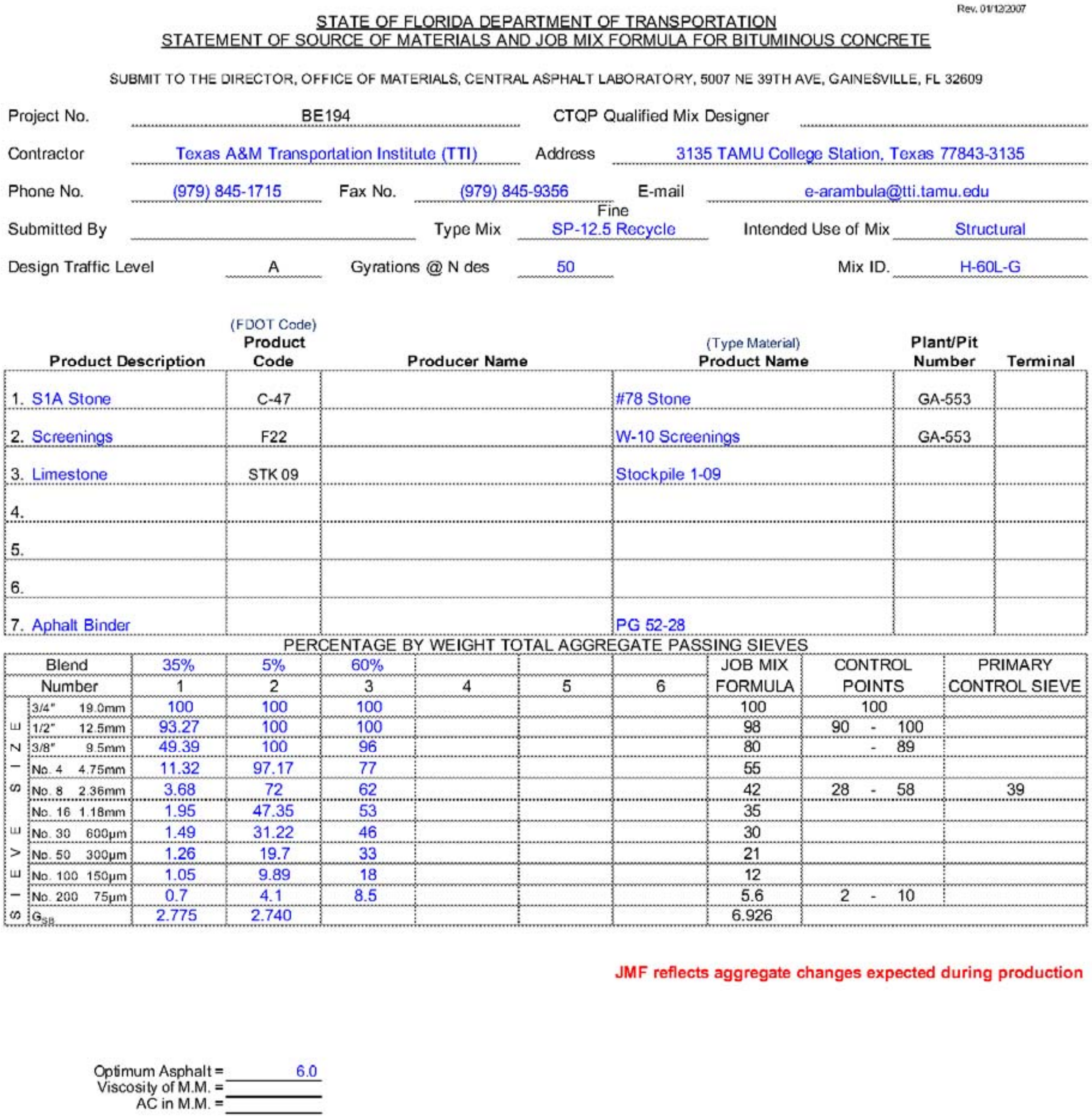
	Blend	20%	20%	60%				JOB MIX	CONTROL	PRIMARY
	Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
SIEVE SIZE	3/4" 19.0mm	100	100	100				100	100	
	1/2" 12.5mm	93.27	100	97				97	90 - 100	
	3/8" 9.5mm	49.39	100	93				86	- 89	
	No. 4 4.75mm	11.32	97.17	71				64		
	No. 8 2.36mm	3.68	72	49				45	28 - 58	39
	No. 16 1.18mm	1.95	47.35	39				33		
	No. 30 600μm	1.49	31.22	32				26		
	No. 50 300μm	1.26	19.7	23				18		
	No. 100 150μm	1.05	9.89	13				10		
	No. 200 75μm	0.7	4.1	7.4				5.4	2 - 10	
	G_{SB}	2.775	2.740					6.893		

JMF reflects aggregate changes expected during production

Optimum Asphalt = 6.0
Viscosity of M.M. =
AC in M.M. =

Figure N.6. Mix Design FDOT Format, Recycled Granite Mixture with Granite/Limestone RAP

Recycled Granite Mixture with Limestone RAP



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STATE OF FLORIDA DEPARTMENT OF TRANSPORTATION
STATEMENT OF SOURCE OF MATERIALS AND JOB MIX FORMULA FOR BITUMINOUS CONCRETE

SUBMIT TO THE DIRECTOR, OFFICE OF MATERIALS, CENTRAL ASPHALT LABORATORY, 5007 NE 39TH AVE, GAINESVILLE, FL 32609

Project No. BE194 CTQP Qualified Mix Designer
Contractor Texas A&M Transportation Institute (TTI) Address 3135 TAMU College Station, Texas 77843-3135
Phone No. (979) 845-1715 Fax No. (979) 845-9356 E-mail e-arambula@tti.tamu.edu
Submitted By Type Mix Fine SP-12.5 Recycle Intended Use of Mix Structural
Design Traffic Level A Gyrations @ N des 50 Mix ID. H-60L-G

Product Description	(FDOT Code) Product Code	Producer Name	(Type Material) Product Name	Plant/Pit Number	Terminal
1. S1A Stone	C-47		#78 Stone	GA-553	
2. Screenings	F22		W-10 Screenings	GA-553	
3. Limestone	STK 09		Stockpile 1-09		
4.					
5.					
6.					
7. Aphalt Binder			PG 52-28		

PERCENTAGE BY WEIGHT TOTAL AGGREGATE PASSING SIEVES

	Blend	35%	5%	60%				JOB MIX	CONTROL	PRIMARY
	Number	1	2	3	4	5	6	FORMULA	POINTS	CONTROL SIEVE
	3/4" 19.0mm	100	100	100				100	100	
E	1/2" 12.5mm	93.27	100	100				98	90 - 100	
Z	3/8" 9.5mm	49.39	100	96				80	- 89	
I	No. 4 4.75mm	11.32	97.17	77				55		
S	No. 8 2.36mm	3.68	72	62				42	28 - 58	39
	No. 16 1.18mm	1.95	47.35	53				35		
E	No. 30 600μm	1.49	31.22	46				30		
V	No. 50 300μm	1.26	19.7	33				21		
E	No. 100 150μm	1.05	9.89	18				12		
I	No. 200 75μm	0.7	4.1	8.5				5.6	2 - 10	
S	G_{SB}	2.775	2.740					6.926		

JMF reflects aggregate changes expected during production

Optimum Asphalt = 6.0
Viscosity of M.M. =
AC in M.M. =

Figure N.7. Mix Design FDOT Format, Recycled Granite Mixture with Limestone RAP

APPENDIX O.
VOLUMETRICS OF PERFORMANCE TEST SPECIMENS

Hot Recycling

Table O.1. Maximum Specific Gravity (G_{mm}), Hot Recycled Mixtures

Mix ID	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)	G_{mm} (-)
H-60L-L	1816.9	1512.8	2549.9	2.330	2.343
	1849.9	1489.6	2554.1	2.355	
H-60L-G	1375.9	1512.8	2328.8	2.457	2.460
	1380.1	1489.6	2309.3	2.463	
H-60G-G	1834.1	1512.8	2610.4	2.490	2.493
	1859.8	1489.6	2604.2	2.496	

Table O.2. Bulk Specific Gravity (G_{mb}), Hot Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	Height (mm)					W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
		1	2	3	4	Average						
H-60G-G	1	38.96	38.26	38.55	39.43	38.80	1541.4	886.1	1551.2	2.318	2.493	7.0
	2	36.18	36.34	36.62	35.78	36.23	1419.3	814.3	1432.5	2.296	2.493	7.9
	3	39.56	39.9	39.32	38.83	39.40	1559.3	897.7	1572.9	2.309	2.493	7.4
	4	35.53	35.7	35.26	35.02	35.38	1398.3	807.5	1411.4	2.315	2.493	7.1
	5	36.05	36.94	37.89	36.8	36.92	1463.2	839.6	1472.3	2.313	2.493	7.2
	6	37.29	39.07	38.69	36.93	38.00	1494.3	857.7	1504.3	2.311	2.493	7.3
	7	38.22	37.4	38.17	39.63	38.36	1530	878.1	1537.9	2.319	2.493	7.0
	8	35.78	36.29	37.58	37.56	36.80	1423.6	820.9	1437.1	2.310	2.493	7.3
H-60G-GO	1	35.98	36.9	37.48	36.48	36.71	1456.5	838.9	1469.5	2.310	2.493	7.3
	2	37.52	37.65	38.96	39.29	38.36	1502.5	865.9	1512.4	2.324	2.493	6.8
	3	36.34	37.44	37.44	35.82	36.76	1454	835	1466.9	2.301	2.493	7.7
	4	38.46	37.37	38.12	39.15	38.28	1507.3	864.4	1518.4	2.305	2.493	7.5
	5	36.55	36.79	38.37	38.35	37.52	1475.5	843	1486.1	2.294	2.493	8.0
	6	37.01	36.85	38.26	38.37	37.62	1479.8	847	1492.4	2.293	2.493	8.0
	7	37.35	38.7	39.89	38.32	38.57	1528.1	874	1539	2.298	2.493	7.8
	8	35.92	37.89	37.18	34.66	36.41	1432.8	819	1441.9	2.300	2.493	7.7
H-60G-GP	1	37.83	38.2	38.208	37.87	38.03	1501.6	866.9	1515.8	2.314	2.493	7.2
	2	36.81	36.7	36.97	37.41	36.97	1457.9	839.9	1469.7	2.315	2.493	7.1
	3	39.97	37.417	36.89	38.81	38.27	1515.1	866.2	1528.7	2.287	2.493	8.3
	4	36.87	39.46	36.87	34.89	37.02	1435.3	820	1451.7	2.272	2.493	8.9
	5	37.05	36.63	37.19	37.79	37.17	1466.9	841.9	1479.2	2.302	2.493	7.7
	6	37.37	36.8	38.26	38.17	37.65	1486	855.6	1489.6	2.344	2.493	6.0
	7	38.36	40.23	39.56	37.43	38.90	1530.1	880.8	1544.1	2.307	2.493	7.5
	8	37.57	35.54	35.28	36.99	36.35	1428.4	826	1444.3	2.310	2.493	7.3

Table O.2 (Cont.). Bulk Specific Gravity (Gmb), Hot Recycled Moisture Susceptibility Specimens

Mix ID	Specimen	Height (mm)					W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
		1	2	3	4	Average						
H-60L-L	1	36.25	36.31	36.93	36.77	36.57	1408.4	782.2	1410.9	2.240	2.343	4.4
	2	37.66	38.04	38.3	38.19	38.05	1406.5	783.5	1416.6	2.222	2.343	5.2
	3	36.69	36.58	37.18	37.36	36.95	1423.1	793.8	1427.1	2.247	2.343	4.1
	4	37.63	36.69	37.09	37.68	37.27	1392.1	779.6	1399.3	2.246	2.343	4.1
	5	36.23	37.41	37.35	35.88	36.72	1401.2	778.6	1404.3	2.239	2.343	4.4
	6	38.44	38.98	37.76	37.43	38.15	1418.8	791.7	1426.2	2.236	2.343	4.6
	7	37.25	38.03	36.65	36.22	37.04	1398.5	781	1406.3	2.237	2.343	4.5
	8	37.88	38.15	36.99	37.19	37.55	1427	799.4	1435.1	2.245	2.343	4.2
H-60L-LO	1	37.04	38.59	39.68	37.86	38.29	1455.4	807.9	1459	2.235	2.343	4.6
	2	36.41	37.56	35.68	35.19	36.21	1356.9	758.2	1363.2	2.243	2.343	4.3
	3	38.81	39.09	38.07	37.63	38.40	1463.5	813.3	1470.7	2.226	2.343	5.0
	4	36.4	36.48	34.86	35.19	35.73	1355.2	756.8	1361	2.243	2.343	4.3
	5	37.22	36.48	35.33	36.08	36.28	1368.1	758.8	1375.6	2.218	2.343	5.3
	6	37.31	38.63	39.71	38.21	38.47	1455.2	808.9	1459.7	2.236	2.343	4.6
	7	38.81	38	37.54	37.96	38.08	1451.2	808.5	1457.9	2.235	2.343	4.6
	8	36.27	36.88	36.56	35.73	36.36	1363.4	763.4	1369.8	2.248	2.343	4.1
H-60L-LP	1	36.69	35.95	36.18	37.26	36.52	1390.1	773.6	1393.6	2.242	2.343	4.3
	2	37.99	37.36	38	38.89	38.06	1430.4	799.1	1436.7	2.243	2.343	4.3
	3	39.31	38.39	37.6	38.32	38.41	1378.4	767.3	1381.4	2.245	2.343	4.2
	4	34.87	35.34	36.46	35.99	35.67	1443.3	806.1	1448.3	2.247	2.343	4.1
	5	38.47	37.27	37.5	38.11	37.84	1460.9	809.9	1466.5	2.225	2.343	5.0
	6	36.66	36.49	36	36.23	36.35	1361.9	756.3	1368.6	2.224	2.343	5.1
	7	38.76	37.62	37.31	38.8	38.12	1453.9	809.1	1458.9	2.237	2.343	4.5
	8	37.03	37.27	35.85	35.73	36.47	1364.4	762	1369	2.248	2.343	4.1
H-60L-GO	1	36.1	37.47	36.83	35.2	36.40	1401.7	799.7	1414.2	2.281	2.460	7.3
	2	37.78	39.01	39.63	38.15	38.64	1485.6	853.3	1495.2	2.314	2.460	5.9
	3	37.45	37.21	36.01	36.29	36.74	1420.3	807.5	1431	2.278	2.460	7.4
	4	38.9	39.2	38.12	37.77	38.50	1476.9	843.6	1491.5	2.280	2.460	7.3
	5	38.41	39.5	38.49	37.53	38.48	1511	855.3	1519.4	2.275	2.460	7.5
	6	34.76	35.26	36.25	35.92	35.55	1382.5	788.1	1392.4	2.288	2.460	7.0
	7	37.22	37.43	35.84	34.85	36.34	1416.9	806.6	1425.1	2.291	2.460	6.9
	8	37.4	38.12	38.83	37.8	38.04	1470.2	839.9	1482.3	2.289	2.460	7.0
H-60L-GP	1	36.3	35.72	34.96	35.47	35.61	1387.6	789.2	1397.9	2.280	2.460	7.3
	2	38.15	38.64	39.04	39.14	38.74	1506.1	857.8	1518.6	2.279	2.460	7.4
	3	34.56	34.74	36.17	36.06	35.38	1393.4	791.6	1400.2	2.290	2.460	6.9
	4	39.23	37.64	38.06	39.45	38.60	1500.3	855.7	1511.2	2.289	2.460	7.0
	5	37.97	37.76	39.27	39.44	38.61	1510.3	861.2	1523.8	2.279	2.460	7.4
	6	35.03	36.53	36.31	34.88	35.69	1378.2	779	1385.2	2.274	2.460	7.6
	7	35.49	36.66	35.93	34.87	35.74	1399.2	797.8	1409.5	2.287	2.460	7.0
	8	38.69	37.74	38.48	38.91	38.46	1487.7	846.6	1497.9	2.284	2.460	7.2

Table O.3. Bulk Specific Gravity (G_{mb}), Hot Recycled Mixtures Rutting Resistance Specimens

Mix ID	Specimen	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
H-60G-G	1	2518.3	1442.1	2544.6	2.284	2.493	8.4
	2	2520.4	1447.0	2540.2	2.306	2.493	7.5
	3	2515.5	1442.9	2541.3	2.290	2.493	8.1
	4	2522.2	1446.1	2541.5	2.303	2.493	7.6
H-60G-GO	1	2514.2	1445.9	2536.3	2.306	2.493	7.5
	2	2518.4	1448.2	2540.1	2.306	2.493	7.5
	3	2510.7	1434.7	2529.8	2.293	2.493	8.0
	4	2515.2	1440.5	2538.4	2.291	2.493	8.1
H-60G-GP	1	2521.3	1451.0	2545.7	2.303	2.493	7.6
	2	2520.5	1447.0	2541.2	2.304	2.493	7.6
	3	2520.8	1444.0	2542.0	2.296	2.493	7.9
	4	2518.6	1428.3	2535.3	2.275	2.493	8.7
H-60L-L	1	2396.9	1320.5	2407.4	2.205	2.343	5.9
	2	2399.9	1332.1	2411.7	2.223	2.343	5.1
	3	2402.2	1324.0	2412.1	2.208	2.343	5.8
	4	2406.1	1332.5	2425.5	2.201	2.343	6.1
H-60L-LO	1	2398.7	1332.2	2408.9	2.228	2.343	4.9
	2	2401.8	1336.7	2412.0	2.234	2.343	4.7
	3	2405.7	1336.1	2416.1	2.228	2.343	4.9
	4	2384.1	1333.3	2399.8	2.235	2.343	4.6
H-60L-LP	1	2395.6	1334.3	2403.8	2.240	2.343	4.4
	2	2402.1	1344.4	2410.5	2.253	2.343	3.8
	3	2382.8	1326.4	2392.9	2.234	2.343	4.7
	4	2405.4	1346.2	2417.2	2.246	2.343	4.1
H-60L-GO	1	2464.1	1407.5	2481.0	2.295	2.460	6.7
	2	2463.2	1404.3	2483.8	2.282	2.460	7.2
	3	2459.5	1402.2	2477.3	2.288	2.460	7.0
	4	2461.6	1401.7	2484.8	2.273	2.460	7.6
H-60L-GP	1	2462.1	1390.4	2477.8	2.264	2.460	8.0
	2	2461.7	1404.7	2479.0	2.291	2.460	6.9
	3	2460.5	1401.8	2479.4	2.283	2.460	7.2
	4	2462.9	1403.2	2483.6	2.280	2.460	7.3

Table O.4. Bulk Specific Gravity (G_{mb}), Hot Recycled Mixtures Intermediate Temperature Cracking Resistance Specimens

Mix ID	Specimen	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
H-60G-G	1	1984.6	1139.5	2001.6	2.302	2.493	7.7
	2	1984.6	1143.5	2008	2.296	2.493	7.9
	3	1985.9	1139	2002.4	2.300	2.493	7.7
H-60G-GO	1	1986	1142.8	2007.7	2.296	2.493	7.9
	2	1987.5	1140.7	2003.2	2.304	2.493	7.6
	3	1985.4	1134.2	2002.1	2.288	2.493	8.2
H-60G-GP	1	1984.9	1133.9	1999.9	2.292	2.493	8.1
	2	1981.7	1133	1992	2.307	2.493	7.5
	3	1984.2	1137.9	2001.6	2.297	2.493	7.9
H-60L-L	1	1888.8	1052.1	1900.2	2.227	2.343	5.0
	2	1891.6	1049	1902	2.218	2.343	5.3
	3	1890.8	1050.6	1902.4	2.220	2.343	5.2
H-60L-LO	1	1889.9	1048	1898.3	2.223	2.343	5.1
	2	1890.2	1057.8	1905.4	2.230	2.343	4.8
	3	1891.9	1054.2	1897.3	2.244	2.343	4.2
H-60L-LP	1	1887.9	1052.6	1898.8	2.231	2.343	4.8
	2	1888.4	1050.5	1897.6	2.229	2.343	4.9
	3	1888.7	1054.6	1897.4	2.241	2.343	4.4
H-60L-GO	1	1942.1	1117.4	1957.7	2.311	2.460	6.1
	2	1939.9	1109.2	1955.5	2.292	2.460	6.8
	3	1941.3	1107.7	1954.7	2.292	2.460	6.8
H-60L-GP	1	1942.7	1101.8	1957.9	2.269	2.460	7.8
	2	1940.1	1098.3	1954.4	2.266	2.460	7.9
	3	1939.2	1109.2	1961.8	2.274	2.460	7.6

Table O.5. Vacuum Saturation, Hot Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	V_{VA} (cm^3)	Vacuum W_{SSD} (g)	V_{WA} (cm^3)	P_{st} (%)
H-60G-G	1	48.1	1565	23.6	0.49
	2	—	—	—	—
	3	—	—	—	—
	4	44.6	1424.2	25.9	0.58
	5	47.1	1485.9	22.7	0.48
	6	—	—	—	—
	7	—	—	—	—
	8	—	—	—	—
H-60G-GO	1	—	—	—	—
	2	—	—	—	—
	3	50.0	1481.3	27.3	0.55
	4	51.0	1536	28.7	0.56
	5	—	—	—	—
	6	—	—	—	—
	7	—	—	—	—
	8	49.8	1458.8	26	0.52
H-60G-GP	1	48.2	1528.8	27.2	0.56
	2	46.6	1482.4	24.5	0.53
	3	—	—	—	—
	4	—	—	—	—
	5	—	—	—	—
	6	—	—	—	—
	7	—	—	—	—
	8	47.1	1457.3	28.9	0.61
H-60L-L	1	28.4	1420.4	12	0.42
	2	—	—	—	—
	3	26.8	1435.6	12.5	0.47
	4	27.3	1406.8	14.7	0.54
	5	—	—	—	—
	6	—	—	—	—
	7	—	—	—	—
	8	27.8	1442.1	15.1	0.54
H-60L-LO	1	—	—	—	—
	2	27.3	1373.7	16.8	0.62
	3	—	—	—	—
	4	27.0	1370.8	15.6	0.58
	5	—	—	—	—
	6	—	—	—	—
	7	—	—	—	—
	8	26.1	1377.8	14.4	0.55
H-60L-LP	1	—	—	—	—
	2	—	—	—	—
	3	28.4	1391.6	13.2	0.47
	4	25.8	1456.7	13.4	0.52
	5	—	—	—	—
	6	—	—	—	—
	7	—	—	—	—
	8	26.1	1375.4	11	0.42
H-60L-GO	1	46.8	1426.5	24.8	0.53
	2	—	—	—	—
	3	—	—	—	—
	4	—	—	—	—
	5	—	—	—	—
	6	43.9	1404.5	22	0.50
	7	—	—	—	—
	8	46.7	1495.8	25.6	0.55

Table O.5 (Continued). Vacuum Saturation, Hot Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	VVA (cm3)	Vacuum WSSD (g)	VWA (cm3)	Pst (%)
H-60L-GP	1	—	—	—	—
	2	—	—	—	—
	3	—	—	—	—
	4	47.4	1523.2	22.9	0.48
	5	—	—	—	—
	6	—	—	—	—
	7	44.4	1427.4	28.2	0.63
	8	48.6	1517.4	29.7	0.61

Cold Recycling with Emulsion

Table O.6. Maximum Specific Gravity (G_{mm}), Emulsified Cold Recycled Mixtures

Mix ID	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)
C-80L-LE	1420.7	1513.2	2326.6	2.339
C-100L-E	1251.3	1513.2	2220.5	2.300
C-60G-GE	1386.6	1513.2	2349.8	2.521
C-60L-GE	1396.5	1513.2	2344.3	2.470
C-60L-LE	1392.7	1489.3	2293.2	2.365
C-80G-GE	1388.0	1489.3	2312.1	2.456

Table O.7. Bulk Specific Gravity (G_{mb}), Emulsified Cold Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	Height (mm)					W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
		1	2	3	4	Average						
C-60L-LE	1	40.53	40.49	39.97	40.21	40.30	1411.4	727.1	1419.7	2.038	2.365	13.8
	2	40.44	40.58	40.53	40.09	40.41	1411.7	724.8	1419.9	2.031	2.365	14.1
	3	40.52	40.29	40.19	40.53	40.38	1411.4	729.9	1422.4	2.038	2.365	13.8
	4	40.44	40.29	39.99	40.01	40.18	1414.4	733.6	1424.7	2.047	2.365	13.5
	5	40.75	40.49	40.27	40.25	40.44	1413.6	730.6	1422.5	2.043	2.365	13.6
	6	41.06	41.05	40.92	40.86	40.97	1411.7	737.8	1427.2	2.048	2.365	13.4
	7	40.08	40.32	40.45	40.09	40.24	1415.6	736.3	1428.6	2.045	2.365	13.5
	8	40.06	40.05	40.19	40.18	40.12	1395.3	716.3	1407	2.020	2.365	14.6
C-80L-LE	1	40.13	39.99	39.72	39.49	39.83	1401.5	726.3	1408.9	2.053	2.339	12.2
	2	40.47	40.2	40.36	40.4	40.36	1402.5	733.6	1416.6	2.053	2.339	12.2
	3	41.11	40.75	40.78	40.89	40.88	1435.5	746.5	1443.2	2.060	2.339	11.9
	4	41.02	40.63	40.63	40.78	40.77	1407.1	733.9	1420.8	2.048	2.339	12.5
	5	40.4	40.55	40.44	40.07	40.37	1421.7	742.5	1430.3	2.067	2.339	11.6
	6	40.15	40.05	39.75	39.84	39.95	1399.6	723.5	1407.1	2.047	2.339	12.5
	7	40.2	40.12	40.29	40.35	40.24	1402.7	729	1413.5	2.049	2.339	12.4
	8	40.44	40.89	40.78	40.42	40.63	1405.8	737.3	1423.3	2.049	2.339	12.4

Table O.7 (Continued). Bulk Specific Gravity (G_{mb}), Emulsified Cold Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	Height (mm)					W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
		1	2	3	4	Average						
C-100L-E	1	38.9	38.96	38.93	38.63	38.86	1302.2	647	1314.7	1.950	2.300	15.2
	2	39.08	38.71	38.67	38.72	38.80	1301.5	644.6	1312.1	1.950	2.300	15.2
	3	38.89	38.87	38.85	38.91	38.88	1302.3	639.9	1310.1	1.943	2.300	15.5
	4	38.98	38.8	38.19	38.6	38.64	1301.4	647.7	1313.2	1.956	2.300	15.0
	5	38.62	38.45	38.89	38.8	38.69	1302.2	646.5	1313.5	1.952	2.300	15.1
	6	38.67	38.91	38.67	38.5	38.69	1301.1	647	1313.2	1.953	2.300	15.1
	7	39.12	38.95	38.53	38.79	38.85	1304.5	651.5	1317.8	1.958	2.300	14.9
	8	37.59	37.38	37.57	37.74	37.57	1253.9	613.1	1262.8	1.930	2.300	16.1
C-60G-GE	1	40.41	40.42	40.01	40.4	40.31	1382.1	762.2	1435.8	2.052	2.521	18.6
	2	40.3	40.03	40.6	40.13	40.27	1384.1	765.4	1435.7	2.065	2.521	18.1
	3	40.5	40.51	41.28	40.83	40.78	1387.7	762.3	1437.5	2.055	2.521	18.5
	4	40.55	40.24	40.48	40.22	40.37	1388.4	772.1	1443.1	2.069	2.521	17.9
	5	40.53	40.42	40.14	40.17	40.32	1387.1	763	1439.8	2.049	2.521	18.7
	6	40.25	40.13	39.97	40.23	40.15	1384.9	761.8	1438.2	2.047	2.521	18.8
	7	40.14	39.95	40.05	40.11	40.06	1386.7	760.2	1439.3	2.042	2.521	19.0
	8	39.85	39.51	39.88	39.72	39.74	1384.4	757.8	1434.9	2.045	2.521	18.9
C-80G-GE	1	41.38	41.45	41.35	41.42	41.40	1386.8	739.7	1440.2	1.980	2.456	19.4
	2	41.72	41.33	41.38	41.24	41.42	1388.6	750.4	1448.4	1.989	2.456	19.0
	3	41.31	41.36	41.21	41.3	41.30	1389.6	757.3	1453.1	1.997	2.456	18.7
	4	41.38	41.42	41.37	41.39	41.39	1389.1	756.3	1446.3	2.013	2.456	18.0
	5	41.16	41.49	41.23	41.47	41.34	1388.3	749.3	1444.3	1.998	2.456	18.6
	6	41.18	41.6	41.72	41.37	41.47	1388.5	749	1447.9	1.987	2.456	19.1
	7	41.15	41.18	41.36	41.31	41.25	1384.8	746.7	1446.2	1.980	2.456	19.4
	8	41.46	41.32	41.4	41.47	41.41	1389.1	751.6	1444	2.006	2.456	18.3
C-60L-GE	1	39.21	39.53	39.02	39.22	39.25	1398.4	737.8	1409.2	2.083	2.470	15.7
	2	39.87	39.68	39.43	39.65	39.66	1398.8	745.7	1417.2	2.083	2.470	15.7
	3	39.83	39.54	39.22	39.15	39.44	1393.6	741.3	1409.6	2.085	2.470	15.6
	4	39.48	39.32	39.04	39.37	39.30	1397.2	738.1	1409.9	2.080	2.470	15.8
	5	39.44	39.27	39.39	39.3	39.35	1399.5	739.7	1414	2.075	2.470	16.0
	6	39.53	39.52	39.25	39.3	39.40	1398.2	736.9	1412.8	2.069	2.470	16.2
	7	39.58	39.41	39.37	39.33	39.42	1398.2	739.6	1411.9	2.080	2.470	15.8
	8	39.46	39.54	39.85	39.7	39.64	1400.6	740.9	1415.9	2.075	2.470	16.0
C-80G-GE-lime	1	36.89	37.26	40.02	40.09	38.57	1323.6	715.4	1371.3	2.018	2.456	17.8
	2	43.5	40.95	41.56	44.13	42.54	1428.2	770.2	1482.7	2.004	2.456	18.4
	3	39.17	41.57	42.75	40.71	41.05	1387.4	737.1	1439.9	1.974	2.456	19.6
	4	42.97	40.6	39.05	40.15	40.69	1355.2	730.6	1419.8	1.966	2.456	19.9

Table O.8. Bulk Specific Gravity (G_{mb}), Emulsified Cold Recycled Mixtures Rutting Resistance Specimens

Mix ID	Specimen	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
C-60L-LE	1	2390.4	1248.4	2399.4	2.077	2.365	12.2
	2	2356.6	1240.3	2370.1	2.086	2.365	11.8
	3	2352.6	1224.9	2364.5	2.064	2.365	12.7
	4	2348.6	1221.8	2360.9	2.062	2.365	12.8
C-80L-LE	1	2223.9	1230.5	2333.4	2.016	2.339	13.8
	2	2294.9	1194.2	2300.7	2.074	2.339	11.3
	3	2346.0	1247.9	2355.3	2.118	2.339	9.5
	4	2344.0	1250.3	2351.6	2.128	2.339	9.0
C-100L-E	1	2175.8	1089.1	2189.9	1.977	2.300	14.1
	2	2177.0	1091.6	2192.9	1.977	2.300	14.1
	3	2176.0	1096.6	2195.7	1.980	2.300	13.9
	4	2154.5	1075.5	2173.2	1.963	2.300	14.7
C-60G-GE	1	2327.5	1272.6	2366.4	2.128	2.521	15.6
	2	2328.0	1282.1	2390.5	2.100	2.521	16.7
	3	2325.0	1282.7	2391.6	2.097	2.521	16.8
	4	2329.1	1293.6	2380.3	2.143	2.521	15.0
C-80G-GE	1	2323.7	1266.1	2389.2	2.069	2.456	15.7
	2	2343.8	1271.4	2391.7	2.092	2.456	14.8
	3	2321.8	1274.6	2373.0	2.114	2.456	13.9
	4	2320.6	1265.4	2391.0	2.062	2.456	16.0
C-60L-GE	1	2330.6	1236.9	2356.2	2.082	2.470	15.7
	2	2267.4	1172.2	2299.3	2.012	2.470	18.5
	3	2329.1	1248.4	2344.3	2.125	2.470	14.0
	4	2330.8	1252.2	2346.6	2.130	2.470	13.8

Table O.9. Bulk Specific Gravity (G_{mb}), Emulsified Cold Recycled Mixtures Raveling Resistance Specimens

Mix ID	Specimen	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
C-60L-LE	1	4245.3	2241.7	4260.5	2.103	2.365	11.1
	2	4244.3	2242.3	4257.9	2.106	2.365	11.0
	3	4219.5	2195.1	4234.9	2.069	2.365	12.5
C-80L-LE	1	4159.6	2174.9	4211.5	2.042	2.339	12.7
	2	4192	2001.1	4219.1	1.890	2.339	19.2
	3	4159.6	2166.9	4185.3	2.061	2.339	11.9
C-100L-E	1	3920	1976.6	3994.8	1.942	2.300	15.6
	2	3930.4	1998.6	3998.1	1.966	2.300	14.5
	3	3901.6	1975.4	3963.1	1.963	2.300	14.7
C-60G-GE	1	4189.4	2355.1	4338.6	2.112	2.521	16.2
	2	4184.1	2338.6	4326.2	2.105	2.521	16.5
	3	4166	2351.6	4327.2	2.109	2.521	16.3

Table O.9 (Continued). Bulk Specific Gravity (G_{mb}), Emulsified Cold Recycled Mixtures Raveling Resistance Specimens

Mix ID	Specimen	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
C-80G-GE	1	4165.4	2312.2	4306	2.089	2.456	14.9
	2	4175.5	2294.8	4286.7	2.096	2.456	14.6
	3	4173.8	2314.1	4307.3	2.094	2.456	14.7
C-60L-GE	1	4216.5	2288.2	4277.4	2.120	2.470	14.2
	2	4212.4	2275.2	4265.2	2.117	2.470	14.3
	3	4228	2299	4290.4	2.123	2.470	14.0

Table O.10. Vacuum Saturation, Emulsified Cold Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	V_{VA} (cm^3)	Vacuum W_{SSD} (g)	V_{WA} (cm^3)	P_{st} (%)
C-60L-LE	1				
	2	100.9	1478.1	66.4	0.66
	3				
	4	95.6	1477.9	63.5	0.66
	5				
	6	97.1	1475.5	63.8	0.66
	7	96.3	1480.5	64.9	0.67
	8				
C-80L-LE	1	86.2	1455.3	53.8	0.62
	2	87.3	1460.2	57.7	0.66
	3	86.3	1490.1	54.6	0.63
	4	89.7	1465.8	58.7	0.65
	5				
	6				
	7				
	8				
C-100L-E	1				
	2				
	3				
	4	102.2	1372.6	71.2	0.70
	5				
	6	103.2	1371.8	70.7	0.69
	7	102.1	1372.5	68	0.67
	8				
C-60G-GE	1	132.5	1460.3	78.2	0.59
	2	128.7	1473.9	89.8	0.70
	3	133.2	1474.1	86.4	0.65
	4				
	5	133.4	1473.9	86.8	0.65
	6				
	7				
	8				

Table O.10 (Continued). Vacuum Saturation, Emulsified Cold Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	V_{VA} (cm^3)	Vacuum W_{SSD} (g)	V_{WA} (cm^3)	P_{st} (%)
C-80G-GE	1	—	—	—	—
	2	139.1	1489.5	100.9	0.73
	3	—	—	—	—
	4	—	—	—	—
	5	—	—	—	—
	6	—	—	—	—
	7	—	—	—	—
	8	134.0	1473.6	84.5	0.63
C-60L-GE	1	108.6	1465.3	66.9	0.62
	2	109.8	1465.7	66.9	0.61
	3	108.6	1458.9	65.3	0.60
	4	—	—	—	—
	5	—	—	—	—
	6	—	—	—	—
	7	—	—	—	—
	8	112.0	1484.6	84	0.75
C-80G-GE-lime	1	121.5	1407	83.4	0.69
	2	138.3	1523.3	95.1	0.69
	3	—	—	—	—
	4	—	—	—	—

Table O.11. Maximum Specific Gravity (G_{mm}), Foamed Cold Recycled Mixtures

Mix ID	$W_{mix\text{-}loose}$ (g)	$W_{pyc\ (soak)}$ (g)	$W_{spyc+mix\ (soak)}$ (g)	G_{mm} (-)
C-60L-LF	2318.6	1488.7	2828.2	2.368
C-80L-LF	2626.5	1512.6	3013.8	2.334
C-100L-F	2581.9	1488.7	2912.9	2.230
C-60L-GF	2659.1	1512.6	3071.2	2.416

Table O.12. Bulk Specific Gravity (G_{mb}), Foamed Cold Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	Height (mm)					W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
		1	2	3	4	Average						
C-60L-LF	1	39.74	39.25	40.58	42.15	40.43	1391.7	738.6	1429.6	2.014	2.368	15.0
	2	39.42	41.22	41.34	39.6	40.40	1378.0	726.9	1415.0	2.003	2.368	15.4
	3	38.79	42.23	41.78	39.02	40.46	1392.1	733.7	1426.6	2.009	2.368	15.2
	4	39.34	40.83	40.77	40.03	40.24	1371.7	722.0	1405.1	2.008	2.368	15.2
	5	40.32	39.29	37.22	38.37	38.80	1325.5	703.5	1361.6	2.014	2.368	15.0
	6	37.28	38.37	40.05	38.94	38.66	1326.4	699.6	1358.5	2.013	2.368	15.0
	7	36.03	38.12	40.91	39.09	38.54	1318.5	694.9	1351.8	2.007	2.368	15.2
	8	40.07	39.4	39.17	38.86	39.38	1344.1	707.5	1376.5	2.009	2.368	15.2
C-80L-LF	1	40.81	39.96	39.32	39.61	39.93	1345.4	696.8	1376.1	1.981	2.334	15.1
	2	39	39.62	39.08	38.9	39.15	1320.6	689.4	1352.5	1.992	2.334	14.7
	3	42.24	40.43	40.6	41.63	41.23	1397.4	734.1	1437.5	1.987	2.334	14.9
	4	39.82	39.02	37.89	38.28	38.75	1312.8	688.9	1345.6	1.999	2.334	14.4
	5	40.46	39.82	38.91	39.97	39.79	1347.5	697.9	1378.3	1.980	2.334	15.2
	6	40.6	40.65	40.76	40.58	40.65	1349.4	704.4	1382.0	1.991	2.334	14.7
	7	39.1	37.07	37.76	40.11	38.51	1286.6	675.9	1325.3	1.981	2.334	15.1
	8	41,98	41.05	39.73	41.36	40.71	1390.9	729.8	1430.4	1.985	2.334	15.0
C-100L-F	1	36.52	37.73	36.71	36.35	36.83	1217.5	619.3	1242.3	1.954	2.230	12.4
	2	38.38	39.98	40.75	38.33	39.36	1308.7	664.5	1335.7	1.950	2.230	12.6
	3	37.18	35.63	34.39	35.88	35.77	1180.2	594.4	1202.0	1.942	2.230	12.9
	4	36.41	36.45	34.94	34.82	35.66	1176.8	595.6	1199.6	1.948	2.230	12.7
	5	37.74	37.44	38.07	38.55	37.95	1273.3	647.7	1299.8	1.953	2.230	12.4
	6	35.44	36.32	35.33	34.18	35.32	1185.5	602.0	1211.2	1.946	2.230	12.7
	7	40.01	40.05	38.45	38.03	39.14	1314.1	661.8	1335.0	1.952	2.230	12.5
	8	37.88	38.22	39.7	39.31	38.78	1305.6	660.7	1330.9	1.948	2.230	12.7

Table O.12 (Continued). Bulk Specific Gravity (G_{mb}), Foamed Cold Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	Height (mm)					W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
		1	2	3	4	Average						
C-60L-GF	1	39.04	39.3	39.31	39.24	39.22	1375.2	746.5	1417.9	2.048	2.416	15.2
	2	36.77	37.04	37.7	37.76	37.32	1319.2	709.2	1352.3	2.051	2.416	15.1
	3	36.4	37	37.46	36.98	36.96	1311.4	703.3	1341.5	2.055	2.416	15.0
	4	33.43	34.97	36.35	35.17	34.98	1241.3	673.5	1278.5	2.052	2.416	15.1
	5	37.81	37.81	37.81	37.94	37.84	1296.0	703.5	1336.3	2.048	2.416	15.2
	6	39.75	38.96	38.49	39.21	39.10	1382.8	743.4	1416.1	2.056	2.416	14.9
	7	39.91	39.3	39.41	40.04	39.67	1393.5	747.4	1425.5	2.055	2.416	15.0
	8	41.79	39.57	39.69	41.52	40.64	1435.8	779.0	1474.2	2.065	2.416	14.5
C-100L-F-pc	1	36.93	36.59	37.63	37.86	37.25	1257	624.9	1268.8	1.952	2.230	12.5
	2	38.83	37.88	38.3	39.29	38.58	1312.2	650.4	1321.5	1.955	2.230	12.3
	3	37.99	36.8	37.37	39.31	37.87	1277.2	634.2	1290.4	1.946	2.230	12.7
	4	37.77	36.74	39.08	39.59	38.30	1300.4	645.3	1308.5	1.961	2.230	12.1

Table O.13. Bulk Specific Gravity (G_{mb}), Foamed Cold Recycled Mixtures Rutting Resistance Specimens

Mix ID	Specimen	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
C-60L-LF	1	2378.9	1295.9	2402.4	2.150	2.368	9.2
	2	2390.4	1292.9	2410.2	2.139	2.368	9.7
	3	2391.7	1284.8	2406.6	2.132	2.368	10.0
	4	2381.2	1295.1	2400.0	2.155	2.368	9.0
	5	2394.7	1295.0	2413.6	2.141	2.368	9.6
C-80L-LF	1	2389.7	1284.7	2402.2	2.138	2.334	8.4
	2	2377.0	1271.8	2388.1	2.129	2.334	8.8
	3	2382.3	1287.5	2393.7	2.154	2.334	7.7
	4	2377.5	1277.7	2386.7	2.144	2.334	8.1
C-100L-F	1	2215.8	1140.5	2254.9	1.988	2.230	10.9
	2	2209.9	1141.5	2254.5	1.986	2.230	10.9
	3	2210.5	1137.0	2245.4	1.994	2.230	10.6
	4	2204.7	1124.9	2236.8	1.983	2.230	11.1
C-60L-GF	1	2391.3	1307.0	2421.3	2.146	2.416	11.2
	2	2383.3	1302.1	2414.4	2.143	2.416	11.3
	3	2387.0	1308.7	2416.6	2.155	2.416	10.8
	4	2375.5	1295.9	2413.6	2.125	2.416	12.1

Table O.14. Bulk Specific Gravity (G_{mb}), Foamed Cold Recycled Mixtures Raveling Resistance Specimens

Mix ID	Specimen	W_{Dry} (g)	W_{soak} (g)	W_{SSD} (g)	G_{mb} (-)	G_{mm} (-)	AV (%)
C-60L-LF	1	4303.9	2350.7	4361.2	2.141	2.368	9.6
	2	4305.5	2323.5	4339.7	2.135	2.368	9.8
	3	4318.6	2345.2	4358.6	2.145	2.368	9.4
C-80L-LF	1	4308.4	2313.7	4333.2	2.133	2.334	8.6
	2	4306.7	2317.5	4330.9	2.139	2.334	8.4
	3	4299.9	2307.4	4325.1	2.131	2.334	8.7
C-100L-F	1	3977.5	2058.5	4063.6	1.984	2.230	11.0
	2	3986	2037.3	4039.9	1.990	2.230	10.8
	3	3984.9	2058.2	4063.6	1.987	2.230	10.9
C-60L-GF	1	4276	2381.2	4384.5	2.134	2.416	11.7
	2	4283.4	2371.6	4365.5	2.148	2.416	11.1
	3	4299.5	2367.5	4375.8	2.141	2.416	11.4

Table O.15. Vacuum Saturation, Foamed Cold Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	V_{VA} (cm^3)	Vacuum W_{SSD} (g)	V_{WA} (cm^3)	P_{st} (%)
C-60L-LF	1	106.8	1466.2	74.5	0.70
	2				
	3	108.4	1465.9	73.8	0.68
	4				
	5	102.5	1401.2	75.7	0.74
	6	102.4	1398.7	72.3	0.71
	7				
	8				
C-80L-LF	1				
	2	101.4	1390.6	70	0.69
	3	108.3	1477.2	79.8	0.74
	4	98.3	1381.3	68.5	0.70
	5				
	6	105.6	1446.2	96.8	0.92
	7				
	8				
C-100L-F	1	80.6	1285.9	68.4	0.85
	2	87.4	1383.4	74.7	0.85
	3				
	4				
	5	83.4	1336.7	63.4	0.76
	6				
	7	86.3	1371.1	57	0.66
	8				
C-60L-GF	1				
	2				
	3	97.7	1386.3	74.9	0.77
	4				
	5				
	6	103.0	1443.8	61	0.59
	7	104.8	1480.2	86.7	0.83
	8	104.4	1505.5	69.7	0.67

Table O.15 (Continued). Vacuum Saturation, Foamed Cold Recycled Mixtures Moisture Susceptibility Specimens

Mix ID	Specimen	V_{VA} (cm^3)	Vacuum W_{SSD} (g)	V_{WA} (cm^3)	P_{st} (%)
C-100L-F-pc	1				
	2	84.1	1380.8	68.6	0.82
	3				
	4	81.7	1369.3	68.9	0.84

APPENDIX P.
CURING PROTOCOL EXPERIMENT

C-100L-E Mixtures

Table P.1. Curing Time for 6.5% Emulsion Content, C-100L-E Recycled Mixture

EC (RBC) (%)	**6.5 (3.9)**							
Curing Time (Hr)		**1.0**	**3.0**	**5.0**	**7.0**	**19.0**	**21.0**	**25.0**
Sample	**1**	1334.5	1328.5	1325.5	1323.5	1313.5	1312.0	1311.5
	2	1349.0	1341.5	1338.0	1336.0	1327.5	1327.0	1326.5
	3	1350.5	1343.0	1338.5	1335.0	1326.5	1323.5	1323.0
	4	1326.0	1317.0	1313.5	1311.0	1302.5	1301.5	1300.5

			Weight Change (%)					
Curing Time (Hr)			**3.0**	**5.0**	**7.0**	**19.0**	**21.0**	**25.0**
Sample	**1**		0.45	0.23	0.15	NA	0.11	0.04
	2		0.56	0.26	0.15	NA	0.04	0.04
	3		0.56	0.34	0.26	NA	0.23	0.04
	4		0.68	0.27	0.19	NA	0.08	0.08
	Average		0.56	0.27	0.19	NA	0.11	0.05

Table P.2. Curing Time for 8% Emulsion Content, C-100L-E Recycled Mixture

EC (RBC) (%)	**8.0 (4.8)**							
Curing Time (Hr)		**2.0**	**4.0**	**6.0**	**8.0**	**20.0**	**22.0**	**26.0**
Sample	**1**	1447.0	1443.0	1441.0	1440.0	1434.0	1433.5	1433.0
	2	1361.0	1358.0	1356.5	1355.5	1350.0	1349.0	1348.5
	3	1349.0	1346.5	1344.5	1343.5	1336.5	1335.5	1334.5
	4	1227.5	1224.0	1222.0	1221.0	1214.5	1214.0	1213.5

		Weight Change (%)					
Curing Time (Hr)		**4.0**	**6.0**	**8.0**	**20.0**	**22.0**	**26.0**
Sample	**1**	0.28	0.14	0.07	NA	0.03	0.03
	2	0.22	0.11	0.07	NA	0.07	0.04
	3	0.19	0.15	0.07	NA	0.07	0.07
	4	0.29	0.16	0.08	NA	0.04	0.04
	Average	0.24	0.14	0.07	NA	0.06	0.05

C-60L-LE Mixture

Table P.3. Curing Time for 6.5% Emulsion Content, C-60L-LE Recycled Mixture

EC (RBC) (%)	**6.5 (3.9)**								
Curing Time (Hr)		**0.5**	**2.0**	**4.0**	**6.0**	**18.0**	**20.0**	**24.0**	**26.0**
Sample	**1**	1445.5	1437.0	1433.0	1430.5	1420.5	1420.0	1419.5	1419.0
	2	1449.5	1437.0	1433.0	1430.0	1420.5	1420.0	1419.5	1419.0
	3	1462.5	1451.5	1446.5	1444.0	1434.5	1433.5	1433.0	1432.5
	4	1458.5	1448.5	1445.0	1442.5	1433.0	1432.5	1432.0	1431.5

Curing Time (Hr)		**2.0**	**4.0**	**6.0**	**18.0**	**20.0**	**24.0**	**26.0**
Sample	**1**	0.59	0.28	0.17	NA	0.04	0.04	0.04
	2	0.86	0.28	0.21	NA	0.04	0.04	0.04
	3	0.75	0.34	0.17	NA	0.07	0.03	0.03
	4	0.69	0.24	0.17	NA	0.03	0.03	0.03
	Average	0.72	0.29	0.18	NA	0.04	0.04	0.04

APPENDIX Q.
EXPANSION RATIO AND HALF-LIFE TESTS

Foaming Temperature Selection

Table Q.1. Initial Measurements for Foaming Temperature Selection

1-Gallon Can Diameter	16.5 cm	6.5 in.
Mass of Dispensed Asphalt	200.0 g	0.44 lb
Measured Thickness of Unfoamed Binder in 1-Gallon Can	0.91 cm	0.36 in.
Volume of Unfoamed Binder (ft³)	0.000195	11.9 in.^{3}

Table Q.2. Foam Height and Asphalt Thickness Measurements for Foaming Temperature Selection

Foaming Temperature (°C)	Water Injection Rate (WIR) (%)	Measurement of Foam Height on the Can Wall (cm)						Asphalt Layer Thickness in the Can Base (cm)			
		#1	#2	#3	#4	#5	Average	#1	#2	#3	Average
160	1.0	9.9	9.6				9.8	0.9	0.8		0.9
	2.0	12.9	13.9				13.4	1.1	0.9		1.0
	3.0	12.8	13.2	13.4			13.1	0.8	1.0		0.9
	5.0	15.7	16.2	16.4			16.1	0.8	0.8		0.8
170	1.0	7.8	7.9	8.1	8.8	9.0	8.3	1.0	1.0		1.0
	2.0	12.5	13.0	13.3			12.9	1.0	1.0	0.9	1.0
	3.0	13.5	13.7	13.9	14.3		13.9	0.9	0.9		0.9
	5.0	14.8	15.0				14.9	0.9	0.9		0.9

Table Q.3. Expansion Ratio and Half-Life for Foaming Temperature Selection

Foaming Temperature (°C)	Maximum Foaming Height (cm)	Max ER (Times)	1/2 Max ER (-)	ER Fitting Constants			$1/2ER_{Max}(HL) = 1 + (a \cdot e^{-b \cdot HL} + (ER_{Max} - a - 1)\, e^{-c \cdot HL})$	HL (Sec)
				a	b	c		
160	10.60	11.65	5.82	7.14	0.66	0.01	5.81	2.44
	14.40	15.82	7.91	11.85	0.40	0.01	7.89	2.72
	14.03	15.42	7.71	9.39	0.67	0.05	7.69	2.20
	16.88	18.54	9.27	7.08	8.32	0.07	9.26	3.30
170	9.32	10.24	5.12	6.28	0.33	0.01	5.11	4.67
	13.90	15.27	7.64	11.19	0.34	0.02	7.62	3.26
	14.75	16.21	8.10	10.40	0.94	0.04	8.09	1.49
	15.75	17.31	8.65	7.40	11.95	0.07	8.64	2.32

Optimum Water Injection Rate Determination

Table Q.4. Asphalt Thickness Measurement for Optimum Foaming Water Content Selection

WIR (%)	Rep.	Initial Mass (g)	Final Mass (g)	Binder Mass (g)	Volume (m^3)	Height of Layer (cm)	Average Layer Height of Unfoamed Binder (cm)
0.7	1	287.2	488.3	201.1	1.92E-04	0.89	0.90
	2	282.3	485.5	203.2	1.94E-04	0.90	
1.5	1	282.4	485.9	203.5	1.94E-04	0.91	0.90
	2	285.5	488.0	202.5	1.93E-04	0.90	
3.0	1	284.4	491.1	206.7	1.97E-04	0.92	0.91
	2	279.3	482.0	202.7	1.93E-04	0.90	
4.0	1	282.9	492.1	209.2	1.99E-04	0.93	0.93
	2	283.6	492.1	208.5	1.99E-04	0.93	

Table Q.5. Foam Height Measurement for Optimum Foaming Water Content Selection

WIR (%)	Rep.	Foaming Height (cm)					Maximum Expansion Height (cm)
		#1	#2	#3	#4	Average	
0.7	1	12.7	12.8	12.5		12.7	5.5
	2	12.5	12.9	12.3		12.6	5.6
1.5	1	5.9	5.0	5.4		5.4	12.8
	2	8.1	8.0	7.8		8.0	10.2
3.0	1	3.5	3.6	3.7		3.6	14.6
	2	3.6	3.1	3.3		3.3	14.9
4.0	1	2.7	1.8	2.5	1.8	2.2	16.0
	2	1.7	1.5	2.1	2.2	1.9	16.3

Table Q.6. Expansion Ratio and Half-Life for Optimum Foaming Water Content Selection

WIR (%)	Rep.	ER Fitting Constants			Max ER (Times)	1/2 Max ER (-)	HL (Sec)
		a	b	c			
0.7	1	2.817	0.005	14.100	6.2	3.11	61.5
	2	2.179	0.183	0.004	6.3	3.17	94.5
1.5	1	10.226	0.256	0.006	14.3	7.17	4.6
	2	7.048	1.451	0.006	11.5	5.75	1.7
3.0	1	11.801	0.337	0.009	16.4	8.20	3.4
	2	12.338	0.371	0.007	16.7	8.35	3.0
4.0	1	14.130	0.226	0.009	18.0	8.99	4.4
	2	13.878	0.373	0.010	18.3	9.17	2.9

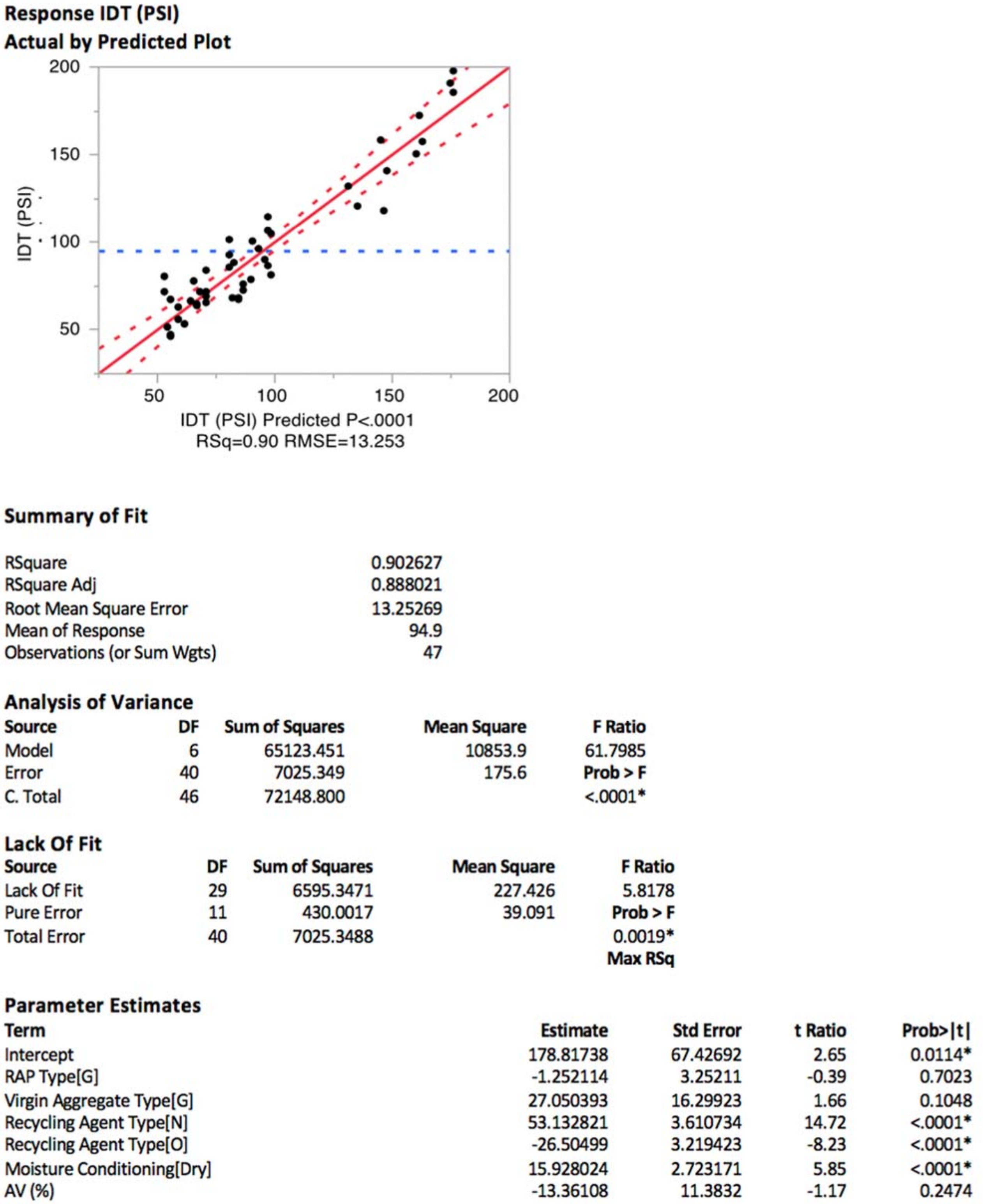
APPENDIX R.
STATISTICAL ANALYSIS OF LABORATORY RESULTS

Hot Recycling

IDT STRENGTH

The objective of this analysis was to assess the effects of several factors on IDT for mixtures obtained with hot recycling. The factors of interest were RAP type with two levels (L, G), virgin aggregate type with two levels (L, G), recycling agent type with three levels (P, O, N), and moisture conditioning with two levels (Dry, Wet). AV content was also measured. Note that the RAP content was fixed at 60 for this dataset.

The multi-factor ANCOVA model having RAP type, virgin aggregate type, recycling agent type, moisture conditioning, and AV as main effects was fitted to the data. It can be observed from the Effects Tests below that the main effects, recycling agent type and moisture conditioning, were statistically significant at $\alpha = 0.05$. For moisture conditioning, it appears that Dry led to a significantly higher IDT value than Wet. For the factors with more than two levels (e.g., recycling agent type), the Tukey's HSD test was also carried out when the effects were statistically significant to determine which of those factor levels were statistically different. The underlying assumptions, including equality of variance, for the multi-factor ANCOVA as well as for Tukey's HSD test were satisfied based on examination of the residual plots (shown at the end of the analysis). For recycling agent type, it can be concluded from the LSMeans Differences Tukey's HSD test table that recycling agent type = N led to a significantly higher IDT value than recycling agent type = O or P.



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Summary of Fit

RSquare                          0.902627
RSquare Adj                      0.888021
Root Mean Square Error           13.25269
Mean of Response                     94.9
Observations (or Sum Wgts)             47

Analysis of Variance
Source          DF   Sum of Squares      Mean Square     F Ratio
Model            6        65123.451          10853.9     61.7985
Error           40         7025.349            175.6     Prob > F
C. Total        46        72148.800                      <.0001*

Lack Of Fit
Source             DF   Sum of Squares      Mean Square     F Ratio
Lack Of Fit        29        6595.3471          227.426      5.8178
Pure Error         11         430.0017           39.091     Prob > F
Total Error        40        7025.3488                      0.0019*
                                                            Max RSq

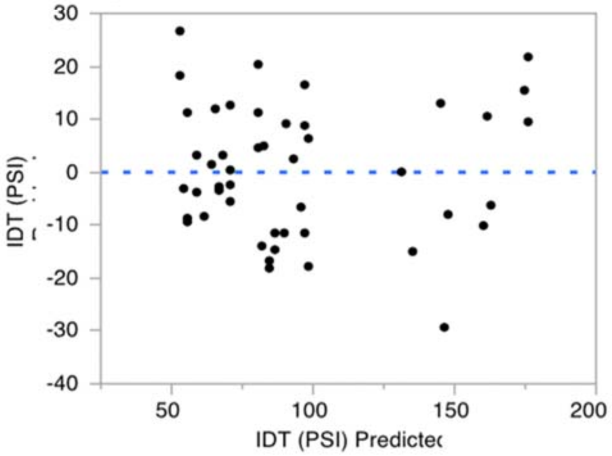
Parameter Estimates
Term                                      Estimate     Std Error    t Ratio    Prob>|t|
Intercept                                178.81738      67.42692       2.65     0.0114*
RAP Type[G]                              -1.252114       3.25211      -0.39      0.7023
Virgin Aggregate Type[G]                 27.050393      16.29923       1.66      0.1048
Recycling Agent Type[N]                  53.132821      3.610734      14.72     <.0001*
Recycling Agent Type[O]                  -26.50499      3.219423      -8.23     <.0001*
Moisture Conditioning[Dry]               15.928024      2.723171       5.85     <.0001*
AV (%)                                   -13.36108       11.3832      -1.17      0.2474
```

Figure R.1. JMP Statistical Package Output, Hot Recycled Mixtures IDT Strength

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Type	1	1	26.035	0.1482	0.7023
Virgin Aggregate Type	1	1	483.750	2.7543	0.1048
Recycling Agent Type	2	2	39158.033	111.4764	<.0001*
Moisture Conditioning	1	1	6008.717	34.2116	<.0001*
AV (%)	1	1	241.970	1.3777	0.2474

Residual by Predicted Plot



Effect Details

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	93.447319	4.6780635	104.333
L	95.951547	6.7756203	89.045

Virgin Aggregate Type

Least Squares Means Table

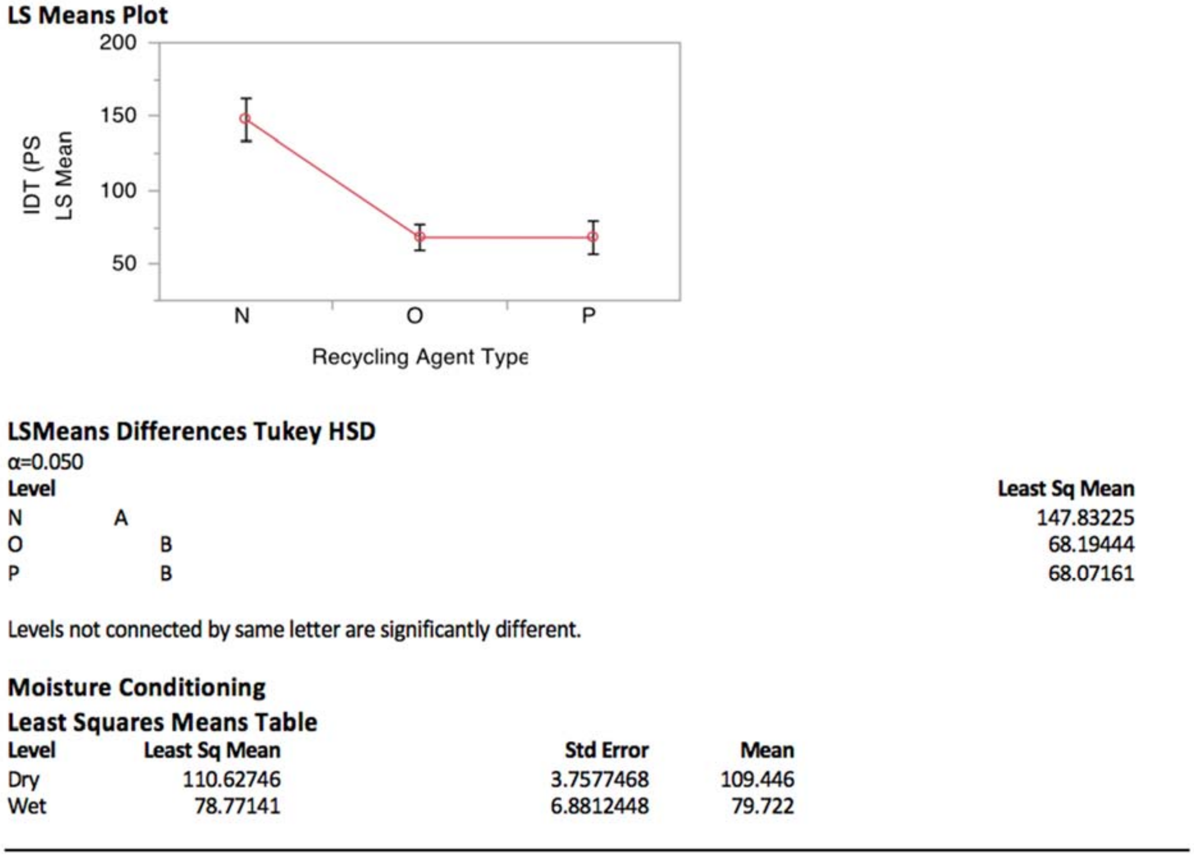
Level	Least Sq Mean	Std Error	Mean
G	121.74983	12.096925	96.1633
L	67.64904	20.775828	92.6706

Recycling Agent Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
N	147.83225	7.1357496	156.427
O	68.19444	4.3396629	75.122
P	68.07161	5.5759264	77.078

Figure R.1 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures IDT Strength



```
LS Means Plot

LSMeans Differences Tukey HSD
α=0.050
Level                                              Least Sq Mean
N        A                                             147.83225
O            B                                          68.19444
P            B                                          68.07161

Levels not connected by same letter are significantly different.

Moisture Conditioning
Least Squares Means Table
Level      Least Sq Mean             Std Error       Mean
Dry            110.62746             3.7577468    109.446
Wet             78.77141             6.8812448     79.722
```

Figure R.1 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures IDT Strength

HAMBURG WHEEL TRACKING TEST

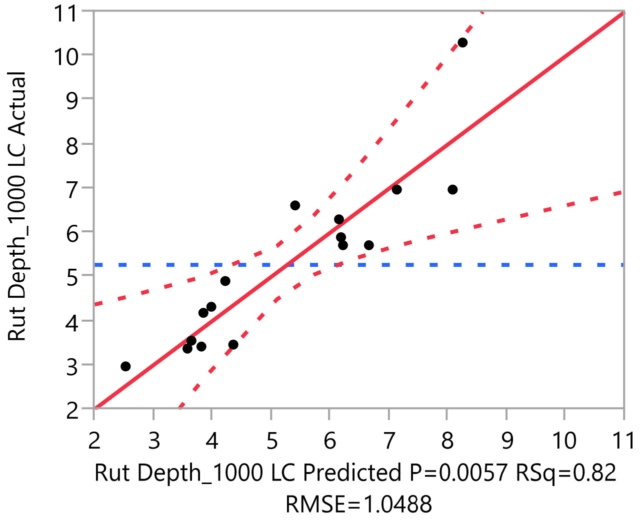
The objective of this analysis was to assess the effects of several factors on the response variables for rutting (HWTT) for mixtures obtained with hot recycling. The response variables considered were (a) rut depth at 1,000 load cycles, (b) SIP, and (c) Delta E. The factors were RAP type with two levels (L, G), virgin aggregate type with two levels (L, G), recycling agent type with three levels (P, O, N), and specimen with two levels (R, L). AVs were also measured from two specimens (Specimen 1 and Specimen 2) for each combination of the aforementioned factor levels and were averaged over those two specimens (and renamed as AV_avg) to be included in the multi-factor ANCOVA analysis. Note that the RAP content was fixed at 60 for this dataset. The analysis was performed separately for each of the five response variables given above.

Rut Depth at 1,000 Load Cycles

The multi-factor ANCOVA model having RAP type, virgin aggregate type, recycling agent type, specimen, and AV_avg as main effects was fitted to the data. It can be observed from the Effects Tests below that only the effect of AV was statistically significant at $\alpha = 0.05$. It appears that the value of rut depth was negatively related with the value of AV. The effect of virgin aggregate type was statistically significant at $\alpha = 0.1$. For virgin aggregate type, the level G seemed to lead to a significantly higher rut depth 1000 LC value than the level L.

Response Rut Depth_1000 LC

Actual by Predicted Plot



Summary of Fit

RSquare	0.821075
RSquare Adj	0.701791
Root Mean Square Error	1.048794
Mean of Response	5.26625
Observations (or Sum Wgts)	16

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	6	45.429060	7.57151	6.8834
Error	9	9.899715	1.09997	**Prob > F**
C. Total	15	55.328775		0.0057*

Parameter Estimates

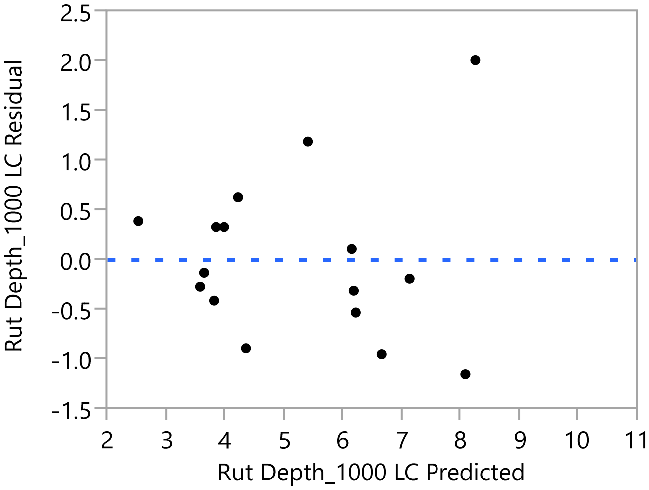
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	19.022308	5.227582	3.64	0.0054*
RAP Type[G]	-0.354278	0.395848	-0.89	0.3941
Virgin Aggregate Type[G]	2.3263317	1.091227	2.13	0.0618
Recycling Agent Type[N]	-0.576405	0.546735	-1.05	0.3192
Recycling Agent Type[O]	0.1155906	0.401128	0.29	0.7797
Specimen[L]	0.4130785	0.281338	1.47	0.1761
AV_avg	-2.194628	0.81597	-2.69	0.0248*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Type	1	1	0.8810704	0.8010	0.3941
Virgin Aggregate Type	1	1	4.9991136	4.5448	0.0618
Recycling Agent Type	2	2	1.5348477	0.6977	0.5228
Specimen	1	1	2.3713059	2.1558	0.1761
AV_avg	1	1	7.9570810	7.2339	0.0248*

Figure R.2. JMP Statistical Package Output, Hot Recycled Mixtures HWTT Rut Depth

Residual by Predicted Plot



Effect Details

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	4.1697693	0.55621727	3.71167
L	4.8783248	0.49628559	6.19900

Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	6.8503787	0.9305522	4.67000
L	2.1977154	1.3258627	6.26000

Recycling Agent Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
N	3.9476420	0.55074030	3.49500
O	4.6396376	0.57843095	5.63833
P	4.9848614	0.59817744	6.07500

Specimen

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
L	4.9371255	0.40653386	5.40500
R	4.1109685	0.48509607	5.12750

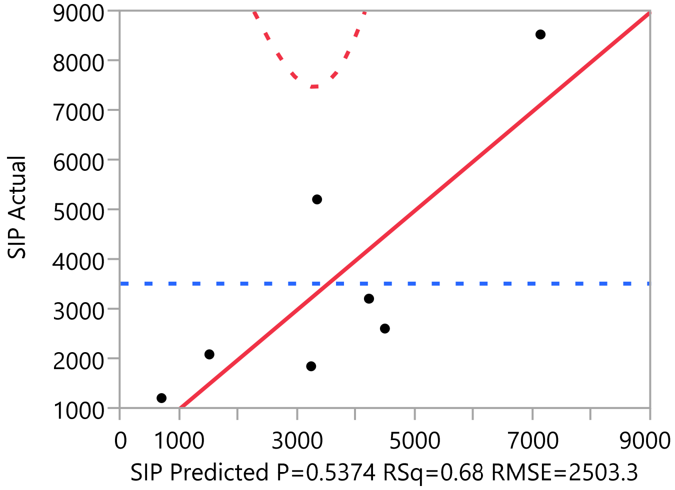
Figure R.2 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures HWTT Rut Depth

Stripping Inflection Point

For the SIP data, there were only seven observations, and the levels of RAP type and virgin aggregate type were confounded, which prevented including both RAP type and virgin aggregate type in the model. The multi-factor ANCOVA model having RAP type, recycling agent type, and AV_avg as main effects was fitted to the SIP data. It can be observed from the Effects Tests below that none of the effects were statistically significant at α = 0.05.

Response SIP

Actual by Predicted Plot



Summary of Fit

RSquare	0.680156
RSquare Adj	0.040468
Root Mean Square Error	2503.33
Mean of Response	3523.429
Observations (or Sum Wgts)	7

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	4	26652425	6663106	1.0633
Error	2	12533327	6266663	**Prob > F**
C. Total	6	39185752		0.5374

Figure R.3. JMP Statistical Package Output, Hot Recycled Mixtures HWTT SIP

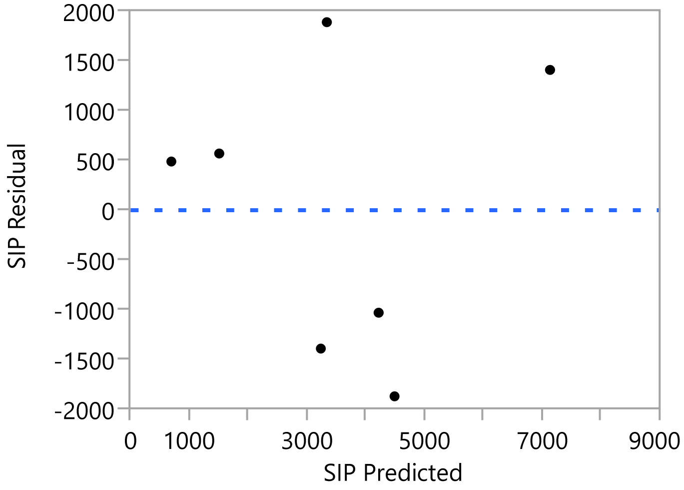
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-21499.92	16689.75	-1.29	0.3266
RAP Type[G]	-5854.985	3773.413	-1.55	0.2609
Recycling Agent Type[N]	-490.8145	1883.293	-0.26	0.8188
Recycling Agent Type[O]	1355.8641	1625.881	0.83	0.4921
AV_avg	3911.4732	2577.195	1.52	0.2684

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Type	1	1	15087570	2.4076	0.2609
Recycling Agent Type	2	2	5709705	0.4556	0.6870
AV_avg	1	1	14435194	2.3035	0.2684

Residual by Predicted Plot



Effect Details

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	-1371.55	3440.4559	3085.00
L	10338.42	4352.0981	4108.00

Recycling Agent Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
N	3992.6189	1939.0487	5194.00
O	5839.2975	2178.6949	3911.50
P	3618.3839	1731.1951	2151.00

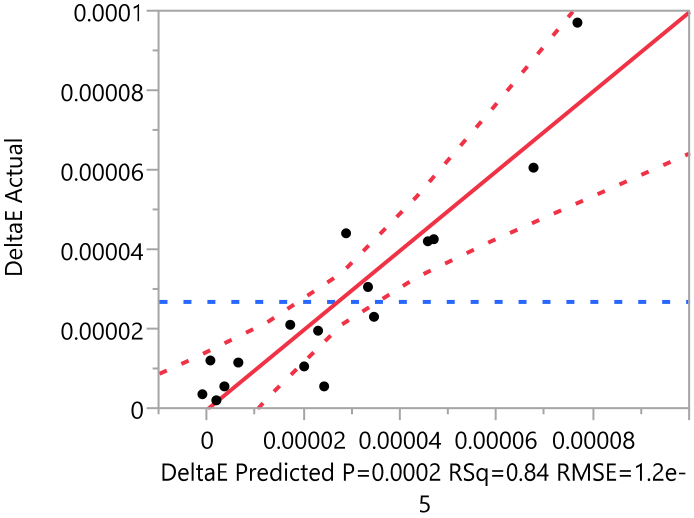
Figure R.3 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures HWTT SIP

Rutting Resistance Parameter $\Delta\varepsilon^{vp}_{SN}$

The multi-factor ANCOVA model having RAP type, virgin aggregate type, recycling agent type, specimen, and AV_avg as main effects was initially fitted to the $\Delta\varepsilon^{vp}_{SN}$ data (named Delta E in this analysis). The initial results of this analysis, however, indicated that the effect of RAP type was statistically very insignificant (with p-value of 0.9268), as was the effect of specimen (with p-value of 0.7335). Both RAP type and specimen were thus excluded from the multi-factor ANCOVA analysis, and the model having virgin aggregate type, recycling agent type, and AV_avg as main effects was refitted to the Delta E data. It can be observed from the Effects Tests results shown below that the effects of virgin aggregate type and AV were statistically significant at $\alpha = 0.05$. For virgin aggregate type, it can be observed that G led to a significantly higher Delta E value than L. Also, it appears that the value of Delta E was negatively related with the value of AV.

Response DeltaE

Actual by Predicted Plot



Summary of Fit

RSquare	0.842727
RSquare Adj	0.785537
Root Mean Square Error	1.182e-5
Mean of Response	0.000027
Observations (or Sum Wgts)	16

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	4	8.24171e-9	2.0604e-9	14.7355
Error	11	1.5381e-9	1.398e-10	**Prob > F**
C. Total	15	9.77981e-9		0.0002*

Figure R.4. JMP Statistical Package Output, Hot Recycled Mixtures HWTT RRP

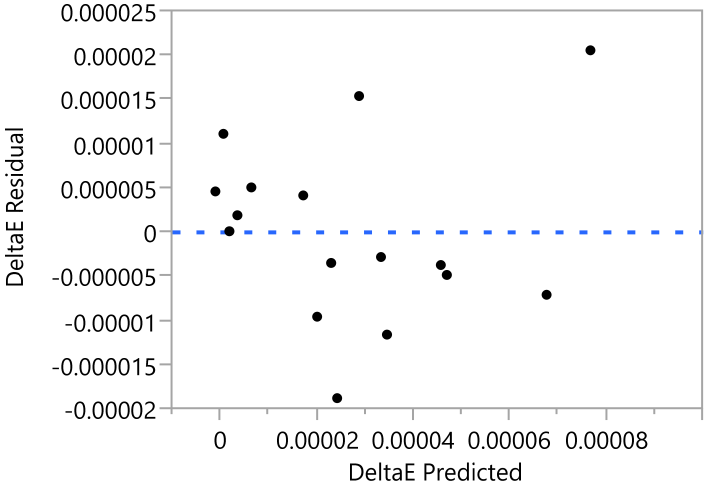
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.0002164	4.932e-5	4.39	0.0011*
Virgin Aggregate Type[G]	2.5952e-5	1.134e-5	2.29	0.0429*
Recycling Agent Type[N]	-6.627e-6	0.000006	-1.10	0.2932
Recycling Agent Type[O]	-1.765e-6	4.479e-6	-0.39	0.7011
AV_avg	-2.979e-5	7.79e-6	-3.82	0.0028*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Virgin Aggregate Type	1	1	7.3184e-10	5.2339	0.0429*
Recycling Agent Type	2	2	4.6565e-10	1.6651	0.2335
AV_avg	1	1	2.04452e-9	14.6217	0.0028*

Residual by Predicted Plot



Effect Details

Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	0.0000456	0.00000949	0.000017
L	-0.0000063	0.00001402	0.000044

Recycling Agent Type

Least Squares Means Table

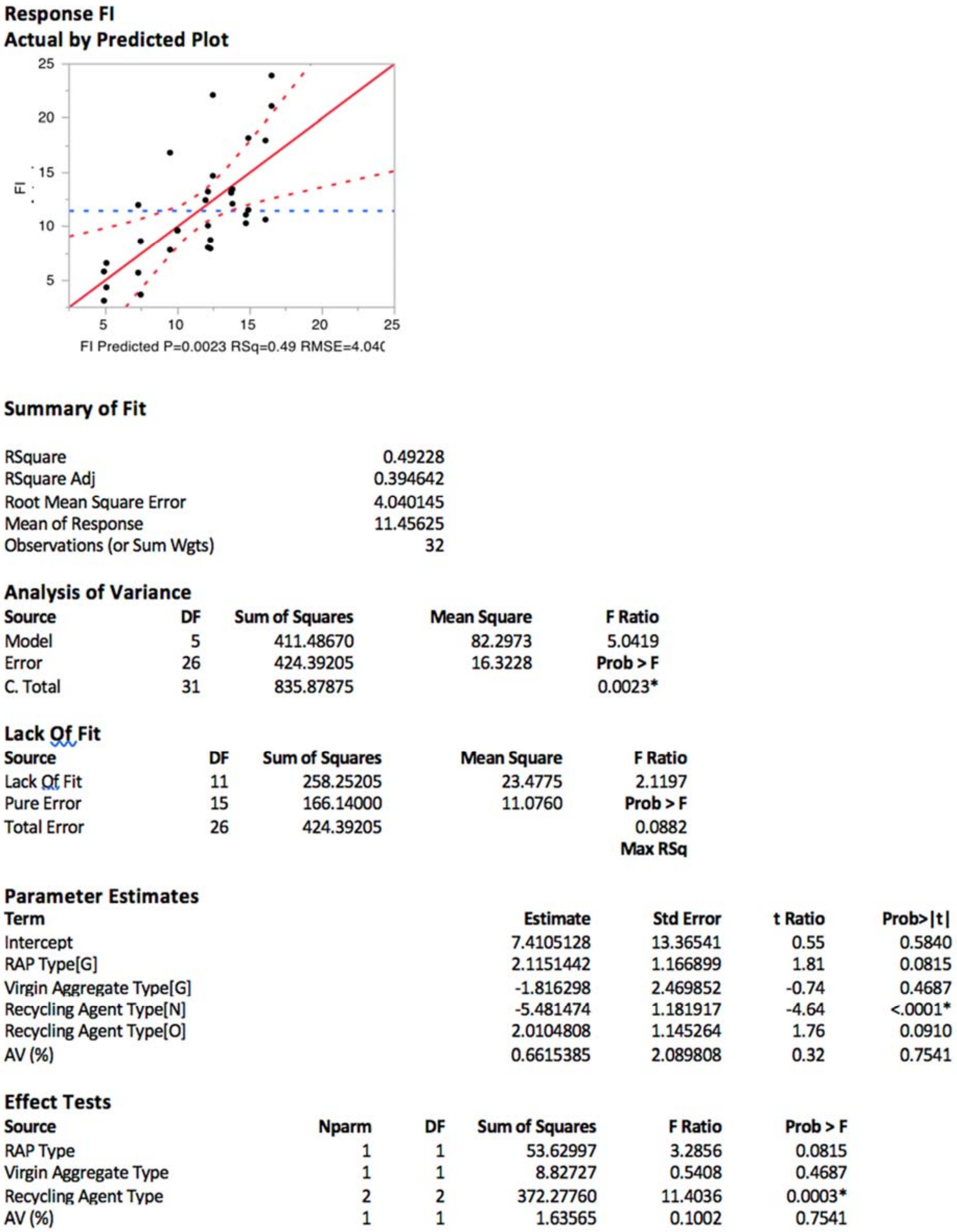
Level	Least Sq Mean	Std Error	Mean
N	0.00001303	6.12687e-6	6.883e-6
O	0.00001789	6.36067e-6	0.000028
P	0.00002805	6.57023e-6	0.000039

Figure R.4 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures HWTT RRP

INTERMEDIATE TEMPERATURE CRACKING—FI, CRI

The objective of this analysis was to assess the effects of RAP type, virgin aggregate type, recycling agent type, and AV content on each of the output test parameters (FI and CRI) from the SCB test. The output test parameters are referred to as response variables in experimental design terminology. The factors of interest and their levels were Aggregate RAP type with two levels (L, G), virgin aggregate type with two levels (L, G), and recycling agent type with three levels (P, O, N). AV content was also measured. Note that the recycling methodology was fixed at H for this dataset.

The multi-factor ANCOVA model having RAP type, virgin aggregate type, recycling agent type, and AV as main effects was first fitted to the FI data. It can be observed from the Effects Tests results shown below that the effect of recycling agent type was statistically significant at $\alpha = 0.05$. The Tukey's HSD test indicated that for recycling agent type, the levels P and O were significantly different from N, while there was no statistically significant difference between P and O.



```
Response FI
Actual by Predicted Plot

Summary of Fit

RSquare                                   0.49228
RSquare Adj                              0.394642
Root Mean Square Error                   4.040145
Mean of Response                         11.45625
Observations (or Sum Wgts)                     32

Analysis of Variance
Source        DF    Sum of Squares      Mean Square      F Ratio
Model          5         411.48670          82.2973       5.0419
Error         26         424.39205          16.3228     Prob > F
C. Total      31         835.87875                       0.0023*

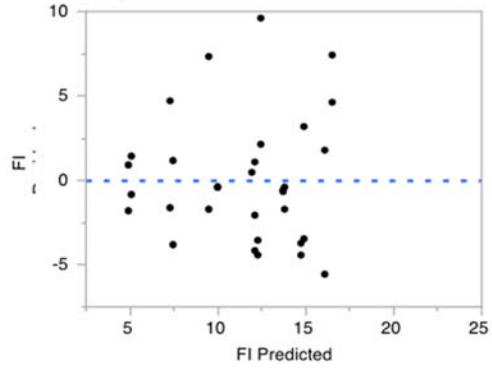
Lack Of Fit
Source             DF    Sum of Squares      Mean Square      F Ratio
Lack Of Fit        11         258.25205          23.4775       2.1197
Pure Error         15         166.14000          11.0760     Prob > F
Total Error        26         424.39205                        0.0882
                                                             Max RSq

Parameter Estimates
Term                                  Estimate    Std Error    t Ratio    Prob>|t|
Intercept                            7.4105128     13.36541       0.55      0.5840
RAP Type[G]                          2.1151442     1.166899       1.81      0.0815
Virgin Aggregate Type[G]             -1.816298     2.469852      -0.74      0.4687
Recycling Agent Type[N]              -5.481474     1.181917      -4.64     <.0001*
Recycling Agent Type[O]              2.0104808     1.145264       1.76      0.0910
AV (%)                               0.6615385     2.089808       0.32      0.7541

Effect Tests
Source                        Nparm    DF    Sum of Squares     F Ratio    Prob > F
RAP Type                          1     1          53.62997      3.2856      0.0815
Virgin Aggregate Type             1     1           8.82727      0.5408      0.4687
Recycling Agent Type              2     2         372.27760     11.4036     0.0003*
AV (%)                            1     1           1.63565      0.1002      0.7541
```

Figure R.5. JMP Statistical Package Output, Hot Recycled Mixtures FI

Residual by Predicted Plot



Effect Details

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	13.869071	1.5392965	12.8583
L	9.638782	1.4157525	10.6150

Virgin Aggregate Type

Least Squares Means Table

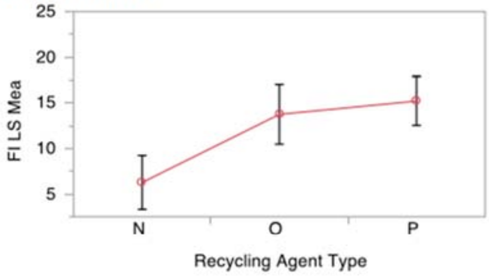
Level	Least Sq Mean	Std Error	Mean
G	9.937628	2.1245543	12.0850
L	13.570224	3.0556655	10.4083

Recycling Agent Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
N	6.272452	1.4409075	6.2125
O	13.764407	1.5963086	12.3333
P	15.224920	1.3043600	14.0750

LS Means Plot



LSMeans Differences Tukey HSD

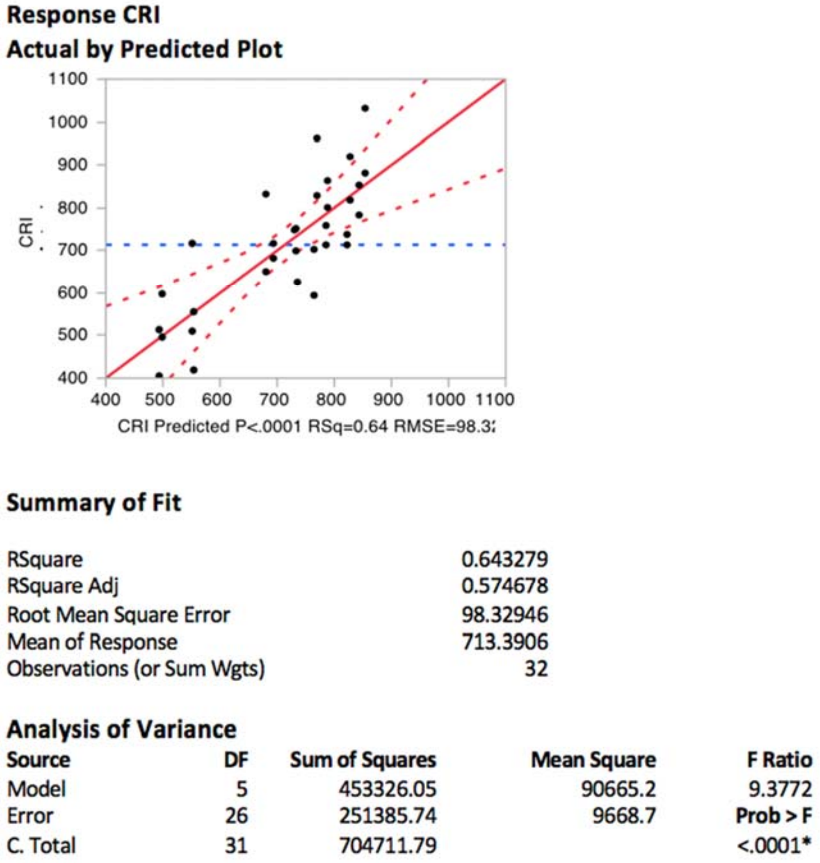
α=0.050

Level			Least Sq Mean
P	A		15.224920
O	A		13.764407
N		B	6.272452

Levels not connected by same letter are significantly different.

Figure R.5 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures FI

Next, the multi-factor ANCOVA model having RAP type, virgin aggregate type, recycling agent type, and AV as main effects was fitted to the CRI data. The standard errors were taken into account in the t Ratio calculation. It can be observed from the Effects Tests below that the effect of recycling agent type was statistically significant at α = 0.05. The Tukey's HSD test indicated that for recycling agent type, the levels P and O were significantly different from N, while there was no statistically significant difference between P and O, as in the case of the FI data.



Response CRI

Actual by Predicted Plot

Summary of Fit

RSquare	0.643279
RSquare Adj	0.574678
Root Mean Square Error	98.32946
Mean of Response	713.3906
Observations (or Sum Wgts)	32

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	453326.05	90665.2	9.3772
Error	26	251385.74	9668.7	**Prob > F**
C. Total	31	704711.79		<.0001*

Figure R.6. JMP Statistical Package Output, Hot Recycled Mixtures CRI

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	11	154969.44	14088.1	2.1918
Pure Error	15	96416.30	6427.8	**Prob > F**
Total Error	26	251385.74		0.0792
				Max RSq

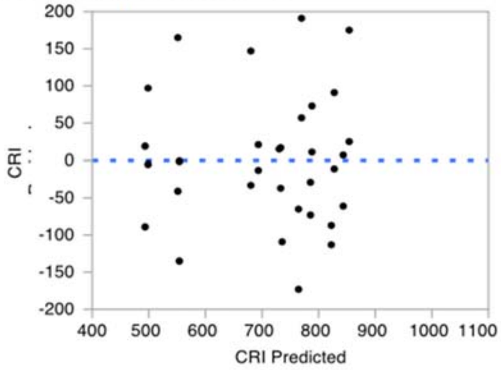
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	601.87361	325.2886	1.85	0.0757
RAP Type[G]	57.605233	28.4001	2.03	0.0529
Virgin Aggregate Type[G]	-52.99162	60.11151	-0.88	0.3861
Recycling Agent Type[N]	-190.1195	28.76562	-6.61	<.0001*
Recycling Agent Type[O]	84.061452	27.87355	3.02	0.0057*
AV (%)	17.576589	50.86195	0.35	0.7324

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Type	1	1	39778.78	4.1142	0.0529
Virgin Aggregate Type	1	1	7513.92	0.7771	0.3861
Recycling Agent Type	2	2	431889.89	22.3345	<.0001*
AV (%)	1	1	1154.65	0.1194	0.7324

Residual by Predicted Plot



Effect Details

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	774.88013	37.463555	743.292
L	659.66967	34.456728	695.450

Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	664.28328	51.707618	730.515
L	770.26652	74.369097	684.850

Recycling Agent Type

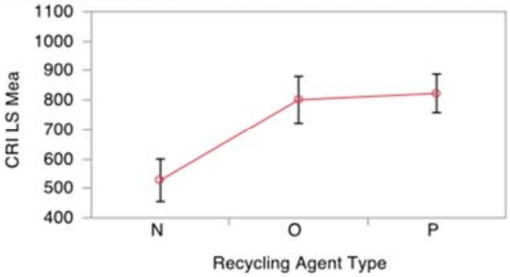
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
N	527.15538	35.068954	525.563
O	801.33635	38.851120	761.267

Figure R.6 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures CRI

Level	Least Sq Mean	Std Error	Mean
P	823.33297	31.745645	790.733

LS Means Plot



LSMeans Differences Tukey HSD

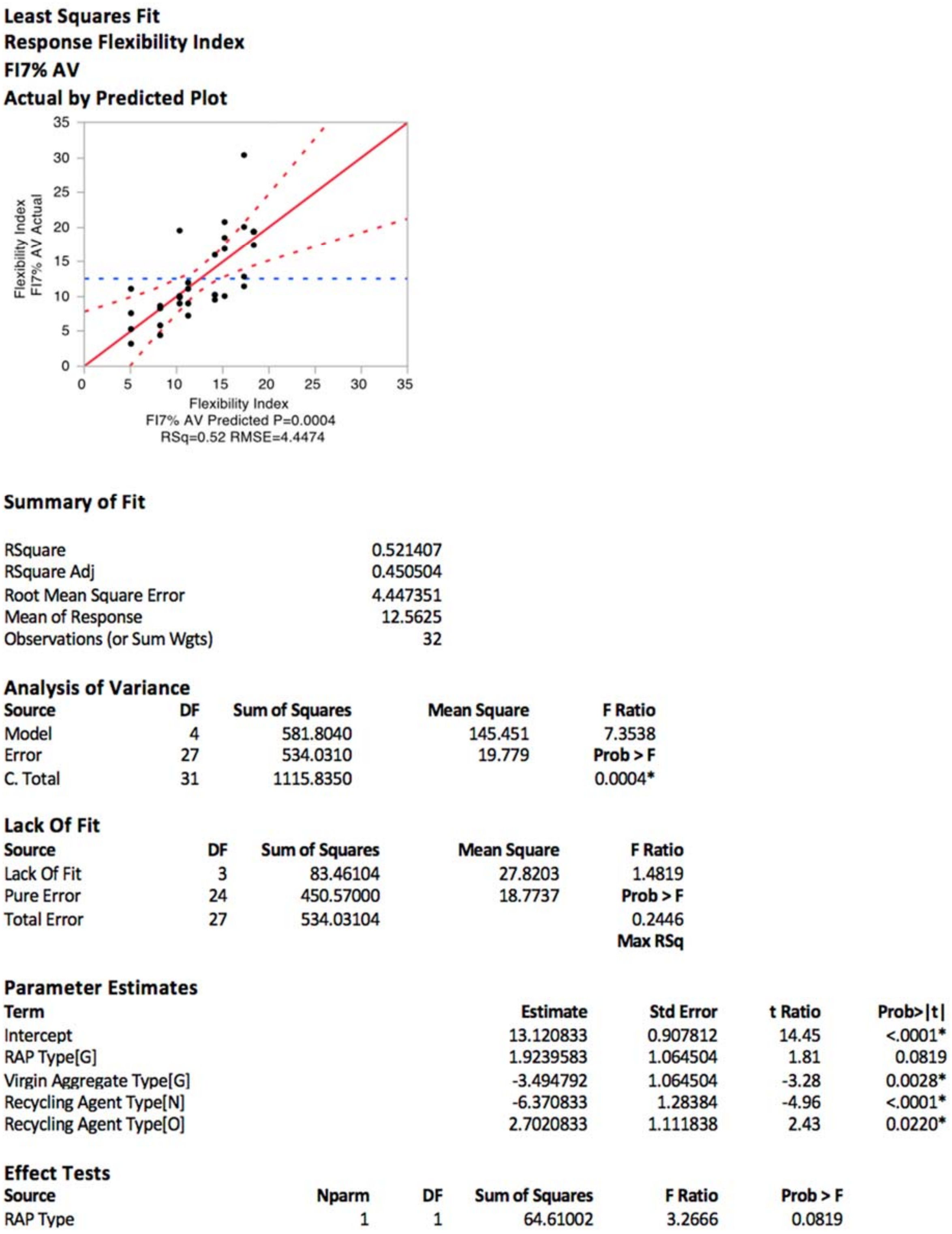
α=0.05

Level			Least Sq Mean
P	A		823.33297
O	A		801.33635
N		B	527.15538

Levels not connected by same letter are significantly different.

Figure R.6 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures CRI

The multi-factor ANCOVA model having RAP type, virgin aggregate type, and recycling agent type as main effects was fitted to the FI normalized by the AV content. It can be observed from the Effects Tests results shown below that the effect of virgin aggregate type as well as the effect of recycling agent type was also statistically significant at α = 0.05. The Tukey's HSD test again indicated that for recycling agent type, the levels P and O were significantly different from N, while there was no statistically significant difference between P and O.



Least Squares Fit

Response Flexibility Index

FI7% AV

Actual by Predicted Plot

Summary of Fit

RSquare	0.521407
RSquare Adj	0.450504
Root Mean Square Error	4.447351
Mean of Response	12.5625
Observations (or Sum Wgts)	32

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	581.8040	145.451	7.3538
Error	27	534.0310	19.779	**Prob > F**
C. Total	31	1115.8350		0.0004*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	3	83.46104	27.8203	1.4819
Pure Error	24	450.57000	18.7737	**Prob > F**
Total Error	27	534.03104		0.2446
				Max RSq

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	13.120833	0.907812	14.45	<.0001*
RAP Type[G]	1.9239583	1.064504	1.81	0.0819
Virgin Aggregate Type[G]	-3.494792	1.064504	-3.28	0.0028*
Recycling Agent Type[N]	-6.370833	1.28384	-4.96	<.0001*
Recycling Agent Type[O]	2.7020833	1.111838	2.43	0.0220*

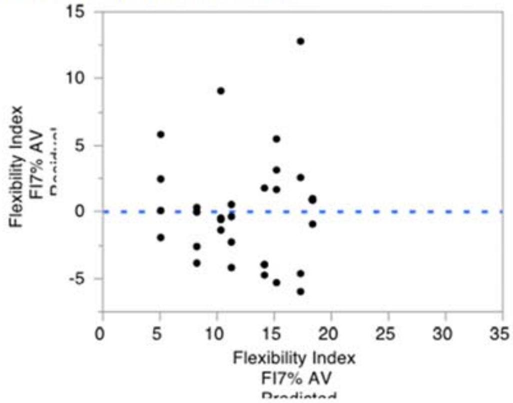
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Type	1	1	64.61002	3.2666	0.0819

Figure R.7. JMP Statistical Package Output, Hot Recycled Mixtures Normalized FI

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Virgin Aggregate Type	1	1	213.18229	10.7783	0.0028*
Recycling Agent Type	2	2	492.65688	12.4541	0.0001*

Residual by Predicted Plot



Effect Details

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	15.044792	1.6677565	11.5500
L	11.196875	1.0645035	13.1700

Virgin Aggregate Type

Least Squares Means Table

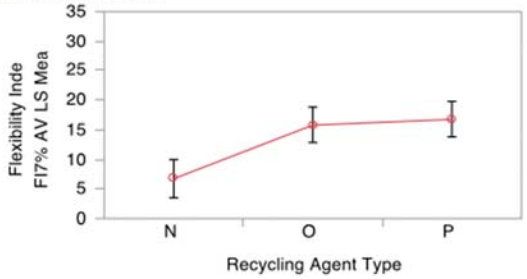
Level	Least Sq Mean	Std Error	Mean
G	9.626042	1.0645035	11.2850
L	16.615625	1.6677565	14.6917

Recycling Agent Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
N	6.750000	1.5723759	6.7500
O	15.822917	1.4353762	14.0167
P	16.789583	1.4353762	14.9833

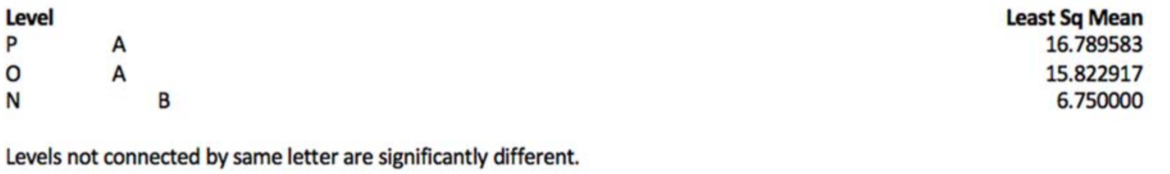
LS Means Plot



LSMeans Differences Tukey HSD

α=0.050

Figure R.7 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures Normalized FI



```
Level                                                    Least Sq Mean
P       A                                                    16.789583
O       A                                                    15.822917
N           B                                                 6.750000

Levels not connected by same letter are significantly different.
```

Figure R.7 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures Normalized FI

The multi-factor ANCOVA model having RAP type, virgin aggregate type, and recycling agent type as main effects was also fitted to the CRI normalized by the AV content. It can be observed from the Effects Tests results shown below that the effect of virgin aggregate type was again statistically significant at α = 0.05 and so was the effect of recycling agent type. The Tukey's HSD test again indicated that for recycling agent type, the levels P and O were significantly different from N, while there was no statistically significant difference between P and O.

Least Squares Fit

Response Cracking Resistance Index
CRI7% AV
Actual by Predicted Plot

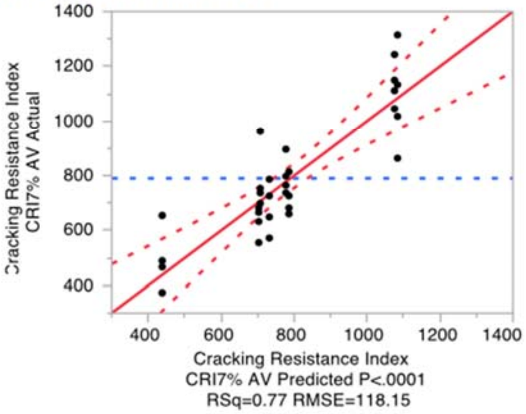


Figure R.8. JMP Statistical Package Output, Hot Recycled Mixtures Normalized CRI

```
Summary of Fit

RSquare                          0.765342
RSquare Adj                      0.730578
Root Mean Square Error           118.1505
Mean of Response                  790.275
Observations (or Sum Wgts)             32

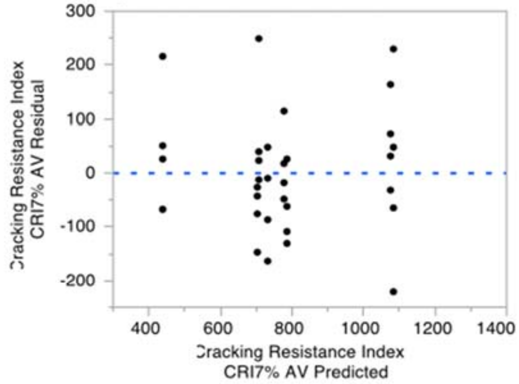
Analysis of Variance
Source        DF   Sum of Squares      Mean Square     F Ratio
Model          4        1229292.6           307323     22.0153
Error         27         376907.3            13960    Prob > F
C. Total      31        1606200.0                     <.0001*

Lack Of Fit
Source            DF   Sum of Squares      Mean Square     F Ratio
Lack Of Fit        3        101185.91          33728.6      2.9359
Pure Error        24        275721.41          11488.4    Prob > F
Total Error       27        376907.32                       0.0538
                                                           Max RSq

Parameter Estimates
Term                                       Estimate    Std Error    t Ratio    Prob>|t|
Intercept                                 817.89583     24.11736      33.91    <.0001*
RAP Type[G]                               38.703125     28.28011       1.37     0.1824
Virgin Aggregate Type[G]                  -186.4906     28.28011      -6.59    <.0001*
Recycling Agent Type[N]                   -229.4208      34.1071      -6.73    <.0001*
Recycling Agent Type[O]                   117.99375     29.53761       3.99    0.0004*

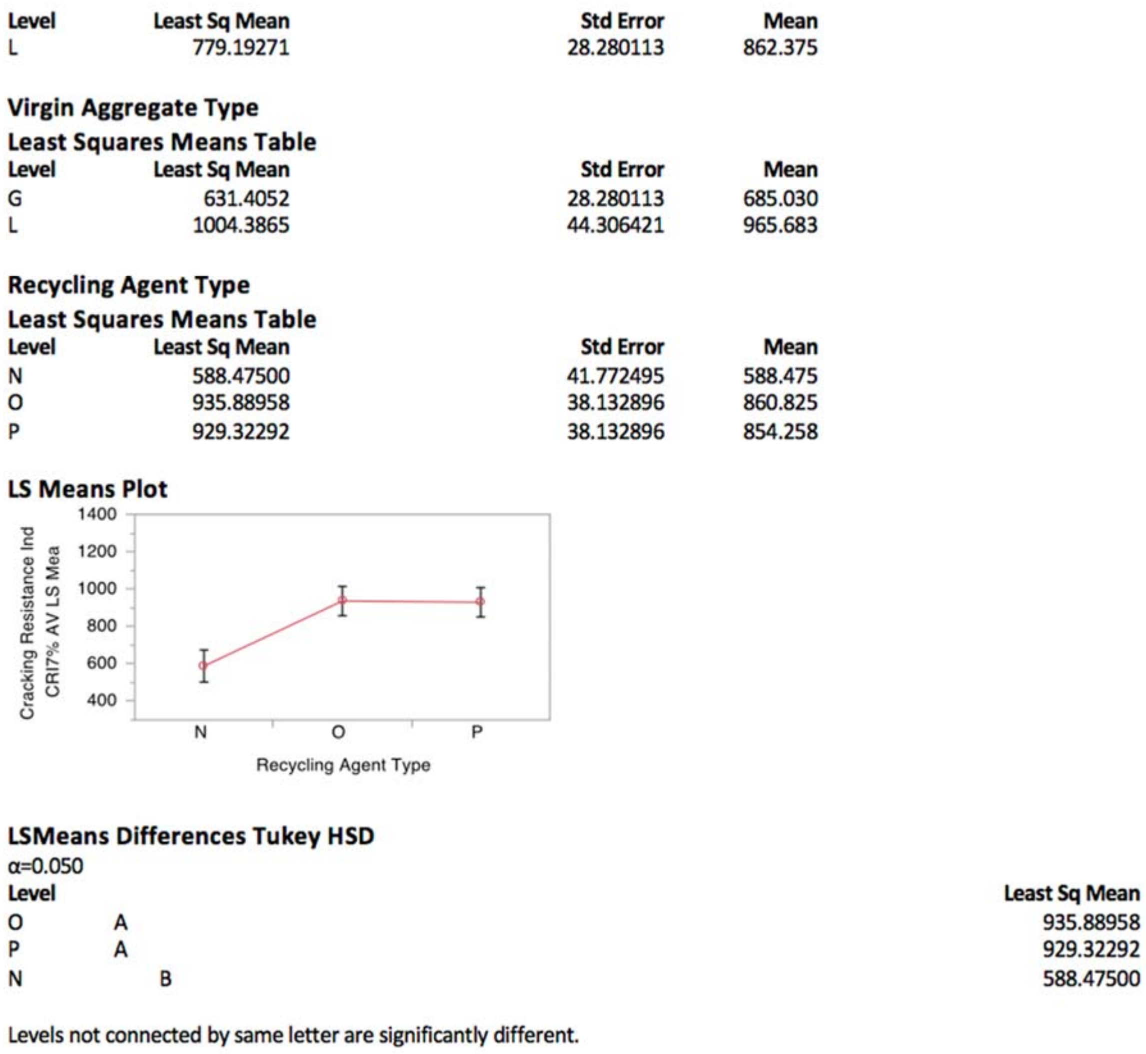
Effect Tests
Source                        Nparm     DF    Sum of Squares     F Ratio     Prob > F
RAP Type                          1      1          26145.72      1.8730       0.1824
Virgin Aggregate Type             1      1         607047.33     43.4862      <.0001*
Recycling Agent Type              2      2         631865.75     22.6321      <.0001*

Residual by Predicted Plot
```



```
Effect Details
RAP Type
Least Squares Means Table
Level      Least Sq Mean                  Std Error       Mean
G              856.59896                  44.306421    670.108
```

Figure R.8 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures Normalized CRI



```
Level        Least Sq Mean                        Std Error       Mean
L                779.19271                        28.280113    862.375

Virgin Aggregate Type
Least Squares Means Table
Level        Least Sq Mean                        Std Error       Mean
G                631.4052                         28.280113    685.030
L               1004.3865                         44.306421    965.683

Recycling Agent Type
Least Squares Means Table
Level        Least Sq Mean                        Std Error       Mean
N                588.47500                        41.772495    588.475
O                935.88958                        38.132896    860.825
P                929.32292                        38.132896    854.258

LS Means Plot
```

```
LSMeans Differences Tukey HSD
α=0.050
Level                                                          Least Sq Mean
O          A                                                       935.88958
P          A                                                       929.32292
N              B                                                   588.47500

Levels not connected by same letter are significantly different.
```

Figure R.8 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures Normalized CRI

Note that goodness of fit (e.g., R-square) improved when models were applied to the normalized data (by AV content). Also, the effect of virgin aggregate type could be estimated more precisely based on the normalized data (the standard errors for virgin aggregate type are smaller for the normalized data). Overall, it appears that it was beneficial to normalize the data by the AV content before the analysis.

STIFFNESS—M_R

The objective of this analysis was to assess the effects of several factors on M_R (Stiffness) for mixtures obtained with hot recycling. The response variable was resilient modulus, and the factors of interest were RAP type with two levels (L, G), virgin aggregate type with two levels (L, G), and recycling agent type with three levels (P, O, N). AV content was also measured. Note that the RAP content was fixed at 60 for this dataset.

The multi-factor ANCOVA model having RAP type, virgin aggregate type, recycling agent type, and AV as main effects was fitted to the data. It can be observed from the Effects Tests results shown below that RAP type and recycling agent type were statistically significant at α = 0.05. For RAP type, it appears that L led to a significantly higher M_R value than G. For recycling agent type, the Tukey's HSD test indicated that recycling agent type = N led to a significantly higher M_R value than recycling agent type = O or P.

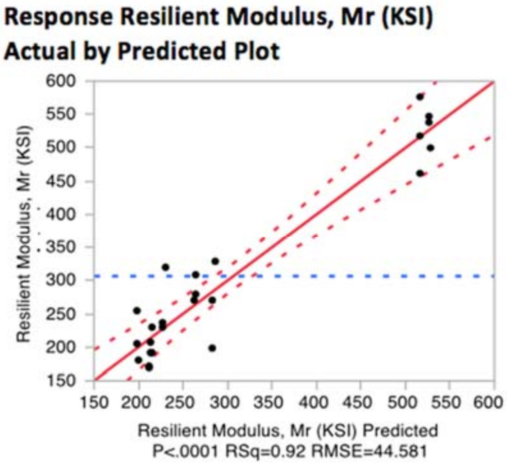


Figure R.9. JMP Statistical Package Output, Hot Recycled Mixtures M_R

Summary of Fit

RSquare	0.915973
RSquare Adj	0.892633
Root Mean Square Error	44.58111
Mean of Response	306.5333
Observations (or Sum Wgts)	24

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	389978.44	77995.7	39.2436
Error	18	35774.56	1987.5	**Prob > F**
C. Total	23	425752.99		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	16	26907.705	1681.73	0.3793
Pure Error	2	8866.850	4433.43	**Prob > F**
Total Error	18	35774.555		0.8976
				Max RSq

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	344.53342	157.9989	2.18	0.0427*
RAP Type[G]	-31.98213	14.43692	-2.22	0.0399*
Virgin Aggregate Type[G]	32.192653	31.94486	1.01	0.3269
Recycling Agent Type[N]	205.95584	15.16753	13.58	<.0001*
Recycling Agent Type[O]	-95.15513	14.29031	-6.66	<.0001*
AV (%)	-4.320504	24.84837	-0.17	0.8639

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Type	1	1	9753.66	4.9076	0.0399*
Virgin Aggregate Type	1	1	2018.43	1.0156	0.3269
Recycling Agent Type	2	2	372855.29	93.8012	<.0001*
AV (%)	1	1	60.09	0.0302	0.8639

Residual by Predicted Plot

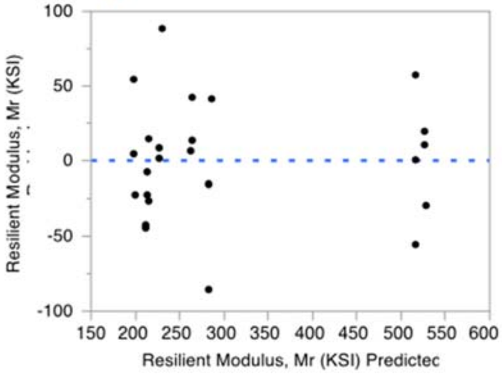
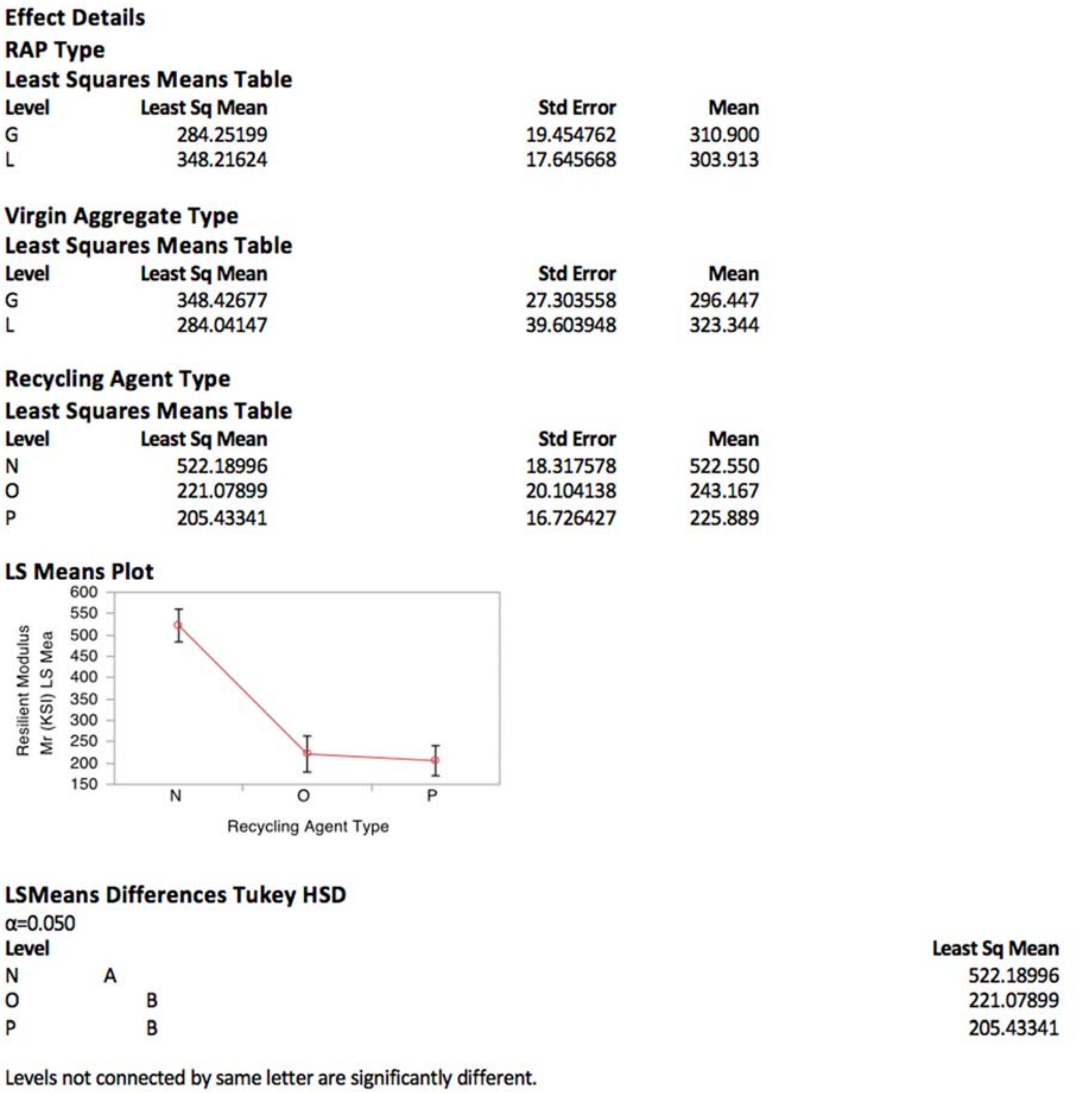


Figure R.9 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures MR



Effect Details

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	284.25199	19.454762	310.900
L	348.21624	17.645668	303.913

Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	348.42677	27.303558	296.447
L	284.04147	39.603948	323.344

Recycling Agent Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
N	522.18996	18.317578	522.550
O	221.07899	20.104138	243.167
P	205.43341	16.726427	225.889

LS Means Plot

LSMeans Differences Tukey HSD

α=0.050

Level			Least Sq Mean
N	A		522.18996
O		B	221.07899
P		B	205.43341

Levels not connected by same letter are significantly different.

Figure R.9 (Continued). JMP Statistical Package Output, Hot Recycled Mixtures MR

Cold Recycling—Emulsion

IDT STRENGTH

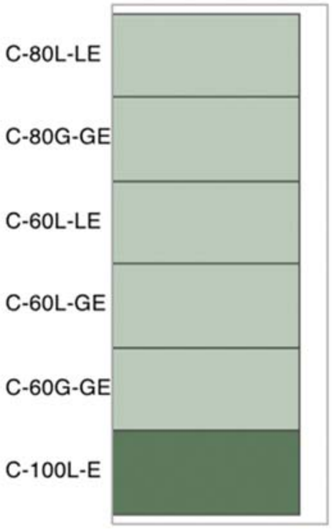
The objective of this analysis was to assess the effects of several factors on IDT for mixtures obtained with emulsified cold recycled mixtures. The factors of interest were RAP content with three levels (60, 80, 100), RAP type with two levels (L, G), virgin aggregate type with three levels (N, L, G), and moisture conditioning with two levels (Dry, Wet). AV content was also measured. Note that the recycling agent type was fixed at E for this dataset.

During the exploratory analysis, it was discovered that the effects of RAP content and virgin aggregate type are partially confounded. The figure below shows that for RAP content = 100, the value of virgin aggregate type was always N, which made fitting the multi-factor ANCOVA model with both RAP content and virgin aggregate type not possible based on all data with n = 36. The analyses were performed in two different ways:

1. Excluding either RAP Content or Virgin Aggregate Type from the model based on the entire data with n = 36.
2. Including both RAP content and virgin aggregate type in the model along with other variables based on the subset of the data with n = 30 obtained from excluding the observations with RAP content = 100 and virgin aggregate type = N (highlighted in the figures below).

Distributions

Mix ID

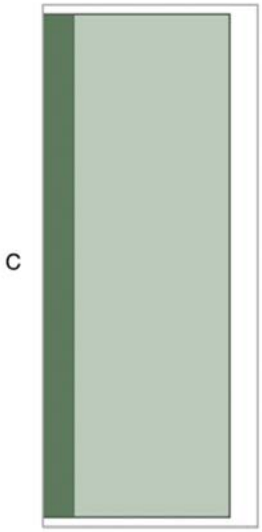


Frequencies

Level	Count	Prob
C-100L-E	6	0.16667
C-60G-GE	6	0.16667
C-60L-GE	6	0.16667
C-60L-LE	6	0.16667
C-80G-GE	6	0.16667
C-80L-LE	6	0.16667
Total	36	1.00000

N Missing
0
6 Levels

Recycling Methodology

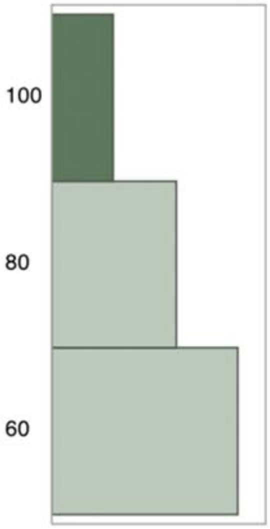


Frequencies

Level	Count	Prob
C	36	1.00000
Total	36	1.00000

N Missing
0
1 Levels

RAP Content



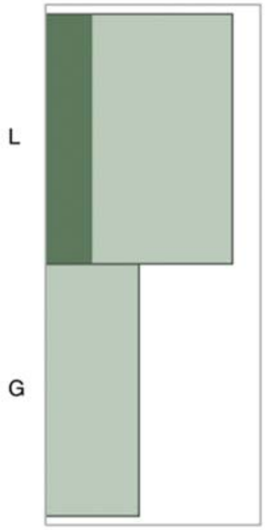
Frequencies

Level	Count	Prob
60	18	0.50000
80	12	0.33333
100	6	0.16667
Total	36	1.00000

N Missing
0
3 Levels

Figure R.10. JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures IDT Strength

RAP Type

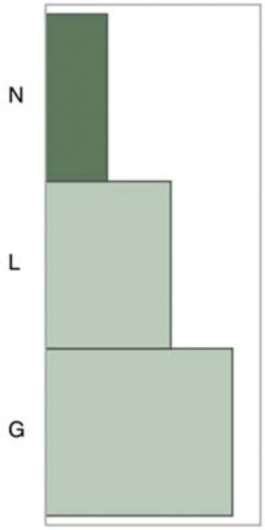


Frequencies

Level	Count	Prob
G	12	0.33333
L	24	0.66667
Total	36	1.00000

N Missing
0
2 Levels

Virgin Aggregate Type

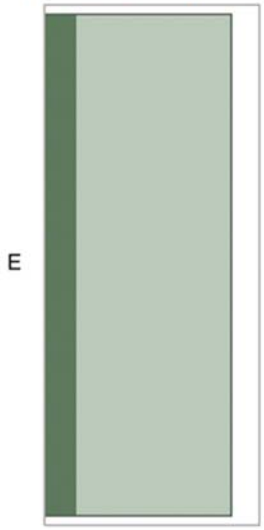


Frequencies

Level	Count	Prob
G	18	0.50000
L	12	0.33333
N	6	0.16667
Total	36	1.00000

N Missing
0
3 Levels

Recycling Agent Type

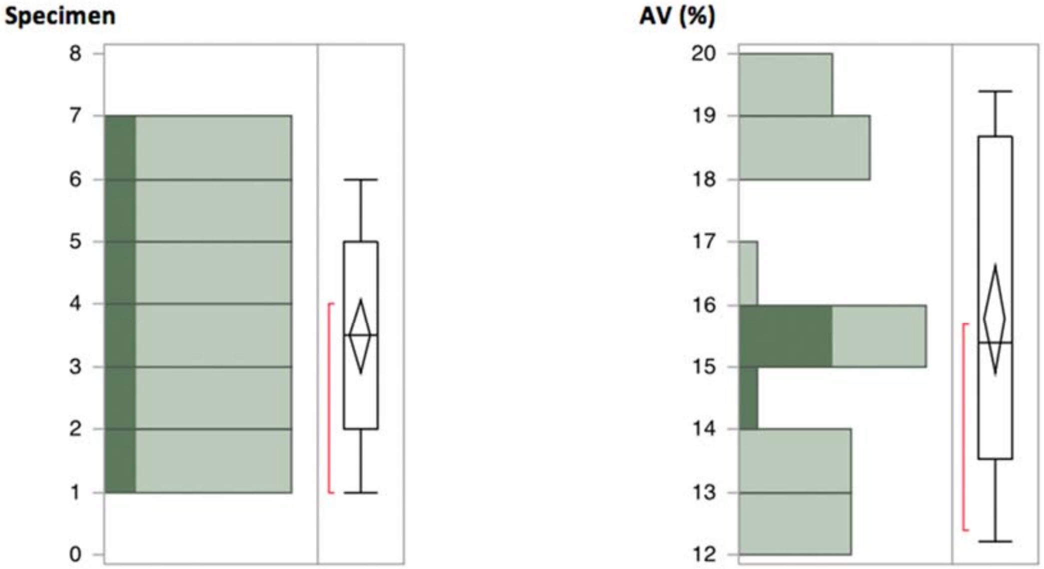


Frequencies

Level	Count	Prob
E	36	1.00000
Total	36	1.00000

N Missing
0
1 Levels

Figure R.10 (Continued). JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures IDT Strength



```
Quantiles

100.0%      maximum        6
99.5%                      6
97.5%                      6
90.0%                      6
75.0%       quartile       5
50.0%       median       3.5
25.0%       quartile       2
10.0%                      1
2.5%                       1
0.5%                       1
0.0%        minimum        1

Summary Statistics

Mean                     3.5
Std Dev            1.7320508
Std Err Mean       0.2886751
Upper 95% Mean     4.0860417
Lower 95% Mean     2.9139583
N                         36
```

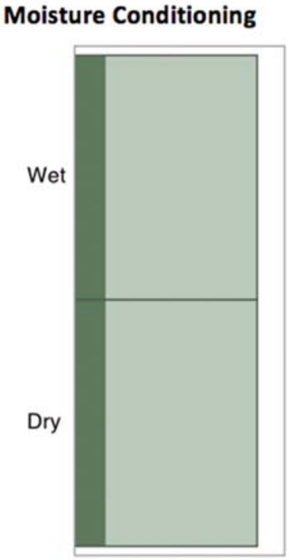
```
Quantiles

100.0%      maximum     19.4
99.5%                   19.4
97.5%                   19.4
90.0%                  19.03
75.0%       quartile  18.675
50.0%       median      15.4
25.0%       quartile  13.525
10.0%                   12.4
2.5%                    12.2
0.5%                    12.2
0.0%        minimum     12.2

Summary Statistics

Mean               15.766667
Std Dev             2.500857
Std Err Mean       0.4168095
Upper 95% Mean     16.612835
Lower 95% Mean     14.920498
N                         36
```

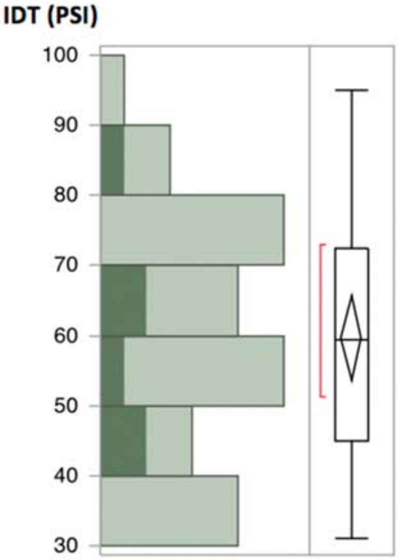
Figure R.10 (Continued). JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures IDT Strength



Frequencies

```
Level      Count      Prob
Dry           18   0.50000
Wet           18   0.50000
Total         36   1.00000

 N Missing
0
2 Levels
```



Quantiles

```
100.0%     maximum     95.1
99.5%                  95.1
97.5%                  95.1
90.0%                 82.35
75.0%     quartile    72.35
50.0%      median      59.5
25.0%     quartile    45.05
10.0%                 31.88
2.5%                   31.1
0.5%                   31.1
0.0%       minimum     31.1
```

Summary Statistics

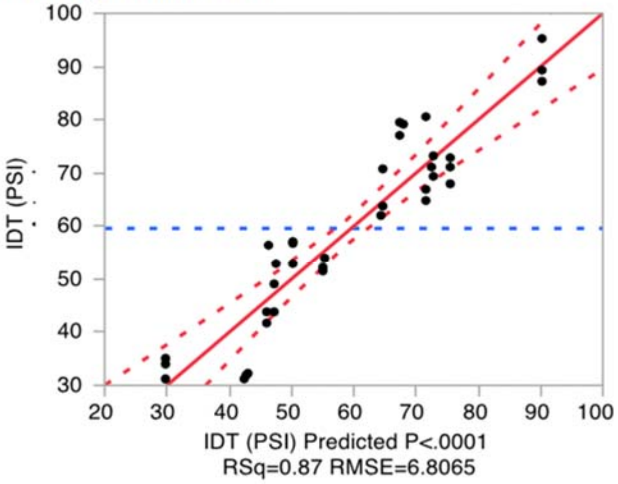
```
Mean               59.583333
Std Dev            17.745704
Std Err Mean       2.9576173
Upper 95% Mean     65.587616
Lower 95% Mean     53.579051
N                         36
```

Figure R.10 (Continued). JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures IDT Strength

The multi-factor ANCOVA model having RAP content, RAP type, moisture conditioning, and AV content as main effects was first fitted to the data. It can be observed from the Effects Tests results shown below that RAP content and moisture conditioning were statistically significant at $\alpha = 0.05$.

Response IDT (PSI)

Actual by Predicted Plot



Summary of Fit

RSquare	0.873899
RSquare Adj	0.852882
Root Mean Square Error	6.806543
Mean of Response	59.58333
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	9631.979	1926.40	41.5808
Error	30	1389.871	46.33	**Prob > F**
C. Total	35	11021.850		<.0001*

Figure R.11. JMP Statistical Package Output with RAP Content and Type, Emulsified Cold Recycled Mixtures IDT Strength

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	22	1213.0808	55.1400	2.4952
Pure Error	8	176.7900	22.0988	**Prob > F**
Total Error	30	1389.8708		0.0919
				Max RSq

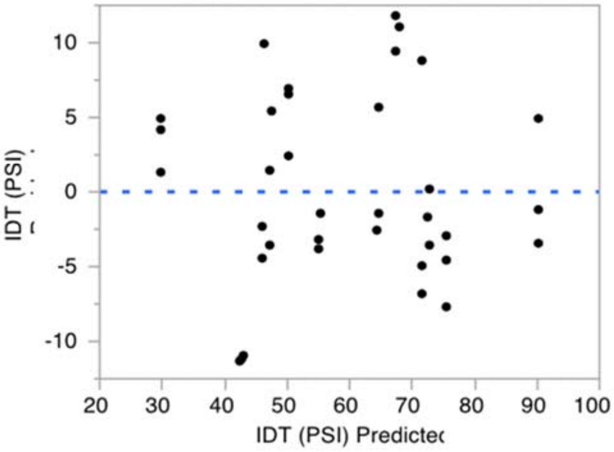
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	77.142292	22.33833	3.45	0.0017*
RAP Content[60]	-3.66838	1.577275	-2.33	0.0270*
RAP Content[80]	9.4010252	2.273898	4.13	0.0003*
RAP Type[G]	-6.877121	3.678589	-1.87	0.0713
AV (%)	-1.280891	1.330397	-0.96	0.3434
Moisture Conditioning[Dry]	12.831897	1.148209	11.18	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Content	2	2	893.9114	9.6474	0.0006*
RAP Type	1	1	161.9213	3.4950	0.0713
AV (%)	1	1	42.9452	0.9270	0.3434
Moisture Conditioning	1	1	5786.1966	124.8935	<.0001*

Residual by Predicted Plot



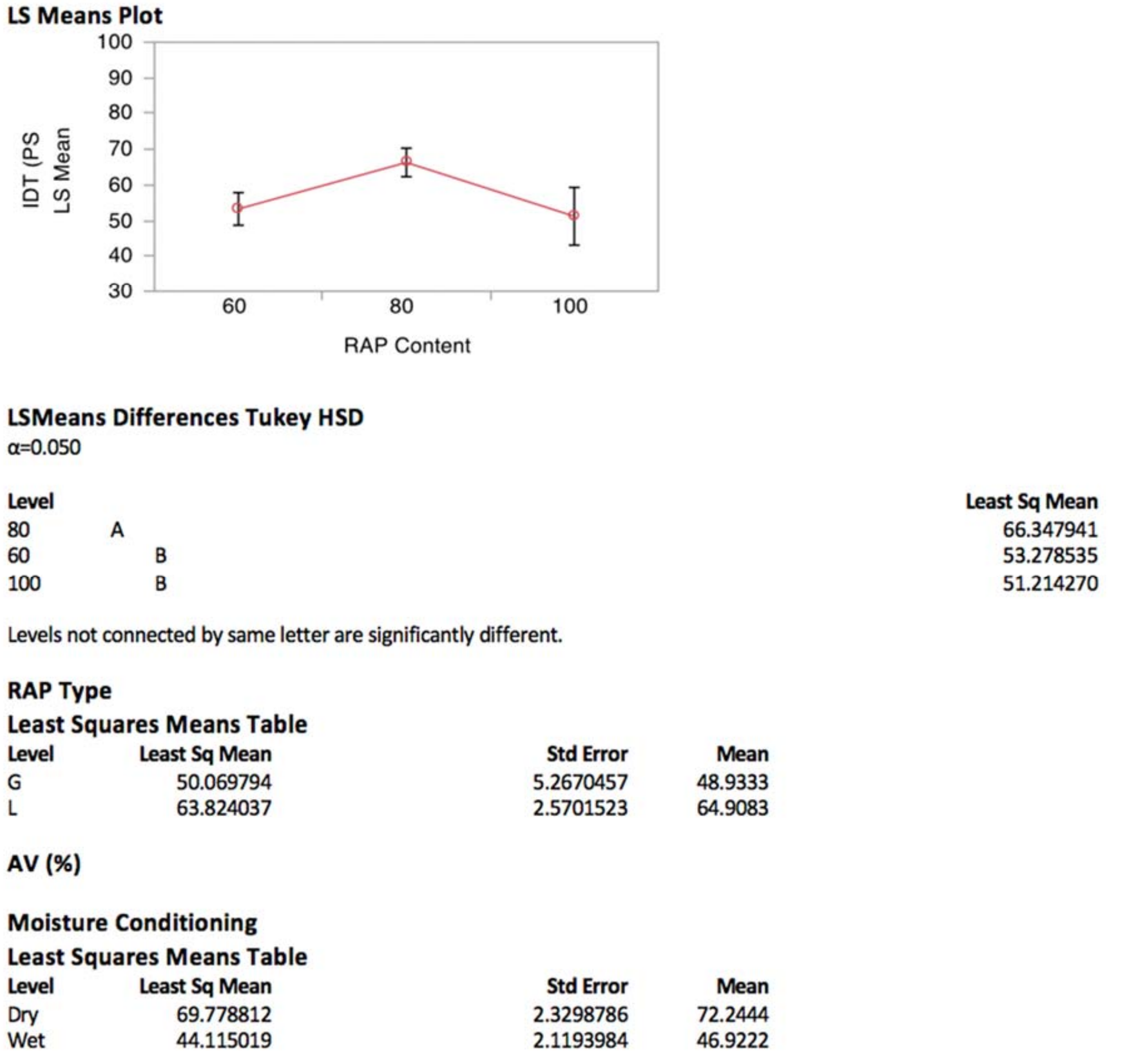
Effect Details

RAP Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
60	53.278535	2.2451398	55.2222
80	66.347941	1.9668805	66.4333
100	51.214270	3.9766552	58.9667

Figure R.11 (Continued). JMP Statistical Package Output with RAP Content and Type, Emulsified Cold Recycled Mixtures IDT Strength



LSMeans Differences Tukey HSD

α=0.050

Level			Least Sq Mean
80	A		66.347941
60		B	53.278535
100		B	51.214270

Levels not connected by same letter are significantly different.

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	50.069794	5.2670457	48.9333
L	63.824037	2.5701523	64.9083

AV (%)

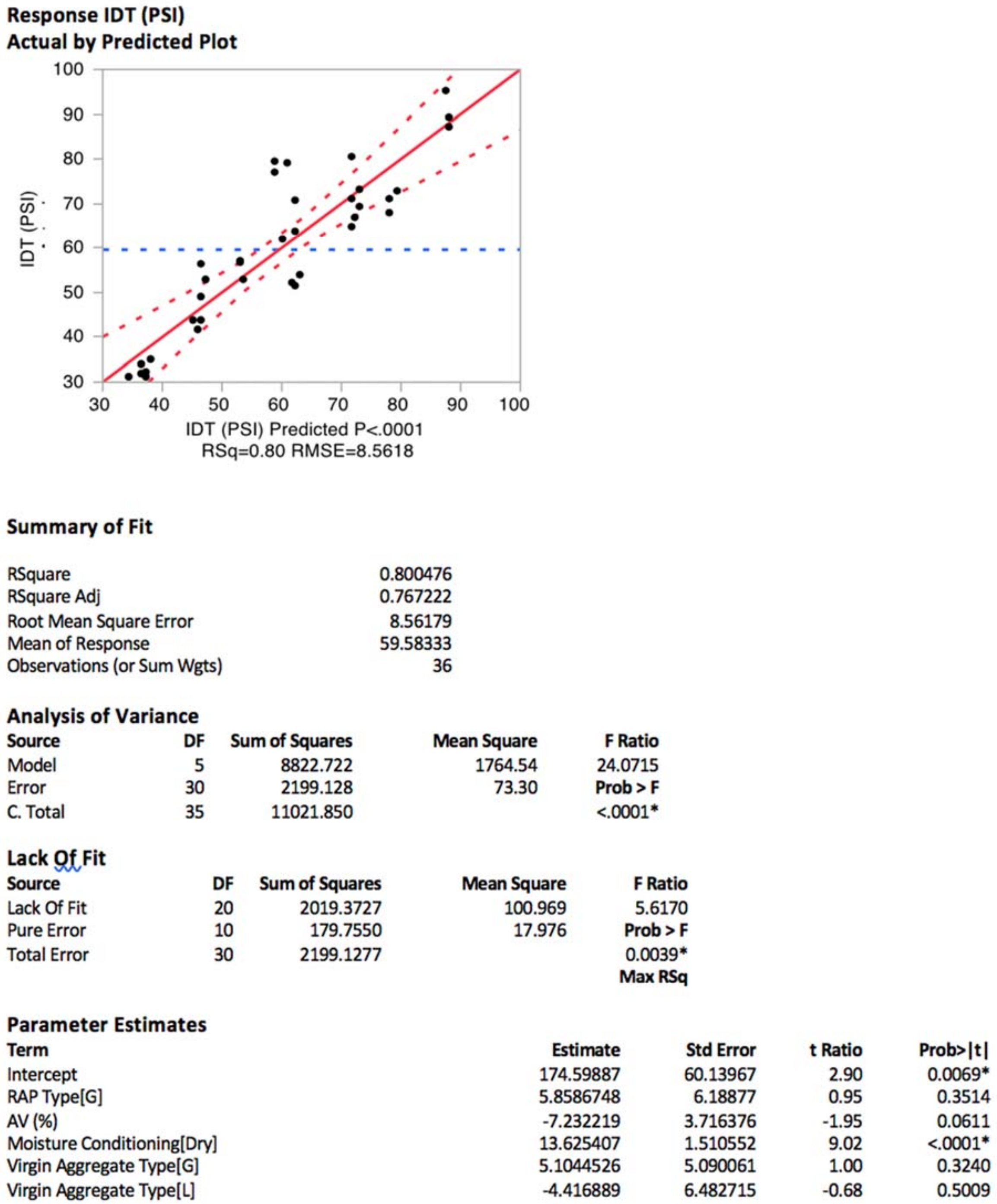
Moisture Conditioning

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Dry	69.778812	2.3298786	72.2444
Wet	44.115019	2.1193984	46.9222

Figure R.11 (Continued). JMP Statistical Package Output with RAP Content and Type, Emulsified Cold Recycled Mixtures IDT Strength

Next, the multi-factor ANCOVA model having RAP type, AV, Moisture Condition, and virgin aggregate type as main effects was fitted to the data. It can be observed from the Effects Tests results shown below that the main effect moisture conditioning was again statistically significant at α = 0.05. The effect of virgin aggregate type was, however, statistically insignificant.



Response IDT (PSI)
Actual by Predicted Plot

Summary of Fit

RSquare	0.800476
RSquare Adj	0.767222
Root Mean Square Error	8.56179
Mean of Response	59.58333
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	8822.722	1764.54	24.0715
Error	30	2199.128	73.30	**Prob > F**
C. Total	35	11021.850		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	20	2019.3727	100.969	5.6170
Pure Error	10	179.7550	17.976	**Prob > F**
Total Error	30	2199.1277		0.0039*
				Max RSq

Parameter Estimates

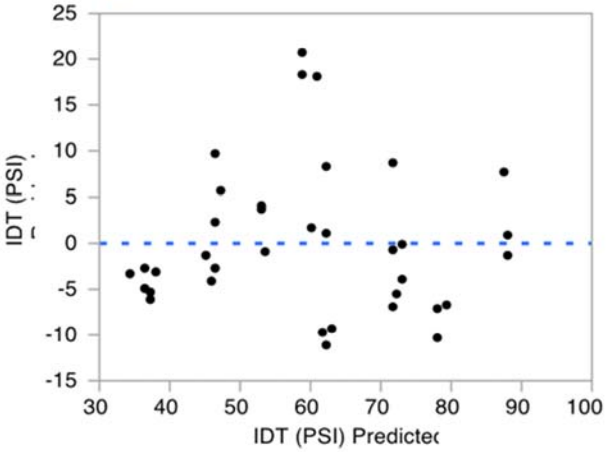
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	174.59887	60.13967	2.90	0.0069*
RAP Type[G]	5.8586748	6.18877	0.95	0.3514
AV (%)	-7.232219	3.716376	-1.95	0.0611
Moisture Conditioning[Dry]	13.625407	1.510552	9.02	<.0001*
Virgin Aggregate Type[G]	5.1044526	5.090061	1.00	0.3240
Virgin Aggregate Type[L]	-4.416889	6.482715	-0.68	0.5009

Figure R.12. JMP Statistical Package Output with RAP and Virgin Aggregate Type, Emulsified Cold Recycled Mixtures IDT Strength

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Type	1	1	65.6930	0.8962	0.3514
AV (%)	1	1	277.6087	3.7871	0.0611
Moisture Conditioning	1	1	5964.2662	81.3632	<.0001*
Virgin Aggregate Type	2	2	84.6545	0.5774	0.5675

Residual by Predicted Plot



Effect Details

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	66.429564	8.1942346	48.9333
L	54.712214	4.6729285	64.9083

AV (%)

Moisture Conditioning

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Dry	74.196296	3.1576201	72.2444
Wet	46.945482	2.6406380	46.9222

Virgin Aggregate Type

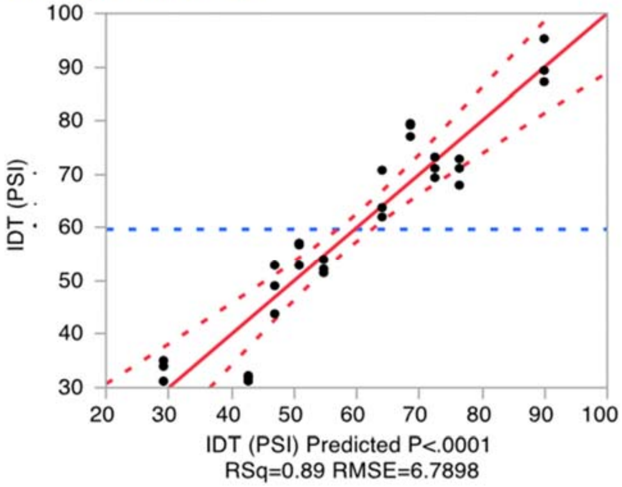
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	65.675341	6.1887696	52.5611
L	56.154000	5.5924284	70.4250
N	59.883325	5.2415865	58.9667

Figure R.12 (Continued). JMP Statistical Package Output with RAP and Virgin Aggregate Type, Emulsified Cold Recycled Mixtures IDT Strength

Finally, the multi-factor ANCOVA model having RAP content, RAP type, virgin aggregate type, moisture conditioning, and AV as main effects was fitted to the subset of data consisting of 30 observations after excluding 6 observations corresponding to RAP content = 100 and virgin aggregate type = N. It can be observed from the Effects Tests results below that main effects RAP content and moisture conditioning were again statistically significant at $\alpha = 0.05$.

Response IDT (PSI)
Actual by Predicted Plot



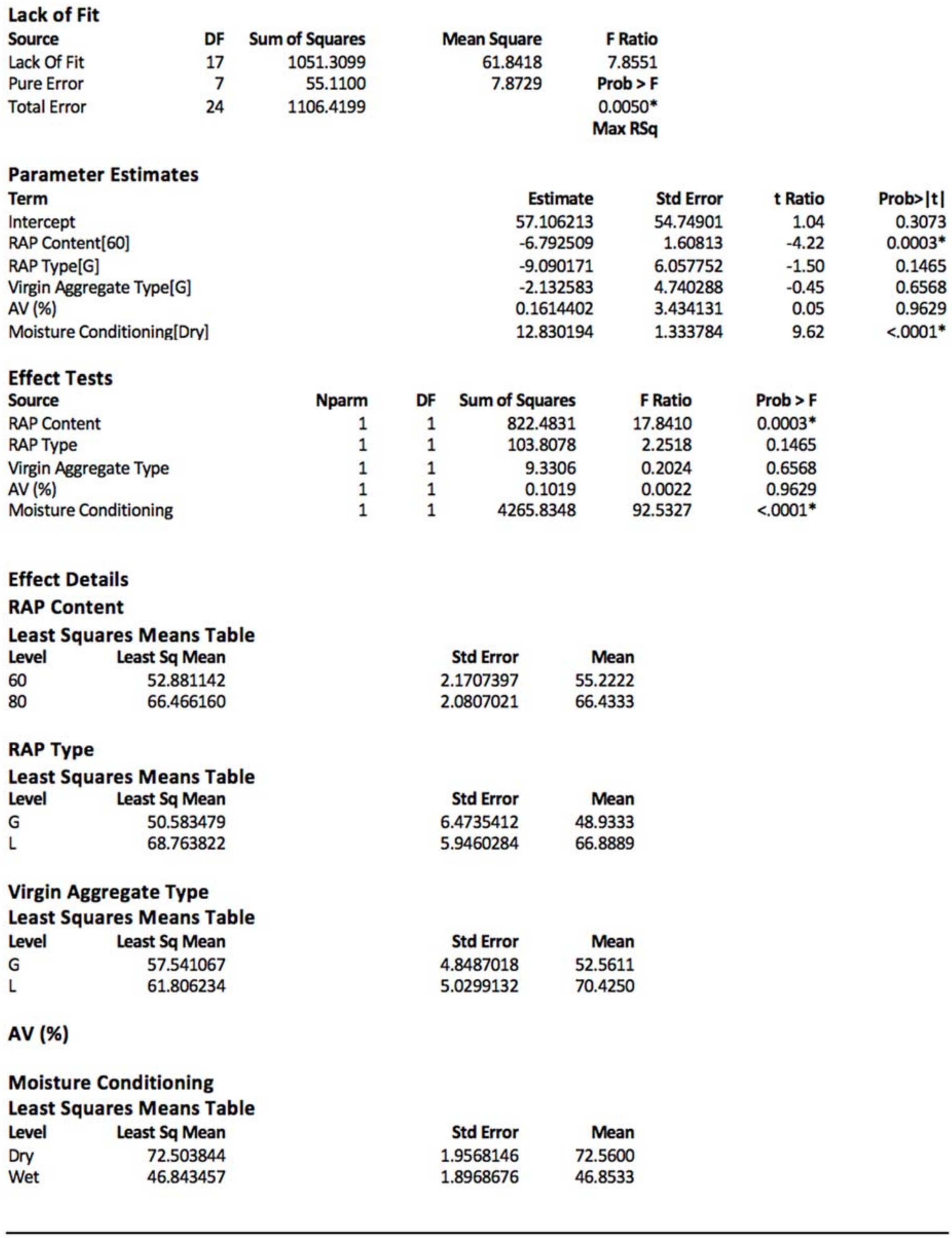
Summary of Fit

```
RSquare                              0.888567
RSquare Adj                          0.865352
Root Mean Square Error               6.789759
Mean of Response                     59.70667
Observations (or Sum Wgts)                 30
```

Analysis of Variance

```
Source      DF   Sum of Squares   Mean Square    F Ratio
Model        5        8822.6388       1764.53    38.2754
Error       24        1106.4199         46.10   Prob > F
C. Total    29        9929.0587                 <.0001*
```

Figure R.13. JMP Statistical Package Output with RAP Content and Type and Virgin Aggregate Type, Emulsified Cold Recycled Mixtures IDT Strength



```
Lack of Fit
Source              DF   Sum of Squares      Mean Square     F Ratio
Lack Of Fit         17        1051.3099          61.8418      7.8551
Pure Error           7          55.1100           7.8729    Prob > F
Total Error         24        1106.4199                      0.0050*
                                                             Max RSq

Parameter Estimates
Term                                       Estimate    Std Error    t Ratio    Prob>|t|
Intercept                                 57.106213     54.74901       1.04      0.3073
RAP Content[60]                           -6.792509      1.60813      -4.22     0.0003*
RAP Type[G]                               -9.090171     6.057752      -1.50      0.1465
Virgin Aggregate Type[G]                  -2.132583     4.740288      -0.45      0.6568
AV (%)                                    0.1614402     3.434131       0.05      0.9629
Moisture Conditioning[Dry]                12.830194     1.333784       9.62     <.0001*

Effect Tests
Source                      Nparm    DF   Sum of Squares    F Ratio    Prob > F
RAP Content                     1     1         822.4831    17.8410     0.0003*
RAP Type                        1     1         103.8078     2.2518      0.1465
Virgin Aggregate Type           1     1           9.3306     0.2024      0.6568
AV (%)                          1     1           0.1019     0.0022      0.9629
Moisture Conditioning           1     1        4265.8348    92.5327     <.0001*


Effect Details
RAP Content
Least Squares Means Table
Level        Least Sq Mean                  Std Error        Mean
60               52.881142                  2.1707397     55.2222
80               66.466160                  2.0807021     66.4333

RAP Type
Least Squares Means Table
Level        Least Sq Mean                  Std Error        Mean
G                50.583479                  6.4735412     48.9333
L                68.763822                  5.9460284     66.8889

Virgin Aggregate Type
Least Squares Means Table
Level        Least Sq Mean                  Std Error        Mean
G                57.541067                  4.8487018     52.5611
L                61.806234                  5.0299132     70.4250

AV (%)

Moisture Conditioning
Least Squares Means Table
Level        Least Sq Mean                  Std Error        Mean
Dry              72.503844                  1.9568146     72.5600
Wet              46.843457                  1.8968676     46.8533
```

Figure R.13 (Continued). JMP Statistical Package Output with RAP Content and Type and Virgin Aggregate Type, Emulsified Cold Recycled Mixtures IDT Strength

HAMBURG WHEEL TRACKING TEST

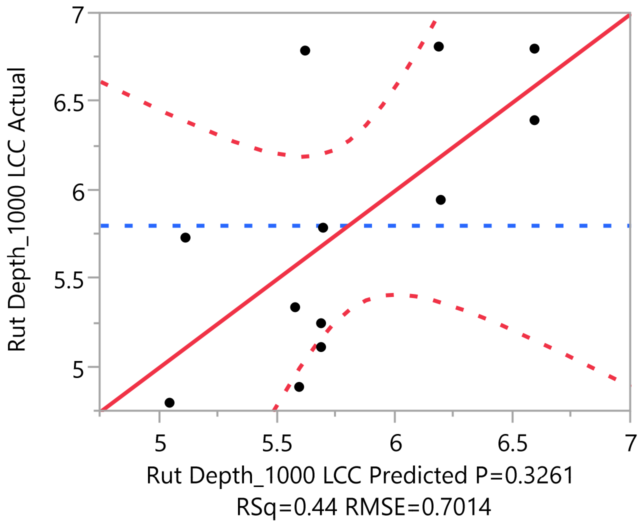
The objective of this analysis was to assess the effects of several factors on the response variables for rutting (HWTT) for the emulsified cold recycled mixtures. The response variables considered were (a) rut depth at 1,000 load cycles, (b) SIP and (c) $\Delta\varepsilon^{vp}_{SN}$ (Delta E). The factors were RAP content with three levels (60, 80, 100), RAP type with two levels (L, G), virgin aggregate type with two levels (L, G), and specimens with two levels (R, L). AVs were also measured from two specimens (Specimen 1 and Specimen 2) for each combination of aforementioned factor levels and were averaged over those two specimens (and renamed as AV_avg) to be included in the multi-factor ANCOVA. Note that the recycling agent type was fixed at E for this dataset. The multi-factor ANCOVA was performed separately for each of the three response variables given above.

Rut Depth at 1,000 Load Cycles

During the exploratory analysis, it was discovered that the effects of RAP content and virgin aggregate type were partially confounded. For RAP content = 100, the value of virgin aggregate type was always N, which made fitting the multi-factor ANCOVA model with both RAP content and virgin aggregate type impossible. The initial results also indicated that the effect of specimen was statistically very insignificant (with p-value greater than 0.8). Therefore, the factors virgin aggregate type and specimen were excluded from the multi-factor ANCOVA, and the model having RAP content, RAP type, and AV_avg as main effects was refitted to the rut depth data. It can be observed from the Effects Tests results shown below that none of the effects were statistically significant at $\alpha = 0.05$.

Response Rut Depth_1000 LCC

Actual by Predicted Plot



Summary of Fit

RSquare	0.444778
RSquare Adj	0.127508
Root Mean Square Error	0.701407
Mean of Response	5.801667
Observations (or Sum Wgts)	12

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	4	2.7587630	0.689691	1.4019
Error	7	3.4438037	0.491972	**Prob > F**
C. Total	11	6.2025667		0.3261

Parameter Estimates

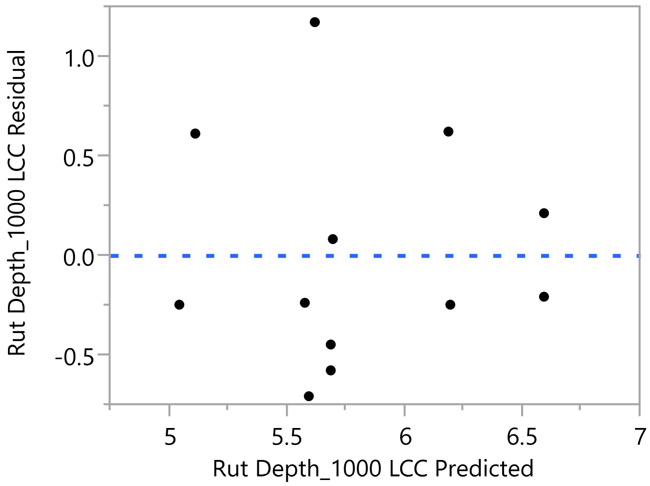
Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	5.7500067	2.138994	2.69	0.0312*
RAP Content[60]	-0.162361	0.2896	-0.56	0.5925
RAP Content[80]	-0.640361	0.395367	-1.62	0.1493
RAP Type[G]	0.2612305	0.316352	0.83	0.4362
AV_avg	0.0213734	0.145439	0.15	0.8873

Effect Tests

Source	**Nparm**	**DF**	**Sum of Squares**	**F Ratio**	**Prob > F**
RAP Content	2	2	1.8647200	1.8951	0.2199
RAP Type	1	1	0.3354658	0.6819	0.4362
AV_avg	1	1	0.0106249	0.0216	0.8873

Figure R.14. JMP Statistical Package Output, Emulsified Cold Recycled Mixtures HWTT Rut Depth

Residual by Predicted Plot



Effect Details

RAP Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
60	5.8872299	0.33789356	5.81333
80	5.4092296	0.38060027	5.38750
100	6.8523121	0.59864970	6.59500

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	6.3108210	0.50241386	5.94250
L	5.7883600	0.28921797	5.73125

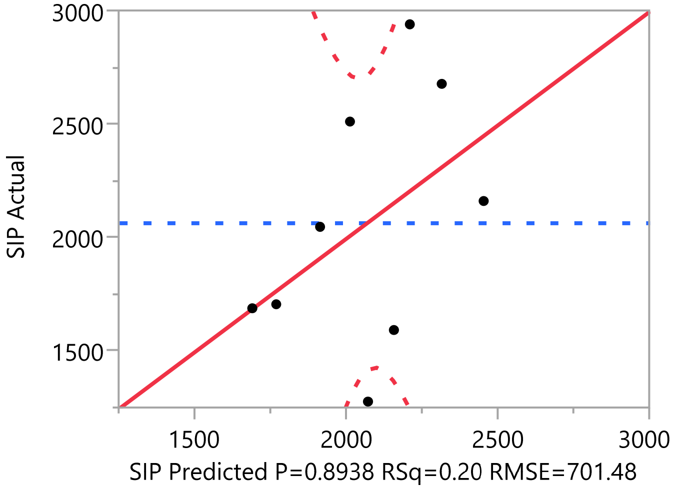
Figure R.14 (Continued). JMP Statistical Package Output, Emulsified Cold Recycled Mixtures HWTT Rut Depth

Stripping Inflection Point

The multi-factor ANOVA model having RAP content with two levels (60, 80), RAP type, virgin aggregate type with two levels (L, G), and specimen as main effects was fitted to the SIP data. Originally, the main effect AV_avg was also included in the model, but the effect was statistically very insignificant (with the p-value of 0.9905) and thus excluded from the model. It can be observed from the Effects Tests results shown below that none of the effects were statistically significant at α = 0.05.

Response SIP

Actual by Predicted Plot



Summary of Fit

RSquare	0.202238
RSquare Adj	-0.59552
Root Mean Square Error	701.4769
Mean of Response	2066.333
Observations (or Sum Wgts)	9

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	498972.5	124743	0.2535
Error	4	1968279.5	492070	**Prob > F**
C. Total	8	2467252.0		0.8938

Figure R.15. JMP Statistical Package Output, Emulsified Cold Recycled Mixtures HWTT SIP

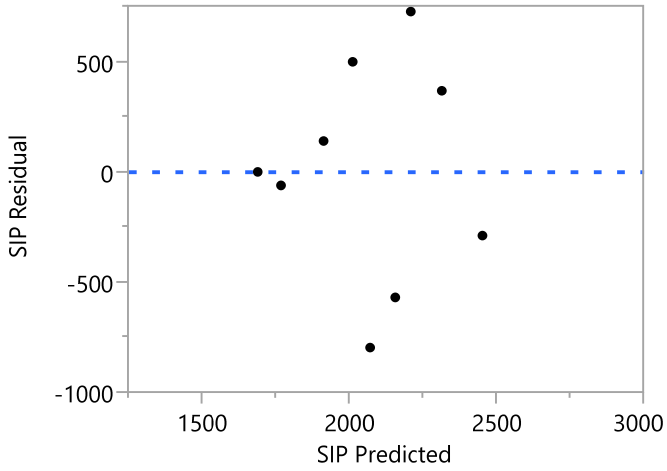
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	2113.625	248.0095	8.52	0.0010*
RAP Content[60]	-70.625	248.0095	-0.28	0.7900
RAP Type[G]	191.625	429.5651	0.45	0.6786
Virgin Aggregate Type[G]	-313.25	429.5651	-0.73	0.5063
Specimen[L]	149.875	248.0095	0.60	0.5782

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Content	1	1	39903.13	0.0811	0.7900
RAP Type	1	1	97920.37	0.1990	0.6786
Virgin Aggregate Type	1	1	261668.17	0.5318	0.5063
Specimen	1	1	179700.12	0.3652	0.5782

Residual by Predicted Plot



Effect Details

RAP Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
60	2043.0000	350.73846	1972.00
80	2184.2500	350.73846	2184.25

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	2305.2500	554.56620	1992.00
L	1922.0000	429.56513	2125.80

Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	1800.3750	429.56513	1931.20

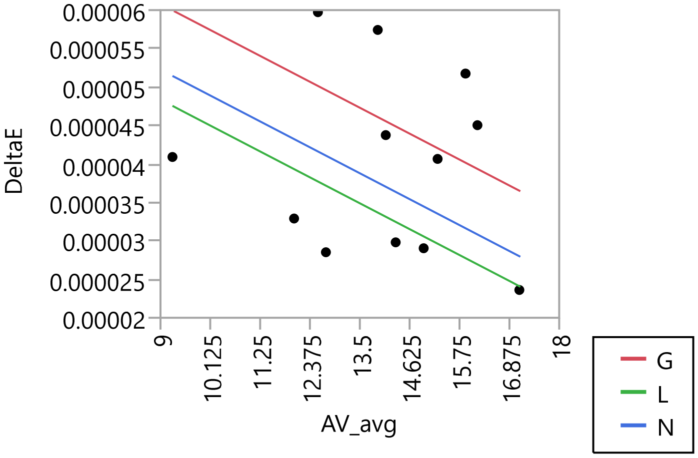
Figure R.15 (Continued). JMP Statistical Package Output, Emulsified Cold Recycled Mixtures HWTT SIP

Rutting Resistance Parameter $\Delta\varepsilon^{vp}_{SN}$

The multi-factor ANCOVA model having RAP type, virgin aggregate type, specimen, and AV_avg as main effects was initially fitted to the $\Delta\varepsilon^{vp}_{SN}$ (Delta E) data. The initial results indicated that the effect of RAP type was statistically very insignificant (with p-value greater than 0.9), as was the effect of specimen. Both RAP type and specimen were thus excluded from the multi-factor ANCOVA, and the model having virgin aggregate type and AV_avg as main effects was refitted to the Delta E data. It can be observed from the Effects Tests results shown below that none of the effects were statistically significant at $\alpha = 0.05$, although it appears that in general the value of Delta E was negatively related with the value of AV, and virgin aggregate type = G led to a higher Delta E value than virgin aggregate type = N or L.

Response DeltaE

Regression Plot



Actual by Predicted Plot

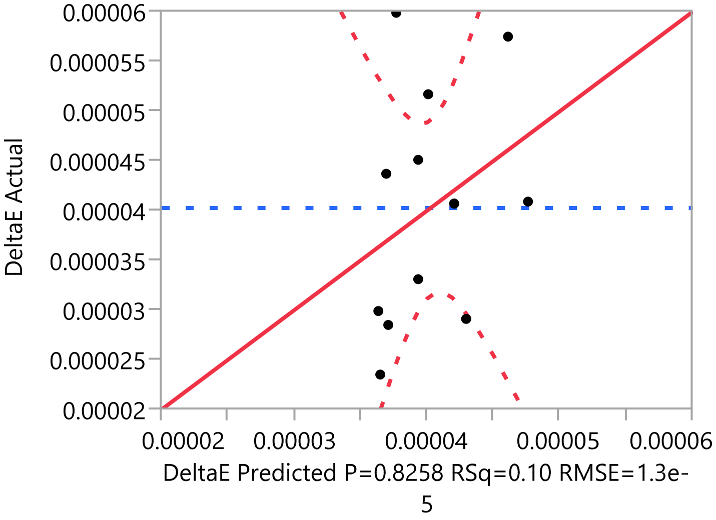


Figure R.16. JMP Statistical Package Output, Emulsified Cold Recycled Mixtures HWTT RRP

```
Summary of Fit

RSquare                              0.100609
RSquare Adj                          -0.23666
Root Mean Square Error               1.321e-5
Mean of Response                     4.026e-5
Observations (or Sum Wgts)                 12

Analysis of Variance
Source          DF  Sum of Squares        Mean Square     F Ratio
Model            3      1.5625e-10          5.208e-11      0.2983
Error            8      1.39678e-9          1.746e-10    Prob > F
C. Total        11      1.55303e-9                         0.8258

Parameter Estimates
Term                                       Estimate     Std Error     t Ratio     Prob>|t|
Intercept                                 8.0828e-5      0.000049        1.65       0.1371
AV_avg                                    -0.000003      3.534e-6       -0.85       0.4213
Virgin Aggregate Type[G]                  6.9799e-6      8.104e-6        0.86       0.4141
Virgin Aggregate Type[L]                  -5.441e-6      9.506e-6       -0.57       0.5828

Effect Tests
Source                      Nparm    DF  Sum of Squares     F Ratio     Prob > F
AV_avg                          1     1      1.2545e-10      0.7185       0.4213
Virgin Aggregate Type           2     2      1.2976e-10      0.3716       0.7009

Effect Details
AV_avg

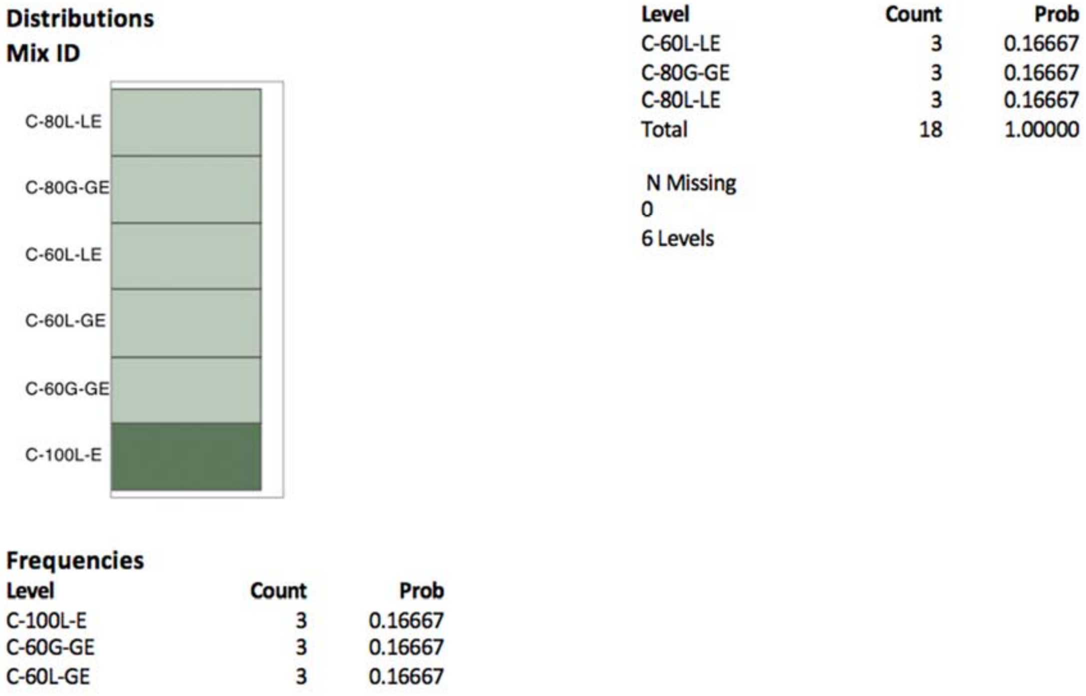
Virgin Aggregate Type
Least Squares Means Table
Level     Least Sq Mean                  Std Error        Mean
G            0.00004582                 0.00000763    0.000041
L            0.00003340                 0.00001069    0.000041
N            0.00003730                 0.00000937    0.000037
```

Figure R.16 (Continued). JMP Statistical Package Output, Emulsified Cold Recycled Mixtures HWTT RRP

DURABILITY—CANTABRO ABRASION LOSS TEST

The objective of this analysis was to assess the effects of several factors on Cantabro abrasion loss (durability) for the emulsified cold recycled mixtures. The response variable was mass loss, and the factors of interest were RAP content with three levels (60, 80, 100) and virgin aggregate type with three levels (L, G, N). AV content was also measured. Note that recycling agent type was fixed at E for this dataset.

During the exploratory analysis, it was discovered that the effects of RAP content and virgin aggregate type were partially confounded. The figure below shows that for RAP content = 100, the value of virgin aggregate type was always N, which made fitting the multi-factor ANCOVA model with both RAP content and virgin aggregate type impossible. The analyses were thus performed by including either RAP content or virgin aggregate type, but not both, along with other variables in the model.



Distributions

Mix ID

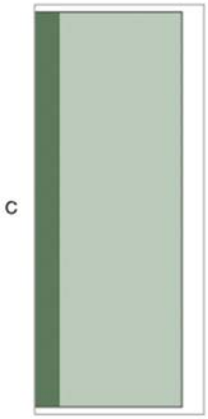
Frequencies

Level	Count	Prob
C-100L-E	3	0.16667
C-60G-GE	3	0.16667
C-60L-GE	3	0.16667
C-60L-LE	3	0.16667
C-80G-GE	3	0.16667
C-80L-LE	3	0.16667
Total	18	1.00000

N Missing
0
6 Levels

Figure R.17. JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures Cantabro

Recycling Methodology

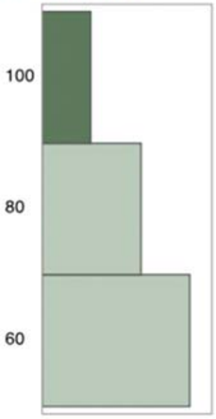


Frequencies

Level	Count	Prob
C	18	1.00000
Total	18	1.00000

N Missing
0
1 Levels

RAP Content

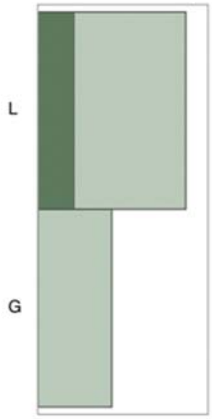


Frequencies

Level	Count	Prob
60	9	0.50000
80	6	0.33333
100	3	0.16667
Total	18	1.00000

N Missing
0
3 Levels

RAP Type

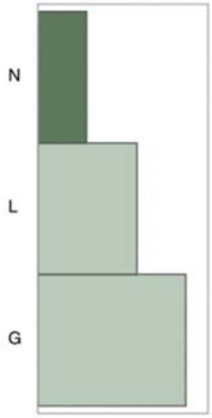


Frequencies

Level	Count	Prob
G	6	0.33333
L	12	0.66667
Total	18	1.00000

N Missing
0
2 Levels

Virgin Aggregate Type



Frequencies

Level	Count	Prob
G	9	0.50000
L	6	0.33333
N	3	0.16667
Total	18	1.00000

N Missing
0
3 Levels

Figure R.17 (Continued). JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures Cantabro

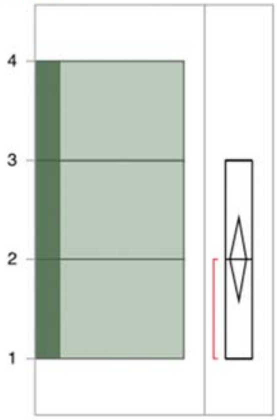
Recycling Agent Type

Frequencies

Level	Count	Prob
E	18	1.00000
Total	18	1.00000

N Missing
0
1 Levels

Specimen



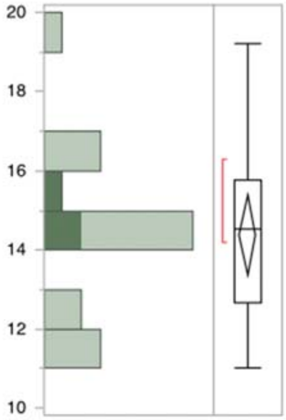
Quantiles

100.0%	maximum	3
99.5%		3
97.5%		3
90.0%		3
75.0%	quartile	3
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	2
Std Dev	0.8401681
Std Err Mean	0.1980295
Upper 95% Mean	2.4178057
Lower 95% Mean	1.5821943
N	18

AV (%)



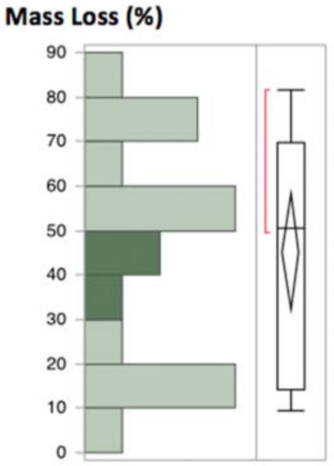
Quantiles

100.0%	maximum	19.2
99.5%		19.2
97.5%		19.2
90.0%		16.77
75.0%	quartile	15.75
50.0%	median	14.55
25.0%	quartile	12.65
10.0%		11.09
2.5%		11
0.5%		11
0.0%	minimum	11

Summary Statistics

Mean	14.383333
Std Dev	2.0526167
Std Err Mean	0.4838064
Upper 95% Mean	15.404076
Lower 95% Mean	13.362591
N	18

Figure R.17 (Continued). JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures Cantabro



Quantiles

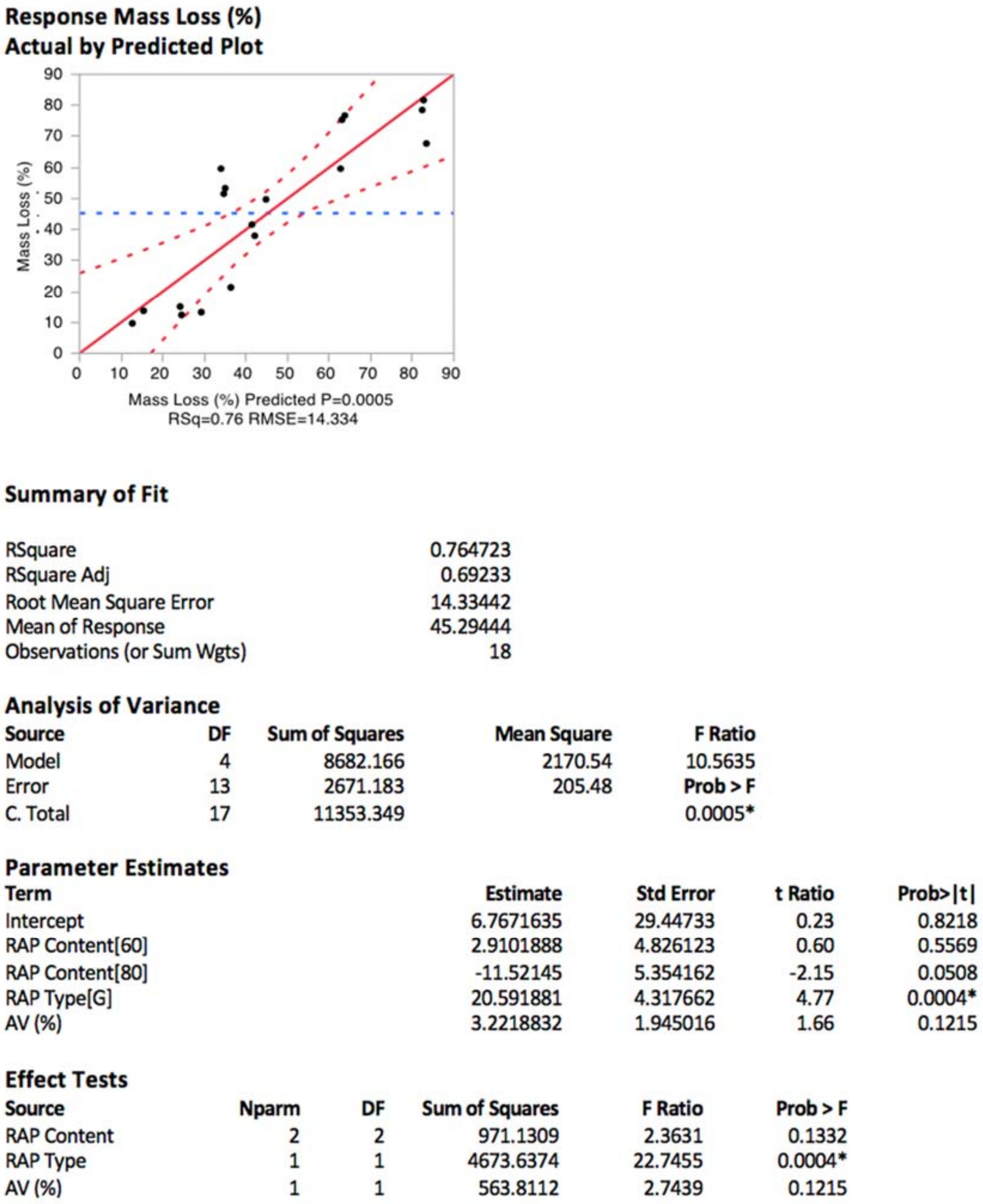
100.0%	maximum	81.6
99.5%		81.6
97.5%		81.6
90.0%		78.54
75.0%	quartile	69.575
50.0%	median	50.6
25.0%	quartile	14.35
10.0%		11.76
2.5%		9.6
0.5%		9.6
0.0%	minimum	9.6

Summary Statistics

Mean	45.294444
Std Dev	25.84268
Std Err Mean	6.091178
Upper 95% Mean	58.145707
Lower 95% Mean	32.443182
N	18

Figure R.17 (Continued). JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures Cantabro

A multi-factor ANCOVA model having RAP content, RAP type, and AV as main effects was first fitted to the data. It can be observed from the Effects Tests results shown below that only the effect of RAP type was statistically significant at α = 0.05. RAP type = G led to a significantly higher predicted value for mass loss than RAP type = L.



Response Mass Loss (%)
Actual by Predicted Plot

Summary of Fit

RSquare	0.764723
RSquare Adj	0.69233
Root Mean Square Error	14.33442
Mean of Response	45.29444
Observations (or Sum Wgts)	18

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	8682.166	2170.54	10.5635
Error	13	2671.183	205.48	Prob > F
C. Total	17	11353.349		0.0005*

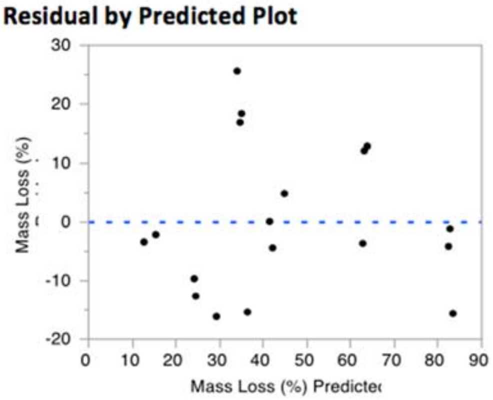
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	6.7671635	29.44733	0.23	0.8218
RAP Content[60]	2.9101888	4.826123	0.60	0.5569
RAP Content[80]	-11.52145	5.354162	-2.15	0.0508
RAP Type[G]	20.591881	4.317662	4.77	0.0004*
AV (%)	3.2218832	1.945016	1.66	0.1215

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Content	2	2	971.1309	2.3631	0.1332
RAP Type	1	1	4673.6374	22.7455	0.0004*
AV (%)	1	1	563.8112	2.7439	0.1215

Figure R.18. JMP Statistical Package Output with RAP Content and Type, Emulsified Cold Recycled Mixtures Cantabro



Effect Details

RAP Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
60	56.018773	4.9462115	47.9556
80	41.587133	5.8778938	42.5000
100	61.719846	9.6197163	42.9000

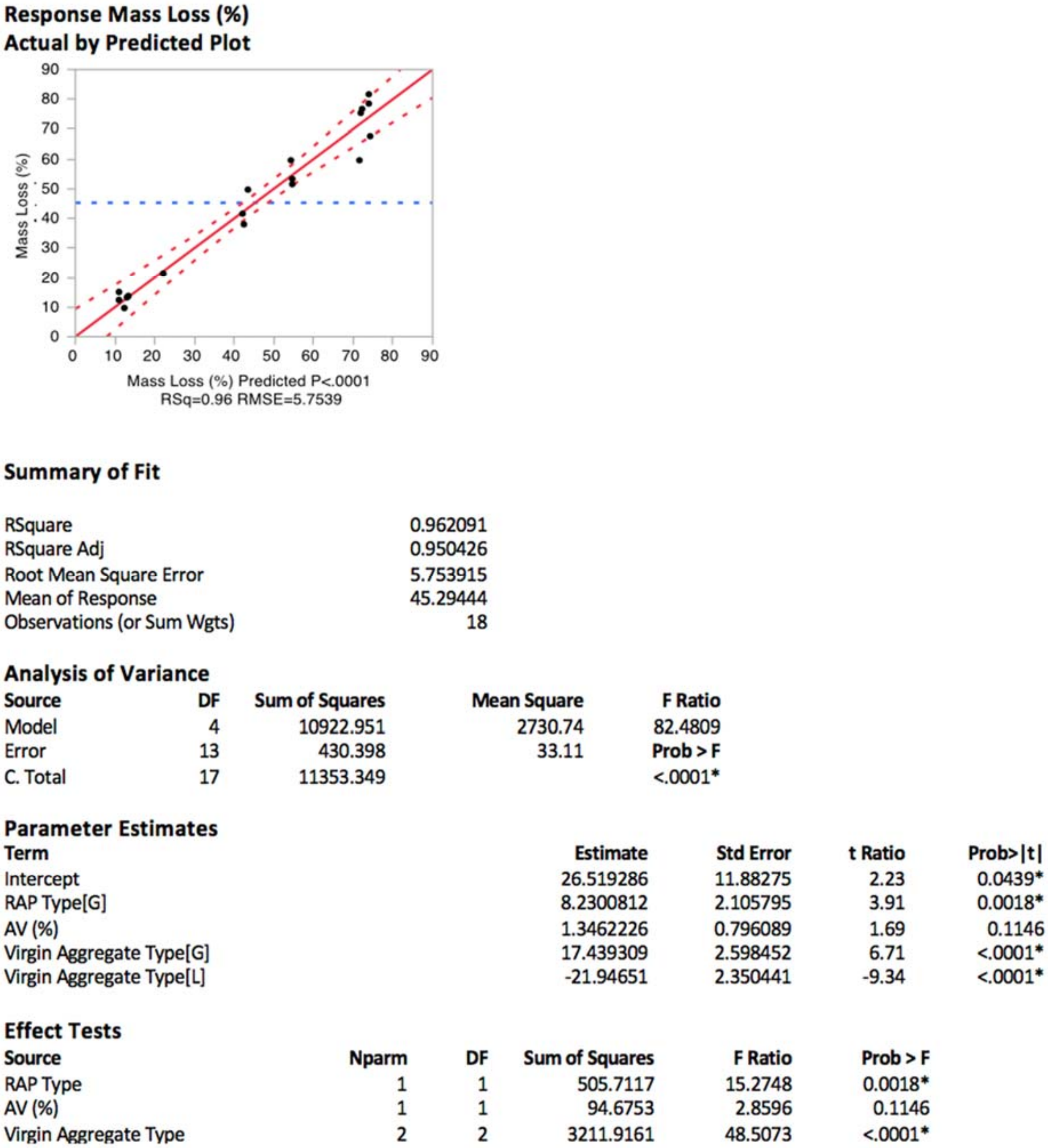
RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	73.700465	7.3930173	73.1000
L	32.516702	4.3742115	31.3917

Figure R.18 (Continued). JMP Statistical Package Output with RAP Content and Type, Emulsified Cold Recycled Mixtures Cantabro

Next, the multi-factor ANCOVA model having RAP type, AV content, and virgin aggregate type as main effects was fitted to the data. It can be observed from the Effects Tests results shown below that the effects of RAP type and virgin aggregate type were statistically significant at α = 0.05.



Response Mass Loss (%)

Actual by Predicted Plot

Summary of Fit

RSquare	0.962091
RSquare Adj	0.950426
Root Mean Square Error	5.753915
Mean of Response	45.29444
Observations (or Sum Wgts)	18

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	10922.951	2730.74	82.4809
Error	13	430.398	33.11	**Prob > F**
C. Total	17	11353.349		<.0001*

Parameter Estimates

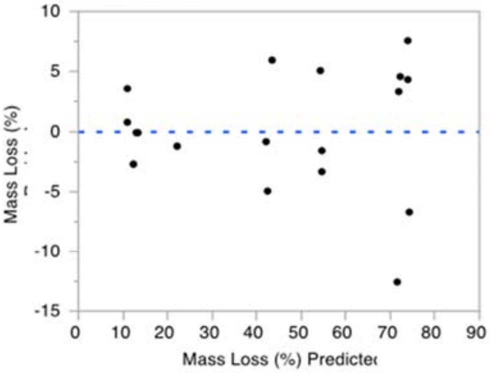
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	26.519286	11.88275	2.23	0.0439*
RAP Type[G]	8.2300812	2.105795	3.91	0.0018*
AV (%)	1.3462226	0.796089	1.69	0.1146
Virgin Aggregate Type[G]	17.439309	2.598452	6.71	<.0001*
Virgin Aggregate Type[L]	-21.94651	2.350441	-9.34	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Type	1	1	505.7117	15.2748	0.0018*
AV (%)	1	1	94.6753	2.8596	0.1146
Virgin Aggregate Type	2	2	3211.9161	48.5073	<.0001*

Figure R.19. JMP Statistical Package Output with RAP and Virgin Aggregate Type, Emulsified Cold Recycled Mixtures Cantabro

Residual by Predicted Plot



Effect Details

RAP Type

Least Squares Means Table

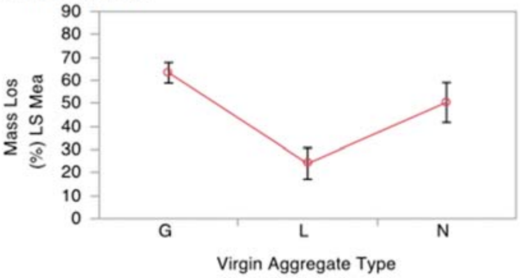
Level	Least Sq Mean	Std Error	Mean
G	54.112535	3.5980634	73.1000
L	37.652373	1.7701985	31.3917

Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	63.321763	2.0679605	67.0000
L	23.935941	3.1481062	13.9333
N	50.389659	4.0172509	42.9000

LS Means Plot



LSMeans Differences Tukey HSD

α=0.050

Level				Least Sq Mean
G	A			63.321763
N		B		50.389659
L			C	23.935941

Levels not connected by same letter are significantly different.

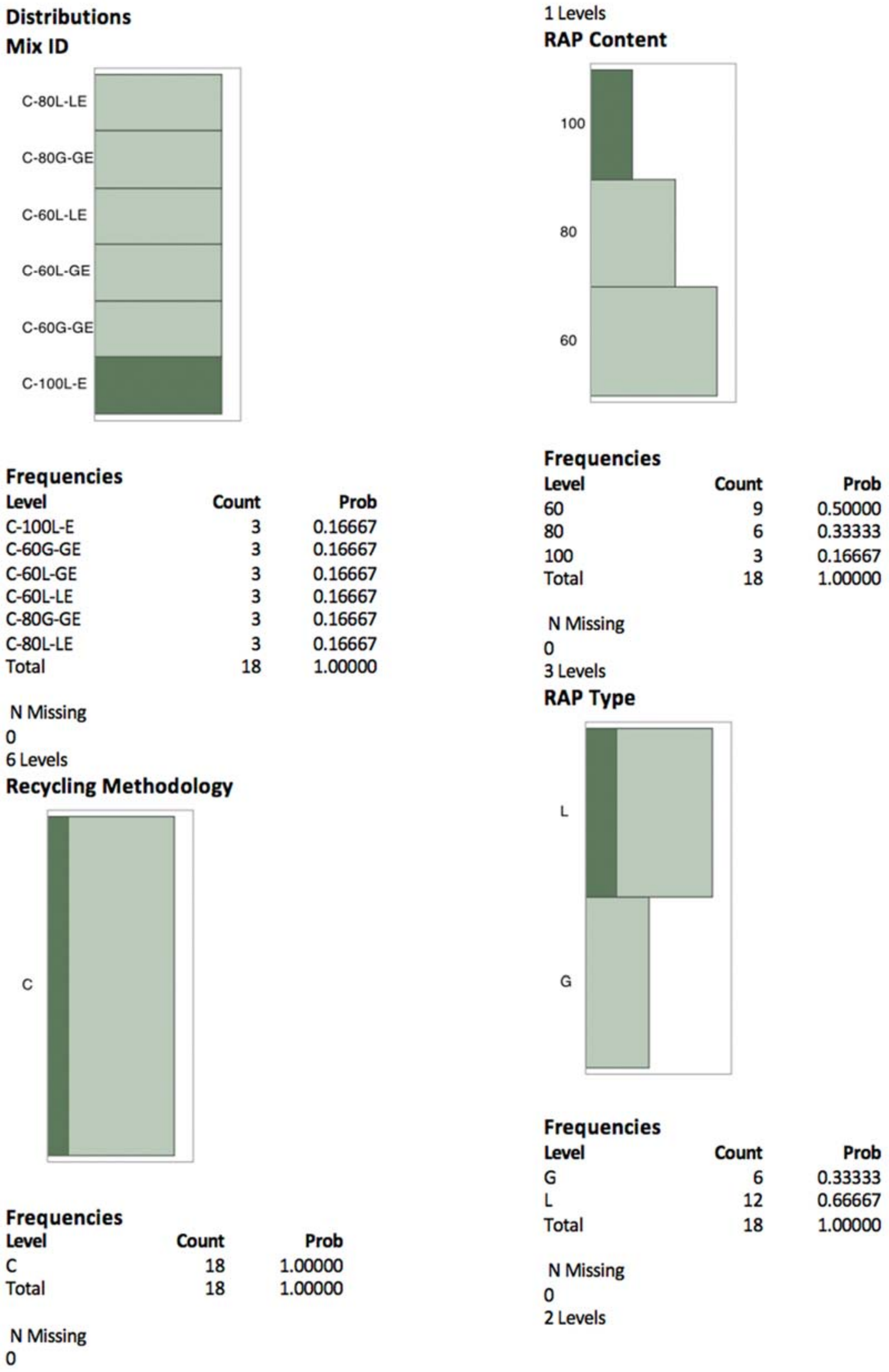
Figure R.19 (Continued). JMP Statistical Package Output with RAP and Virgin Aggregate Type, Emulsified Cold Recycled Mixtures Cantabro

STIFFNESS—M_R

The objective of this analysis was to assess the effects of several factors on M_R (Stiffness) for the emulsified cold recycled mixtures. The factors of interest were RAP content with three levels (60, 80, 100), RAP type with two levels (L, G), and virgin aggregate type with three levels (N, L, G). AV content was also measured. Note that the recycling agent type was fixed at E for this dataset.

During the exploratory analysis, it was discovered that the effects of RAP content and virgin aggregate type were partially confounded. The figure below shows that for RAP content = 100, the value of virgin aggregate type was always N, which made fitting the multi-factor ANCOVA model with both RAP content and virgin aggregate type impossible based on all data with n = 18. The analyses were performed in two different ways:

1. Excluding either RAP content or virgin aggregate type from the model based on the entire data with n = 18.
2. Including both RAP content and virgin aggregate type in the model along with other variables based on the subset of the data with n = 15, obtained from excluding 3 observations with RAP content = 100 and virgin aggregate type = N (highlighted in the figures below).



Distributions

Mix ID

Frequencies

Level	Count	Prob
C-100L-E	3	0.16667
C-60G-GE	3	0.16667
C-60L-GE	3	0.16667
C-60L-LE	3	0.16667
C-80G-GE	3	0.16667
C-80L-LE	3	0.16667
Total	18	1.00000

N Missing
0
6 Levels

Recycling Methodology

Frequencies

Level	Count	Prob
C	18	1.00000
Total	18	1.00000

N Missing
0

1 Levels

RAP Content

Frequencies

Level	Count	Prob
60	9	0.50000
80	6	0.33333
100	3	0.16667
Total	18	1.00000

N Missing
0
3 Levels

RAP Type

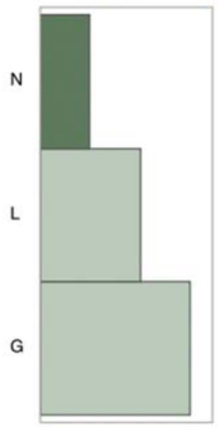
Frequencies

Level	Count	Prob
G	6	0.33333
L	12	0.66667
Total	18	1.00000

N Missing
0
2 Levels

Figure R.20. JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures M_R

Virgin Aggregate Type

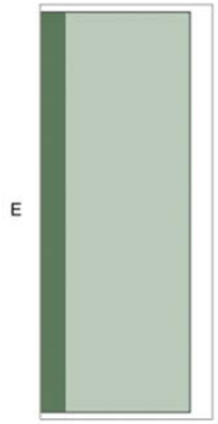


Frequencies

Level	Count	Prob
G	9	0.50000
L	6	0.33333
N	3	0.16667
Total	18	1.00000

N Missing
0
3 Levels

Recycling Agent Type

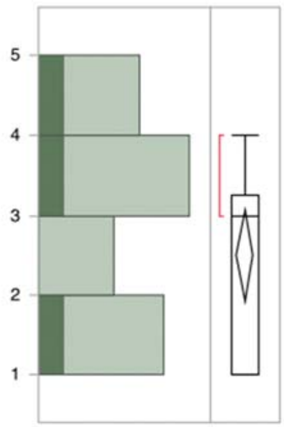


Frequencies

Level	Count	Prob
E	18	1.00000
Total	18	1.00000

N Missing
0
1 Levels

Specimen



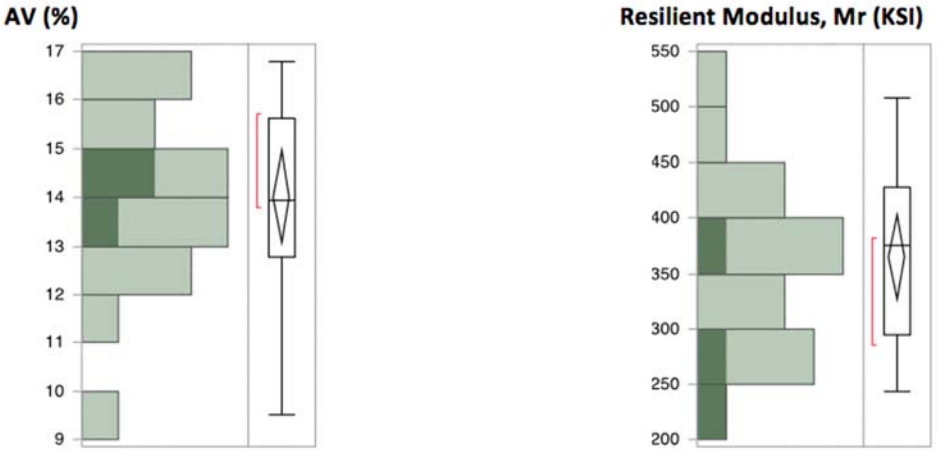
Quantiles

100.0%	maximum	4
99.5%		4
97.5%		4
90.0%		4
75.0%	quartile	3.25
50.0%	median	3
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	2.5
Std Dev	1.1504475
Std Err Mean	0.2711631
Upper 95% Mean	3.0721041
Lower 95% Mean	1.9278959
N	18

Figure R.20 (Continued). JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures M_R



AV (%)

Quantiles

100.0%	maximum	16.8
99.5%		16.8
97.5%		16.8
90.0%		16.71
75.0%	quartile	15.625
50.0%	median	13.95
25.0%	quartile	12.775
10.0%		11.12
2.5%		9.5
0.5%		9.5
0.0%	minimum	9.5

Summary Statistics

Mean	14.016667
Std Dev	1.8743626
Std Err Mean	0.4417915
Upper 95% Mean	14.948765
Lower 95% Mean	13.084568
N	18

Resilient Modulus, Mr (KSI)

Quantiles

100.0%	maximum	508.2
99.5%		508.2
97.5%		508.2
90.0%		490.11
75.0%	quartile	428.65
50.0%	median	375.2
25.0%	quartile	294.2
10.0%		264.94
2.5%		242.8
0.5%		242.8
0.0%	minimum	242.8

Summary Statistics

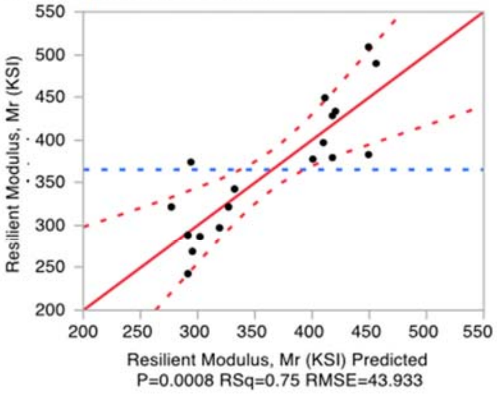
Mean	365.27222
Std Dev	76.149851
Std Err Mean	17.948692
Upper 95% Mean	403.14065
Lower 95% Mean	327.40379
N	18

Figure R.20 (Continued). JMP Exploratory Analysis Output, Emulsified Cold Recycled Mixtures M_R

The multi-factor ANCOVA model having RAP content, RAP type, and AV content as main effects was first fitted to the data. It can be observed from the Effects Tests results shown below that the effect of RAP content was statistically significant at α = 0.05. RAP content = 60 led to a significantly higher M_R value than RAP content = 80 or 100.

Response Resilient Modulus, Mr (KSI)

Actual by Predicted Plot



Summary of Fit

RSquare	0.745468
RSquare Adj	0.667151
Root Mean Square Error	43.93318
Mean of Response	365.2722
Observations (or Sum Wgts)	18

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	73487.975	18372.0	9.5186
Error	13	25091.621	1930.1	**Prob > F**
C. Total	17	98579.596		0.0008*

Parameter Estimates

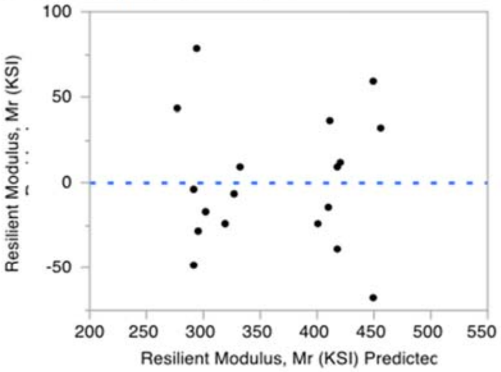
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	436.34162	141.0156	3.09	0.0085*
RAP Content[60]	83.118279	14.6408	5.68	<.0001*
RAP Content[80]	-51.03802	21.35103	-2.39	0.0327*
RAP Type[G]	27.457482	18.79128	1.46	0.1677
AV (%)	-5.787158	9.583096	-0.60	0.5563

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Content	2	2	63720.371	16.5068	0.0003*
RAP Type	1	1	4120.921	2.1351	0.1677
AV (%)	1	1	703.889	0.3647	0.5563

Figure R.21. JMP Statistical Analysis Output with RAP Content and Type, Emulsified Cold Recycled Mixtures M_R

Residual by Predicted Plot



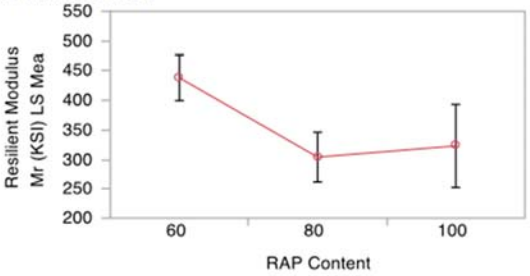
Effect Details

RAP Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
60	438.34324	17.788752	426.522
80	304.18694	19.505443	308.817
100	323.14470	32.584093	294.433

LS Means Plot



LSMeans Differences Tukey HSD

α=0.050

Level			Least Sq Mean
60	A		438.34324
100		B	323.14470
80		B	304.18694

Levels not connected by same letter are significantly different.

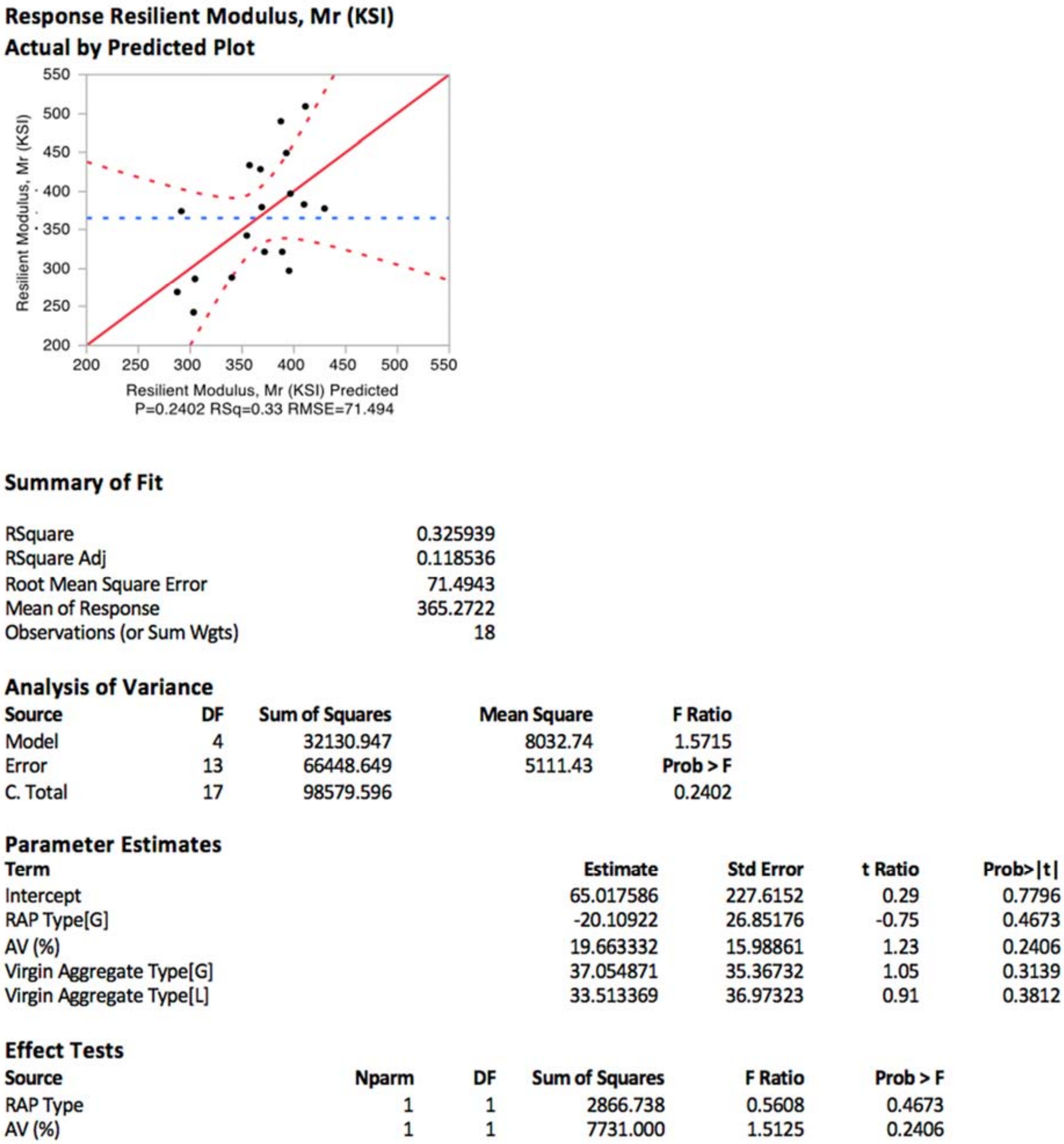
RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	382.68244	29.178805	389.367
L	327.76748	15.702226	353.225

Figure R.21 (Continued). JMP Statistical Analysis Output with RAP Content and Type, Emulsified Cold Recycled Mixtures M_R

Next, the multi-factor ANCOVA model having RAP type, AV content, and virgin aggregate type as main effects was fitted to the data. It can be observed from the Effects Tests results shown below that none of the main effects were significant at α = 0.05.



Response Resilient Modulus, Mr (KSI)

Actual by Predicted Plot

Summary of Fit

RSquare	0.325939
RSquare Adj	0.118536
Root Mean Square Error	71.4943
Mean of Response	365.2722
Observations (or Sum Wgts)	18

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	32130.947	8032.74	1.5715
Error	13	66448.649	5111.43	**Prob > F**
C. Total	17	98579.596		0.2402

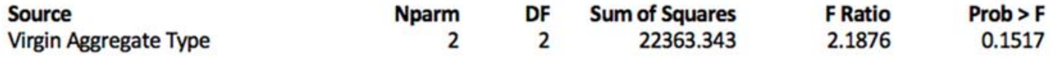
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	65.017586	227.6152	0.29	0.7796
RAP Type[G]	-20.10922	26.85176	-0.75	0.4673
AV (%)	19.663332	15.98861	1.23	0.2406
Virgin Aggregate Type[G]	37.054871	35.36732	1.05	0.3139
Virgin Aggregate Type[L]	33.513369	36.97323	0.91	0.3812

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Type	1	1	2866.738	0.5608	0.4673
AV (%)	1	1	7731.000	1.5125	0.2406

Figure R.22. JMP Statistical Analysis Output with RAP and Virgin Aggregate Type, Emulsified Cold Recycled Mixtures M_R



Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Virgin Aggregate Type	2	2	22363.343	2.1876	0.1517

Residual by Predicted Plot

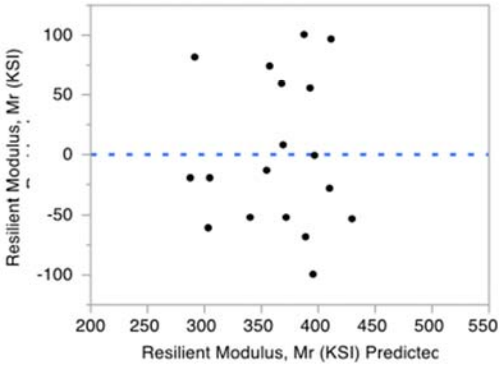
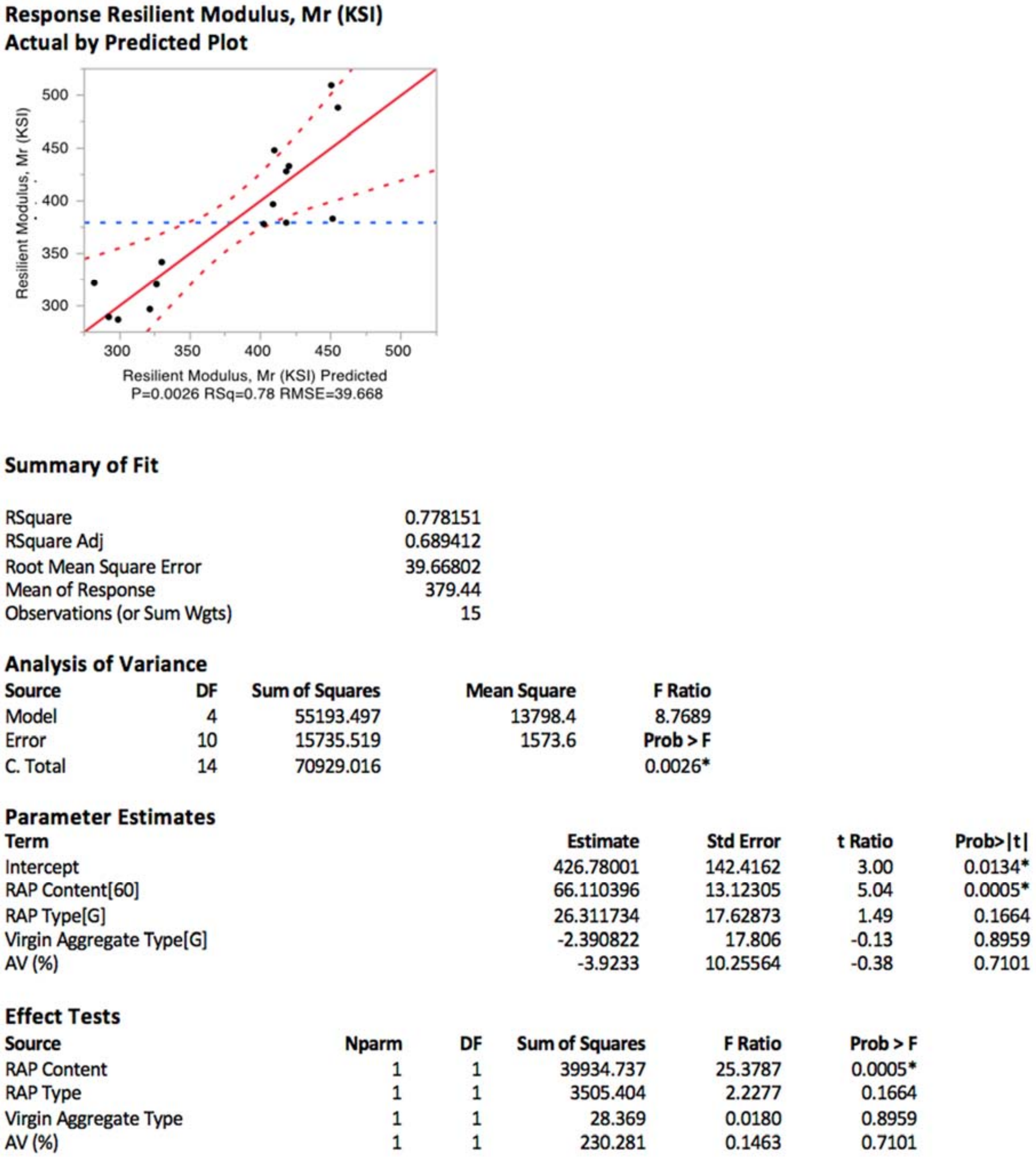


Figure R.22 (Continued). JMP Statistical Analysis Output with RAP and Virgin Aggregate Type, Emulsified Cold Recycled Mixtures M_R

Finally, the multi-factor ANCOVA model having RAP content, RAP type, virgin aggregate type, and AV content as main effects was fitted to the subset of data consisting of 15 observations after excluding 3 observations corresponding to RAP content = 100 and virgin aggregate type = N. It can be observed from the Effects Tests results shown below that the effect of RAP content was statistically significant at $\alpha = 0.05$. RAP content = 60 led to a significantly higher predicted value for M_R than RAP content = 80.



Response Resilient Modulus, Mr (KSI)
Actual by Predicted Plot

Summary of Fit

RSquare	0.778151
RSquare Adj	0.689412
Root Mean Square Error	39.66802
Mean of Response	379.44
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	55193.497	13798.4	8.7689
Error	10	15735.519	1573.6	**Prob > F**
C. Total	14	70929.016		0.0026*

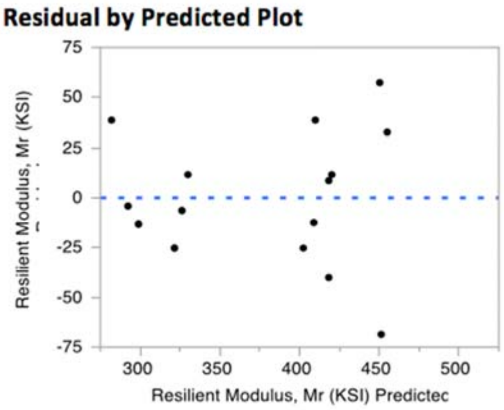
Parameter Estimates

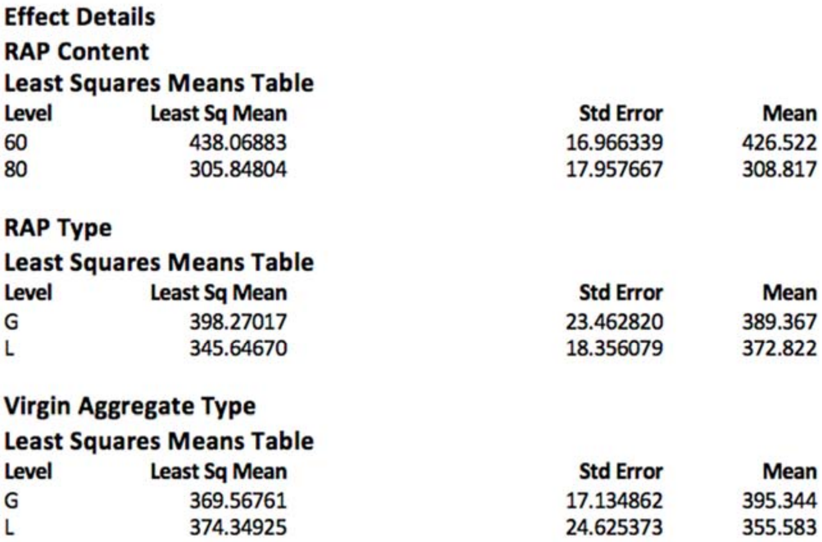
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	426.78001	142.4162	3.00	0.0134*
RAP Content[60]	66.110396	13.12305	5.04	0.0005*
RAP Type[G]	26.311734	17.62873	1.49	0.1664
Virgin Aggregate Type[G]	-2.390822	17.806	-0.13	0.8959
AV (%)	-3.9233	10.25564	-0.38	0.7101

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Content	1	1	39934.737	25.3787	0.0005*
RAP Type	1	1	3505.404	2.2277	0.1664
Virgin Aggregate Type	1	1	28.369	0.0180	0.8959
AV (%)	1	1	230.281	0.1463	0.7101

Figure R.23. JMP Statistical Analysis Output with RAP Content and Type and Virgin Aggregate Type, Emulsified Cold Recycled Mixtures M_R


Residual by Predicted Plot


Effect Details

RAP Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
60	438.06883	16.966339	426.522
80	305.84804	17.957667	308.817

RAP Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	398.27017	23.462820	389.367
L	345.64670	18.356079	372.822

Virgin Aggregate Type

Least Squares Means Table

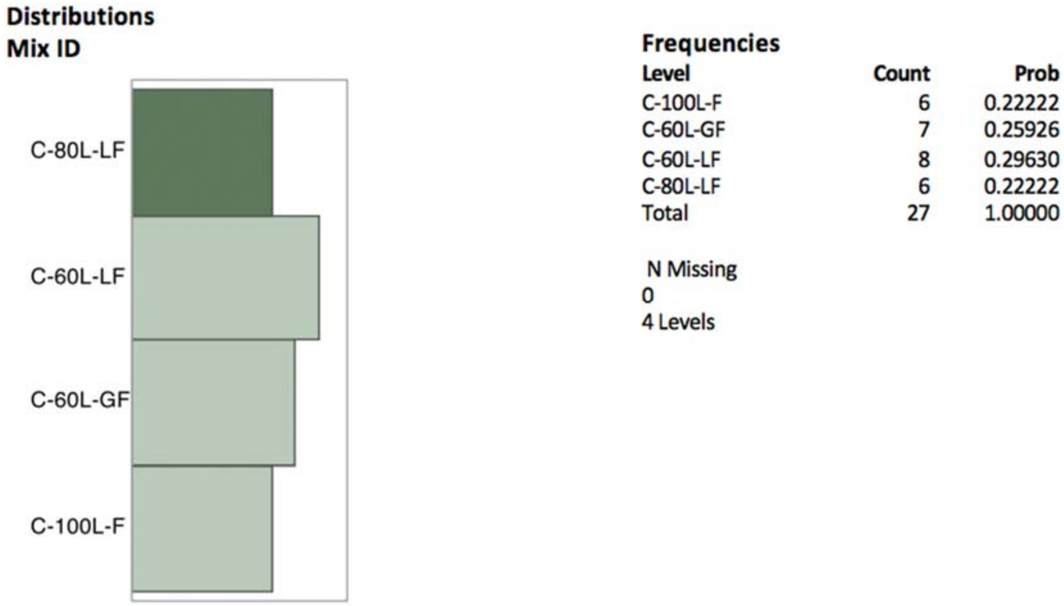
Level	Least Sq Mean	Std Error	Mean
G	369.56761	17.134862	395.344
L	374.34925	24.625373	355.583

Figure R.23 (Continued). JMP Statistical Analysis Output with RAP Content and Type and Virgin Aggregate Type, Emulsified Cold Recycled Mixtures M_R

IDT STRENGTH

The objective of this analysis was to assess the effects of several factors on IDT for foamed cold recycled mixtures. The factors of interest were RAP content with three levels (60, 80, 100), virgin aggregate type with three levels (L, G, N), and moisture conditioning with two levels (Dry, Wet). AV content was also measured. Note that the RAP type and recycling agent type were fixed at L and F, respectively, for this dataset.

During the exploratory analysis, it was discovered that the effects of RAP content and virgin aggregate type were almost confounded. The figure below shows that for RAP content = 100, the value of virgin aggregate type was always N, and for RAP content = 80, the value of virgin aggregate type was always L, which made fitting the multi-factor ANCOVA model with both RAP content and virgin aggregate type impossible. The analyses were thus performed by including either RAP Content or Virgin Aggregate Type, but not both, along with other variables in the model.



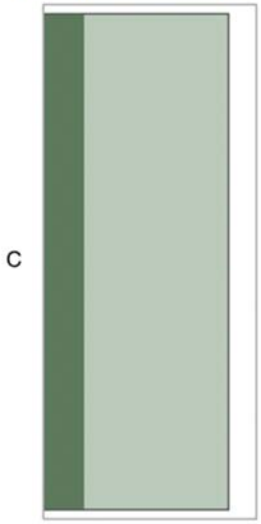
Frequencies

Level	Count	Prob
C-100L-F	6	0.22222
C-60L-GF	7	0.25926
C-60L-LF	8	0.29630
C-80L-LF	6	0.22222
Total	27	1.00000

N Missing
0
4 Levels

Figure R.24. JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures IDT Strength

Recycling Methodology

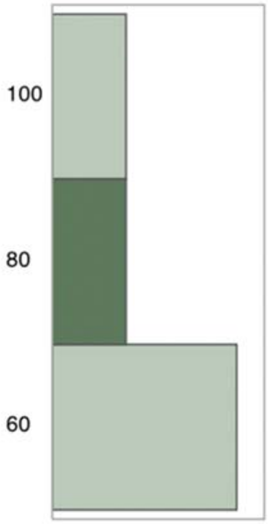


Frequencies

Level	Count	Prob
C	27	1.00000
Total	27	1.00000

N Missing
0
1 Levels

RAP Content

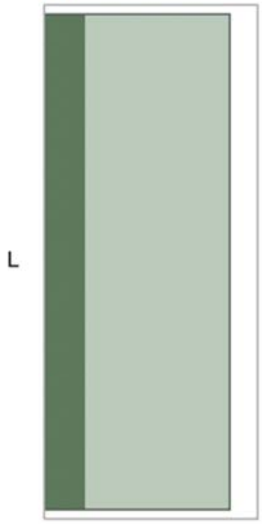


Frequencies

Level	Count	Prob
60	15	0.55556
80	6	0.22222
100	6	0.22222
Total	27	1.00000

N Missing
0
3 Levels

RAP Type



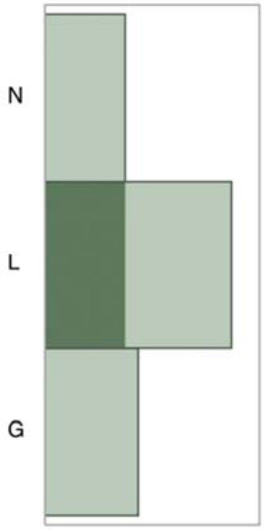
Frequencies

Level	Count	Prob
L	27	1.00000
Total	27	1.00000

N Missing
0
1 Levels

Figure R.24 (Continued). JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures IDT Strength

Virgin Aggregate Type

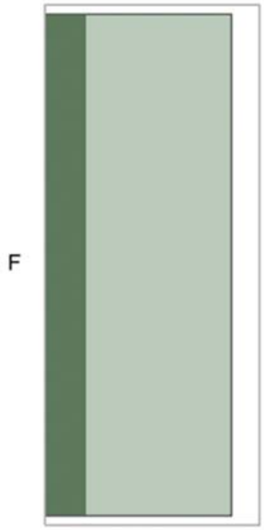


Frequencies

Level	Count	Prob
G	7	0.25926
L	14	0.51852
N	6	0.22222
Total	27	1.00000

N Missing
0
3 Levels

Recycling Agent Type

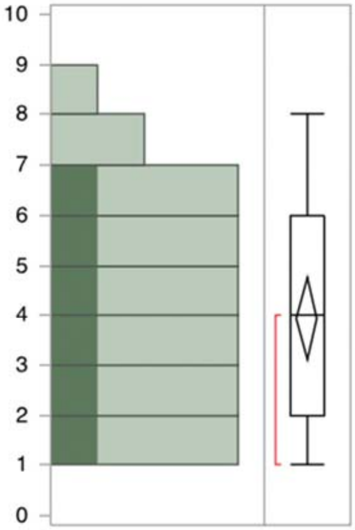


Frequencies

Level	Count	Prob
F	27	1.00000
Total	27	1.00000

N Missing
0
1 Levels

Specimen



Quantiles

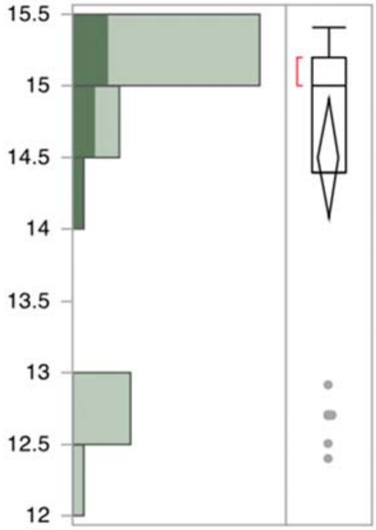
100.0%	maximum	8
99.5%		8
97.5%		8
90.0%		7
75.0%	quartile	6
50.0%	median	4
25.0%	quartile	2
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	3.9259259
Std Dev	2.0554978
Std Err Mean	0.3955807
Upper 95% Mean	4.7390538
Lower 95% Mean	3.1127981
N	27

Figure R.24 (Continued). JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures IDT Strength

AV (%)



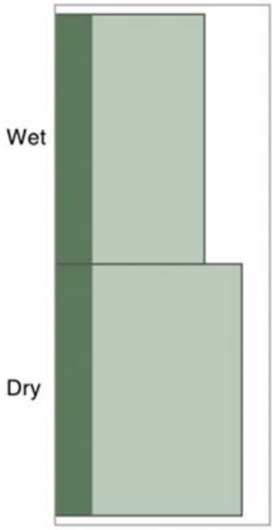
Quantiles

100.0%	maximum	15.4
99.5%		15.4
97.5%		15.4
90.0%		15.2
75.0%	quartile	15.2
50.0%	median	15
25.0%	quartile	14.4
10.0%		12.66
2.5%		12.4
0.5%		12.4
0.0%	minimum	12.4

Summary Statistics

Mean	14.496296
Std Dev	1.0308628
Std Err Mean	0.1983896
Upper 95% Mean	14.904092
Lower 95% Mean	14.088501
N	27

Moisture Conditioning



Frequencies

Level	Count	Prob
Dry	15	0.55556
Wet	12	0.44444
Total	27	1.00000

N Missing
0
2 Levels

IDT (PSI)

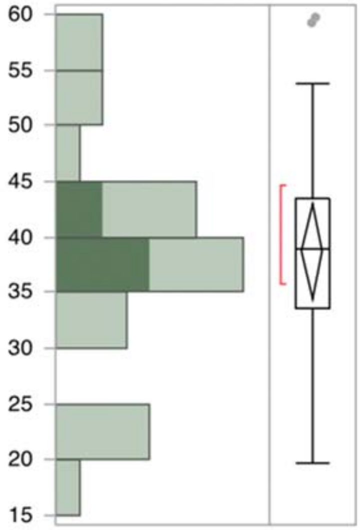
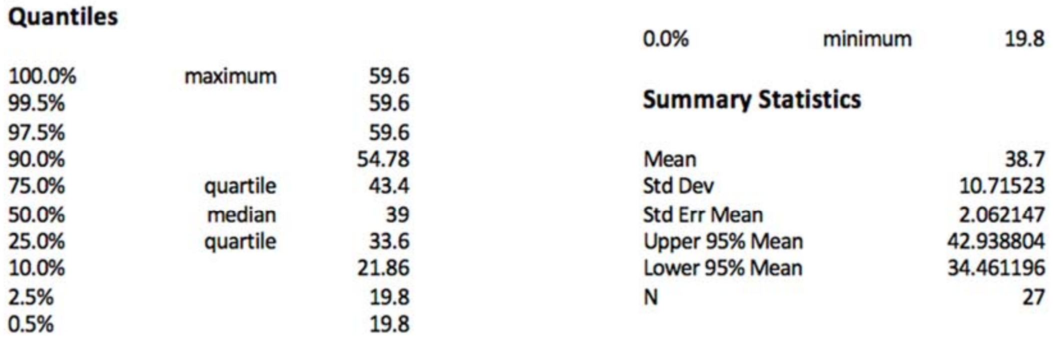


Figure R.24 (Continued). JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures IDT Strength



```
Quantiles

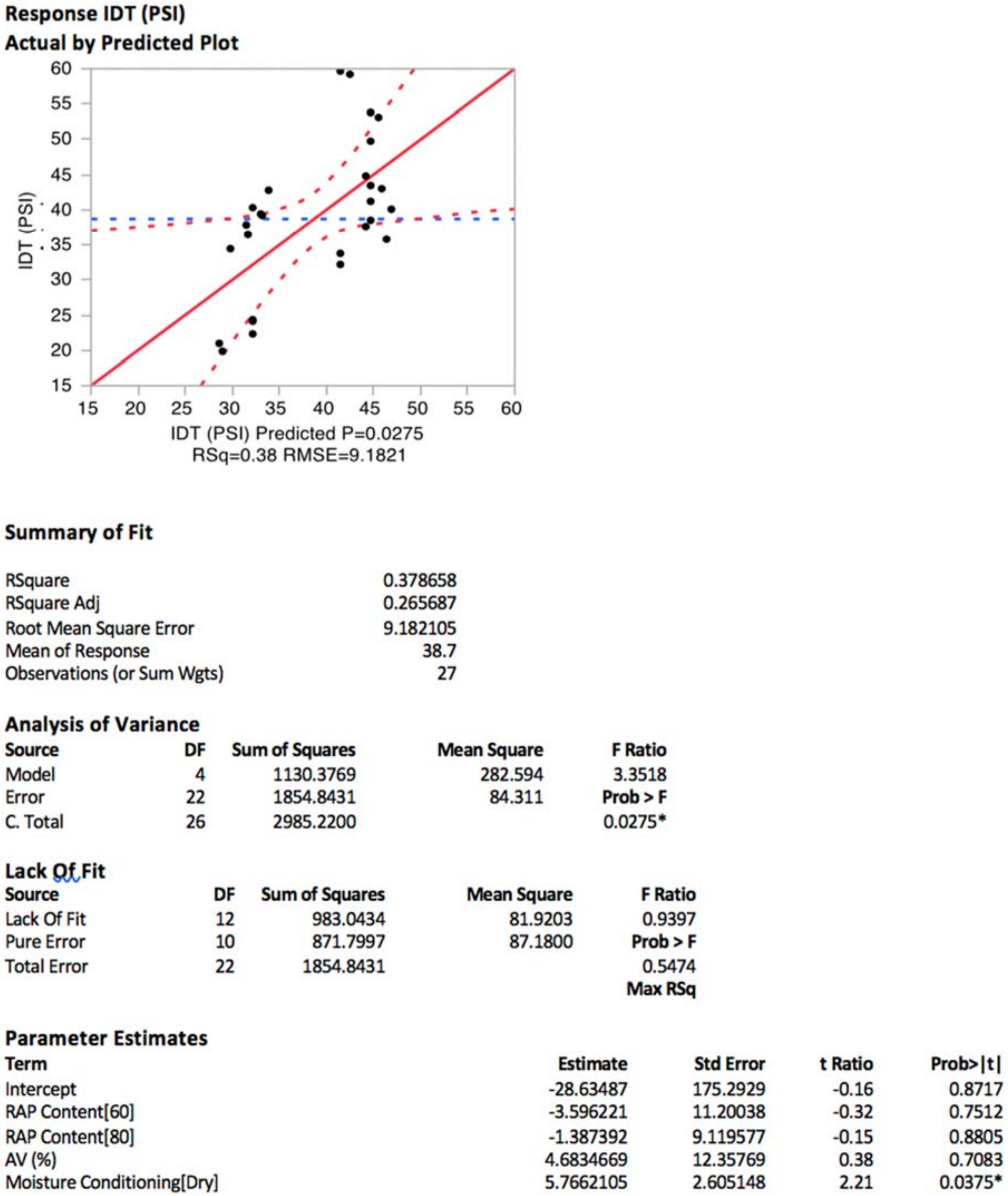
100.0%    maximum    59.6
99.5%                59.6
97.5%                59.6
90.0%                54.78
75.0%     quartile   43.4
50.0%     median     39
25.0%     quartile   33.6
10.0%                21.86
2.5%                 19.8
0.5%                 19.8
0.0%      minimum    19.8

Summary Statistics

Mean                 38.7
Std Dev              10.71523
Std Err Mean         2.062147
Upper 95% Mean       42.938804
Lower 95% Mean       34.461196
N                    27
```

Figure R.24 (Continued). JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures IDT Strength

The multi-factor ANCOVA model having RAP content, moisture conditioning, and AV content as main effects was first fitted to the data. It can be observed from the Effects Tests results shown below that the effect of moisture conditioning was statistically significant at α = 0.05. For moisture conditioning, it appears that Dry leads to a significantly higher IDT value than Wet.



Response IDT (PSI)

Actual by Predicted Plot

Summary of Fit

RSquare	0.378658
RSquare Adj	0.265687
Root Mean Square Error	9.182105
Mean of Response	38.7
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	1130.3769	282.594	3.3518
Error	22	1854.8431	84.311	**Prob > F**
C. Total	26	2985.2200		0.0275*

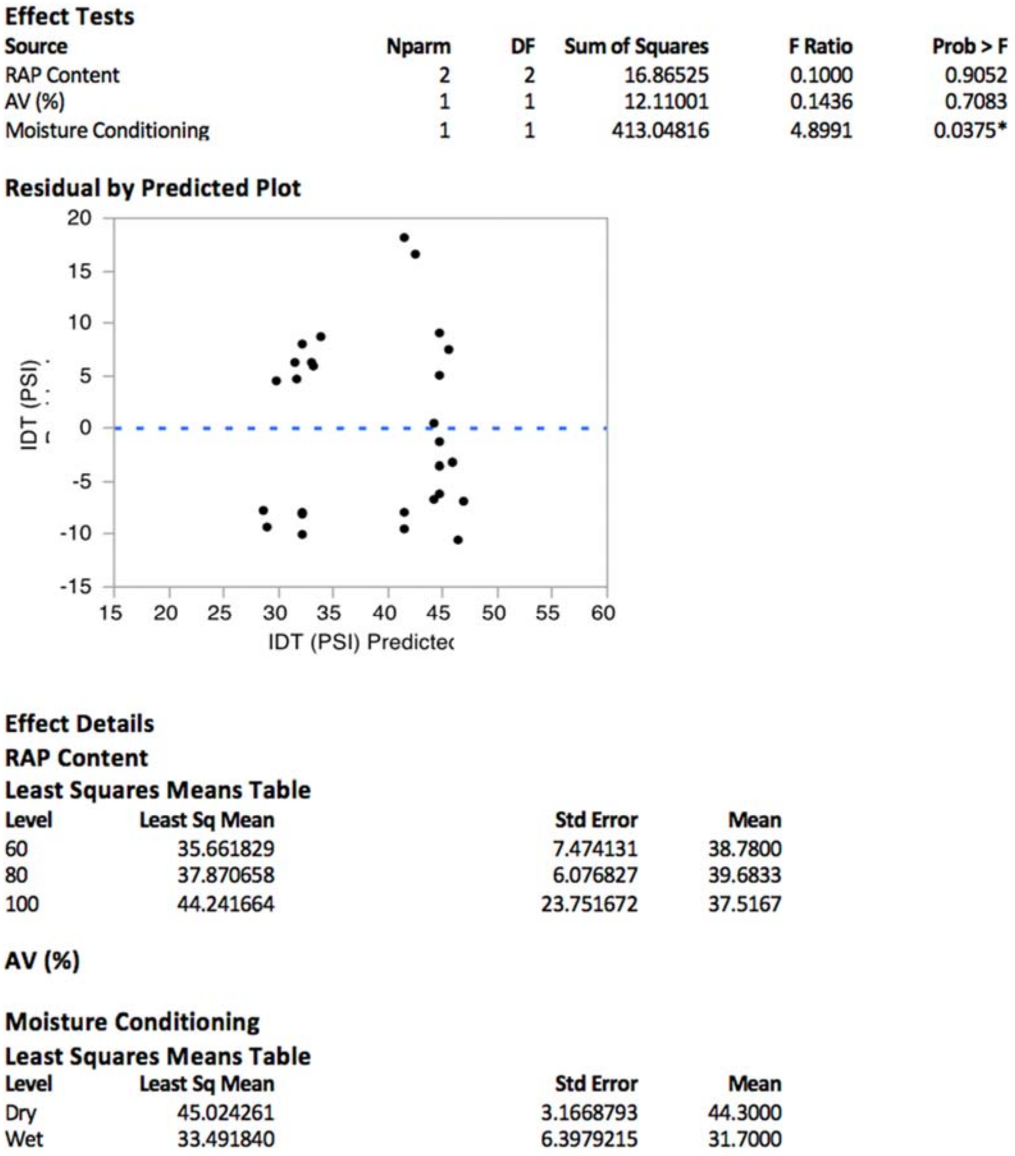
Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	12	983.0434	81.9203	0.9397
Pure Error	10	871.7997	87.1800	**Prob > F**
Total Error	22	1854.8431		0.5474
				Max RSq

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-28.63487	175.2929	-0.16	0.8717
RAP Content[60]	-3.596221	11.20038	-0.32	0.7512
RAP Content[80]	-1.387392	9.119577	-0.15	0.8805
AV (%)	4.6834669	12.35769	0.38	0.7083
Moisture Conditioning[Dry]	5.7662105	2.605148	2.21	0.0375*

Figure R.25. JMP Statistical Analysis Output with RAP Content, Foamed Cold Recycled Mixtures IDT Strength



Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Content	2	2	16.86525	0.1000	0.9052
AV (%)	1	1	12.11001	0.1436	0.7083
Moisture Conditioning	1	1	413.04816	4.8991	0.0375*

Residual by Predicted Plot

Effect Details

RAP Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
60	35.661829	7.474131	38.7800
80	37.870658	6.076827	39.6833
100	44.241664	23.751672	37.5167

AV (%)

Moisture Conditioning

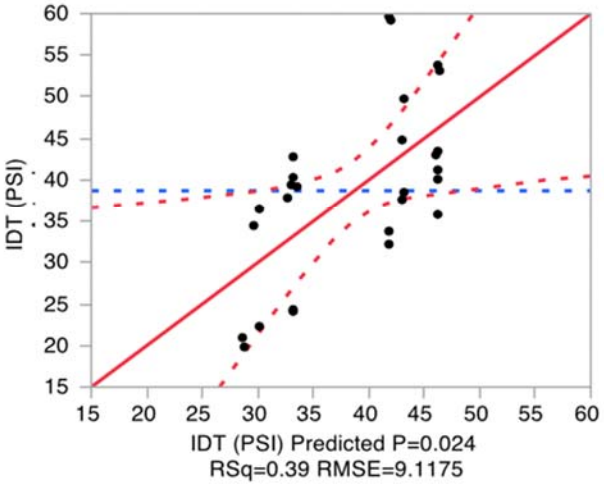
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Dry	45.024261	3.1668793	44.3000
Wet	33.491840	6.3979215	31.7000

Figure R.25 (Continued). JMP Statistical Analysis Output with RAP Content, Foamed Cold Recycled Mixtures IDT Strength

Next, the multi-factor ANCOVA model having AV content, moisture condition, and virgin aggregate type as main effects was fitted to the data. It can be observed from the Effects Tests results shown below that the main effect moisture conditioning was again statistically significant at α = 0.05.

Response IDT (PSI)
Actual by Predicted Plot



Summary of Fit

RSquare	0.38737
RSquare Adj	0.275983
Root Mean Square Error	9.117501
Mean of Response	38.7
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	1156.3860	289.097	3.4777
Error	22	1828.8340	83.129	**Prob > F**
C. Total	26	2985.2200		0.0240*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	13	973.4881	74.8837	0.7879
Pure Error	9	855.3458	95.0384	**Prob > F**
Total Error	22	1828.8340		0.6627
				Max RSq

Parameter Estimates

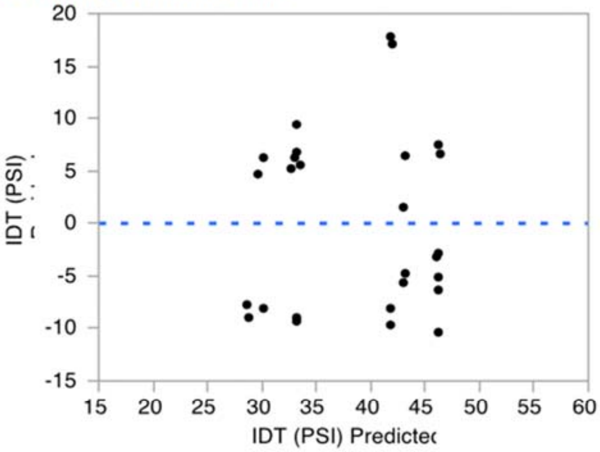
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	23.191239	156.4471	0.15	0.8835
AV (%)	0.9897666	11.0137	0.09	0.9292
Moisture Conditioning[Dry]	6.3925111	2.479251	2.58	0.0171*
Virgin Aggregate Type[G]	-1.36524	8.951573	-0.15	0.8802
Virgin Aggregate Type[L]	1.691198	9.462773	0.18	0.8598

Figure R.26. JMP Statistical Analysis Output with Virgin Aggregate Type, Foamed Cold Recycled Mixtures IDT Strength

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
AV (%)	1	1	0.67135	0.0081	0.9292
Moisture Conditioning	1	1	552.65429	6.6482	0.0171*
Virgin Aggregate Type	2	2	42.87435	0.2579	0.7750

Residual by Predicted Plot



Effect Details

AV (%)

Moisture Conditioning

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Dry	43.931701	2.8301155	44.3000
Wet	31.146679	5.6787112	31.7000

Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	36.173949	6.328072	37.5857
L	39.230388	6.421303	39.7643
N	37.213232	21.246299	37.5167

Figure R.26 (Continued). JMP Statistical Analysis Output with Virgin Aggregate Type, Foamed Cold Recycled Mixtures IDT Strength

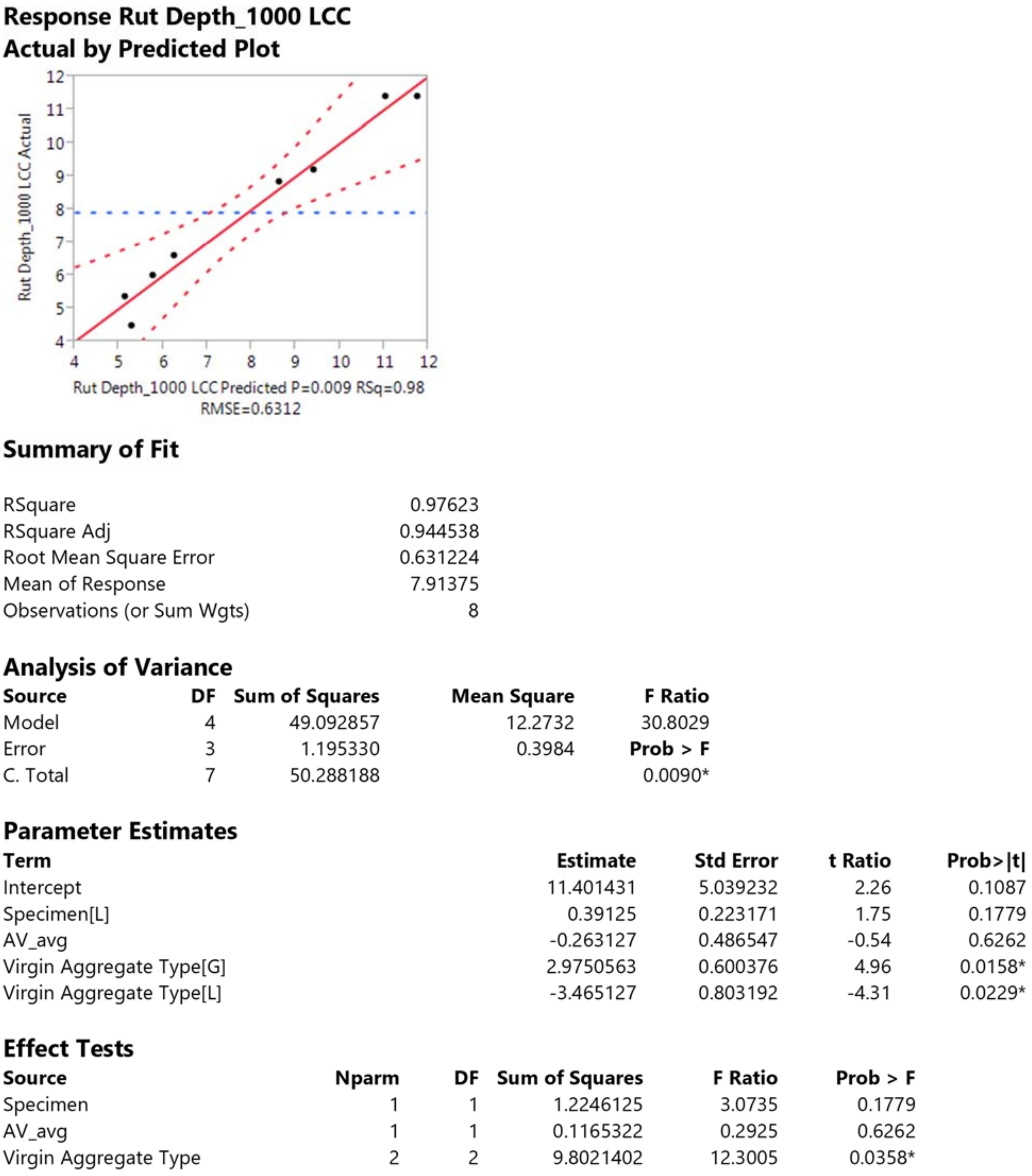
HAMBURG WHEEL TRACKING TEST

The objective of this analysis was to assess the effects of several factors on the response variables for rutting (HWTT) for the foamed cold recycled mixtures. The response variables considered were (a) rut depth at 1,000 load cycles, (b) SIP, and (c) $\Delta\varepsilon^{vp}_{SN}$ (Delta E). The factors were RAP content with three levels (60, 80, 100), virgin aggregate type with two levels (L, G), and specimens with two levels (R, L). AVs were also measured from two specimens (Specimen 1 and Specimen 2) for each combination of aforementioned factor levels and were averaged over those two specimens (and renamed as AV_avg) to be included in the multi-factor ANCOVA analysis. Note that RAP type and recycling agent type were fixed at L and F, respectively, for this dataset. The multi-factor ANCOVA analysis was performed separately for each of the three response variables given above.

Rut Depth at 1,000 Load Cycles

During the exploratory analysis, it was discovered that the effects of RAP content and virgin aggregate type were almost confounded. Figure 1 shows that for RAP content = 100, the value of virgin aggregate type was always N, and for RAP content = 80, the value of virgin aggregate type was always L, which made fitting the multi-factor ANCOVA model with both RAP content and virgin aggregate type impossible. The analyses were thus performed by including either RAP content or virgin aggregate type, but not both, along with specimen, and AV_avg in the model.

The multi-factor ANCOVA model having virgin aggregate type, specimen, and AV_avg as main effects was selected to fit the rut depth data because it resulted in a better goodness of fit for the data (a much higher R^2 value). It can be observed from the Effects Tests results shown below that the effect of virgin aggregate type was statistically significant at $\alpha = 0.05$.



Response Rut Depth_1000 LCC

Actual by Predicted Plot

Summary of Fit

RSquare	0.97623
RSquare Adj	0.944538
Root Mean Square Error	0.631224
Mean of Response	7.91375
Observations (or Sum Wgts)	8

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	49.092857	12.2732	30.8029
Error	3	1.195330	0.3984	**Prob > F**
C. Total	7	50.288188		0.0090*

Parameter Estimates

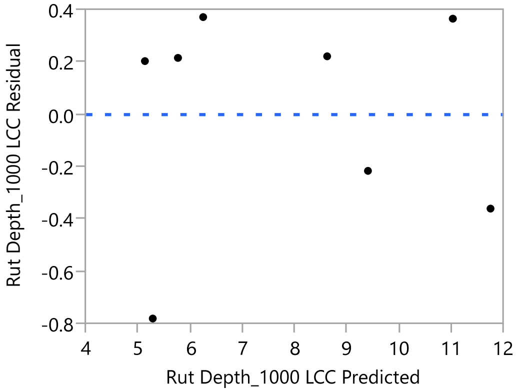
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	11.401431	5.039232	2.26	0.1087
Specimen[L]	0.39125	0.223171	1.75	0.1779
AV_avg	-0.263127	0.486547	-0.54	0.6262
Virgin Aggregate Type[G]	2.9750563	0.600376	4.96	0.0158*
Virgin Aggregate Type[L]	-3.465127	0.803192	-4.31	0.0229*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Specimen	1	1	1.2246125	3.0735	0.1779
AV_avg	1	1	0.1165322	0.2925	0.6262
Virgin Aggregate Type	2	2	9.8021402	12.3005	0.0358*

Figure R.27. JMP Statistical Analysis Output, Foamed Cold Recycled Mixtures HWTT Rut Depth

Residual by Predicted Plot



Effect Details

Specimen

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
L	9.1712819	0.37407314	8.30500
R	8.3887819	0.37407314	7.52250

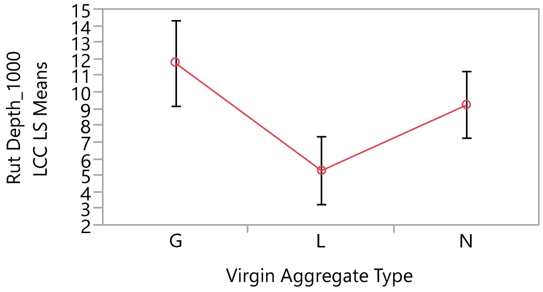
AV_avg

Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	11.755088	0.80929649	11.3900
L	5.314904	0.64240495	5.6175
N	9.270103	0.62955148	9.0300

LS Means Plot



LSMeans Differences Tukey HSD

α=0.050

Level			Least Sq Mean
G	A		11.755088
N	A	B	9.270103
L		B	5.314904

Levels not connected by same letter are significantly different.

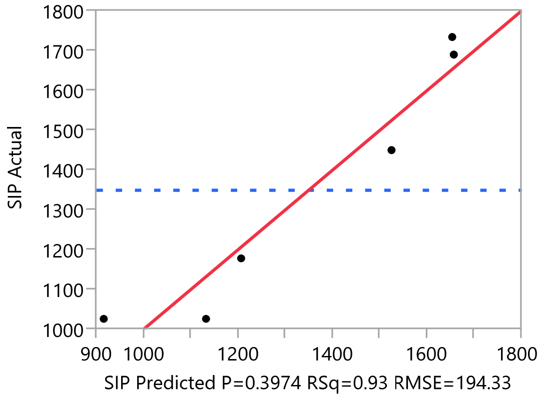
Figure R.27 (Continued). JMP Statistical Analysis Output, Foamed Cold Recycled Mixtures HWTT Rut Depth

Stripping Inflection Point

The multi-factor ANCOVA model having RAP content with two levels (60, 80), virgin aggregate type with two levels (L, G), specimen, and AV_avg as main effects was fitted to the SIP data. The analysis output obtained by JMP is shown below. It can be observed from the Effects Tests table below that none of the effects were statistically significant at α = 0.05, probably due to a very small sample size. (Note that there are only six observations for the SIP data.)

Response SIP

Actual by Predicted Plot



Summary of Fit

RSquare	0.926228
RSquare Adj	0.631139
Root Mean Square Error	194.3298
Mean of Response	1349
Observations (or Sum Wgts)	6

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	474137.91	118534	3.1388
Error	1	37764.09	37764	**Prob > F**
C. Total	5	511902.00		0.3974

Parameter Estimates

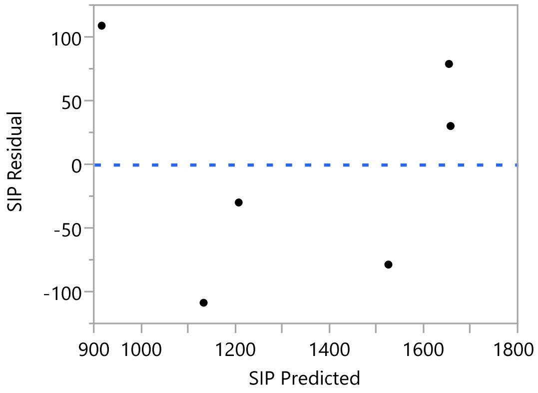
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1293.576	2954.887	-0.44	0.7373
RAP Content[60]	-66.26202	195.3858	-0.34	0.7918
Virgin Aggregate Type[G]	-537.1378	313.05	-1.72	0.3359
Specimen[L]	-134.478	79.37457	-1.69	0.3395
AV_avg	257.35471	301.356	0.85	0.5500

Figure R.28. JMP Statistical Analysis Output, Foamed Cold Recycled Mixtures HWTT SIP

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Content	1	1	4343.33	0.1150	0.7918
Virgin Aggregate Type	1	1	111179.09	2.9440	0.3359
Specimen	1	1	108397.31	2.8704	0.3395
AV_avg	1	1	27541.24	0.7293	0.5500

Residual by Predicted Plot



Effect Details

RAP Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
60	1125.7794	233.39221	1307.00
80	1258.3034	210.72861	1433.00

Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	654.9036	379.62395	1024.00
L	1729.1792	272.78835	1511.50

Specimen

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
L	1057.5635	133.33561	1216.67
R	1326.5194	131.71763	1481.33

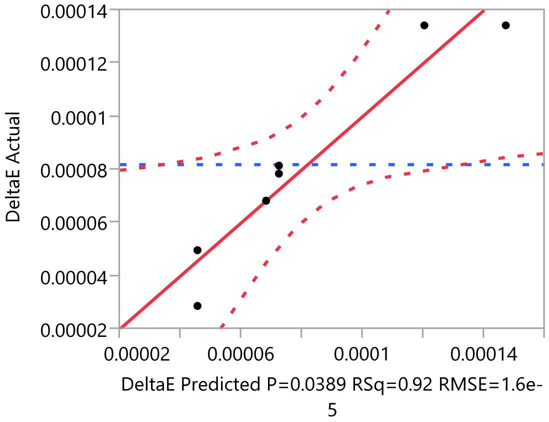
Figure R.28 (Continued). JMP Statistical Analysis Output, Foamed Cold Recycled Mixtures HWTT SIP

Rutting Resistance Parameter $\Delta\varepsilon^{vp}_{SN}$

The multi-factor ANOVA model having virgin aggregate type and specimen as main effects was fitted to the $\Delta\varepsilon^{vp}_{SN}$ (Delta E) data and selected as the best model based on the goodness of fit. It can be observed from the Effects Tests results shown below that the effect of virgin aggregate type was statistically significant at $\alpha = 0.05$. The Tukey's HSD test results for virgin aggregate type suggests that only the difference between G and L were statistically significant at $\alpha = 0.05$.

Response DeltaE

Actual by Predicted Plot



Summary of Fit

RSquare	0.917924
RSquare Adj	0.835848
Root Mean Square Error	1.617e-5
Mean of Response	8.187e-5
Observations (or Sum Wgts)	7

Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	3	8.77474e-9	2.9249e-9	11.1838
Error	3	7.8459e-10	2.615e-10	**Prob > F**
C. Total	6	9.55933e-9		0.0389*

Lack Of Fit

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Lack Of Fit	1	5.5081e-10	5.508e-10	4.7121
Pure Error	2	2.3378e-10	1.169e-10	**Prob > F**
Total Error	3	7.8459e-10		0.1621
				Max RSq

Figure R.29. JMP Statistical Analysis Output, Foamed Cold Recycled Mixtures HWTT RRP

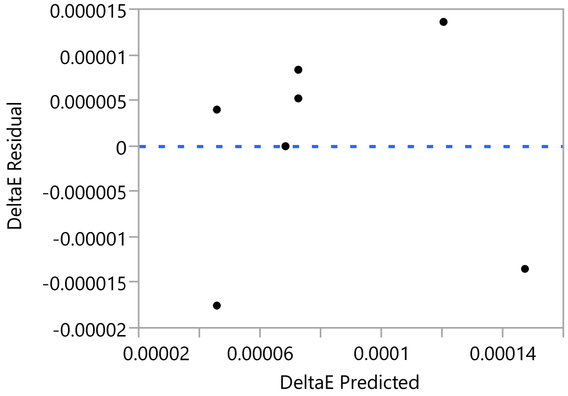
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	8.2625e-5	7.463e-6	11.07	0.0016*
Specimen[L]	1.355e-5	6.602e-6	2.05	0.1325
Virgin Aggregate Type[G]	5.1375e-5	0.00001	5.16	0.0141*
Virgin Aggregate Type[L]	-2.34e-5	8.803e-6	-2.66	0.0765

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Specimen	1	1	1.10161e-9	4.2122	0.1325
Virgin Aggregate Type	2	2	8.10775e-9	15.5006	0.0262*

Residual by Predicted Plot



Effect Details

Specimen

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
L	0.00009618	0.00000838	0.000090
R	0.00006908	0.00001133	0.000071

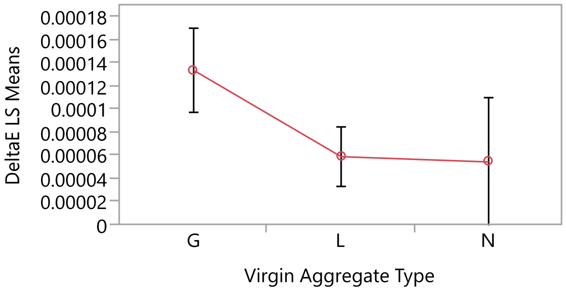
Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	0.00013400	0.00001144	0.000134
L	0.00005923	0.00000809	0.000059
N	0.00005465	0.00001747	0.000068

Figure R.29 (Continued). JMP Statistical Analysis Output, Foamed Cold Recycled Mixtures HWTT RRP

LS Means Plot



LSMeans Differences Tukey HSD

α=0.050

Level			**Least Sq Mean**
G	A		0.00013400
L		B	0.00005923
N	A	B	0.00005465

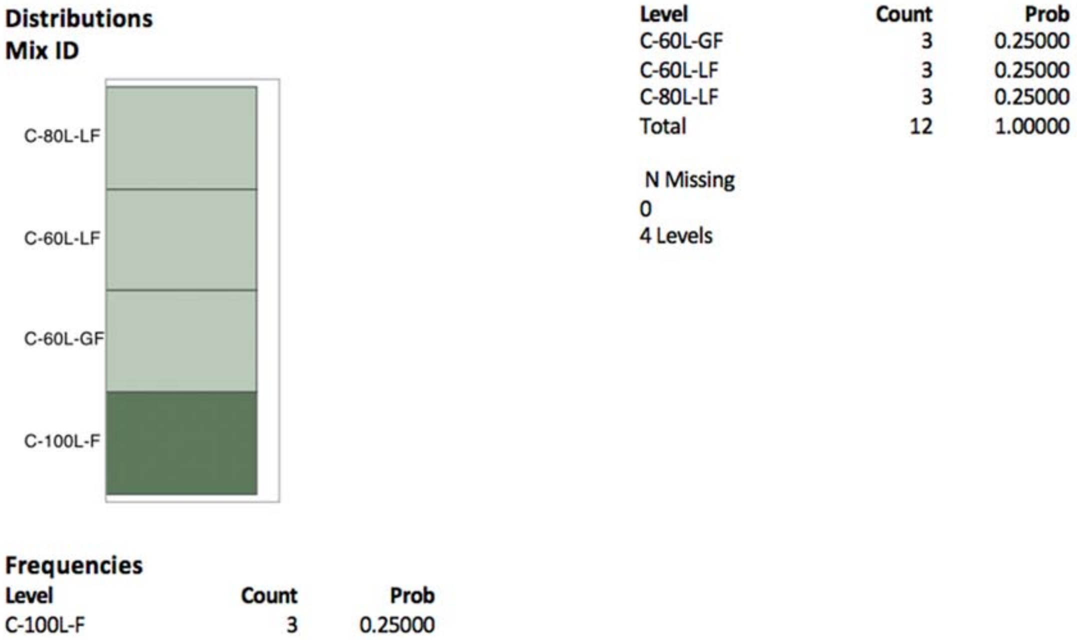
Levels not connected by same letter are significantly different.

Figure R.29 (Continued). JMP Statistical Analysis Output, Foamed Cold Recycled Mixtures HWTT RRP

DURABILITY—CANTABRO ABRASION LOSS TEST

The objective of this analysis was to assess the effects of several factors on Cantabro abrasion loss (durability) for foamed cold recycled mixtures. The response variable was mass loss, and the factors of interest were RAP content with three levels (60, 80, 100) and virgin aggregate type with three levels (L, G, N). AV content was also measured. Note that the RAP type and recycling agent type were fixed at L and F, respectively, for this dataset.

During the exploratory analysis, it was discovered that the effects of RAP content and virgin aggregate type were almost confounded. The figure below shows that for RAP content = 100, the value of virgin aggregate type was always N, and for RAP content = 80, the value of virgin aggregate type was always L, which made fitting the multi-factor ANCOVA model with both RAP content and virgin aggregate type impossible. The analyses were thus performed by including either RAP content or virgin aggregate type, but not both, along with other variables in the model.



Distributions
Mix ID

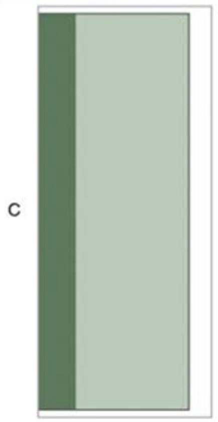
Frequencies

Level	Count	Prob
C-100L-F	3	0.25000
C-60L-GF	3	0.25000
C-60L-LF	3	0.25000
C-80L-LF	3	0.25000
Total	12	1.00000

N Missing
0
4 Levels

Figure R.30. JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures Cantabro

Recycling Methodology

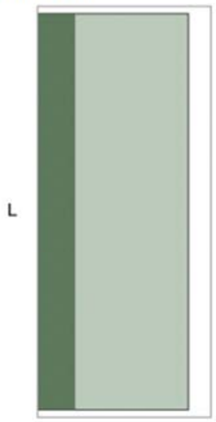


Frequencies

Level	Count	Prob
C	12	1.00000
Total	12	1.00000

N Missing
0
1 Levels

RAP Type

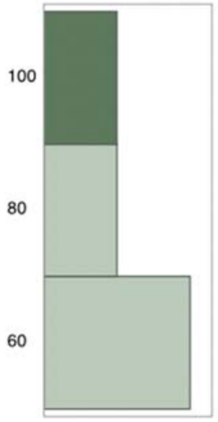


Frequencies

Level	Count	Prob
L	12	1.00000
Total	12	1.00000

N Missing
0
1 Levels

RAP Content

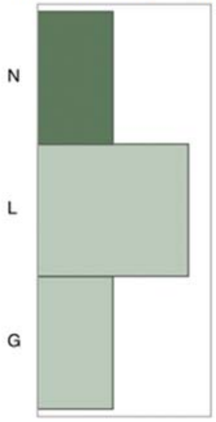


Frequencies

Level	Count	Prob
60	6	0.50000
80	3	0.25000
100	3	0.25000
Total	12	1.00000

N Missing
0
3 Levels

Virgin Aggregate Type



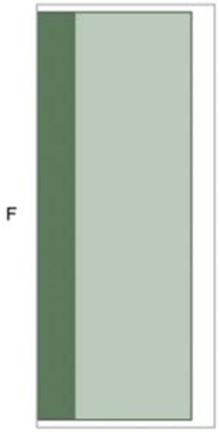
Frequencies

Level	Count	Prob
G	3	0.25000
L	6	0.50000
N	3	0.25000
Total	12	1.00000

N Missing
0
3 Levels

Figure R.30 (Continued). JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures Cantabro

Recycling Agent Type

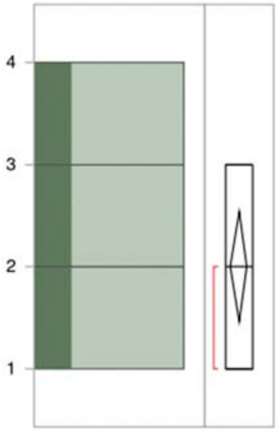


Frequencies

Level	Count	Prob
F	12	1.00000
Total	12	1.00000

N Missing
0
1 Levels

Specimen



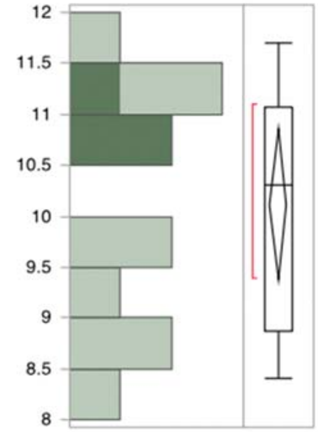
Quantiles

100.0%	maximum	3
99.5%		3
97.5%		3
90.0%		3
75.0%	quartile	3
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	2
Std Dev	0.8528029
Std Err Mean	0.246183
Upper 95% Mean	2.5418451
Lower 95% Mean	1.4581549
N	12

AV (%)



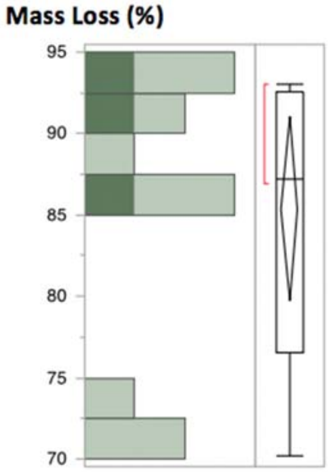
Quantiles

100.0%	maximum	11.7
99.5%		11.7
97.5%		11.7
90.0%		11.61
75.0%	quartile	11.075
50.0%	median	10.3
25.0%	quartile	8.875
10.0%		8.46
2.5%		8.4
0.5%		8.4
0.0%	minimum	8.4

Summary Statistics

Mean	10.116667
Std Dev	1.1722809
Std Err Mean	0.3384083
Upper 95% Mean	10.861498
Lower 95% Mean	9.3718349
N	12

Figure R.30 (Continued). JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures Cantabro



Quantiles

100.0%	maximum	93
99.5%		93
97.5%		93
90.0%		92.97
75.0%	quartile	92.525
50.0%	median	87.25
25.0%	quartile	76.575
10.0%		70.35
2.5%		70.2
0.5%		70.2
0.0%	minimum	70.2

Summary Statistics

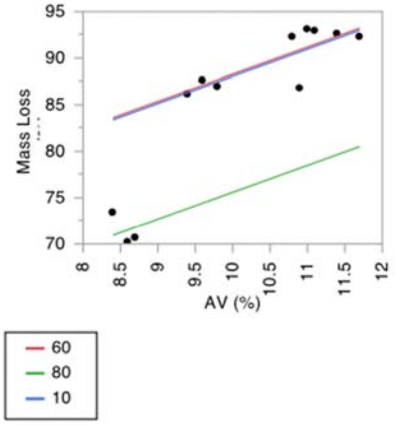
Mean	85.391667
Std Dev	8.8495977
Std Err Mean	2.5546588
Upper 95% Mean	91.014433
Lower 95% Mean	79.768901
N	12

Figure R.30 (Continued). JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures Cantabro

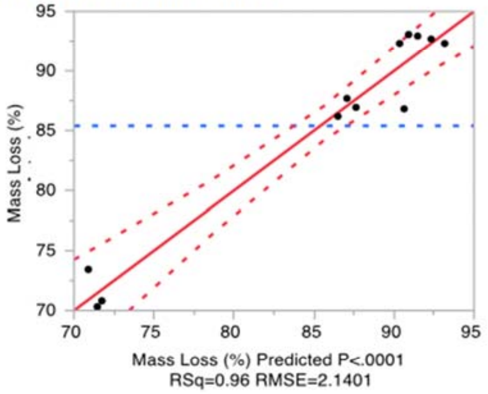
The multi-factor ANCOVA model having RAP Content and AV content as main effects was first fitted to the data. It can be observed from the Effects Tests results shown below that the effects of RAP content and AV were statistically significant at α = 0.05.

Response Mass Loss (%)

Regression Plot



Actual by Predicted Plot



Summary of Fit

RSquare	0.957469
RSquare Adj	0.94152
Root Mean Square Error	2.140067
Mean of Response	85.39167
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	824.83006	274.943	60.0328
Error	8	36.63911	4.580	**Prob > F**
C. Total	11	861.46917		<.0001*

Parameter Estimates

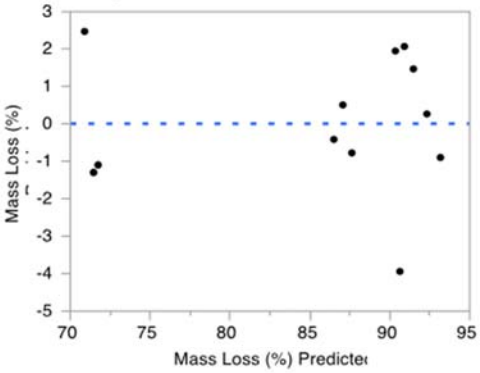
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	54.934297	9.408992	5.84	0.0004*
RAP Content[60]	4.3044987	0.953507	4.51	0.0020*

Figure R.31. JMP Statistical Analysis Output with RAP Content, Foamed Cold Recycled Mixtures Cantabro

```
Term                                  Estimate     Std Error    t Ratio    Prob>|t|
RAP Content[80]                      -8.380634     1.648946      -5.08     0.0010*
AV (%)                               2.9042416     0.939687       3.09     0.0149*

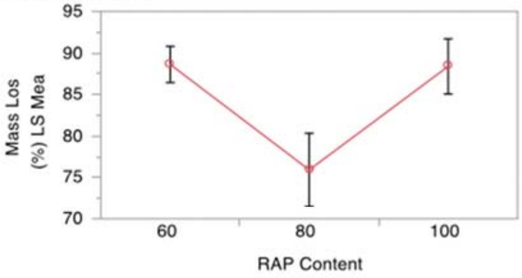
Effect Tests
Source          Nparm     DF    Sum of Squares     F Ratio     Prob > F
RAP Content         2      2         131.82916     14.3922     0.0022*
AV (%)              1      1          43.74756      9.5521     0.0149*

Residual by Predicted Plot
```



```
Effect Details
RAP Content
Least Squares Means Table
Level        Least Sq Mean                    Std Error        Mean
60               88.620041                    0.9450230     89.7333
80               75.934908                    1.9099910     71.4333
100              88.391677                    1.4382126     90.6667

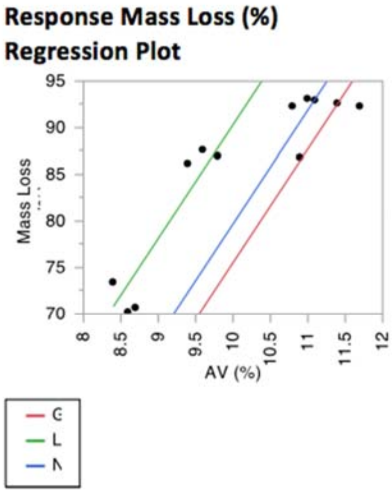
LS Means Plot
```



```
LSMeans Differences Tukey HSD
α=0.050
Level                                                                Least Sq Mean
60          A                                                            88.620041
100         A                                                            88.391677
80              B                                                        75.934908
```

Figure R.31 (Continued). JMP Statistical Analysis Output with RAP Content, Foamed Cold Recycled Mixtures Cantabro

Next, the multi-factor ANCOVA model having AV content and virgin aggregate type as main effects was fitted to the data. It can be observed from the Effects Tests results shown below that the effect of AV content was statistically significant at α = 0.05.


Response Mass Loss (%)
Regression Plot

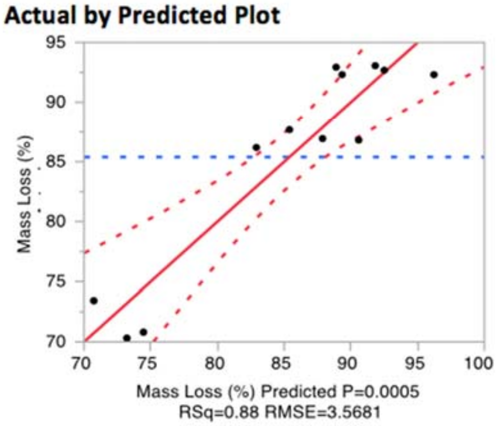

Actual by Predicted Plot

Figure R.32. JMP Statistical Analysis Output with Virgin Aggregate Type, Foamed Cold Recycled Mixtures Cantabro

Summary of Fit

RSquare	0.881769
RSquare Adj	0.837432
Root Mean Square Error	3.568133
Mean of Response	85.39167
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	759.61659	253.206	19.8880
Error	8	101.85258	12.732	**Prob > F**
C. Total	11	861.46917		0.0005*

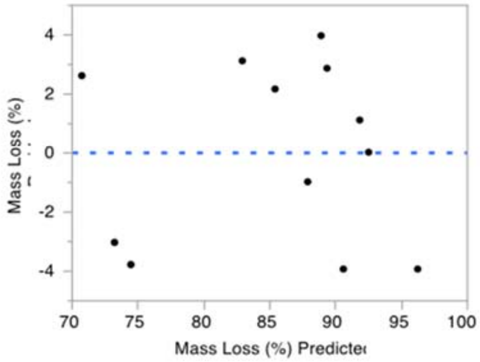
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-40.04122	26.90183	-1.49	0.1750
AV (%)	12.189283	2.569508	4.74	0.0015*
Virgin Aggregate Type[G]	-6.316604	2.90061	-2.18	0.0611
Virgin Aggregate Type[L]	8.4719005	3.797269	2.23	0.0562

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
AV (%)	1	1	286.50909	22.5038	0.0015*
Virgin Aggregate Type	2	2	66.61568	2.6162	0.1336

Residual by Predicted Plot



Effect Details

AV (%)

Virgin Aggregate Type

Least Squares Means Table

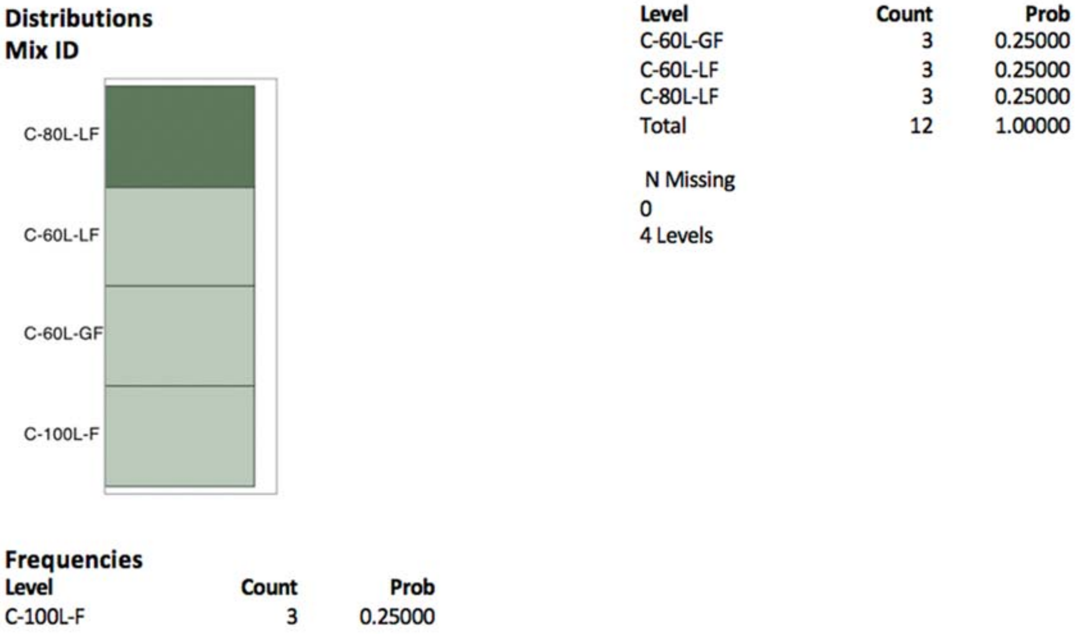
Level	Least Sq Mean	Std Error	Mean
G	76.957087	3.8881353	92.6000
L	91.745592	3.0284970	79.1500
N	81.118395	2.8801295	90.6667

Figure R.32 (Continued). JMP Statistical Analysis Output with Virgin Aggregate Type, Foamed Cold Recycled Mixtures Cantabro

STIFFNESS—M_R

The objective of this analysis was to assess the effects of several factors on M_R (Stiffness) for the foamed cold recycled mixtures. The response variable was resilient modulus, and the factors of interest were RAP content with three levels (60, 80, 100) and virgin aggregate type with three levels (L, G, N). AV content was also measured. Note that the RAP type and recycling agent type were fixed at L and F, respectively, for this dataset.

During the exploratory analysis, it was discovered that the effects of RAP content and virgin aggregate type were almost always confounded. For RAP content = 100, the value of virgin aggregate type was always N, and for RAP content = 80, the value of virgin aggregate type was always L, which made fitting the multi-factor ANCOVA model with both RAP content and virgin aggregate type impossible. The analyses were thus performed by including either RAP content or virgin aggregate type, but not both, along with other variables in the model.



Distributions
Mix ID

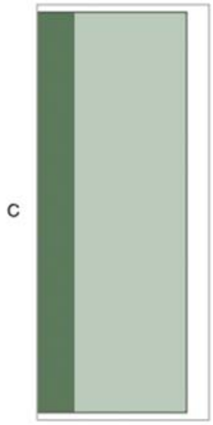
Frequencies

Level	Count	Prob
C-100L-F	3	0.25000
C-60L-GF	3	0.25000
C-60L-LF	3	0.25000
C-80L-LF	3	0.25000
Total	12	1.00000

N Missing
0
4 Levels

Figure R.33. JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures M_R

Recycling Methodology

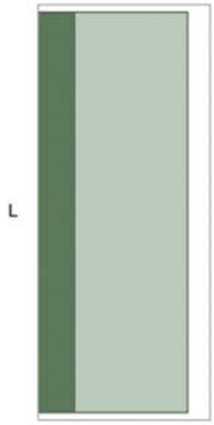


Frequencies

Level	Count	Prob
C	12	1.00000
Total	12	1.00000

N Missing
0
1 Levels

RAP Type

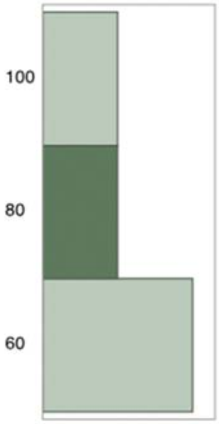


Frequencies

Level	Count	Prob
L	12	1.00000
Total	12	1.00000

N Missing
0
1 Levels

RAP Content



Frequencies

Level	Count	Prob
60	6	0.50000
80	3	0.25000
100	3	0.25000
Total	12	1.00000

N Missing
0
3 Levels

Virgin Aggregate Type

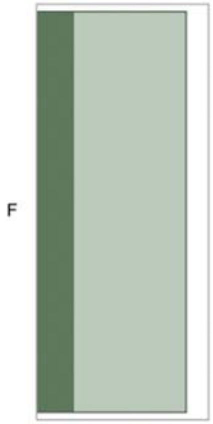
Frequencies

Level	Count	Prob
G	3	0.25000
L	6	0.50000
N	3	0.25000
Total	12	1.00000

N Missing
0
3 Levels

Figure R.33 (Continued). JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures M_R

Recycling Agent Type

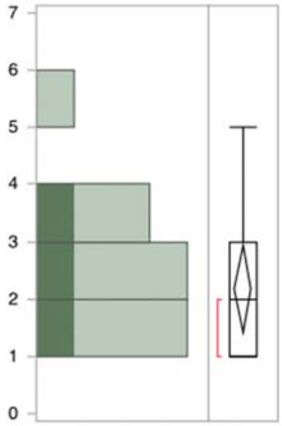


Frequencies

Level	Count	Prob
F	12	1.00000
Total	12	1.00000

N Missing
0
1 Levels

Specimen



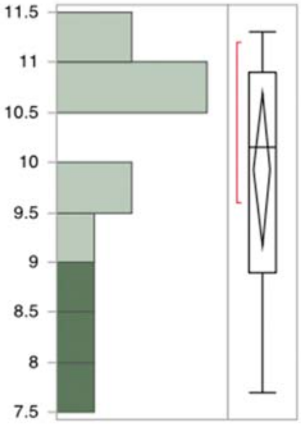
Quantiles

100.0%	maximum	5
99.5%		5
97.5%		5
90.0%		4.4
75.0%	quartile	3
50.0%	median	2
25.0%	quartile	1
10.0%		1
2.5%		1
0.5%		1
0.0%	minimum	1

Summary Statistics

Mean	2.1666667
Std Dev	1.1934163
Std Err Mean	0.3445096
Upper 95% Mean	2.9249272
Lower 95% Mean	1.4084061
N	12

AV (%)



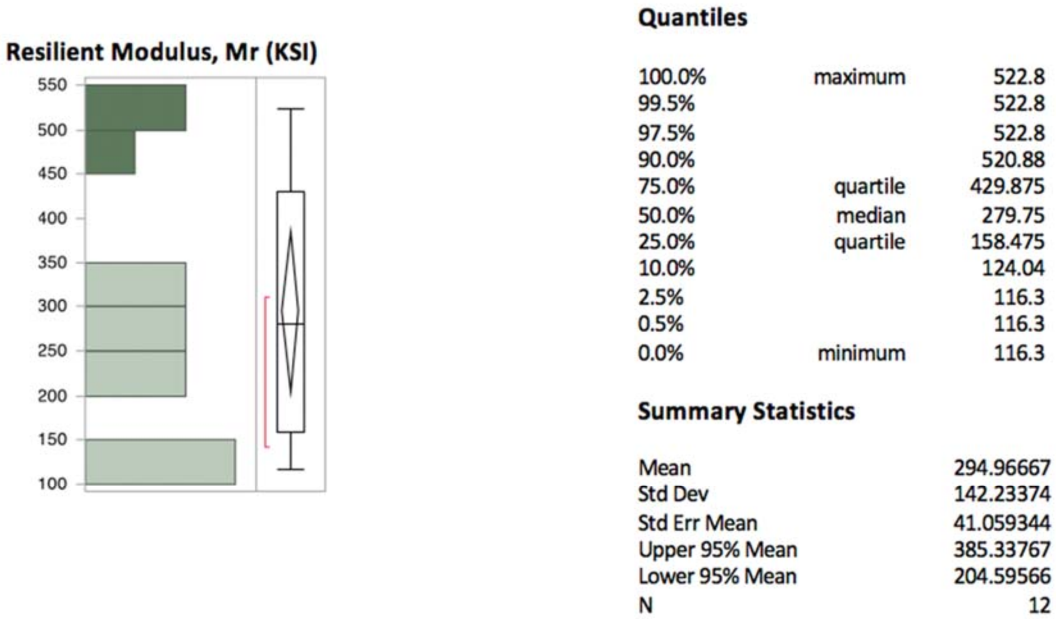
Quantiles

100.0%	maximum	11.3
99.5%		11.3
97.5%		11.3
90.0%		11.27
75.0%	quartile	10.9
50.0%	median	10.15
25.0%	quartile	8.9
10.0%		7.91
2.5%		7.7
0.5%		7.7
0.0%	minimum	7.7

Summary Statistics

Mean	9.925
Std Dev	1.200852
Std Err Mean	0.3466561
Upper 95% Mean	10.687985
Lower 95% Mean	9.1620151
N	12

Figure R.33 (Continued). JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures M_R



```
Quantiles

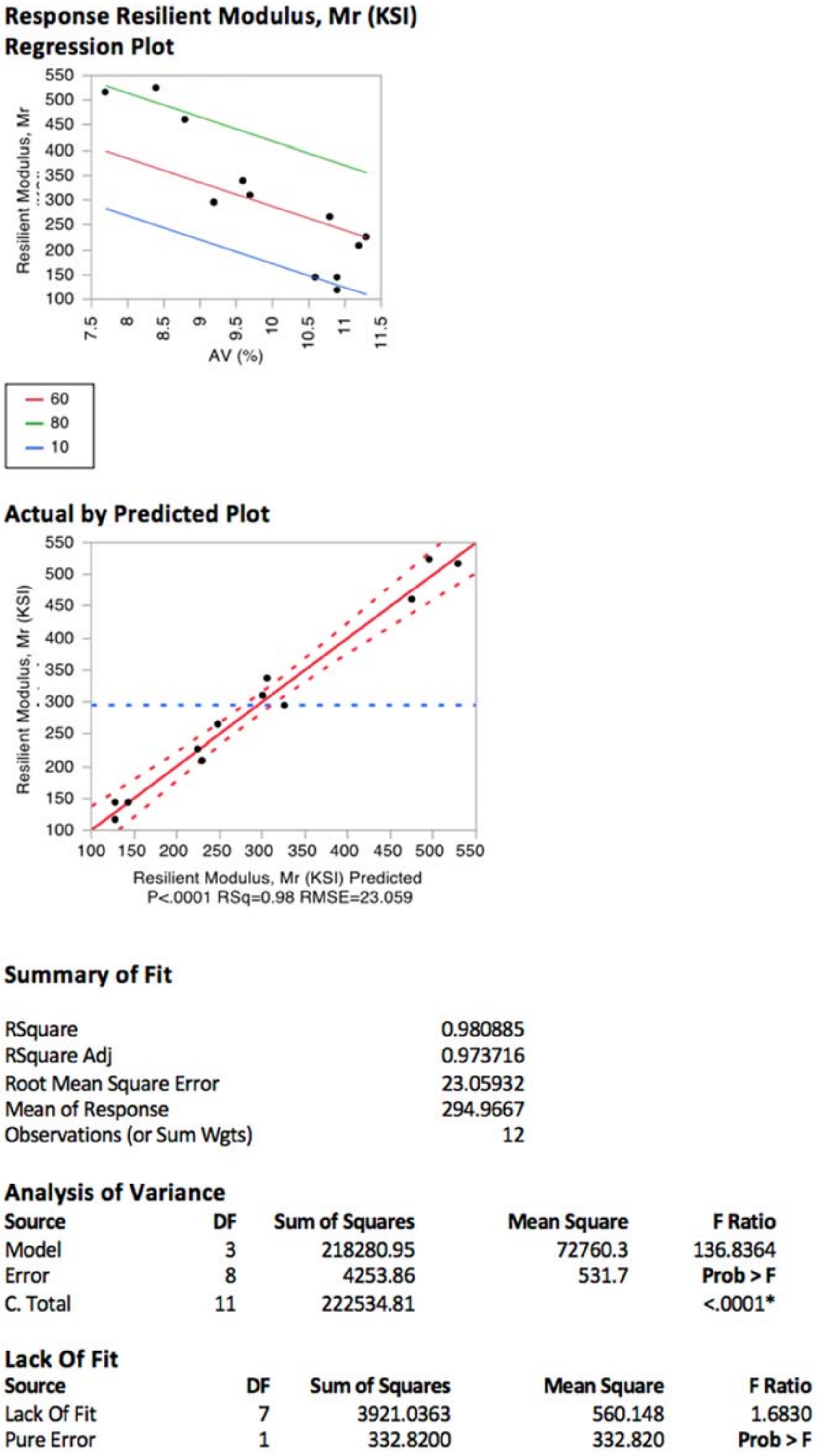
100.0%      maximum       522.8
99.5%                     522.8
97.5%                     522.8
90.0%                    520.88
75.0%       quartile    429.875
50.0%       median       279.75
25.0%       quartile    158.475
10.0%                    124.04
2.5%                      116.3
0.5%                      116.3
0.0%        minimum       116.3

Summary Statistics

Mean                  294.96667
Std Dev               142.23374
Std Err Mean          41.059344
Upper 95% Mean        385.33767
Lower 95% Mean        204.59566
N                            12
```

Figure R.33 (Continued). JMP Exploratory Analysis Output, Foamed Cold Recycled Mixtures M_R

The multi-factor ANCOVA model having RAP Content and AV content as main effects was first fitted to the data. It can be observed from the Effects Tests results shown below that the effects of RAP Content and AV content were statistically significant at α = 0.05.


Response Resilient Modulus, Mr (KSI)

Regression Plot

Actual by Predicted Plot

Summary of Fit

```
RSquare                          0.980885
RSquare Adj                      0.973716
Root Mean Square Error           23.05932
Mean of Response                 294.9667
Observations (or Sum Wgts)             12
```

Analysis of Variance

```
Source       DF   Sum of Squares     Mean Square     F Ratio
Model         3        218280.95         72760.3    136.8364
Error         8          4253.86           531.7    Prob > F
C. Total     11        222534.81                    <.0001*
```

Lack Of Fit

```
Source          DF   Sum of Squares     Mean Square     F Ratio
Lack Of Fit      7        3921.0363         560.148      1.6830
Pure Error       1         332.8200         332.820    Prob > F
```

Figure R.34. JMP Statistical Analysis Output with RAP Content, Foamed Cold Recycled Mixtures M_R

Source	DF	Sum of Squares	Mean Square	F Ratio
Total Error	8	4253.8563		0.5340
				Max RSq

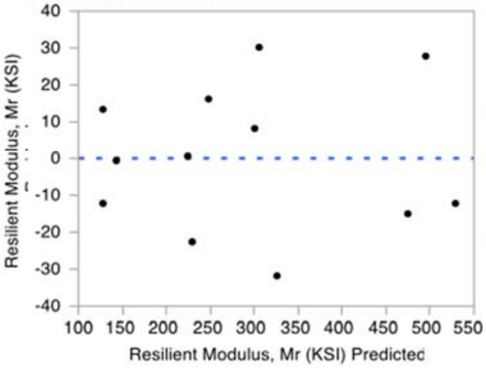
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	774.76222	103.3843	7.49	<.0001*
RAP Content[60]	-4.980556	10.31841	-0.48	0.6422
RAP Content[80]	125.43611	18.90939	6.63	0.0002*
AV (%)	-48.21667	10.52509	-4.58	0.0018*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RAP Content	2	2	35287.728	33.1819	0.0001*
AV (%)	1	1	11159.265	20.9866	0.0018*

Residual by Predicted Plot



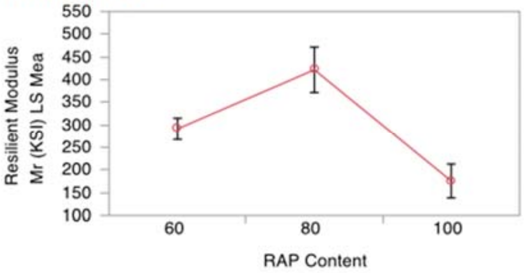
Effect Details

RAP Content

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
60	291.23125	10.207845	273.150
80	421.64792	21.674083	500.000
100	175.75625	16.188207	133.567

LS Means Plot

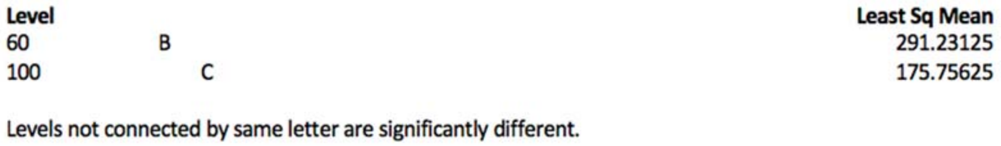


LSMeans Differences Tukey HSD

α=0.050

Level		Least Sq Mean
80	A	421.64792

Figure R.34 (Continued). JMP Statistical Analysis Output with RAP Content, Foamed Cold Recycled Mixtures M_R

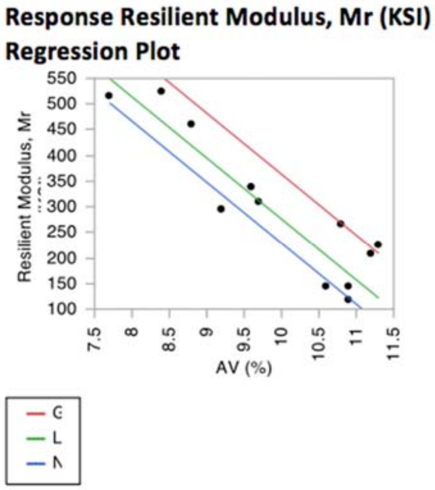


Level			Least Sq Mean
60	B		291.23125
100		C	175.75625

Levels not connected by same letter are significantly different.

Figure R.34 (Continued). JMP Statistical Analysis Output with RAP Content, Foamed Cold Recycled Mixtures M_R

Next, the multi-factor ANCOVA model having AV content and virgin aggregate type as main effects was fitted to the data. It can be observed from the Effects Tests results shown below that the main effects AV content and virgin aggregate type were statistically significant at α = 0.05.

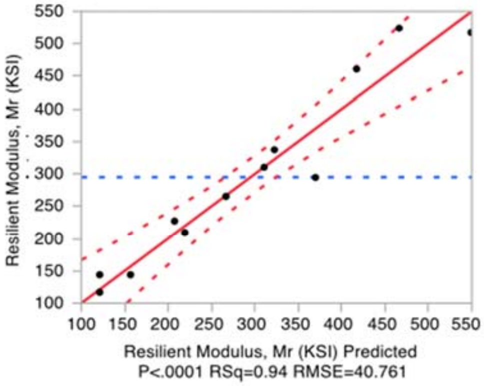


Response Resilient Modulus, Mr (KSI)

Regression Plot

Figure R.35. JMP Statistical Analysis Output with Virgin Aggregate Type, Foamed Cold Recycled Mixtures M_R

Actual by Predicted Plot



Summary of Fit

RSquare	0.940271
RSquare Adj	0.917873
Root Mean Square Error	40.7612
Mean of Response	294.9667
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	209243.01	69747.7	41.9794
Error	8	13291.80	1661.5	**Prob > F**
C. Total	11	222534.81		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	7	12958.982	1851.28	5.5624
Pure Error	1	332.820	332.82	**Prob > F**
Total Error	8	13291.802		0.3157
				Max RSq

Parameter Estimates

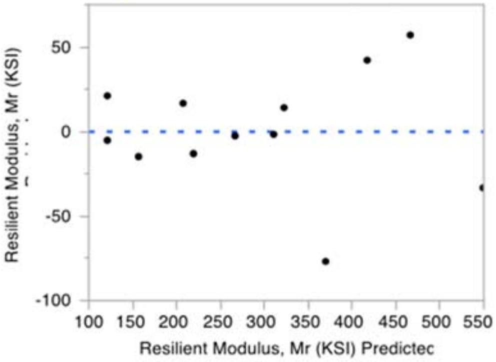
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1479.3175	237.243	6.24	0.0002*
AV (%)	-118.9936	23.07648	-5.16	0.0009*
Virgin Aggregate Type[G]	73.977991	26.6131	2.78	0.0239*
Virgin Aggregate Type[L]	-13.35791	35.22472	-0.38	0.7144

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
AV (%)	1	1	44177.560	26.5894	0.0009*
Virgin Aggregate Type	2	2	26249.783	7.8995	0.0128*

Figure R.35 (Continued). JMP Statistical Analysis Output with Virgin Aggregate Type, Foamed Cold Recycled Mixtures M_R

Residual by Predicted Plot



Effect Details

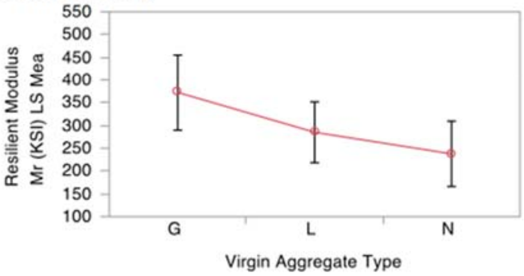
AV (%)

Virgin Aggregate Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
G	372.28413	35.903219	232.467
L	284.94824	28.920506	406.917
N	237.68606	31.008690	133.567

LS Means Plot



LSMeans Differences Tukey HSD

α=0.050

Level			Least Sq Mean
G	A		372.28413
L	A	B	284.94824
N		B	237.68606

Levels not connected by same letter are significantly different.

Figure R.35 (Continued). JMP Statistical Analysis Output with Virgin Aggregate Type, Foamed Cold Recycled Mixtures M_R