EVALUATION OF HYBRID BINDER USE IN SURFACE MIXTURES IN FLORIDA

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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 yards	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.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	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	35.71	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	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°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	psi

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

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16. Abstract

Binder and mixture tests were performed to evaluate the relative performance of a PG 67-22 base binder and six other commercially available binders produced by modifying the same base binder with the following modifiers: one Styrene Butadiene Styrene (SBS) polymer, three commercially available hybrid binders composed of different percentages of rubber and SBS polymer, and two asphalt rubber binders (5% and 12 % rubber: ARB-5 and ARB-12). Results indicated that hybrid binders (modified with more rubber than SBS) that exceed the cracking performance characteristics of unmodified binder and asphalt rubber binders, and have about the same cracking performance characteristics of SBS polymer modified binder can be produced commercially. Results also indicated that hybrid binder can be suitably specified using existing specification requirements for PG76-22 binder and solubility. Therefore, it appears that hybrid binder has the potential to replace three binders currently used by FDOT in hot mix asphalt: SBS polymer modified asphalt, ARB-5, and ARB-12. It was recommended that FDOT develop a transition plan to accomplish this. The research also showed that existing binder tests do not accurately predict cracking performance at intermediate temperatures, even in a relative sense. A new binder direct tension test configuration was conceived and designed in this study that has the potential to obtain properties from which cracking performance of binders can be predicted. It was recommended that FDOT pursue development and evaluation of the proposed test.

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Unclassified	Unclassified	162	

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Finally, we would like to extend our thanks to Alvaro Guarin, who assisted in the flow and organization of the mixture portions of the final report and the difficult task of wading through all the mixture testing data and making sense of it all.

EXECUTIVE SUMMARY

Florida has been recognized as using more recycled tires in highway applications on a continuing basis than any other state in the Union. Research in Florida and elsewhere has shown that use of polymer modified asphalt results in improved cracking and rutting performance of pavement, a benefit not achieved by asphalt modified with ground tire rubber alone. Hybrid asphalt binders are produced using ground tire rubber and a polymer as modifiers, with the amount of ground tire rubber exceeding the amount of polymer. This research effort was initiated to evaluate commercially available hybrid asphalt binders to determine if they can exceed the performance characteristics of currently used unmodified asphalt and currently used asphalt rubber binders, as well as meet or exceed the performance characteristics of currently used polymer modified binders in both dense and open-graded hot mix asphalt.

Input and support was encouraged from asphalt binder suppliers, ground tire rubber producers, Florida Department of Environmental Regulation, hot mix asphalt contractors, and asphalt technologists in government and private industry in the United States. A carefully crafted experiment was designed and conducted to evaluate whether commercially available hybrid binder could exceed the cracking performance characteristics of the base and asphalt rubber binders, as well as approach, meet or exceed the cracking performance characteristics of the Styrene Butadiene Styrene (SBS) polymer modified binder. Secondary goals were to determine whether available binder tests and characterization methods are suitable for specifying hybrid binder, and to evaluate the effectiveness of available binder tests to accurately predict the relative cracking performance of the binder systems evaluated.

Binder and mixture tests were performed to evaluate the relative performance of a PG 67-22 base binder and six other binders produced by modifying the same base binder with the following modifiers: one SBS polymer, three commercially available hybrid binders composed of different percentages of rubber and SBS polymer, and two asphalt rubber binders (5% and 12% rubber: ARB-5 and ARB-12). Results indicated that hybrid binders (modified with more rubber than SBS) can exceed the cracking performance characteristics of unmodified binder and asphalt rubber binders, and can have about the same cracking performance characteristics of SBS polymer modified binder. Although all the hybrid binders in this study did not meet all the Superpave binder tests, results indicated that hybrid binder can be suitably specified using existing specification requirements for PG76-22 binder and solubility should not be waived. Therefore, it appears that properly specified hybrid binder has the potential to replace three binders currently used by FDOT in hot mix asphalt: SBS polymer modified asphalt, ARB-5, and ARB-12. This would result in numerous benefits, including: continued and probably increased use of tire ground rubber in asphalt; the ground tire rubber will not settle out like asphalt rubber binders; elimination of a method recipe specification asphalt rubber binder for performance related hybrid binder; simplification of storage of binders at the hot mix plant by replacing three currently used asphalt binders; and improved cracking and rutting resistance of dense-graded friction course mixtures (FC9.5 and FC12.5). Therefore, it is recommended that FDOT consider the change to using hybrid binders and develop a transaction plan to accomplish this.

The transaction process should involve an assessment of impact and cost, as well as development of a draft specification and strategy for implementation. Consideration should be given to first allowing the use of hybrid binder as an alternate binder, then eventually requiring its use. The process should also include a number of demonstration projects where the hybrid binder is specified in addition to the polymer modified binder. The asphalt suppliers' timeline to supply hybrid binder to Florida will have to be taken into account, and suppliers will need to know the level of Florida's commitment to this product before making the necessary investments.

Finally, the research also showed that existing binder tests, including newly developed tests (Multiple Stress Creep Recovery and Elastic Recovery), as well an energy-based interpretation of Force Ductility data developed in this study, do not accurately predict cracking performance at intermediate temperatures, even in a relative sense. A new binder direct tension test configuration was conceived and designed in this study that has the potential to obtain properties from which cracking performance of binders can be predicted. It was recommended that FDOT pursue development and evaluation of the proposed test.

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CHAPTER 1

INTRODUCTION

1.1 Background

According to the 2007 estimates of the United States Census Bureau, the State of Florida is the fourth most populous state in the union with a population of approximately 18.25 million people and growing by approximately 1000 residents every day. This population growth not only increases the number of vehicles using the state's infrastructure, but also adds to the state's waste management efforts with respect to the increasing number of waste tires which will eventually accompany the growth in the number of automobiles using Florida's highways.

The Florida Department of Environmental Protection (DEP) reports that prior to 1989, almost all waste tires were either land filled (whole carcasses) or stockpiled. That same year, legislation was passed requiring all tires to be cut or shredded into 8 or more pieces prior to disposal thereby, reducing the total volume of the waste product. This effort consequently sparked the development of alternative uses for this waste product; including asphalt and soil modification; playground or sporting area surfacing or covers; the molding of new rubber-based consumer products, and other applications.

The Florida Department of Transportation (FDOT) utilizes tons of crumb rubber annually, from local producers, for use in FDOT contracted Asphalt Rubber Membrane Interlayer (ARMI), friction courses and sealants used in roadway construction and maintenance. In fact, Florida is the only state which routinely specifies Rubber Modified Asphalts (RMAs) for use in their final surface asphalt mixture (friction courses) on all state highways. The following figure indicates that although both the total number of waste tires and the amount of crumb rubber generated from these waste tires have remained relatively constant over the period; the usage by FDOT has been decreasing, from approximately 18% to 10% of the total crumb rubber generation.

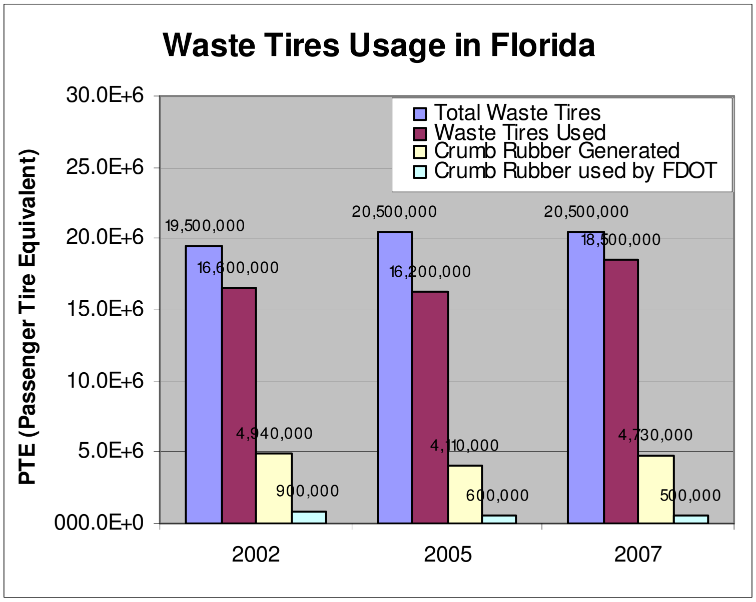


Figure 1-1 Waste Tires Use History in Florida

Currently, Florida's specifications identify asphalt binders incorporating the use of crumb rubber by binder type and application. These include:

ARB-5 (5% rubber by weight of asphalt), used in Dense Graded Surface Mixtures

ARB-12 (12% rubber by weight of asphalt), used in Open Graded Friction Courses (OGFCs)

ARB-20 (20% rubber by weight of asphalt), used as part of an anti-reflective crack relief layer or ARMI

The use of these binders was not introduced just to consume crumb rubber as a means to an end, that is, to comply with the comprehensive 1988 Florida State Solid Waste Law. Research conducted in-house by FDOT, the National Center for Asphalt Technology at Auburn University (NCAT) and the University of Florida has shown the beneficial effects of these materials. OGFCs have benefited from asphalt rubber binders by exhibiting improved short-term raveling resistance, and improved cracking resistance; and Florida's dense graded friction courses, FC-9.5 and FC-12.5, exhibited small improvements in rut resistance over a conventional binder as determined, in an FDOT accelerated pavement analyzer study (Moseley, et al, 2003). In addition, it is generally well accepted that rubber reduces the rate of oxidative age-hardening, which can have a beneficial effect on cracking.

Polymer Modified Asphalts, or PMAs, have been used in Florida since 2001. PMAs are modified by the reacted addition of Styrene Butadiene (SB) polymer or Styrene Butadiene Styrene (SBS) polymers to a base binder. Based on research performed on Florida's Accelerated Pavement Tester (APT) and work performed at NCAT, PMAs have been shown to improve the rutting resistance of *good* performing asphalt mixtures. Consequently, Florida now uses polymer modified asphalt mixtures for the top layer, or top two layers, on Interstate high truck volume construction projects. In 2004, Florida decided to include the use of PMAs in Interstate high truck volume OGFC based on data from University of Florida testing which indicated better rutting and cracking performance of OGFC (Tia, et al, 2002), and as a method to simplify construction by allowing contractors to purchase larger quantities of a single binder.

The cost of Hot Mix Asphalt (HMA) tripled from about $35 a ton in 1999 to over $100 a ton in 2007. This is mainly due to the reduction in crude oil supply, which therefore, increased the cost of asphalt as a by-product of crude. The increased price of aggregate due to shortages also contributed to the increased cost of HMA. From 1999 to about 2005, asphalt binder prices remained relatively flat, from $100 to $200 a ton, but spiked to almost $500 a ton by 2008 (Figure 1.Y). In 2008, a Florida Department of Transportation commissioned economic study included information regarding the supply shortage of styrene-butadiene polymers for the asphalt industry. This was not new information, just corroboration of well known industry facts. Both reports recommended that alternate asphalt modifiers be considered during supply shortages, including a very interesting alternative: hybrid binders.

A hybrid binder, as described here, is a blending of SB or SBS polymer with digested ground tire rubber (GTR) to produce a cross-linked storage stable polymer-modified asphalt (in some states called Terminal Blend Crumb Rubber). As a consequence of this type hybrid binder, the use of waste tire rubber in Florida pavements would continue and possibly increase. PMAs are normally formulated with about 4% ± SB(S). If the percent SB(S) was reduced and substituted with equal or more GTR, which is more readily available, a likely substitute for the standard PMA could be obtained. We know that both asphalt rubber binders and polymer modified binders can improve the performance of mixtures over the same mixtures produced with unmodified binders. Therefore, it is important to identify and evaluate whether different hybrid binders can perform competitively versus other modified asphalts currently used in Florida's highway applications and identify critical specification properties that must be met.

1.2 Objectives

The overall objective of this work is to determine whether a hybrid binder, composed of tire rubber and polymer, results in an asphalt mixture with improved performance related to a mixture produced with unmodified asphalt. More specifically, project objectives include:

- Identify three hybrid binder producers and binders which are currently available or that can be produced for evaluation in this study.
- Characterize the hybrid binders to verify that they can meet all appropriate specifications for polymer–modified binders (PG76-22) and to identify potential issues associated with the specifying and implementing the use of hybrid binders in Florida.
- Compare the performance of OGFC and dense-graded asphalt mixtures produced with hybrid binders to the performance of the same mixtures produced with an unmodified binder, an SBS polymer-modified binder, an ARB-5 binder for dense graded mixtures, and an ARB-12 for OGFCs. Performance will be evaluated in terms of the mixture's resistance to cracking, because one primary concern was that just stiffening the binder could result in brittleness and reduced cracking resistance.
- Provide recommendations for future work to further understand the behavior of this type of binder, so that blends can be optimized for enhanced performance and to identify properties that accurately reflect the binder's performance in asphalt mixtures and pavement.

1.3 Scope

The primary focus of the work will be on three hybrid binders obtained from different producers. Tests were performed to assess the performance of the binders and their controls; and the performance of the mixtures produced with these binders.

Binder performance was characterized using traditional Superpave binder tests (FDOT Standard Specifications 916-1 for PG Superpave asphalt binders) as well as tests for Elastic Recovery (ER) and a newer test called the Multiple Stress Creep Recovery test or MSCR. The

MSCR test was primarily developed to identify the presence of polymer in an asphalt binder and to better characterize the high temperature elastic component of polymer modified binders. One hybrid binder producer emphatically supported a test which they have been using to characterize their binder, this being the Force Ductility test. After reviewing their test data, it was decided that this test method merited further investigation and could be used to characterize the binders.

Mixture performance was evaluated for two mixture types: an OGFC and a dense-graded Superpave mixture. In addition, two different aggregates, limestone and granite, which are extensively used in Florida, were evaluated with each mixture type. For each of the mixtures, hybrid binder performance was compared to the following: unmodified binder (PG 67-22), SBS-modified binder (PG 76-22), and crumb-rubber modified binder (ARB-5) for dense-graded mixtures; SBS-modified binder (PG 76-22), and crumb-rubber modified binder (ARB-12) for OGFC mixtures.

Performance evaluation involved the most advanced laboratory tests and interpretation methods available to assess asphalt mixture resistance to cracking in order to ensure that the modified binders did not stiffen the mix to the point that it was brittle and prone to cracking. The primary tools were the Superpave indirect tension test (IDT) along with the HMA fracture mechanics model and energy ratio concept developed at the University of Florida.

CHAPTER 2

LITERATURE REVIEW

Over the last three decades, many different modifiers have been added to asphalt binders to improve both the rutting and cracking resistance of Hot Mix Asphalt (HMA). Of all the available modifiers, two major categories see extensive use today: Rubber and Polymers.

Rubber, as an asphalt binder modifier most normally referred to as crumb rubber modifier or CRM, is composed of natural rubber (latex), synthetic rubber (polymer), and carbon black. It is known that the natural rubber enhances elastic properties, whereas the synthetic rubber improves thermal stability (NCAT, 1996). CRM is obtained from whole tire recycling and retreading operations.

Heitzman (1992) summarized factors that affect the CRM-binder interaction: production method (ambient versus cryogenic grinding), particle size, specific surface area and chemical composition. Among these, the specific surface area has been reported as the most influential. This document has become the prime source document for specifications for both the recycled tire rubber and asphalt rubber binders. Putman, (2005) found that the CRM-binder interaction can be described by two essential effects: the Interaction Effect (IE) and the Particle Effect (PE). The IE is related to the absorption of aromatic oils from the binder by the rubber, while the PE considers the rubber acting as filler in the binder. He concluded that the IE is greatly influence by the crude source of the binder and could potentially be used as an indicator of a binder’s compatibility with CRM. A higher IE value would indicate a more compatible binder.

Currently, there are three methods of incorporating rubber into HMA: the wet process, the dry process, and the terminal blend process. It should be noticed that wet and dry processes are performed at the plant site rather than at a refinery or terminal.

Wet process: the rubber and asphalt binder are mixed together prior to addition with the aggregates (by far, the most widely accepted and used method, in Florida, this is primarily done at the asphalt terminals and can cause confusion with the Terminal blend process definition)

Dry process: the rubber and the aggregates are mixed together prior to the addition of the asphalt binder.

Terminal blend process: the rubber is dissolved in the asphalt binder at the terminal with addition of other additives/modifiers. Generally, a proprietary means using a combination of chemicals, heat and physical processing is used to achieve solubility.

In many different regions of the country, pavements using asphalt rubber binders have exhibited better cracking resistance and increased durability over pavements using conventional asphalts. Several State experiences are summarized by Hicks et al (1995):

The Arizona Department of Transportation (ADOT) started using rubber in HMA test sections in the 1970s. With the experience gained from these test sections, ADOT used both open-graded and gap-graded mixtures over existing rigid and flexible pavements. Since 1989, over 40 projects have been placed using rubber modified mixtures, and as a result, ADOT has observed a dramatic decrease in their pavement cracking.

California (CalDOT or Caltrans) has experimented with both wet and dry rubber processes for HMA since the 70s, but stopped using the dry process due to erratic pavement performance. Cook, et al.(2005), utilized Superpave tests, as well as, the Hamburg wheel tracking device to evaluate the fatigue and rutting performance of rubber modified mixtures in 2005. They concluded that asphalt rubber modified mixtures performed at least as well as, if not better than, the conventional dense-graded asphalt mixtures; therefore, they recommended the use of CRM mixtures.

The Florida Department of Transportation (FDOT) started using rubber in asphalt mixtures in 1988 and fully implementing its use in 1994. They used an asphalt rubber binder (ARB-5) in dense graded friction courses 25 mm thick to improve the resistance to shoving and rutting, particularly at intersections. On Interstate high truck volume highways, they placed a thin 15 mm open graded friction course (using ARB-12) to improve their durability.

Polymers are characterized as thermoplastic rubbers or elastomers and examples of these include: Styrene Butadiene Rubber (SBR or SB), Styrene Butadiene Styrene (SBS), Styrene Isoprene Styrene (SIS), Polybutadiene, and Polyisoprene. (NCAT, 1996) These elastomers have an important effect on the temperature susceptibility and stiffness of the asphalt binder. Due to their chemical structure, polymers are generally less susceptible to changes in temperature than standard asphalt binders; therefore, polymer modified asphalt binders (PMAs) offer a great reduction in their temperature susceptibility. A small sampling of PMA experiences is presented here:

Kentucky Transportation Center and Kentucky Department of Transportation (KDOT) tests showed that polymer modified binders can improve the rutting (using wheel tracking tests) and the cracking resistance of asphalt mixtures (Fleckenstein, et al, 1992).

The Oregon Department of Transportation (ODOT) validates that polymers are a practical way to reduce the temperature susceptibility of asphalt pavements. They also found that polymerized asphalt mixtures are more resistant to freeze-thaw damage (Rogge, et al, 1992).

At the University of Florida, Kim (2003) showed that SBS modified mixtures generally have a lower m-value than the same unmodified mixture; indicating a reduced rate of damage in the mixture.

The hybrid binder composed of SBS, rubber and asphalt was a relatively new approach at the beginning of this study. Therefore, there were very few research papers on these materials. Essentially, there is little to no knowledge of the engineering performance of hybrid binder.

An FHWA evaluation of modified binders included lab as well as accelerated loading of test sections. The rutting performance of Section 5 Terminal Blend Crumb Rubber (a hybrid binder) performed as well as SBS polymer modified binders (Tia, 2002).

According to the “SBS Polymer Supply Outlook” (by Association of Modified Asphalt Producers, 2008), there was a shortage of SBS for the asphalt industry and the price of SBS was increasing, which could happen again. Because of this background, hybrid binder provides an attractive alternative.

Most research studies have focused on SBS modified binder or Asphalt Rubber Binder separately. A summary of research is presented below on the fracture resistance of these two systems.

As for the SBS modified binder and Asphalt Rubber Binder, most researchers have primarily used traditional test methods including Dynamic Shear Rheometer, Bending Beam Rheometer, Penetration, Brookfield Viscosity, Elastic Recovery, Ductility, Softening Point, thin layer chromatography, etc. Comparisons have generally been based on the traditional test properties such as the complex shear modulus G*, phase angle δ and other Superpave indices. Some researchers have developed other parameters to evaluate performance of different modified binders. For example, Gilberto et al (2006) used the Binder Aging Ratio (BAR) calculated from G* to differentiate binders, and found that Asphalt Rubber can decrease BAR 40%-50% compared with unmodified asphalt, but its aging level is similar to Polymer Modified Binders. Other researchers used traditional test devices such as the Dynamic Shear Rheometer to evaluate the creep behavior of binders (e.g., Felice et al, 2006).

Some researchers noticed the limitations of traditional Superpave indices. For example, Bahia et al (2008) found that G*sinδ only reflects linear viscoelastic behavior, but neglects the nonlinear viscoelastic behavior that may be more indicative of resistance to fracture and rutting. As an alternative, he performed time sweep tests based on the Dynamic Shear Rheometer. He found that both Yield Energy and strain at maximum stress obtained from these tests correlated well with field performance. Bahia et al, (2008) also evaluated the Elastic Recovery and Multiple Stress Creep Recovery tests for modified binders, and found that Elastic Recovery is a good tool to identify Polymer Modified Binders, and Jnr from Multiple Stress Creep Recovery tests characterizes nonlinear behavior.

In addition, some new test devices have been developed. For instance, the Asphalt Binder Cracking Device (ABCD) was used to evaluate the Low Temperature Thermal Cracking (Sang-Soo Kim, 2008). When temperature drops, asphalt shrinks 100 times or more than the ABCD invar ring, so the asphalt compresses the ring, and an Electrical Strain Gauge measures this compression at cracking, which is related to the tensile fracture resistance of the binders. This device was also found to be able to characterize Polymer Modified Binders but only at low temperatures.

Generally speaking, it has been found that traditional Superpave tests and indices cannot clearly differentiate between modified binders. Also, although the Multiple Stress Creep Recovery, Elastic Recovery and Force Ductility test are able to identify polymer-like behavior to some extent, they may not differentiate between different modified binders: SBS, hybrid binder and rubber modified binder. These and other limitations with the current binder test methods need to be explored to determine whether development of new test methods which can accurately reflect the different properties of various modified binders, and reflect their relative cracking or fatigue performance at ambient temperatures is needed. The goal would be to obtain as accurate as possible stress, strain, time and fracture energy relationships and other crucial properties, so reliable relationship between asphalt binder and mixture properties can be established.

CHAPTER 3

MATERIALS AND METHODS

Since this is the first research project focused on the evaluation of hybrid binder in Florida, two commonly used aggregate types in the State were chosen (limestone and granite). Following FDOT instructions, typical gradations currently used in Florida were selected to quantify the effect of CRM and hybrid binder on mixture cracking performance.

Two mixture types frequently utilized in Florida were considered for this study: dense-graded (DG) and open-graded friction course (OGFC). DG mixtures are widely used for structural purposes; whereas OGFCs are used for their outstanding capacity for providing and maintaining good pavement frictional characteristics to reduce hydroplaning and improve safety in wet weather.

3.1 Binders

A search was conducted to gather information regarding possible sources or producers for hybrid binders as defined by this project. At first, seven vendors or companies were identified as possible participants or sources of binder for this study. When available, an assessment was made regarding the current products these companies produced and whether any of their binders would qualify for this project. It was also questioned that if the company did not currently produce a hybrid binder, would there be enough interest in this project that the company would undertake a timely development of such a material.

Of the original producers list, it was determined that two of them were actually working in concert and could produce a viable product, and that another company already had an existing product and had been producing it for some time. Of the remaining companies, one had extensive experience in polymer modification of asphalt and showed great interest in the project but, did not currently have a product to offer. They speculated that development of such a product would take between six months to one year to complete. Lastly, a fourth company was developing some similar interesting product ideas but, was looking for someone to help them bring it to fruition, i.e., no product available. The remaining suppliers were either out of business, or produced a dead-end lead. Therefore, the initial search for hybrid binder producers identified only two existing viable sources for these materials.

According to the original project proposal, the study was to contain three hybrid binders obtained from different producers, and this was proving to be a difficult task. After much due diligence, a third producer was identified, who produced a hybrid binder for use as a bonding agent, but had no experience using this product to produce hot mix asphalt. This was not deemed important and since it met the requirements for a hybrid binder, it was added as our third and final binder. These three suppliers heartily agreed to participate in this study

The project originally intended to establish guidelines for the design of the hybrid binders; controlling the amount of rubber and polymer, and the ratio between the two components. More importantly, specifying that the amount of ground tire rubber must exceed that of polymer. Discussions with the FDOT project manager and committee resulted in a relaxation and then an outright dismissal of these controls. The producers would be allowed free range in producing their hybrid binders. The only requirement to which the producers would be subject to: that their final product must be formulated to meet and pass the Superpave PG 76-22 binder specifications.

Upon further reflection, this decision would cause the project and researchers to relinquish considerable control over any aspect of the binder production, including the source of the original binder prior to modification. Therefore, it was decided to establish a baseline for the modification, that is, that all the hybrid binder producers should start with the same base binder. The three binder producers were informed of this decision and all concurred with the rationale, and agreed to modify any supplied base binder.

The project manager and the researchers agreed to use CITGO Petroleum products, PG 67-22 and PG 76-22, as the control binders. CITGO Petroleum delivered, to each of the three hybrid binder participants, a minimum of 10 gallons of their PG 67-22 binder for modification. The University of Florida received enough PG 67-22 binder for binder testing, for mixture production, and as a base binder, to produce the rubber modified binders (ARB-5, and ARB-12) needed for the project.

The researchers received two interesting comments from different hybrid binder participants regarding the base binder:

One of the hybrid binder participants reported that the base binder, as received, was not a PG 67-22, but rather a PG 70-28. CITGO Petroleum was made aware of this finding, and delivered to the researchers, Certificates of Analysis and independent

Reports of Analysis conducted by Intertek Caleb Brett, for both of their binders. The independent Reports of Analysis are more precise, because they interpolate between PG grades, and they reported that the PG 67-22 binder tested as a PG 69.78-26.50, and the PG 76-22 binder tested as a PG 76.7-27.16. Regardless, each participant received the same base binder for modification, and it is common for PG graded binders to test better than its PG grade indicates. The CITGO Certificates of Analysis and independent Reports of Analysis are available in the appendix C.

Another of the hybrid binder participants asked why CITGO Petroleum was chosen to supply the base binder for the project. (CITGO Petroleum products have a history of consistency and they are produced from a known single source.) It is claimed by this participant that CITGO binders are difficult to SBS modify and that they require the addition of sulfur to promote the linking of the SBS to the base material. Regardless, the participant agreed to proceed with their modification.

Each of the hybrid binder participants was asked to disclose as much about the formulation of their product as they were willing, without infringing on proprietary products or processes. More specifically, the researchers were interested in the SBS and ground tire rubber content for comparison between producers, and for possible explanations in binder and mixture performance. In total, seven different binders were used in this project. These are outlined in the table 3-1:

Table 3-1 Asphalt Binder and the Constituents/Formulations

Binder	Modifying Components
PG 67-22	None (tested as a PG69.78-26.50)
PG 76-22	4.25% SBS (tested as a PG76.7-27.16)
Hybrid Binder A	1% SBS (approximately 30 mesh, incorporated dry), 8% of Type B GTR, 1% hydrocarbon
Hybrid Binder B	3.5% crumb rubber, 2.5% SBS, 0.4%-plus Link PT-743-cross linking agent
Hybrid Binder C	10% rubber, 3%± 0.1% radial SBS
ARB-5	5% Type B rubber
ARB-12	12% Type B rubber

Binder testing was performed by the Florida Department of Transportation State Materials Office. The tests performed were all those required by FDOT Standard Specifications 916-1 for PG Superpave asphalt binders. In addition, DSR and creep stiffness were performed after PAV at 110˚C, in addition to the standard 100˚C. The basic binder testing program is summarized in table 3-2.

Table 3-2 Binder Tests Summary

Binder Type	Number	Number of Tests*	Number of Replicates	Total Number of Binder Tests
Base	1	12	2	24
Hybrid	3	12	2	72
SBS-modified	1	12	2	24
ARB-12	1	12	2	24
ARB-5	1	12	2	24
Totals	7	12	2	168

* Binder tests are as follows (FDOT Specifications 916-1; Superpave PG Asphalt Binder):

- Original Binder: Spot Test, Solubility, Smoke Point, Flash Point, Rotational Viscosity, Absolute Viscosity, Dynamic Shear Rheometer (DSR)
- Rolling Thin Film Oven Test Residue: Mass Loss, Dynamic Shear Rheometer
- Pressure Aging Vessel Residue: Dynamic Shear Rheometer (2 temperatures), Creep Stiffness

The test results were used to verify that all binders met appropriate specifications for a PG 76-22 Superpave asphalt binder. In addition, test results were evaluated to identify binder properties or parameters that may be suitable to uniquely characterize these hybrid binders and to identify potential issues associated with specifying and implementing the use of hybrid binders in Florida.

Several non-routine tests were performed on these binders: 1) binders were PAV aged at 110° C, which may possibly be used to identify potential aging issues of concern to Florida, 2) binders were subjected to the Elastic Recovery test, which according to Bahia (2008) will identify the presence of polymer modification, 3) binders were subjected to the Multiple Stress Creep Recovery test (AASHTO TP70-08), which according to Bahia (2008) can be used to characterize a binder's nonlinear behavior, and 4) binders were tested using the Force Ductility test, which is unique in that it loads the specimen to failure. This last test may be used to calculate energy to failure, which may be correlated to binder and possibly mixture cracking performance. This is essentially the standard ductility test with an added load cell to measure the load applied to the sample throughout its elongation.

3.2 Aggregates

Aggregates sources were chosen based on previous research work and FDOT directions; detailed information is presented in the Table 3-3. Both dense-graded (DG) and open-graded friction course (OGFC) mixtures were designed for each aggregate type (limestone and granite).

Table 3-3 Aggregate Source

Source	Type	FDOT Code	Pit No.	Producer
Nova Scotia Granite	# 7 Stone	44	NS-315	Martin Mariette Aggregates
	# 789 Stone	51	NS-315	Martin Mariette Aggregates
	Stone Screenings	22	NS-315	Martin Mariette Aggregates
South FL Limestone	S-1-A Stone	41	87-339	White Rock Quarries
	S-1-B Stone	53	87-339	White Rock Quarries
	Asphalt Screenings	22	87-339	White Rock Quarries
Georgia Granite	# 78 Stone	43	GA-553	Junction City Mining
	# 89 Stone	51	GA-553	Junction City Mining
	W-10 Screenings	20	GA-553	Junction City Mining
Rinker South FL Limestone	# 67 Stone	42	87-090	Rinker Materials Corp.
	S-1-B	55	87-090	Rinker Materials Corp.
	Med. Screenings	21	87-090	Rinker Materials Corp.
Local Sand	Local Sand	-	Starvation Hill	V. E. Whitehurst & Sons

3.2.1 Dense Graded (DG) Mixture Gradations

The particle size distribution of DG mixes is presented in the Figures 3-1 and 3-2.

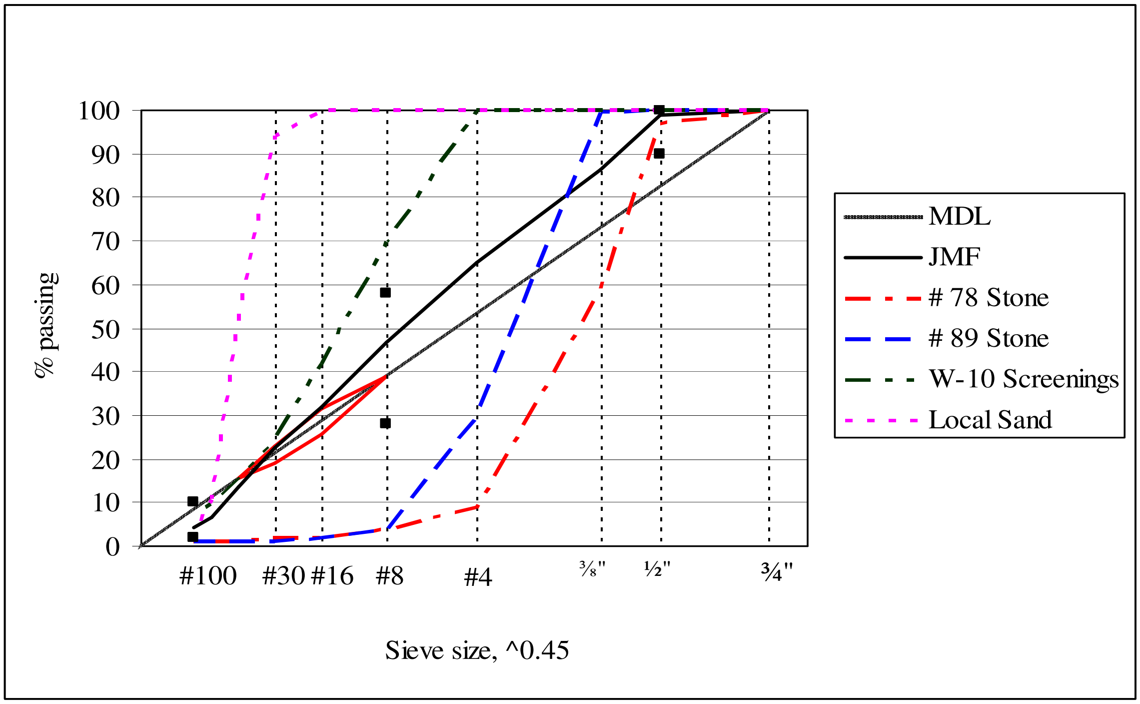


Figure 3-1 DG Granite Gradation

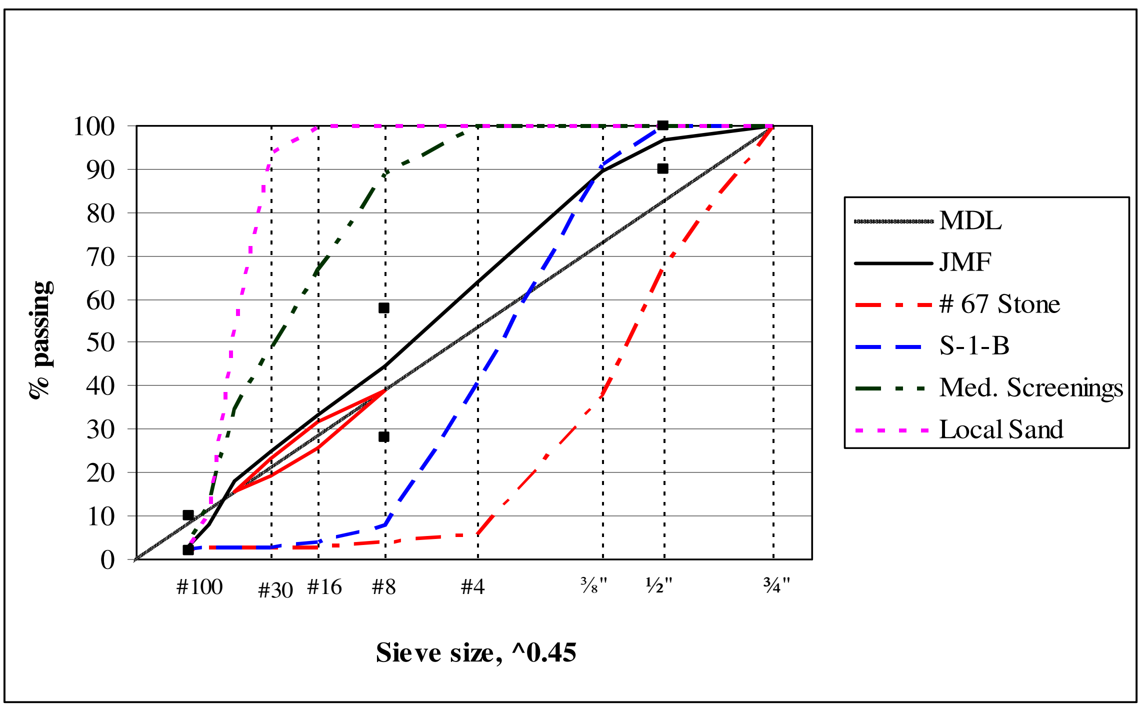


Figure 3-2 DG Limestone Gradation

3.2.2 Open Graded Friction Course (OGFC) Gradations

The OGFC gradation curves are shown in the Figures 3-3 and 3-4: the granite blend was added with hydrated lime (1% by weight) to prevent stripping.

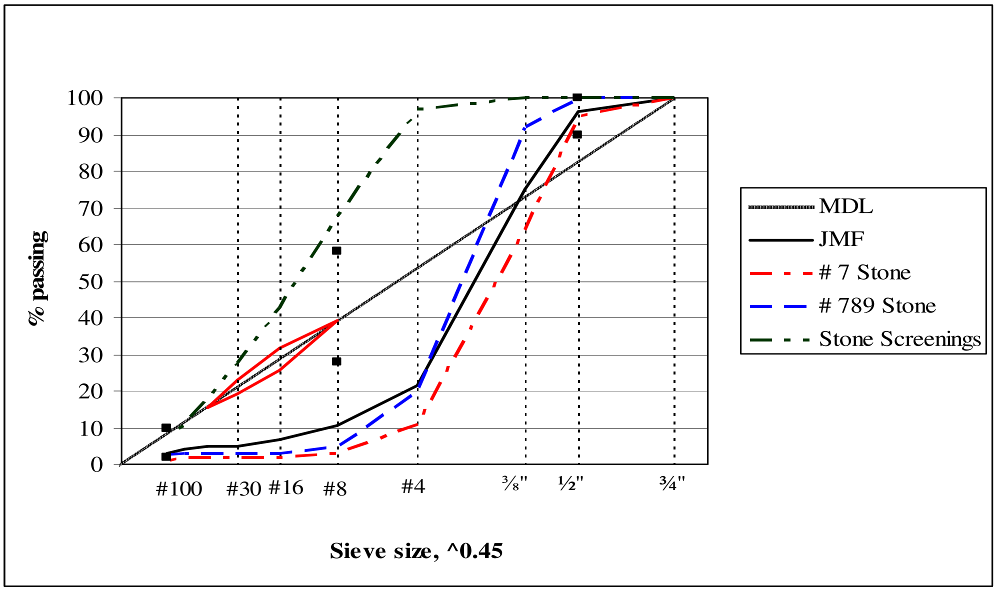


Figure 3-3 OGFC Granite Gradation

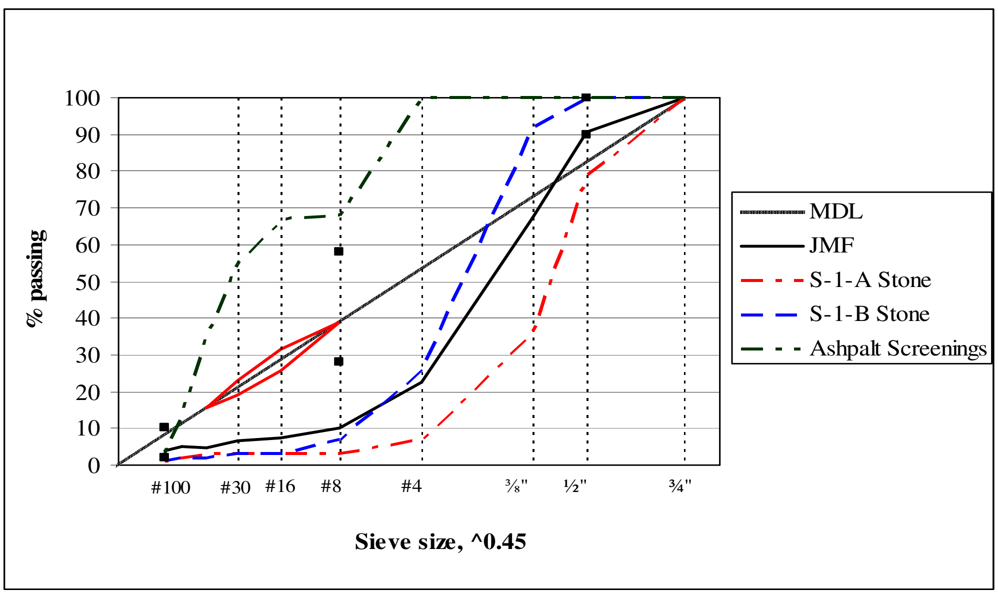


Figure 3-4 OGFC Limestone Gradation

3.3 Mixtures

All dense-graded mixtures were designed to be 12.5 mm nominal maximum aggregate size mixes and to meet specification requirements for a traffic level C, which corresponds to 3 to 10 million Equivalent Single Axle Loads (ESALs) over a 20 year period. A summary of the mixture testing plan for this project is presented in the Figure 3-5. A total of 88 gyratory specimens were prepared.

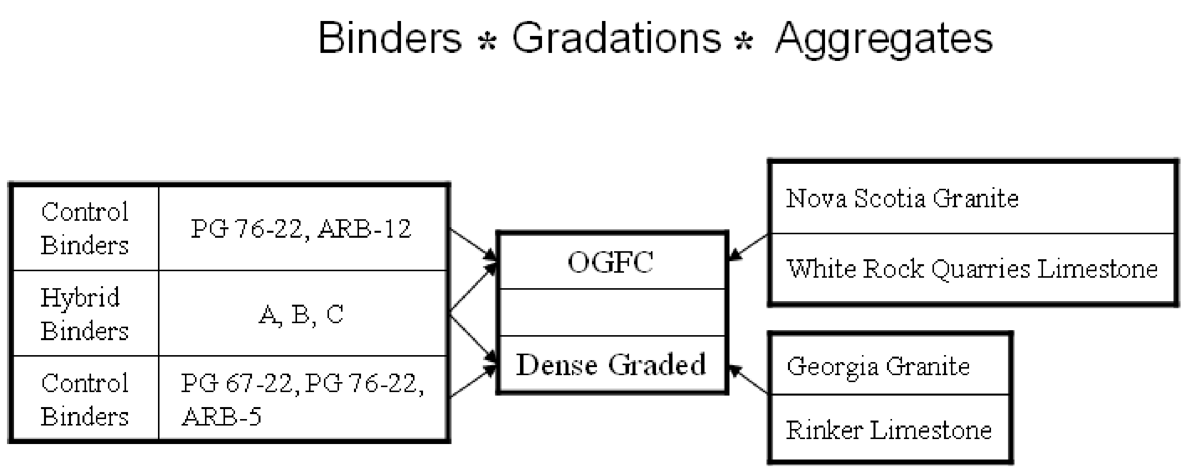


Figure 3-5 Mixture Testing Plan for Each Mixture and Aggregate Type

Each mixture in the test plan was designed with a particular binder type while the aggregate gradation was kept constant in order to evaluate binder effect on mixture cracking performance. In total, 12 DG (6 binders and 2 aggregate types) and 10 OGFC (5 binders and 2 aggregate types, 0.4% fiber by weight of the mix was added to granite OGFCs to prevent drain-down) mixtures were evaluated and have identifications (IDs) shown in Tables 3-4 and 3-5 (next page).

Initially, all mixtures (conventional and modified) with the same aggregate type and gradation were prepared in the laboratory with the same percentage of binder by weight. Theoretically, all mixes should have had the same effective asphalt volume, and consequently the same volumetric properties.

However, during the laboratory work, the effective asphalt volume was found to be about the same for OFGC mixtures but different for DG mixtures. Two factors were thought to have caused this difference: specific gravity of binder (G_b) and aggregate absorption. As mentioned previously, G_b was measured in the laboratory and also aggregate absorption tests conducted on the different binders indicated definite differences in absorption. Consequently, asphalt contents were adjusted to ensure that all mixtures had the same effective asphalt by volume.

Table 3-4 DG Mixtures IDs for Testing

Binder	PG 67-22	PG 76-22	Hybrid Binder A	Hybrid Binder B	Hybrid Binder C	ARB-5
Limestone	DLU	DLM	DLA	DLB	DLC	DLR
Granite	DGU	DGM	DGA	DGB	DGC	DGR

Table 3-5 OGFC Mixtures IDs for Testing

Binder	PG 76-22	Hybrid Binder A	Hybrid Binder B	Hybrid Binder C	ARB-12
Limestone	OLM	OLA	OLB	OLC	OLR
Granite	OGM	OGA	OGB	OGC	OGR

3.4 Mixture Preparation

Aggregates and binders were preheated in the oven for 3 hours before mixing; mixing temperature was set to 310 ± 5º F for unmodified and ARB-5 binder mixes and 330 ± 5º F for PMA and hybrid binder mixes. After preheating the hybrid binders, in some containers for all hybrid binders, undissolved modifiers (rubber particles) were found accumulated on the surface of the binder resulting in about a 2 mm thick film; thus, before pouring the binder into the mixing bucket with the aggregates, a clean steel stick was used to stir the binder evenly to dissolve the film into the binder. The aggregates and binder were then mixed in a rotating bucket until the aggregates were well coated with the binder.

Before the DG and OGFC samples were compacted, they were placed in a pan and heated in an oven for about 2 hours at the mixing temperature, which is the Short Term Oven Aging (STOA). The mix was stirred after one hour of heating to obtain a more uniformly aged sample.

DG and OGFC mixtures were compacted at 310 ± 5º F and 330 ± 5º F respectively. Even though the DG mixes were designed to have 4% air void content at N_{design}, they were compacted in the Servopac Gyratory Compactor to the number of gyrations needed to get 7% air voids. The number of gyrations obtained from mix design to get 7% air voids for DG mixtures was 20 for limestone and 24 for granite mixes.

For OGFC mixtures, 50 gyrations were used to achieve compaction level similar to field after traffic consolidation (Varadhan, 2004). Specimens were allowed to cool for 30 minutes before extruding from the molds, and for at least 24 hours before cutting or preparation for testing.

LTOA is meant to represent 15 years of field aging in a Wet-No-Freeze climate and 7 years in a Dry-Freeze climate. LTOA requires a compacted sample (after STOA) be placed in a force draft oven at 185 ± 5°F for 5 days (Harrigan et al., 1994). The same aging procedure was used for both DG and OGFC mixtures.

Because of the very coarse and open structure of OGFC; there was a possibility of these mixes falling apart at the high temperature used for LTOA. Hence, a procedure was developed to protect the pills.

A wire mesh with openings of 0.125 in and steel clamps were used. The mesh size was chosen in order to ensure that there is good air circulation within the sample for oxidation and to prevent the smaller aggregate particles from falling through the mesh. The specimen was wrapped twice with the mesh cloth and two clamps were used to contain the specimen without applying excessive pressure on it. The system is shown in the Figure 3-6.

Figure 3-6 Pill Contained with Mesh

After cooling the specimens at room temperature, they were cut to the required thickness for testing. The bulk specific gravity for DG mixes was determined in accordance with AASHTO T166 to ensure that the air voids of the specimens were within the required range of 7.0 ± 0.5 %. The DG mixture volumetric information is shown in Table 3-6.

Table 3-6 Dense Graded Mixture Volumetric Information

Mixture	DGU	DGM	DGA	DGB	DGC	DGR	DLU	DLM	DLA	DLB	DLC	DLR
P_b	4.80%	4.82%	4.90%	4.89%	4.89%	4.84%	6.60%	6.49%	6.33%	6.18%	6.42%	6.60%
G_{mm}	2.578	2.579	2.581	2.580	2.580	2.579	2.319	2.316	2.312	2.309	2.314	2.319
G_{mb}	2.390	2.380	2.388	2.408	2.399	2.386	2.165	2.145	2.153	2.155	2.150	2.148

For OGFC mixtures, physical parameters were obtained from the CoreLok test. The procedure is described in the Appendix D. After the sample was sealed, it was weighed in the water tank.

Figure 3-7 CoreLok Sample Sealing Process (Photo courtesy of InstroTek Inc.)

The OGFC and DG mixture volumetric information is shown in Table 3-7.

Table 3-7 OGFC Mixture Volumetric Information

Mixture Type	**Aging Condition**	G_{mm}	G_{mb}	**AV %**
OGFC Granite	STOA	2.441	1.995	18.28
	LTOA		1.996	18.23
OGFC Limestone	STOA	2.309	1.990	13.80
	LTOA		1.978	14.33

CHAPTER 4

BINDER TEST RESULTS AND ANALYSIS

Conventional Superpave binder tests were performed using the Dynamic Shear Rheometer and Bending Beam Rheometer. The following tests, which have been specifically developed and identified to evaluate modified binders, were also performed:

- Multiple Stress Creep Recovery (AASHTO TP70-08))
- Elastic Recovery (AASHTO T301-99(2003))
- Force Ductility (AASHTO T300-00)

In addition, physical property tests including specific gravity, solubility, smoke point, flash point, rolling thin film oven mass change and spot tests were performed. A summary of test results and findings of binder tests is presented in the sections below. Additional binder test results are presented in Appendix A.

4.1 Physical Properties

4.1.1 Specific Gravity of Binders

Results of specific gravity of binders based on the Standard Test Method for Density of Semi-Solid Bituminous Materials (ASTM Designation: D 70-03, Pycnometer Method) are presented in Table 4-1. As expected, all of the modified binders had a higher specific gravity than that of the base binder.

Table 4-1 Specific Gravity of Binders

Binders	Relative Density	Density (kg/m^3)
PG 67-22	1.031	1027.907
(SBS Modified) PG 76-22	1.033	1031.389
Hybrid Binder A	1.044	1040.918
Hybrid Binder B	1.036	1032.892
Hybrid Binder C	1.043	1040.356
ARB-5	1.036	1033.004
ARB-12	1.042	1038.824

4.1.2 Solubility

The solubility of hybrid binder A (92.76%), hybrid binder B (96.905%), ARB-5 (93.835%) and ARB-12 (88.765%) did not meet the specification requirement (minimum 99%). As illustrated in Figure 4-1, the solubility was lower for binders with higher coarse rubber content (hybrid binder A (8%), hybrid binder B (3.5%), ARB-5 (5%) and ARB-12 (12%)), indicating that the rubber may not have been fully digested in the base binder. Consequently, test results on these binders determined from the Dynamic Shear Rheometer (DSR), including the newly proposed MSCR test, which also uses DSR, were considered suspect, because the presence of particulates in the binder is well known to affect DSR results. Hybrid binder C, which was produced with finer grained rubber, did meet FDOT's solubility specification, indicating that the rubber was fully digested in the base binder, thereby making it more suitable for DSR testing.

Based on these results, it appears that solubility may be a good way to distinguish binders that may have excessively coarse particles (e.g.undigested rubber particles) that would make them unsuitable for DSR testing. Also, results of hybrid binder C show that hybrid binder can meet the solubility requirement. Therefore, solubility appears to be a good way distinguish hybrid binder, which includes polymer and rubber, from asphalt rubber binder.

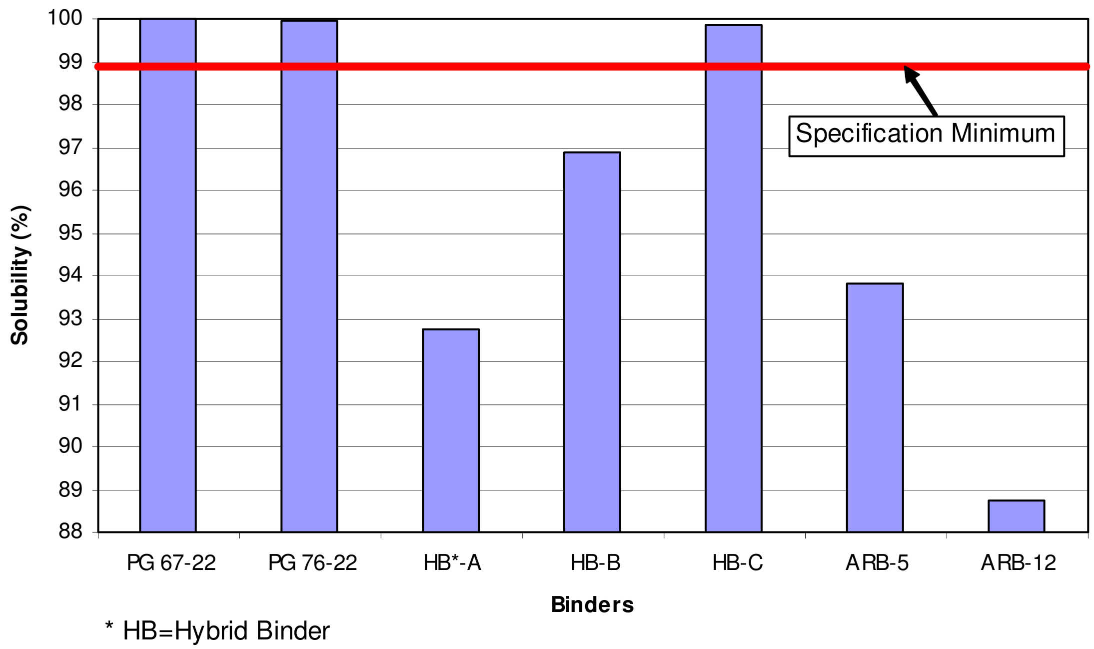


Figure 4-1 Solubility of Original Binders

4.1.3 Mass Loss after Rolling Thin Film Oven Test (RTFOT)

As indicated in Figure 4-2, all binders except hybrid binder C, which had a Mass Loss of -0.524%, met the specification requirement for Mass Loss after RTFOT (±0.5%). The Mass Loss of hybrid binder A, B was the smallest.

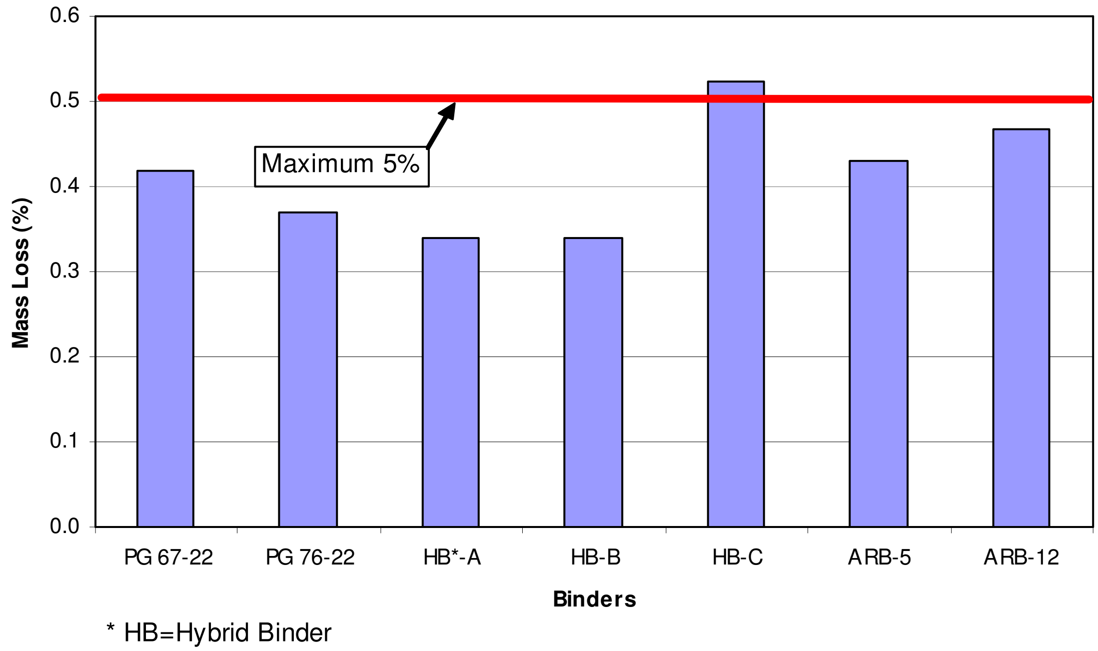


Figure 4-2 RTFOT, Mass Loss (at 163 C (325.4 F))

4.2 Dynamic Shear Rheometer & Bending Beam Rheometer

Results of Dynamic Shear Rheometer and Bending Beam Rheometer tests are presented according to testing temperature, i.e. Dynamic Shear Rheometer at high and intermediate temperatures, and Bending Beam Rheometer at low temperature.

4.2.1 Dynamic Shear Rheometer at High Temperature

As indicated in Figure 4-3, all modified binders resulted in an increase in $G^*/\sin\delta$ (indicator of rutting resistance) relative to the base binder. Also, $G^*/\sin\delta$ of all modified binders was above the minimum requirements for PG 76-22 binder. A significant difference was observed in the magnitude of $G^*/\sin\delta$ for the different modified binders

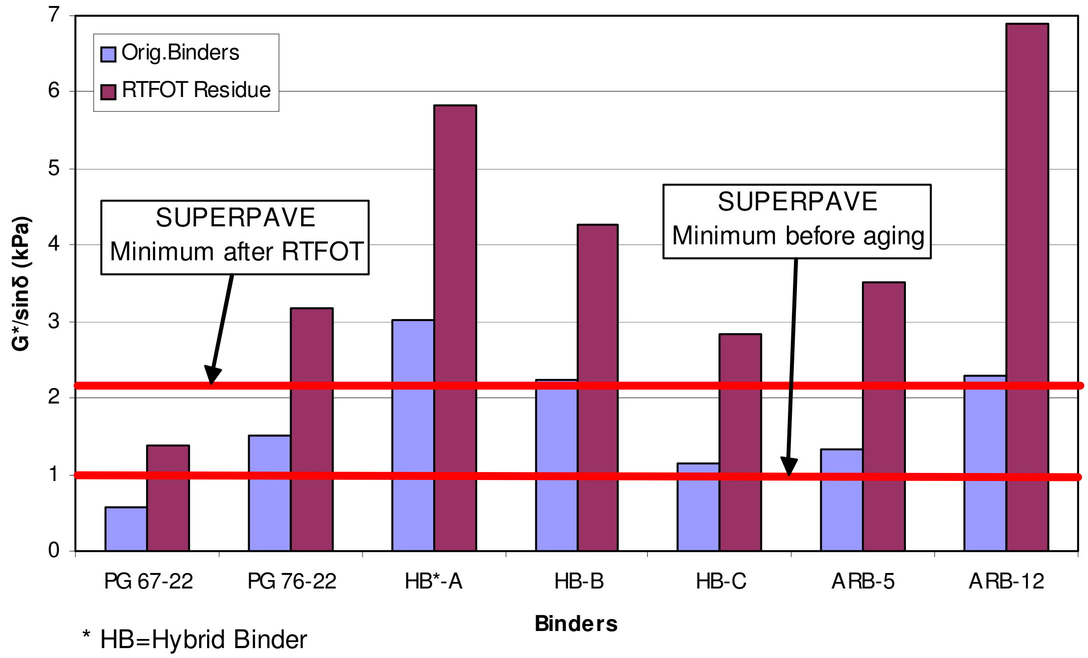


Figure 4-3 G*/sinδ at 76 C (168.8 F)

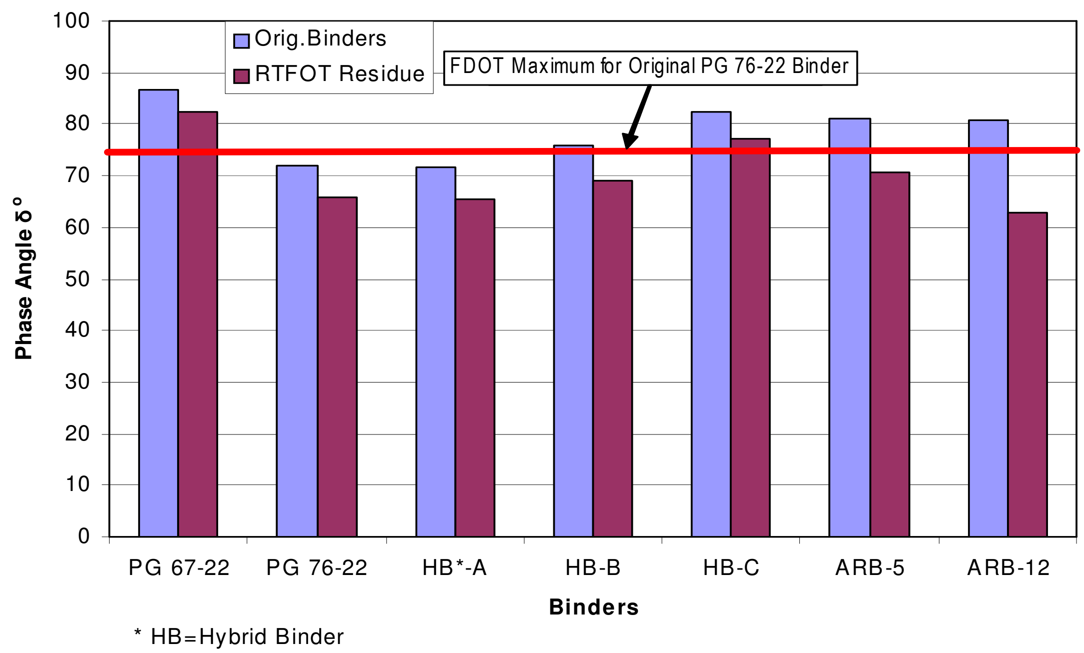


Figure 4-4 Phase Angle δ^{o} at 76 C (168.8 F)

in both original and RTFOT conditions. The largest values of G*/sin δ were observed for binders with the highest concentration of coarse rubber (hybrid binder A, hybrid binder B and ARB-12) and may be suspect.

Figure 4.4 illustrates that all modified binders exhibited a lower phase angle (δ) than the base binder. The SBS modified binder and hybrid binder A and B resulted in the greatest reduction. Lower phase angle is associated with lower energy loss or more elastic behavior, which would indicate better rutting and cracking resistance.

Solubility results indicated that the coarser rubber in hybrid binder A and B as well as the ARB binders were not fully digested in the base binder made the test results from DSR suspect because the presence of particulates in the binder is well known to affect DSR results. The binders produced with the coarser grained rubber met, and even far exceeded requirements for PG76-22 binder, resulting in binder performance parameters that indicated better performance characteristics than all other binders evaluated, including the SBS polymer modified binder. These results were not consistent with relative cracking performance characteristics determined from mixture tests.

Conversely, solubility results indicated that the finer rubber in Hybrid binder C was fully digested in the base binder, which made it suitable for DSR testing. This binder also met requirements for PG76-22 binder with the exception of the maximum phase angle (which is an FDOT requirement).

4.2.2 Dynamic Shear Rheometer at Intermediate Temperature

Figure 4-5 shows that all binders, including the base binder, met the specification requirement for a maximum G*sin δ of 5000 kPa for both the 100 C and 110 C PAV residue. All modified binders, except hybrid binder C, exhibited lower G*sinδ than the base binder. G*sinδ was intended to be an indicator of resistance to fatigue cracking because it represents a measure of energy loss (higher G*sinδ, higher energy loss). However, post-SHRP research has revealed that this parameter may not relate very well to fatigue cracking resistance because a large part of the energy loss associated with G*sinδ is not related to damage.

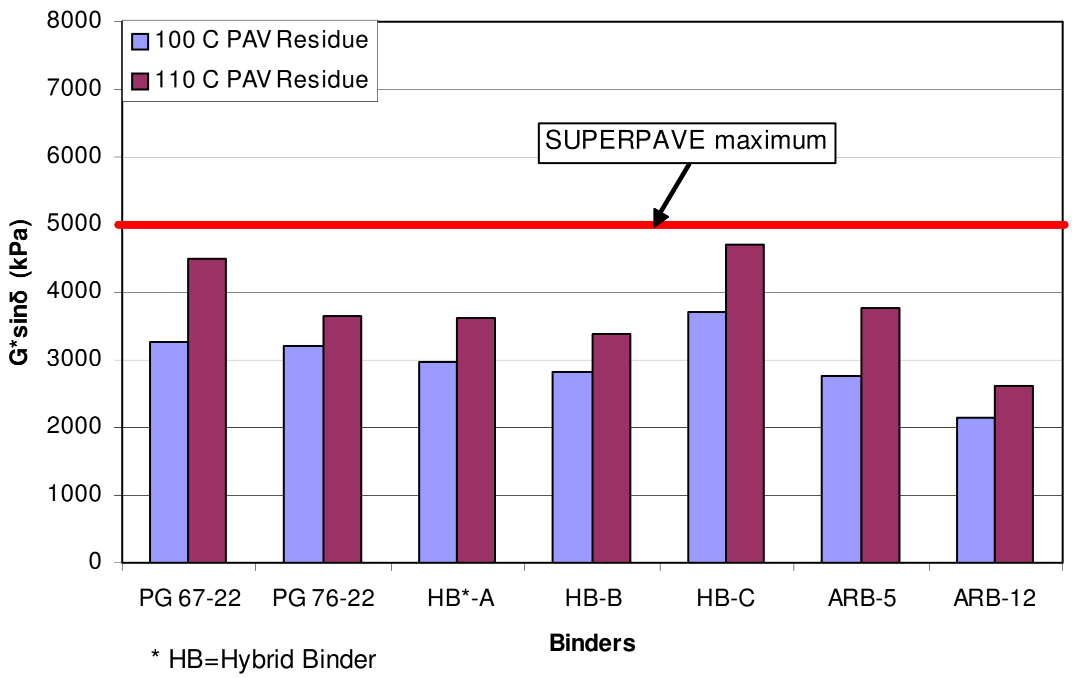


Figure 4-5 G*sinδ at 25 C (77 F)

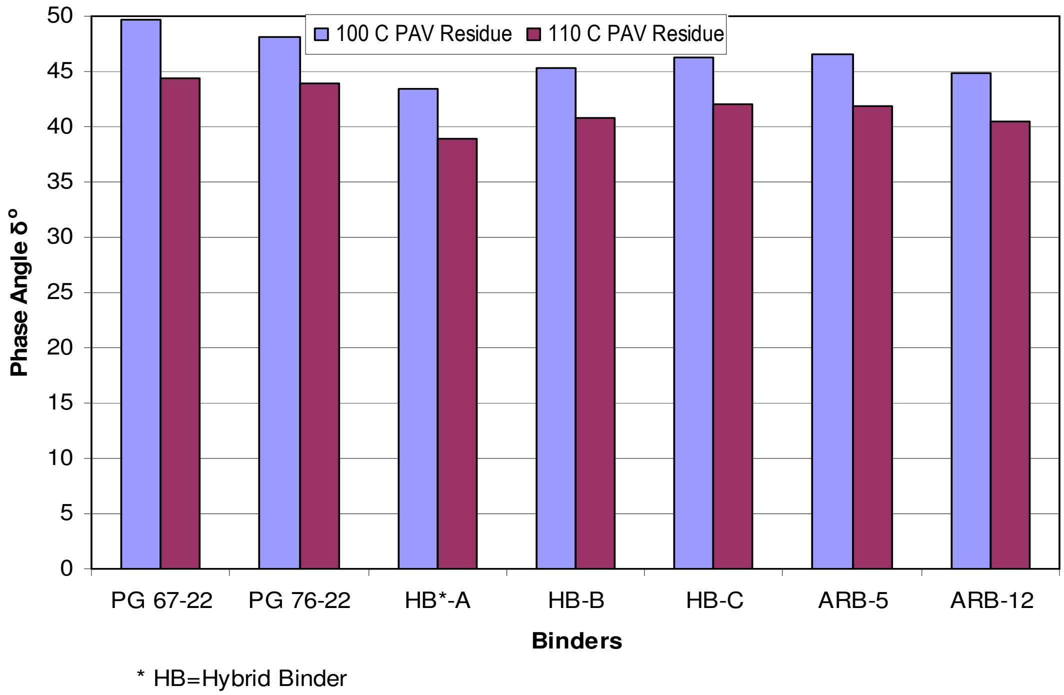


Figure 4-6 Phase Angle δ^{o} at 25 C (77 F)

Figure 4-6 shows that all modified binders result in phase angles lower than the base binder. Lower phase angles imply lower energy loss, but as with G*sinδ, the energy loss associated with lower δ is not necessarily related to damage.

4.2.3 Bending Beam Rheometer at Low Temperature

Figure 4.7 and 4.8 show that all binders, including the base binder meet specification requirement for both creep stiffness (S) and m-value at 60 seconds. Lower stiffness and higher m-value are associated with better thermal cracking resistance.

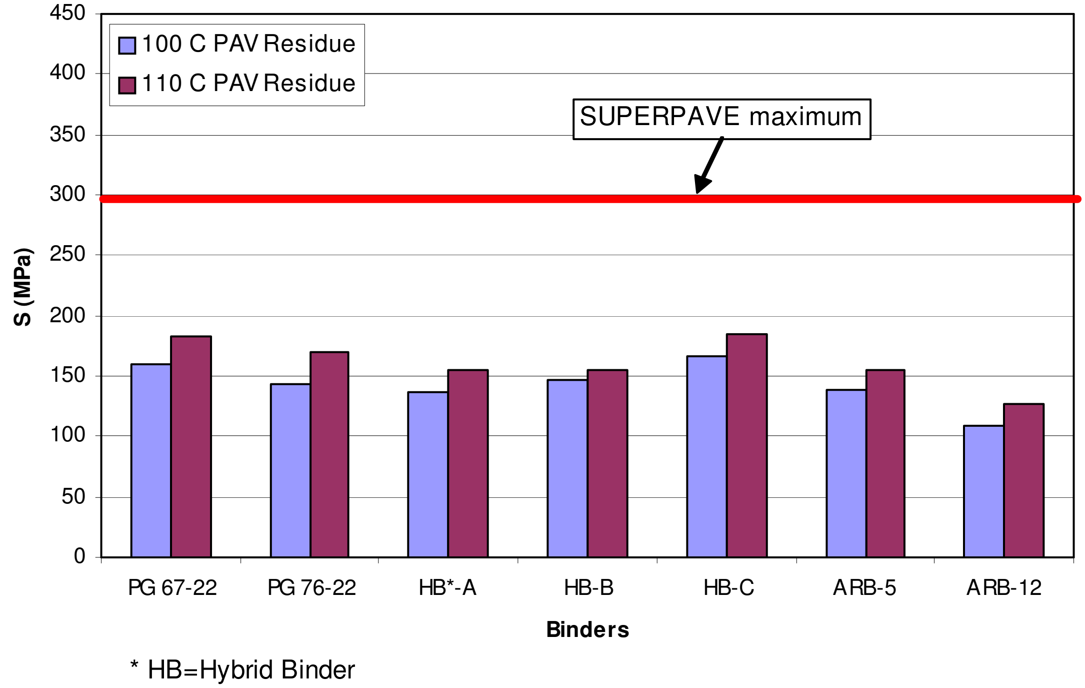


Figure 4-7 BBR, Creep Stiffness, S at -12 C (10.4 F)

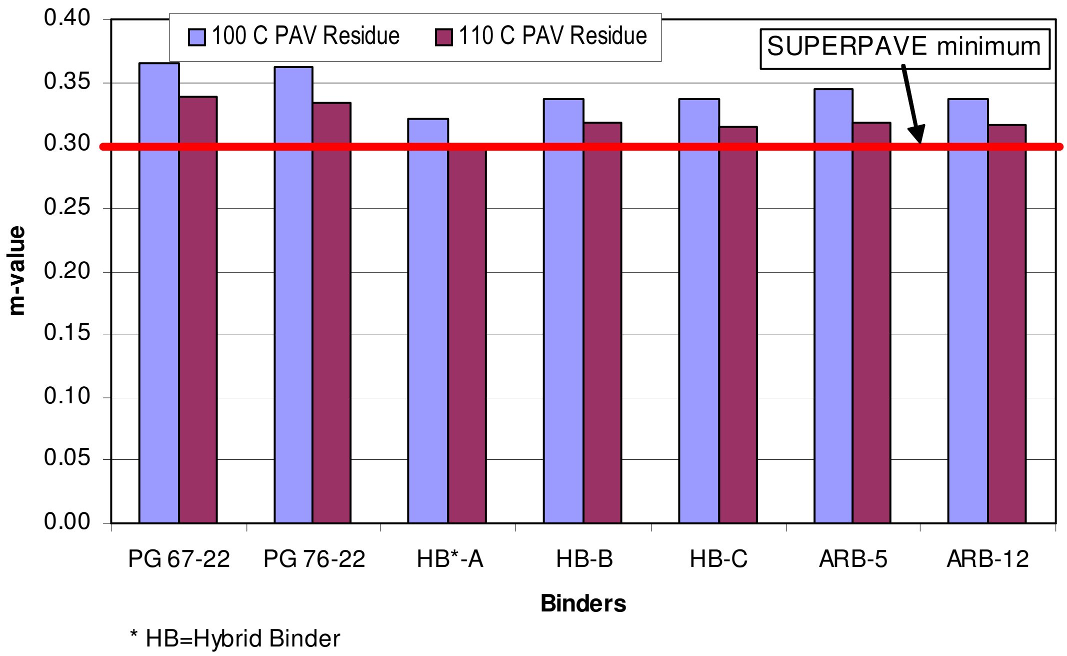


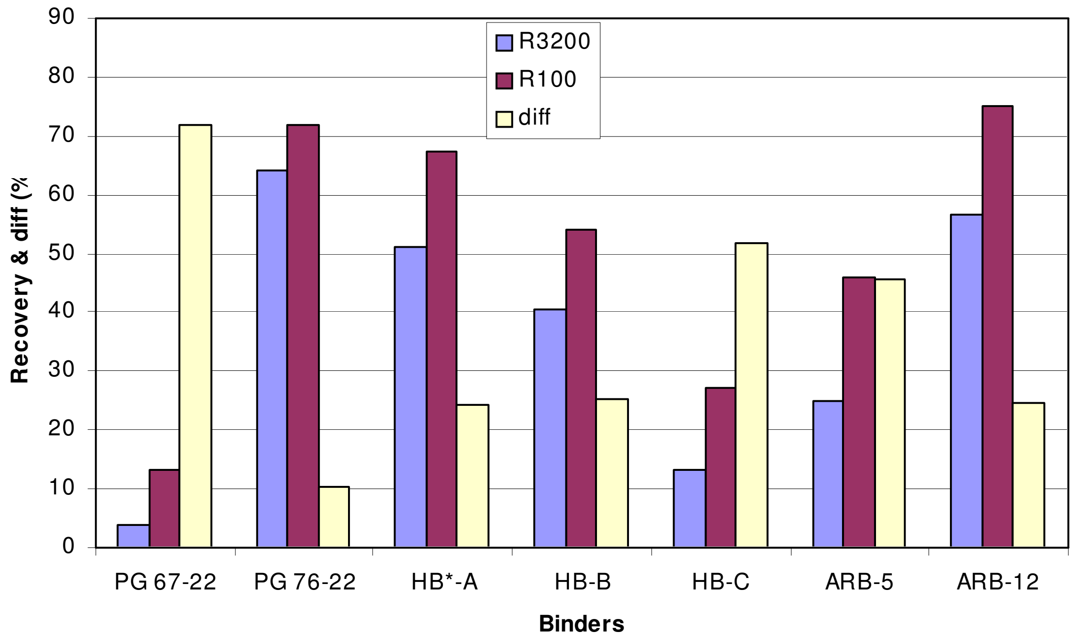
Figure 4-8 BBR, m-Value at -12 C (10.4 F)

4.3 Multiple Stress Creep Recovery (MSCR)

Figures 4-9 through 4-12 provide MSCR results in terms of percent recovery at different stress levels and percent difference in recovery between stress levels (Figures 4-9 and 4-11), and creep compliance at different stress levels and difference in creep compliance between stress levels (Figure 4-10 and 4-12) at two test temperatures 67 C (Figures 4-9 and 4-10), and 76 C (Figures 4-11 and 4-12).

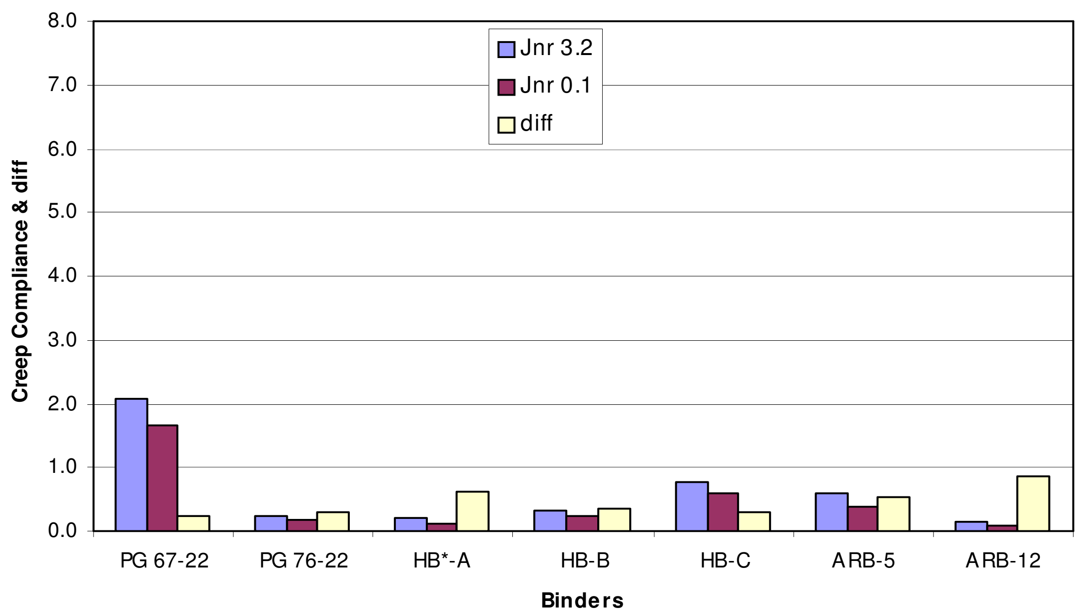
Percent recovery was greater and percent difference was less for all modified binders than for the base binder. Similar trends were observed between the binders at both test temperatures. Also, creep compliance was lower and difference in compliance was greater for all modified binders than for the base binder. However, fairly dramatic differences were observed between the modified binders, where hybrid binder C and ARB-5 binders resulted in much less change in all parameters relative to the base binder. The SBS modified binder PG 76-22 and the binders with higher coarse rubber content (hybrid binder A, hybrid binder B, ARB-12) resulted in the greatest change.

Given that this test is relatively new, it is difficult to comment on the meaning of the observed differences. Assuming the primary intent of the test is to identify the presence of polymer or polymer-like behavior, then it appears the test was relatively successful. In other words, all modified binders exhibited a difference relative to the base binder. However, the rubber modified binders, which do not include polymer (ARB-5 and ARB-12), exhibited greater difference than hybrid binder C, which does include a polymer. Once again it appears that results of this test are also strongly related the presence and concentration of coarse rubber (hybrid binder A, hybrid binder B and ARB-12) and not



* HB=Hybrid Binder

Figure 4-9 Average % Recovery at 67 C (152.6 F) (RTFOT Residue)



* HB=Hybrid Binder

Figure 4-10 Average Non-recoverable Creep Compliance at 67 C (152.6 F) (RTFOT Residue)

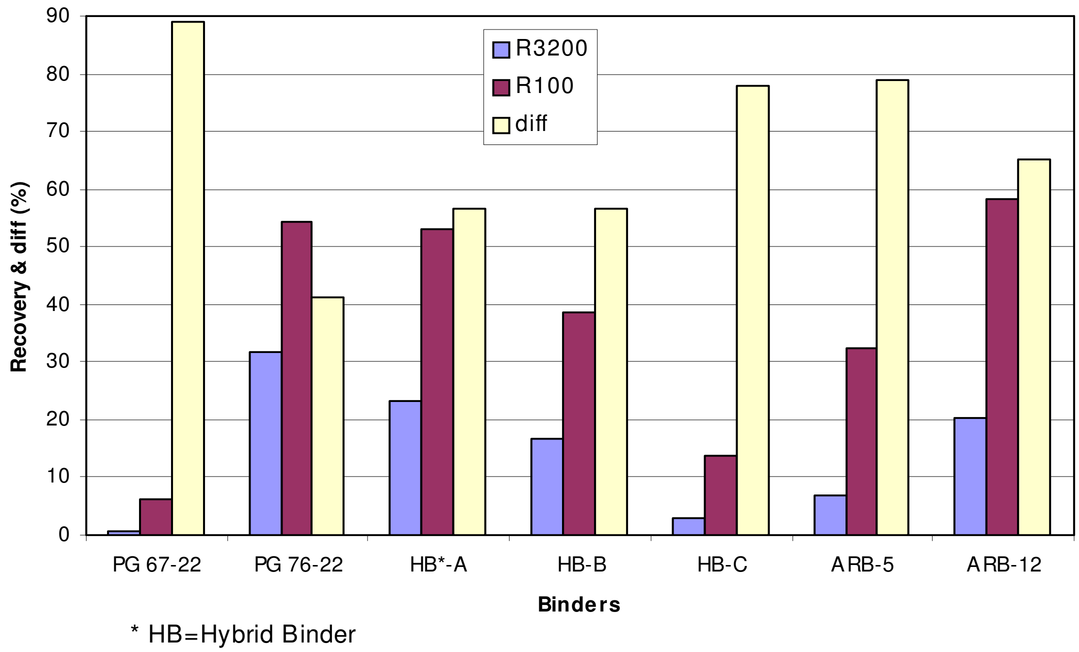


Figure 4-11 Average % Recovery at 76 C (168.8 F) (RTFOT Residue)

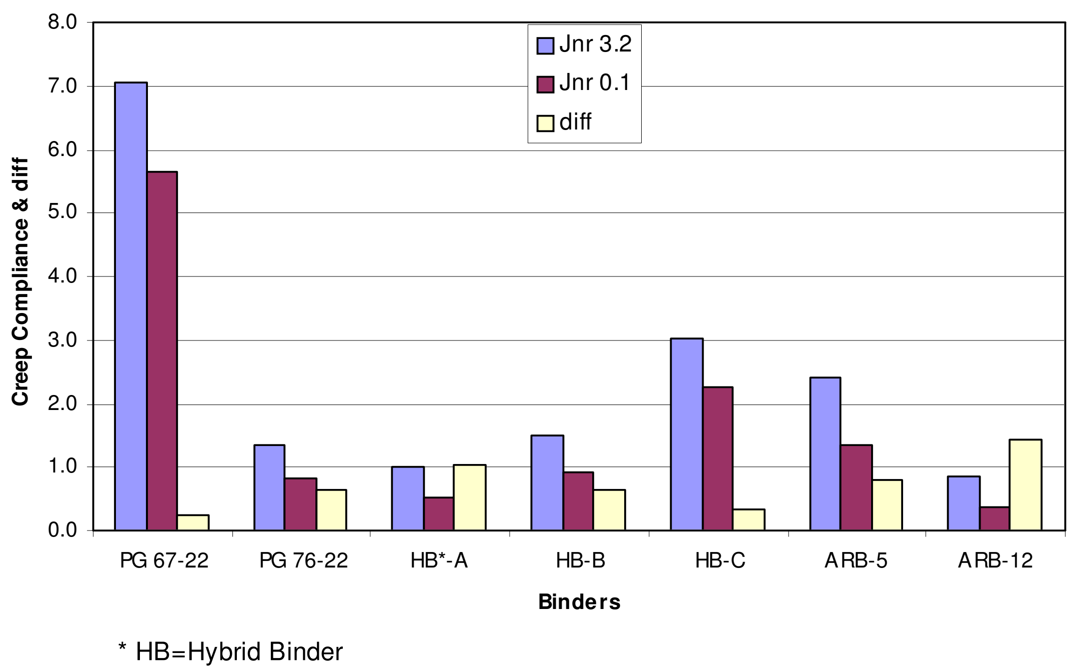


Figure 4-12 Average Non-recoverable Creep Compliance at 76 C (168.8 F) (RTFOT Residue)

just SBS polymer. As stated before, the presence of coarse rubber also made the test results suspect because MSCR tests are performed using DSR.

Parameters obtained from the MSCR test distinguished the SBS polymer modified binder, but not hybrid binder C, from the base binder. Therefore, it appears questionable whether this test is suitable in its present form to specify hybrid binder.

4.4 Elastic Recovery

Figure 4-13 illustrates that the SBS modified binder and the hybrid binders exhibited greater elastic recovery at 25 C than the base binder. Both rubber modified binders broke before the specified elongation of 20cm was reached, indicating that the rubber appears to make the binder more brittle at this temperature (obviously, elastic recovery could not be

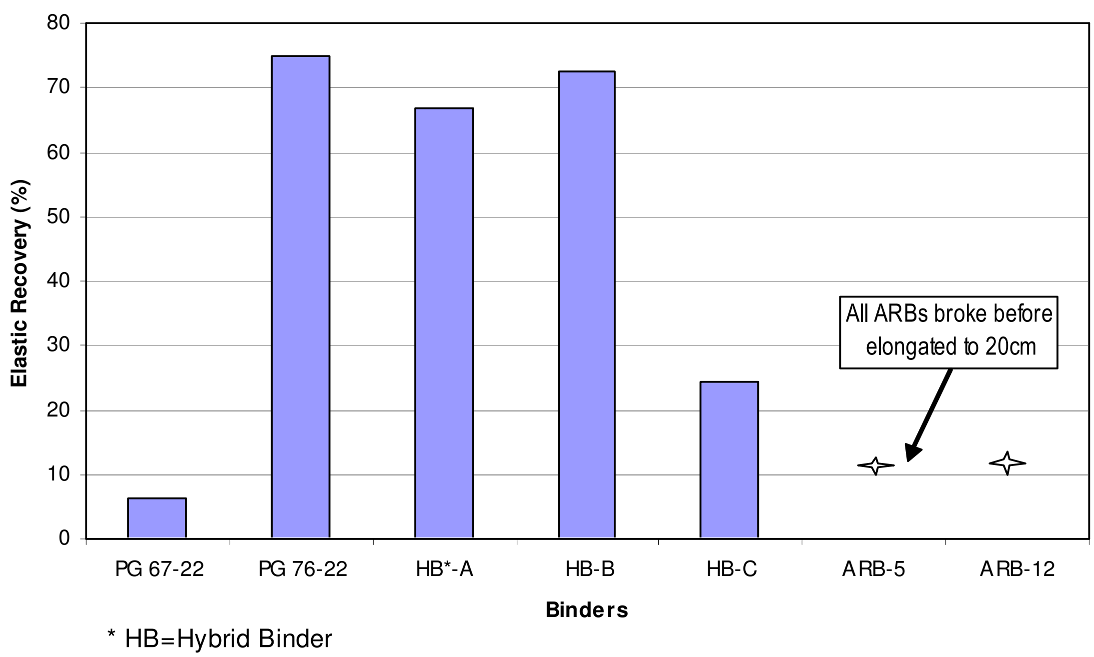


Figure 4-13 Elastic Recovery at 25 C (77 F) (RTFOT Residue)

determined for the ARBs). Also, it appears that the presence of SBS made the binder less brittle (even when combined with rubber). hybrid binder C, which used rubber with the finest gradation, did not increase the elastic recovery as much as the SBS modified binder or the other two hybrid binders.

The results obtained from Elastic Recovery distinguished the SBS polymer modified binder, but not hybrid binder C, from the base binder. Therefore, it also appears questionable whether this test is suitable in its present form to specify hybrid binder.

4.5 Force Ductility Test

4.5.1 Test Result

Figure 4-14 shows that all modified binders increased the ratio of residual to peak force (f_2 / f_1) from the Force Ductility Test relative to the base binder. The relative results are similar to observations made based on MSCR test results.

Significant differences were observed between the modified binders, where hybrid binder C and ARB-5 binders resulted in less change in f_2 / f_1 relative to the base binder (except ARB-5 in PAV condition, where f_2 / f_1 of ARB-5 is slightly greater than that of ARB-12). The SBS modified binder PG 76-22 and the binders with higher coarse rubber content (hybrid binder A, hybrid binder B, ARB-12) resulted in the greatest change (except ARB-12 in PAV condition). The rubber modified binders, which did not include polymer (ARB-5 and ARB-12), exhibited greater difference than hybrid binder C, which does include a polymer. It appears that results of this test are also strongly related to the presence and concentration of coarse rubber (hybrid binder A, hybrid binder B and ARB-12) and not just SBS polymer.

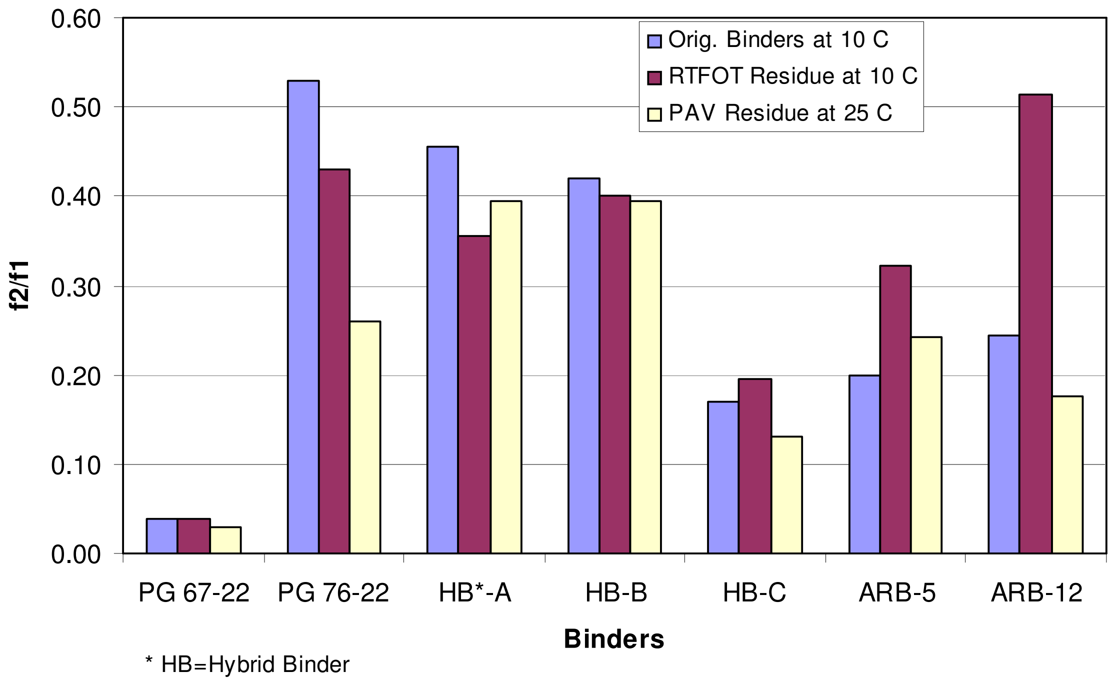


Figure 4-14 Force Ductility Test Result

4.5.2 Energy-Based Interpretation of Force Ductility Data

Although the f_2 / f_1 parameter appeared to clearly distinguish between the base binder and the modified binders, it is difficult to say whether the magnitude of the differences between the binders is related in any way to cracking or rutting performance. Also, the parameter did not clearly distinguish between binders modified with only rubber and binders that had polymers (SBS only or hybrids). As mentioned previously in this report, some studies have indicated that asphalt rubber alone does not provide as much benefit as polymer modified binders in terms of cracking resistance.

There are two major reasons why there may be significant limitations in using the f_2 / f_1 parameter to evaluate the cracking performance of binder, even on a relative basis. First, being a ratio, the parameter is independent of the magnitudes of force carried by the binder. Secondly, the strain levels at which the peak and residual forces are obtained can be significantly different for different binders, and it is sometimes difficult to determine the strain level associated with f_2.

A procedure was developed to convert Force-Deformation measurements obtained from Force Ductility Tests to Stress-Strain response. Since this test produces large strain, there is a significant change in cross-sectional area that must be considered when calculating the stress associated with a particular force. Strain may be calculated as follows:

$$\varepsilon_t = \int_{L_0}^{L} \frac{dL}{L} = \ln \frac{L}{L_0} = \ln \frac{A_0}{A}$$

Where,

L_0 — Original length of specimen

L — Length of specimen after elongation

A_0 — Original cross-sectional area of specimen

A — Cross-sectional area of specimen after elongation

As illustrated in Figure 4-15, in fact, the stress tolerance of base binder continues to decrease as strain increases, indicating the lack of a secondary structure produced by the modifiers.

The polymer modified binders (SBS and hybrid binders) exhibit a strain range where the stress tolerance remains constant after yielding, after which the stress tolerance starts to increase or recover. Hybrid binder C, which is composed of the fine rubber, exhibits a slight reduction in stress tolerance prior to recovery and its recovery begins at a higher level of strain than for the other polymer modified binders. The ARB-12 exhibits a continuous increase in stress tolerance, while the ARB-5 exhibits little or no increase after yielding. In addition, as mentioned earlier, the ARBs were more brittle than all other binders tested.

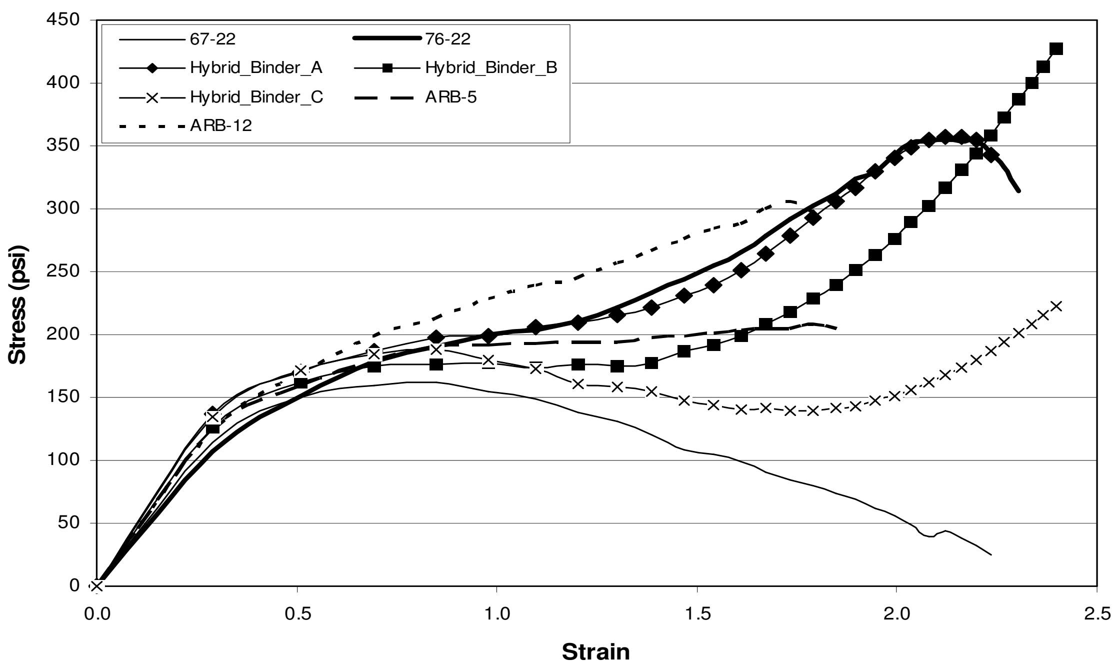


Figure 4-15 Stress-Strain Diagram of RTFOT Residue (10 C (50 F))

The fracture energy of binders can be determined as the area under the Stress-Strain curve to the instant of fracture. Since not all binders actually fractured, an alternate approach was used to determine energy for relative comparison. It was decided that the cumulative energy density to a specified strain level for all binders would provide a reasonable surrogate for fracture energy density. The strain level at which the ARB-12 binder failed was selected for this purpose, since all other binders exceeded this strain level prior to failure.

Cumulative energy density was determined at a constant strain level for each binder at the three test conditions evaluated (original binder at 10 C, RTFOT residue at 10 C, and PAV residue at 25 C). The results are presented in Figures 4-16, 4-17 and 4-18, respectively along with the peak force (f_2 / f_1) from the Force Ductility results (shown in Figure 4-14) for each of the binders at the three test conditions evaluated.

In Figure 4-16, it appears that the cumulative energy interpretation for the original binder results in similar relative ranking as the f_2 / f_1 parameter. However, similar comparisons for RTFOT residue (Figure 4-17) and PAV residue (Figure 4-18) indicate that the two approaches yield significantly different results. The f_2 / f_1 parameter indicates that hybrid binder C has the lowest f_2 / f_1 value for all aging conditions. The ARB binders exhibit higher f_2 / f_1 values than hybrid binder C at all aging conditions. Conversely, the cumulative energy approach indicates that cumulative energy of hybrid binder C increases relative to the other binders as aging progresses, and exceeds the cumulative energy of the ARB binders after PAV aging.

These results indicate that the cumulative energy approach, which accounts for both the stress and strain tolerance, will provide a different assessment of the relative performance of binders from f_2 / f_1. Whether or not the particular approach evaluated here, based on available Force Ductility data, is in fact more closely related to cracking performance is uncertain. Mixture test results and field performance studies will provide better data to make this assessment. However, the PAV results, which showed that ARB binders had lower cumulative energy than SBS modified binder, do agree with prior experience. In addition, prior experience with energy based approaches for mixtures indicates that these approaches work quite well and may be worth pursuing further for use in binders. Based on this premise, a new binder testing system specially designed to determine fracture energy density of binder was conceived and is presented later in this report.

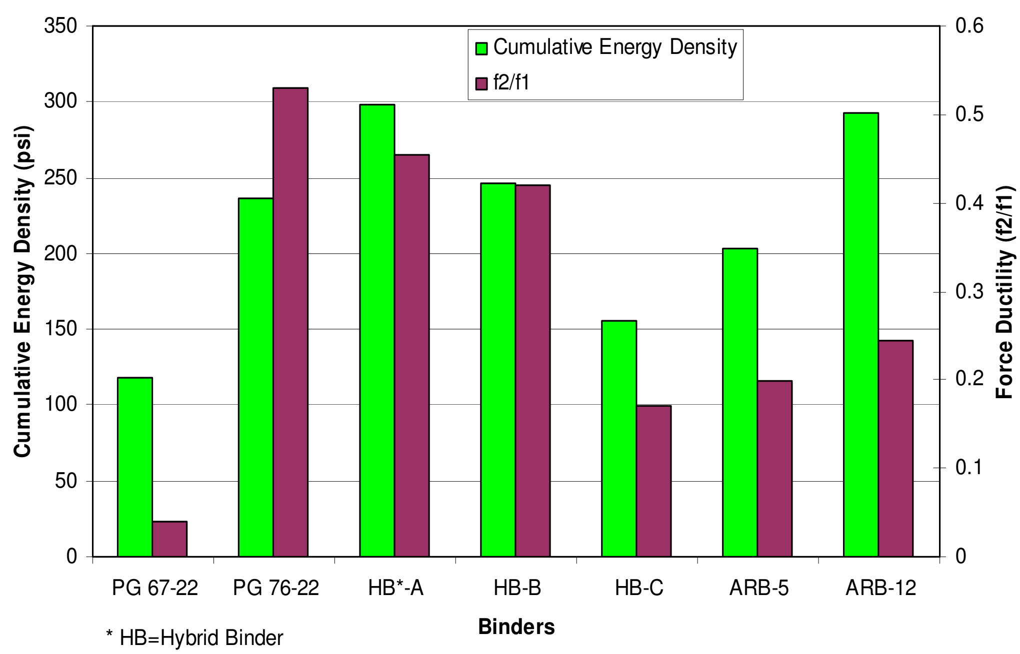


Figure 4-16 Original Binder (10 C (50 F)) Cumulative Energy Comparison to Force Ductility (f_2/f_1)

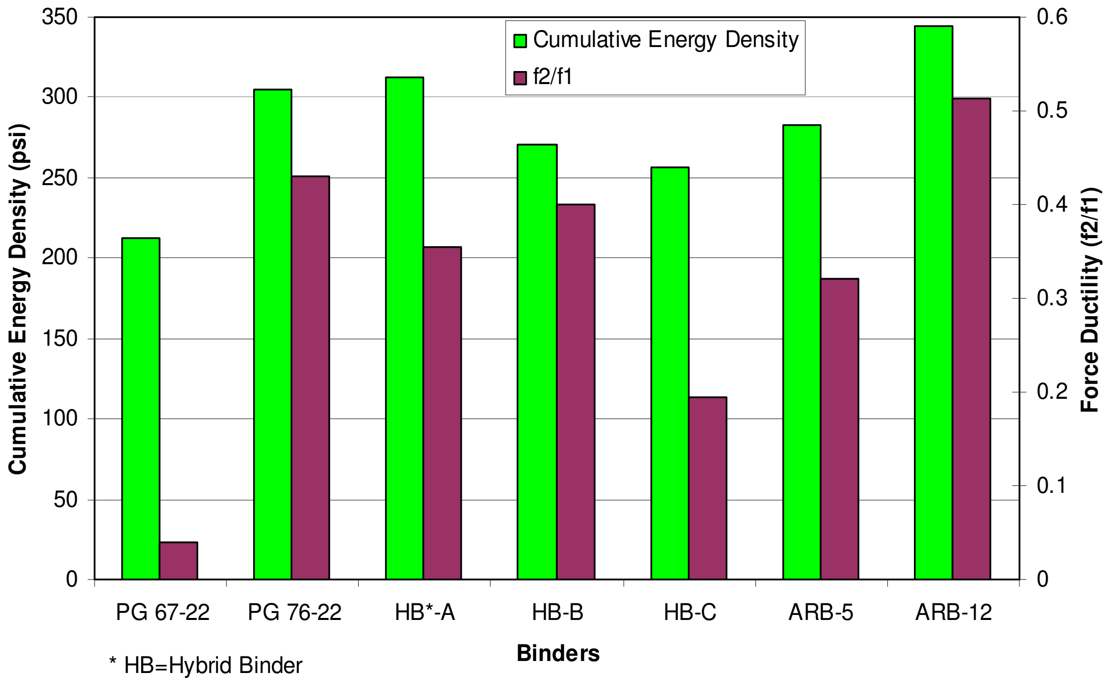


Figure 4-17 RTFOT residue 10 C (50 F) Cumulative Energy Comparison to Force Ductility (f_2 / f_1)

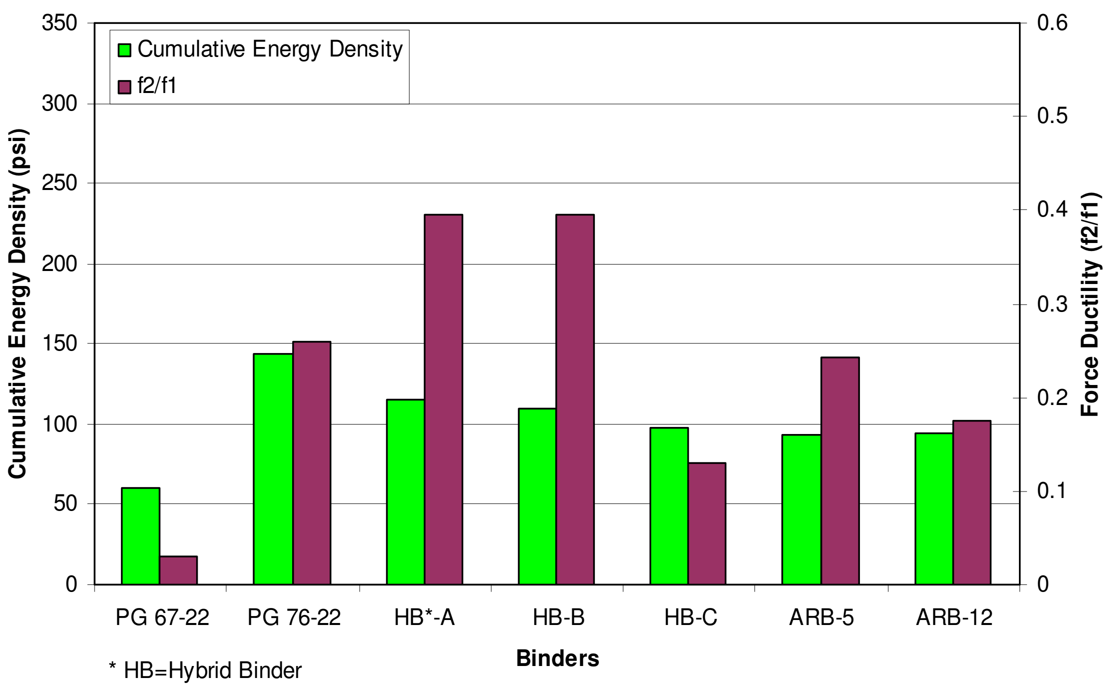


Figure 4-18 PAV residue 25 C (77 F) Cumulative Energy Comparison to Force Ductility (f_2 / f_1)

4.6 Rating of Binders

4.6.1 Rating System

A binder rating system was developed in order to compare the relative performance of binders based on different test parameters using the same scale. A normalized rating system was conceived to calculate a rating from 0 to 10 for each binder and parameter being evaluated. If the higher the parameter, the better the performance, then the rating of 10 corresponds to a value equal to or slightly greater than the highest (best) value of all binders tested. Conversely, if lower the parameter, the better the performance, then the rating of 10 corresponds to a value equal to or slightly less than the lowest (best) value of all binders tested. The corresponding rating for each binder was calculated as follows:

If higher is better:

$$Rating = \frac{Individual\ Binder\ Value}{Highest\ Value\ of\ All\ Binders\ Tested} \times 10$$

If lower is better:

$$Rating = \frac{Lowest\ Value\ of\ All\ Binders\ Tested}{Individual\ Binder\ Value} \times 10$$

Highest Value: equal or slightly greater than parameter of the highest (best) value of all binders tested.

A summary of the binder ratings for each of the binder tests and associated parameters is presented in the following section.

4.6.2 Summary of Rating

A summary of all ratings is presented in table 4-2. Comparisons of the ratings for each parameter are presented in Figures 4-19 to 4-25. Note that only the results of PAV residue were presented for the Force Ductility Tests since this was the condition where the greatest difference occurred between the f_2 / f_1 parameter and the cumulative energy approach.

Generally speaking, ratings for the modified binders were greater than for the base binder for all parameters evaluated. However, the relative rating between binders and the relative difference in rating varied significantly for the different parameters. The difference in BBR test results between binders was very small so there was no need to calculate rating based on this test. The least difference in rating between binders was observed for G*sinδ (Figure 4-19.), indicating that according to this parameter, there was relatively little difference in fatigue or fracture resistance between these binders. Also, ARB-12 had the highest rating, and the SBS modified binder's rating was only slightly greater than that of the base binder. Both observations are contrary to prior experience with cracking performance of these materials in the laboratory and in the field. As discussed earlier, the presence of coarse rubber in binder affected the DSR test and made the results questionable for hybrid binder A and B, and for the ARBs.

Figure 4.20 shows that G*/sinδ resulted in greater differences between binders than G*sin δ, indicating that significant difference in rutting performance should be expected for these binders. G*/sin δ for hybrid binder A was almost 100% greater than that of the base binder, although hybrid binder C had the lowest rating of the modified binders and only 25% greater than that of the base binder. As indicated earlier, it appears that the presence and concentration of coarse rubber affects the DSR test. The results of binders with coarse rubber obtained from DSR test are considered suspect.

The effect of coarse rubber was particularly pronounced for the non-recoverable creep compliance (Figure 4-21) from the MSCR test, where the ARB-12 had a rating that was almost nine times as high as the base binder. The next highest rating was for hybrid binder A, which also had coarse rubber, whereas hybrid binder C, which was composed of fine rubber, had the lowest rating of all modified binders. Since MSCR test also utilized the DSR, the results of coarse rubber binders were questionable.

The percent recovery from the MSCR test (Figure 4-22) appeared to be more sensitive to the presence of polymer, but was also strongly affected by the presence and concentration of coarse rubber. The SBS modified binder had the highest rating by far of all binders (over six times as high as the base binder). The binder with coarse rubber (hybrid binder A and B, ARB-12 and ARB-5) exhibited significantly lower rating, but still higher than hybrid binder C (fine rubber).

Elastic Recovery ratings (Figure 4-23) exhibited a similar trend as MSCR recovery, except results could not be obtained for the ARB binders because they fractured prior to reaching the specified length for this test. This brittle failure was the first indication that something other than recovery (MSCR or Elastic Recovery), which is probably an indicator of microdamage, may be needed to make a more reliable assessment of resistance to fracture.

Parameters obtained from MSCR and Elastic Recovery distinguished the SBS polymer modified binder, but not hybrid binder C, from the base binder. Therefore, it appears questionable whether either of these tests is suitable in their present form to specify hybrid binder.

Finally, Force Ductility results presented in Figures 4-24 and 4-25, indicate that for PAV aged binders, f_2 / f_1 was strongly influenced by the presence and concentration of coarse rubber, while the cumulative energy density was affected to a much lesser degree, if at all. The f_2 / f_1 rating presented in Figure 4-24 indicates that the coarse rubber hybrid binders A and B exhibited the highest rating, while the fine rubber hybrid binder C exhibited the lowest rating of all modified binders. It appears that the combination of coarse rubber and polymer in hybrid binders A and B had a strong influence on f_2 / f_1. However, Figure 4-25 shows that the cumulative energy ratings were very similar for all rubber modified binders. The SBS modified binder exhibited the highest rating based on cumulative energy.

In summary, it is difficult to interpret performance in some binder tests. Although the fracture energy analysis is a good approach to identify modified binders, we did not get the complete and accurate fracture energy for all binders due to some limitations of Force Ductility test. We may need other binder tests to get more accurate fracture energy limit and rate of damage.

Table 4-2 Rating for Binders

Binders	G*sinδ	G*/sinδ	MSCR, Non-recoverable Creep Compliance	MSCR, Recovery	Elastic Recovery	Force Ductility, f2/f1 (PAV residue)	Force Ductility, Cumulative Energy (PAV residue)
PG 67-22	7.3	4.9	1.3	1.6	0.8	0.8	4.0
PG 76-22	7.7	7.2	4.7	9.7	10.0	6.5	9.6
Hybrid Binder A	8.5	9.3	6.9	6.9	8.9	9.9	7.7
Hybrid Binder B	8.4	7.9	4.2	5.7	9.7	9.9	7.3
Hybrid Binder C	7.3	6.1	2.2	2.4	3.3	3.3	6.5
ARB-5	8.1	6.7	3.6	3.6	n/a	6.1	6.2
ARB-12	9.6	9.0	9.6	6.9	n/a	4.4	6.3

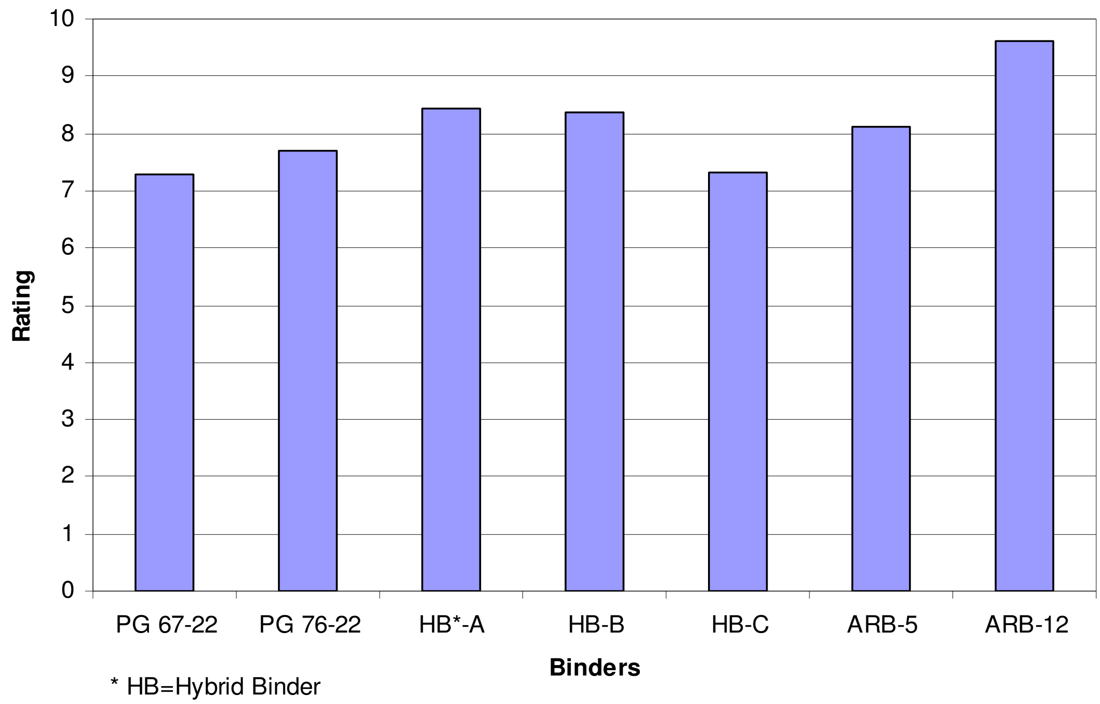


Figure 4-19 Rating Based on G*sinδ

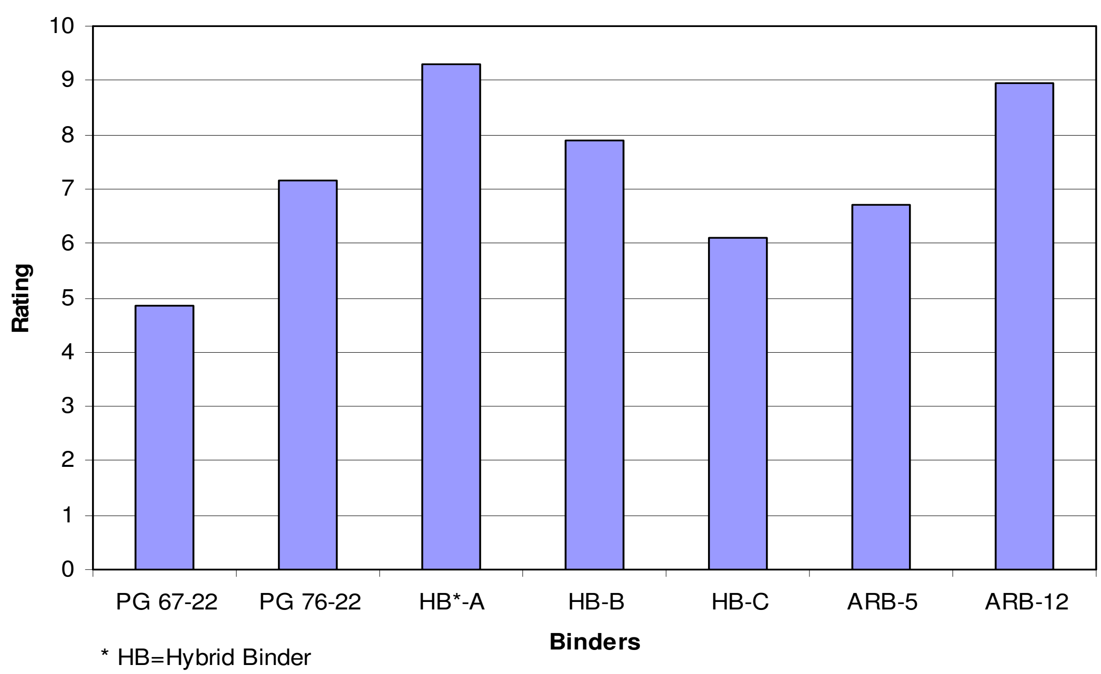


Figure 4-20 Rating Based on G*/sinδ

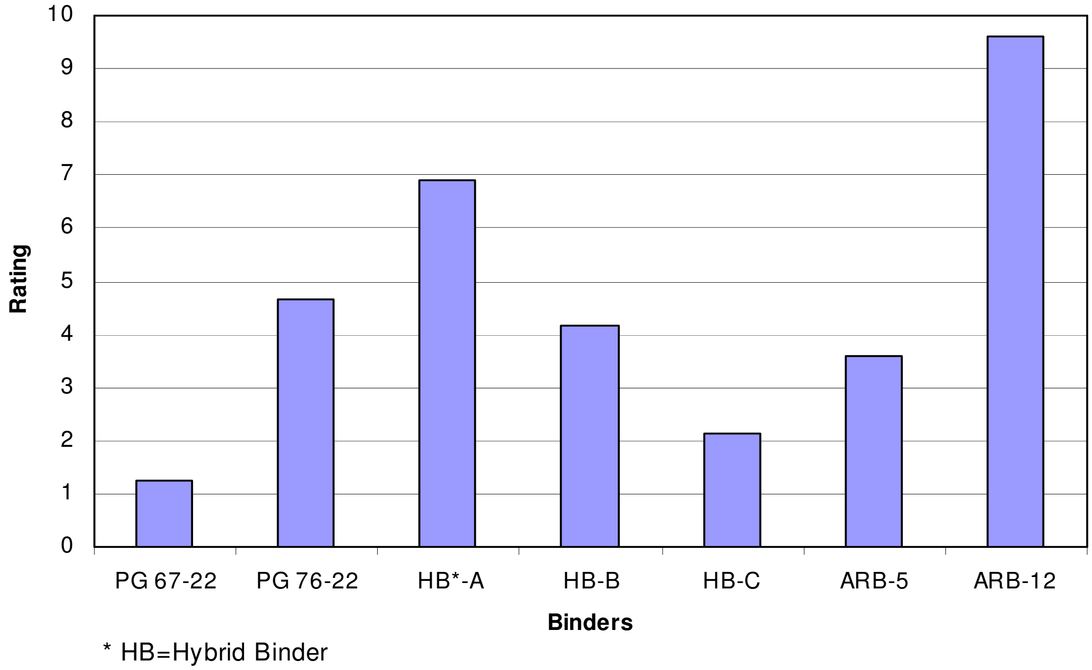


Figure 4-21 Rating Based on MSCR, Non-recoverable Creep Compliance

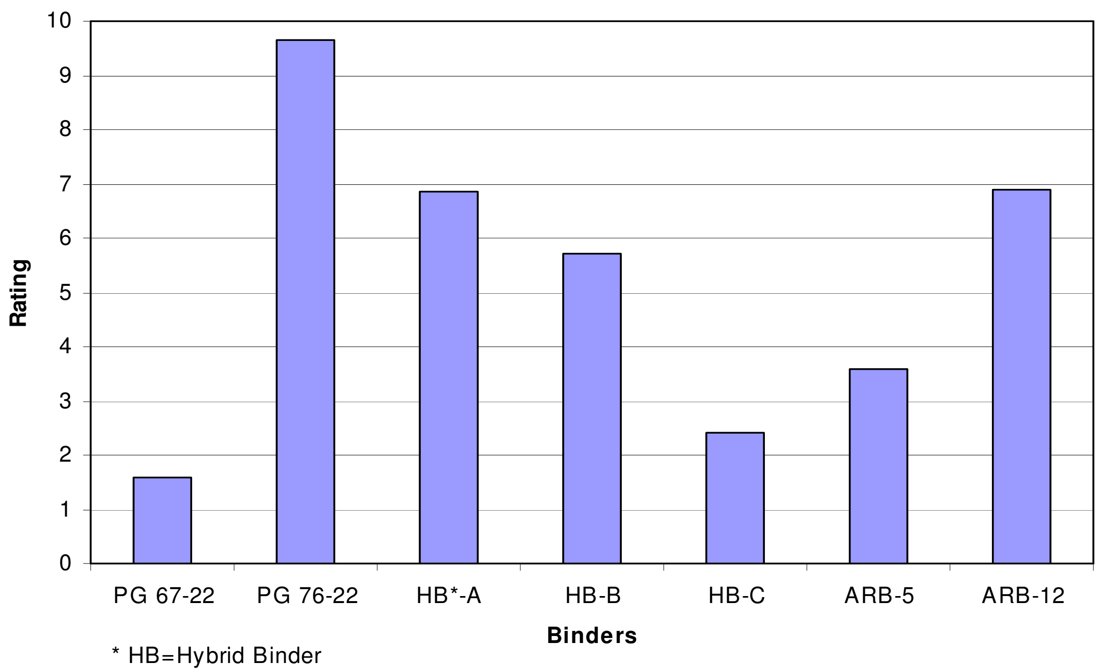


Figure 4-22 Rating Based on MSCR, Recovery

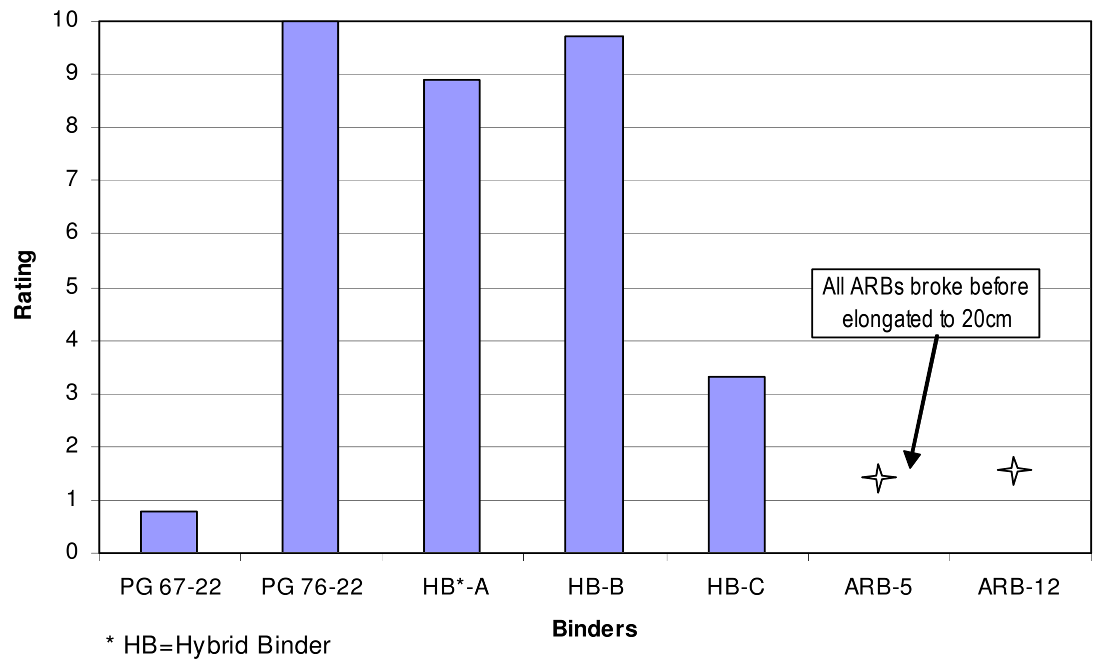


Figure 4-23 Rating Based on Elastic Recovery

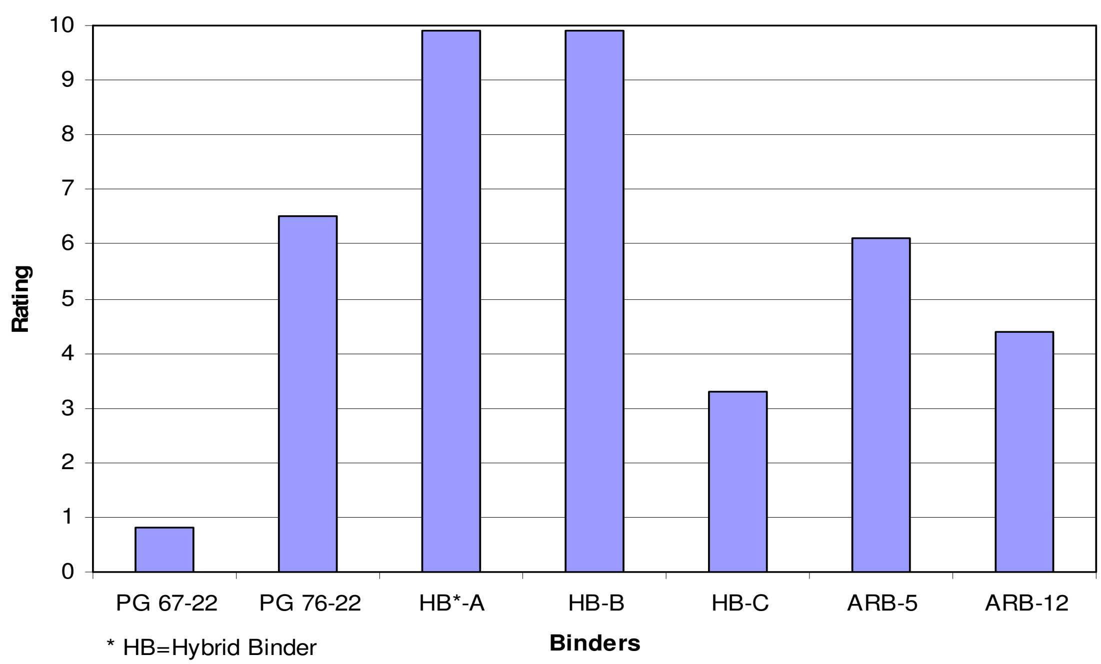


Figure 4-24 Rating Based on Force Ductility,f2/f1 (PAV residue)

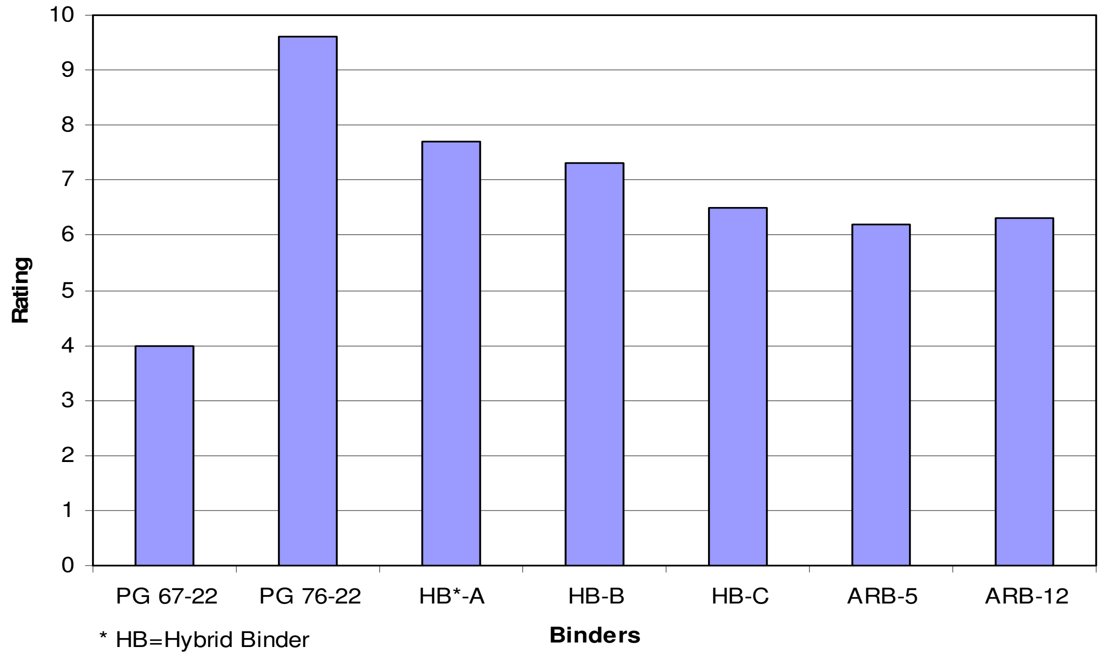


Figure 4-25 Rating Based on Force Ductility, Cumulative Energy (PAV residue)

CHAPTER 5

MIXTURE TEST RESULTS AND ANALYSIS

5.1 Mixture Test Results

In accordance with AASHTO T 322, standard Superpave Indirect Tension Test (IDT) was performed at 10°C on all mixtures to determine resilient modulus (M_r), creep compliance (m-value and D_1), tensile strength (S_t), failure strain (ε_f), fracture energy (FE) and dissipated creep strain energy (DCSE) (Roque, 1997) to failure (plots of these parameters could be found in Appendix B). Results were combined and analyzed using Hot-Mix-Asphalt (HMA) Fracture Mechanics Model (Zhang, 2001) and Energy Ratio Theories (Roque, 2004), to evaluate the mixtures' resistance to cracking.

The number of specimens and testing cycles are listed in Table 5-1. A total number of 132 IDT specimens were tested for this project. For each specific type of mixture, three specimens were tested and the variability of the specimens was considered and treated by using a trimmed mean approach.

Table 5-1 Summary of Total Tests

Mixture Type	Aggregate Type	Conditions	Types of Binders	Number of Replicates	Total No. of Mixture Tests
OGFC	Limestone	LTOA/STOA	5	3	90
	Granite	LTOA/STOA	5	3	90
Superpave Dense	Limestone	LTOA/STOA	6	3	108
	Granite	LTOA/STOA	6	3	108
Totals	4	2	7	132	396

All test results and calculated parameters are listed in Table 5-2 through Table 5-7.

Table 5-2 DG Mixtures Creep and Damage Test Results

Aggregate	Binder Type	Aging Conditions	m-value	D_1 (1/psi)	D(1000 sec) (1/GPa)	d(D)/dt(1000 sec)
Granite	PG 67-22	STOA	0.668	4.77E-07	7.055	3.20E-08
		LTOA	0.532	4.48E-07	2.619	9.43E-09
	PG 76-22	STOA	0.534	7.54E-07	4.414	1.61E-08
		LTOA	0.413	5.43E-07	1.414	3.88E-09
	Hybrid Binder A	STOA	0.446	5.93E-07	1.926	5.76E-09
		LTOA	0.411	4.35E-07	1.128	3.05E-09
	Hybrid Binder B	STOA	0.455	9.17E-07	3.110	9.64E-09
		LTOA	0.438	5.18E-07	1.584	4.66E-09
	Hybrid Binder C	STOA	0.521	7.52E-07	4.074	1.43E-08
		LTOA	0.402	6.73E-07	1.602	4.33E-09
	ARB-5	STOA	0.600	3.841E-07	3.575	1.45E-08
		LTOA	0.576	3.05E-07	2.444	9.44E-09
Limestone	PG 67-22	STOA	0.477	5.42E-07	2.176	6.99E-09
		LTOA	0.385	4.892E-07	1.062	2.69E-09
	PG 76-22	STOA	0.436	5.44E-07	1.665	4.83E-09
		LTOA	0.308	6.60E-07	0.83	1.70E-09
	Hybrid Binder A	STOA	0.376	6.24E-07	1.291	3.15E-09
		LTOA	0.327	4.12E-07	0.628	1.29E-09
	Hybrid Binder B	STOA	0.386	4.26E-07	0.948	2.38E-09
		LTOA	0.300	5.30E-07	0.652	1.27E-09
	Hybrid Binder C	STOA	0.406	5.38E-07	1.353	3.63E-09
		LTOA	0.348	3.44E-07	0.592	1.32E-09
	ARB-5	STOA	0.506	6.08E-07	3.019	1.02E-08
		LTOA	0.392	4.72E-07	1.069	2.78E-09

Table 5-3 DG Mixtures Strength and Fracture Test Results

Aggregate	Binder Type	Aging Conditions	S_t (MPa)	M_R (GPa)	e_f (micro)	$N_{initiation}$	$N_{propagation}$ (2in)	FE (kJ/m^3)	$DCSE_{HMA}$ (kJ/m^3)
Granite	PG 67-22	STOA	2.14	10.85	2566.05	1.63E+04	5.58E+03	4.2	4.0
		LTOA	2.25	11.99	1336.78	2.02E+04	6.92E+03	2.2	2.0
	PG 76-22	STOA	2.23	10.55	3326.20	3.15E+04	1.08E+04	5.5	5.3
		LTOA	2.59	11.37	1824.64	6.01E+04	2.06E+04	3.5	3.2
	Hybrid Binder A	STOA	1.90	11.55	1272.15	2.24E+04	7.68E+03	1.8	1.6
		LTOA	2.26	14.13	940.13	3.14E+04	1.07E+04	1.5	1.3
	Hybrid Binder B	STOA	1.92	10.12	2426.19	2.84E+04	9.73E+03	3.6	3.4
		LTOA	2.08	11.96	1537.91	3.51E+04	1.20E+04	2.3	2.1
	Hybrid Binder C	STOA	2.02	11.35	2285.38	2.17E+04	7.42E+03	3.5	3.3
		LTOA	2.44	13.23	1423.10	3.73E+04	1.28E+04	2.5	2.3
	ARB-5	STOA	2.12	13.26	1470.04	1.64E+04	5.62E+03	2.3	2.1
		LTOA	2.12	13.85	1100.17	1.62E+04	5.53E+03	1.6	1.4
Limestone	PG 67-22	STOA	2.17	11.88	1167.65	1.69E+04	5.80E+03	1.6	1.4
		LTOA	2.2	13.62	1066.45	1.69E+04	5.80E+03	1.5	1.3
	PG 76-22	STOA	2.41	11.36	1431.47	3.25E+04	1.11E+04	2.3	2.0
		LTOA	2.71	11.97	1294.71	7.37E+04	2.52E+04	2.5	2.2
	Hybrid Binder A	STOA	2.04	11.16	1000.95	2.57E+04	8.81E+03	1.4	1.2
		LTOA	2.02	12.00	707.20	3.38E+04	1.16E+04	0.9	0.7
	Hybrid Binder B	STOA	2.40	11.87	1116.24	4.49E+04	1.54E+04	1.8	1.6
		LTOA	2.33	11.94	864.94	4.76E+04	1.63E+04	1.3	1.1
	Hybrid Binder C	STOA	2.32	12.56	1116.28	3.14E+04	1.07E+04	1.8	1.6
		LTOA	2.62	12.88	962.87	6.80E+04	2.33E+04	1.7	1.4
	ARB-5	STOA	1.9	10.81	1185.45	1.18E+04	4.05E+03	1.5	1.3
		LTOA	2.38	13.53	999.93	3.48E+04	1.19E+04	1.6	1.4

Table 5-4 DG Mixtures Energy Ratio Results

Aggregate	Binder Type	Aging Conditions	$DCSE_{MIN}$ (kJ/m^3)	ER@ stress 150 psi
Granite	PG 67-22	STOA	2.971	1.34
		LTOA	1.440	1.38
	PG 76-22	STOA	2.440	2.16
		LTOA	0.852	3.76
	Hybrid Binder A	STOA	1.081	1.52
		LTOA	0.646	2.04
	Hybrid Binder B	STOA	1.773	1.93
		LTOA	0.910	2.33
	Hybrid Binder C	STOA	2.206	1.51
		LTOA	0.956	2.38
	ARB-5	STOA	1.738	1.23
		LTOA	1.226	1.17
Limestone	PG 67-22	STOA	1.247	1.12
		LTOA	0.595	2.22
	PG 76-22	STOA	0.984	2.08
		LTOA	0.438	5.01
	Hybrid Binder A	STOA	0.695	1.75
		LTOA	0.302	2.42
	Hybrid Binder B	STOA	0.537	2.90
		LTOA	0.312	3.43
	Hybrid Binder C	STOA	0.781	2.03
		LTOA	0.325	4.41
	ARB-5	STOA	1.617	0.82
		LTOA	0.619	2.25

Table 5-5 OGFC Mixtures Creep and Damage Test Results

Aggregate	Binder Type	Aging Conditions	m-value	D_1 (1/psi)	D(1000 sec) (1/Gpa)	d(D)/dt(1000 sec)
Granite	PG 76-22	STOA	0.599	1.49E-06	13.601	5.59E-08
		LTOA	0.577	8.68E-07	6.851	2.70E-08
	Hybrid Binder A	STOA	0.487	1.15E-06	4.929	1.63E-08
		LTOA	0.459	6.88E-07	2.496	7.52E-09
	Hybrid Binder B	STOA	0.478	1.64E-06	6.491	2.13E-08
		LTOA	0.439	1.65E-06	5.035	1.50E-08
	Hybrid Binder C	STOA	0.537	1.31E-06	7.932	2.87E-08
		LTOA	0.570	6.29E-07	4.804	1.84E-08
	ARB-12	STOA	0.557	8.38E-07	5.828	2.19E-08
		LTOA	0.555	7.47E-07	5.118	1.91E-08
Limestone	PG 76-22	STOA	0.434	8.83E-07	2.657	7.65E-09
		LTOA	0.365	9.02E-07	1.741	4.11E-09
	Hybrid Binder A	STOA	0.458	6.35E-07	2.254	6.86E-09
		LTOA	0.366	5.12E-07	0.994	2.36E-09
	Hybrid Binder B	STOA	0.451	9.50E-07	3.199	9.62E-09
		LTOA	0.416	4.89E-07	1.310	3.61E-09
	Hybrid Binder C	STOA	0.521	6.53E-07	3.522	1.24E-08
		LTOA	0.408	9.95E-07	2.484	6.80E-09
	ARB-12	STOA	0.533	5.87E-07	3.500	1.25E-08
		LTOA	0.427	6.26E-07	1.824	5.13E-09

Table 5-6 OGFC Mixtures Strength and Fracture Test Results

Aggregate	Binder Type	Aging Conditions	S_t (MPa)	M_R (GPa)	e_f (micro)	$N_{initiation}$	$N_{propagation}$ (2in)	FE (kJ/m^3)	$DCSE_{HMA}$ (kJ/m^3)
Granite	PG 76-22	STOA	1.61	5.29	3601.16	2.14E+04	7.33E+03	4.5	4.3
		LTOA	1.44	6.46	1454.68	1.39E+04	4.77E+03	1.5	1.3
	Hybrid Binder A	STOA	1.35	6.13	1538.19	2.51E+04	8.58E+03	1.6	1.5
		LTOA	1.38	8.92	674.36	1.84E+04	6.31E+03	0.6	0.5
	Hybrid Binder B	STOA	1.33	5.47	1966.58	2.43E+04	8.33E+03	2.0	1.8
		LTOA	1.54	4.92	2638.98	5.35E+04	1.83E+04	3.1	2.9
	Hybrid Binder C	STOA	1.07	5.81	1018.97	5.91E+03	2.02E+03	0.7	0.6
		LTOA	1.43	6.59	1136.02	1.60E+04	5.46E+03	1.2	1.0
	ARB-12	STOA	1.17	6.93	1499.10	1.54E+04	5.28E+03	1.3	1.2
		LTOA	1.27	7.29	1215.67	1.46E+04	4.98E+03	1.1	1.0
Limestone	PG 76-22	STOA	1.58	7.83	1107.59	3.83E+04	1.31E+04	1.2	1.0
		LTOA	1.50	8.53	732.86	3.89E+04	1.33E+04	0.7	0.6
	Hybrid Binder A	STOA	1.59	7.42	1175.16	5.04E+04	1.73E+04	1.4	1.2
		LTOA	1.82	9.71	916.91	1.11E+05	3.80E+04	1.1	0.9
	Hybrid Binder B	STOA	1.64	7.28	1211.57	3.55E+04	1.22E+04	1.4	1.2
		LTOA	1.77	8.23	1220.33	1.02E+05	3.49E+04	1.5	1.3
	Hybrid Binder C	STOA	1.56	7.99	1073.92	2.15E+04	7.34E+03	1.1	0.9
		LTOA	1.62	7.03	975.14	3.78E+04	1.29E+04	1.1	0.9
	ARB-12	STOA	1.45	9.10	1058.80	2.45E+04	8.38E+03	1.2	1.1
		LTOA	1.57	10.16	1013.60	5.37E+04	1.84E+04	1.1	1.0

Table 5-7 OGFC Mixtures Energy Ratio Results

Aggregate	Binder Type	Aging Conditions	$DCSE_{MIN}$ (kJ/m^3)	ER @ stress 150 psi
Granite	PG 76-22	STOA	6.326	0.7
		LTOA	3.246	0.41
	Hybrid Binder A	STOA	2.578	0.56
		LTOA	1.290	0.38
	Hybrid Binder B	STOA	3.449	0.53
		LTOA	2.758	1.04
	Hybrid Binder C	STOA	3.793	0.16
		LTOA	2.265	0.46
	ARB-12	STOA	2.740	0.44
		LTOA	2.436	0.41
Limestone	PG 76-22	STOA	1.427	0.73
		LTOA	0.868	0.65
	Hybrid Binder A	STOA	1.208	1.02
		LTOA	0.515	1.80
	Hybrid Binder B	STOA	1.735	0.70
		LTOA	0.715	1.83
	Hybrid Binder C	STOA	1.821	0.52
		LTOA	1.348	0.68
	ARB-12	STOA	1.735	0.62
		LTOA	0.969	1.01

5.2 Analysis of IDT Test Results

Since currently there is no single mixture property or characteristic that can reliably predict top-down cracking performance of HMA (Roque, 2004), a number of mixture parameters obtained from the IDT were evaluated by using HMA fracture mechanics and DCSE theory to determine the mixtures' potential to cracking. In addition, some observations regarding mixture preparation were cited as they helped to explain some of the findings. Since the relative cracking performance was different in the two types of mixtures evaluated, the analysis was categorized into two parts: dense-graded (DG) mixtures and open-graded friction course (OGFC) mixtures.

5.2.1 DG Mixtures

The number of loading cycles for crack initiation ($N_{initiation}$) and to 50-mm of propagation ($N_{propagation}$) were calculated from Dissipated Creep Strain Energy to failure ($DCSE_f$) and the DCSE/cycle concepts based on resilient modulus, creep test and tensile strength test results (Appendix B and C). Energy Ratio, defined as the dissipated creep strain energy threshold of the mixture divided by the minimum dissipated creep strain energy required, is a criterion recently developed by Roque et al.(2004) to evaluate top-down cracking performance of mixtures. These three parameters: $N_{initiation}$, $N_{propagation}$ and ER were used as the principal basis to evaluate the mixtures cracking performance in this research.

Figures 5-1 through 5-6 show that hybrid binder mixtures generally performed better than both PG 67-22 and ARB-5 mixtures regardless of aggregate types and aging

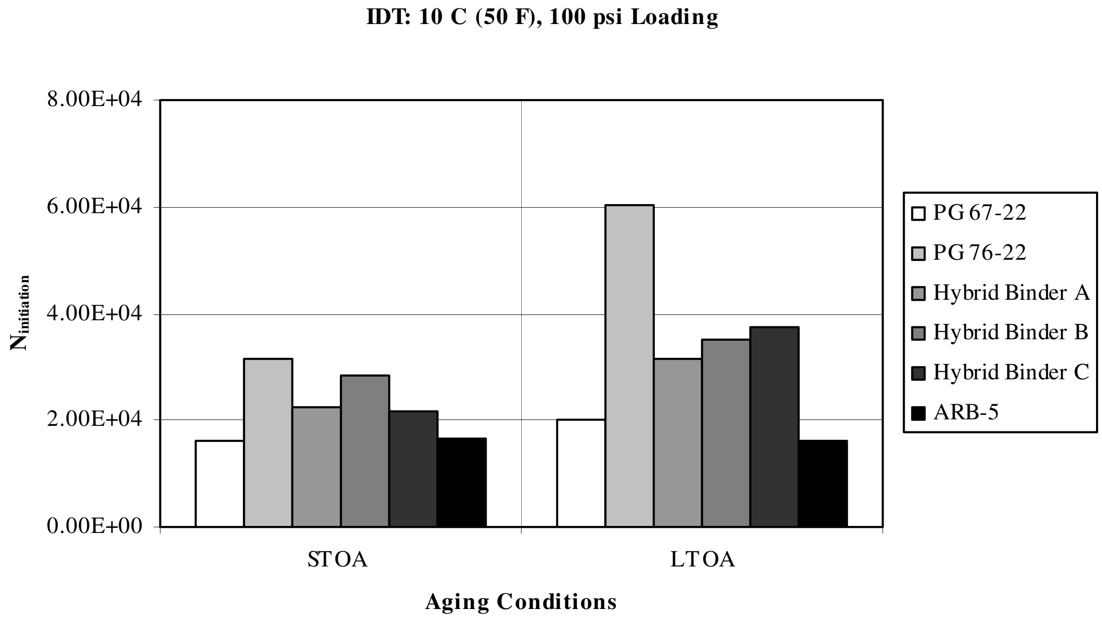


Figure 5-1 $N_{initiation}$ for DG Granite Mixtures

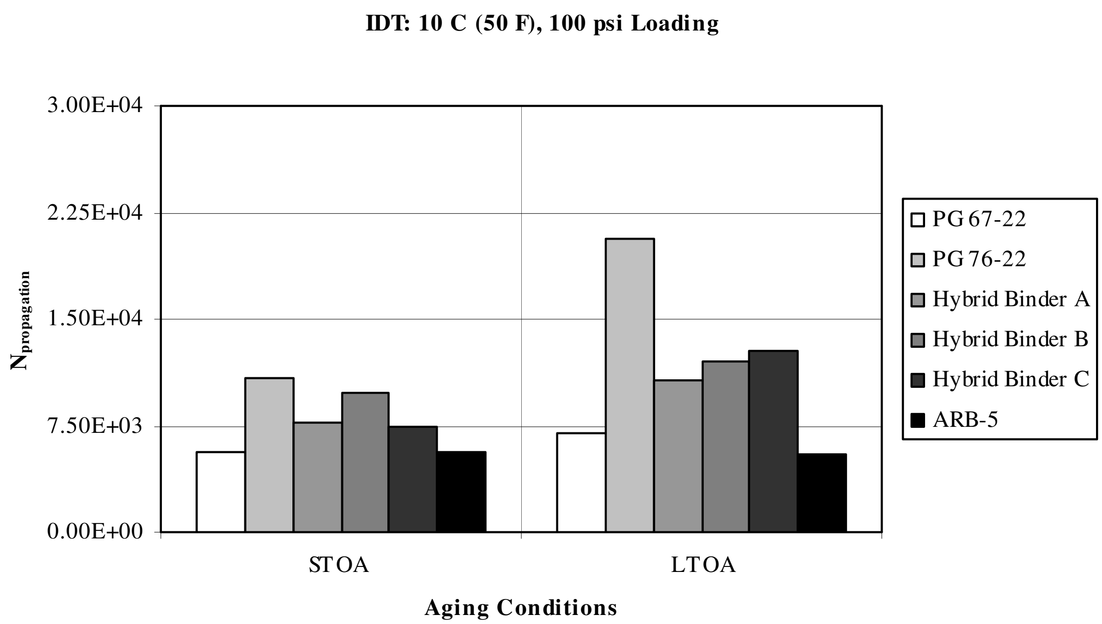


Figure 5-2 $N_{propagation}$ for DG Granite Mixtures

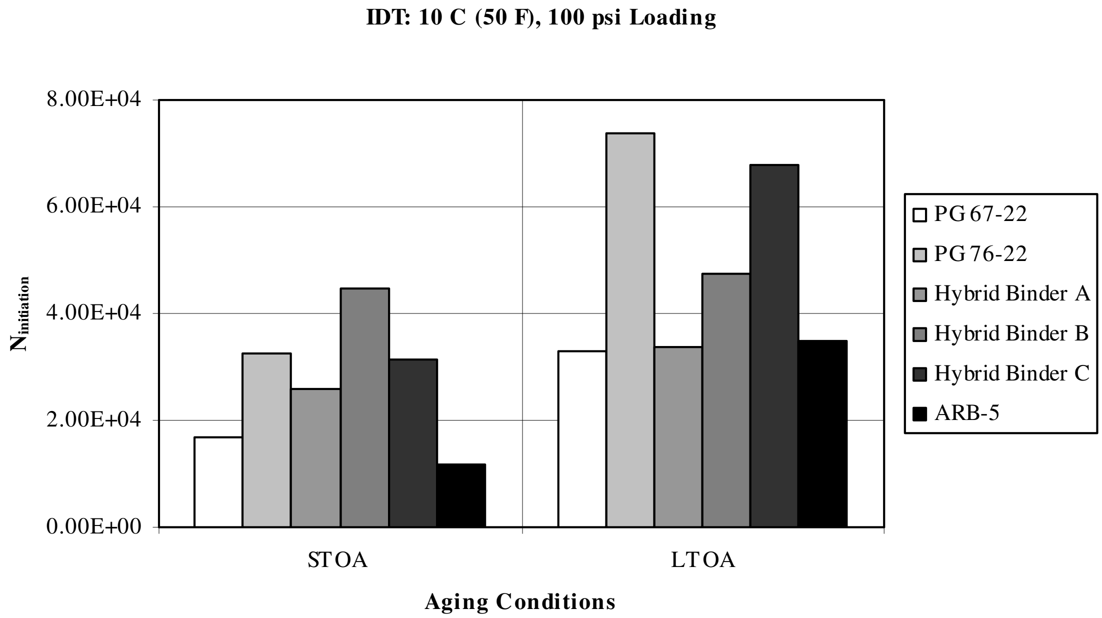


Figure 5-3 $N_{initiation}$ for DG Limestone Mixtures

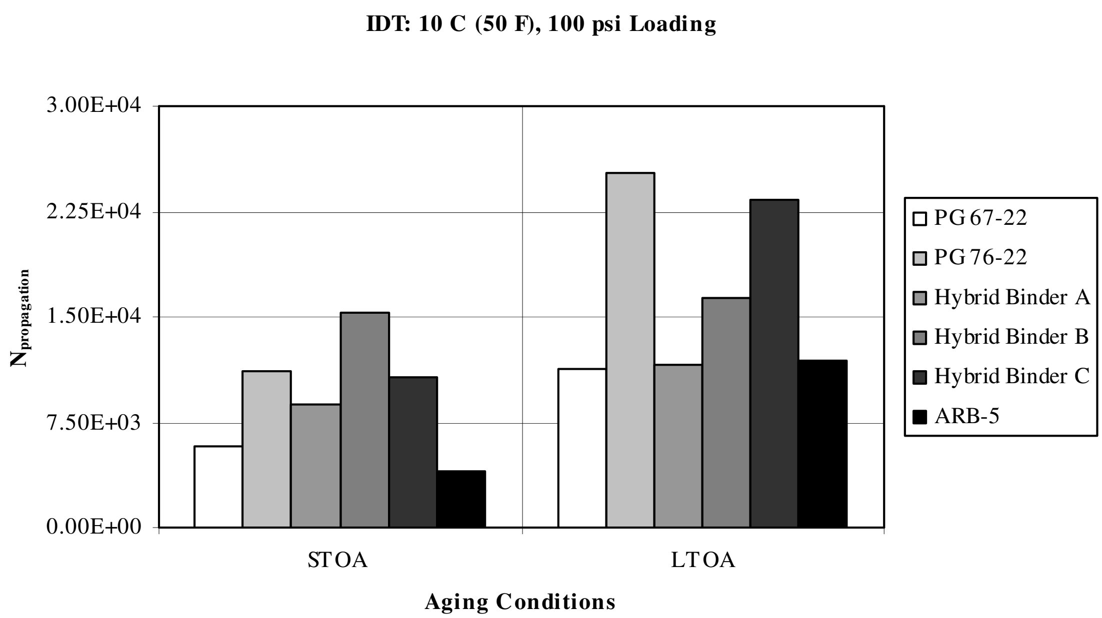


Figure 5-4 $N_{propagation}$ for DG Limestone Mixtures

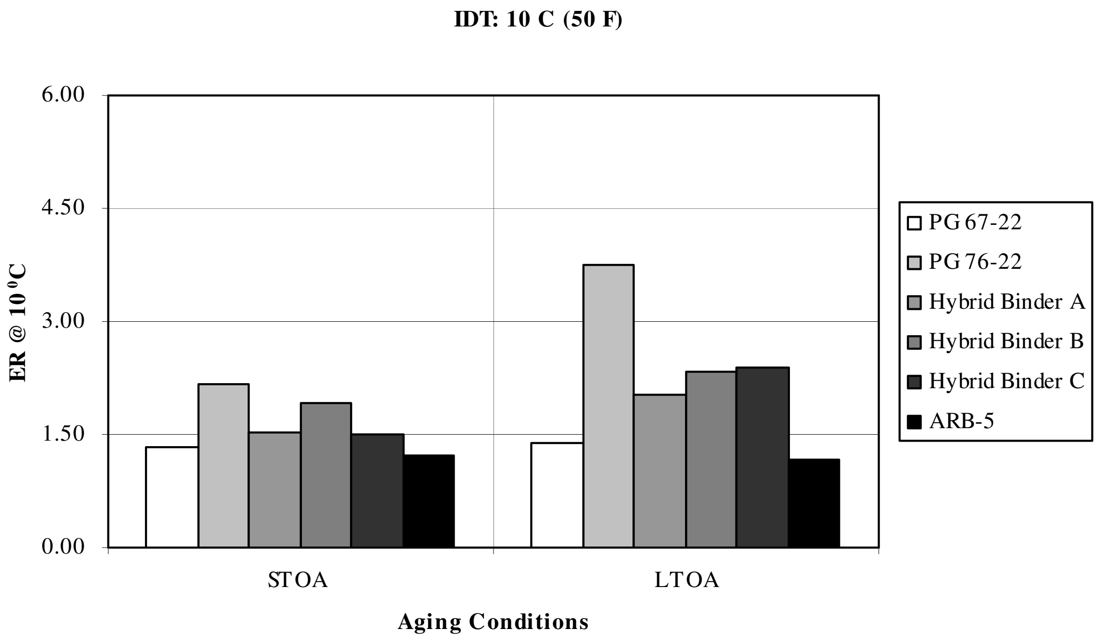


Figure 5-5 ER for DG Granite Mixtures

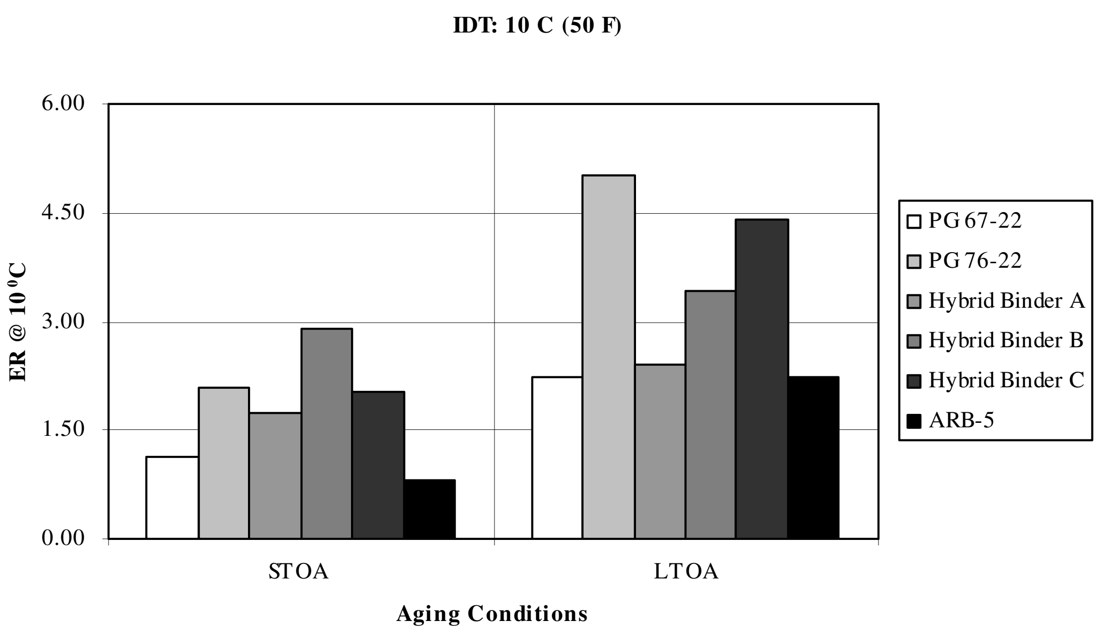


Figure 5-6 ER for DG Limestone Mixtures

conditions. These figures also show that SBS polymer modified binder mixtures exhibited superior performance among all mixtures regardless of aggregate type or aging condition.

If considered by STOA and LTOA separately, all three hybrid binders were found exhibiting similar cracking resistance trends for both granite and limestone mixtures. However, if compared for the same mixtures with different aging conditions, different cracking performance trends were observed: the LTOA apparently increased the cracking resistance of hybrid binder mixtures. A larger increase in cracking resistance was observed for limestone mixtures, which could be explained by the fact that limestone has a much rougher surface texture and greater absorption than granite. Therefore, it is hypothesized that laboratory aging at 85℃ (LTOA) results in more binder being absorbed by the limestone, which in these mixtures appeared to increase resistance to damage with little or no reduction in fracture energy limit.

The ARB-5 mixtures did not exhibit improvements in cracking resistance to the PG 67-22 mixtures. This result is consistent with previous research which indicated that rubber alone did not improve cracking resistance of mixtures.

As for the other mixtures, aging effects were found to be particularly acute in the limestone mixtures. Once again it is hypothesized that these effects may be somewhat artificially caused by increased absorption in these aggregates during LTOA.

5.2.2 OGFC Mixtures

Although the relative performance of hybrid binders in OGFC mixtures was somewhat different from that observed in DG mixtures, Figures 5.7 through 5.12 show that hybrid binders exhibited similar or better cracking resistance than both SBS polymer modified binder and ARB-12 in OGFC mixtures, except for one special case (hybrid binder C, STOA in granite mixture). This result was true for all parameters evaluated ($N_{initiation}$, $N_{propagation}$ and ER) for both aggregate types and aging levels. Hybrid binders A and B resulted in OGFC mixtures with particularly high resistance to cracking, especially for the LTOA condition and limestone aggregate. These effects are likely responsible: the coarse rubber binders may be more resistant to age-hardening and the limestone aggregate absorbs more asphalt during LTOA, therefore making the mixture more resistant to damage (lower creep rate, Appendix E). It is interesting to note that the hybrid binders exhibited greater cracking resistance than ARB-12, indicating that the addition of SBS polymer provided an added benefit.

The relatively low fracture resistance exhibited by hybrid binder C with the fine rubber, and granite aggregate was probably a result of binder redistribution (partial draindown), rather than the quality of the binder itself. The smoother texture and lower absorption of the granite, combined with the lower viscosity of the finer rubber binder provide an explanation for this phenomenon. These factors may have contributed to the binder's inability to maintain a uniform distribution within the granite OGFC, therefore creating areas of relative weakness within the mixture. This effect was minimized or eliminated where the rougher, more absorptive limestone aggregate was used.

In summary, it appears that the hybrid binders evaluated in this study can be used as a substitute for either SBS modified (PG 76-22) or ARB-12 in OGFC mixtures. However, there may be a need to check on draindown potential of hybrid binder produced with finer rubber when used in smooth textured, non-absorptive aggregate OGFC mixtures.

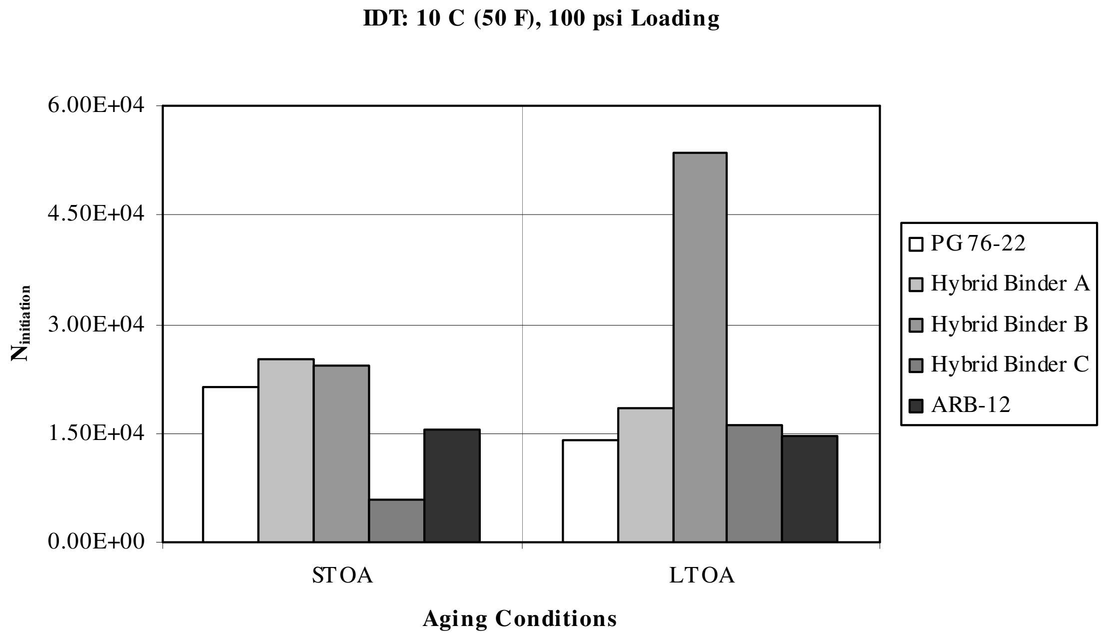


Figure 5-7 $N_{initiation}$ for OGFC Granite Mixtures

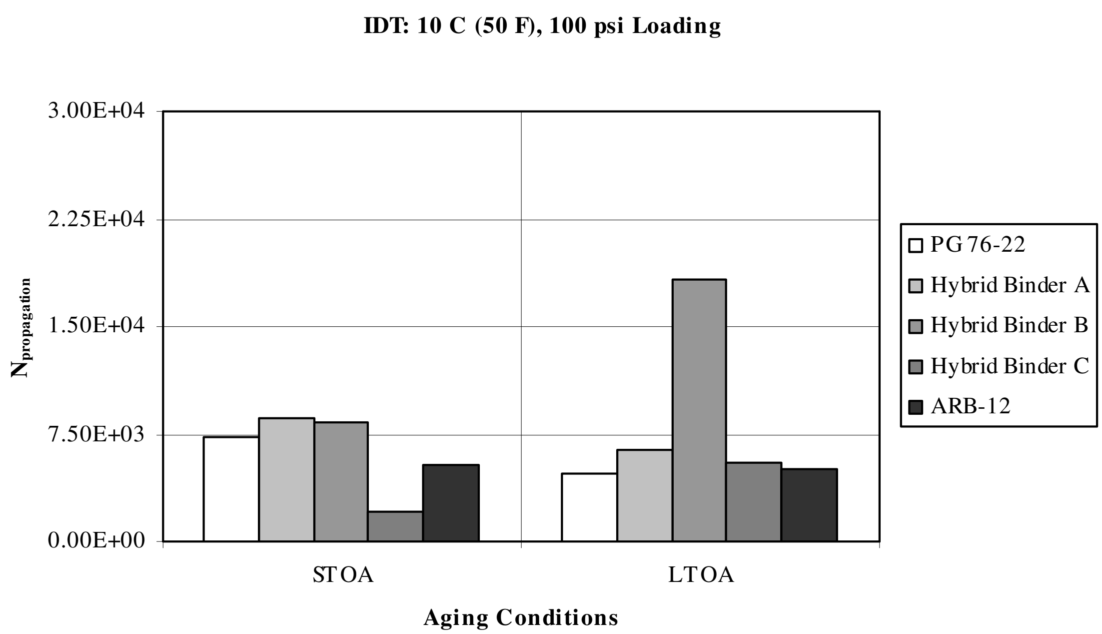


Figure 5-8 $N_{propagation}$ for OGFC Granite Mixtures

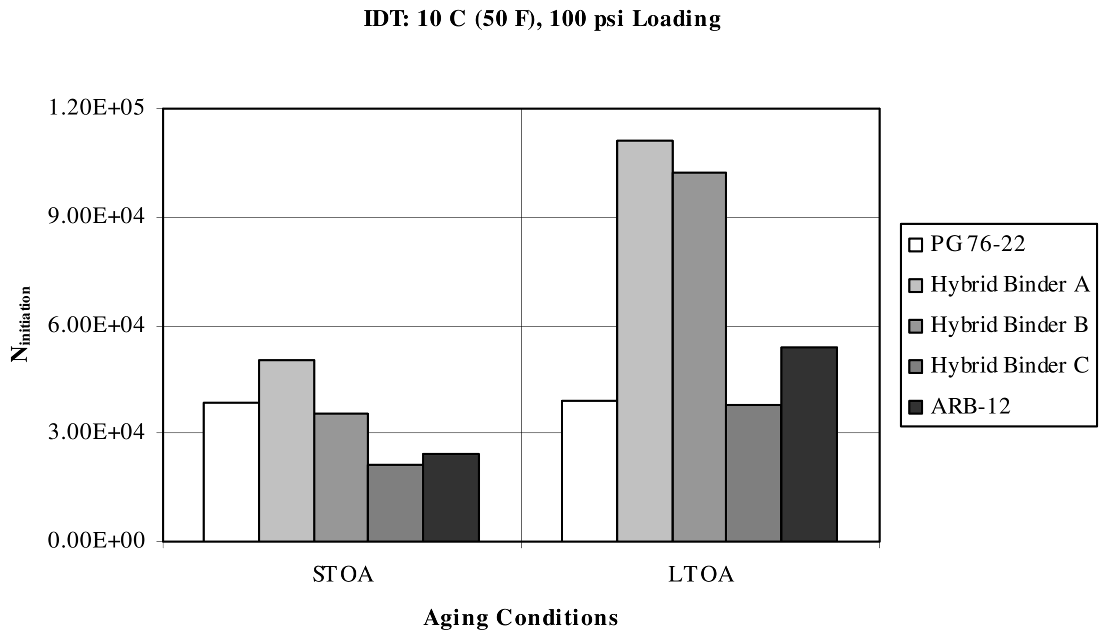


Figure 5-9 $N_{initiation}$ for OGFC Limestone Mixtures

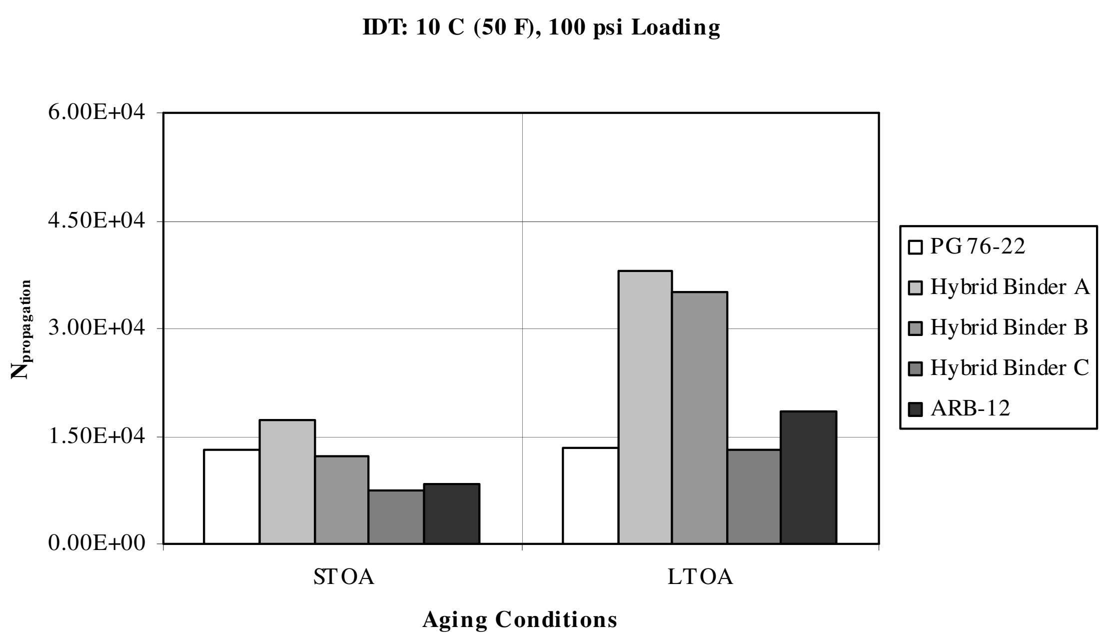


Figure 5-10 $N_{propagation}$ for OGFC Limestone Mixtures

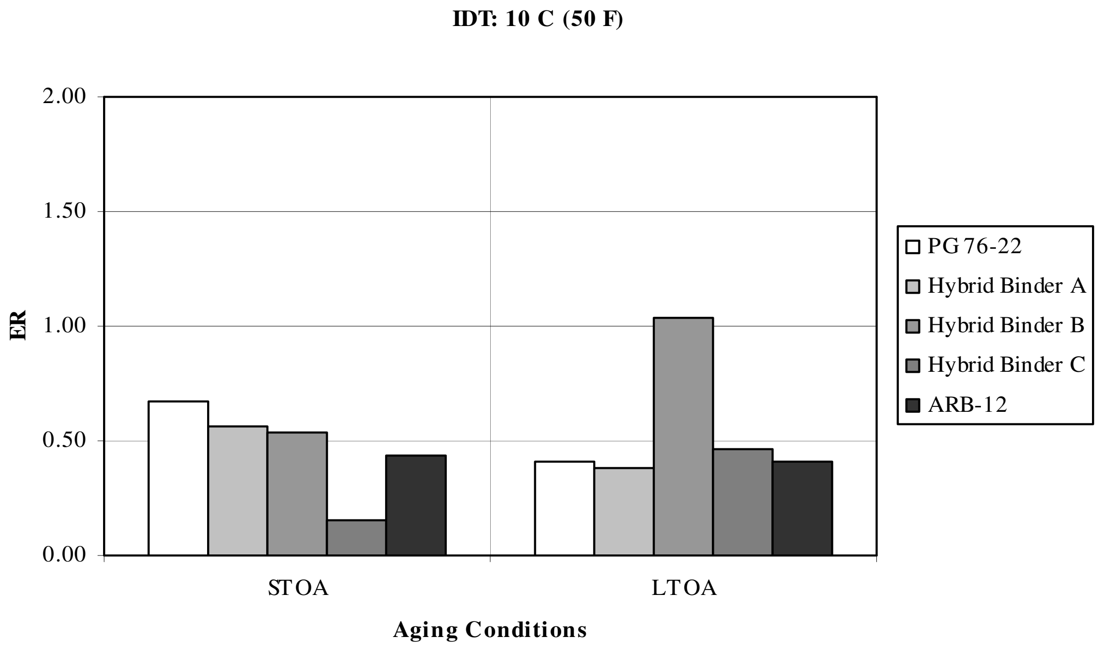


Figure 5-11 ER for OGFC Granite Mixtures

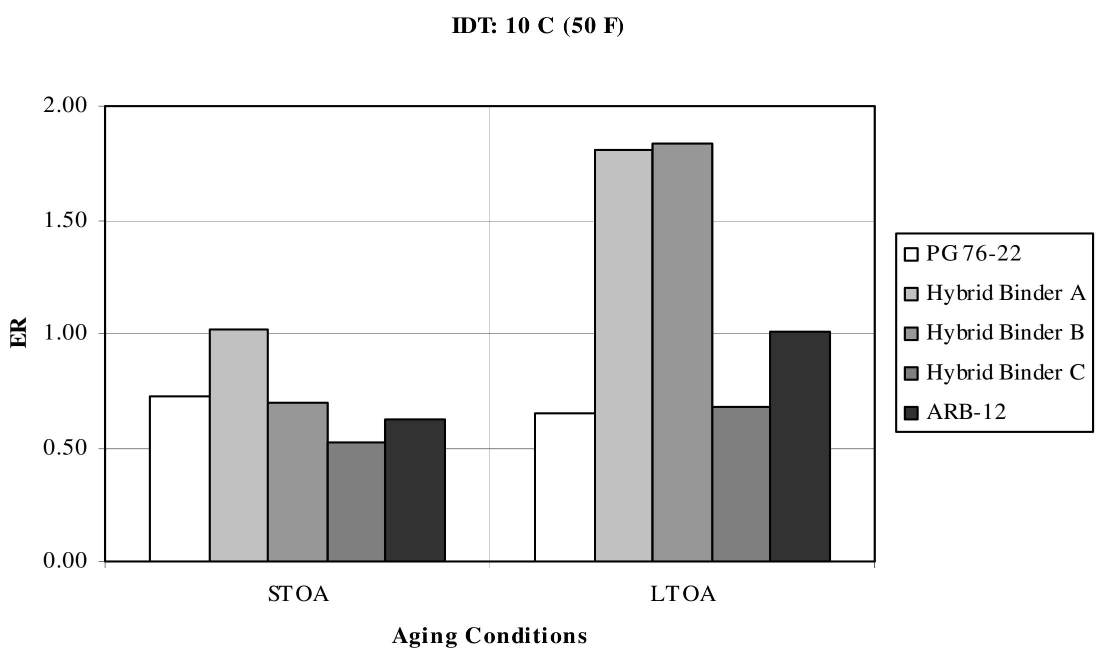


Figure 5-12 ER for OGFC Limestone Mixtures

5.3 Summary

In general, the IDT test results showed that all mixtures with hybrid binders, regardless of aggregate types and aging conditions, performed comparatively better than PG 67-22 and ARB-5 mixtures in terms of cracking resistance. Better cracking response observed in hybrid binder mixtures compared to both unmodified and asphalt rubber modified binders offer the promise of using tire rubber while providing similar performance benefit as polymer modified asphalts.

If STOA and LTOA were considered separately, all three hybrid binders exhibited similar cracking resistance trends for both granite and limestone mixtures. However, the same mixtures showed different cracking performance trends at different aging conditions: the LTOA apparently increased the cracking resistance of hybrid binder mixtures. A larger increase in cracking resistance was observed for limestone mixtures, which could be explained by the fact that limestone has a much rougher surface texture and greater absorption than granite.

In summary, it appears that the hybrid binders evaluated in this study can be used as a substitute for either SBS modified (PG 76-22) or ARB-12 in OGFC mixtures. However, there maybe a need to check the draindown potential of hybrid binder produced with finer rubber when used in smooth textured, non-absorptive aggregate OGFC mixtures.

CHAPTER 6

PROPOSED BINDER TEST

Combined results of binder and mixture tests presented in Chapter 4 and 5, clearly indicated that none of the existing or proposed intermediate temperature binder tests including DSR (G*sinδ), Elastic Recovery (ER), and Force Ductility (FD) were found to provide parameters that consistently correlated with the relative cracking performance of mixtures. An approach developed in this study to determine cumulative energy to failure from FD results showed some improvement compared to G*sinδ. However, cumulative energy was still not found to be adequately correlated to mixture test results, probably because of the very high strains involved in the FD test compared to actual strain experienced by binder in mixtures.

Therefore, it seems clear that a binder test is needed that provides properties and/or parameters that more accurately reflect fatigue cracking resistance of binder in mixtures. The test should induce damage and failure in tension at strain levels consistent with actual strain experienced by binder in mixtures. In addition, the test should minimize the significant problems associated with the current dog-bone Superpave Direct Tension test, including excessive variability and potential for eccentric loading, which introduces measurement error.

A new binder testing system was conceived, designed, and analytically evaluated in this study to satisfy the need for accurate determination of tensile fracture properties of binders at intermediate temperatures. The system and its evaluation are presented in the following sections.

6.1 Basic Principles

The idea for the proposed system was based on the observed configuration of asphalt binder within an asphalt mixture. As illustrated in Figure 6-1, the asphalt mastic (including fines) resides between coarser aggregate particles, and has variable thickness throughout the mixture. The binder thickness is narrowest in the vicinity of contact points between two larger aggregates and increases with distance from the contact points. The result is a highly non-uniform stress state within the binder with tensile stress concentrations occurring in the vicinity of contact points. In addition, the aggregate's restraint is significant within these narrow gaps, resulting in confinement, which further concentrates tensile stresses. This phenomenon which is not replicated by tests on bulk specimens (e.g. BBR or dog-bone Direct Tension) is the main reason asphalt mixture and binder fail at relatively low strain levels. Therefore, it is very important to create these same conditions in binder tensile testing to obtain relevant fracture properties.

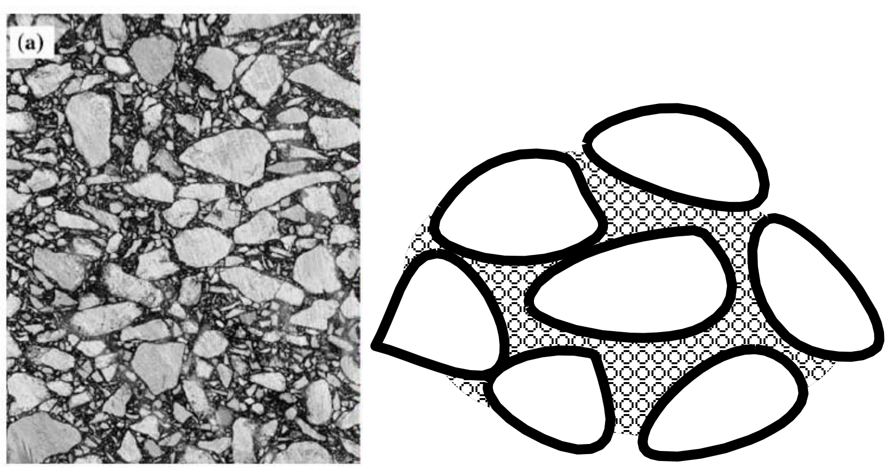
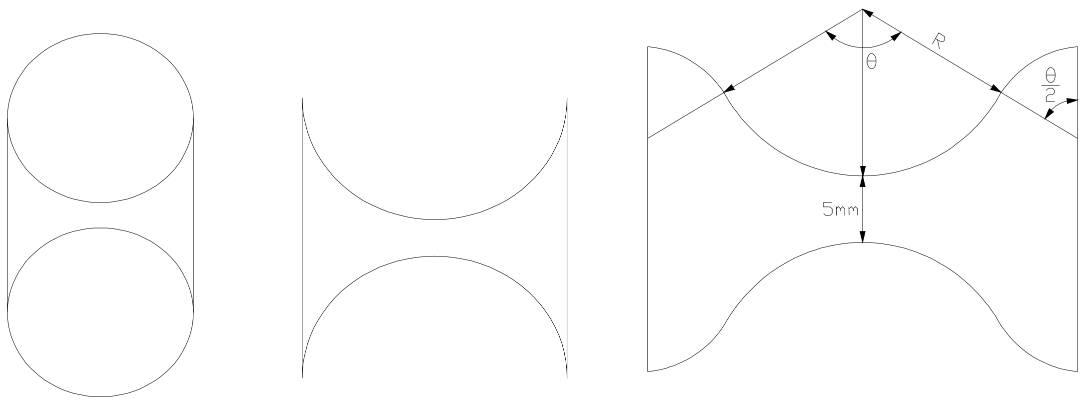


Figure 6-1 Asphalt Binder between Aggregates

6.2 Proposed Test Configuration

Several configurations were considered to replicate the laboratory behavior of binder within an asphalt mixture (see Figure 6-2).



(a) Simple Spheres (b) 2-D Semi-circles (c) 2-D Complex Curves

Figure 6-2 Models of Asphalt Binder

Figure 6-2 (a) shows two adjacent hemispherical surfaces, which would probably result in the testing system that would most closely replicate, in an idealized sense, the physical conditions between two aggregates. Unfortunately, this system is not suitable for determining fundamental binder properties accurately and precisely. The resulting 3-D stress distribution within the binder specimen, although realistic, is highly non-uniform, making it very difficult or impossible to interpret resulting force-deformation measurements reliably. For the same reasons, it would also be difficult or impossible to identify the instant of fracture for this test geometry, which is necessary for accurate determination of fracture energy.

Figure 6-2 (b) reduces the problem to two-dimensions (2-D) by using two semicircular cylindrical surfaces. This approach enhances uniformity by inducing conditions approaching plane stress or strain, depending on binder specimen thickness, such that only in-plane stresses (i.e. on the plane with the semicircular cross-section) vary. However, the semicircular cross-section would still result in excessive nonuniformity as one approaches the narrow gap between the surfaces, which would again likely preclude accurate and precise determination of fundamental binder properties. Also, the near vertical surface near the edge of the specimen would result in very high shear, which may lead to adhesive failure between binder and loading head.

The proposed solution presented in Figure 6-2 (c) is to use a complex cross-section with a uniformly thick central area (at the narrow gap), and much thicker specimen edges that culminate in a horizontal surface to minimize shear and adhesive failure. In addition, an equally narrow specimen depth is proposed in the uniform central area to minimize potential problems with eccentricity and thereby reducing potential for premature failure and interpretation errors. The resulting shape of the proposed specimen is similar to an hour-glass as shown in Figure 6-3.

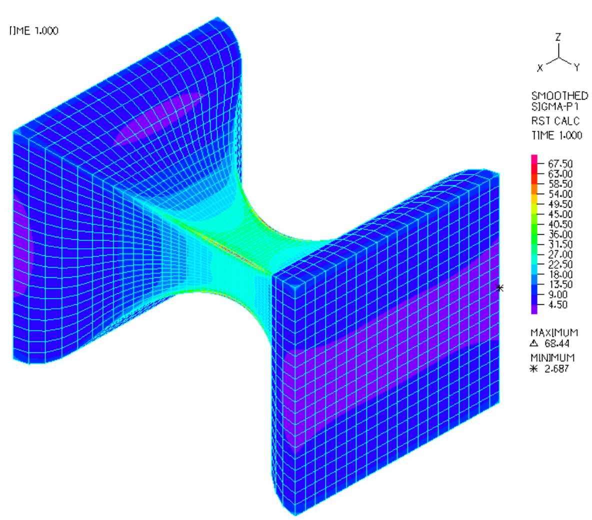


Figure 6-3 Proposed Specimen of Asphalt Binder (FEM Model)

6.3 Analysis and Optimization

A parametric study was conducted using 3-D Finite Element Method (FEM) analysis to optimize the dimensions of the specimen. Criteria used to optimize specimen dimensions included:

- Achieving as uniform a tensile stress distribution as possible over a broad enough width within the narrow portion of the hour-glass shape to allow for accurate and precise interpretation of fundamental binder properties.
- Achieving the maximum possible difference in tensile stress between the central narrow portion and the specimen edges to help ensure the specimen will fail first within the region of the narrow gap.
- Selection of a target cross-section of 3mm×3mm as the minimum over which near-uniform tensile stresses should be achieved. 3-mm was selected to allow for reasonably precise measurements with available instrumentation, and to allow for testing of mastics as well as pure binder. Allowing for 1-mm to account for end-effects at the binder-loading head interface a cross-section of 5mm×5mm was selected. The final dimensions identified are shown in Figure 6-4.

Three-D FEM results of a specimen of these dimensions in Figure 6-5 indicate that a highly uniform, nearly isotropic stress state exists in its central narrow portion. Also, the tensile stresses are eleven times higher than tensile stresses near the edge.

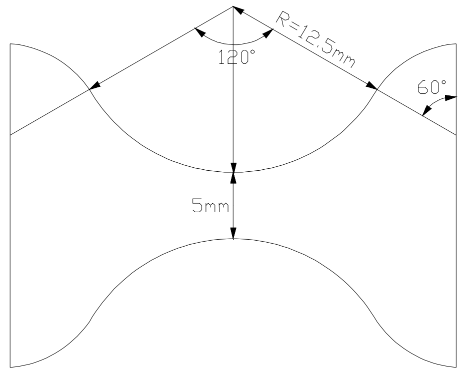
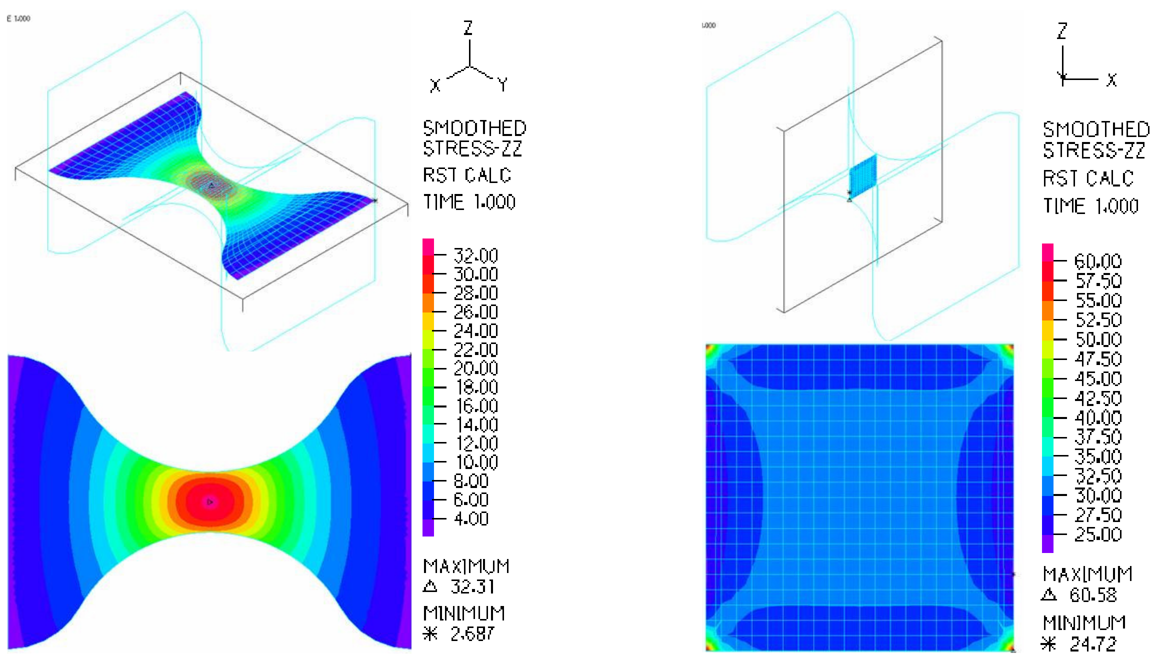


Figure 6-4 Final Dimensions of Asphalt Binder Specimen



(a) Horizontal Section, Stress-ZZ

(b) Vertical Section, Stress-ZZ

Figure 6-5 3-D FEM Results

This unique test configuration offers clear advantages over existing tensile testing systems for binders. These advantages give this system the potential to obtain binder fracture properties that heretofore have been elusive to the industry.

CHAPTER 7

CLOSURE AND RECOMMENDATIONS

7.1 Summary

Binder and mixture tests were performed to evaluate the relative performance of a PG 67-22 base binder and six other binders produced by modifying the same base binder with the following modifiers: one SBS polymer, three commercially available hybrid binders composed of different percentages of rubber and SBS polymer, and two asphalt rubber binders (5% and 12 % rubber: ARB-5 and ARB-12). The primary goal was to evaluate whether commercially available hybrid binder could exceed the performance characteristics of the base and asphalt rubber binders, as well as approach, meet or exceed the performance characteristics of the SBS polymer modified binder. Secondary goals were to determine whether available binder tests and characterization methods are suitable for specifying hybrid binder. Key findings from the study are summarized below:

- Mixture tests indicated that cracking performance characteristics of dense-graded mixtures (granite and limestone) produced with the commercially available hybrid binders used in this study exceeded the cracking performance characteristics of mixtures produced with the base binder and the ARB-5 binder, and were about the same as the cracking performance characteristics of the SBS polymer modified binder.

- Results of tests on open-graded friction course (OGFC) mixtures (granite and limestone) indicated that except for one special case (granite OGFC mixture with hybrid binder C), the commercially available hybrid binders used in this study exhibited cracking performance characteristics that were about the same as those exhibited by mixtures produced with SBS polymer modified binder and ARB-12. It was concluded that hybrid binder C, which included the finer grained rubber, may not have maintained appropriate consistency to achieve and maintain uniform distribution within the smoother textured and less absorptive granite OGFC during mixing and compaction. The resulting non-uniformity is the most probable cause of the anomalous result (lower cracking performance characteristics). Addition of fibers or mixing and compaction at lower temperatures would likely have resulted in better distribution and cracking performance characteristics.

- The two hybrid binders produced with coarser grained rubber (hybrid binders A and B), as well as the two asphalt rubber binders (ARB-5 and ARB-12) did not meet FDOT's solubility specification, indicating that the rubber may not have been fully digested in the base binder. Consequently, test results on these binders determined from the dynamic shear rheometer (DSR), including $G^*/\sin\delta$, $G^*\sin\delta$, and parameters derived from the newly proposed MSCR test, were considered suspect, because the presence of particulates in the binder is well known to affect DSR results. The binders produced with the coarser grained rubber met, and in most cases far exceeded requirements for PG76-22 binder, resulting in binder performance parameters that indicated better performance characteristics than all other binders evaluated, including the SBS polymer modified binder. These results were suspect and not consistent with relative cracking performance characteristics determined from mixture tests.

- Hybrid binders A and B were also found to result in significantly lower absorption than all other binders, including ARB-5. This indicated that the combination of coarser rubber particles and polymer affected absorption into the aggregate. Differences in absorption were taken into account when determining the effective asphalt content, which was the same for all binder-mixture combinations.

- Hybrid binder C, which was produced with finer grained rubber, did meet FDOT's solubility specification, indicating that the rubber was fully digested in the base binder, thereby making it suitable for DSR testing. This binder also met all requirements for PG76-22 binder with the exception of maximum phase angle (an additional FDOT requirement).

- None of the existing or currently proposed intermediate temperature binder tests, including DSR ($G^*\sin\delta$), Elastic Recovery (ER), and Force-Ductility (FD) were found to provide parameters that consistently correlated with the relative cracking performance of mixtures.

- Parameters obtained from the new multiple stress creep recovery (MSCR) test and from Elastic Recovery (ER) distinguished the SBS polymer modified binder, but not hybrid binder C, from the base binder. Therefore, it appears questionable whether either of these tests are suitable in their present form to specify hybrid binder.

- An approach to determine cumulative energy to failure from FD results developed in this study showed some improvement compared to $G^*\sin\delta$, but was still not adequately correlated to mixture test results, probably because of the very high strains involved in the FD test compared to actual strain experienced by binder in mixtures.

- Only the elongation at failure from either the ER or FD tests was able to clearly distinguish the observed relative cracking performance of the SBS polymer modified and hybrid binders from that of the asphalt rubber binders. The asphalt rubber binders were more brittle (less elongation to failure) than the SBS and hybrid binders.

- Analyses based on 3-D FEM models indicate that the new binder direct tension test configuration conceived and designed in this study may provide the means to accurately determine more relevant cracking performance properties, including fracture energy limit.

7.2 Conclusions

The following conclusions may be drawn on the basis of the research findings:

- Hybrid binders produced commercially, consisting of crumb rubber and SBS polymer (more rubber than SBS), can approach, meet or exceed the cracking performance characteristics of the SBS polymer modified binder.

- Although all the hybrid binders in this study did not meet all the Superpave binder tests, it appears that hybrid binder can be suitably specified using existing specification requirements for PG76-22 binder and solubility (to distinguish it from asphalt rubber binder and to assure the validity of DSR test results).

- Hybrid binder specified in this manner has the potential to replace three binders currently used by FDOT in hot mix asphalt: SBS polymer modified asphalt, ARB-5, and ARB-12. This would result in the following benefits:

  - Continued and probably increased use of tire rubber in asphalt.
  - The ground tire rubber will not settle out like asphalt rubber binders.
  - Eliminate a method recipe specification asphalt rubber for performance related hybrid binder.
  - Simplify storage of binders at the hot mix plant by replacing three currently used asphalt binders.
  - Improved cracking, and probably rutting, resistance of dense-graded friction courses (FC9.5 and FC12.5)

- Existing binder tests to evaluate cracking performance at intermediate temperatures do not accurately predict cracking performance, even in a relative sense.

- Development and evaluation of the new binder direct tension test configuration conceived and designed in this study should be pursued as it has the potential to obtain binder properties from which cracking performance of binders can be predicted.

7.3 Recommendations

As indicated above, hybrid binder specified in a proper manner, has the potential to replace three binders currently used by FDOT in hot mix asphalt: SBS polymer modified asphalt, ARB-5, and ARB-12. It also appears that a benefit may be derived by taking this course of action (i.e. eventually specifying hybrid binder exclusively for use in FDOT hot mix asphalt). Therefore, it is recommended that FDOT develop a transition plan to accomplish this. This should involve an assessment of impact and cost, development of a draft specification and strategy for implementation. Consideration should be given to first allowing the use of hybrid binder as an alternate binder, then eventually requiring its use.

Hybrid Binders have never been used on an actual project in Florida. The implementation process should include a number of demonstration projects where the hybrid binder is specifically specified in addition to the polymer modified binder for the project. The asphalt suppliers' timeline to supply hybrid binder to Florida will have to be taken into account, and suppliers will need to know the level of Florida's commitment to this product before making the necessary investments.

Finally, it is recommended that FDOT pursue development and evaluation of the new binder direct tension test configuration conceived and designed in this study for eventual use in performance based specification of hybrid binder, particularly since not even the newest MSCR test was successful in identifying its benefits. The proposed test method has the potential to obtain binder properties from which cracking performance of binders can be predicted.

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APPENDIX A BINDER TEST RESULTS

APPENDIX A.1 DYNAMIC SHEAR RHEOMETER

Table A- 1 G*/sinδ at 67 C (152.6 F)

Binders	G*/sinδ (Orig.Binders) (kPa)	G*/sinδ (RTFOT Residue) (kPa)
PG 67-22	1.65	3.95
PG 76-22	n/a	n/a
Hybrid Binder A	n/a	n/a
Hybrid Binder B	n/a	n/a
Hybrid Binder C	n/a	n/a
ARB-5	3.36	n/a
ARB-12	5.98	n/a

Table A- 2 Phase Angle δ^o at 67 C (152.6 F)

Binders	Phase Angle δ^o (Orig.Binders)	Phase Angle δ^o (RTFOT Residue)
PG 67-22	84.05	78.55
PG 76-22	n/a	n/a
Hybrid Binder A	n/a	n/a
Hybrid Binder B	n/a	n/a
Hybrid Binder C	n/a	n/a
ARB-5	76.60	n/a
ARB-12	75.40	n/a

* n/a means no need to test at this temperature.

Table A- 3 G*/sinδ at 70 C (158 F)

Binders	G*/sinδ (Orig.Binders) (kPa)	G*/sinδ (RTFOT Residue) (kPa)
PG 67-22	1.14	2.73
PG 76-22	n/a	n/a
Hybrid Binder A	n/a	n/a
Hybrid Binder B	n/a	n/a
Hybrid Binder C	n/a	n/a
ARB-5	2.40	6.14
ARB-12	4.46	12.27

Table A- 4 Phase Angle δ^o at 70 C (158 F)

Binders	Phase Angle δ^o (Orig.Binders)	Phase Angle δ^o (RTFOT Residue)
PG 67-22	84.80	79.80
PG 76-22	n/a	n/a
Hybrid Binder A	n/a	n/a
Hybrid Binder B	n/a	n/a
Hybrid Binder C	n/a	n/a
ARB-5	78.40	67.55
ARB-12	77.05	59.35

* n/a means no need to test at this temperature.

Table A- 5 G*/sinδ at 76 C (168.8 F)

Binders	G*/sinδ (Orig.Binders) (kPa)	G*/sinδ (RTFOT Residue) (kPa)
PG 67-22	1.14	2.73
PG 76-22	1.52	3.19
Hybrid Binder A	3.03	5.83
Hybrid Binder B	2.25	4.28
Hybrid Binder C	1.15	2.83
ARB-5	1.34	3.52
ARB-12	2.30	6.91

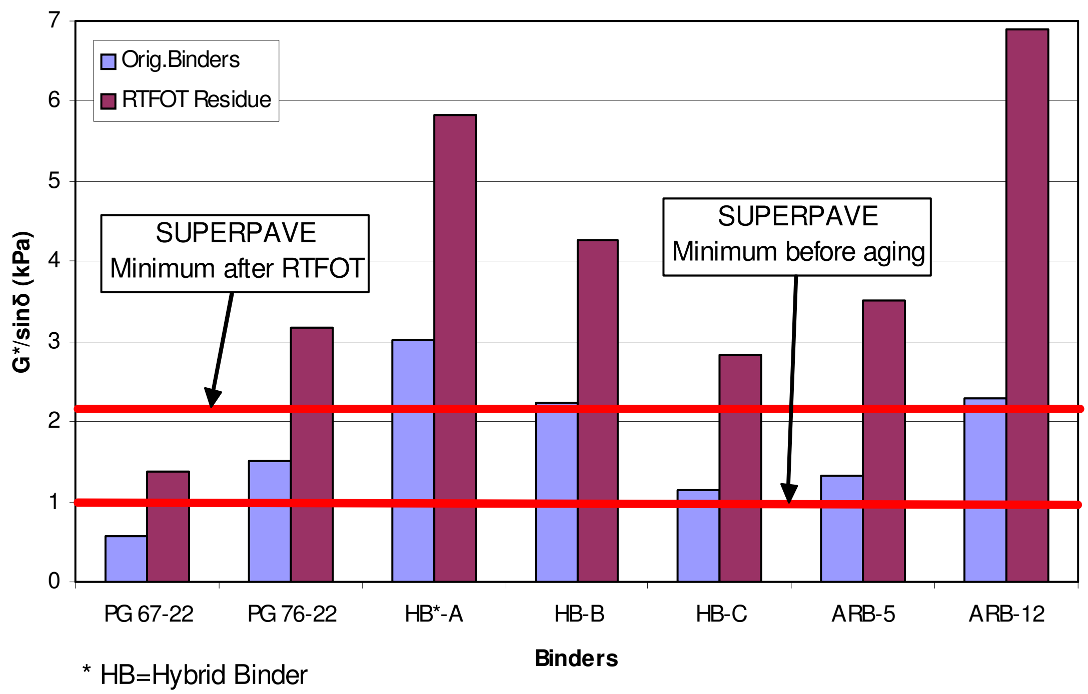


Figure A- 1 G*/sinδ at 76 C (168.8 F)

Rating for G*/sinδ at 76 C (168.8 F)

(denominator=3.1 and 7 for original binder and RTFOT residue respectively)

Binders	Original Binder	RTFOT Residue	Average
PG 67-22	1.9	2.0	1.9
PG 76-22	4.9	4.6	4.7
Hybrid Binder A	9.8	8.3	9.0
Hybrid Binder B	7.2	6.1	6.7
Hybrid Binder C	3.7	4.0	3.9
ARB-5	4.3	5.0	4.7
ARB-12	7.4	9.9	8.6

Table A- 6 Phase Angle δ^o at 76 C (168.8 F)

Binders	Phase Angle δ^o (Orig.Binders)	Phase Angle δ^o (RTFOT Residue)
PG 67-22	86.60	82.30
PG 76-22	71.95	65.80
Hybrid Binder A	71.65	65.45
Hybrid Binder B	75.90	69.10
Hybrid Binder C	82.55	77.20
ARB-5	81.15	70.60
ARB-12	80.65	63.00

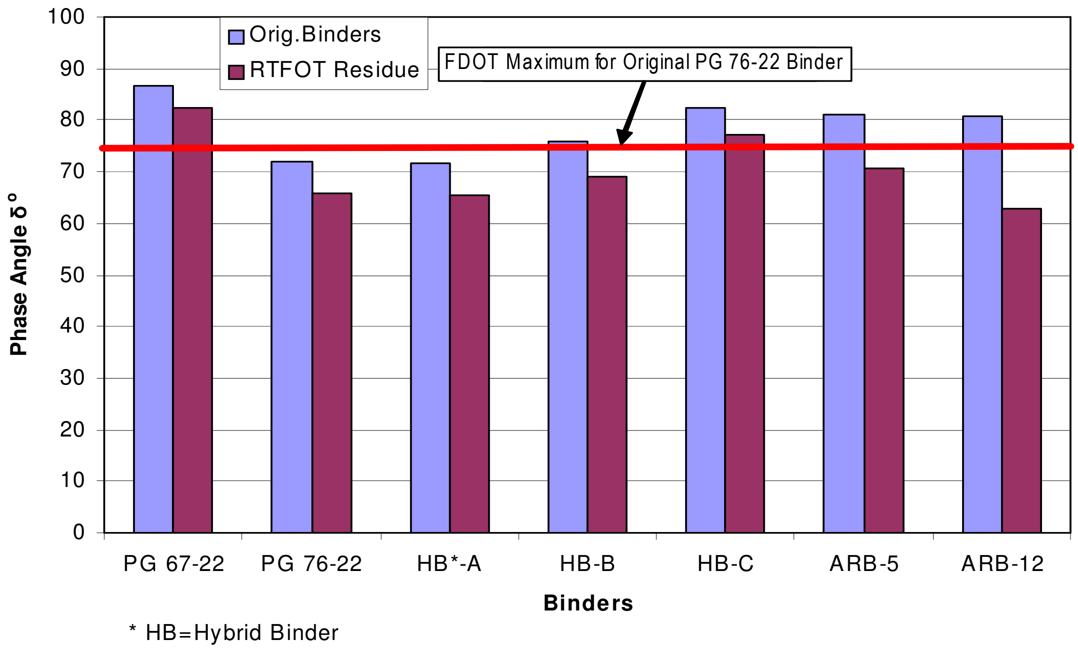


Figure A- 2 Phase Angle δ^o at 76 C (168.8 F)

Rating for Phase Angle δ^o at 76 C (168.8 F)

(numerator=70 and 62 for original binder and RTFOT residue respectively)

Binders	Original Binder	RTFOT Residue	Average
PG 67-22	7.2	7.5	7.8
PG 76-22	8.6	9.4	9.6
Hybrid Binder A	8.7	9.5	9.6
Hybrid Binder B	8.2	9.0	9.1
Hybrid Binder C	7.5	8.0	8.3
ARB-5	7.6	8.8	8.7
ARB-12	7.7	9.8	9.3

Table A- 7 G*/sinδ at 82 C (179.6 F)

Binders	G*/sinδ (Orig.Binders) (kPa)	G*/sinδ (RTFOT Residue) (kPa)
PG 67-22	n/a	n/a
PG 76-22	0.91	1.88
Hybrid Binder A	1.70	3.34
Hybrid Binder B	1.26	2.44
Hybrid Binder C	0.64	1.49
ARB-5	0.76	1.94
ARB-12	1.27	4.10

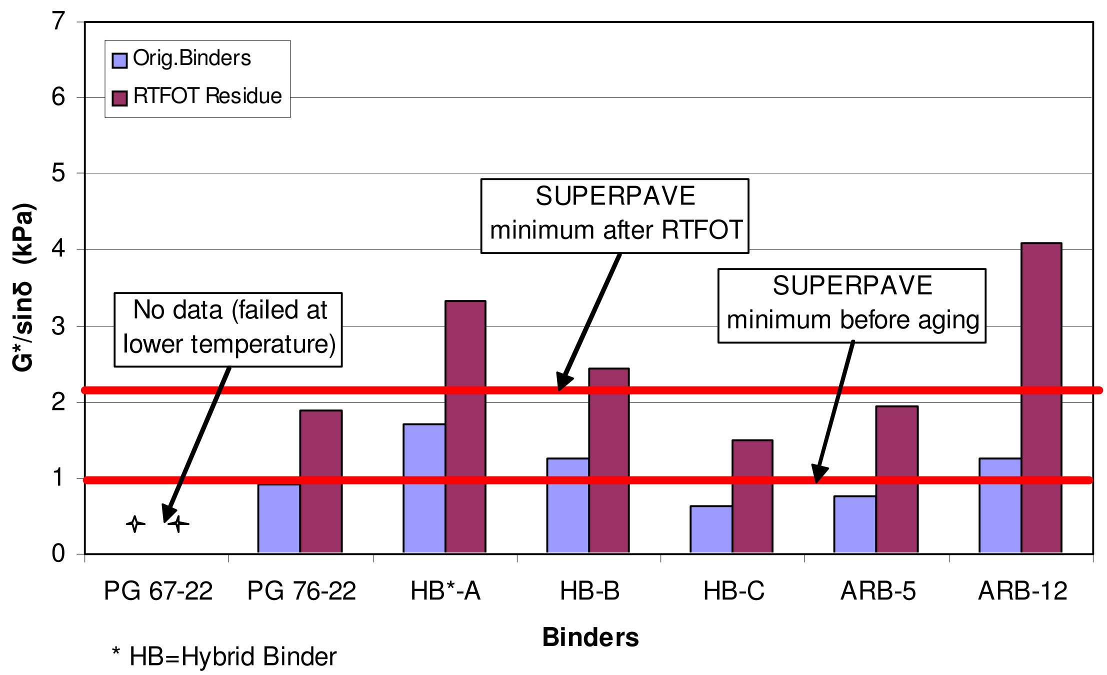


Figure A- 3 G*/sinδ at 82 C (179.6 F)

Table A- 8 Phase Angle δ^o at 82 C (179.6 F)

Binders	Phase Angle δ^o (Orig.Binders)	Phase Angle δ^o (RTFOT Residue)
PG 67-22	n/a	n/a
PG 76-22	74.25	68.15
Hybrid Binder A	74.95	68.60
Hybrid Binder B	79.25	72.40
Hybrid Binder C	83.55	80.20
ARB-5	83.55	73.75
ARB-12	82.90	66.40

* n/a means this binder had already failed at previous lower temperature. No need to test at this temperature.

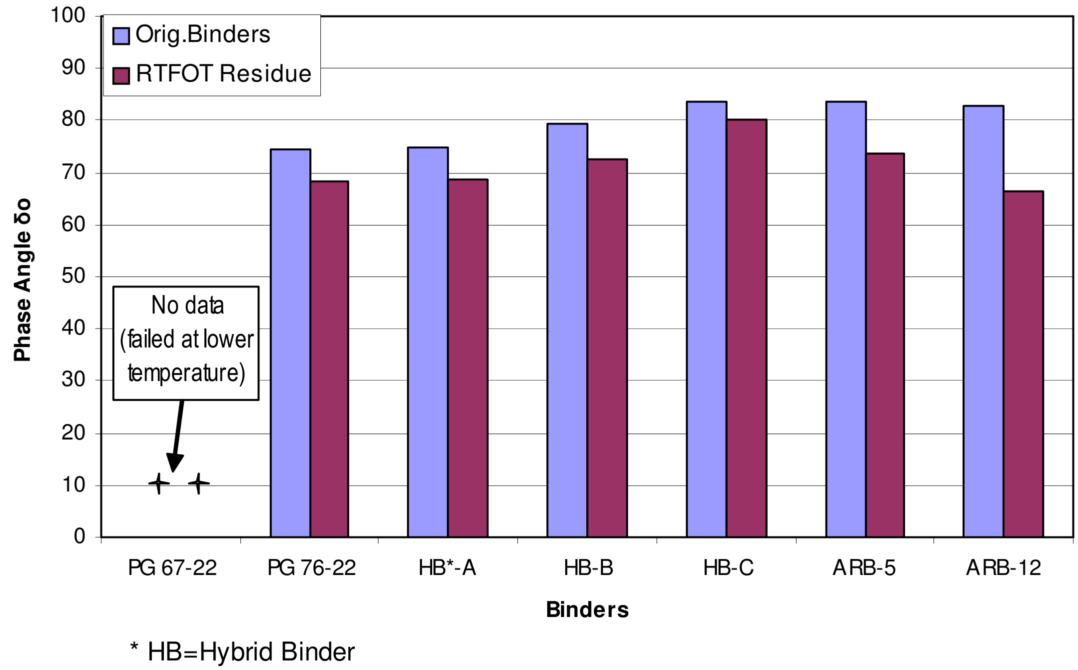


Figure A- 4 Phase Angle δ^o at 82 C (179.6 F)

Table A- 9 G*/sinδ at 88 C (190.4 F)

Binders	G*/sinδ (Orig.Binders) (kPa)	G*/sinδ (RTFOT Residue) (kPa)
PG 67-22	n/a	n/a
PG 76-22	n/a	n/a
Hybrid Binder A	1.03	1.99
Hybrid Binder B	0.77	1.39
Hybrid Binder C	n/a	n/a
ARB-5	n/a	n/a
ARB-12	1.27	4.10

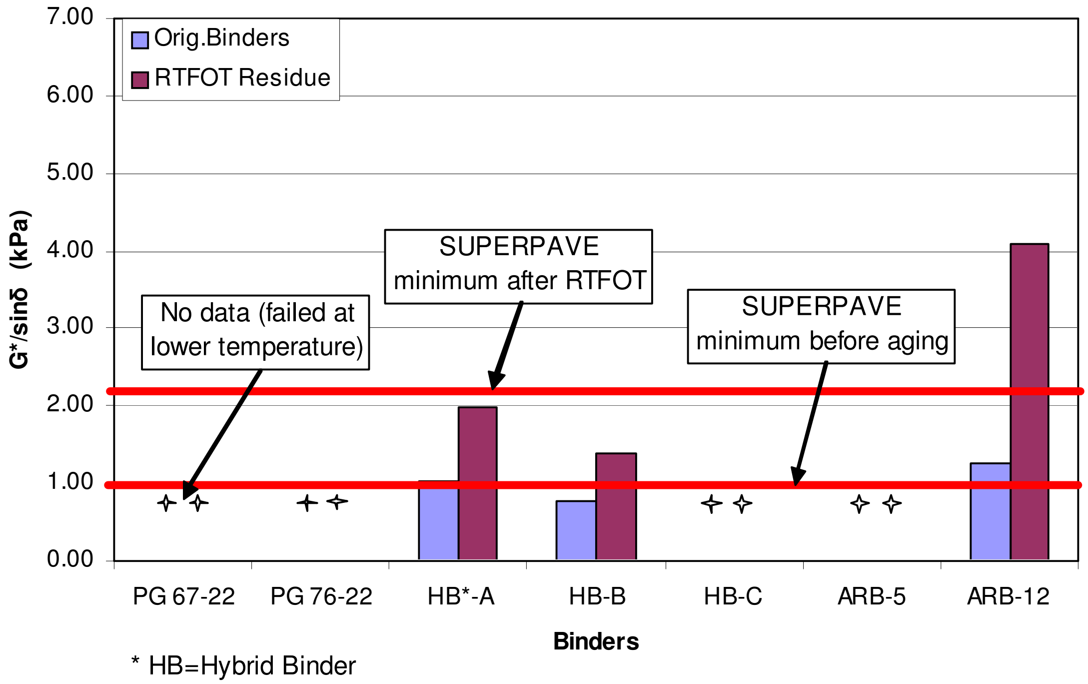


Figure A- 5 G*/sinδ at 88 C (190.4 F)

Table A- 10 Phase Angle δ^o at 88 C (190.4 F)

Binders	Phase Angle δ^o (Orig.Binders)	Phase Angle δ^o (RTFOT Residue)
PG 67-22	n/a	n/a
PG 76-22	n/a	n/a
Hybrid Binder A	77.30	70.90
Hybrid Binder B	81.60	76.10
Hybrid Binder C	n/a	n/a
ARB-5	n/a	n/a
ARB-12	84.85	70.60

* n/a means this binder had already failed at previous lower temperature. No need to test at this temperature.

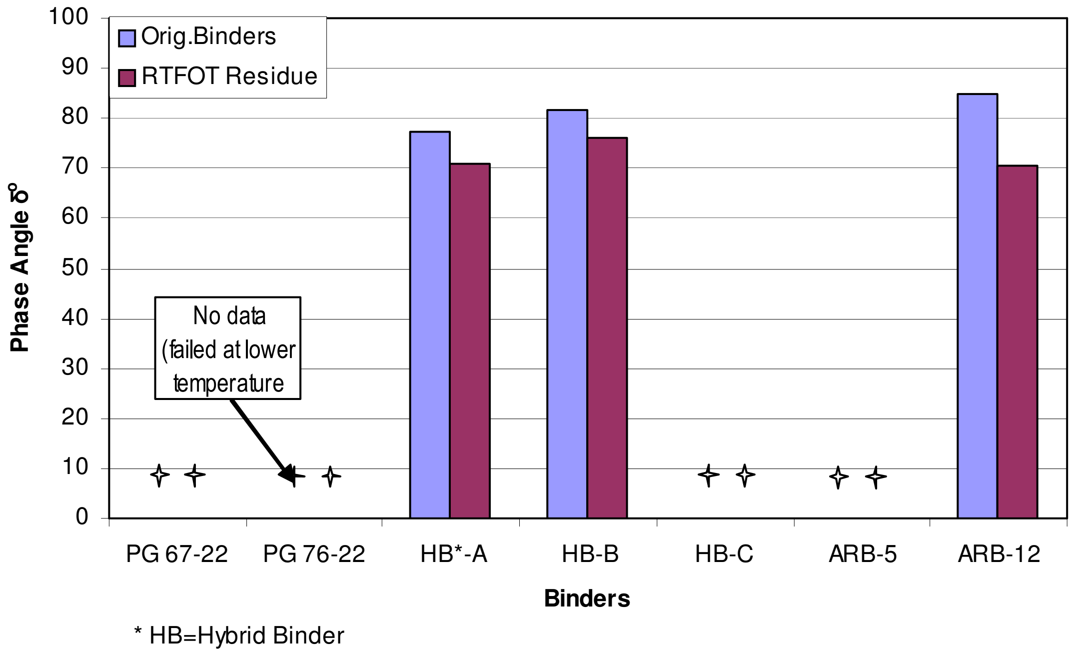


Figure A- 6 Phase Angle δ^o at 88 C (190.4 F)

Table A- 11 G*/sinδ at 90 C (194 F)

Binders	G*/sinδ (Orig.Binders) (kPa)	G*/sinδ (RTFOT Residue) (kPa)
PG 67-22	n/a	n/a
PG 76-22	n/a	n/a
Hybrid Binder A	0.86	n/a
Hybrid Binder B	n/a	n/a
Hybrid Binder C	n/a	n/a
ARB-5	n/a	n/a
ARB-12	n/a	n/a

Table A- 12 Phase Angle δ^o at 90 C (194 F)

Binders	Phase Angle δ° (Orig.Binders)	Phase Angle δ° (RTFOT Residue)
PG 67-22	n/a	n/a
PG 76-22	n/a	n/a
Hybrid Binder A	78.20	n/a
Hybrid Binder B	n/a	n/a
Hybrid Binder C	n/a	n/a
ARB-5	n/a	n/a
ARB-12	n/a	n/a

* n/a means this binder had already failed at previous lower temperature. No need to test at this temperature.

Table A- 13 G*sinδ at 25 C (77 F)

Binders	G*sinδ (kPa) (100°C PAV Residue)	G*sinδ (kPa) (110°C PAV Residue)
PG 67-22	3255.5	4508.0
PG 76-22	3192.0	3633.0
Hybrid Binder A	2969.0	3626.5
Hybrid Binder B	2828.5	3372.0
Hybrid Binder C	3693.0	4692.5
ARB-5	2770.5	3750.0
ARB-12	2139.5	2604.5

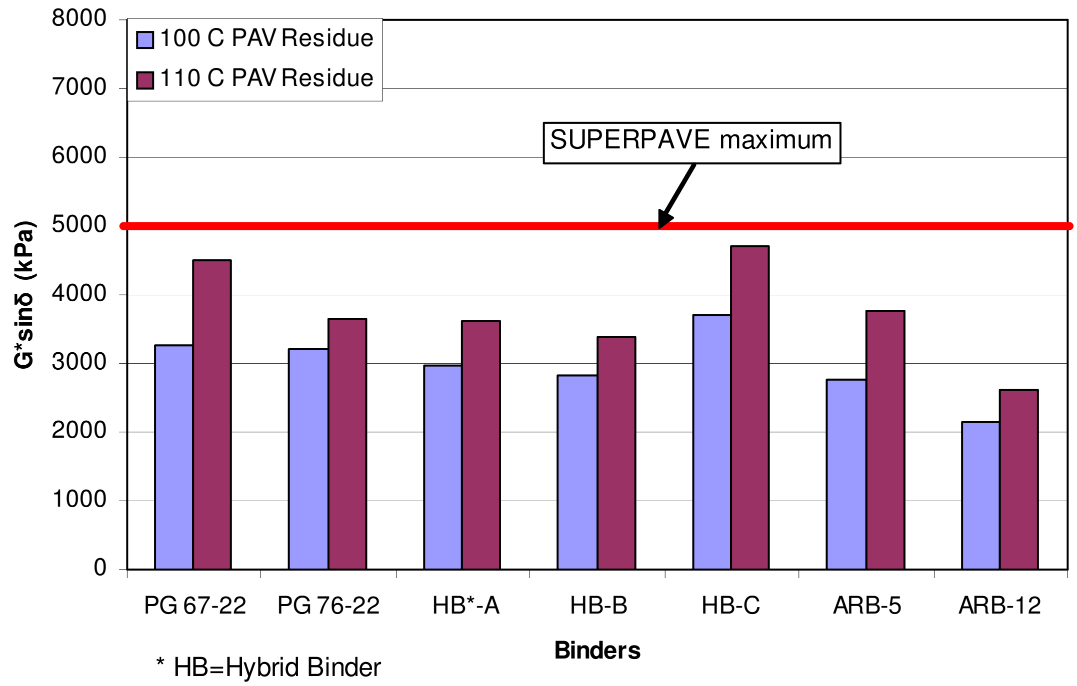


Figure A- 7 G*sinδ at 25 C (77 F)

Rating for G*sinδ at 25 C (77 F)

(numerator=2100 and 2500 for 100 C PAV Residue and 110 C PAV Residue respectively)

Binders	100 C PAV Residue	110 C PAV Residue	Average
PG 67-22	6.5	5.5	6.0
PG 76-22	6.6	6.9	6.7
Hybrid Binder A	7.1	6.9	7.0
Hybrid Binder B	7.4	7.4	7.4
Hybrid Binder C	5.7	5.3	5.5
ARB-5	7.6	6.7	7.1
ARB-12	9.8	9.6	9.7

Table A- 14 Phase Angle δ^o at 25 C (77 F)

Binders	Phase Angle δ^o (100°C PAV Residue)	Phase Angle δ^o (110°C PAV Residue)
PG 67-22	49.8	44.3
PG 76-22	48.2	44.0
Hybrid Binder A	43.5	38.9
Hybrid Binder B	45.3	40.8
Hybrid Binder C	46.3	42.1
ARB-5	46.6	41.8
ARB-12	44.9	40.5

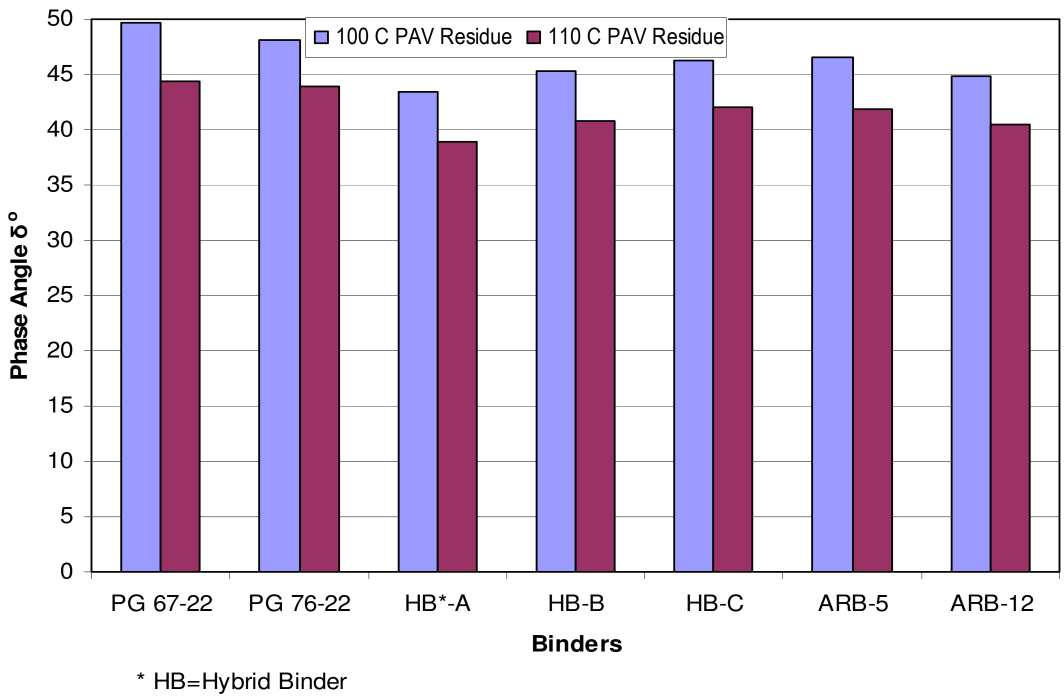


Figure A- 8 Phase Angle δ^o at 25 C (77 F)

Rating for Phase Angle δ^o at 25 C (77 F)

(numerator=43 and 38 for 100 C PAV Residue and 110 C PAV Residue respectively)

Binders	100 C PAV Residue	110 C PAV Residue	Average
PG 67-22	8.6	8.6	8.6
PG 76-22	8.9	8.6	8.8
Hybrid Binder A	9.9	9.8	9.8
Hybrid Binder B	9.5	9.3	9.4
Hybrid Binder C	9.3	9.0	9.2
ARB-5	9.2	9.1	9.2
ARB-12	9.6	9.4	9.5

Table A- 15 G*sinδ at 22 C (71.6 F)

Binders	G*sinδ (kPa) (100°C PAV Residue)	G*sinδ (kPa) (110°C PAV Residue)
PG 67-22	4901.5	6446.0
PG 76-22	4812.5	5238.0
Hybrid Binder A	4193.5	4976.5
Hybrid Binder B	4122.5	4749.0
Hybrid Binder C	5475.5	6655.5
ARB-5	4074.0	5226.5
ARB-12	3047.5	3566.5

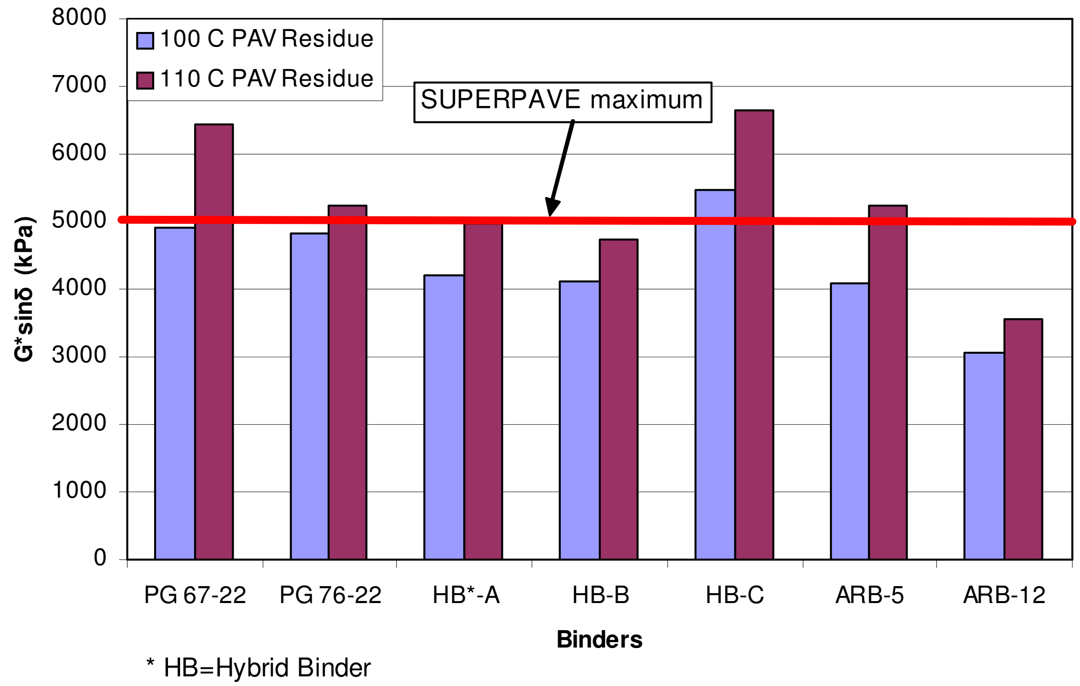


Figure A- 9 G*sinδ at 22 C (71.6 F)

Rating for G*sinδ at 22 C (71.6 F)

(numerator=3000 and 3500 for 100 C PAV Residue and 110 C PAV Residue respectively)

Binders	100 C PAV Residue	110 C PAV Residue	Average
PG 67-22	6.1	5.4	5.8
PG 76-22	6.2	6.7	6.5
Hybrid Binder A	7.2	7.0	7.1
Hybrid Binder B	7.3	7.4	7.3
Hybrid Binder C	5.5	5.3	5.4
ARB-5	7.4	6.7	7.0
ARB-12	9.8	9.8	9.8

Table A- 16 Phase Angle δ^o at 22 C (71.6 F)

Binders	Phase Angle δ^o (100^{o}C PAV Residue)	Phase Angle δ^o (110^{o}C PAV Residue)
PG 67-22	46.9	41.7
PG 76-22	46.0	41.8
Hybrid Binder A	41.2	36.8
Hybrid Binder B	42.9	38.8
Hybrid Binder C	43.8	39.7
ARB-5	44.1	39.7
ARB-12	42.8	38.7

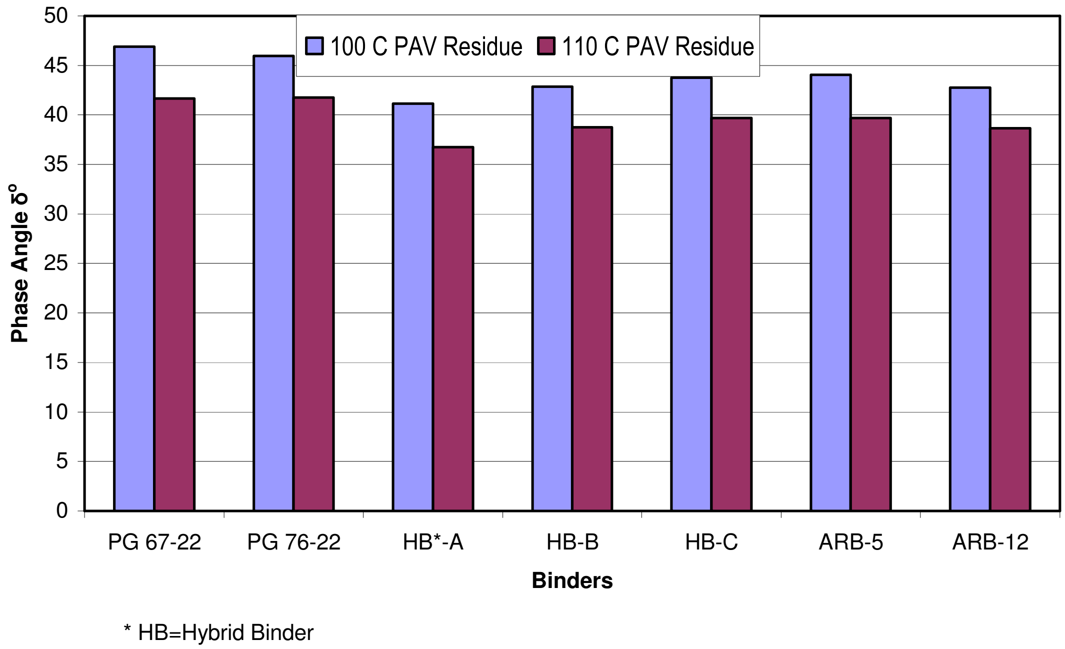


Figure A- 10 Phase Angle δ^o at 22 C (71.6 F)

Rating for Phase Angle δ^o at 22 C (71.6 F)

(numerator=41 and 36 for 100 C PAV Residue and 110 C PAV Residue respectively)

Binders	100 C PAV Residue	110 C PAV Residue	Average
PG 67-22	8.7	8.6	8.7
PG 76-22	8.9	8.6	8.8
Hybrid Binder A	10.0	9.8	9.9
Hybrid Binder B	9.6	9.3	9.4
Hybrid Binder C	9.4	9.1	9.2
ARB-5	9.3	9.1	9.2
ARB-12	9.6	9.3	9.5

Table A- 17 G*sinδ at 19 C (66.2 F)

Binders	G*sinδ (kPa) (100°C PAV Residue)	G*sinδ (kPa) (110°C PAV Residue)
PG 67-22	7053.0	n/a
PG 76-22	6962.0	n/a
Hybrid Binder A	5921.0	6705.0
Hybrid Binder B	5877.0	6542.0
Hybrid Binder C	n/a	n/a
ARB-5	5946.0	n/a
ARB-12	4246.5	4868.0

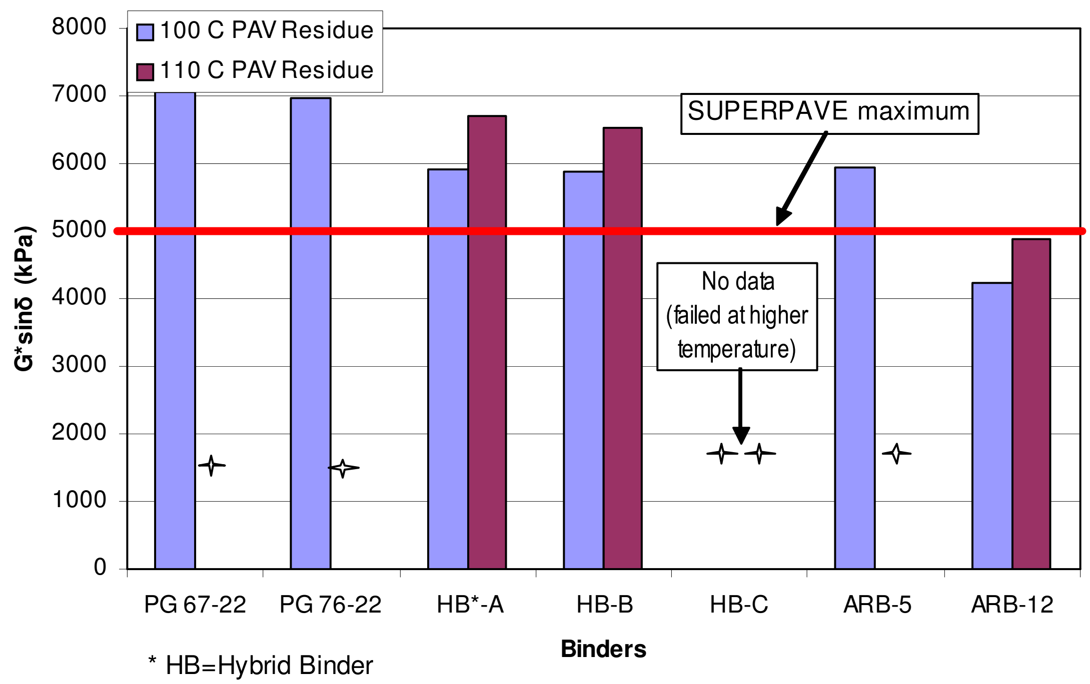


Figure A- 11 G*sinδ at 19 C (66.2 F)

Table A- 18 Phase Angle δ° at 19 C (66.2 F)

Binders	Phase Angle δ° (100°C PAV Residue)	Phase Angle δ° (110°C PAV Residue)
PG 67-22	44.2	n/a
PG 76-22	43.2	n/a
Hybrid Binder A	38.9	34.8
Hybrid Binder B	40.7	36.8
Hybrid Binder C	n/a	n/a
ARB-5	41.6	n/a
ARB-12	40.6	37.0

* n/a means this binder had already failed at previous higher temperature. No need to test at this temperature.

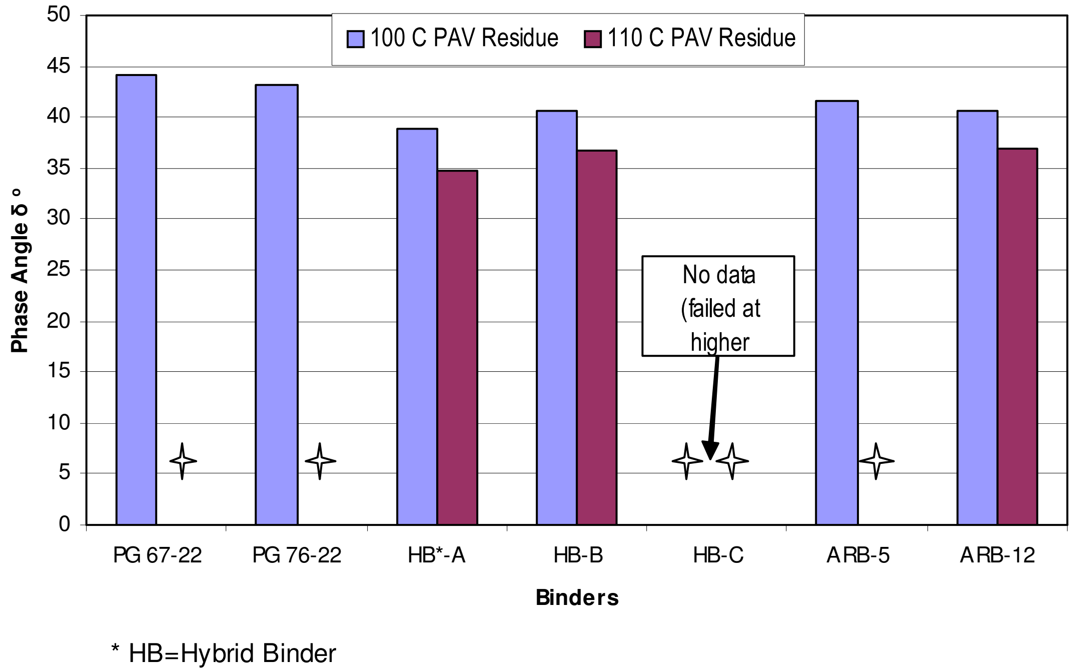


Figure A- 12 Phase Angle δ° at 19 C (66.2 F)

Table A- 19 G*sinδ at 16 C (60.8 F)

Binders	G*sinδ (kPa) (100°C PAV Residue)	G*sinδ (kPa) (110°C PAV Residue)
PG 67-22	n/a	n/a
PG 76-22	n/a	n/a
Hybrid Binder A	n/a	n/a
Hybrid Binder B	n/a	n/a
Hybrid Binder C	n/a	n/a
ARB-5	n/a	n/a
ARB-12	5867.5	6459.5

Table A- 20 Phase Angle δ° at 16 C (60.8 F)

Binders	Phase Angle δ° (100°C PAV Residue)	Phase Angle δ° (110°C PAV Residue)
PG 67-22	n/a	n/a
PG 76-22	n/a	n/a
Hybrid Binder A	n/a	n/a
Hybrid Binder B	n/a	n/a
Hybrid Binder C	n/a	n/a
ARB-5	n/a	n/a
ARB-12	35.1	34.9

* n/a means this binder had already failed at previous higher temperature. No need to test at this temperature.

Rating at Intermediate Temperature (DSR):

PG 67-22	PG 76-22	Hybrid Binder A	Hybrid Binder B	Hybrid Binder C	ARB-5	ARB-12
7.3	7.7	8.5	8.4	7.3	8.1	9.6

APPENDIX A.2 BENDING BEAM RHEOMETER

Table A- 21 BBR, Creep Stiffness, S at -12 C (10.4 F)

Binders	BBR, S (Mpa) (100°C PAV Residue)	BBR, S (Mpa) (110°C PAV Residue)
PG 67-22	159.5	182.5
PG 76-22	144.0	170.0
Hybrid Binder A	137.5	154.5
Hybrid Binder B	147.0	155.5
Hybrid Binder C	166.5	185.0
ARB-5	138.0	155.5
ARB-12	109.0	127.5

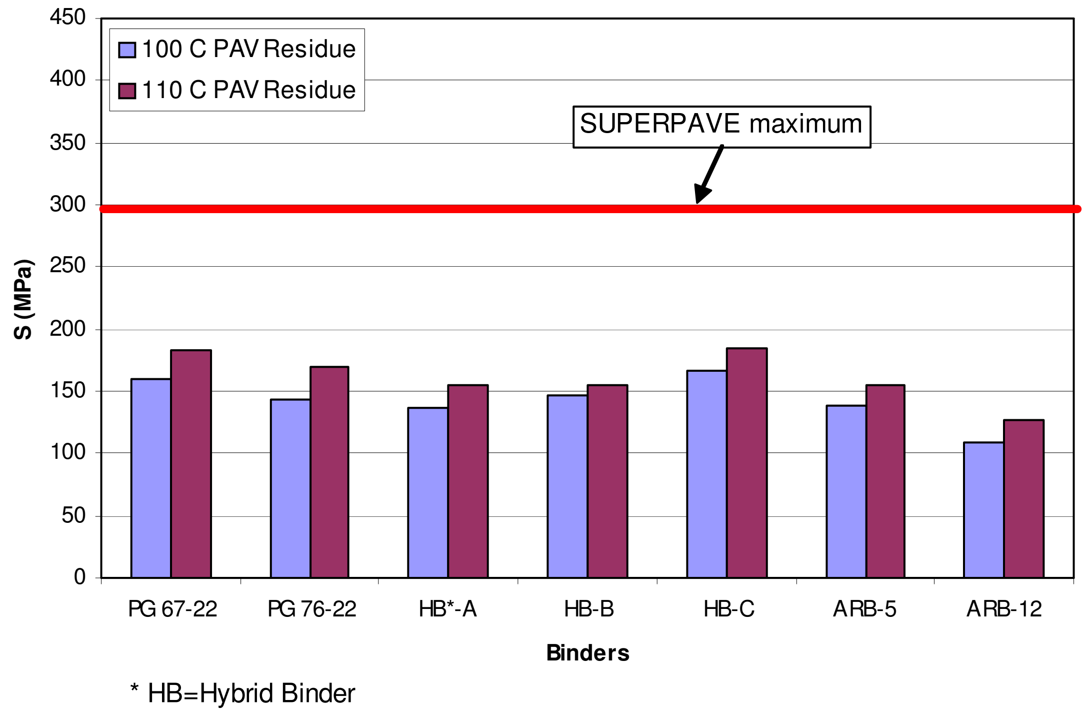


Figure A- 13 BBR, Creep Stiffness, S at -12 C (10.4 F)

Rating for BBR Creep Stiffness S at -12 C (10.4 F)

(numerator=105 and 125 for 100 C PAV Residue and 110 C PAV Residue respectively)

Binders	100 C PAV Residue	110 C PAV Residue	Average
PG 67-22	6.6	6.8	6.7
PG 76-22	7.3	7.4	7.3
Hybrid Binder A	7.6	8.1	7.9
Hybrid Binder B	7.1	8.0	7.6
Hybrid Binder C	6.3	6.8	6.5
ARB-5	7.6	8.0	7.8
ARB-12	9.6	9.8	9.7

Table A- 22 BBR, m-Value at -12 C (10.4 F)

Binders	BBR, m-Value (100°C PAV Residue)	BBR, m-Value (110°C PAV Residue)
PG 67-22	0.365	0.339
PG 76-22	0.362	0.334
Hybrid Binder A	0.322	0.301
Hybrid Binder B	0.336	0.318
Hybrid Binder C	0.337	0.315
ARB-5	0.345	0.318
ARB-12	0.337	0.316

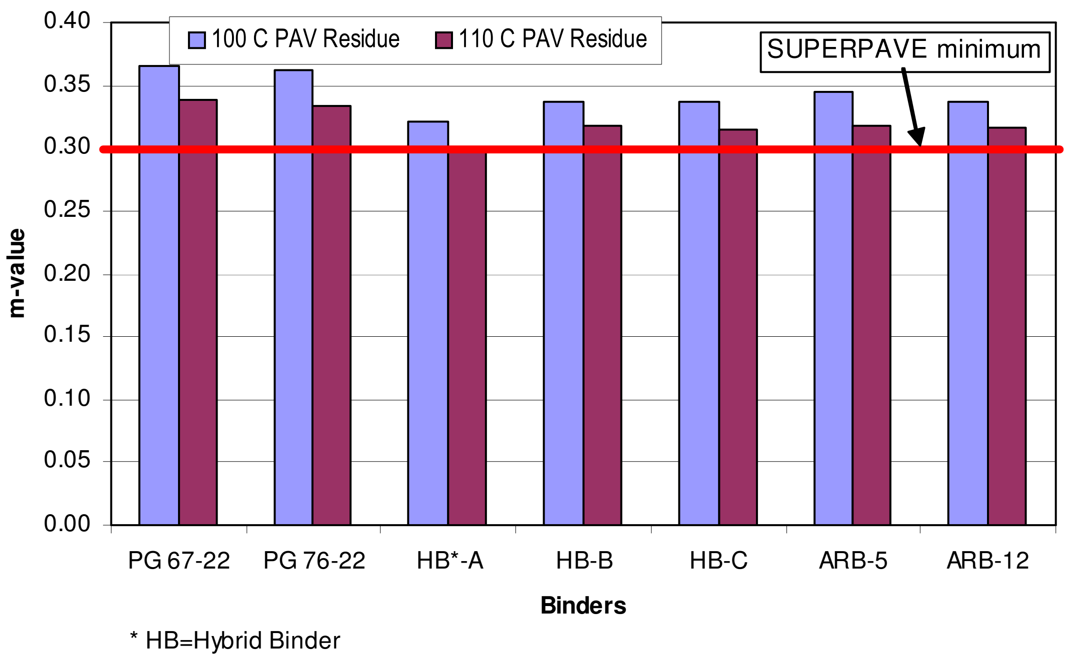


Figure A- 14 BBR, m-Value at -12 C (10.4 F)

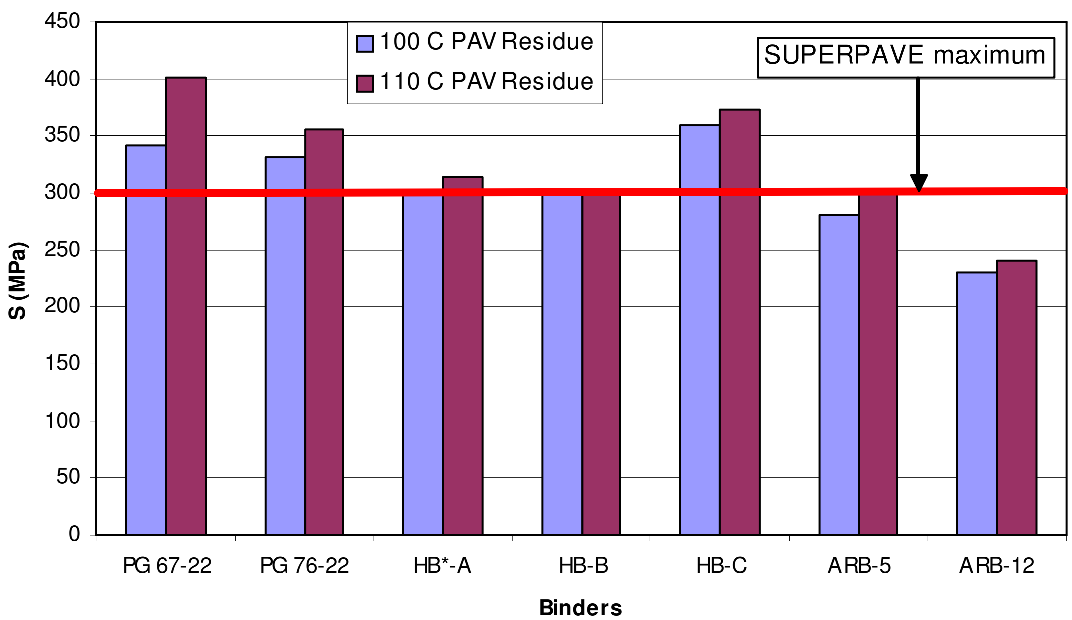
Rating for BBR m-Value at -12 C (10.4 F)

(denominator=0.37 and 0.34 for 100 C PAV Residue and 110 C PAV Residue respectively)

Binders	100 C PAV Residue	110 C PAV Residue	Average
PG 67-22	9.9	10.0	9.9
PG 76-22	9.8	9.8	9.8
Hybrid Binder A	8.7	8.9	8.8
Hybrid Binder B	9.1	9.3	9.2
Hybrid Binder C	9.1	9.3	9.2
ARB-5	9.3	9.4	9.3
ARB-12	9.1	9.3	9.2

Table A- 23 BBR, Creep Stiffness, S at -18 C (0.4 F)

Binders	BBR, S (Mpa) (100°C PAV Residue)	BBR, S (Mpa) (110°C PAV Residue)
PG 67-22	341.5	400.5
PG 76-22	331.0	356.5
Hybrid Binder A	298.0	313.5
Hybrid Binder B	303.0	303.5
Hybrid Binder C	358.5	373.5
ARB-5	281.0	302.0
ARB-12	231.0	241.5



* HB=Hybrid Binder

Figure A- 15 BBR, Creep Stiffness, S at -18 C (0.4 F)

Rating for BBR Creep Stiffness S at -18 C (0.4 F)

(numerator=230 and 240 for 100 C PAV Residue and 110 C PAV Residue respectively)

Binders	100 C PAV Residue	110 C PAV Residue	Average
PG 67-22	6.7	6.0	6.4
PG 76-22	6.9	6.7	6.8
Hybrid Binder A	7.7	7.7	7.7
Hybrid Binder B	7.6	7.9	7.7
Hybrid Binder C	6.4	6.4	6.4
ARB-5	8.2	7.9	8.1
ARB-12	10.0	9.9	9.9

Table A- 24 BBR, m-Value at -18 C (0.4 F)

Binders	BBR, m-Value (100°C PAV Residue)	BBR, m-Value (110°C PAV Residue)
PG 67-22	0.291	0.276
PG 76-22	0.295	0.279
Hybrid Binder A	0.262	0.252
Hybrid Binder B	0.279	0.269
Hybrid Binder C	0.274	0.265
ARB-5	0.287	0.270
ARB-12	0.288	0.274

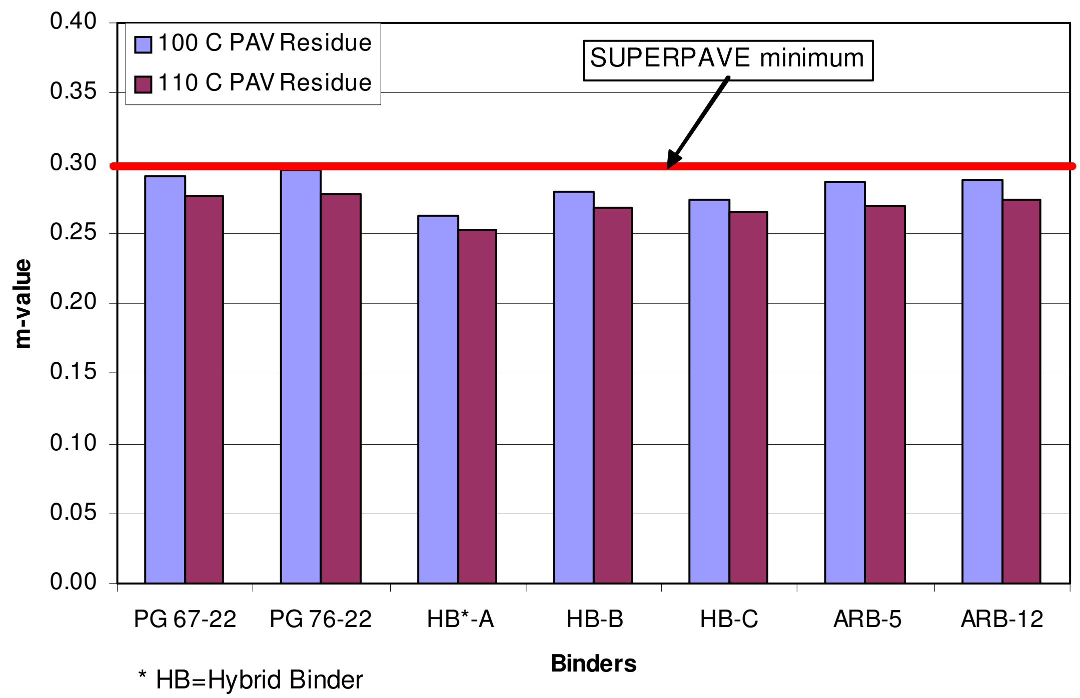


Figure A- 16 BBR, m-Value at -18 C (0.4 F)

Rating for BBR m-Value at -18 C (0.4 F)

(denominator=0.3 and 0.28 for 100 C PAV Residue and 110 C PAV Residue respectively)

Binders	100 C PAV Residue	110 C PAV Residue	Average
PG 67-22	9.7	9.9	9.8
PG 76-22	9.8	9.9	9.9
Hybrid Binder A	8.7	9.0	8.9
Hybrid Binder B	9.3	9.6	9.4
Hybrid Binder C	9.1	9.5	9.3
ARB-5	9.6	9.6	9.6
ARB-12	9.6	9.8	9.7

Rating at Low Temperature (BBR)

Binders	BBR,S	BBR, m-Value
PG 67-22	6.6	9.9
PG 76-22	7.1	9.9
Hybrid Binder A	7.8	8.9
Hybrid Binder B	7.7	9.3
Hybrid Binder C	6.5	9.3
ARB-5	8.0	9.5
ARB-12	9.8	9.5

APPENDIX A.3 MULTIPLE STRESS CREEP RECOVERY

Table A- 25 Average % Recovery at 67 C (152.6 F) (RTFOT Residue)

Binders	Average Recovery at 3.2 kPa (R3200) (%)	Average Recovery at 0.1 kPa (R100) (%)	% Difference (Rdiff)
PG 67-22	3.73	13.27	71.88
PG 76-22	64.25	71.79	10.50
Hybrid Binder A	51.11	67.38	24.14
Hybrid Binder B	40.52	54.15	25.15
Hybrid Binder C	13.13	27.23	51.71
ARB-5	25.03	46.02	45.61
ARB-12	56.64	74.97	24.52

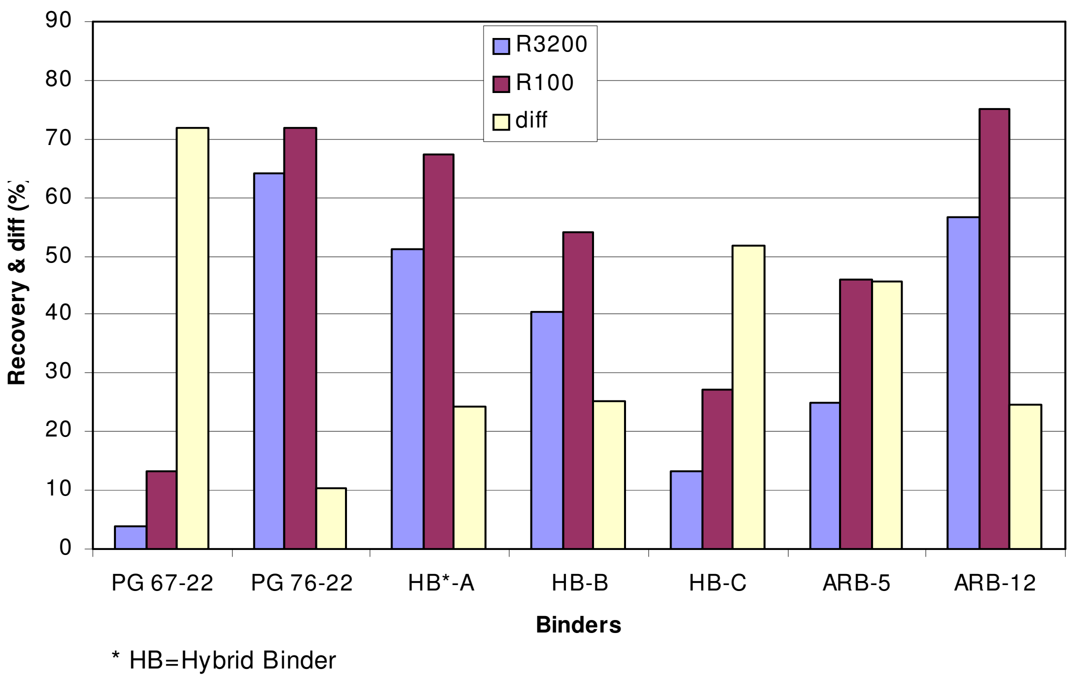


Figure A- 17 Average % Recovery at 67 C (152.6 F) (RTFOT Residue)

Rating for Average % Recovery at 67 C (152.6 F) (RTFOT Residue)

(denominator=65 and 75 for R3200 and R100 respectively, numerator=10 for difference)

Binders	R3200	R100	Difference	Average
PG 67-22	0.6	1.8	1.4	1.3
PG 76-22	9.9	9.6	9.5	9.7
Hybrid Binder A	7.9	9.0	4.1	6.0
Hybrid Binder B	6.2	7.2	4.0	5.1
Hybrid Binder C	2.0	3.6	1.9	2.0
ARB-5	3.9	6.1	2.2	3.0
ARB-12	8.7	10.0	4.1	6.4

Table A- 26 Average Non-recoverable creep compliance at 67 C (152.6 F) (RTFOT Residue)

Binders	Avg. Non-recoverable creep compliance (J_{nr}3.2)	Avg. Non-recoverable creep compliance (J_{nr}0.1)	Difference in Jnr 0.1 and Jnr 3.2 (%)
PG 67-22	2.06	1.66	24.51
PG 76-22	0.24	0.19	29.30
Hybrid Binder A	0.21	0.13	63.20
Hybrid Binder B	0.34	0.25	36.17
Hybrid Binder C	0.78	0.61	28.85
ARB-5	0.58	0.38	0.5332
ARB-12	0.15	0.08	0.8663

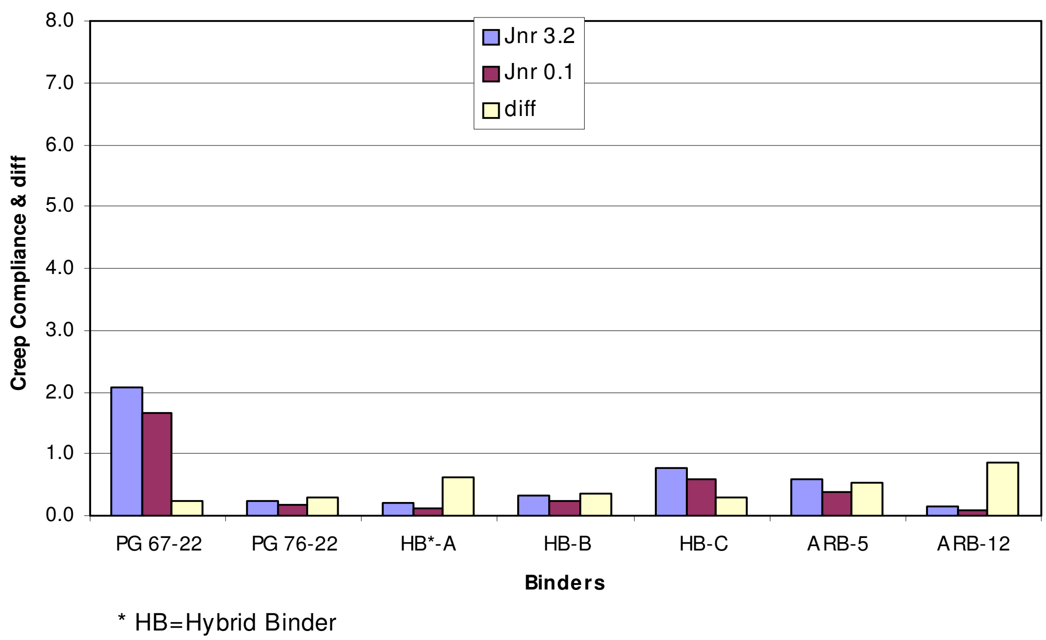


Figure A- 18 Average Non-recoverable creep compliance at 67 C (152.6 F) (RTFOT Residue)

Rating for Average Non-recoverable creep compliance at 67 C (152.6 F)

(denominator=0.9 for difference, numerator= 0.14 and 0.07 for Jnr 3.2 and Jnr 0.1 respectively)

Binders	Jnr 3.2	Jnr 0.1	Difference	Average
PG 67-22	0.7	0.4	2.7	1.3
PG 76-22	5.8	3.8	3.3	4.3
Hybrid Binder A	6.7	5.4	7.0	6.4
Hybrid Binder B	4.2	2.9	4.0	3.7
Hybrid Binder C	1.8	1.2	3.2	2.1
ARB-5	2.4	1.8	5.9	3.4
ARB-12	9.7	9.3	9.6	9.5

Table A- 27 Average % Recovery at 76 C (168.8 F) (RTFOT Residue)

Binders	Average Recovery at 3.2 kPa (R3200) (%)	Average Recovery at 0.1 kPa (R100) (%)	% Difference (Rdiff)
PG 67-22	0.68	6.16	88.93
PG 76-22	31.87	54.24	41.25
Hybrid Binder A	23.08	53.05	56.46
Hybrid Binder B	16.85	38.75	56.58
Hybrid Binder C	3.05	13.84	78.01
ARB-5	6.81	32.27	78.86
ARB-12	20.30	58.37	65.21

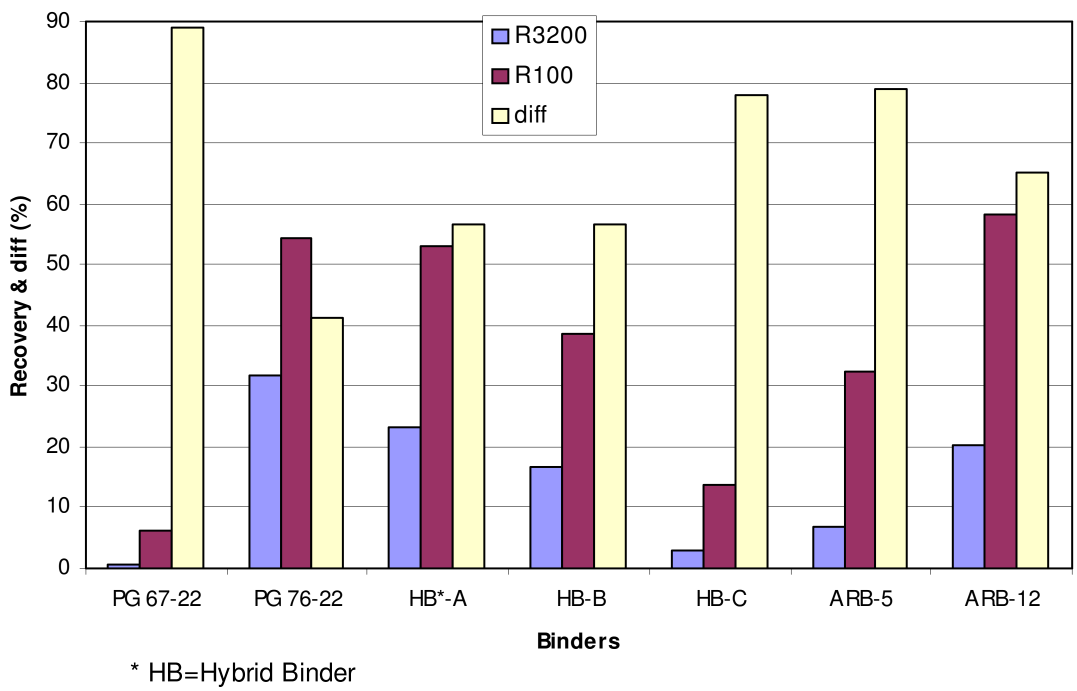


Figure A- 19 Average % Recovery at 76 C (168.8 F) (RTFOT Residue)

Rating for Average % Recovery at 76 C (168.8 F)

(denominator=32 and 60 for R3200 and R100 respectively, numerator=40 for difference)

Binders	R3200	R100	Difference	Average
PG 67-22	0.2	1.0	4.5	1.9
PG 76-22	10.0	9.0	9.7	9.6
Hybrid Binder A	7.2	8.8	7.1	7.7
Hybrid Binder B	5.3	6.5	7.1	6.3
Hybrid Binder C	1.0	2.3	5.1	2.8
ARB-5	2.1	5.4	5.1	4.2
ARB-12	6.3	9.7	6.1	7.4

Table A- 28 Average Non-recoverable creep compliance at 76 C (168.8 F) (RTFOT Residue)

Binders	Avg. Non-recoverable creep compliance (J_{nr}3.2)	Avg. Non-recoverable creep compliance (J_{nr}0.1)	Difference in Jnr 0.1 and Jnr 3.2 (%)
PG 67-22	7.05	5.65	24.84
PG 76-22	1.34	0.81	65.54
Hybrid Binder A	1.02	0.51	103.42
Hybrid Binder B	1.51	0.92	63.76
Hybrid Binder C	3.02	2.25	34.46
ARB-5	2.42	1.35	0.7919
ARB-12	0.87	0.36	1.4319

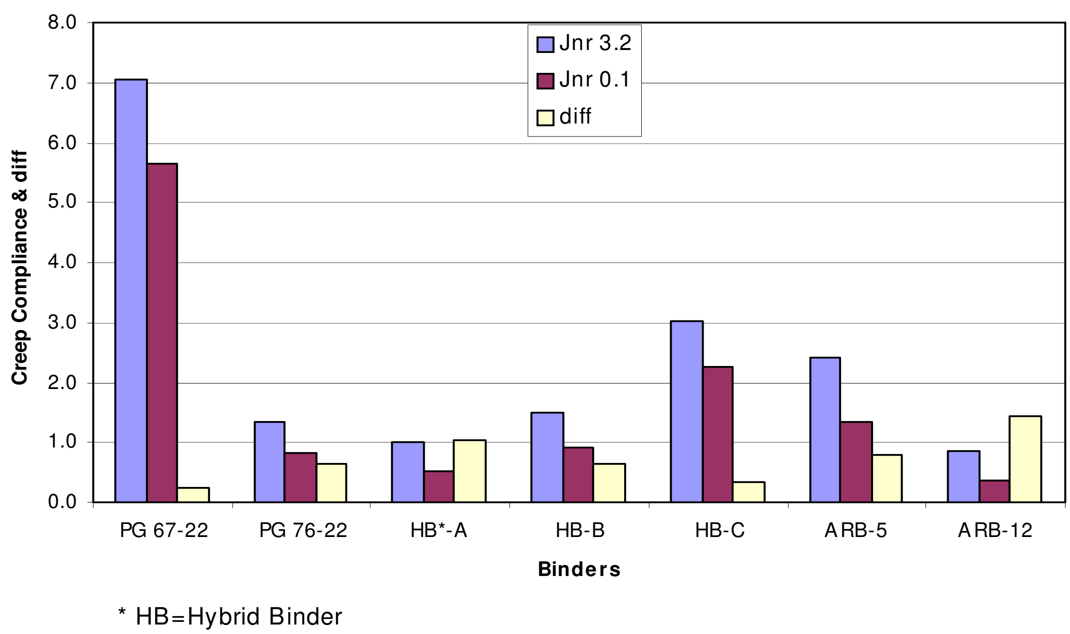


Figure A- 20 Average Non-recoverable creep compliance at 76 C (168.8 F) (RTFOT Residue)

Rating for Average Non-recoverable creep compliance at 76 C (168.8 F)

(denominator=1.5 for difference, numerator= 0.85 and 0.35 for Jnr 3.2 and Jnr 0.1 respectively)

Binders	Jnr 3.2	Jnr 0.1	Difference	Average
PG 67-22	1.2	0.6	1.7	1.2
PG 76-22	6.4	4.3	4.4	5.0
Hybrid Binder A	8.3	6.9	6.9	7.4
Hybrid Binder B	5.6	3.8	4.3	4.6
Hybrid Binder C	2.8	1.6	2.3	2.2
ARB-5	3.5	2.6	5.3	3.8
ARB-12	9.8	9.7	9.5	9.7

Rating (MSCR):

Binders	MSCR,Recovery	MSCR, Non-recoverable Creep Compliance
PG 67-22	1.6	1.3
PG 76-22	9.7	4.7
Hybrid Binder A	6.9	6.9
Hybrid Binder B	5.7	4.2
Hybrid Binder C	2.4	2.2
ARB-5	3.6	3.6
ARB-12	6.9	9.6

APPENDIX A.4 ELASTIC RECOVERY

Table A- 29 Elastic Recovery at 25 C (77 F) (RTFOT Residue)

Binders	Replicate A (%)	Replicate B (%)	Average (%)
PG 67-22	7.41	4.94	6.18
PG 76-22	75.00	75.00	75.00
Hybrid Binder A	66.25	67.50	66.88
Hybrid Binder B	72.50	72.50	72.50
Hybrid Binder C	23.75	25.00	24.38

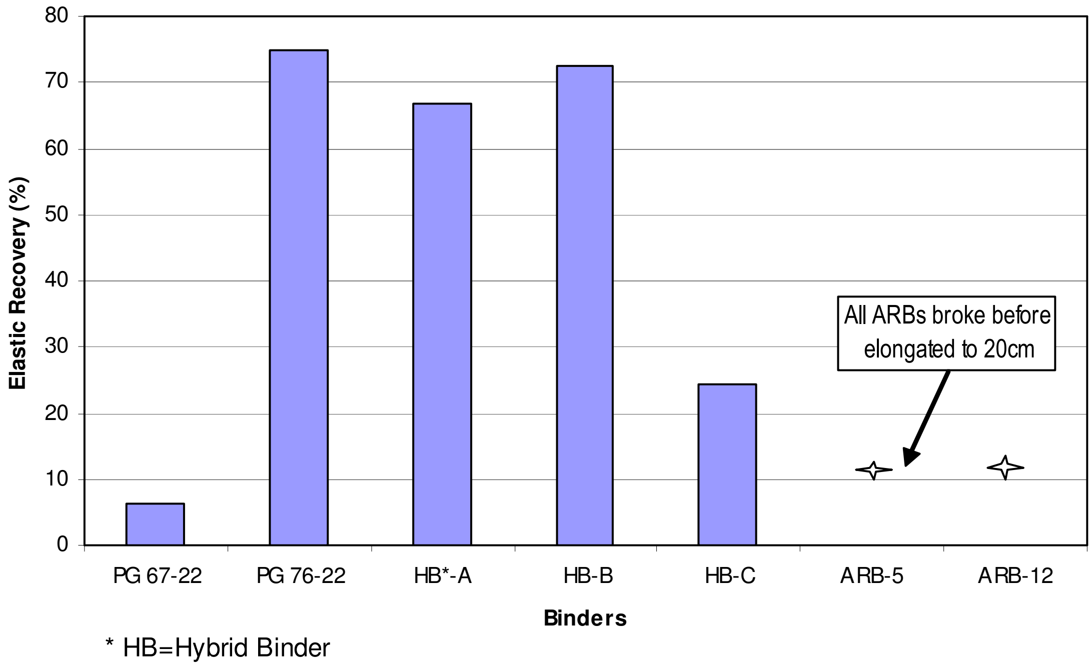


Figure A- 21 Elastic Recovery at 25 C (77 F) (RTFOT Residue)

Rating for Elastic Recovery at 25 C (77 F)

(denominator=75)

Binders	Elastic Recovery
PG 67-22	0.8
PG 76-22	10.0
Hybrid Binder A	8.9
Hybrid Binder B	9.7
Hybrid Binder C	3.3
ARB-5	n/a
ARB-12	n/a

APPENDIX A.5 FORCE DUCTILITY TEST

Table A- 30 Force Ductility Test Result

Binders	f2/f1 (Orig.Binders at 10 °C)	f2/f1 (RTFOT Residue at 10 °C)	f2/f1 (PAV Residue at 25 °C)
PG 67-22	0.04	0.04	0.03
PG 76-22	0.53	0.43	0.26
Hybrid Binder A	0.46	0.36	0.40
Hybrid Binder B	0.42	0.40	0.40
Hybrid Binder C	0.17	0.20	0.13
ARB-5	0.20	0.32	0.24
ARB-12	0.24	0.51	0.18

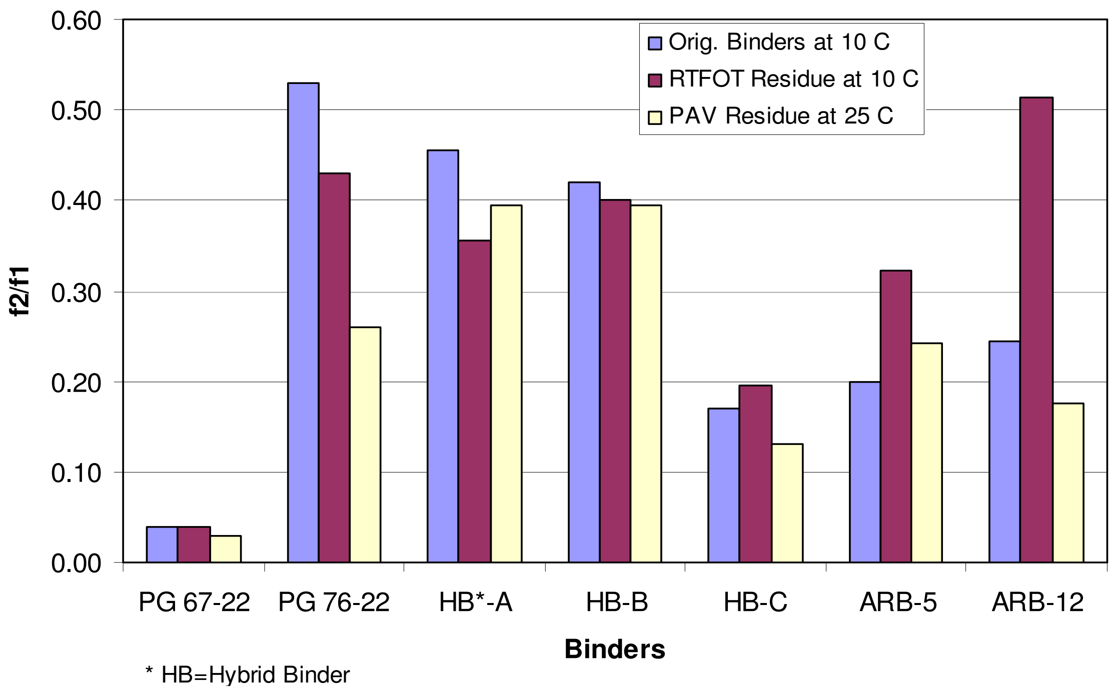


Figure A- 22 Force Ductility Test Result

Rating for Force Ductility Test

(denominator=0.55, 0.52 and 0.4 for Original Binder, RTFOT and PAV Residue respectively)

Binders	Original Binder	RTFOT Residue	PAV Residue	Average
PG 67-22	0.7	0.8	0.8	0.7
PG 76-22	9.6	8.3	6.5	8.1
Hybrid Binder A	8.3	6.8	9.9	8.3
Hybrid Binder B	7.6	7.7	9.9	8.4
Hybrid Binder C	3.1	3.8	3.3	3.4
ARB-5	3.6	6.2	6.1	5.3
ARB-12	4.4	9.9	4.4	6.2

Table A- 31 Force Ductility Test, Force vs. Elongation

	(lbs) - PG 67-22					
	Original		RTFOT		PAV	
cm	sample 1	sample 2	sample 1	sample 2	sample 1	sample 2
0	0	0	0	0	0	0
1	6.18	6.47	12.52	13.93	3.02	3.29
2	6.54	6.84	13.48	14.39	3.39	3.52
3	5.89	6.21	12.08		3.21	3.31
4	5.18	5.49	10.54		2.86	2.93
5	4.32	4.73	8.84		2.40	2.53
6	3.85	4.11	7.62	7.81	2.03	2.06
7	3.18	3.34	6.30	6.55	1.73	1.78
8	2.71	2.97	5.31	5.73	1.15	1.49
9	2.34	2.43	4.58	4.70	1.18	1.20
10	2.20	2.13	3.94	3.85	1.01	1.01
11	1.67	1.88	3.52	3.40	0.87	0.90
12	1.50	1.66	3.08	3.05	0.75	0.70
13	1.39	1.44	2.65	2.61	0.66	0.66
14	1.18	1.28	2.35	2.26	0.59	0.58
15	1.00	1.15	2.11	2.00	0.51	0.51
16	0.93	1.04	1.84		0.47	0.46
17	0.80	0.91	1.63		0.42	0.41
18	0.75	0.85	1.39		0.36	0.37
19	0.68	0.78	1.21	1.18	0.34	0.31
20	0.59	0.69	0.96	1.02	0.31	0.29
21	0.50	0.66	0.64	0.89	0.29	0.26
22	0.45	0.54		0.81	0.26	0.23
23	0.45	0.51		0.69	0.23	0.20
24	0.40	0.45		0.55	0.22	0.16
25	0.38	0.41		0.42	0.20	0.15
26	0.36	0.38			0.17	0.14
27	0.30	0.35			0.16	0.12
28	0.30	0.32			0.15	0.10
29	0.28	0.32			0.14	0.09
30	0.26	0.31			0.13	0.07

Table A- 32 Force Ductility Test, Force vs. Elongation

	(lbs) - PG 76-22					
	Original		RTFOT		PAV	
cm	sample 1	sample 2	sample 1	sample 2	sample 1	sample 2
0	0	0	0	0	0	0
1	7.11	7.49	12.64	12.32	4.08	3.26
2	7.58	7.84	14.00	14.08	4.97	
3	7.43	7.50	13.89	13.88	5.14	
4	6.74	7.00	12.65	12.66	5.07	
5	6.42	6.50	11.64	11.60	4.88	4.08
6	5.98	6.08	10.52	10.53	4.63	
7	5.64	5.73	9.72	9.88	4.42	
8	5.41	5.49	9.38	9.35	4.21	
9	5.19	5.31	9.07	9.02	3.94	
10	5.11	5.16	8.75	8.70	3.77	3.76
11	5.00	5.06	8.44	8.47	3.54	
12	4.93	4.97	8.25	8.19	3.32	
13	4.87	4.89	8.11	8.08	3.14	
14	4.81	4.85	7.99	7.97	2.87	
15	4.80	4.81	7.85	7.76	2.65	2.83
16	4.75	4.76	7.70	7.56	2.39	
17	4.71	4.74	7.57	7.46	2.07	
18	4.70	4.72	7.43	7.20	1.70	
19	4.66	4.68			1.14	
20	4.64	4.66	7.12		1.10	1.27
21	4.61	4.63	6.84			
22	4.58	4.61	6.59			
23	4.54	4.58	6.32			
24	4.50	4.53	6.10			
25	4.42	4.47	5.72			
26	4.38	4.40	5.34			
27	4.31	4.33	4.88			
28	4.22	4.27				
29	4.15	4.18				
30	4.06	4.08				

Table A- 33 Force Ductility Test, Force vs. Elongation

	(lbs) – Hybrid Binder A					
	Original		**RTFOT**		**PAV**	
cm	sample 1	sample 2	sample 1	sample 2	sample 1	sample 2
0	0	0	0	0	0	0
1	10.23	10.74	16.02	15.70		4.03
2	11.30	11.58	16.22	15.50		4.56
3	9.85	10.10	14.92	14.12		4.43
4	9.11	9.18	13.29	12.92		4.09
5	8.01	8.28	11.87	11.28	3.68	3.67
6	7.56	7.57	10.94	10.34		3.26
7	7.00	7.30	9.98	9.46		2.95
8	6.57	6.82	9.28	8.89		2.71
9	6.29	6.31	8.78	8.36		2.48
10	6.10	6.18	8.40	8.13	2.39	2.32
11	5.94	6.01	8.08	7.80		2.20
12	5.87	5.97	7.93	7.68		2.07
13	5.80	5.86	7.80	7.57		2.02
14	5.77	5.83	7.74	7.52		1.92
15	5.75	5.80	7.68	7.48	1.94	1.85
16	5.74	5.78	7.62	7.38		1.79
17	5.73	5.76	7.47	7.28		1.70
18	5.71	5.72	7.42	7.18		1.59
19	5.69	5.71	7.30	7.11		
20	5.62	5.61	7.16	6.96	1.64	
21	5.42	5.42	6.93	6.80		
22	5.20	5.23	6.70	6.58		
23			6.46	6.33		
24			6.16	6.06		
25			5.68	5.69		
26						
27						
28						
29						
30						

Table A- 34 Force Ductility Test, Force vs. Elongation

cm	(lbs) - Hybrid Binder B					
	Original		RTFOT		PAV	
	sample 1	sample 2	sample 1	sample 2	sample 1	sample 2
0	0	0	0	0	0	0
1	9.80	9.77	14.53	14.88		
2	10.14	10.30	15.04	14.99		
3	9.30	9.46	13.64	13.44		
4	8.36	8.46	11.71	11.66		
5	7.40	7.50	10.40	10.22	3.38	3.04
6	6.61	6.68	9.18	8.78		
7	5.98	6.01	8.26	8.16		
8	5.38	5.50	7.45	7.30		
9	5.13	5.14	6.94	6.80		
10	4.86	4.88	6.74	6.65	2.38	2.15
11	4.60	4.65	6.39	6.33		
12	4.44	4.48	6.23	6.12		
13	4.26	4.30	6.09	6.02		
14	4.26	4.30	6.01	5.94		
15	4.19	4.20	5.94	5.84	2.06	1.87
16	4.14	4.13	5.92	5.82		
17	4.13	4.12	5.90	5.80		
18			5.89	5.78		
19	4.13	4.11	5.88	5.78		
20	4.13	4.11	5.89	5.79	1.88	1.68
21	4.14	4.12	5.90	5.82		
22	4.15	4.14	5.93	5.83		
23	4.19	4.16	5.96	5.86		
24	4.21	4.19	5.97	5.88		
25	4.24	4.22	6.00	5.91	1.71	1.53
26	4.26	4.25	6.02	5.92		
27	4.28	4.28	6.04	5.94		
28	4.30	4.33	6.05	5.95		
29	4.30	4.33	6.06	5.96		
30	4.30	4.33	6.06	5.97	1.53	1.36

Table A- 35 Force Ductility Test, Force vs. Elongation

cm	(lbs) – Hybrid Binder C					
	Original		**RTFOT**		**PAV**	
	sample 1	sample 2	sample 1	sample 2	sample 1	sample 2
0	0	0	0	0	0	0
1	7.49	7.00	15.80	15.61		
2	7.86	7.58	16.21	15.59		
3	7.31	7.28	14.59	14.00		
4	6.42	6.43	12.58	12.41		
5	5.64	5.62	10.75	10.14	4.62	3.97
6	4.69	4.86	9.08	8.71		
7	4.22	4.19	7.69	7.28		
8	3.70	3.69	6.82	6.59		
9	3.28	3.20	6.14	5.86		
10	2.97	2.91	5.36	5.18	1.76	1.70
11	2.62	2.58	4.81	4.72		
12	2.39	2.34	4.41	4.29		
13	2.23	2.17	4.16	4.05		
14	2.07	2.01	3.87	3.74		
15	1.96	1.90	3.60	3.57	1.11	0.96
16	1.82	1.77	3.51	3.44		
17	1.77	1.70	3.38	3.27		
18	1.65	1.60	3.31	3.23		
19	1.57	1.55	3.25	3.16		
20	1.51	1.52	3.21	3.11	0.86	0.72
21	1.49	1.47	3.20	3.07		
22	1.44	1.45	3.19	3.05		
23	1.41	1.40	3.19	3.02		
24	1.38	1.39	3.20	3.01		
25	1.35	1.35	3.22	3.00	0.71	0.60
26	1.34	1.34	3.23	3.00		
27	1.33	1.33	3.25	3.00		
28	1.33	1.32	3.26	3.00		
29	1.31	1.32	3.27	3.00		
30	1.30	1.32	3.28	3.01	0.61	0.51

Table A- 36 Force Ductility Test, Force vs. Elongation

	(lbs) - ARB-5					
	Original		RTFOT		PAV	
cm	sample 1	sample 2	sample 1	sample 2	sample 1	sample 2
0	0	0	0	0	0	0
1	7.49	8.00	14.56	14.28	3.79	3.60
2	8.03	8.67	14.88	14.83	3.86	3.80
3	7.54	8.20	14.03	13.76	3.64	3.77
4	6.89	7.54	12.77	12.54	3.37	3.59
5	6.33	6.81	11.15	11.19	2.99	3.07
6	5.69	6.08	10.07	9.84	2.74	2.96
7	5.12	5.55	9.11	8.89	2.45	2.83
8	4.71	5.17	8.30	8.10	2.37	2.72
9	4.39	4.79	7.82	7.46	2.12	2.50
10	4.07	4.45	7.30	6.95	1.71	2.10
11	3.85	4.26	6.85	6.52	1.61	1.99
12	3.72	4.00	6.49	6.10	1.62	1.81
13	3.50	3.88	6.21	5.72	1.50	1.80
14	3.34	3.60	5.84	5.36	1.35	1.74
15	3.17	3.50	5.49	5.25	1.28	1.65
16	3.02	3.26	5.01	5.00	1.28	1.32
17	2.85	3.16	4.56		1.13	1.20
18	2.66	2.96	7.01		1.02	1.19
19	2.53	2.80			0.96	1.05
20	2.37	2.52			0.91	0.99
21	2.19	2.42				0.95
22	2.08	2.22				
23	1.92	1.98				
24	1.73	1.79				
25	1.54					
26						
27						
28						
29						
30						

Table A- 37 Force Ductility Test, Force vs. Elongation

	(lbs) - ARB-12					
	Original		RTFOT		PAV	
cm	sample 1	sample 2	sample 1	sample 2	sample 1	sample 2
0	0	0	0	0	0	0
1	10.19	9.06	14.79	14.02	3.53	2.80
2	11.17	10.86	16.01	15.38	3.96	3.37
3	11.38	10.91	15.71	15.03	4.02	3.47
4	10.62	10.28	14.41	13.92	3.82	3.26
5	9.60	9.47	13.40	13.15	3.47	3.04
6	9.08	8.83	12.70	11.99	3.14	3.71
7	8.42	8.13	11.68	11.14	2.90	2.40
8	7.82	7.57	11.18	10.56	2.67	2.19
9	7.22	7.09	10.59	10.04	2.47	1.98
10	6.81	6.64	10.15	9.60	2.29	1.82
11	6.45	6.29	9.65	9.24	2.19	1.65
12	6.06	5.93	8.97	8.90	2.06	1.49
13	5.73	5.55	8.83	8.63	1.91	1.39
14	5.28	5.20	8.45	8.28	1.81	1.28
15	4.92	4.80		7.69	1.66	1.16
16	4.51	4.33			1.58	1.08
17	4.23	3.98			1.49	0.95
18	3.84	3.43			1.35	0.89
19	3.47	2.92			1.20	0.77
20	3.17	2.60			1.08	0.68
21	2.84				0.90	0.63
22						0.55
23						0.44
24						
25						
26						
27						
28						
29						
30						

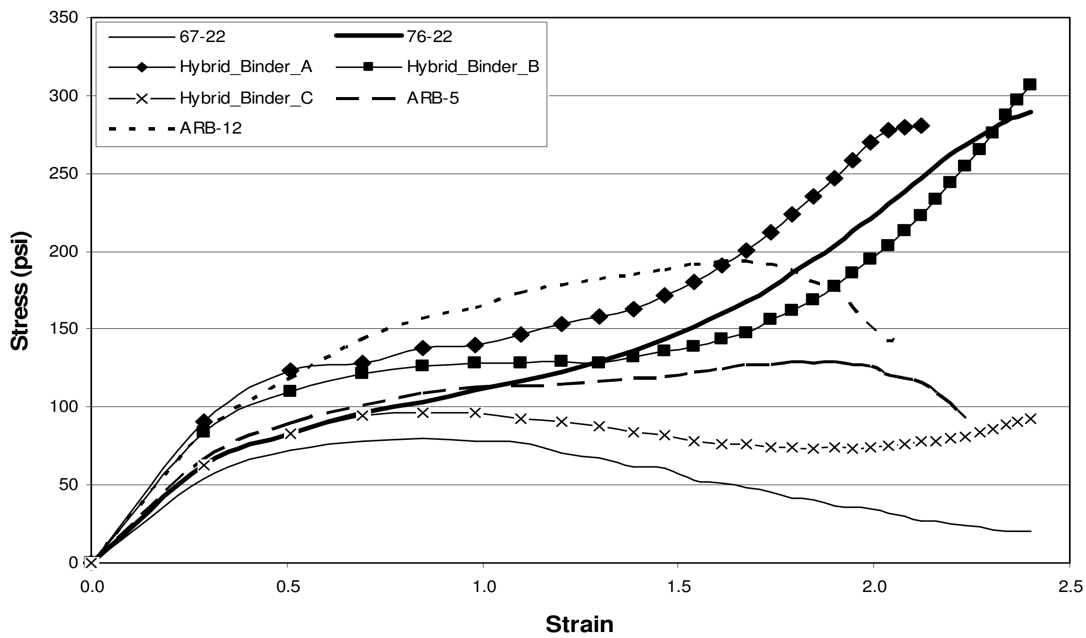


Figure A- 23 Original Binders' Stress-Strain Diagram (10 C (50 F))

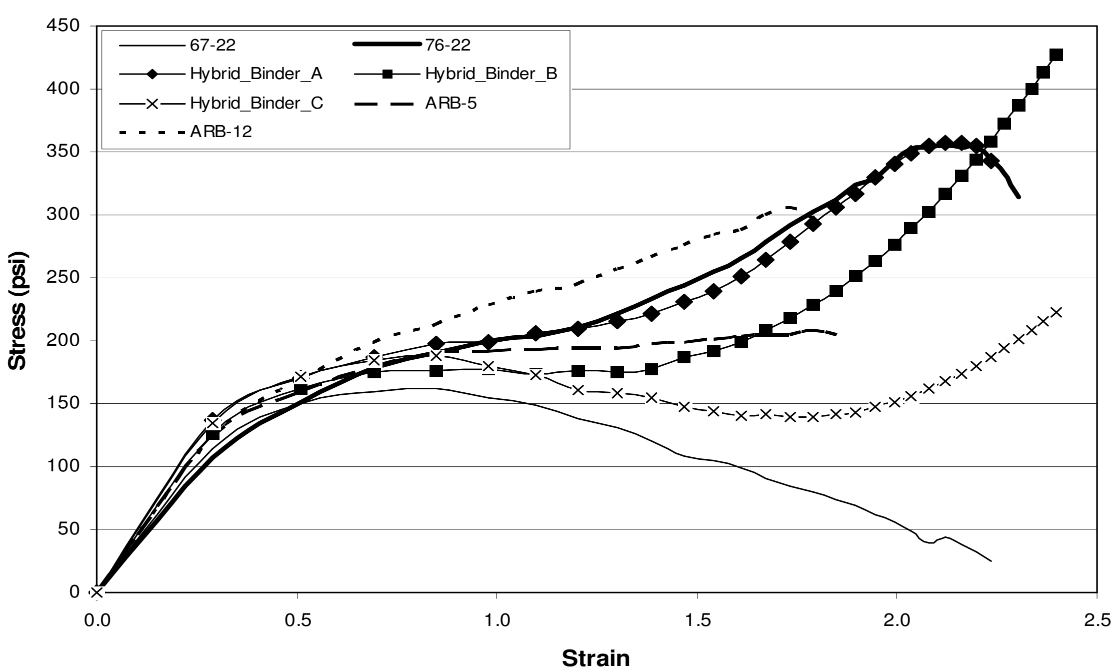


Figure A- 24 RTFOT Residues' Stress-Strain Diagram (10 C (50 F))

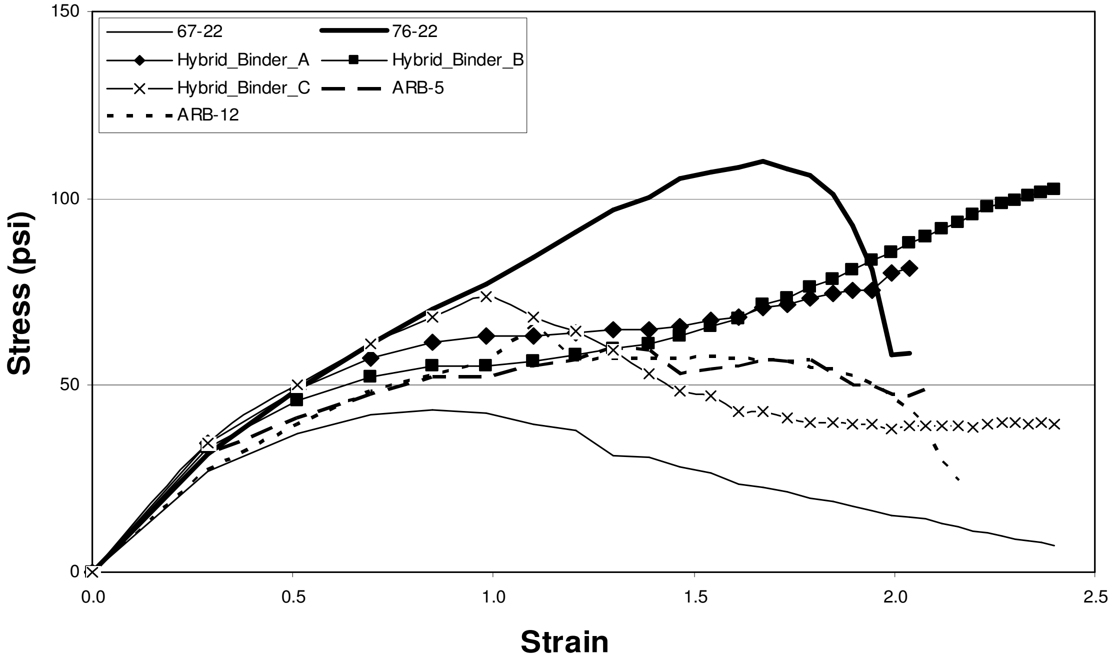


Figure A- 25 PAV Residues' Stress-Strain Diagram (25 C (77 F))

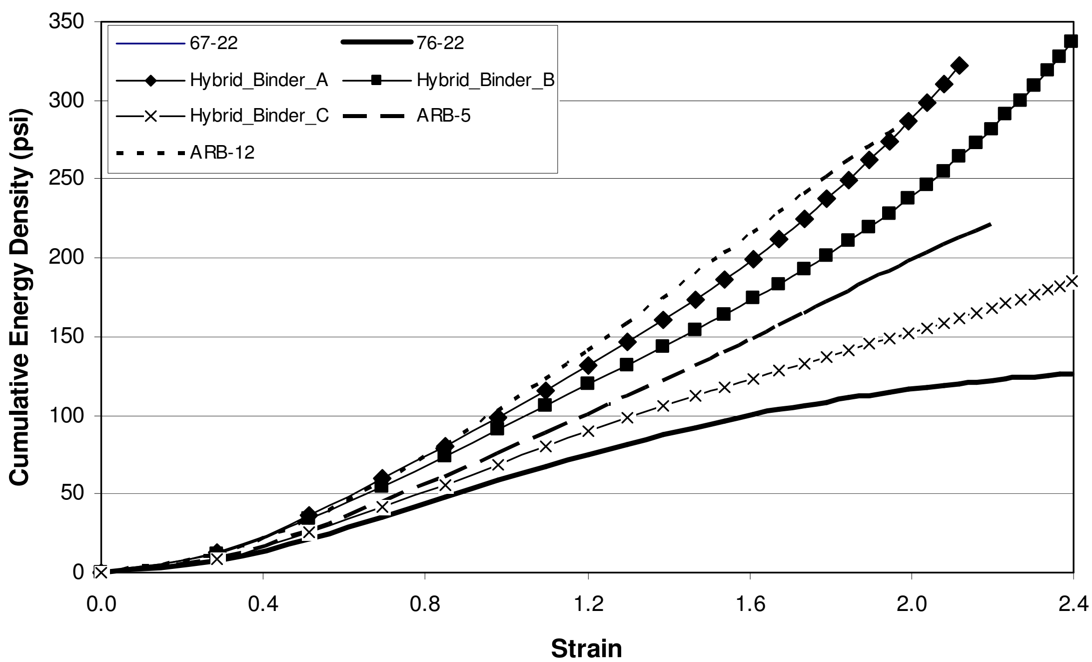


Figure A- 26 Original Binders' Cumulative Energy Density at 10 C (50 F)

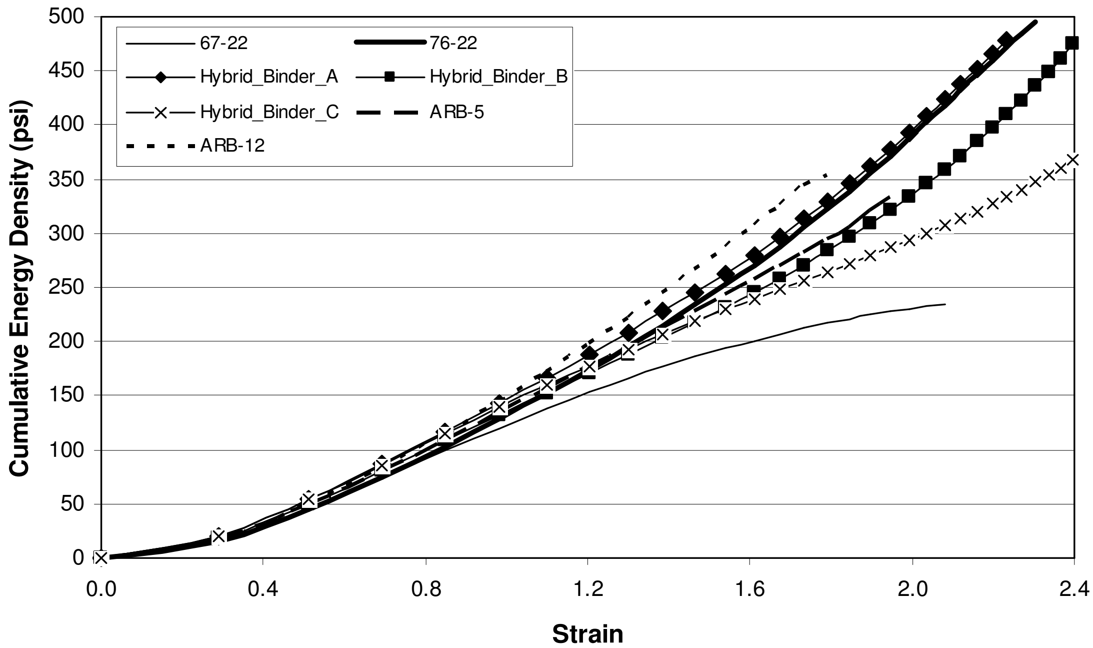


Figure A- 27 RTFOT Residues' Cumulative Energy Density at 10 C (50 F)

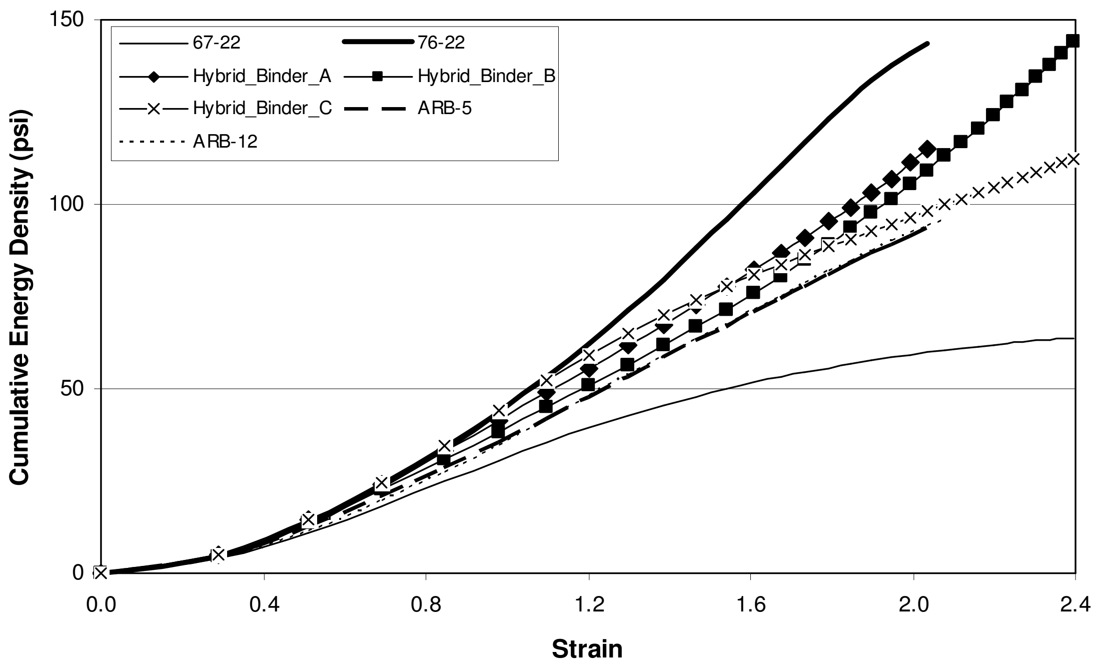


Figure A- 28 PAV Residues' Cumulative Energy Density at 25 C (77 F)

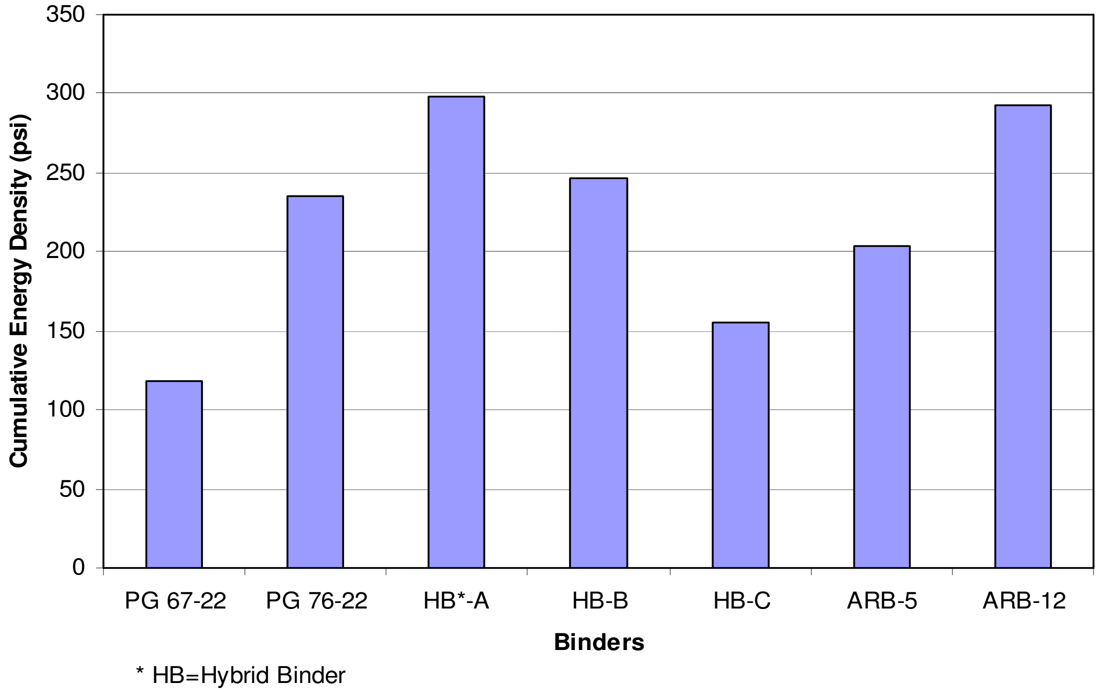


Figure A- 29 Original Binder (10 C (50 F)) Cumulative Energy Comparison at Same Strain 2.04 at which ARB-12 cracks

Rating for Cumulative Energy of Original Binder

Rating: (denominator=300)

PG 67-22	PG 76-22	A	B	C	ARB-5	ARB-12
3.9	7.9	10.0	8.2	5.2	6.8	9.8

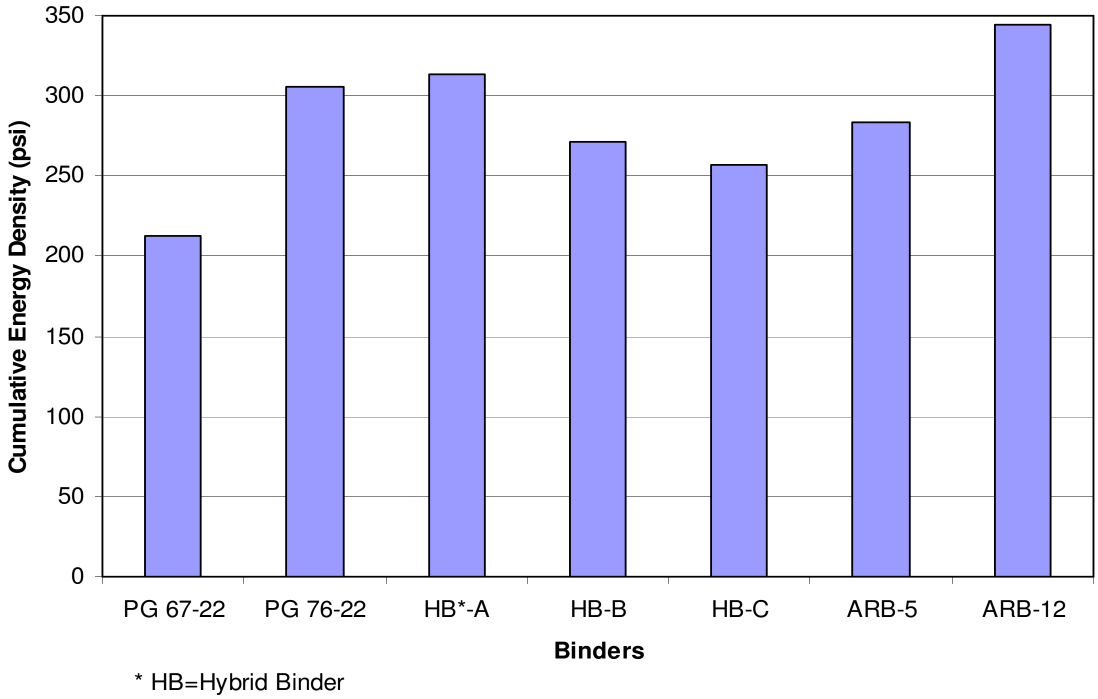


Figure A- 30 A.30 RTFOT residue 10 C (50 F) Cumulative Energy Comparison at Same Strain 1.73 at which ARB-12 cracks

Rating for Cumulative Energy of RTFOT Residue

(denominator=350)

PG 67-22	PG 76-22	A	B	C	ARB-5	ARB-12
6.1	8.7	8.9	7.7	7.3	8.1	9.8

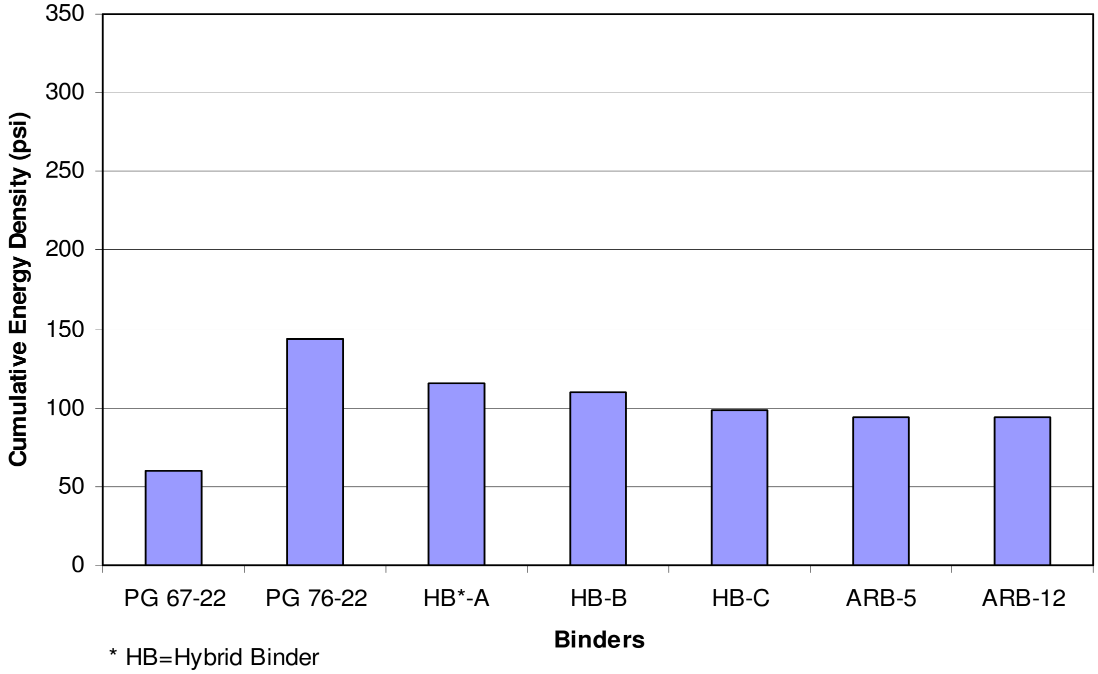


Figure A- 31 PAV residue 25 C (77 F) Cumulative Energy Comparison at Same Strain 2.04 at which PG 76-22 cracks

Rating for Cumulative Energy of PAV Residue

(denominator=150)

PG 67-22	PG 76-22	A	B	C	ARB-5	ARB-12
4.0	9.6	7.7	7.3	6.5	6.2	6.3

Table A- 38 Rating for Binders

Binders	G*/sinδ	G*sinδ	MSCR, Recovery	MSCR, Non-recoverable Creep Compliance	Elastic Recovery	Force Ductility, f2/f1 (PAV residue)	Force Ductility, Cumulative Energy (PAV residue)
PG 67-22	4.9	7.3	1.6	1.3	0.8	0.8	4.0
PG 76-22	7.2	7.7	9.7	4.7	10.0	6.5	9.6
Hybrid Binder A	9.3	8.5	6.9	6.9	8.9	9.9	7.7
Hybrid Binder B	7.9	8.4	5.7	4.2	9.7	9.9	7.3
Hybrid Binder C	6.1	7.3	2.4	2.2	3.3	3.3	6.5
ARB-5	6.7	8.1	3.6	3.6	n/a	6.1	6.2
ARB-12	9.0	9.6	6.9	9.6	n/a	4.4	6.3

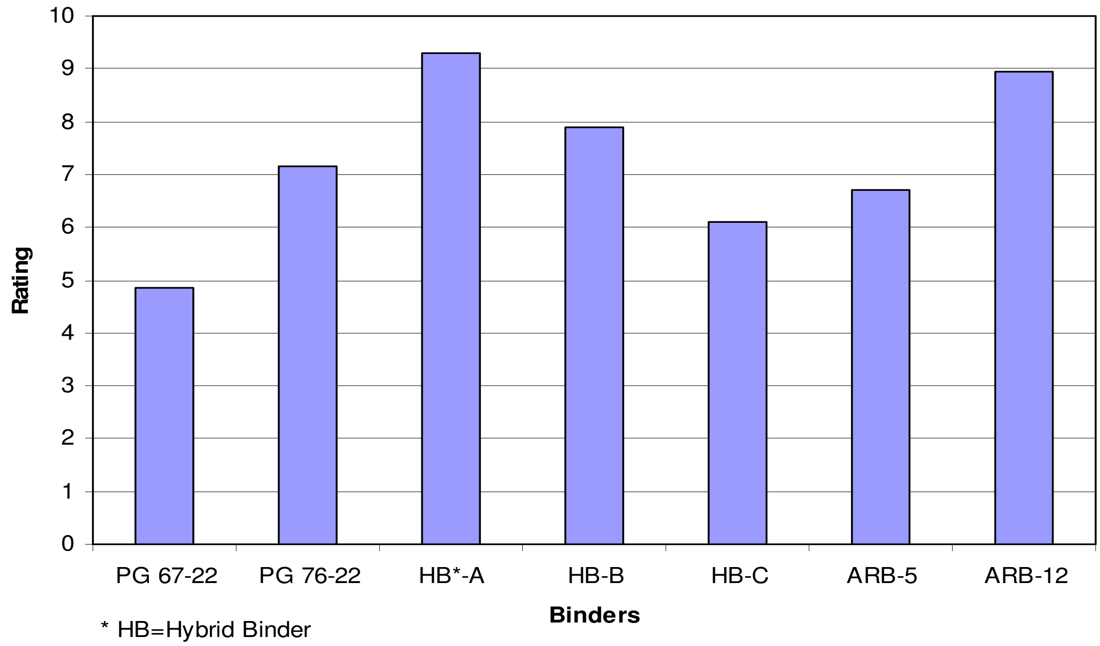


Figure A- 32 Rating based on G*/sinδ

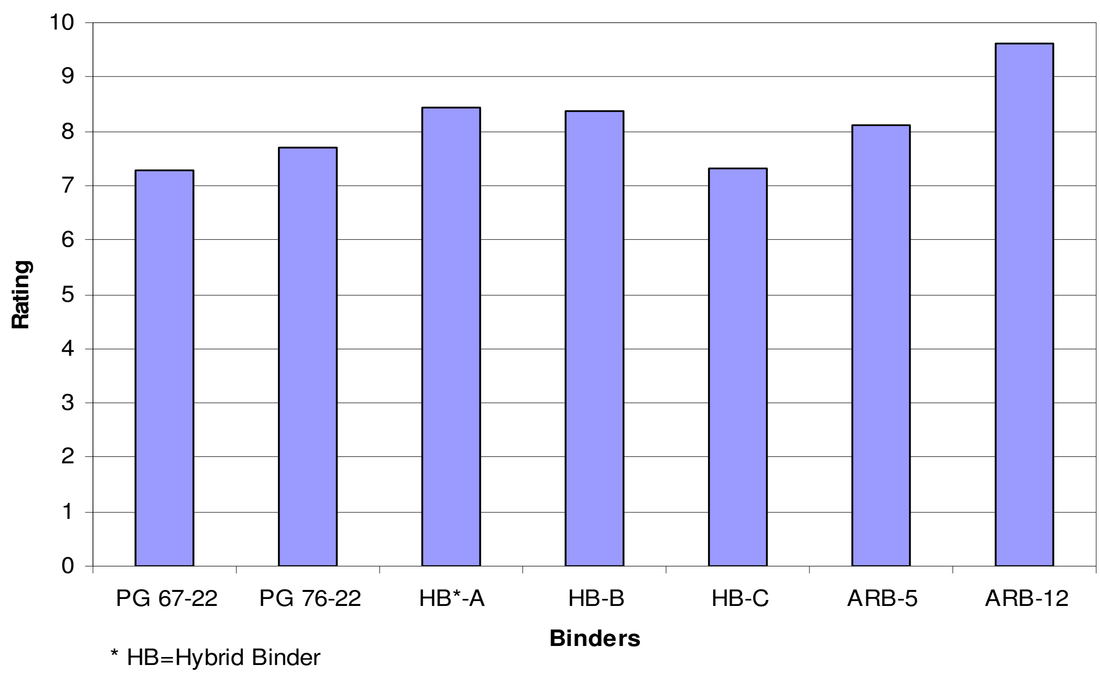


Figure A- 33 Rating based on G*sinδ

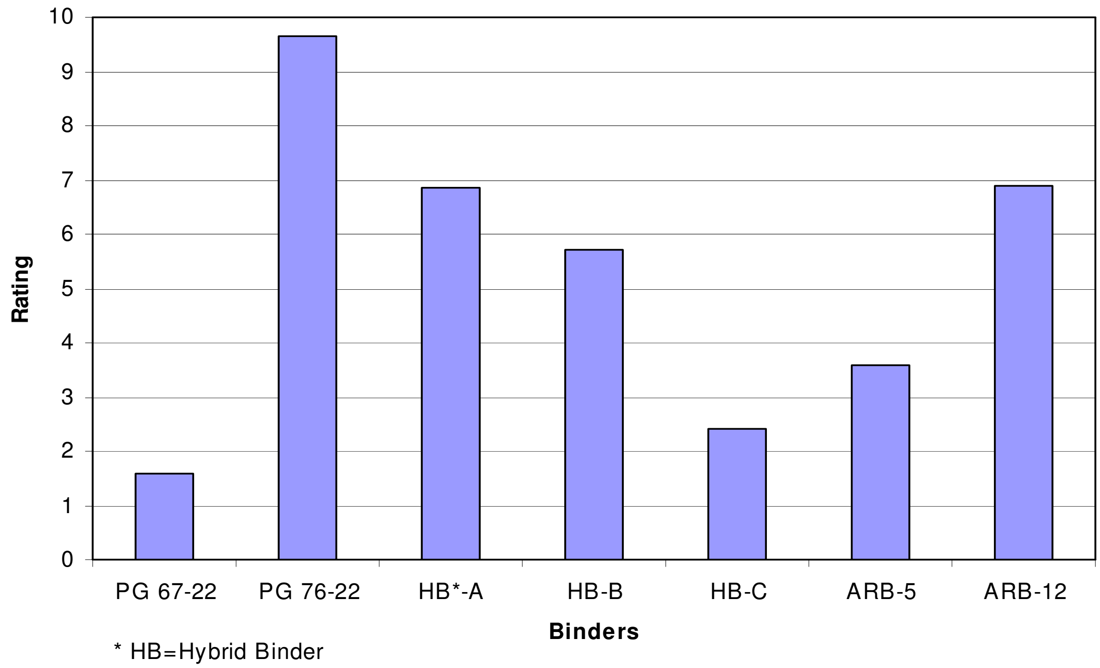


Figure A- 34 Rating based on MSCR, Recovery

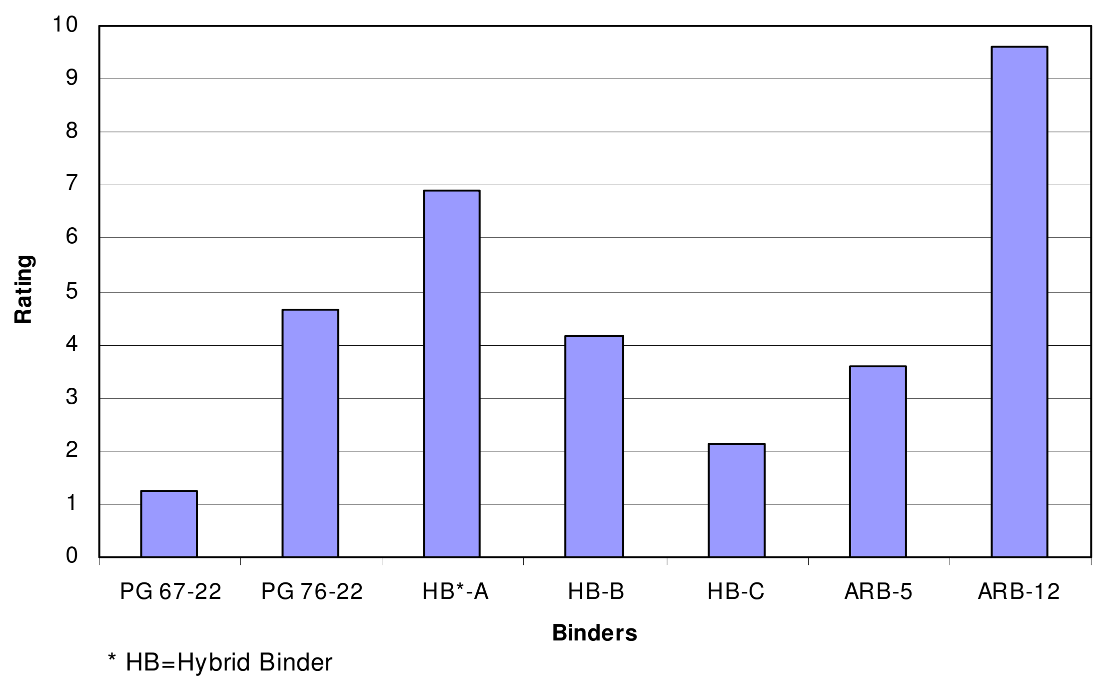


Figure A- 35 Rating based on MSCR, Non-recoverable Creep Compliance

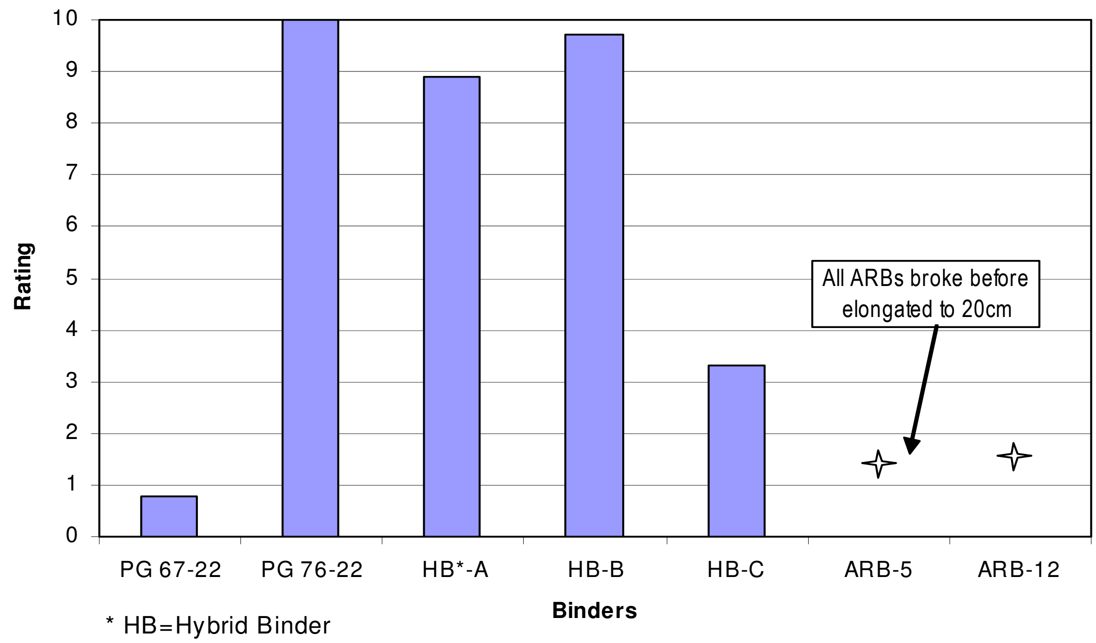


Figure A- 36 Rating based on Elastic Recovery

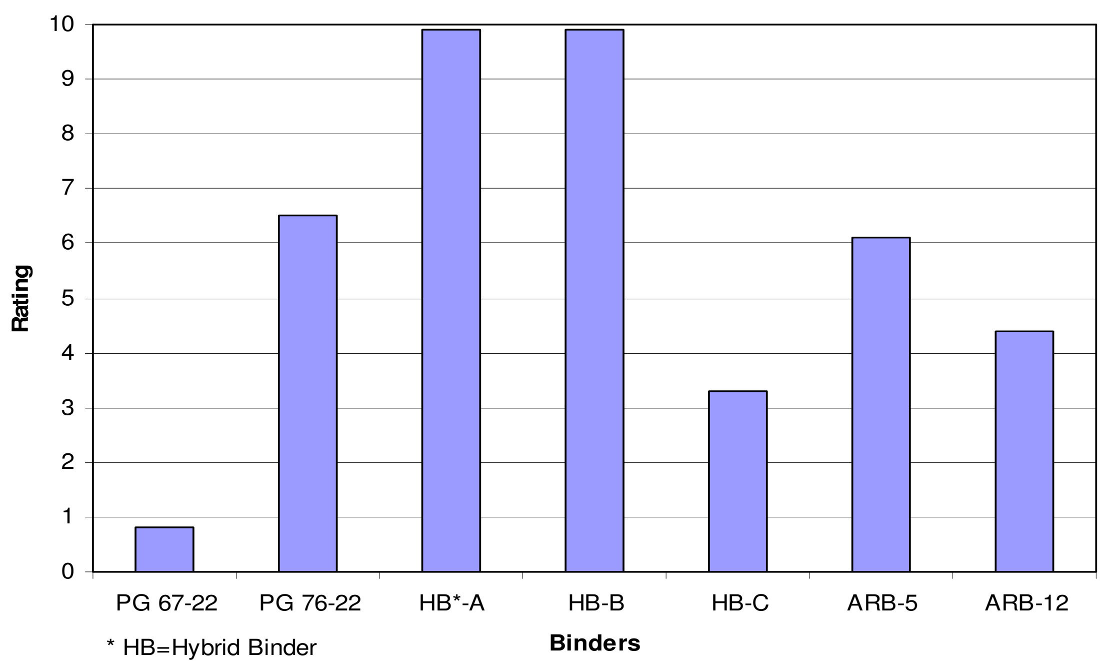


Figure A- 37 Rating based on Force Ductility,f2/f1 (PAV residue)

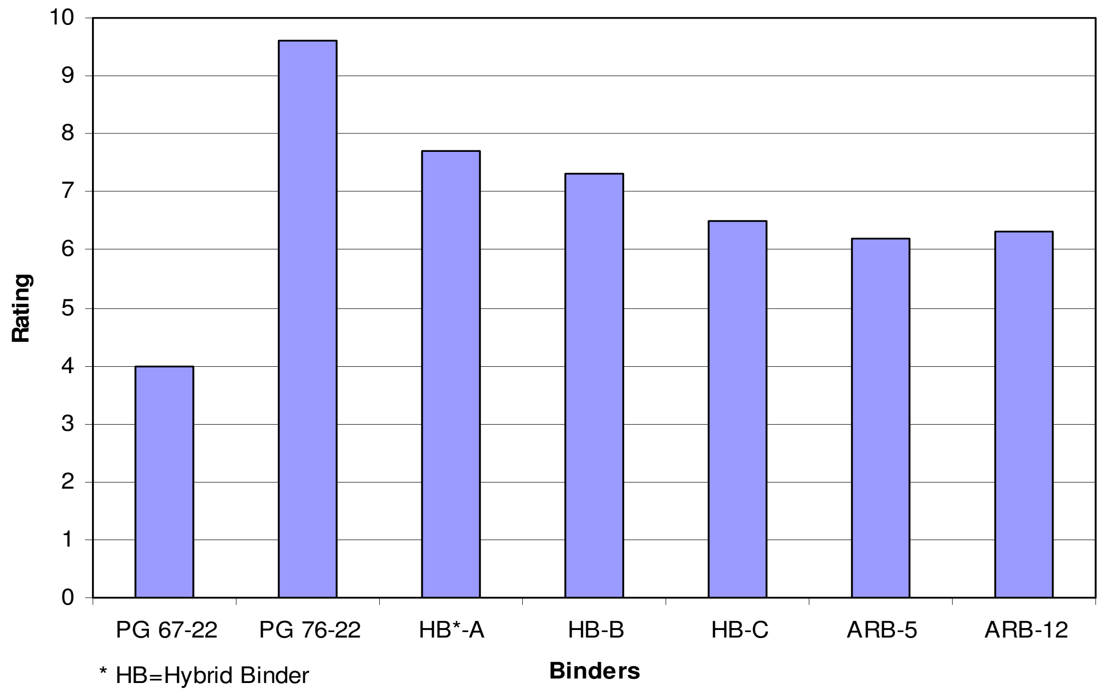


Figure A- 38 Rating based on Force Ductility, Cumulative Energy (PAV residue)

APPENDIX A.6 SOLUBILITY

Table A- 39 Solubility of Original Binders

Binders	Solubility (%)
PG 67-22	99.995
PG 76-22	99.975
Hybrid Binder A	92.760
Hybrid Binder B	96.905
Hybrid Binder C	99.860
ARB-5	93.835
ARB-12	88.765

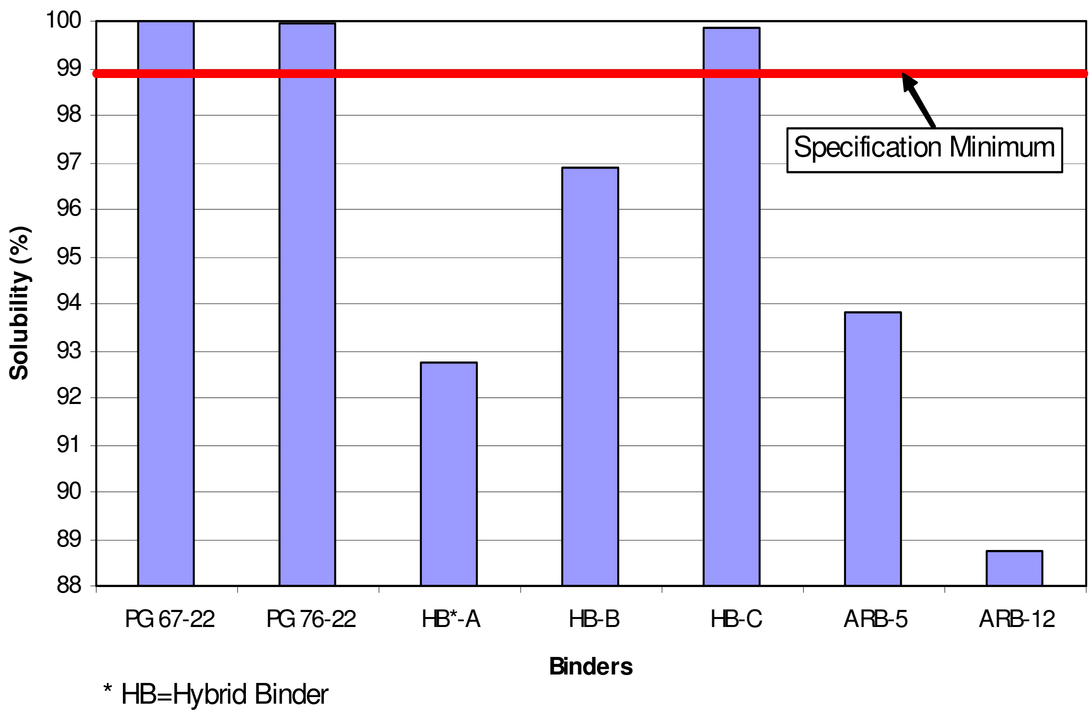


Figure A- 39 Solubility of Original Binders

APPENDIX A.7 SMOKE POINT

Table A- 40 Smoke Points of Original Binders

Binders	Smoke Point (F)
PG 67-22	322.5
PG 76-22	330.0
Hybrid Binder A	325.0
Hybrid Binder B	320.0
Hybrid Binder C	320.0
ARB-5	315.0
ARB-12	320.0

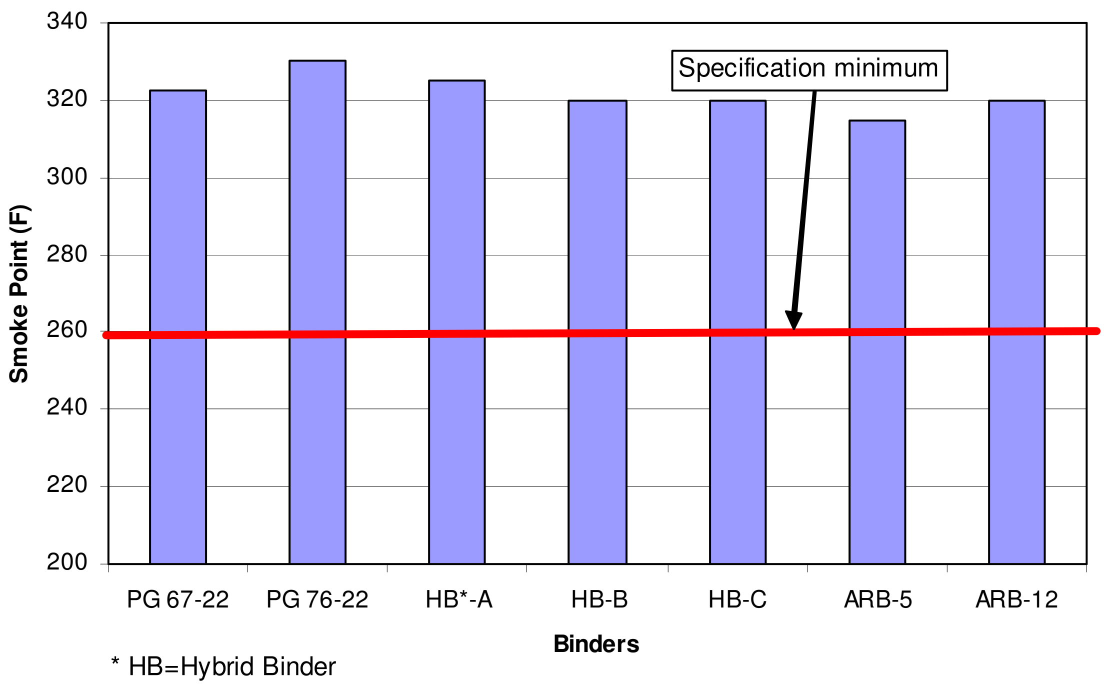


Figure A- 40 Smoke Points of Original Binders

APPENDIX A.8 FLASH POINT

Table A- 41 Flash Point of Original Binders

Binders	Flash Point (F)
PG 67-22	545.0
PG 76-22	552.5
Hybrid Binder A	557.5
Hybrid Binder B	550.0
Hybrid Binder C	495.0
ARB-5	545.0
ARB-12	547.5

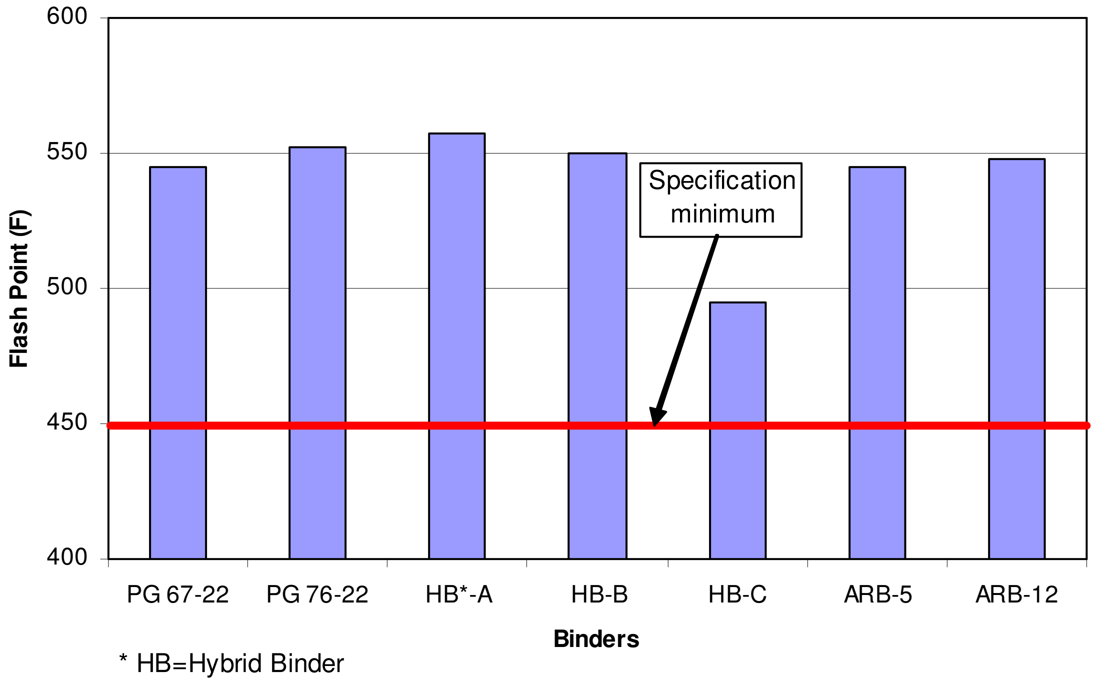


Figure A- 41 Flash Point of Original Binders

APPENDIX A.9 SPOT TEST

Table A- 42 Spot Tests of Original Binders

Binders	Replicate A	Replicate B
PG 67-22	Negative	Negative
PG 76-22	Negative	Negative
Hybrid Binder A	Negative	Negative
Hybrid Binder B	Negative	Negative
Hybrid Binder C	Positive	Negative
ARB-5	Negative	Negative
ARB-12	Negative	Negative

APPENDIX A.10 RTFOT, MASS CHANGE

Table A- 43 RTFOT, Mass Loss (at 163 C (325.4 F))

Binders	Replicate A (%)	Replicate B (%)	Average (%)
PG 67-22	-0.423	-0.412	-0.418
PG 76-22	-0.370	-0.369	-0.370
Hybrid Binder A	-0.341	-0.340	-0.341
Hybrid Binder B	-0.359	-0.319	-0.339
Hybrid Binder C	-0.525	-0.522	-0.524
ARB-5	-0.429	-0.433	-0.431
ARB-12	-0.463	-0.472	-0.468

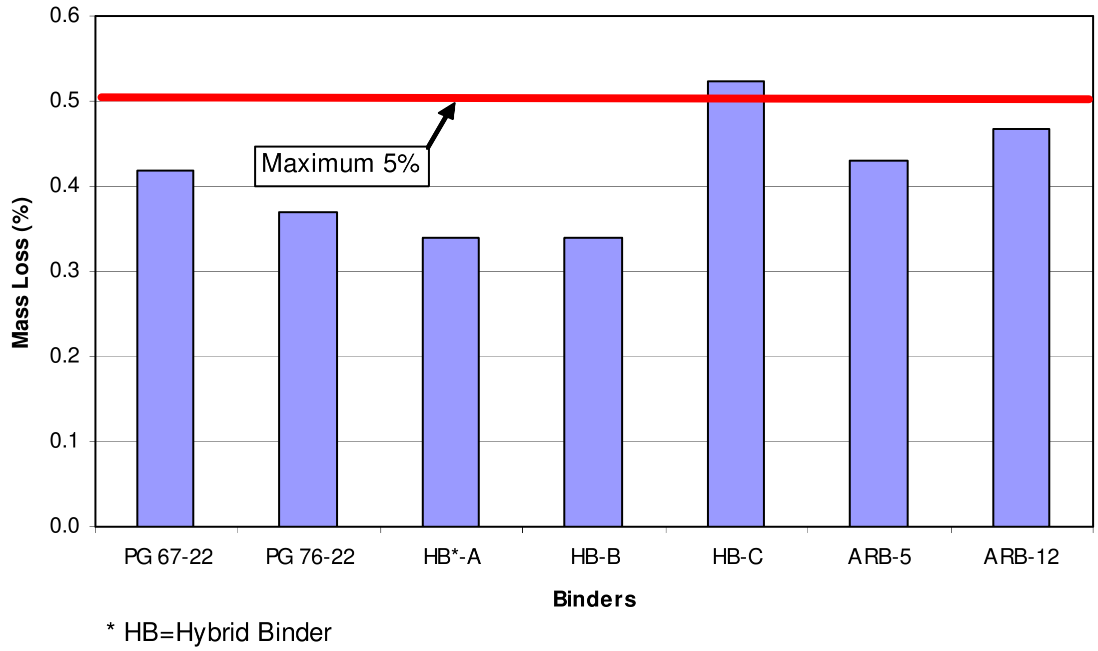


Figure A- 42 RTFOT, Mass Loss (163 C (325.4 F))

APPENDIX B MIXTURE IDT TEST RESULTS

APPENDIX B.1 GRANITE DG MIXTURE IDT TEST RESULTS

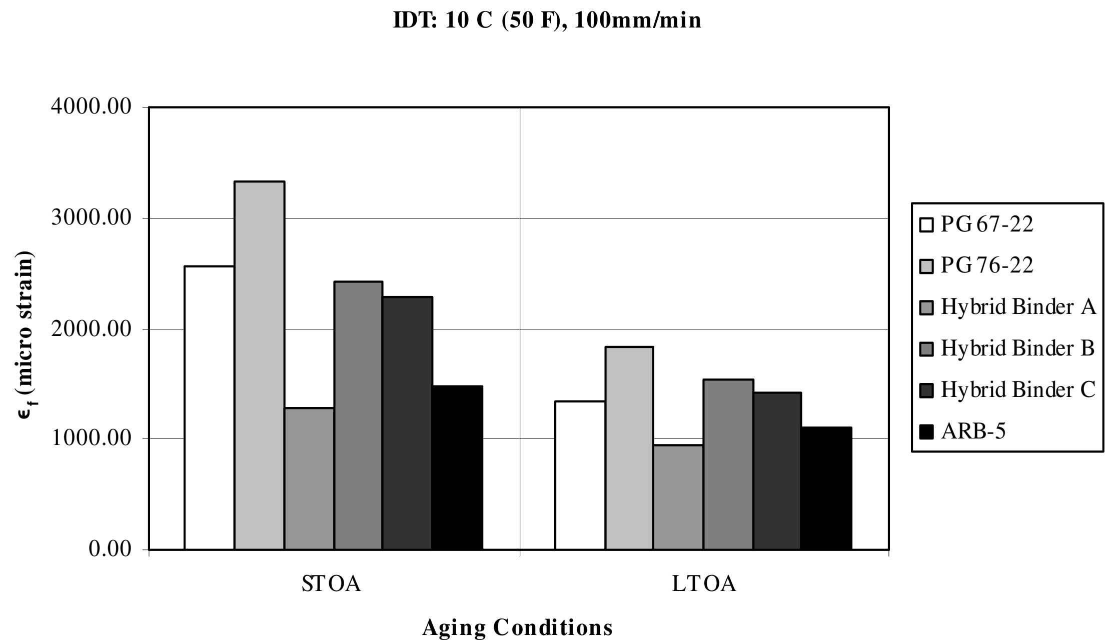


Figure B- 1 Failure Strain: DG Granite Mixtures

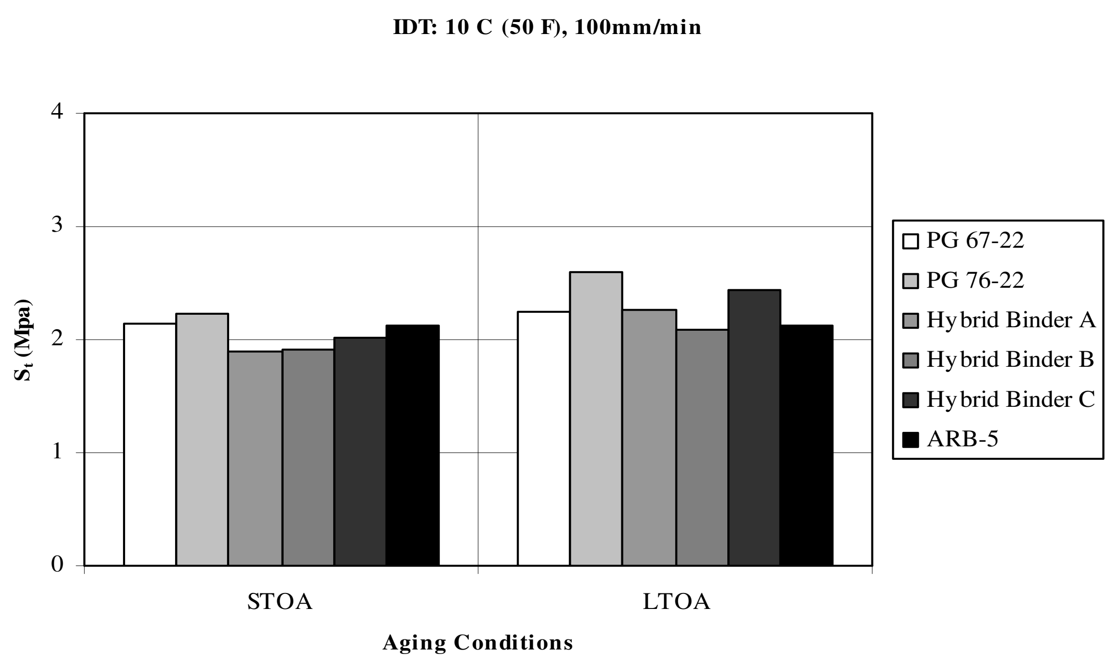


Figure B- 2 Tensile Strength: DG Granite Mixtures

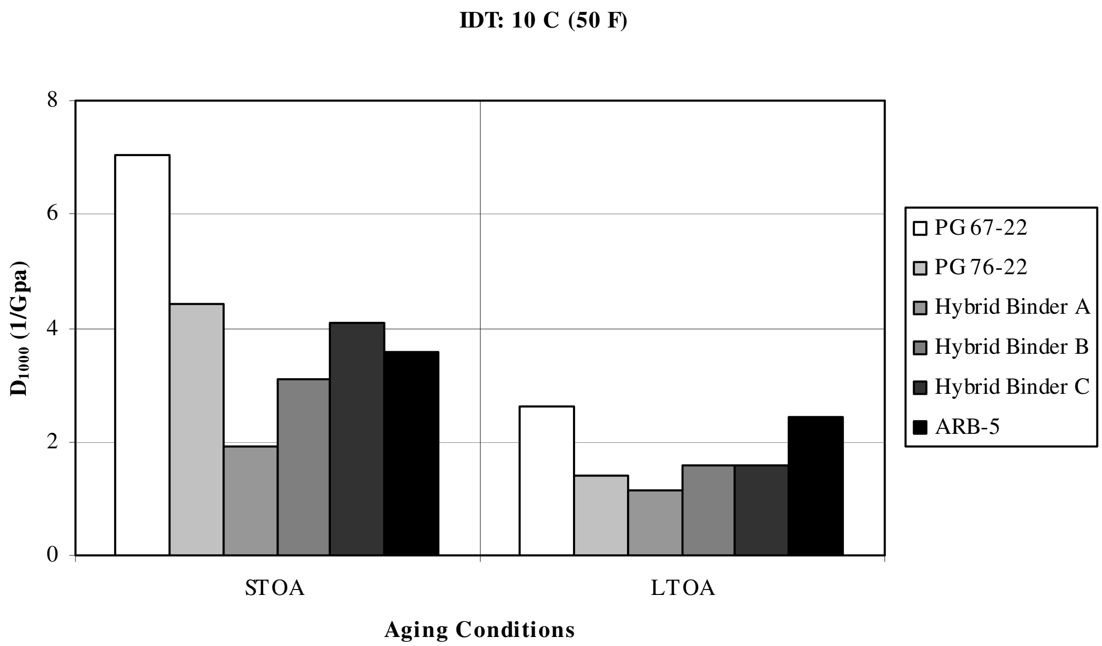


Figure B- 3 Creep Compliance @ 1000 second: DG Granite Mixtures

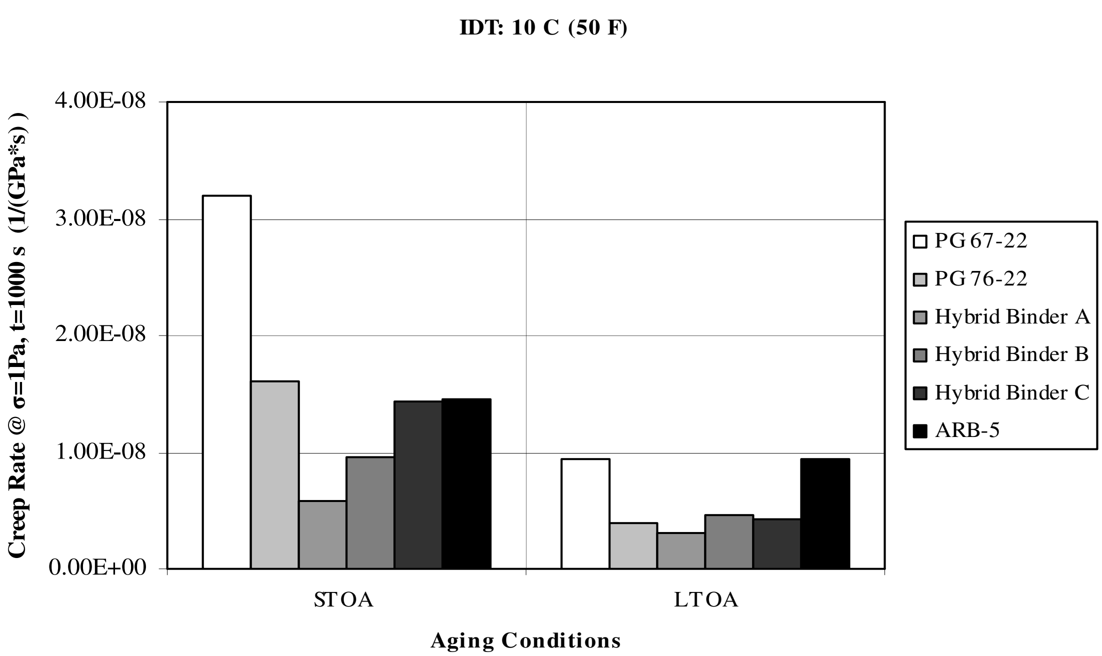


Figure B- 4 Creep Rate @σ=1Pa, 1000 second: DG Granite Mixtures

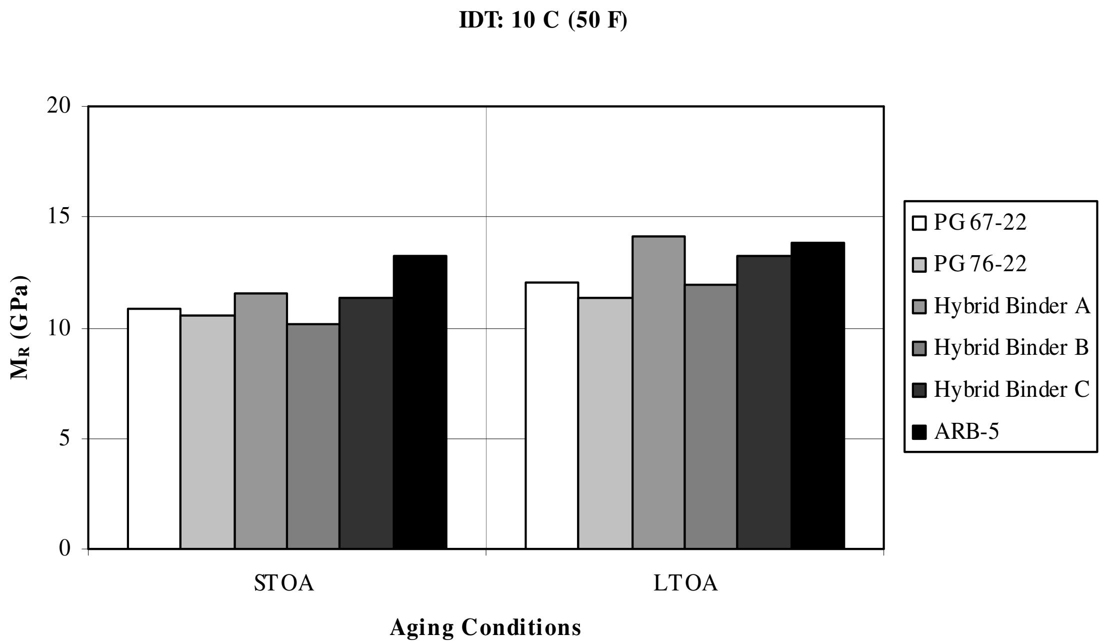


Figure B- 5 Resilient Modulus: DG Granite Mixtures

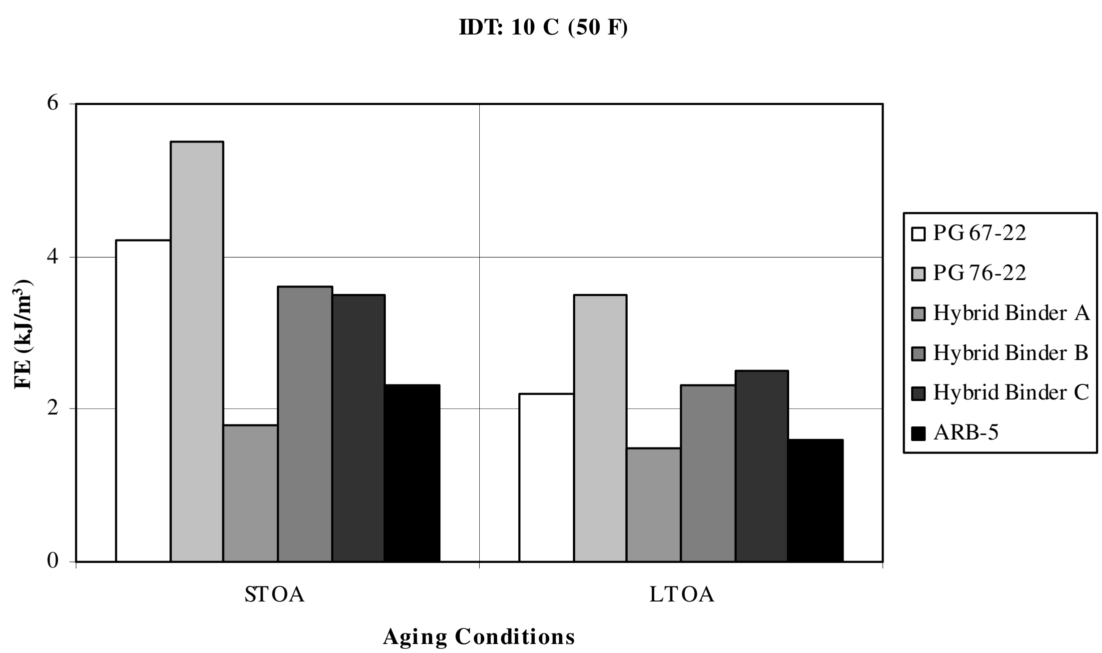


Figure B- 6 Fracture Energy: DG Granite Mixtures

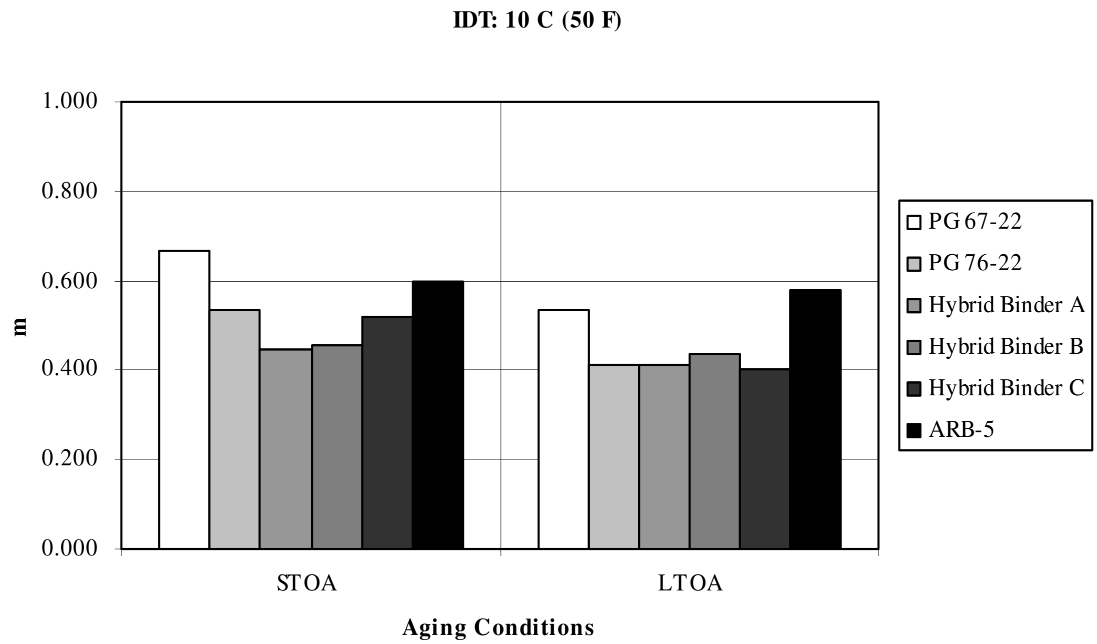


Figure B- 7 Creep Rate: DG Granite Mixtures

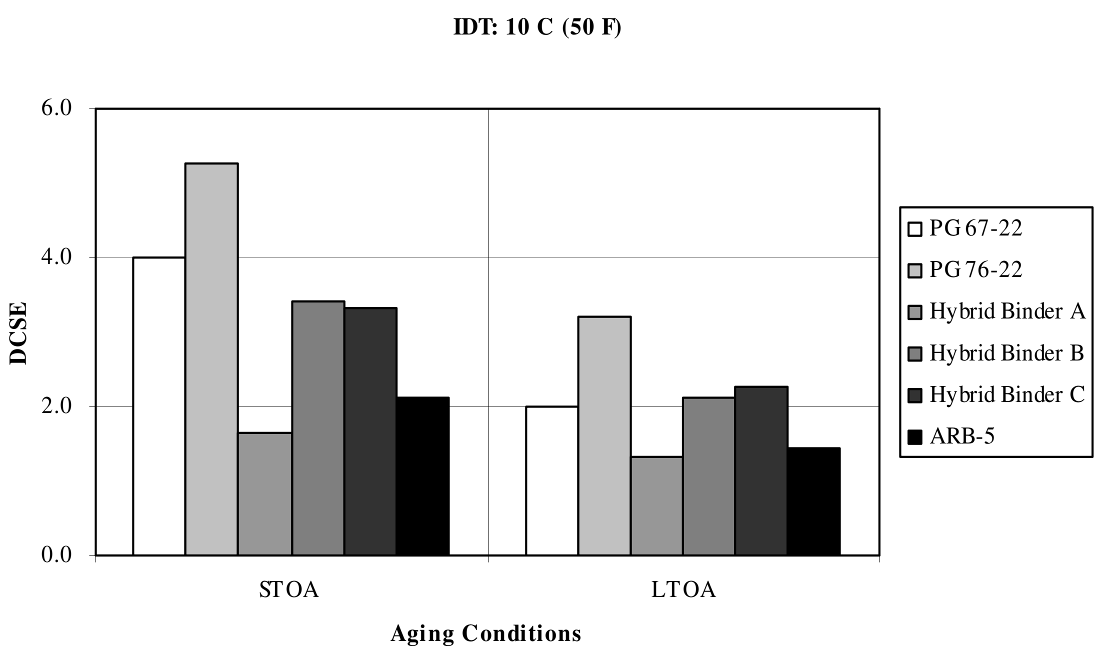


Figure B- 8 DCSE: DG Granite Mixtures

APPENDIX B.2 LIMESTONE DG MIXTURE IDT TEST RESULTS

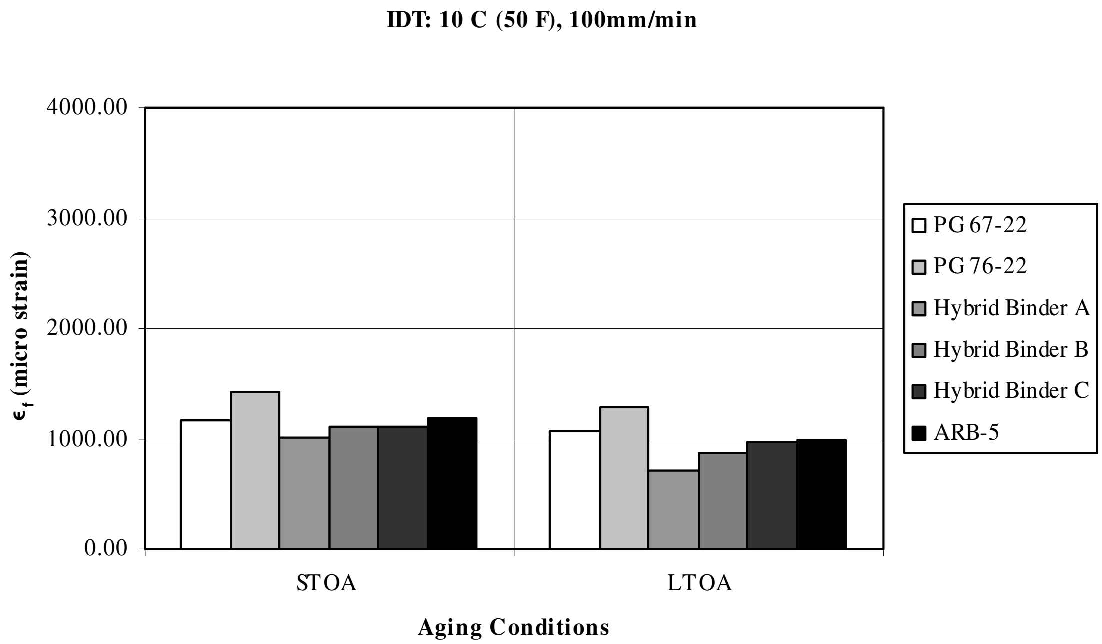


Figure B- 9 Failure Strain: DG Limestone Mixtures

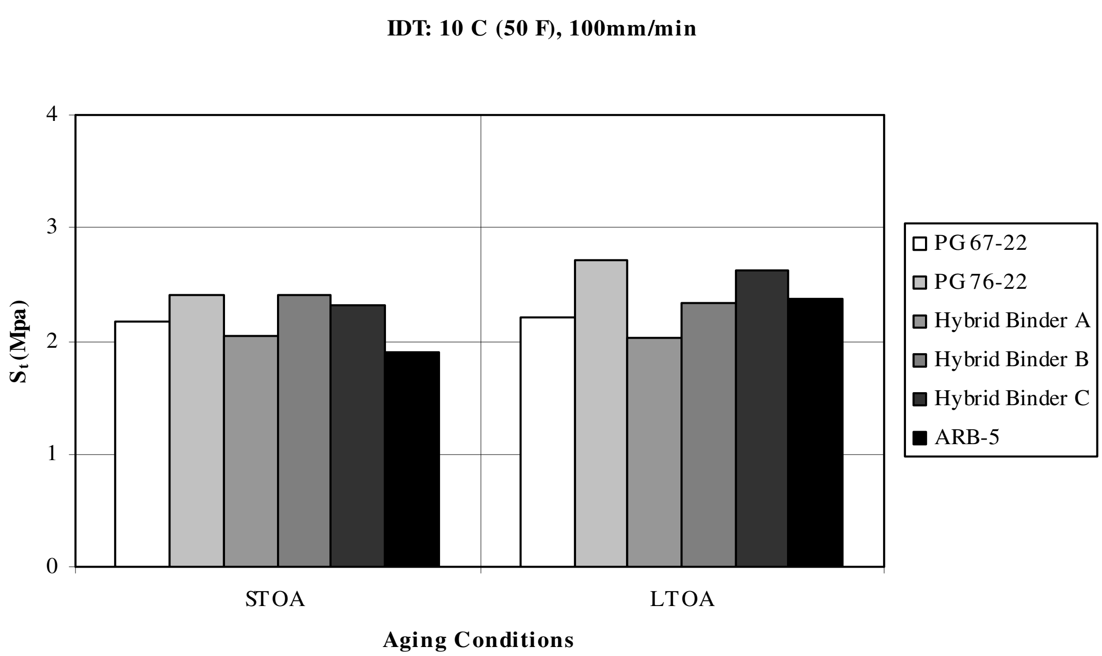


Figure B- 10 Tensile Strength: DG Limestone Mixtures

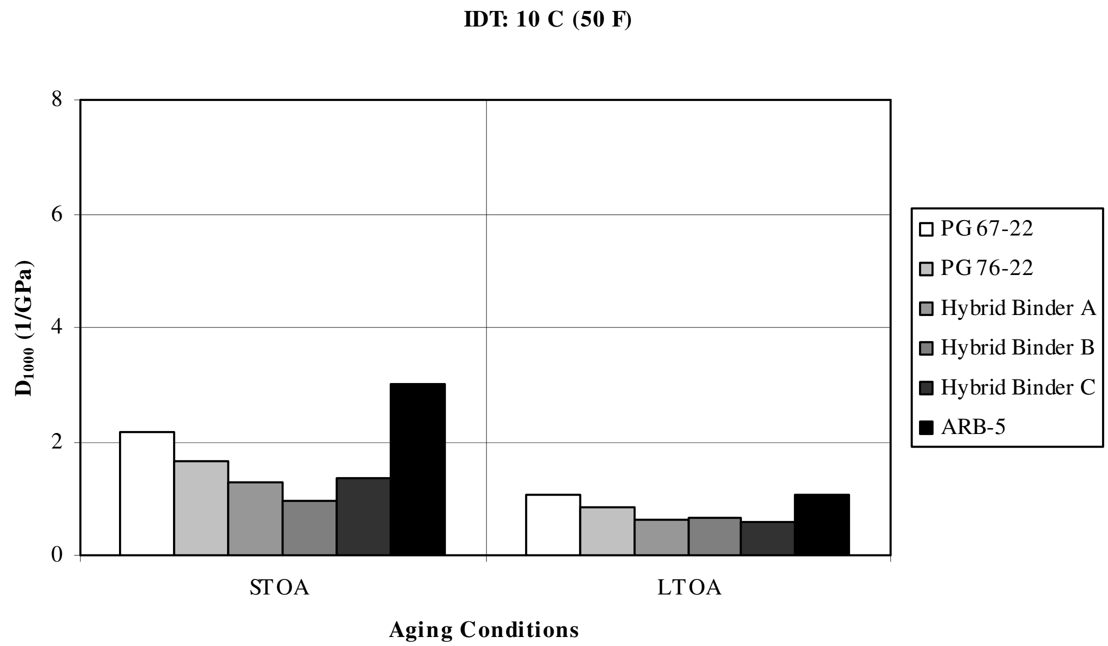


Figure B- 11 Creep Compliance @ 1000 second: DG Limestone Mixtures

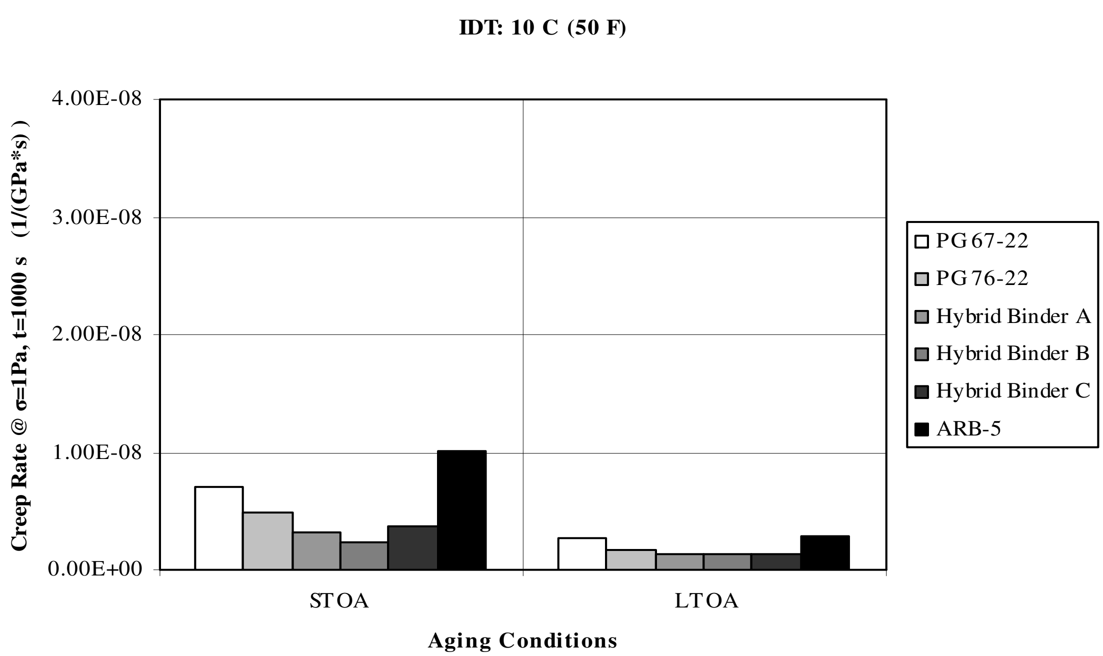


Figure B- 12 Creep Rate @σ=1Pa, 1000 second: DG Limestone Mixtures

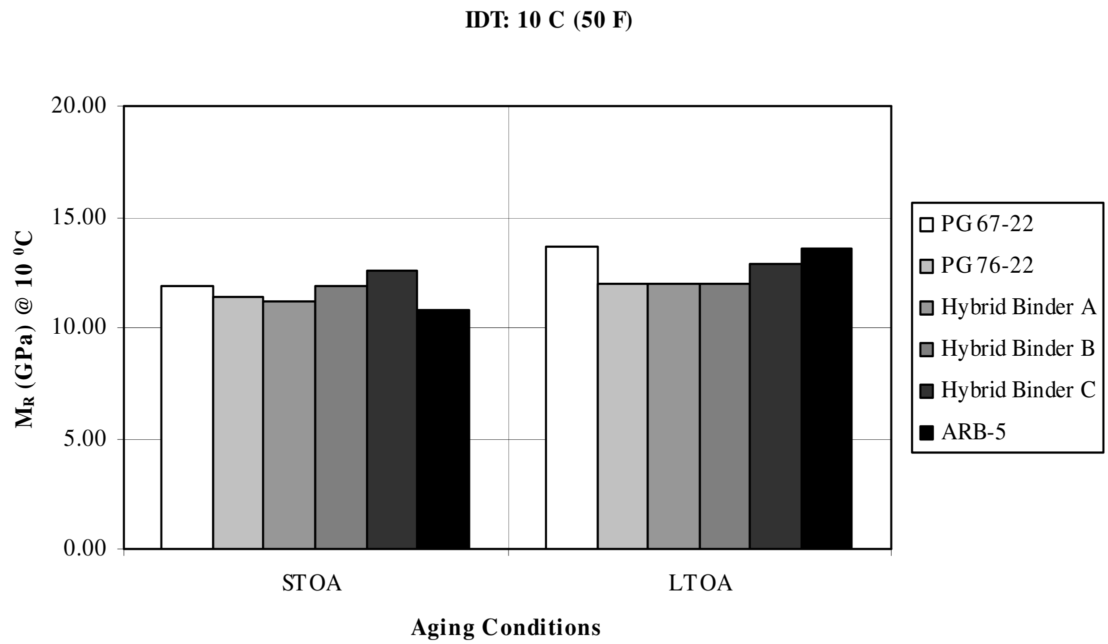


Figure B- 13 Resilient Modulus: DG Limestone Mixtures

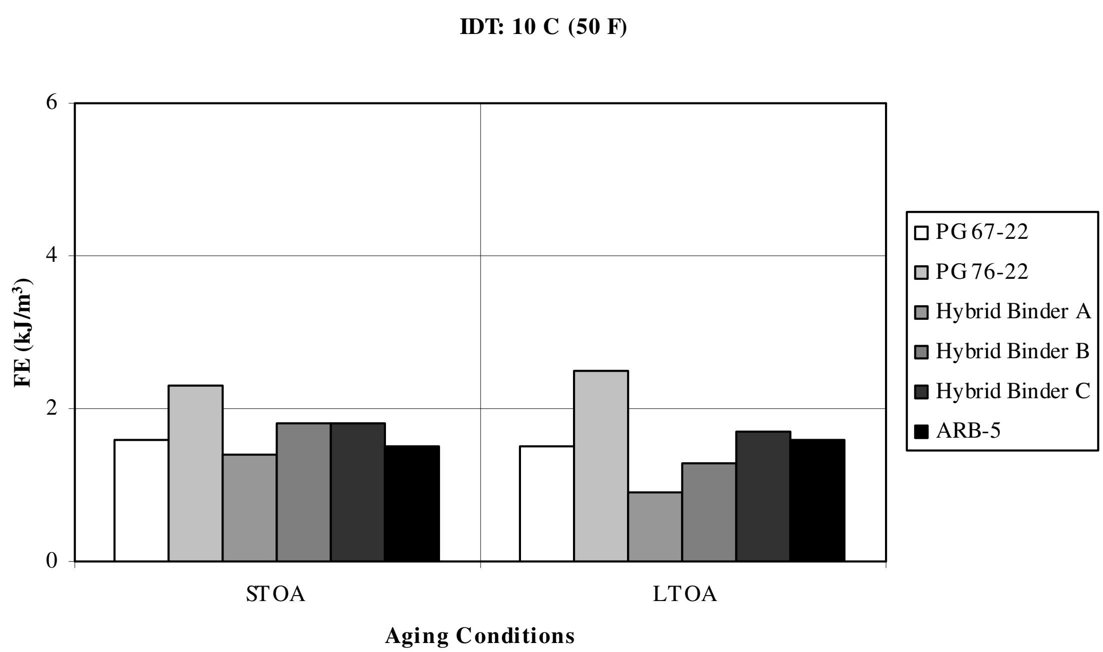


Figure B- 14 Fracture Energy: DG Limestone Mixtures

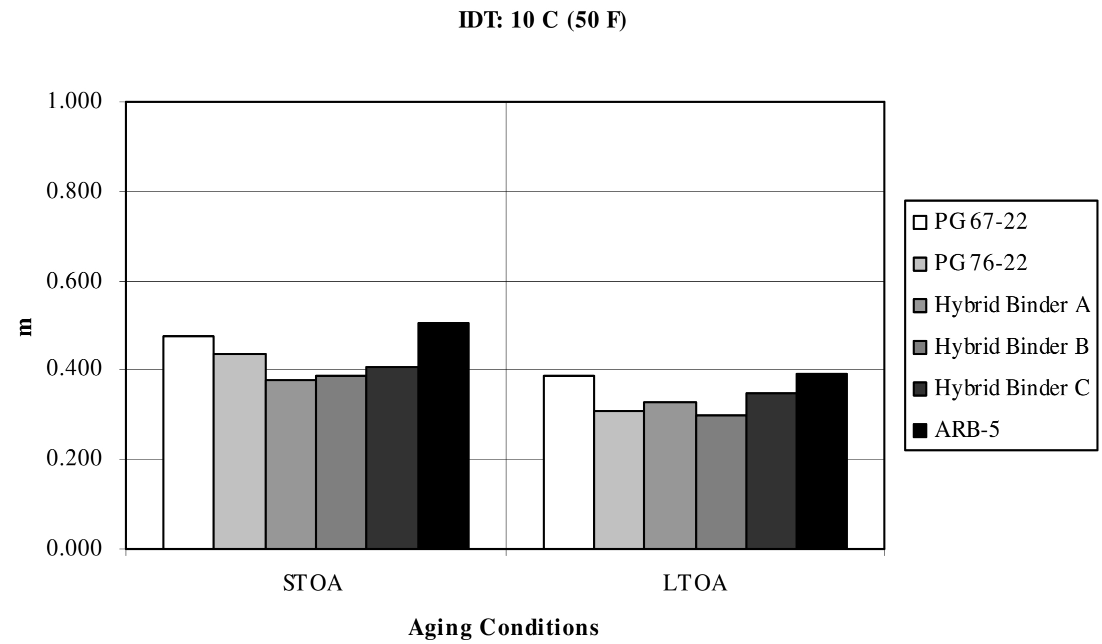


Figure B- 15 Creep Rate: DG Limestone Mixtures

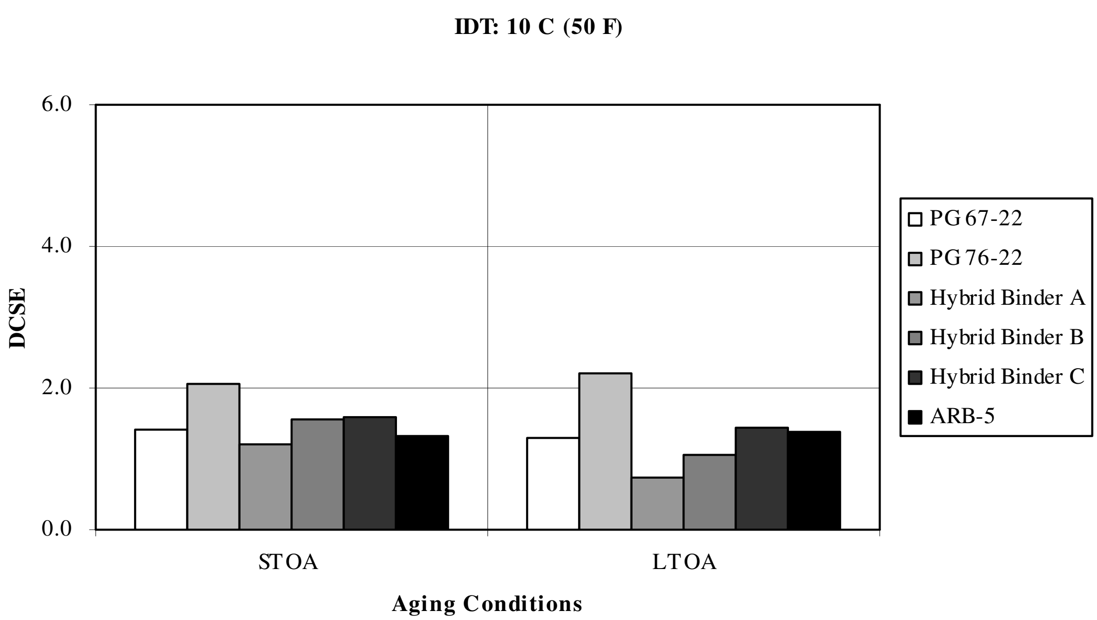


Figure B- 16 DCSE: DG Limestone Mixtures

APPENDIX B.3 GRANITE OGFC IDT TEST RESULTS

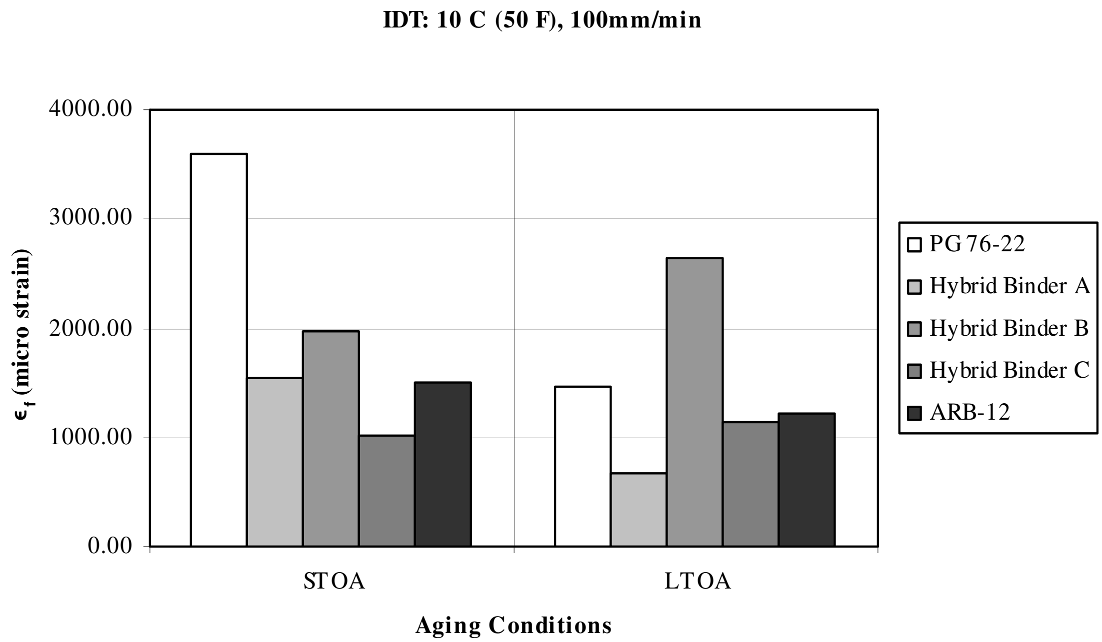


Figure B- 17 Failure Strain: OGFC Granite Mixtures

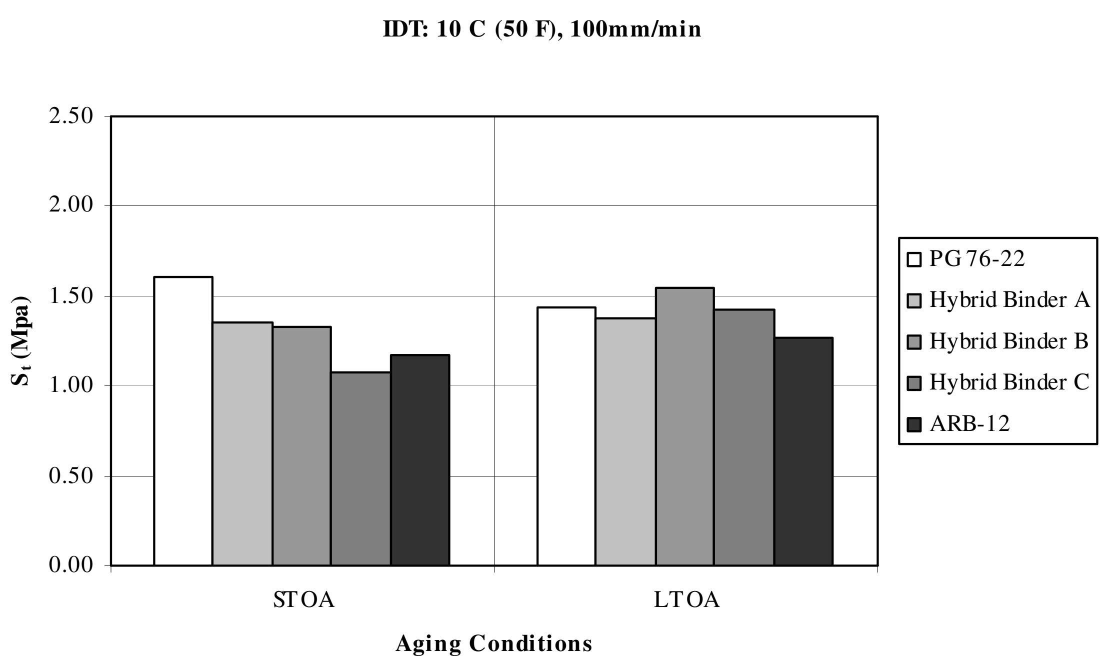


Figure B- 18 Tensile Strength: OGFC Granite Mixtures

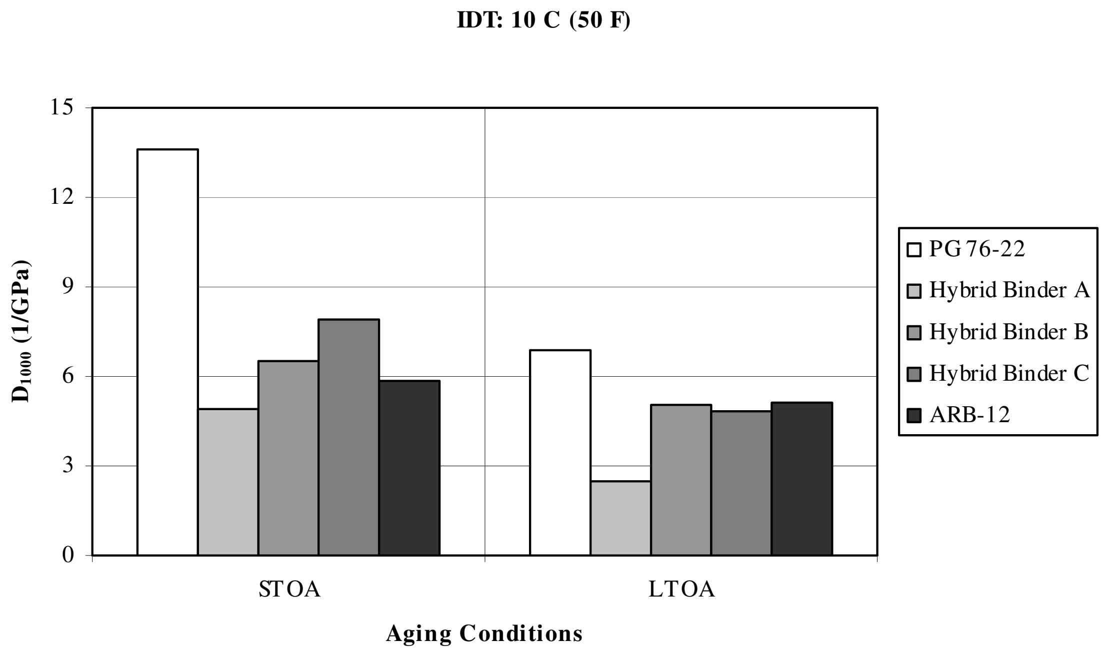


Figure B- 19 Creep Compliance @ 1000 second: OGFC Granite Mixtures

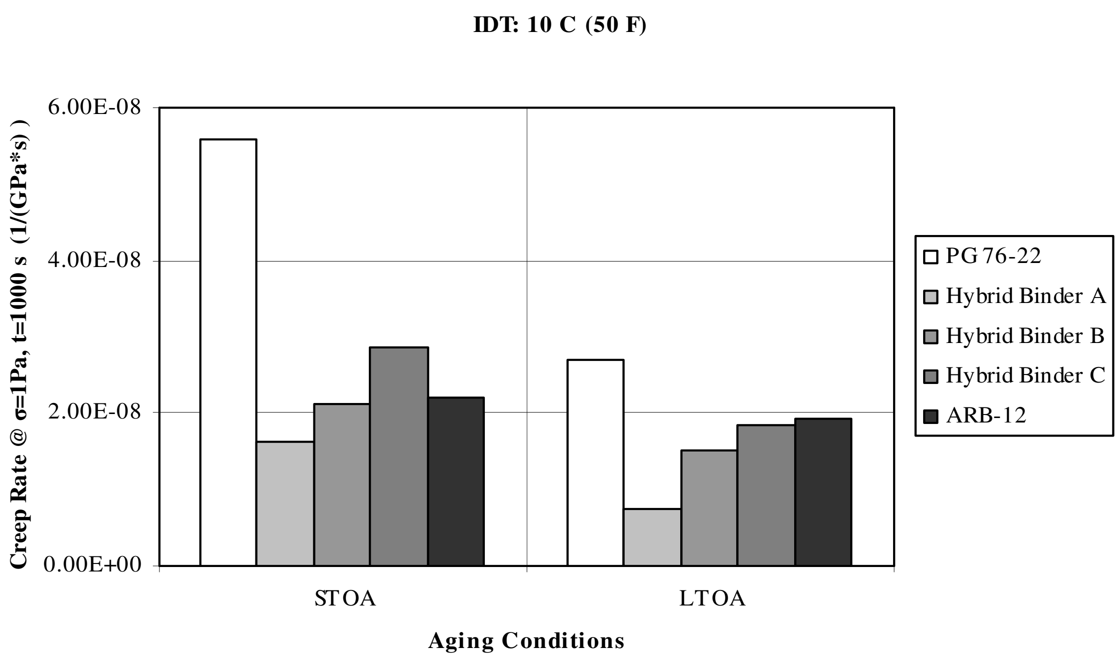


Figure B- 20 Creep Rate @σ=1Pa, 1000 second: OGFC Granite Mixtures

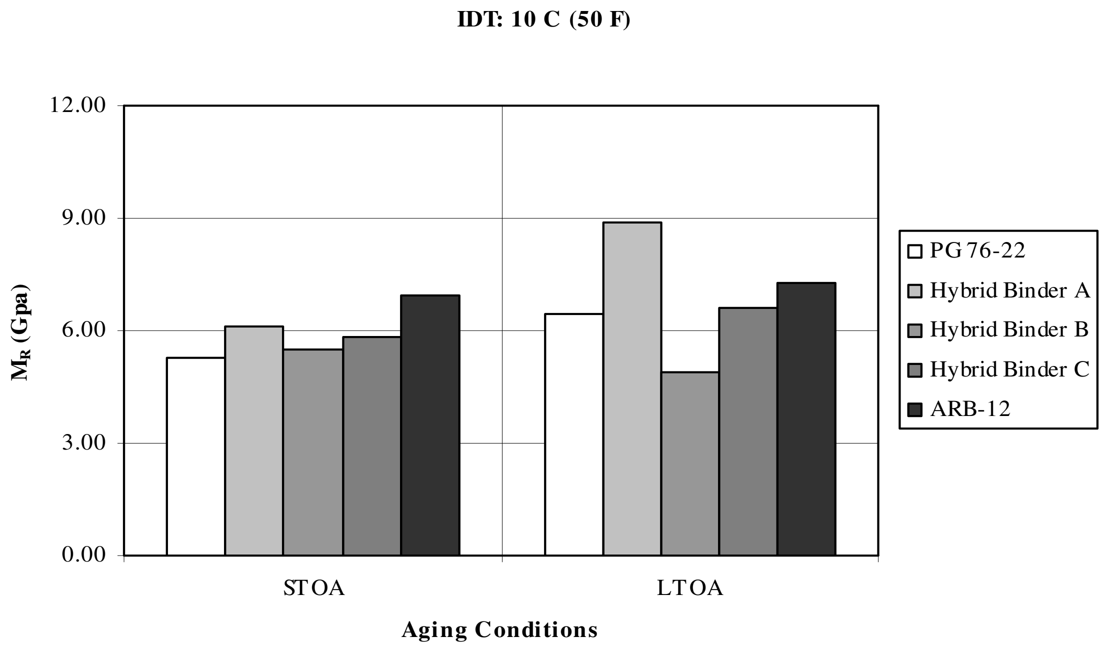


Figure B- 21 Resilient Modulus: OGFC Granite Mixtures

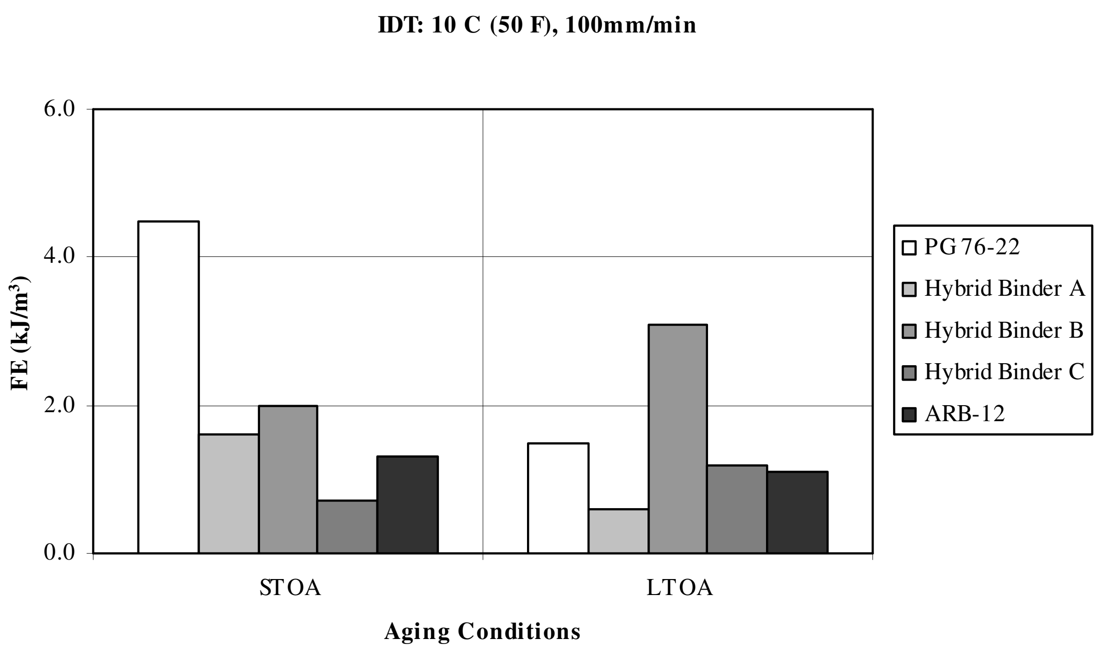


Figure B- 22 Fracture Energy: OGFC Granite Mixtures

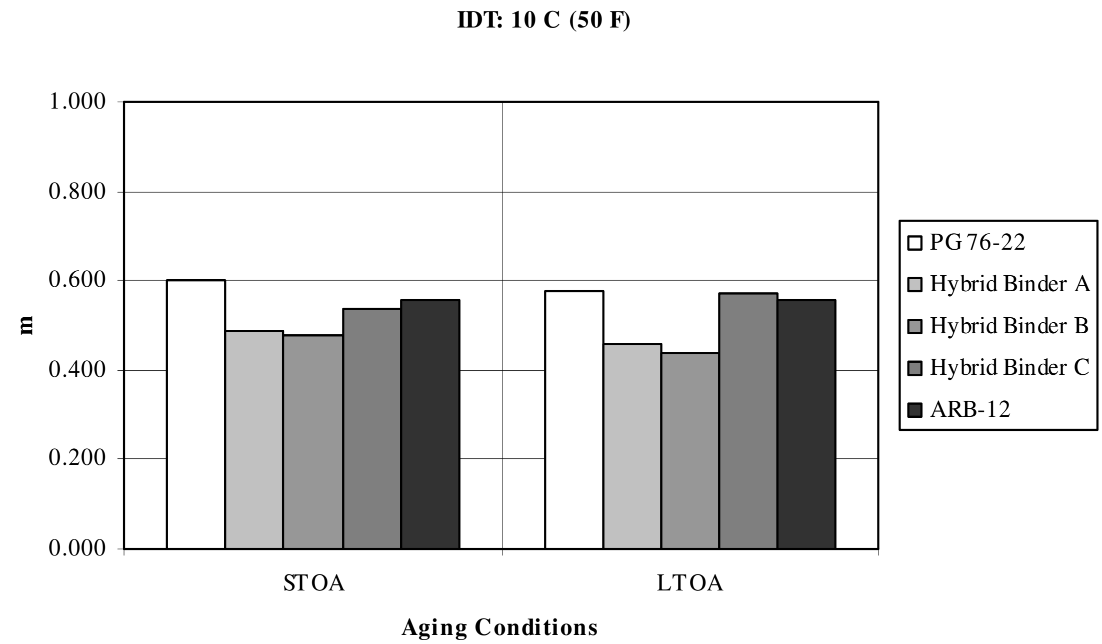


Figure B- 23 Creep Rate: OGFC Granite Mixtures

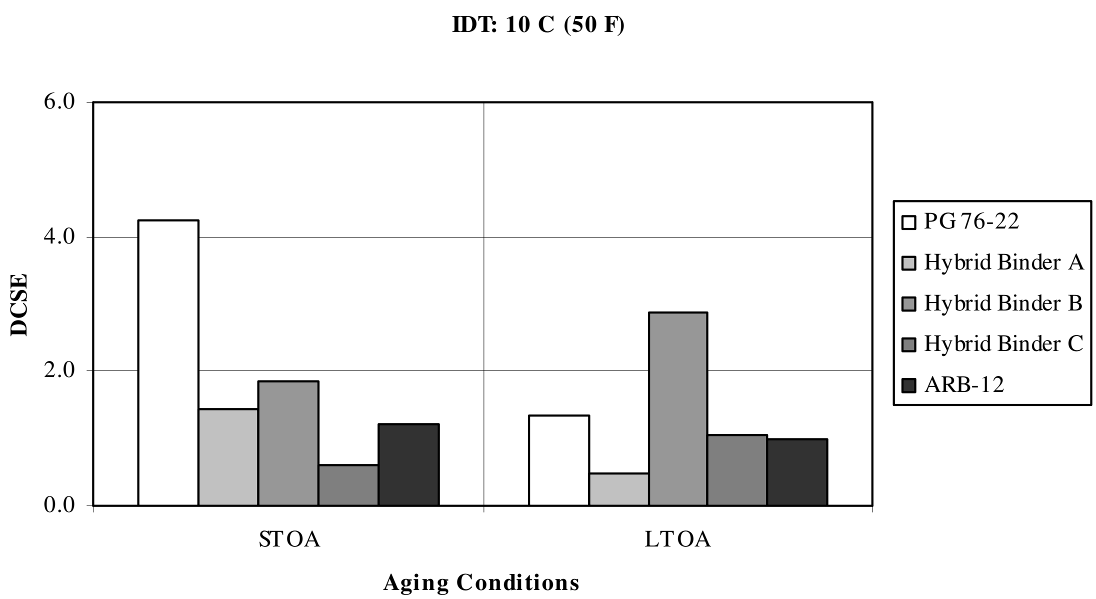


Figure B- 24 DCSE: OGFC Granite Mixtures

APPENDIX B.4 LIMESTONE OGFC IDT TEST RESULTS

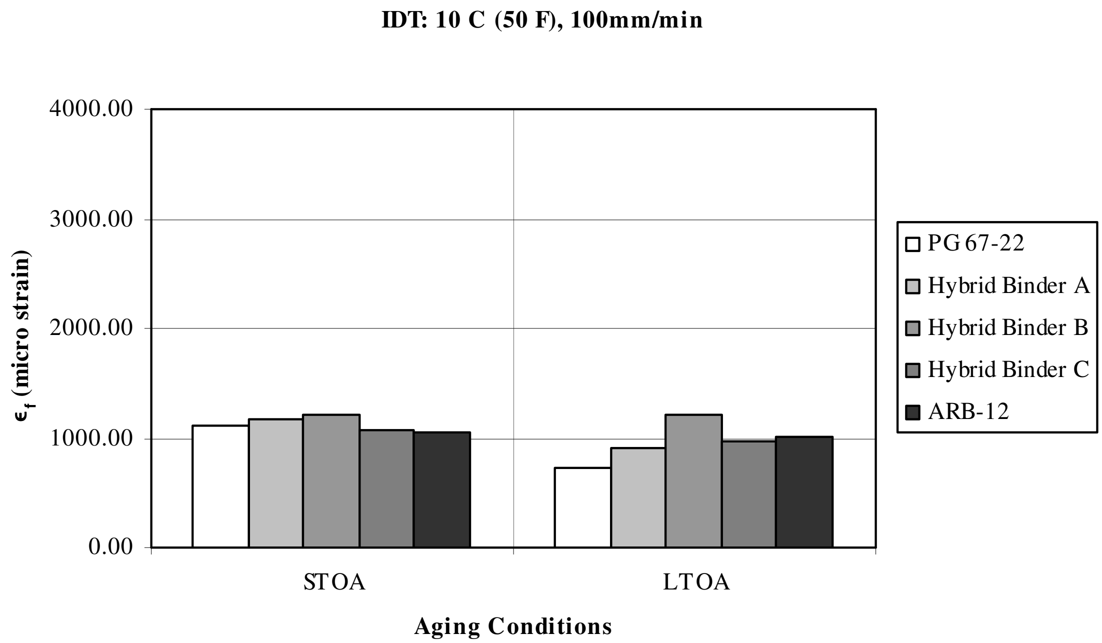


Figure B- 25 Failure Strain: OGFC Limestone Mixtures

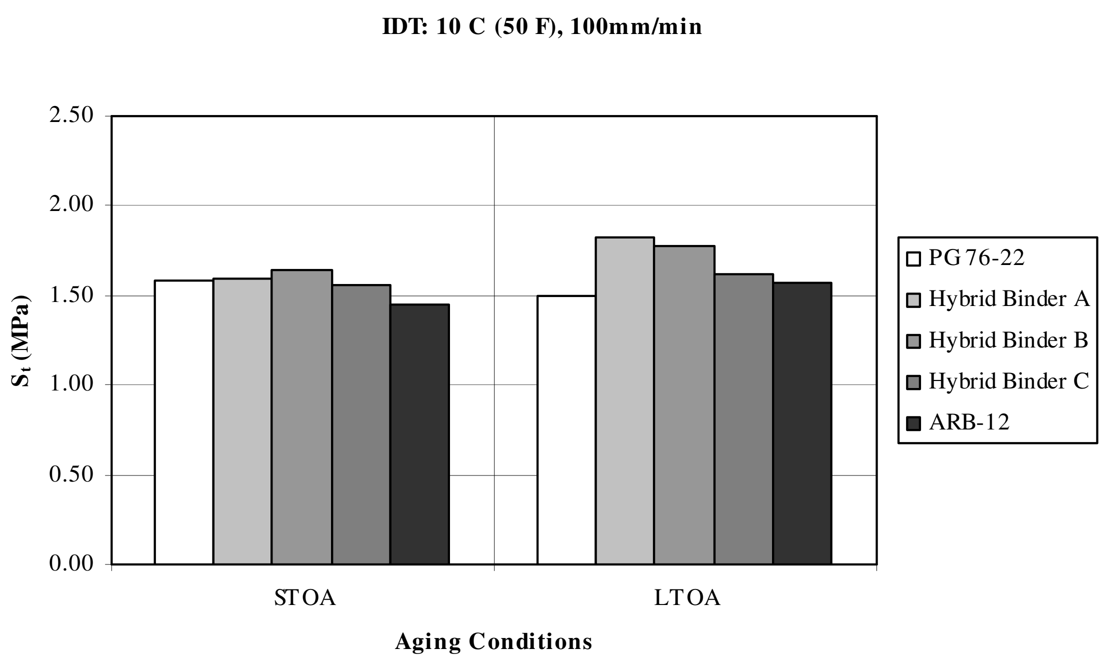


Figure B- 26 Tensile Strength: OGFC Limestone Mixtures

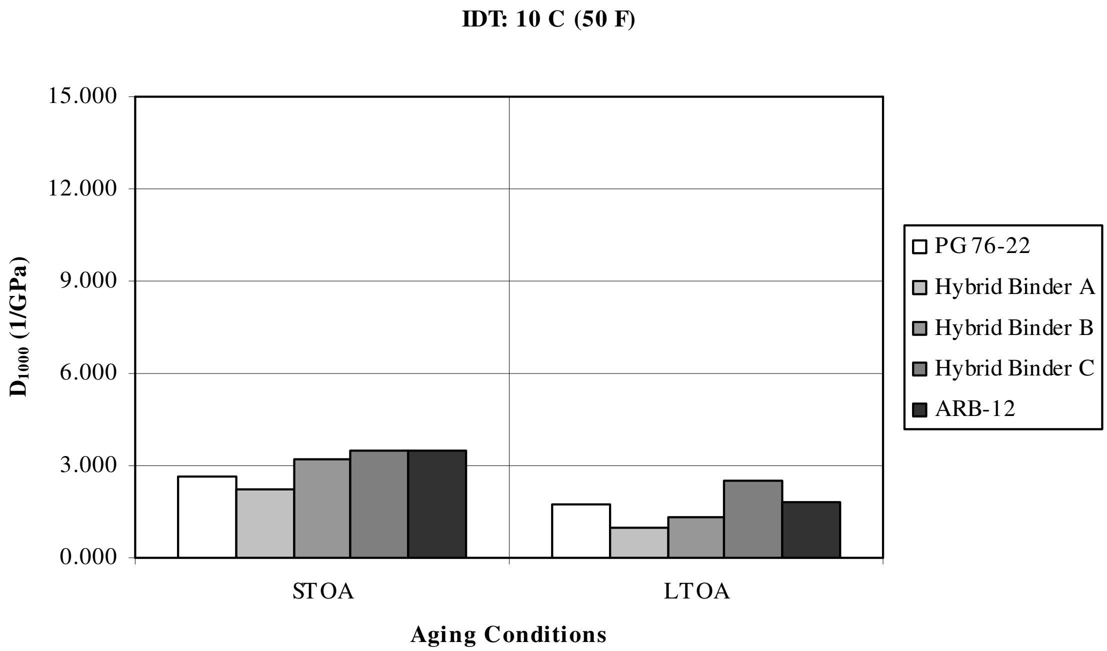


Figure B- 27 Creep Compliance @ 1000 second: OGFC Limestone Mixtures

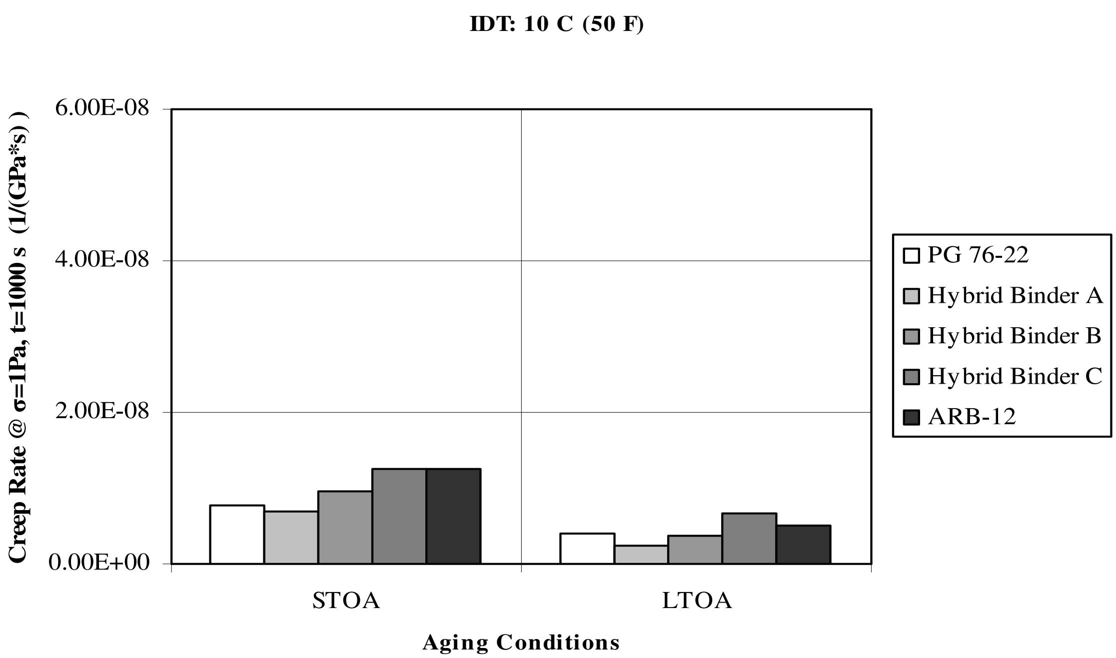


Figure B- 28 Creep Rate @σ=1Pa, 1000 second: OGFC Limestone Mixtures

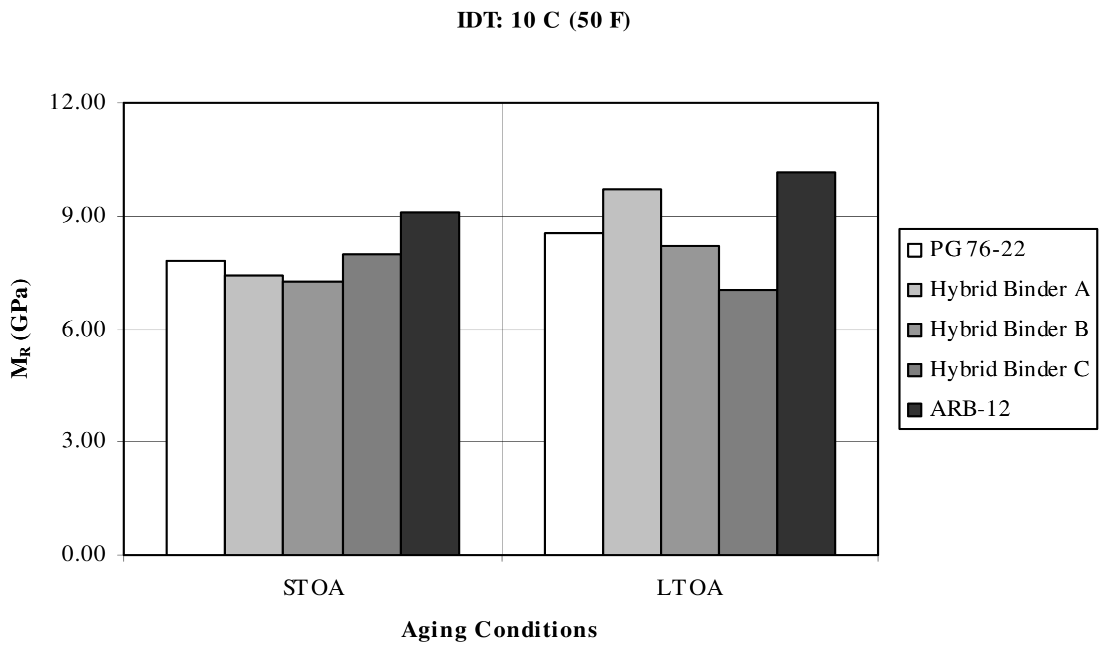


Figure B- 29 Modulus: OGFC Limestone Mixtures

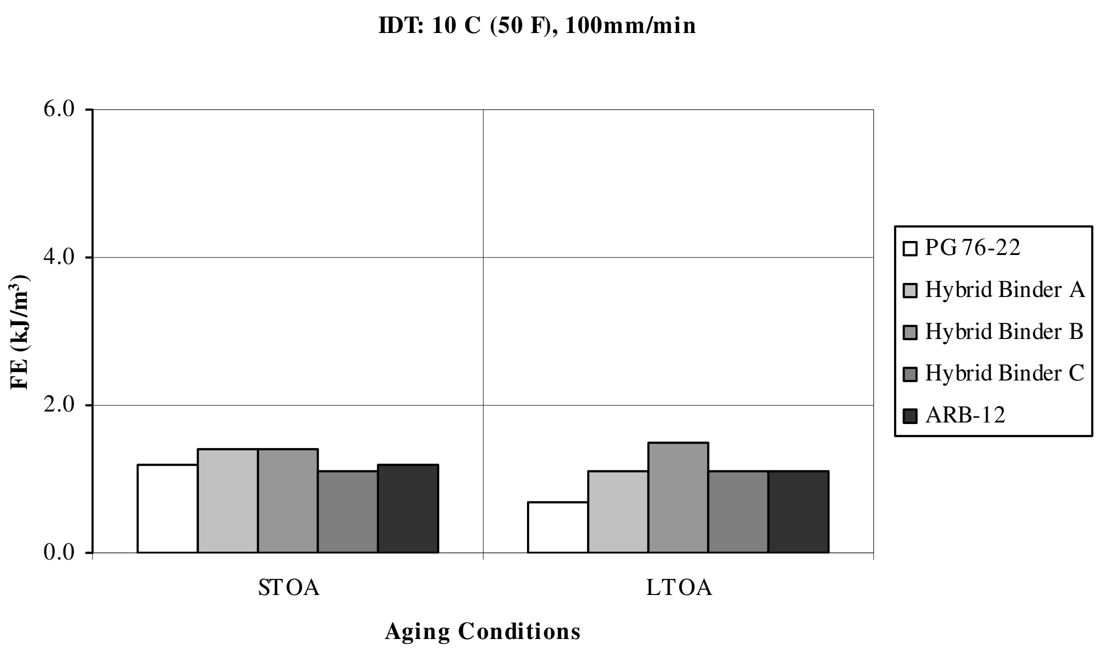


Figure B- 30 Fracture Energy: OGFC Limestone Mixtures

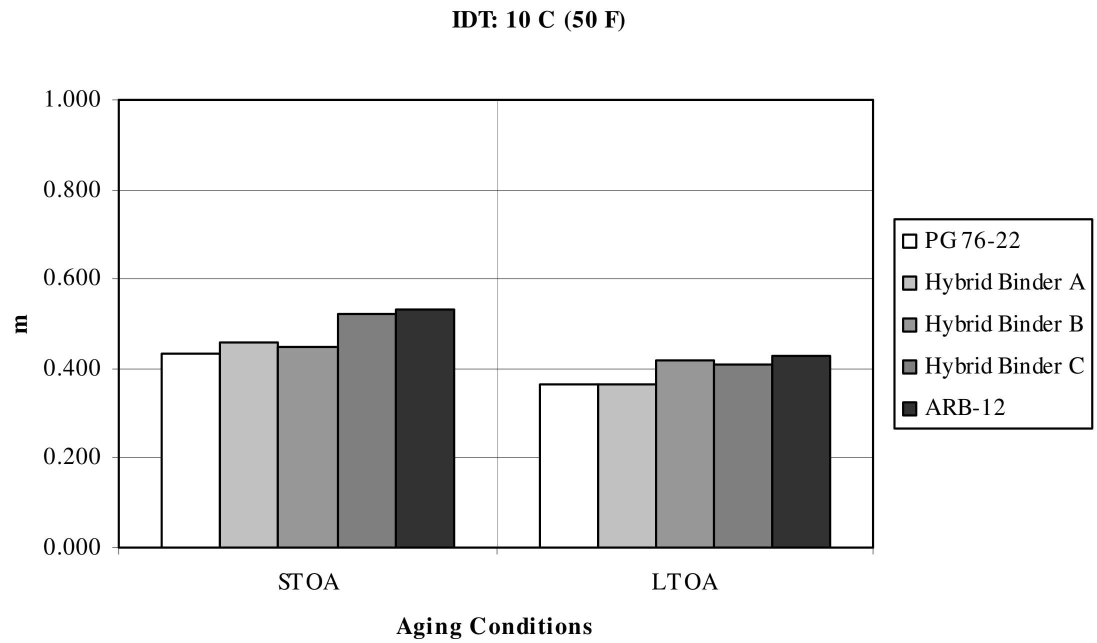


Figure B- 31 Creep Rate: OGFC Limestone Mixtures

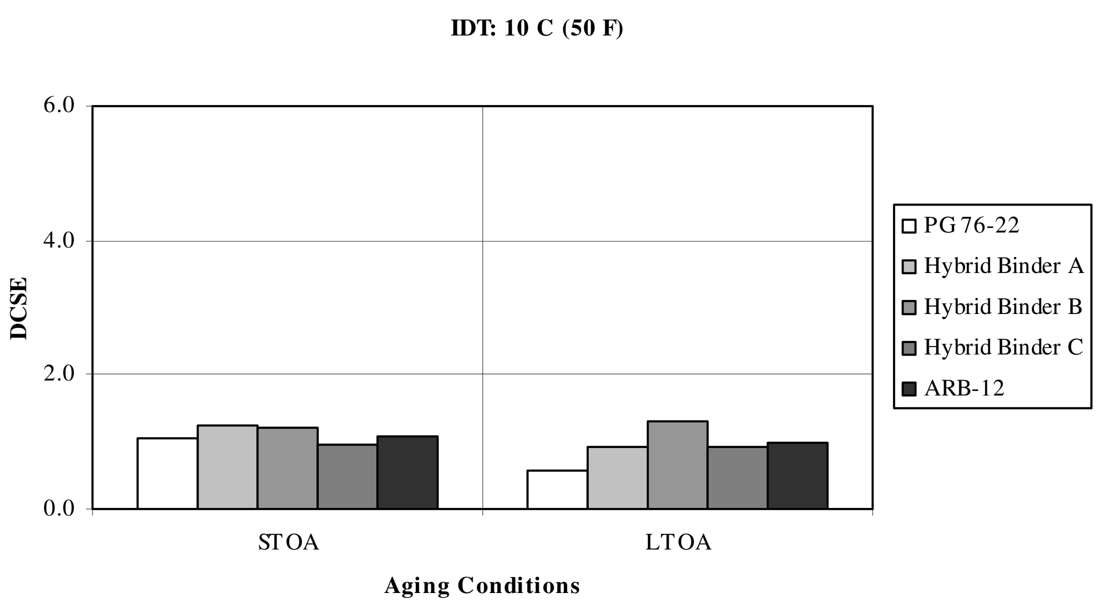


Figure B- 32 DCSE: OGFC Limestone Mixtures

APPENDIX C CITGO CERTIFICATES OF ANALYSIS

Certificate of Analysis

Supplier:	CITGO Asphalt Refining Co	Phone:	856-224-7409
Terminal:	Savannah Refinery	Fax:	856-423-7289
Address:	Savannah, GA 31408		

Date Sampled	7/5/2007	Grade	67-22	Specification	AASHTO M-320
Date Tested	7/5/2007	Tank # 52	Lot # 7	Sampled By	Jerome Hall
Date Received	7/5/2007	Volume	tons	DOT #	

TEST		METHOD	TEST LAB	SPECIFICATION REQUIREMENTS	TEST RESULTS
Unaged Binder					
Spot Test		AASHTO T 102		Negative	Negative
Absolute Viscosity @ 140°F		AASHTO T 202		Report	3310
Sp. Gravity @ 15.6°C, gm/cm³		AASHTO T 228		Report	1.043
Sp. Gravity @ 25.0°C, gm/cm³		AASHTO T 228		Report	1.037
Smoke Point		Fla Specs		> 125°C	177
Flash Point, °C		AASHTO T 48		> 230°C	277
Viscosity @ 135°C, Pa-s		AASHTO T 316		< 3.0 Pa-s	0.585
Viscosity @ 165°C, Pa-s		AASHTO T 316		Report	0.165
Lab Mixing Temp,°C				Max: 169	Min: 162
Lab Compaction Temp,°C				Max: 155	Min: 150
G*/sin(delta) (kPa)	67°C	AASHTO T 315	CICS	> 1.00 kPa	1.346
Phase Angle, δ		AASHTO T 315	CICS		84.9
RTFOT					
G*/sin(delta) (kPa)	67°C	AASHTO T 315	CICS	> 2.20 kPa	3.226
RTFOT Mass Change (%)		AASHTO T 240	CICS	< 0.500 %	-0.347
PAV					
G*sin(delta) (kPa)	25°C	AASHTO T 315	CICS	< 5,000 kPa	3529
Stiffness (MPa) @ 60 s	-12°C	AASHTO T 313	CICS	< 300 MPa	157
m-value @ 60 s	-12°C	AASHTO T 313.	CICS	> 0.300	0.360

This Binder classifies as a PG67-22

This material meets requirements set forth in AASHTO M320 and ASTM D6373 and FLDOT Specification Section 916-1.1

By providing this data under my signature, I attest to the accuracy and validity of the data contained on this form and certify that no deliberate misrepresentation of test results, in any manner, has occurred.

Remarks Solubility = 99.98 %

Testing Laboratory:
CITGO Savannah
Savannah, GA
AASHTO #: 1303

Responsible Technician:
Jerome Hall
Signature:

Person responsible for certification:
Larry Bristow 7/6/2007
Signature:

Certificate of Analysis

Supplier:	CITGO Asphalt Refining Co	Phone:	856-224-7409
Terminal:	Savannah Refinery	Fax:	856-423-7289
Address:	Savannah, GA 31408		

Date Sampled	7/6/2007	Grade	76-22			Specification	AASHTO M-320
Date Tested	7/6/2006	Tank #	18	Lot #	7	Sampled By	Jerome Hall
Date Received	7/6/2007	Volume			2,091 tons	DOT #	QC-0200162

TEST		METHOD	TEST LAB	SPECIFICATION REQUIREMENTS	TEST RESULTS
Unaged Binder					
Sp. Gravity @ 15.6°C, gm/cm³		AASHTO T 228		Report	1.039
Sp. Gravity @ 25.0°C, gm/cm³		AASHTO T 228		Report	1.033
Flash Point, °C		AASHTO T 48		> 230°C	282
Smoke Point, °C		FM-5-519		> 230°C	177
Spot Test		AASHTO T102		Negative	Negative
Viscosity @ 135°C, Pa-s		AASHTO T 316		< 3.0 Pa-s	1.515
Viscosity @ 165°C, Pa-s		AASHTO T 316		Report	0.425
Lab Mixing Temp,°C				Max: 163	Min: 157
Lab Compaction Temp,°C				Max: 157	Min: 152
G*/sin(delta) (kPa)	76°C	AASHTO T 315	CICS	> 1.00 kPa	1.347
Phase Angle, δ		AASHTO T 315	CICS		72.8
RTFOT					
G*/sin(delta) (kPa)	76°C	AASHTO T 315	CICS	> 2.20 kPa	2.965
RTFOT Mass Change (%)		AASHTO T 240	CICS	< 0.500 %	-0.341
PAV					
G*sin(delta) (kPa)	31°C	AASHTO T 315	CICS	< 5,000 kPa	1365
G*sin(delta) (kPa)	25°C	AASHTO T 315	CICS	< 5,000 kPa	3006
Stiffness (MPa) @ 60 s	-12°C	AASHTO T 313	CICS	< 300 MPa	146
m-value @ 60 s	-12°C	AASHTO T 313.	CICS	> 0.300	0.362

This Binder classifies as a PG76-22

This product conforms to the specifications of AASHTO M-320, ASTM D-6373, The State of Georgia's Provision: Section 820.01, and The State of Florida's Provision: Section 916-1 for Superpave Asphalt Binders.

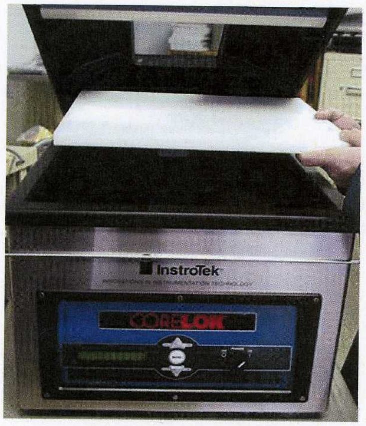
By providing this data under my signature, I attest to the accuracy and validity of the data contained on this form and certify that no deliberate misrepresentation of test results, in any manner, has occurred.

Remarks Solubilty = 99.98%

Testing Laboratory:	Responsible Technician:	Person responsible for certification:
CITGO Savannah	Jerome Hall	Larry Bristow 7/7/2007
Savannah, GA	Signature:	Signature:
AASHTO #: 1303		

APPENDIX D OGFC SAMPLE SEALING PROCEDURE FOR CORELOK TEST

The clear bag is shown for illustration only.



1. Place appropriate number of filler plates into the vacuum chamber. One plate is sufficient for 150 mm gyratory specimens.

2. Place sliding plate towards the backside of the chamber on top of the filler plate. Make sure the rubber strips are facing up and the smooth side is resting on the filler plate.

3. Select a bag and inspect the bag for holes or stress points. Weigh the inspected "good" bag.

4. Weigh the dry sample (review Sample preparation step in procedure).

5. Place the bag in the CoreLok and on the sliding plate.

6. Place a sample in the bag. Smoothest side down.

7. Place the bag over the seal bar. Make certain the open end of the bag is approximately 1" over the seal bar.

8. Close the door with both hands and hold down firmly for 2-3 seconds.

9. Weigh the sealed sample in water in the provided cushioned weighing basket and complete the other required measurements.