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16. Abstract

A laboratory investigation was conducted wherein smooth, rounded, siliceous river gravel aggregates were coated with fine-grained polyethylene, carpet co-product, or cement + styrene butadiene rubber latex and used to prepare hot mix asphalt concrete specimens. Only the coarse (+ No. 4) aggregates were coated. The concept was that the coatings would enhance surface roughness of the aggregates and, thus, produce asphalt mixtures with superior engineering properties.

Hot mix asphalt specimens were prepared and evaluated using several standard and non-standard test procedures. Based on experiences during the coating processes and analyses of these limited test results, the following was concluded: All three aggregate coating materials increased Hveem and Marshall stability, tensile strength, resilient modulus (stiffness), and resistance to moisture damage of the asphalt mixture and reduced the energy required to achieve a given level of compaction. These findings are indicative of improved resistance to rutting and cracking in hot mix asphalt pavements fabricated using coated gravel aggregates in comparison to similar uncoated aggregates.

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COATINGS TO IMPROVE LOW-QUALITY LOCAL AGGREGATES FOR HOT MIX ASPHALT PAVEMENTS

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ABSTRACT

A laboratory investigation was conducted wherein smooth, rounded, siliceous river gravel aggregates were coated with fine-grained polyethylene, carpet co-product, or cement + styrene butadiene rubber latex and used to prepare hot mix asphalt concrete specimens. Only the coarse (+ No. 4) aggregates were coated. The concept was that the coatings would enhance surface roughness of the aggregates and, thus, produce asphalt mixtures with superior engineering properties.

Hot mix asphalt specimens were prepared and evaluated using several standard and non-standard test procedures. Based on experiences during the coating processes and analyses of these limited test results, the following was concluded: All three aggregate coating materials increased Hveem and Marshall stability, tensile strength, resilient modulus (stiffness), and resistance to moisture damage of the asphalt mixture and reduced the energy required to achieve a given level of compaction. These findings are indicative of improved resistance to rutting and cracking in hot mix asphalt pavements fabricated using coated gravel aggregates in comparison to similar uncoated aggregates.

- EXECUTIVE SUMMARY -

INTRODUCTION

STATEMENT OF PROBLEM

There are generally three basic types of coarse aggregates used in hot mix asphalt (HMA) pavement construction: naturally occurring (uncrushed) gravels, crushed or partially crushed gravels, and quarried or crushed stone. As a result of the production process, quarried stone particles have 100% crushed faces. This is a desirable trait from the standpoint of cohesive strength of paving mixtures, adhesive strength of cements (such as asphalt or cement), and shear strength of a stabilized compacted paving mixture. Naturally occurring gravels and sands, on the other hand, often have smooth, rounded surfaces (particularly those in the southeastern United States) and thus yield lower values of cohesive, adhesive, and shear strength in HMA.

Poor adhesion at the asphalt-aggregate interface may lead to premature failure of a pavement (rutting or disintegration) due to moisture susceptibility. Smooth, rounded aggregates also produce asphalt-paving mixtures with relatively low stability. Low stability mixtures are subject to premature rutting and/or shoving in the wheelpaths. These types of premature pavement distresses act to significantly reduce the service life and thus the cost effectiveness of paving materials.

Generally, high quality, angular aggregates are most desirable and, therefore, are generally required in asphalt paving applications. In fact, pavement construction specifications are customarily written to limit or even disallow the use of the lower quality, rounded aggregates having smooth surface textures.

Consequently, high quality aggregates suitable for paving purposes have been depleted or nearly depleted in many areas of the U.S. Only sands and gravels, which do not meet current state DOT specifications without crushing, are available at certain locations. Costs for hauling high-quality aggregates suitable for use in hot mix asphalt (HMA) can exceed the cost of the aggregate itself when the haul distant is only 20 to 50 miles!

Therefore, the benefits of a process that permits the use of otherwise unusable locally available aggregates could be tremendous.

It should be feasible to treat the surface of aggregate particles to enhance surface texture and/or angularity and thus improve resulting pavement performance. A potentially beneficial treatment method is to permanently coat the aggregate particles with a hard, rough material that would improve adhesive strength of the asphalt-aggregate interface and cohesive strength or stability of a compacted asphalt paving mixture. The coating would need to be tough enough to resist being abraded off the particle surface during mixing in the asphalt plant and during subsequent handling associated with pavement construction.

OBJECTIVES

The principle objectives of this research are to:

- review existing information on coating of marginal aggregates to improve the quality of asphalt paving mixtures,
- identify promising materials for coating marginal aggregates (particularly industrial by-products and consumer waste materials), and
- conduct a laboratory study to investigate the feasibility of using selected coating materials for improvement of aggregate and/or paving mixture quality.

LABORATORY TESTS AND RESULTS

EXPERIMENTAL DESIGN

Low-quality aggregates typical of those found in southern and southeastern Texas as well as the southeastern United States were used to perform a comparative evaluation of the changes in engineering properties of asphalt concrete mixtures using uncoated and coated aggregates. The experiment design consisted of one type of aggregate (siliceous gravel), one type of asphalt binder, and three different types of coating materials. The coating materials included polyethylene, carpet co-product, and cement + latex.

Asphalt mixture designs were performed; then a total of 48 hot mix asphalt mixture specimens were fabricated and tested to accomplish the objectives of this study. Several common laboratory test protocols were employed to evaluate any benefits of the aggregate coatings on HMA properties. Triplicate tests were performed to ensure statistical validity of the findings. Table 1 provides a summary of experimental design.

ASPHALT CEMENT PROPERTIES

Asphalt cement with a grade of PG 64-22 was selected for use in the asphalt-aggregate mixtures tested in this research.

AGGREGATE PROPERTIES

Uncrushed siliceous river gravel and sand (field sand and concrete sand) were obtained from local sources that mine the Brazos River flood plain. These materials ranged in size from 3/4 inch (19 mm) to minus No. 200 (0.075 mm). Additionally, silt-size material from iron ore gravel obtained from East Texas was used to supplement the fine material in the HMA mixture design. All aggregates were separated using preselected sieves then recombined to accurately produce the desired gradation.

Specific gravity of the coarse and fine aggregates was measured in accordance with the ASTM C 127 (AASHTO T 85) and C 128 (AASHTO T 84), respectively. Water

Table 1. Summary of Experimental Design.

Properties of Specimens Tested		Type of Coating			
		Control (None)	Polyethylene	Carpet Co-product	Cement & Latex
Mixture Properties	Specimen Height, in	2.03	2.07	2.02	2.03
	Bulk Specific Gravity	2.39	2.35	2.41	2.41
	Rice Specific Gravity	2.49	2.39	2.44	2.47
	Air Voids, %	3.9	2.2	1.3	2.6
Stability	Hveem Stability, %	32	38	36	35
	Marshall Stability, lbs.	992	1287	1296	1267
	Marshall Flow, 0.01 in	11.0	14.7	11.5	12.8
Resilient Modulus, Ksi	Tested at 104^{o}F	52	78	83	106
	Tested at 77 ^{o}F	345	421	474	507
	Tested at 68 ^{o}F	639	656	840	803
	Tested at 33 ^{o}F	1229	1448	1865	1480
Indirect Tension	Tensile Strength, psi	110	162	151	130
	Tensile Strain at Failure, in/in	0.0071	0.0064	0.0063	0.0063
	Secant Modulus, psi	15,534	26,732	24,067	20,813
Water Susceptibility	Tensile Strength Ratio (TSR)	96	116	104	110

Note: These values were obtained from the averages of three test results.

absorption was also obtained from these procedures. The basic physical properties of these aggregates are presented in Table 2. These values represent the averaged results from standard laboratory tests conducted on the three different aggregate samples that were blended to produce design gradation.

HOT MIX ASPHALT MIXTURE DESIGN

Aggregate Gradation

Gradation of the aggregates used to prepare the asphalt specimens was achieved in accordance with TxDOT Type C hot mix asphalt mixture design. Coincidentally, this gradation also meets the Superpave gradation requirements for a 12.5-mm nominal size hot mix asphalt.

Optimum Asphalt Content

Hot mix asphalt mixture design was performed in accordance with TxDOT Method Tex-204-F. The Texas gyratory shear compactor was used to fabricate all asphalt-aggregate mixture specimens in this research. Air voids in the compacted asphalt-aggregate mixtures were plotted versus the corresponding asphalt contents. A best-fit line was constructed through the plotted points. An air void content of 4% was used to establish the optimum asphalt content. The optimum asphalt content was determined to be 4.3% by weight of total mix.

Table 2. Physical Properties of Aggregates.

Aggregate Grading	Physical Property				Test Designation
	Bulk Specific Gravity	Bulk Specific Gravity (SSD)	Apparent Specific Gravity	Water Absorption, %	
Coarse Aggregate (+ No. 4)	2.62	2.64	2.68	0.74	ASTM C127
Fine Aggregate (-No. 4)	2.61	2.65	2.71	1.44	ASTM C128
Filler (-No. 200)	2.63	--	--	--	ASTM C128
Project Design Gradation	2.61	2.65	2.71	1.24	ASTM C127 & ASTM C128

Note: These values are obtained from the averages of three tests.

DESCRIPTION OF COATING MATERIALS

Three different types of materials were used to coat the coarse aggregates prior to their use in fabrication the hot mix asphalt specimens. Each coating material was applied to the surfaces of the aggregates retained on the No. 4 sieve. The coating materials utilized included:

- Fine-grained recycled polyethylene
- Carpet co-product, and
- Cement plus styrene butadiene rubber latex.

A description of each coating material and the methodology employed during application of the coatings are presented below.

Polyethylene

Low-density granulated polyethylene was used herein to coat the coarse aggregate. Polyethylene particle sizes ranged from 1 mm to 2 mm. A description of the coating process follows.

Coarse aggregates were placed in a 370°F oven for 24. Temperature and duration in the oven were chosen from many trial and error laboratory experiments. An oven temperature at 370°F was selected for this particular polyethylene because it was just hot enough to melt the polyethylene such that it would stick to the aggregate surfaces and leave a textured polyethylene surface with minimal adhesion between the coated aggregates. A significantly higher temperature would completely melt the polyethylene such that it would form a smooth surface on the aggregate and would glue the aggregate particles firmly together upon cooling.

By experimentation, the appropriate amount of polyethylene was determined to be 2.5% by weight of coarse aggregate, which equates to 1.0% of total aggregate. This amount did not completely coat all individual aggregate particles but did provide a rougher surface texture. It is also believed that this amount is near the maximum that is economically attractive.

A bowl of aggregates was removed from the oven and, immediately, the granulated polyethylene was slowly sprinkled onto the hot aggregate while during mixing to coat the aggregate particles as uniformly as possible. Mixing was continued until the aggregate had cooled sufficiently to avoid sticking of the aggregates. Typically, aggregates should be heated to a temperature 10 to 20 degrees above the desired temperature to ensure adequate time to accomplish the mixing/coating process before excessive cooling.

Recycled Carpet Co-Product

A co-product from the Allied Signal nylon carpet recycling process was used to coat coarse the gravel aggregate. The composition of the co-product is approximately 45% $CaCO_3$, 11% styrene-butadiene rubber (SBR from latex), 35% polypropylene, and 7-9% other (including dirt, etc.).

Coating the carpet co-product onto surfaces of aggregates involves essentially the same process as that of coating with polyethylene. The appropriate amount of co-product for coating was visually determined to be 2.5% by weight of coarse aggregate. The oven temperature used was 370°F, but, for future work, the authors suggest that a higher temperature may improve the process and the resulting coating quality.

Cement & Latex

A small amount of styrene butadiene rubber (SBR) latex was incorporated into the wet cement paste in an attempt to improve the toughness and thus abrasion resistance of the subsequent coating on the coarse aggregate. The basic premise of the cement + latex coating is to create a rough-textured surface on the coarse aggregate particles in order to enhance inter-particle friction and promote adhesion between the asphalt binder and aggregate surface.

The concept was to coat aggregate particles with a hydrated cement film, which is thick enough to permanently shield the aggregate particle surface, but not so thick as to cause the particles to stick together and form cemented aggregate agglomerations.

The portland cement content calculated and used for this research was a 4.3% by weight of the coarse aggregates. After coating the aggregates with cement and allowing it to hydrate, latex was applied onto the coated aggregates. The ideal amount of latex for coating the cement-treated aggregates was determined by trial and error. The idea was to apply as much latex as possible without causing the aggregates to stick together. Latex content was selected as 0.5% by weight of aggregate for subsequent HMA sample fabrication. An excessive quantity of latex caused agglomerations between the cement coated aggregates.

The aggregates coarser than the No.4 sieve were coated using an appropriate amount of cement paste and allowed to cure. Then, the calculated amount of latex was added onto the coated aggregates in an attempt to increase adhesion between asphalt cement and surfaces of aggregates. After cement and latex coating of the aggregates is completed, the coated aggregates were cured in a humidity and temperature controlled environment for at least two days. The latex content selected was 0.5% by weight of coarse aggregates.

MIXTURE PROPERTIES AND DISCUSSION OF RESULTS

Sample Preparation

Uncoated aggregates were separated using appropriate sieves and then recombined in accordance with the mixture design to ensure an accurate and consistent gradation in all HMA specimens. Asphalt concrete specimens (4-inch diameter by 2-inch height) were mixed by hand and prepared using the Texas gyratory compactor in accordance with TxDOT standard Tex-206-F. Mechanical properties of the asphalt mixture specimens containing uncoated and coated aggregates with the three different coating materials were compared based on Hveem stability, Marshall stability, resilient modulus, indirect tension, and water susceptibility.

Hveem Stability

Hveem stability tests were conducted in accordance with ASTM D 1560. Hveem stability is an empirical measure of the interparticle friction of the aggregates comprising an HMA mixture. Hveem stability of the coated samples was consistently higher than that of the uncoated samples.

This result indicates that all three coating materials improved the surface texture of the aggregates thereby improving the internal friction and thus enhancing the Hveem stability of mixture. This is indicative that the HMA mixtures containing coated aggregates will exhibit improved resistance to rutting in a pavement. Figure 1 shows a bar chart to facilitate comparing Hveem stability of the different sample types. Each value represents an average from three independent tests. Polyethylene coated aggregates appear to provide the largest improvement Hveem stability.

Marshall Stability

Marshall and Hveem tests have been used for more than 50 years to design and evaluate HMA paving materials. Marshall stability was performed in accordance with ASTM D 1559. Marshall stability and flow values of asphalt concrete materials are recognized as measures of the material's ability to resist plastic flow. Typically, aggregates with higher angularity and surface texture will produce HMA with higher Marshall stabilities and lower Marshall flow.

Marshall stabilities of the mixtures containing the three different types of coating materials and the uncoated mixture are compared in Figure 2. Generally, the asphalt samples containing coated aggregates exhibited approximately 30% higher stability values than uncoated sample. The carpet co-product yielded the highest stability.

Resilient Modulus (M_R)

Repeated load indirect tension resilient modulus tests (ASTM D 4123) were performed on compacted HMA specimens containing coated and uncoated aggregates at temperatures of 33°F, 68°F, 77°F and 104°F (1°C, 20°C, 25°C, and 40°C, respectively).

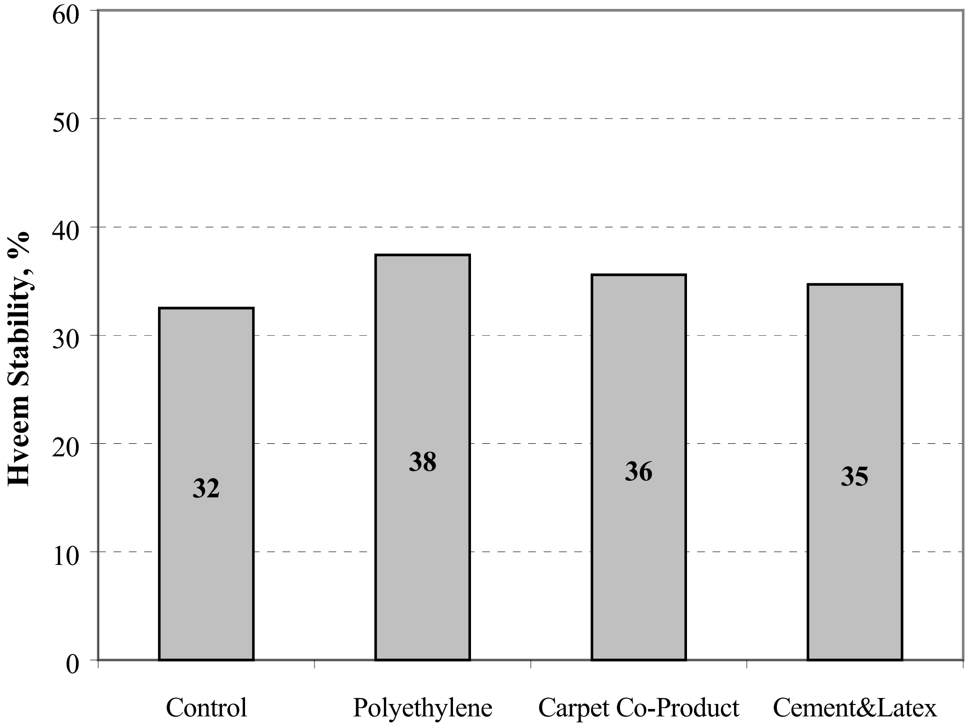

Figure 1. Hveem Stability for Mixtures Containing Uncoated Aggregates and Coated Aggregates.

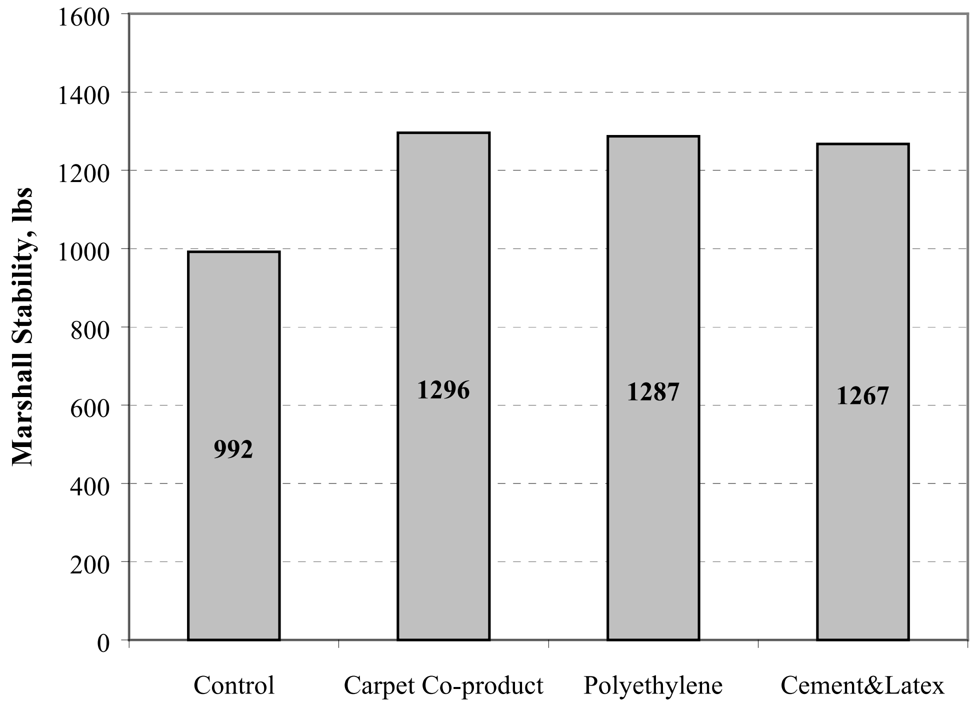

Figure 2. Comparison of Marshall Test Results of Uncoated and Coated Asphalt Mixtures.

M_R of the four different types of specimens were plotted as a function of temperature (Figure 3). The asphalt samples containing coated materials consistently exhibited higher M_R values than uncoated (control) samples. These findings indicate the coated aggregates produce HMA mixtures with greater stiffness and thus higher load bearing capacity.

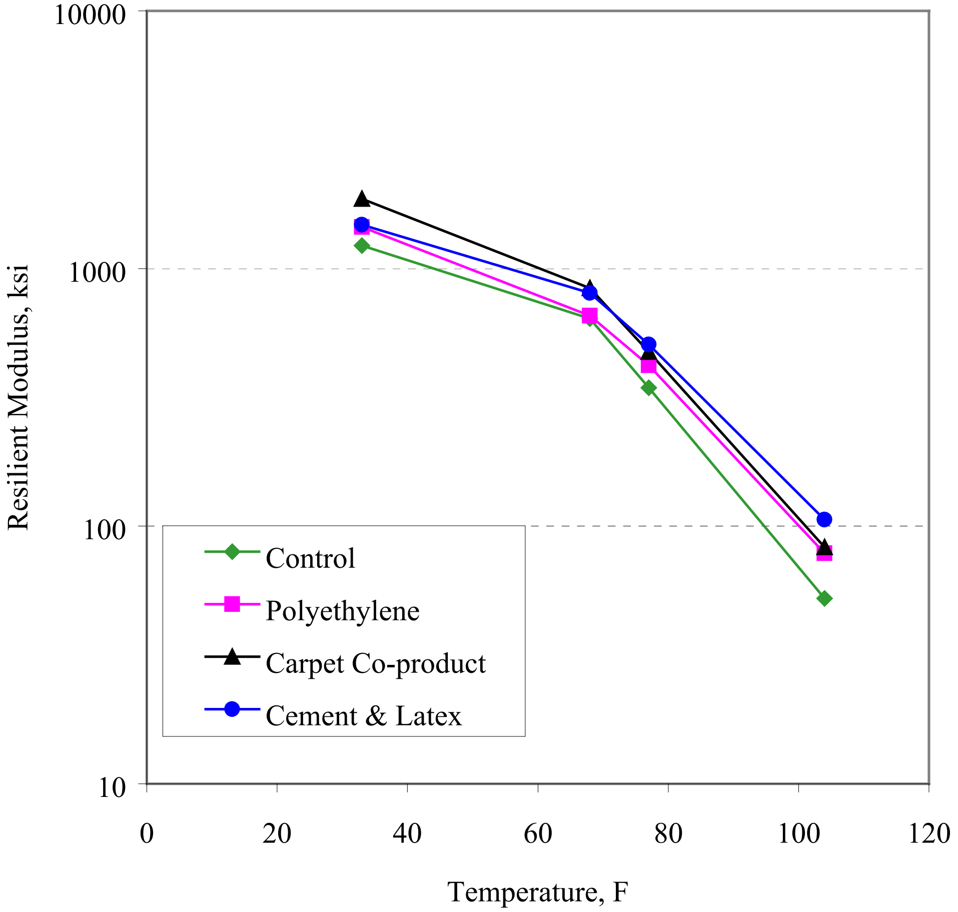

Figure 3. Resilient Modulus of Asphalt Concrete Mixtures Containing Uncoated and Coated Aggregates.

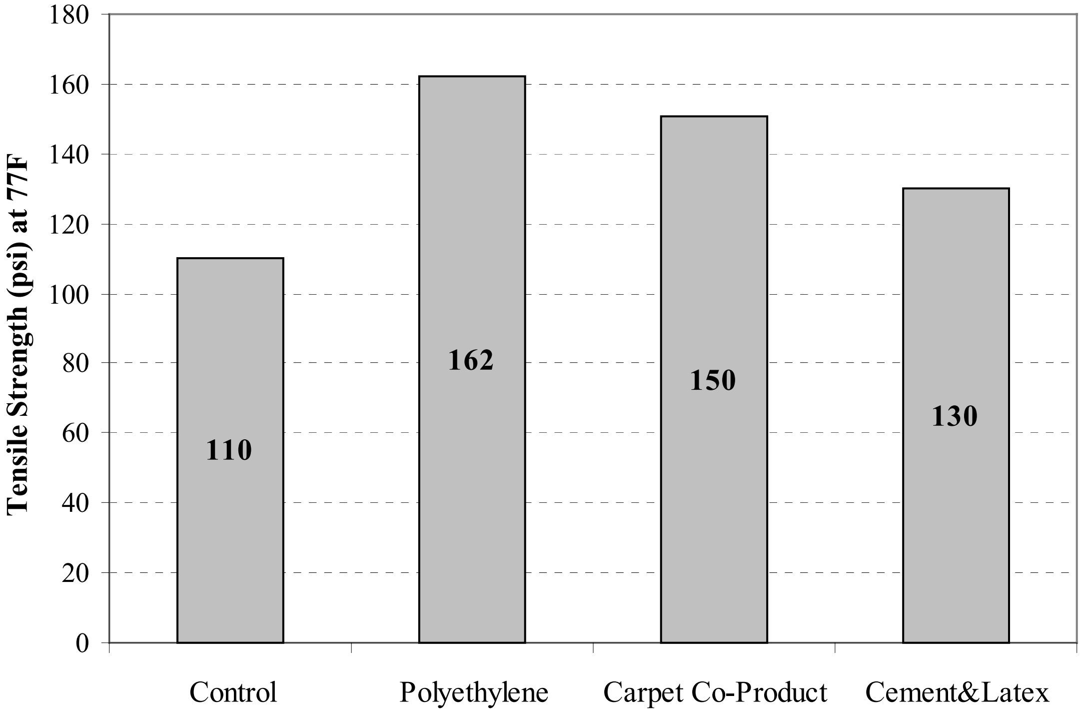

Figure 4. Tensile Strength for Mixtures Containing Uncoated Aggregates and Coated Aggregates.

Inspection of Coated Aggregate Surfaces

A common magnifying glass was used to carefully inspect surfaces of uncoated aggregates and compare them with those of the coated aggregates. It was clearly evident that the coated aggregate particles possessed significantly greater surface texture or roughness than the uncoated aggregates.

Inspection of Coated Aggregates After Mixing and Molding

Loss of the coatings was a concern during this study. Compacted asphalt-aggregate specimens containing aggregates coated with the three materials were subjected to a solvent to extract the asphalt. Individual aggregates were then visually inspected to estimate the quality of the coating remaining. The results, particularly for the carpet co-product and the cement/latex, were disappointing. It was observed that about 30% of the carpet co-product and about 20% of the cement/latex remained on the surfaces of aggregates. However, more than 60% of the polyethylene remained. The polyethylene coating adhered well to the aggregate surfaces and resisted wear during handling and compacting. Based on this finding, fine-grained polyethylene appears to be most promising of the three coating materials tested.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

A laboratory investigation was conducted wherein smooth, rounded, siliceous gravel aggregates were coated with fine-grained polyethylene, carpet co-product, or cement + latex and used to prepare asphalt concrete specimens. Hot mix asphalt specimens were subsequently evaluated using several standard and non-standard test procedures. Based on experiences during the coating processes and analyses of these limited test results, the following conclusions are tendered:

1. All three aggregate coatings slightly increased Hveem stability of the asphalt mixture.
2. All three aggregate coatings substantially increased Marshall stability of the asphalt mixture.
3. All three the aggregate coatings reduced the energy required to achieve a given level of compaction.
4. All three aggregate coatings consistently increased tensile strength of the asphalt mixture.
5. All three aggregate coatings consistently increased resilient modulus (stiffness) of the asphalt mixture.
6. Conclusions 1 through 5 are indicative of improved resistance to rutting and cracking in hot mix asphalt pavements fabricated using coated rounded gravel aggregates in comparison to pavements made using similar uncoated aggregates.

7. All three aggregate coating materials improved resistance to moisture damage of the asphalt mixture. Fine-grained polyethylene and carpet co-product appeared to be the most promising aggregate coating materials to improve an adhesion between asphalt binder and aggregate surfaces based on the laboratory results. (It should be pointed out, however, that these tests were not performed in accordance with the standard procedure.)
8. Although the cement + SBR latex coated aggregates demonstrated improved mechanical properties of the asphalt mixtures, extraction of the asphalt and examination of the coarse aggregates indicated that 80% of the coating was abraded away during mixing with asphalt and compaction of the specimens.

RECOMMENDATIONS

1. The authors believe that, with a small follow-up research effort, the coating process could be substantially improved such that more durable coatings could be achieved that would resist abrasion and further improve engineering properties of the asphalt mixture.
2. This study demonstrated that the aggregate coating process is feasible and capable of improving HMA paving mixture properties, the economics of using these aggregate coating materials in full-scale industrial processes needs to be investigated.
3. To assist in implementation of the findings of this research, materials specifications and construction guidelines will need to be prepared.

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DISCLAIMER

ACKNOWLEDGMENT

This publication was developed as part of the University Transportation Centers Program which is funded 50% with general revenue funds from the State of Texas.

CHAPTER I

INTRODUCTION

STATEMENT OF PROBLEM

There are generally three basic types of coarse aggregates used in hot mix asphalt (HMA) pavement construction: naturally occurring uncrushed gravels, crushed or partially crushed gravels, and quarried or crushed stone. As a result of the production process, quarried stone particles have 100% crushed faces. This is a desirable trait from the standpoint of cohesive strength of paving mixtures, adhesive strength of cements (such as asphalt or cement), and shear strength of a stabilized compacted paving mixture. Naturally occurring gravels and sands, on the other hand, often have smooth, rounded surfaces (particularly those in the southeastern United States) and thus yield lower values of cohesive, adhesive, and shear strength in HMA.

Poor adhesion at the asphalt-aggregate interface may lead to premature failure of a pavement (rutting or disintegration) due to moisture susceptibility. Smooth, rounded aggregates also produce asphalt-paving mixtures with relatively low stability. Low stability mixtures are subject to premature rutting and/or shoving in the wheelpaths. These types of premature pavement distresses act to significantly reduce the service life and thus the cost effectiveness of paving materials.

Generally, high quality, angular aggregates are most desirable and, therefore, are generally required in asphalt paving applications. In fact, pavement construction specifications are customarily written to limit or even disallow the use of the lower quality, rounded aggregates having smooth surface textures.

Consequently, high quality aggregates suitable for paving purposes have been depleted or nearly depleted in many areas of the U.S. Only sands and gravels, which do not meet current state DOT specifications without crushing, are available at certain locations. Further, many of these materials are too small in diameter to crush and provide a usable product. Costs for hauling high-quality aggregates suitable for use in hot mix asphalt (HMA) can exceed the cost of the aggregate itself when the haul distant is only 20 to 50 miles! Therefore, the benefits of a process that permits the use of otherwise unusable locally available aggregates could be tremendous.

It should be feasible to treat the surface of aggregate particles to enhance surface texture and/or angularity and thus improve resulting pavement performance. A potentially beneficial treatment method is to permanently coat the aggregate particles with a hard, rough material that would improve adhesive strength of the asphalt-aggregate interface and cohesive strength or stability of a compacted asphalt paving mixture. The coating would need to be tough enough to resist being abraded off the particle surface during mixing in the asphalt plant and during subsequent handling associated with pavement construction.

OBJECTIVES

The principal objectives of this research are to:

- review existing information on coating of marginal aggregates to improve the quality of asphalt paving mixtures,
- identify promising materials for coating marginal aggregates (particularly industrial by-products and consumer waste materials), and
- conduct a laboratory study to investigate the feasibility of using selected coating materials for improvement of aggregate and/or paving mixture quality.

ORGANIZATION OF THE REPORT

This research is divided into five chapters. Following this introduction, Chapter II reviews selected published information on coating of marginal aggregates to improve the quality of asphalt paving mixtures. This activity assisted in identifying promising materials for coating marginal. Chapter III describes a laboratory study to investigate the feasibility of using selected coating materials for improvement of aggregate and thus pavement quality, describes the results of laboratory tests, and addresses the effects of coating materials on the quality of HMA paving mixtures. Chapter IV briefly describes the application of this research to highway practice. Chapter V presents conclusions based on this research and recommendations for future related research studies.

CHAPTER II

LITERATURE REVIEW

Because of the rounded shape and smooth surface texture of most naturally occurring sand and gravel particles, these types of low-quality aggregates often yield poor-performance in asphalt pavements from the standpoints of stability (resistance to rutting and shoving), flushing, moisture susceptibility, and skid resistance.

The mechanism of adhesion between an aggregate surface and the bituminous binder and past experience of the authors and the industry indicates that a rough-textured aggregate develops improved mechanical interlock at the asphalt-aggregate interface that will promote adhesion and retard stripping. Furthermore, such roughness provides a significant increase in the internal friction of an asphalt paving mixture which, in turn, improves the shear strength and thus increases the load-bearing capacity of the HMA mixture.

Particle shape and surface texture of aggregate significantly affects mechanical properties of asphalt-aggregate mixtures. In compacted HMA mixtures, angular-shaped particles exhibit greater interlock and internal friction, and hence yield greater mechanical stability than do rounded or subrounded particles.

Surface texture of aggregates, like particle shape, influences the workability and strength of hot mixed asphalt (Button et al., 1992). A rough, sandpaper-like surface texture, such as that found on most crushed stones, tends to increase shear and even tensile strength but requires additional asphalt cement to overcome the decrease in workability, as compared to the smooth surface such as that found on many naturally occurring river gravels and sands. Voids in a compacted mass of rough-textured aggregate are also usually higher which is important for providing adequate voids in the mineral aggregate (VMA). Adequate VMA ensures sufficient space for asphalt cement and thus contributes to resistance to rutting and flushing during pavement service.

Limited research to investigate the effects of coatings on round, smooth aggregate particles has shown considerable potential for alleviating these problems. Portland cement paste, certain polymers, styrene butadiene rubber (SBR) from latex, and phenolics have been used separately to apply thin, rough, hard films to the surface of smooth and rounded aggregate particles. These coated aggregates were subsequently used in asphalt concrete paving mixtures and showed varying degrees of improved resistance to damage by plastic deformation, fatigue cracking, and moisture. Currently, no highway paving agencies routinely use any of these aggregate-coating products.

Hunter and Button (1984) examined certain benefits in HMA from coating aggregates with a proprietary polymer called Accorex. Laboratory experiments indicated that a very small quantity of this material added to hot aggregate and subsequently used to prepare HMA specimens provided a coating that yielded significant improvements in resistance to cracking and rutting of pavements. Although not identified by the supplier, Accorex appeared similar to polyethylene or polypropylene. Coating of aggregates for use in HMA could prove to be a beneficial use of these common waste materials.

Button et al. (1992) investigated the effects of cement mortar coatings on round, smooth aggregate particles in HMA. A paste of portland cement and water was applied to coarse and intermediate sized aggregates, allowed to cure for at least seven days, and then used in HMA in the laboratory and in the field. Laboratory tests included Hveem and Marshall stability, resilient modulus as a function of temperature, indirect tension, moisture susceptibility, creep, and permanent deformation. Laboratory test results indicated that asphalt mixtures made using cement-coated aggregate exhibited higher stability and lower creep-compliance than similar uncoated mixtures. This indicates that the cement coating process will decrease the rutting potential of asphalt mixtures made using marginal aggregates. Full-scale coating tests and subsequent production of HMA were successfully conducted in the field. The chief problem associated with the portland cement paste treatment was loss of the coating due to abrasion during mixing in the asphalt plant and subsequent handling associated with loading, hauling, placement, and compaction. Based on this work, a tougher, more abrasion-resistant coating was clearly desirable.

Williams et al. (1998) coated aggregates with SBR from latex to retard stripping in HMA. Stripping is defined as the loss of adhesion between the asphalt binder and the aggregate surface as a result of moisture infiltration into the asphalt concrete. Coating of aggregates with latex exhibited improved adhesion at the asphalt-aggregate interface as evidenced by improved resistance to moisture damage in the laboratory.

One task of the Strategic Highway Research Program (SHRP), Project A-004, was to examine the utility of coating marginal aggregates for use in HMA (Brown et al., 1991). Most of this work was devoted to coating coarse aggregates with phenol. Phenol is a by-product of the petroleum refining industry and is thus quite chemically compatible with asphalt. The primary objective was to improve resistance of HMA to moisture damage. The objective was achieved and, furthermore, phenol also produced significant improvements in stability of compacted HMA mixtures as measured in the laboratory. The phenol coating process was not attempted in the field, since, based on the laboratory experiments, the process did not appear to be cost effective.

CHAPTER III

LABORATORY TESTS AND RESULTS

EXPERIMENTAL DESIGN

Low-quality aggregates typical of those found in southern and southeastern Texas as well as the southeastern United States were used to perform a comparative evaluation of the changes in engineering properties of asphalt concrete mixtures using uncoated and coated aggregates. The experiment design consisted of one type of aggregate (uncoated and coated), one type of asphalt binder, and three different types of coating materials. The coating materials included:

- fine-grained recycled polyethylene,
- a by-product or co-product from the nylon carpet recycling process, and
- portland cement paste plus styrene butadiene rubber latex.

Asphalt mixture designs were performed; then a total of 48 hot mix asphalt mixture specimens were fabricated and tested to accomplish the objectives of this study. Several common laboratory test protocols were employed to evaluate any benefits of the aggregate coatings on HMA properties. Triplicate tests were performed to ensure statistical validity of the findings. Table 1 provides a summary of experimental design.

ASPHALT CEMENT PROPERTIES

Asphalt cement with a grade of PG 64-22 was selected for use in the asphalt-aggregate mixtures tested in this research. A summary of the properties of this asphalt binder is provided in Appendix A.

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	Marshall Stability, lbs.	992	1287	1296	1267
	Marshall Flow, 0.01 in	11.0	14.7	11.5	12.8
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	Tested at 77 ^{o}F	345	421	474	507
	Tested at 68 ^{o}F	639	656	840	803
	Tested at 33 ^{o}F	1229	1448	1865	1480
Indirect Tension	Tensile Strength, psi	110	162	151	130
	Tensile Strain at Failure, in/in	0.0071	0.0064	0.0063	0.0063
	Secant Modulus, psi	15,534	26,732	24,067	20,813
Water Susceptibility	Tensile Strength Ratio (TSR)	96	116	104	110

Note: These values were obtained from the averages of three test results.

AGGREGATE PROPERTIES

Uncrushed siliceous river gravel and sand (field sand and concrete sand) were obtained from local sources that mine the Brazos River flood plain. These materials ranged in size from 3/4 inch (19 mm) to minus No. 200 (0.075 mm). Additionally, silt-size material from iron ore gravel obtained from East Texas was used to supplement the fine material in the HMA mixture design. All aggregates were separated using preselected sieves then recombined to accurately produce the desired gradation.

Specific gravity of the coarse and fine aggregates was measured in accordance with the ASTM C 127 (AASHTO T 85) and C 128 (AASHTO T 84), respectively. Water absorption was also obtained from these procedures. The basic physical properties of these aggregates are presented in Table 2. These values represent the averaged results from standard laboratory tests conducted on the three different aggregate samples that were blended to produce design gradation.

HOT MIX ASPHALT MIXTURE DESIGN

Aggregate Gradation

Gradation of the aggregates used to prepare the asphalt specimens was achieved in accordance with TxDOT Type C hot mix asphalt mixture design. Coincidentally, this gradation also meets the Superpave gradation requirements for a 12.5-mm nominal size hot mix asphalt. A gradation chart is provided in Figure B1 in Appendix B.

Optimum Asphalt Content

Hot mix asphalt mixture design was performed in accordance with TxDOT Method Tex-204-F. The Texas gyratory shear compactor was used to fabricate all asphalt-aggregate mixture specimens in this research. Air voids in the compacted asphalt-aggregate mixtures were plotted versus the corresponding asphalt contents. A best-fit line was constructed through the plotted points. An air void content of 4% was used to establish the optimum asphalt content. The optimum asphalt content was determined to be 4.3% by weight of total mix. Air void content as a function of asphalt content and Hveem stability as a function of asphalt content are shown in Figure B2 in Appendix B.

Table 2. Physical Properties of Aggregates.

Aggregate Grading	Physical Property				Test Designation
	Bulk Specific Gravity	Bulk Specific Gravity (SSD)	Apparent Specific Gravity	Water Absorption, %	
Coarse Aggregate (+ No. 4)	2.62	2.64	2.68	0.74	ASTM C127
Fine Aggregate (-No. 4)	2.61	2.65	2.71	1.44	ASTM C128
Filler (-No. 200)	2.63	--	--	--	ASTM C128
Project Design Gradation	2.61	2.65	2.71	1.24	ASTM C127 & ASTM C128

Note: These values are obtained from the averages of three tests.

DESCRIPTION OF COATING MATERIALS

Three different types of materials were used to coat the coarse aggregates prior to their use in fabrication the hot mix asphalt specimens. Each coating material was applied to the surfaces of the aggregates retained on the No. 4 sieve. The coating materials utilized included:

- Fine-grained recycled polyethylene
- Carpet co-product, and
- Cement plus styrene butadiene rubber latex.

A description of each coating material and the methodology employed during application of the coatings are presented below.

Polyethylene

Millions of tons of polyethylene are recycled each year. Many more millions of tons are deposited in landfills. Virgin or recycled polyethylene is relatively easily obtained at many locations across the United States. Due to convenience and availability, virgin polyethylene was used in this study; however, the primary concept was to use recycled polyethylene. They should perform similarly in this application.

Low density granulated polyethylene was used herein to coat the coarse aggregate. Polyethylene particle sizes ranged from 1 mm to 2 mm. A description of the coating process follows.

Coarse aggregates were placed in a 370°F oven for 24. Temperature and duration in the oven were chosen from many trial and error laboratory experiments. An oven temperature at 370°F was selected for this particular polyethylene because it was just hot enough to melt the polyethylene such that it would stick to the aggregate surfaces and leave a textured polyethylene surface with minimal adhesion between the coated aggregates. A significantly higher temperature would completely melt the polyethylene such that it would form a smooth surface on the aggregate and would glue the aggregate particles firmly together upon cooling.

By experimentation, the appropriate amount of polyethylene was determined to be 2.5% by weight of coarse aggregate, which equates to 1.0% by weight of total aggregate. This amount did not completely coat all individual aggregate particles but did provide a rougher surface texture. It is also believed that this amount is near the maximum that is economically attractive.

A bowl of aggregates was removed from the oven and, immediately, the granulated polyethylene was slowly sprinkled onto the hot aggregate while during mixing to coat the aggregate particles as uniformly as possible. Mixing was continued until the aggregate had cooled sufficiently to avoid sticking of the aggregates. Typically, aggregates should be heated to a temperature 10 to 20°F above the desired temperature to ensure adequate time to accomplish the mixing/coating process before excessive cooling.

Recycled Carpet Co-Product

A co-product from the Allied Signal nylon carpet recycling process was used to coat coarse the gravel aggregate. The composition of the co-product is approximately 45% $CaCO_3$, 11% styrene-butadiene rubber (SBR from latex), 35% polypropylene, and 7-9% other (including dirt, etc.). The raw co-product consists of "flakes" up to one inch in diameter and about 6mm thick. After grinding, the material has the appearance of brown dust with a grain size of approximately 2.4 mm to 0.15 mm. In this experiment, the finer carpet co-product was used to enhance uniform distribution onto the aggregate surfaces and to facilitate rapid melting when the material contacted the hot aggregate. The smaller particles assisted adhesion to the aggregates. The coarser (unground) co-product would likely induce nonuniform coatings on the aggregates and agglomerations among the aggregate particles upon cooling.

Coating the carpet co-product onto surfaces of aggregates involves essentially the same process as that of coating with polyethylene. The appropriate amount of co-product for coating was visually determined to be 2.5% by weight of coarse aggregate. The oven temperature used was 370°F, but, for future work, the authors suggest that a higher temperature may improve the process and the resulting coating quality.

Cement & Latex

Button et al. (1992) coated aggregate with portland cement paste (no latex) and allowed the paste to completely cure prior to fabricating asphalt-aggregate mixtures in the laboratory and in the field. They found that a major portion (> 90%) of the cement coating was abraded off the aggregate surfaces during subsequent handling of the aggregates (i.e., transporting, mixing with asphalt, and compacting). Therefore, they concluded that the cement paste was not effective for coating aggregates to permanently improve roughness of aggregate surface texture and angularity nor other properties of asphalt-aggregate mixtures.

In this research, a small amount of styrene butadiene rubber (SBR) latex was incorporated into the wet cement paste in an attempt to improve the toughness and thus abrasion resistance of the subsequent coating on the coarse aggregate. The basic premise of the cement + latex coating is to create a rough-textured surface on the coarse aggregate particles in order to enhance inter-particle friction and promote adhesion between the asphalt binder and aggregate surface. These material alterations should, in turn, improve resistance to permanent deformation (pavement rutting) and moisture damage.

The concept was to coat aggregate particles with a hydrated cement film, which is thick enough to permanently shield the aggregate particle surface, but not so thick as to cause the particles to stick together and form cemented aggregate agglomerations. To formulate optimum cement coating quantities, the following three parameters were previously determined by Bayomy et al. (1984):

- Percent of cement added for each type and size of aggregate,
- Water content needed for cement hydration and bringing the aggregate to the saturated-surface-dry condition, and

- Minimum hydration time needed to achieve permanent bond of the cement coating film to the particle surfaces.

Cement Content

The ideal cement content required for coating the aggregates is dependent upon the particle size and size range. It is about 7% by the weight of dry aggregate for a particle diameter of 0.02 inches and remains constant for particle diameters up to 0.2 inch, after which the cement content decreases with increasing particle diameter. For aggregates above 0.2 inches in diameter, the amount of cement added to the aggregate is determined as follows (Bayomy et al., 1984):

$$C = 1.52 - 6.34 \log d$$

Where

C = cement to be added in percent by weight of the aggregate, and
d = mean diameter of the aggregate particles.

The portland cement content calculated and used for this research was a 4.3% by weight of the coarse aggregates.

Water Content

The water content required to optimize the coating process is the sum of the amount of water needed to bring the aggregate to saturated surface dry condition and the amount of water needed for cement hydration (Bayomy et al., 1984). This work demonstrated that the amount of water added was a critical factor in obtaining a satisfactory coating. An excessive amount of water yielded a thin or non-uniform coating while an insufficient amount resulted in a very weak cement coating (i.e., cement not completely hydrated) which was subject to loss by abrasion. The amount of water added was calculated using the following equation (Bayomy et al., 1984):

$$W = 0.2\,C + (Wa - Wn) * \text{Aggregate Weight}$$

Where

W = amount of water,
Wa = water absorption of the aggregate,
Wn = natural water content of the aggregate, and
C = weight of cement (cement percent × aggregate weight).

Latex Content

After much experimentation, researchers determined that latex and cement would not perform properly if mixed together before applying to the aggregate surfaces. Therefore, the cement mortar was applied to the aggregates and allowed to cure, then the latex was applied. This process appeared to best accomplish the project goal.

After coating the aggregates with cement and allowing it to hydrate, latex was applied onto the coated aggregates. The ideal amount of latex for coating the cement-treated aggregates was determined by trial and error. The idea was to apply as much latex as possible without causing the aggregates to stick together. Latex content was selected as 0.5% by weight of coarse aggregate for subsequent HMA sample fabrication.

The latex was about 65% solids, therefore, the SBR coating was approximately 3.3% by weight of coarse aggregates. An excessive quantity of latex caused agglomerations between the cement coated aggregates.

Cement & Latex Coating Procedure

The aggregates coarser than the No.4 sieve were coated using an appropriate amount of cement paste and allowed to cure. Then, the calculated amount of latex was added onto the coated aggregates in an attempt to increase adhesion between asphalt cement and surfaces of aggregates. After cement and latex coating of the aggregates was completed, the coated aggregates were kept in a humidity and temperature controlled environment for at least two days. The latex content was 0.5% by weight of coarse aggregates.

MIXTURE PROPERTIES AND DISCUSSION OF RESULTS

Sample Preparation

Uncoated aggregates were separated using appropriate sieves and then recombined in accordance with the mixture design to ensure an accurate and consistent gradation in all HMA specimens. Asphalt concrete specimens (4-inch diameter by 2-inch height) were mixed by hand and prepared using the Texas gyratory compactor in accordance with TxDOT standard Tex-206-F. Mechanical properties of the asphalt mixture specimens containing uncoated and coated aggregates with the three different coating materials were compared based on Hveem stability, Marshall stability, resilient modulus, indirect tension, and water susceptibility.

Hveem Stability

Hveem stability tests were conducted in accordance with ASTM D 1560. Hveem stability is an empirical measure of the interparticle friction of the aggregates comprising an HMA mixture. Hveem stability of the coated samples was consistently higher than that of the uncoated samples.

This result indicates that all three coating materials improved the surface texture of the aggregates thereby improving the internal friction and thus enhancing the Hveem stability of mixture. This is indicative that the HMA mixtures containing coated aggregates will exhibit improved resistance to rutting in a pavement. Figure 1 shows a bar chart to facilitate comparing Hveem stability of the different sample types. Each value represents an average from three independent tests. Polyethylene coated aggregates appear to provide the largest improvement Hveem stability. Test results on individual samples are given in Table C1 in Appendix C.

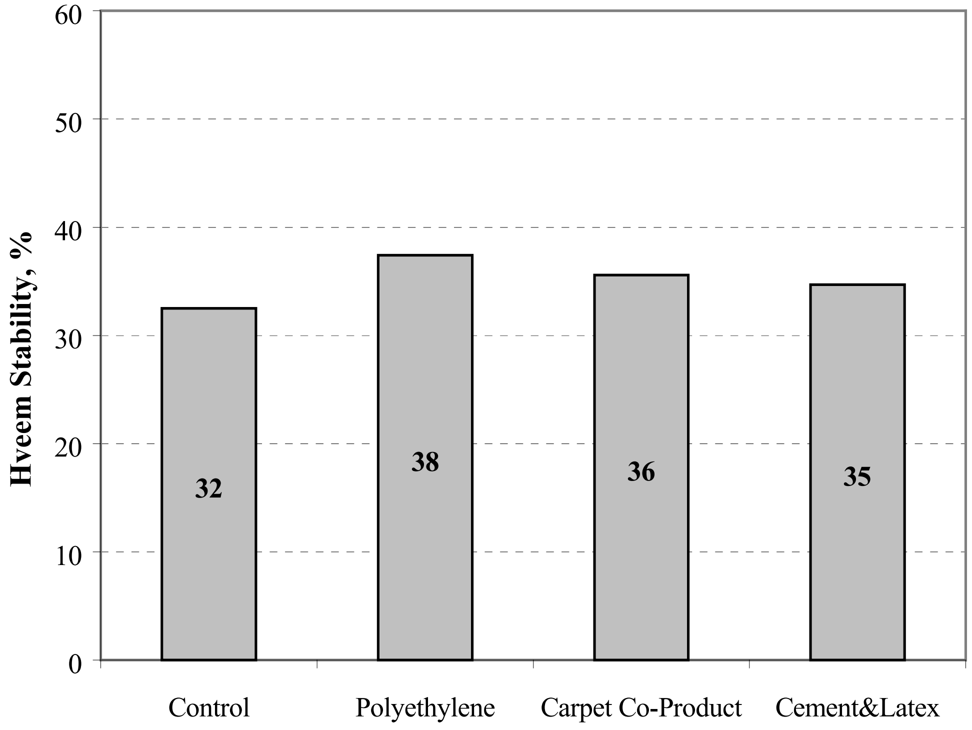

Figure 1. Hveem Stability for Mixtures Containing Uncoated Aggregates and Coated Aggregates.

Marshall Stability

Marshall and Hveem tests have been used for more than 50 years to design and evaluate HMA paving materials. Marshall stability was performed in accordance with ASTM D 1559. Marshall stability and flow values of asphalt concrete materials are recognized as measures of the material's ability to resist plastic flow. Typically, aggregates with higher angularity and surface texture will produce HMA with higher Marshall stabilities and lower Marshall flow.

Marshall stabilities of the mixtures containing the three different types of coating materials and the uncoated mixture are compared in Figure 2. Generally, the asphalt samples containing coated aggregates exhibited approximately 30% higher stability values than uncoated sample. The carpet co-product yielded the highest stability. Results for individual samples are presented in Table C2 in Appendix C.

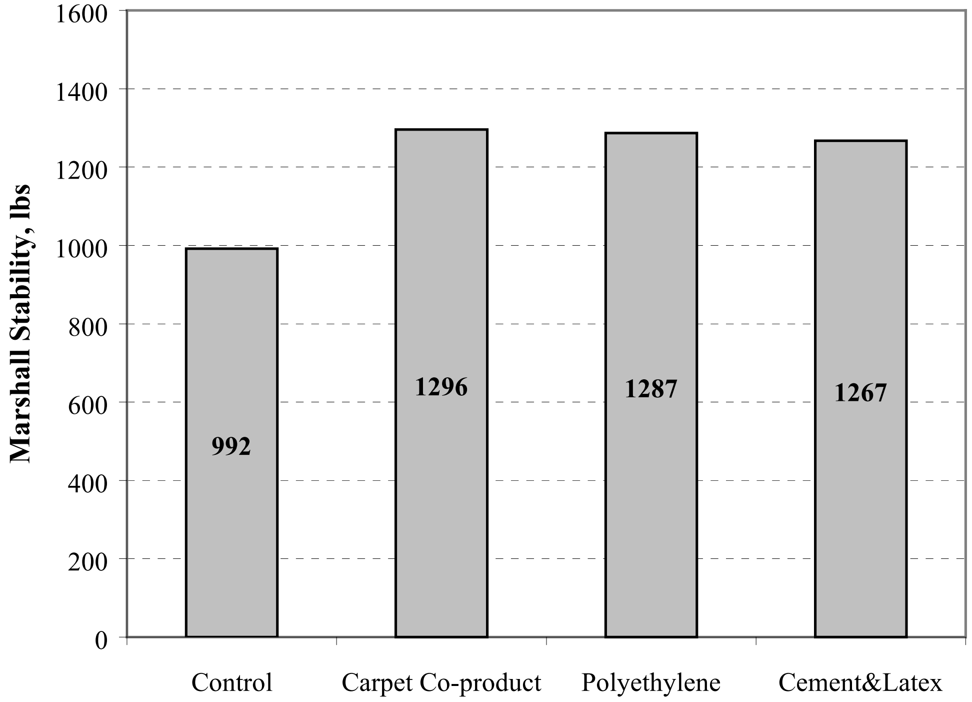

Figure 2. Comparison of Marshall Test Results of Uncoated and Coated Asphalt Mixtures.

Resilient Modulus (M_R)

Repeated load indirect tension resilient modulus tests (ASTM D 4123) were performed on compacted HMA specimens containing coated and uncoated aggregates at temperatures of 33°F, 68°F, 77°F and 104°F (1°C, 20°C, 25°C, and 40°C, respectively). The resilient modulus test, developed by Schmidt (1972), was designed to measure the stiffness or load bearing capacity of asphalt stabilized aggregate mixtures. This method is simple, fast, and economical and can be performed on standard size (4-inch by 2-inch) cylindrical asphalt specimens. During the course of test, a dynamic load was applied and total deformation was recorded. In the computation of M_R, Poisson's ratio was assumed to be 0.35.

M_R of the four different types of specimens were plotted as a function of temperature (Figure 3). The asphalt samples containing coated materials consistently exhibited higher M_R values than uncoated (control) samples. These findings indicate the coated aggregates produce HMA mixtures with greater stiffness and thus higher load bearing capacity. Results of tests on individual specimens are presented in Table C3 in Appendix C.

Resilient modulus was calculated using the following equation:

$$M_R = P\frac{(\upsilon + 0.273)}{t\delta}$$

Where

P = vertical load (kg),

ν = Poisson's ratio,

t = specimen thickness (cm),

δ = horizontal deformation (cm) and,

M_R = resilient modulus (kg/cm^2).

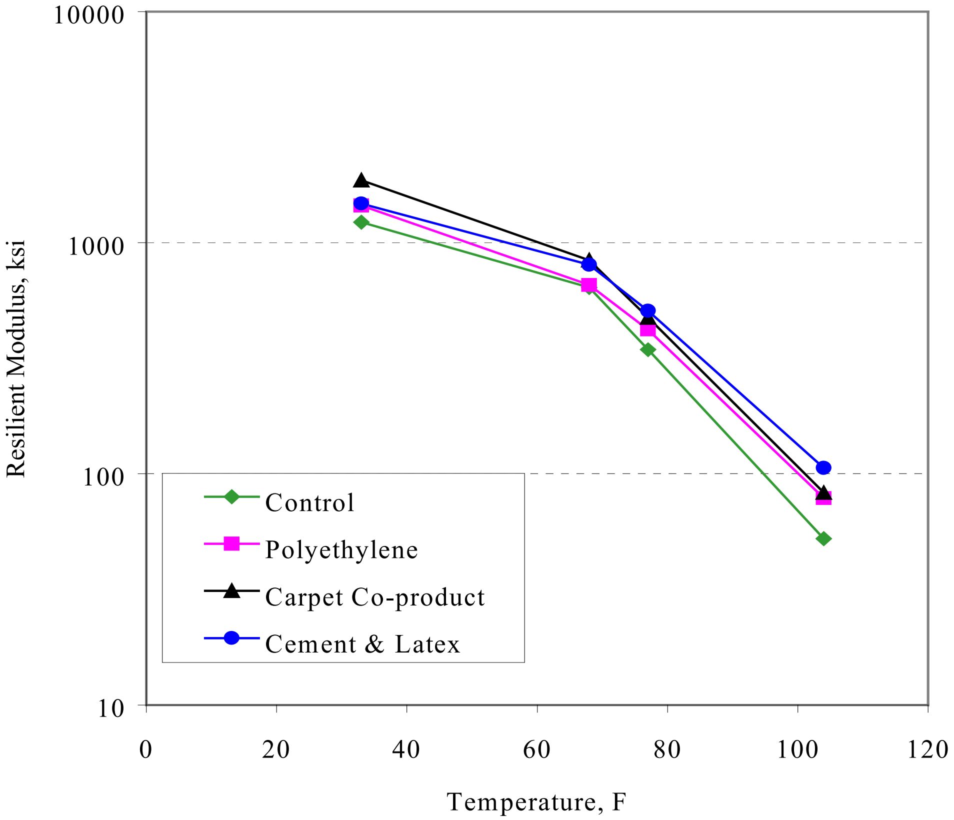

Figure 3. Resilient Modulus of Asphalt Concrete Mixtures Containing Uncoated and Coated Aggregates.

Tensile Properties

Tensile properties of asphalt mixtures with and without coating were measured using the indirect tension test method (Tex-226-F). Two-inch tall and four-inch diameter cylindrical specimens were loaded diametrally at a constant rate of deformation until complete failure occurred. All tests were conducted at a temperature of 77°F and a deformation rate of two inches per minute. Based on these test results, tensile strength of this asphalt mixture was consistently and significantly increased by the three coating materials (Figure 4). Tensile properties (strength, strain at failure, and secant modulus) of the individual test specimens are presented in Table C4 in Appendix C.

Water Susceptibility

For asphalt pavements utilizing low-quality aggregates, moisture susceptibility is often a serious problem. This is due to the fact that smooth, rounded siliceous

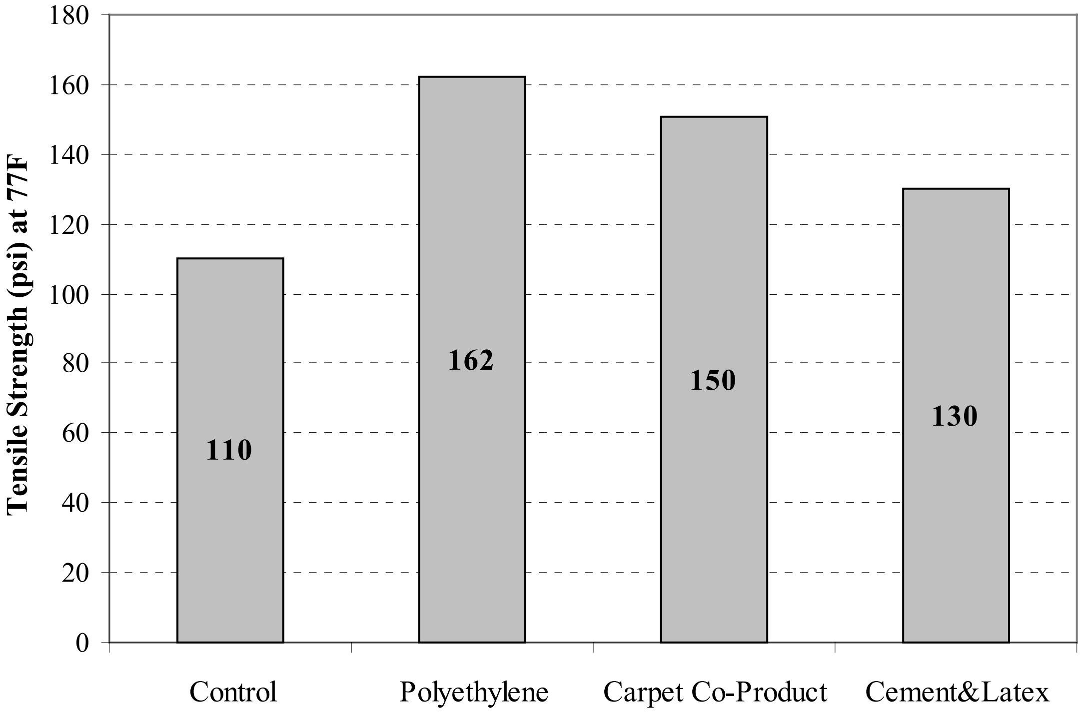

Figure 4. Tensile Strength for Mixtures Containing Uncoated Aggregates and Coated Aggregates.

aggregates with low porosity tend to form very weak mechanical bonds with the asphalt binder. Indirect tension tests were performed before and after the specimens were exposed to vacuum saturation in water plus freezing and thawing in accordance with TxDOT's Tex-531-C test method. A summary of test results is listed in Table 3. Test results on the individual specimens are provided in Table C5 in Appendix C.

After these specimens were tested, it was determined that the specimens were prepared using the design air void content. The standard procedure requires that the specimens be compacted to a higher air void content of 7% plus or minus 1%. The low air void contents of these specimens did not allow sufficient water into the specimens to significantly damage the specimens during the conditioning process. Therefore, the reported results are questionable. Unfortunately, there were insufficient materials to repeat these tests.

Table 3. Summary of Results of Moisture Susceptibility.

Mixture Type	Before Moisture Treatment			After Moisture Treatment		
	Air Void Content, %	Tensile Properties		Tensile Properties		
		Tensile Strength, psi	Strain @ Failure, in/in	Tensile Strength, psi	Strain @ Failure, in/in	Tensile Strength Ratio (TSR)
Uncoated	3.9	117	0.0060	113	0.0077	96
Polyethylene	2.1	145	0.0072	168	0.0065	116
Carpet Co-Product	1.9	155	0.0075	161	0.0062	104
Cement & Latex	2.3	136	0.0059	149	0.0061	110

Note: These values are obtained from the averages of three tests.

Ratios of tensile strength before and after exposure to moisture were calculated. Tensile strength ratio (TSR) is expressed as a percent and indicates the effect of moisture on the tensile strength of these asphalt mixtures. Figure 5 indicates that all three coating materials improved resistance to damage by moisture. The TSR values should have been lower than 100%. TSR values greater than 100% indicates errors in preparing the specimens or in performing the tests.

Inspection of Coated Aggregate Surfaces

A common magnifying glass was used to carefully inspect surfaces of uncoated aggregates and compare them with those of the coated aggregates. It was clearly evident that the coated aggregate particles possessed significantly greater surface texture or roughness than the uncoated aggregates. Photographs with a 3X magnification (Figures 6 through 9) show the surfaces of uncoated and coated aggregates.

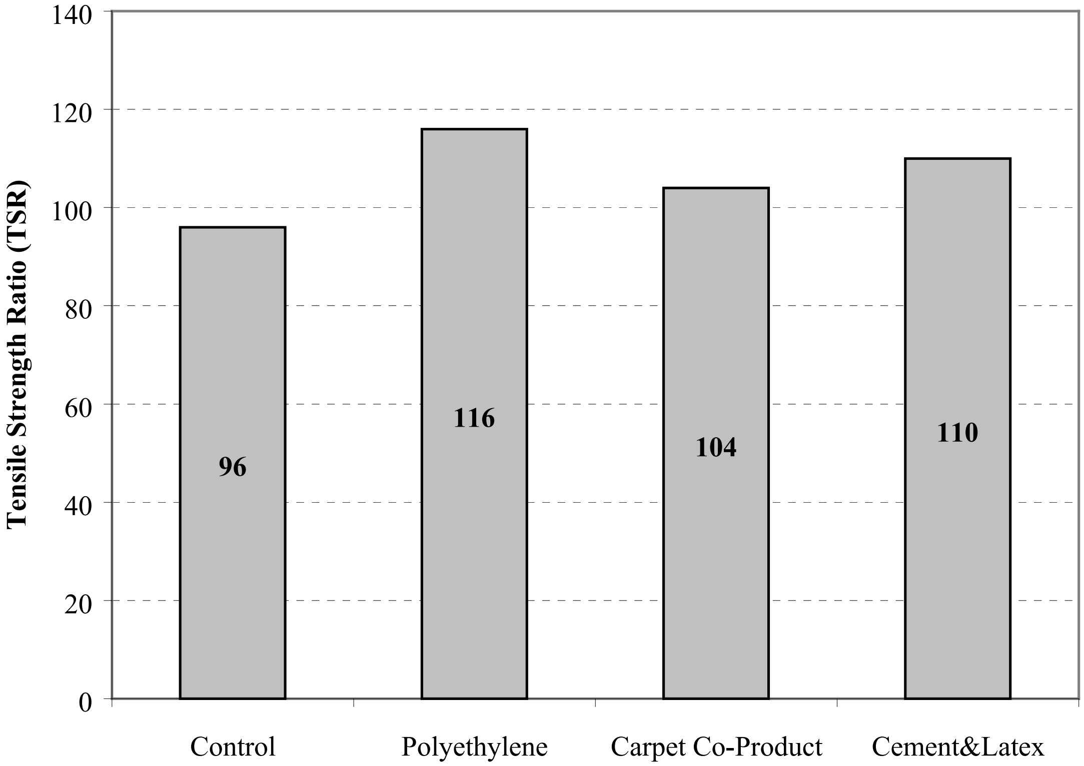

Figure 5. Tensile Strength Ratio (TSR) of Mixtures Containing Uncoated and Coated Aggregates.

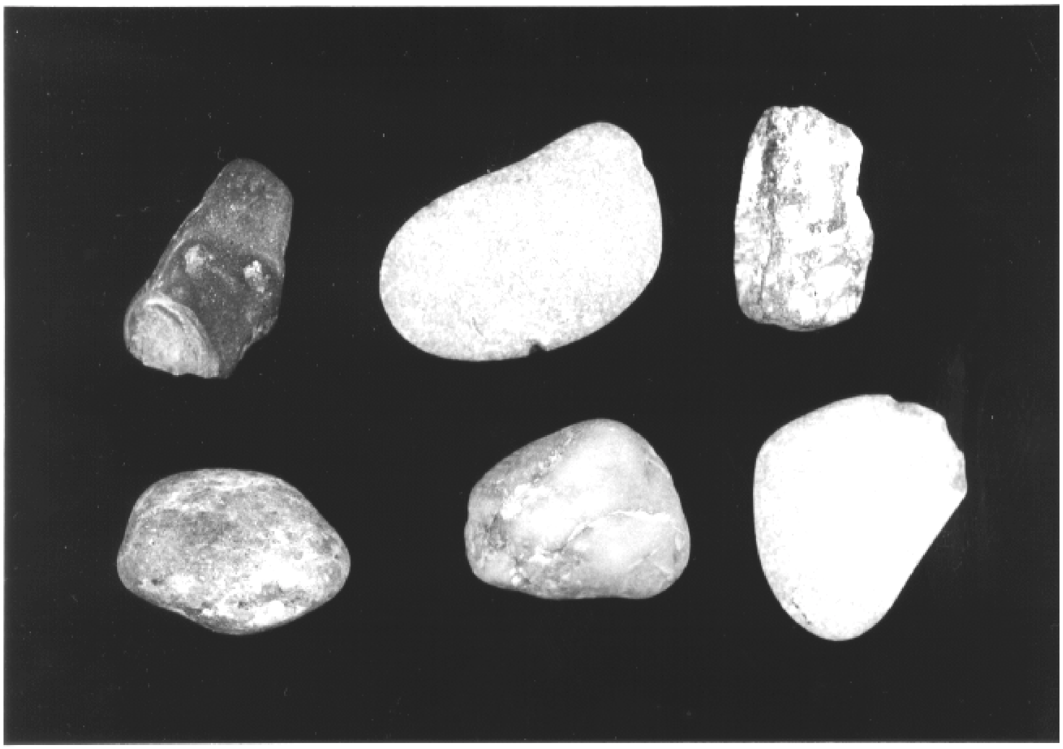

Figure 6. Typical Uncoated (Control) Aggregates (Magnified 3 Times).

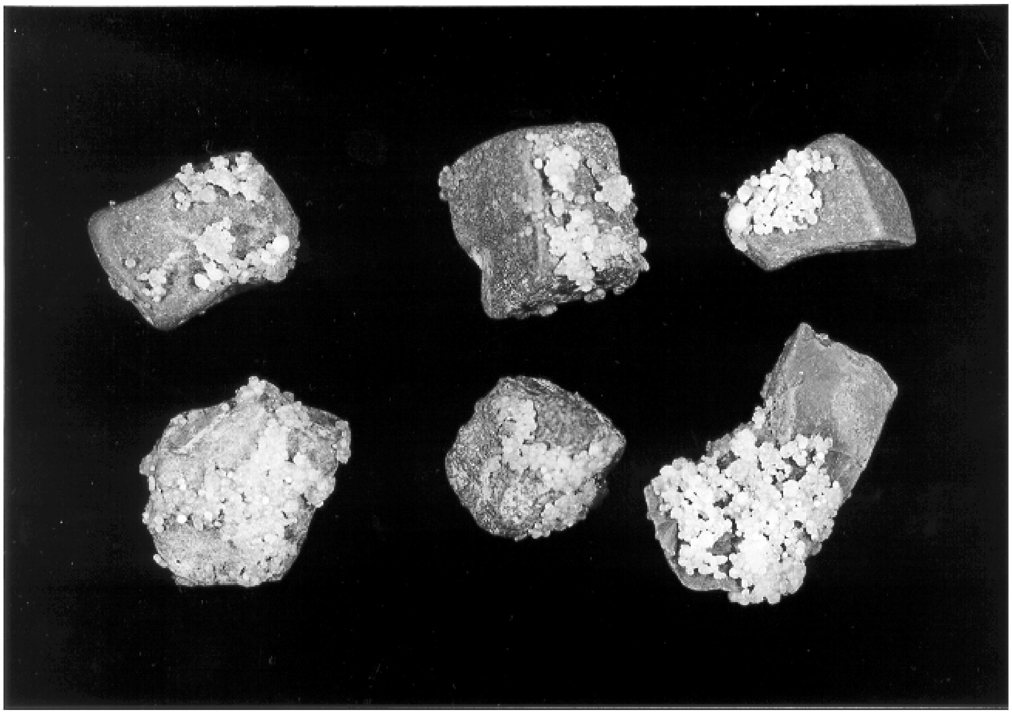

Figure 7. Typical Aggregates Coated with Fine-Grained Polyethylene (Magnified 3 Times).

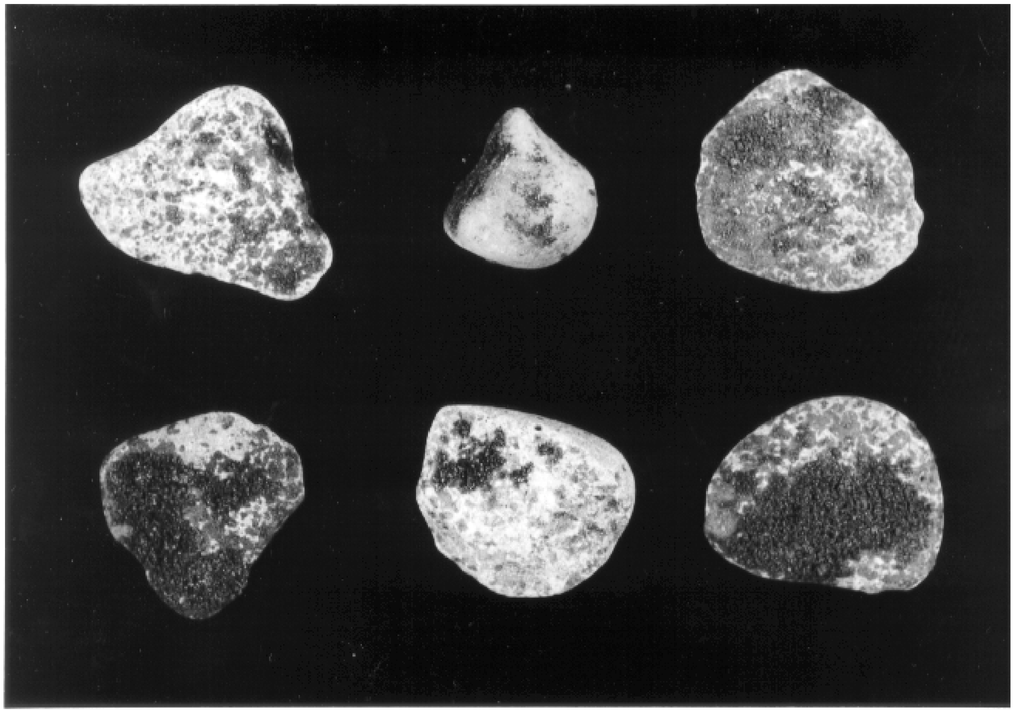

Figure 8. Typical Aggregates Coated with Carpet Co-Product (The coating appears in the photograph as dark stains). (Magnified 3 Times).

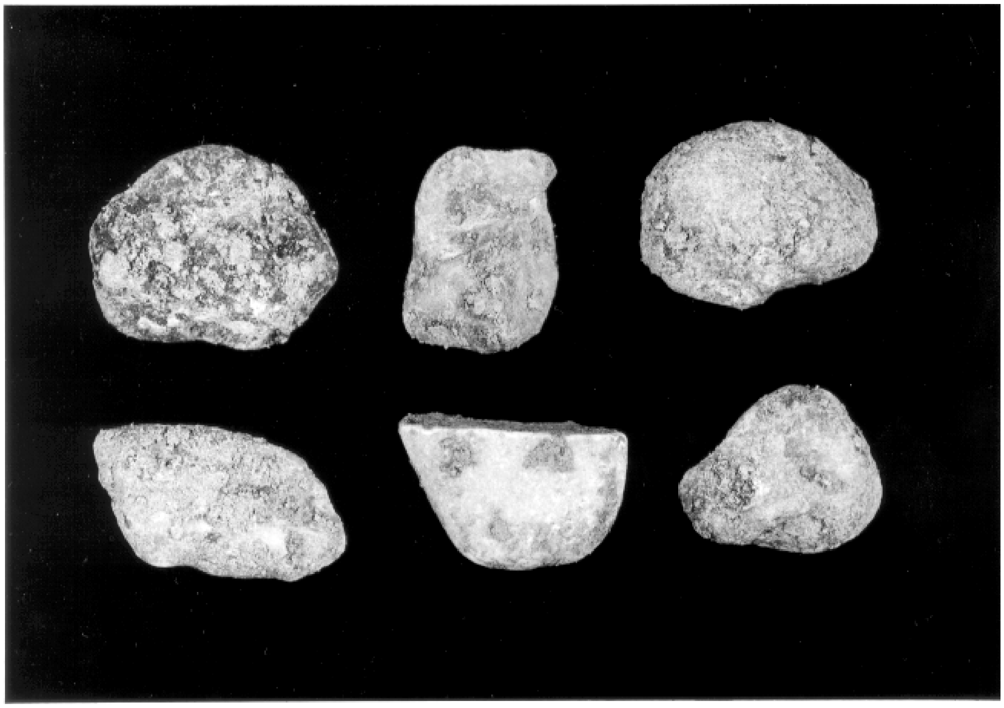

Figure 9. Typical Aggregates Coated with Cement Modified with Latex (Magnified 3 Times).

Inspection of Coated Aggregates After Mixing and Molding

In earlier work at TTI on coating of marginal aggregates with cement mortar (Button et al., 1992), it was found that, during mixing with asphalt and molding of specimens, much of the coating was abraded off the aggregate particles. This loss of coating was a particular problem during the field phase of that earlier work. Therefore, loss of the coatings was a concern during this study.

Compacted asphalt-aggregate specimens containing aggregates coated with the three materials were subjected to a solvent to extract the asphalt. Individual aggregates were then visually inspected to estimate the quality of the coating remaining. The results, particularly for the carpet co-product and the cement/latex, were disappointing. It was observed that about 30% of the carpet co-product and about 20% of the cement/latex remained on the surfaces of aggregates. However, more than 60% of the polyethylene remained. The polyethylene coating adhered well to the aggregate surfaces and resisted wear during handling and compacting. Based on this finding, fine-grained polyethylene appears to be most promising of the three coating materials tested.

CHAPTER IV
APPLICATION TO HIGHWAY PRACTICE

The cost of hauling aggregates may exceed the cost of the aggregate when the hauling distance is more than about 20 miles! This fact alone should demonstrate the importance and economics of using aggregates from local sources whenever possible.

In particular, the results of this research may have impact in southeast Texas and the southeastern United States. This is because these areas of the country possess very few remaining sites where stone of suitable quality can be quarried and crushed. However, much of this area has large supplies of river gravel and sand composed of rounded to subrounded particles. Engineering properties of these gravels and sands may be dramatically improved by using one of the coating materials described herein, thus improving their suitability for use in hot mix asphalt pavements. It is believed that with a little work, the coating process could be substantially improved such that more durable coatings could be achieved.

Now that this aggregate coating process has been demonstrated to be feasible and capable of improving HMA paving mixture properties, the economics of using these aggregate coating materials in a full-scale process needs to be investigated. Materials specifications and construction guidelines will need to be prepared to assist in implementation of the findings of this research.

In general, this SWUTC-funded research addresses potential improvements in economy and the environment, potential development of partnerships with industry, technology transfer, sustaining of materials supplies, reduced aggregate hauling requirements (thus enhanced safety, mobility, and accessibility), and potential for business development in marketing local aggregates and sustaining communities.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

A laboratory investigation was conducted wherein smooth, rounded, siliceous gravel aggregates were coated with fine-grained polyethylene, carpet co-product, or cement + SBR latex and used to prepare asphalt concrete specimens. Only the coarse (+ No. 4) aggregates were coated. The concept was that the coatings would enhance surface roughness of the aggregates and, thus, produce asphalt mixtures with superior engineering properties. Hot mix asphalt specimens were subsequently evaluated using several standard and non-standard test procedures. Based on experiences during the coating processes and analyses of these limited test results, the following conclusions are tendered:

1. Hveem stability of the asphalt mixture was slightly increased by all three aggregate coatings.
2. Marshall stability of the asphalt mixture was substantially increased by all three aggregate coatings.
3. The energy required to achieve a given level of compaction was reduced by all three the aggregate coatings.
4. Tensile strength of the asphalt mixture was consistently increased by all three aggregate coatings.
5. Resilient modulus (stiffness) of the asphalt mixture was consistently increased by all three aggregate coatings.
6. Conclusions 1 through 5 are indicative of improved resistance to rutting and cracking in hot mix asphalt pavements fabricated using coated rounded gravel aggregates in comparison to pavements made using similar uncoated aggregates.

7. Resistance to moisture damage of the asphalt mixture was improved by all three aggregate coating materials. Fine-grained polyethylene and carpet co-product appeared to be the most promising aggregate coating materials to improve an adhesion between asphalt binder and aggregate surfaces based on the laboratory results. (It should be pointed out, however, that these tests were not performed in accordance with the standard procedure.)
8. Although the cement + SBR latex coated aggregates demonstrated improved mechanical properties of the asphalt mixtures, extraction of the asphalt and examination of the coarse aggregates indicated that about 80% of the coating was abraded away during mixing with asphalt and compaction of the specimens.

RECOMMENDATIONS

1. The authors believe that, with a small follow-up research effort, the coating process could be substantially improved such that more durable coatings could be achieved that would resist abrasion and further improve engineering properties of the asphalt mixture.
2. This study demonstrated that the aggregate coating process is feasible and capable of improving HMA paving mixture properties, the economics of using these aggregate coating materials in full-scale industrial processes needs to be investigated.
3. To assist in implementation of the findings of this research, materials specifications and construction guidelines will need to be prepared.

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APPENDIX A

ASPHALT CEMENT CHARACTERIZATION

This Appendix presents properties of the asphalt cement used in the asphalt mixtures studied herein. The performance grade (PG) of the asphalt was determined in accordance with the Superpave asphalt binder specification (AASHTO MP1). These results confirm that the grade of the asphalt cement is PG 64-22. Mixing and compaction temperatures and complex shear moduli at different frequencies and temperatures were also determined. A summary of the results obtained is provided in Table A1.

Table A1. Test Results and PG 64-22 Requirements.

Binder Property	Binder Aging Condition	Test Result	Requirement
Flash Point (°C)	Unaged	299	>230
Viscosity at 135 C (Pa x second)	Unaged	0.41	<3.00
Dynamic Shear, G*/sin δ at 64 C (kPa)	Unaged	1.045	>1.00
Mass Loss (%)	RTFO aged	0.55	<1.00
Dynamic Shear, G*/sin δ at 64 C (kPa)	RTFO aged	2.91	>2.20
Dynamic Shear, G* x sin δ at 25 C (kPa)	PAV aged	2842	<5000
Creep Stiffness, S at -12 C (Mpa)	PAV aged	176	<300
m-value at -12 C	PAV aged	0.301	>0.300

Rheological properties of the asphalt cement were determined according to AASHTO TP5. The test apparatus used was a Bohlin Controlled Stress Rheometer. In Table A2, A3, and A4, test conditions and results obtained with the Dynamic Shear Rheometer (DSR) are listed.

The asphalt cement was aged using a James Cox and Sons Inc., Rolling Thin Film Oven Test (ASTM D2872/AASHTO T240) and a Pressure Aging Vessel developed in Texas Transportation Institute (AASHTO PP1).

Stiffness of the aged asphalt residue at very low temperatures was measured according to AASHTO TP1. A Bending Beam Rheometer by Cannon Instrument Company was used for this work. In Table A5 and A6, test results obtained with the Bending Beam Rheometer (BBR) are listed.

Table A2. DSR Test Conditions and Results for Original Binder.

Test temperature (°C)	52	58	64
Complex Shear Modulus (kPa)	5.299	2.257	1.042
Shear phase angle (degrees)	82.5	84.8	86.1
G*/sin δ (kPa)	5.345	2.266	1.045
Test plate diameter (mm)	25.0	25.0	25.0
Plate Gap (mm)	1.0	1.0	1.0
Test Frequency (rad/sec)	10.08	10.08	10.08
Final Temperature (^{o} C)	52.0	58.0	64.0
Strain amplitude (%)	11.73	11.84	11.95
TEST STATUS	Passed	Passed	Passed

Table A3. DSR Test Conditions and Results for Binder after RTFO.

Test temperature (°C)	70	64	58
Complex Shear Modulus (kPa)	1.602	2.887	6.458
Shear phase angle (degrees)	85.7	83.1	80.1
G*/sin δ (kPa)	1.606	2.909	6.556
Test plate diameter (mm)	25.0	25.0	25.0
Plate Gap (mm)	1.0	1.0	1.0
Test Frequency (rad/sec)	10.08	10.08	10.08
Final Temperature (°C)	70.1	64.0	58.0
Strain amplitude (%)	10.04	9.90	9.99
TEST STATUS	Failed	Passed	Passed

Table A4. DSR Test Conditions and Results for PAV Residue.

Test temperature (°C)	19	22	25
Complex Shear Modulus (kPa)	8275.8	6190.0	4511.7
Shear phase angle (degrees)	42.4	41.36	39.05
G* x sin δ (kPa)	5580.4	4090.3	2842.4
Test plate diameter (mm)	8.0	8.0	8.0
Plate Gap (mm)	2.0	2.0	2.0
Test Frequency (rad/sec)	10.08	10.08	10.08
Final Temperature (°C)	18.9	22.0	25.0
Strain amplitude (%)	1.01	1.01	1.03
TEST STATUS	Failed	Passed	Passed

Table A5. BBR Test Results at –12°C.

Time (sec)	Force (mN)	Deflection (mm)	Measured Stiffness (MPa)	Estimated Stiffness (MPa)	Difference (%)	m-value
8	993	0.262	306	305	-0.327	0.249
15	994	0.309	259	260	0.386	0.265
30	994	0.374	214	215	0.467	0.283
60	**995**	**0.457**	**176**	**176**	**0.000**	**0.301**
120	995	0.565	142	142	0.000	0.318
240	1000	0.716	113	113	0.000	0.336

A = 2.69B = -0.196 C = -0.0295 R^2 = 0.999965

Table A6. BBR, Test Results at –18°C.

Time (sec)	Force (mN)	Deflection (mm)	Measured Stiffness (MPa)	Estimated Stiffness (MPa)	Difference (%)	m-value
8	994	0.179	448	447	-0.223	0.230
15	994	0.209	383	385	0.522	0.246
30	994	0.249	322	322	0.000	0.264
60	**994**	**0.300**	**267**	**267**	**0.000**	**0.282**
120	995	0.367	219	218	-0.457	0.301
240	997	0.458	176	176	0.000	0.319

A = 2.83 B = -0.175 C = -0.0302 R^2 = 0.999945

Flash point temperature of the asphalt was determined according to ASTM D92. The viscosity was measured using a Brookfield Rheometer according to ASTM D 4402. The viscosity obtained at 135°C was 410 cP (0.41 Pa x sec) (See Figure A1).

In order to compare the asphalt cement rheology with the asphalt concrete, the complex modulus and the shear phase angle were determined at different frequencies and temperatures. The data obtained is listed in Tables A7, A8, and A9.

Table A7. Complex Shear Modulus at 46°C.

Temperature (°C)	Frequency (Hz)	Phase angle	Shear Complex Modulus (Pa)
46	10	76.11	6.16E6
46	5	77.57	3.43E6
46	2	79.80	1.54E6
46	1	81.28	8.25E5
46	0.5	82.92	4.36E5
46	0.2	84.61	1.85E5
46	0.1	85.82	9.51E4
46	0.05	87.06	4.87E4
46	0.02	88.64	1.01E4

Table A8. Complex Shear Modulus at 20°C.

Temperature (°C)	Frequency (Hz)	Phase angle	Shear Complex Modulus (Pa)
20	10	58.77	5.19E6
20	5	60.64	3.46E6
20	2	63.37	1.91E6
20	1	65.40	1.22E6
20	0.5	67.19	7.36E5
20	0.2	69.67	3.71E5
20	0.1	71.09	2.17E5
20	0.05	73.15	1.20E5
20	0.02	76.67	3.13E4

Table A9. Shear Complex Modulus at 7°C.

Temperature (°C)	Frequency (Hz)	Phase angle	Shear Complex Modulus (Pa)
7	10	45.24	2.27E7
7	5	48.12	1.61E7
7	2	51.83	9.82E6
7	1	54.86	6.69E6
7	0.5	57.32	4.38E6
7	0.2	60.62	2.48E6
7	0.1	62.85	1.55E6
7	0.05	65.13	9.78E5
7	0.02	68.49	3.34E5

APPENDIX B

PROJECT DESIGN GRADATION
AND
DETERMINATION OF OPTIMUM ASPHALT CONTENT

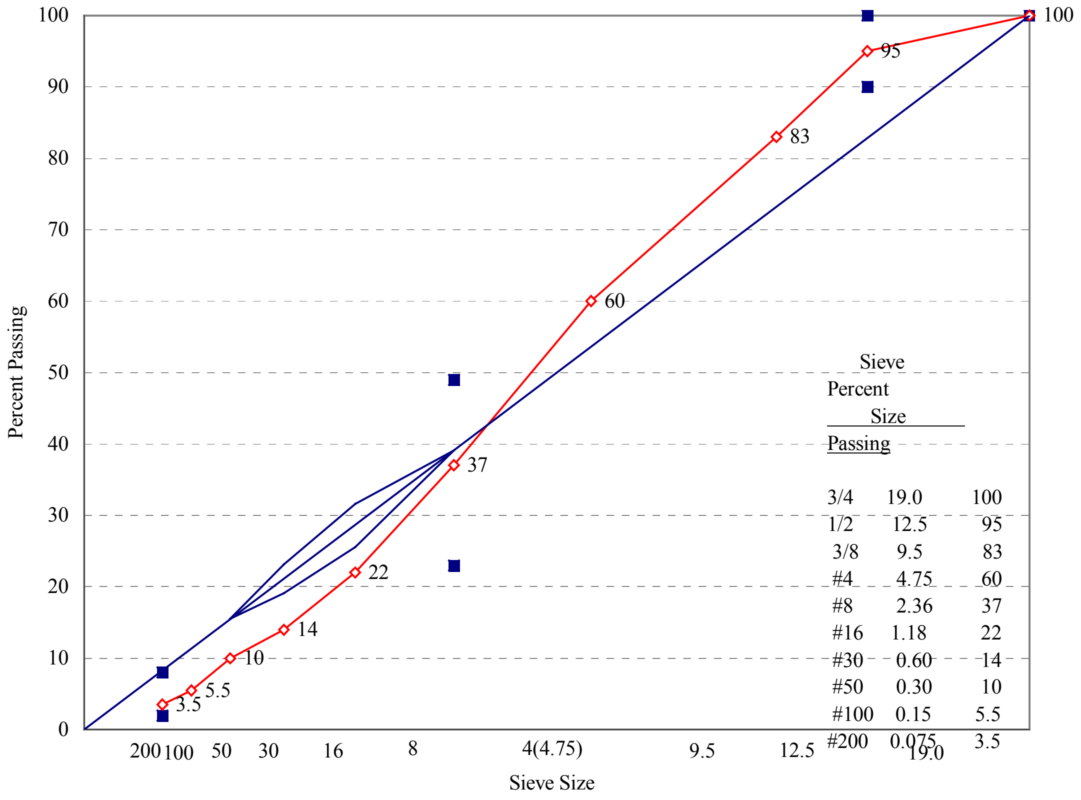

Figure B1. Gradation Curve for 12.5 mm Nominal Aggregate Size.

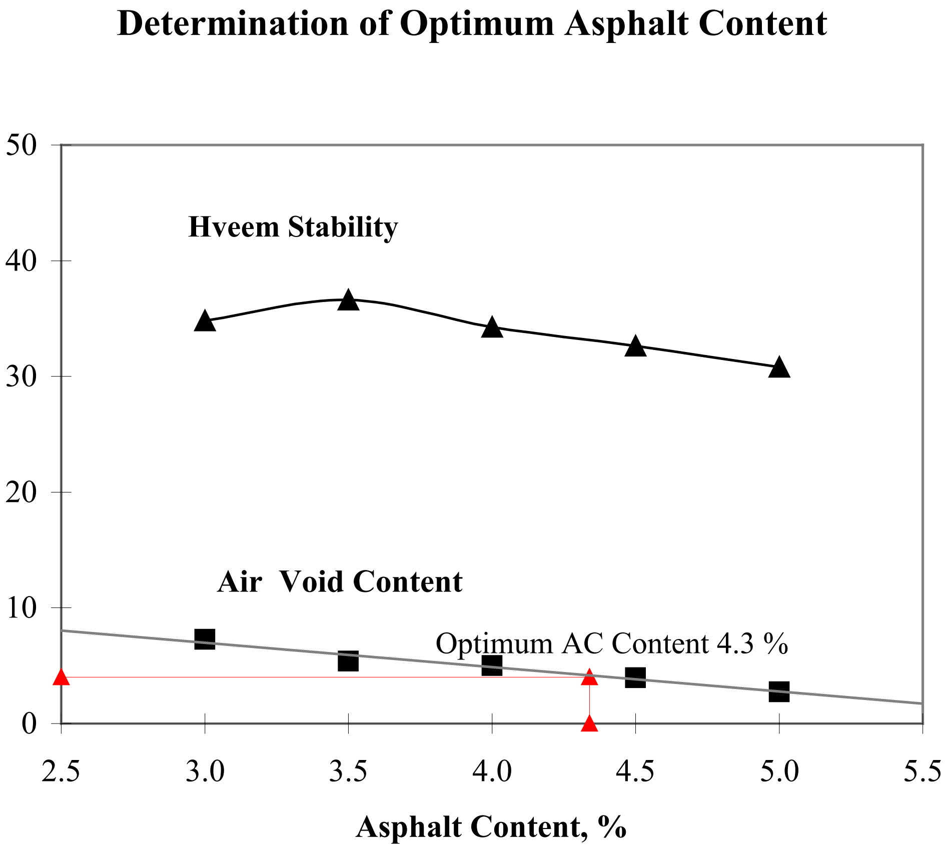

Figure B2. Chart for Determining of Optimum Asphalt Content and Hveem Stability at Optimum.

APPENDIX C

TEST RESULTS FOR UNCOATED AND COATED ASPHALT MIXTURES

Table C1. Hveem Stability Test Results for Uncoated and Coated Asphalt Mixtures.

Type	Sample No.	Height, in	Bulk Specific Gravity	Air Voids, %	Hveem Stability, %
Control	Cont-1	2.03	2.41	3.0	33.4
	Cont-2	2.00	2.39	3.8	32.2
	Cont-3	1.97	2.40	3.2	31.7
Polyethylene	PE-1	2.10	2.33	2.6	34.5
	PE-2	2.11	2.35	2.0	38.7
	PE-3	2.09	2.35	1.9	39.7
Carpet Co-Product	CP-1	2.00	2.44	1.4	36.3
	CP-2	2.01	2.43	1.9	36.2
	CP-3	2.03	2.41	2.4	35.4
Cement & Latex	CL-1	2.01	2.42	2.4	34.9
	CL-2	2.03	2.39	2.3	35.1
	CL-3	2.04	2.41	2.3	33.6

Table C2. Marshall Stability Results for Uncoated and Coated Asphalt Mixtures.

Type	Sample No.	Height, in	Bulk Specific Gravity	Air Voids, %	Marshall Stability, lbs	Marshall Flow, 0.01 in
Control	Cont-1	2.03	2.41	3.0	1001	10.0
	Cont-2	2.00	2.39	3.8	919	12.0
	Cont-3	1.97	2.40	3.2	1057	11.0
Polyethylene	PE-1	2.10	2.33	2.6	1229	15.0
	PE-2	2.11	2.35	2.0	1283	14.0
	PE-3	2.09	2.35	1.9	1350	15.0
Carpet Co-Product	CP-1	2.00	2.44	1.4	1308	10.0
	CP-2	2.01	2.43	1.9	1292	12.0
	CP-3	2.03	2.41	2.4	1287	12.5
Cement & Latex	CL-1	2.01	2.42	2.4	1305	11.5
	CL-2	2.03	2.39	2.3	1224	13.5
	CL-3	2.04	2.41	2.3	1273	13.5

Table C3. Resilient Modulus of Uncoated and Coated Asphalt Mixtures.

Type	Sample No.	Resilient Modulus, ksi			
		33°F	68°F	77°F	104°F
Control	Cont-1	1208	693	317	52
	Cont-2	1033	613	361	20
	Cont-3	1446	612	356	55
Polyethylene	PE-1	1220	648	387	71
	PE-2	1310	656	454	83
	PE-3	1813	662	423	81
Carpet Co-Product	CP-1	2215	884	463	76
	CP-2	1488	775	485	93
	CP-3	1893	859	475	78
Cement & Latex	CL-1	1454	1084	539	107
	CL-2	1611	646	480	98
	CL-3	1374	678	503	112

Table C4. Indirect Tension Test Results for Asphalt Mixtures.

Type	Sample No.	Tensile Strength, psi	Strain at Failure, in/in	Secant Modulus, psi
Control	Cont-1	103	0.0068	15319
	Cont-2	108	0.0073	14954
	Cont-3	119	0.0073	16330
Polyethylene	PE-1	161	0.0056	29024
	PE-2	144	0.0082	17687
	PE-3	180	0.0054	33485
Carpet Co-Product	CP-1	150	0.0069	21873
	CP-2	149	0.0064	23379
	CP-3	152	0.0057	26950
Cement & Latex	CL-1	121	0.0061	19998
	CL-2	135	0.0057	23557
	CL-3	134	0.0071	18883

Table C5. Results from Water Susceptibility Tests on Asphalt Mixtures.

Type	Sample No.	Before Moisture Treatment (Dry)			Sample No.	After Moisture Treatment (Wet)		
		Air Void, %	Tensile Strength, psi	Strain at Failure, in/in		Tensile Strength, psi	Strain at Failure, in/in	Tensile Strength Ratio
Control	Cont-10	3.6	113	0.0063	Cont-7	93	0.0085	96
	Cont-11	3.0	136	0.0053	Cont-8	107	0.0073	
	Cont-12	4.9	102	0.0064	Cont-9	138	0.0074	
Polyethylene	PE-10	1.8	167	0.0070	PE-7	189	0.0058	116
	PE-11	1.8	139	0.0072	PE-8	156	0.0072	
	PE-12	2.7	129	0.0073	PE-9	160	0.0066	
Carpet Co-Product	CP-10	1.4	160	0.0075	CP-7	170	0.0056	104
	CP-11	1.9	148	0.0073	CP-8	131	0.0078	
	CP-12	2.4	158	0.0077	CP-9	181	0.0052	
Cement & Latex	CL-10	2.4	140	0.0059	CL-7	137	0.0062	110
	CL-11	2.3	138	0.0062	CL-8	147	0.0062	
	CL-12	2.3	129	0.0055	CL-9	164	0.0059	