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16. Abstract

The Texas Department of Transportation has experienced problems with inconsistent performance of the coarse aggregate fraction of hotmix asphalt pavements. This project was initiated to address problems associated with variations in hotmix coarse aggregate quality. More specifically, the researchers wanted to identify simple tests that can be performed at the aggregate quarries to assess the durability of aggregates and determine what percentage of an aggregate is poor quality. The researchers surveyed civil engineering and geological literature to identify simple tests that can identify poor performing aggregates and can be performed in the field with a minimal amount of skill. Following the identification of potential tests, the researchers visited several quarries in Texas and used these techniques to differentiate good and poor quality coarse aggregates. The researchers identified several simple tests that inspectors can perform in the field to identify poor quality aggregates, including: aggregate angularity (more rounded = poorer quality), water absorption (more absorbed = poorer quality), hardness (soft = poorer quality), and fines content (more fines = poorer quality). Things that can be done at the aggregate quarries include: constructing smaller stockpiles, selective quarrying of good rock, and utilizing a wash system to remove some of the poorer quality aggregates. The preceeding tests and quarry recommendations can be utilized by inspectors to regulate the quality of coarse aggregate used in hotmix applications.

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by

John P. Harris, P.G.
Associate Research Scientist
Texas Transportation Institute

and

Arif Chowdhury, P.E.
Associate Transportation Researcher
Texas Transportation Institute

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Research Project Title: Controlling Mineralogical Segregation in Bituminous Mixes

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The Texas A&M University System
College Station, Texas 77843-3135

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CHAPTER 1
COARSE AGGREGATE TESTS FOR BITUMINOUS MIXES

INTRODUCTION

Hotmix asphalt concrete (HMAC) contains about 94 percent (by weight) coarse and fine aggregate (Kandhal and Parker, 1998); the quality of that aggregate has a profound impact on the performance of the asphalt pavement. The Texas Department of Transportation (TxDOT) has experienced problems obtaining consistent performance from the coarse aggregate fraction. Studies performed at the Geotechnical, Soils, and Aggregates Branch of the TxDOT Construction Division indicate that many of these aggregate sources contain as many as eight distinctive rock types. The quantity of each of these rock types present at any point in time can vary significantly. Some of these heterogeneities can be addressed at the quarry, but current specifications and test procedures do not adequately address this problem. For example, an aggregate stockpile run in a five-cycle Magnesium Sulfate Soundness (MSS) Test (Tex-411-A) can have as much as 30 percent loss and still be considered acceptable. Asphalt produced one day may have a MSS loss of 30 percent coarse aggregate and the next day may only have a MSS loss of 5 percent coarse aggregate. Asphalt quality and performance will be different for each day.

This project was initiated to address problems associated with variations in hotmix coarse aggregate quality. More specifically, the researchers wanted to identify tests that can be performed at the aggregate quarries to control variations in aggregate quality that result from multiple layers of durable and non-durable strata within a quarry. The tests should monitor aggregate variation with a frequency necessary to take corrective action before large quantities of poor quality aggregate are produced. Second, the researchers wanted to define the term "mineralogical segregation" coined by TxDOT.

According to Fookes et al. (1988), durability is a rock material's ability to resist degradation during its working life and is dependent on a number of parameters. The original stage of weathering of the rock mass; the degree of imposed stressing during winning, production, placing, and service; the climate; and topographical and hydrological environments in service are the parameters that Fookes et al. (1988) list as affecting durability.

ROLE OF COARSE AGGREGATE IN HMAC

Properties of the coarse aggregate fraction, related to mineralogy, that influence the performance of HMAC and seal coat are briefly described. Coarse aggregate is defined as material larger than 2.38 mm (#8 U.S. standard sieve) in accordance with TxDOT specifications**.**

Shape and Surface Texture

Angular shape and rough surface texture are among the most desirable aggregate properties for resistance to rutting and fatigue fracture (Chowdhury et al., 2000). Cubic and angular aggregate shapes provide increased internal friction and improved resistance to rutting (Kandhal et al., 1990). Rough surface texture is also important in the frictional resistance of a mixture. Rough surface texture yields better bonding between the aggregate surface and asphalt binder, which is desirable for minimizing stripping problems. Excessively flat and/or elongated aggregates are undesirable because there is a chance of those aggregates breaking under traffic loading, making the mixture more moisture susceptible. There are numerous research studies showing the importance of shape and surface texture for aggregate. The shape of aggregate depends mainly on the rock mineralogy, reduction ratio, and crushing methods, whereas surface texture is mostly dependent on the mineralogy of the rock.

Toughness and Abrasion Resistance

Toughness and abrasion resistance are associated with degradation of aggregate occurring during construction and under traffic loading. Aggregate must be tough and resistant to abrasion, to resist crushing, degradation, and disintegration when stockpiled, fed through the HMAC plant, compacted with a paving roller, and subjected to heavy traffic loading. These properties are more critical for open-graded and gap-graded mixtures than dense-graded mixtures (Kandhal and Parker, 1998). Excessive degradation of aggregate during mixture compaction and trafficking is a severe problem as; aggregate faces are exposed and uncoated, resulting in stripping and less durability (Amirkhanian et al., 1991). The Los Angeles Abrasion Test is widely used to measure this property.

Durability and Soundness

Soundness and durability are related to the degradation of aggregate upon exposure to environmental factors. Aggregate must be resistant to breakdown or disintegration when subjected to wetting and drying and/or freezing and thawing cycles during its service life. If the asphalt coating remains intact, these weathering cycles do not significantly affect the HMA mixture. However, water can penetrate the aggregate particles if some degradation of the HMA mixture occurs during construction. Soft, weak particles that break down during compaction provide convenient access for water. Water can also penetrate if the HMA mixture has experienced stripping. Raveling, stripping, and, in some cases, rutting of HMA pavement can result from the use of unsound aggregate. Kandhal and Parker (1998) mentioned that aggregate durability and soundness are closely related to aggregate toughness and abrasion resistance.

Polish and Frictional Characteristics

Asphalt concrete and seal coat are primarily used as the topmost layer in a flexible pavement and, therefore, the layer in contact with vehicle tires. As a result, the frictional characteristics of an aggregate are as important as its structural characteristics. Frictional characteristics of a layer are provided by macrotexture (aggregate gradation control) and microtexture (mineralogy of the aggregate). There has been considerable effort to correlate coarse aggregate polish and frictional properties with frictional resistance of pavement. Pavement frictional resistance is most often measured with a locked-wheel skid trailer.

Porosity and Absorption

Mineral aggregate used in HMA and seal coat are somewhat porous and as such tend to absorb some asphalt and water. Sometimes this absorption of asphalt may be beneficial to the mixture properties (Kandhal and Parker, 1998). If this asphalt absorption is time dependent and the aggregate continues to absorb asphalt, the portion of the binder that is asphalt is no longer available as binder (Kandhal and Koehler, 1985). Excessive absorption of asphalt binder in mineral aggregate may lead to incorrect computation of void of mineral aggregate (VMA) and void filled with asphalt (VFA); lack of enough effective binder may lead to raveling and cracking or stripping, possible premature hardening, and low-temperature cracking.

Cleanliness and Deleterious Materials

Cleanliness and deleterious materials refer to the coating of aggregate particles with clay and/or the presence of weak, reactive, or unsound materials. Deleterious materials inhibit asphalt binder from coating the aggregate particles and sometimes react with the environment. Some examples of deleterious materials are clay lumps, friable particles, shale, coal, glassy particles, and free mica. The presence of free mica in HMA mixtures is believed to reduce fatigue life and increase rutting (Seigel, 1992).

Expansive Properties

Some materials like gypsum or steel slag, if present in an aggregate, have a tendency to swell with the presence of moisture. The swelling of aggregate in HMA can cause loss of adhesion and disintegration of the pavement. Proper curing of aggregate can reduce the chance of swell.

Chemical Properties

The chemical composition of a mineral usually dictates the chemical properties of that mineral or aggregate. Surface chemistry of an aggregate is very important because it affects the strength and durability of the bond between the aggregate and asphalt. This property is more important in the presence of moisture. Some aggregates appear to have a greater affinity for water than for asphalt cement. If the aggregate's affinity for water is higher than its affinity for asphalt, the asphalt film on these aggregate particles may become detached or stripped after exposure to water. Most siliceous aggregates become negatively charged in the presence of water, whereas calcareous aggregates carry a positive charge in the presence of water. The aggregates that have a tendency to be hydrophilic are usually acidic in nature. On the other hand, aggregates having more affinity for asphalt are basic in nature and are called hydrophobic (Kandhal and Parker, 1998).

Improvement of Aggregate Quality

Most aggregate properties are a result of their mineralogical composition. The quality of the aggregate depends on many factors, such as rock source, mineralogy, quarry operation, handling, and continuous quality control. Once a source is selected, there are few methods of improving aggregate quality; however, some aggregate properties can be improved in an economical manner. A few of the common techniques employed for improving aggregate quality used in HMAC are described below.

Rock Quality Monitoring

One way to improve aggregate quality to identify the location of poor quality rocks in a quarry and to exclude them from the quarry operation. This can be done using a rock quality monitoring process where a geologist maps the rock types present in the quarry (Barksdale, 2001).

Blending

The most widely used method of improving aggregate quality is blending a marginal aggregate with superior aggregate/s. Aggregates may also be blended to meet the gradation criterion. The aggregate supplier adopts this technique to meet the agency criterion. However, this method does not always work. The properties of the blend do not always represent the weighted average of the constituent aggregates. For instance, mixing uncrushed smooth aggregate with a crushed rough one does not significantly improve the quality of the blend. To achieve good interlocking, all the particles in the mixture should be angular and rough.

Proper Crushing

Shape and surface texture of aggregate used in HMAC are by far the most important properties. Angular shape and rough surface texture are two of the most desirable aggregate properties for resistance to rutting and fatigue fracture. Cubic and angular aggregates provide increased internal friction and improved resistance to rutting. These properties of the aggregate are mainly affected by the mineralogy of the rock. Another factor influencing the shape and surface texture is the crushing technique. Rock is crushed when a force is applied with sufficient energy to disrupt atomic bonds within minerals or along planes of weakness that exist within the rock. There are many types of crushers used by aggregate producers. One common technique involves a series of more than one crusher. A primary crusher reduces the large rock generated from blasting, and a secondary crusher further reduces the size and shape of aggregates passed through the primary crusher. The primary crusher is usually a jaw or gyratory crusher. The secondary crusher is commonly an impact crusher, which applies a high-speed impact force to the feed rock. The primary factor determining the shape of the crushed product is the reduction ratio (i.e., size ratio between the feed rock and the broken aggregate) (Barksdale, 2001). Impact-type crushers are thought to be the best type for producing angular and cubical aggregate, so they make good secondary crushers.

Washing

Most coarse aggregates and some fine aggregates can be rinsed over a vibrating inclined screen with a pressure spray nozzle (Barksdale, 2001). Washing the aggregate reduces the clay-sized particles (excessive dust) and other deleterious materials (Roberts et al., 1996). Prewetting the aggregate further enhances the removal of clay particles during washing over the screen.

TxDOT Aggregate Test Methods

The Texas Department of Transportation currently runs four tests for quality control of coarse aggregate in HMAC pavements. These tests are generally time-consuming and must be performed in a laboratory environment.

Tests used to determine coarse aggregate quality for bituminous materials are outlined in TxDOT's Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges (Table 1). The Polish Value Test (Tex-438-A) is also performed on aggregate from rated sources (Ed Morgan, TxDOT geologist, pers. Comm., 2003).

Table 1. Coarse Aggregate Quality Requirements.

Requirements	Test Method	Manufactured or Natural Aggregate (% max. loss)
Deleterious Material	Tex-217-F Part I	1.5
Decantation	Tex-217-F Part II	1.5
Los Angeles Abrasion	Tex-410-A	40
5-cycle Magnesium Sulfate Soundness	Tex-411-A	30*

*Unless otherwise shown on the plans.

There is a need for tests that can be performed in the field at the aggregate quarry and that require a minimum amount of skill. The geologic literature contains numerous tests (requiring different levels of skill) that can be performed rapidly in the field for identification of mineral constituents, textural parameters, and engineering properties. We will review some of these techniques later in the report.

Other States' Aggregate Practices

As part of this project the researchers documented how other states with problematic carbonate aggregates detect poorly performing materials. Two states that use carbonate aggregates almost exclusively are Iowa and Florida. Iowa uses predominantly Paleozoic Era carbonates typical of rocks found in central Texas (Brownwood District), while Florida uses predominantly Cenozoic Era carbonates typical of many parts of west-central Texas (Abilene and San Angelo Districts).

Robert Dawson of the Iowa DOT (pers. comm., 2003) informed the researchers that most of their aggregates are quarried carbonate rocks. Iowa DOT geologists spend a good deal of time making detailed maps of all of the rocks that are quarried in Iowa. From the mapping, they determine what rocks pose potential problems. The Iowa DOT can then focus attention on certain aggregate sources. However, they still perform a detailed chemical analysis of all aggregate sources.

The Iowa DOT performs X-ray diffraction (XRD), X-ray fluorescence (XRF), and the Iowa Pore Index Test to predict the performance of an aggregate. Their experience has shown that aggregates with extensive capillary pore systems and a high clay mineral content are subject to durability problems. Iowa uses a combination of XRD and XRF to identify deleterious clay minerals and Al_2O_3 content, respectively. The Pore Index Test gives an indication of the extent of the capillary pore system

The Iowa DOT coarse aggregate tests (limits) for HMAC are freeze and thaw (10), Los Angeles (LA) Abrasion (45 percent), absorption (6.0 percent), clay lumps (0.5 percent), Al_2O_3 content (0.7 percent), and gradation. They run the Magnesium Sulfate Soundness Test only for Portland cement concrete (PCC) aggregates.

Gale Page, Flexible Pavement Materials Engineer for the Florida DOT (pers. comm., 2003) discussed problems they have with limestone aggregates. All of the limestone aggregates in Florida are soft and porous. Florida has only one specification for asphalt coarse aggregate, they use the LA Abrasion test, and allow a maximum loss of 45 percent for limestone aggregates. Florida used to have a sodium sulfate loss requirement, but too many good performing aggregates were failing, so the test was discontinued. They do not have any criteria for specific gravity or water absorption. Water absorption values are typically around 3% for limestone aggregates. Mr. Page informed the researchers that the keys to quality hotmix are having the hotmix association on your side and having large penalties for violations of specifications (i.e., like taking contractors off the bid list). The penalties will help keep the contractors honest.

Soft Aggregates

Aggregate breakdown is a problem that the Florida DOT anticipates; there is a change in gradation due to asphalt plant processing. Most soft limestones do not show a change on coarse sieves but generate a lot of dust in the finer sieve fractions; the Florida DOT is accustomed to managing dust. They design for a change in gradation from the beginning. They determine or anticipate from experience with certain aggregates the amount of fines that will be generated in the asphalt processing plant and then design the mix based on that gradation. For example, Florida commonly uses a mix of Georgia granite and Florida limestone for the coarse aggregate in a hotmix. When they fabricate samples the limestone generates a lot of dust, so only limestone dust is added in the mix design and granite dust is not added. To stabilize the dust generation, the asphalt mixing plant must change the production rates slowly to maintain a consistent dust content. The mixing plants anticipate how much dust is generated from startup to shutdown, so they change production rates slowly.

Porous Aggregates

Florida limestone aggregates commonly have about 3 percent absorbed moisture, so the Florida DOT does not allow asphalt plants to run at maximum capacity; production rates are cut in half because of the absorbed moisture. They allow the asphalt plants to run at only half the maximum to allow time for the aggregates to dry out. If an asphalt truck arrives at a job site with water in it, then the inspector shuts the plant down until the water problem is taken care of. If a plant can run 400 tons of hotmix a day, then the Florida DOT will recommend they only run 200 tons a day to allow time for the porous aggregates to dry out.

Literature Review

The literature review is split into aggregate quarrying, sampling, and testing techniques sections. Kandhal and Parker (1998) performed an extensive literature review on asphalt aggregate test methods currently in use. We see no need to repeat their thorough literature review, so we refer interested readers to their work.

Aggregate Quarrying

The quality of aggregate changes throughout the quarry. Two important controls on aggregate quality are (1) what geologic environment the rock originally formed in and (2) what happened to the rock after it was formed. For example, basalt is an extrusive igneous rock that is extremely hard and makes excellent railroad ballast when not heavily altered. If the basalt is exposed to humid, tropical conditions for an extended period of time, the minerals will be altered by a process called weathering. The ferromagnesian minerals and glass in the basalt alter to hydrous clay minerals. Day (1962) reported problems with basalt aggregates in Idaho that were a result of severe alteration of the basalt to clay minerals by physical and chemical weathering.

A quarrying technique available to operators to combat heterogeneous aggregates is termed selective quarrying. For example, Hanson Aggregates commonly performs aggregate tests on cores to classify the rocks in a quarry based on engineering properties (Vartan Babakhanian, pers. comm., 2003). Using this technique, Hanson Aggregates may identify a soft limestone down to a depth of 20 feet that is only good for base material and a hard limestone suitable for concrete aggregate from 20 to 35 feet. They will quarry the top 20 feet and stockpile the material for base courses. The next 15 feet will then be quarried and stockpiled for concrete aggregate. This technique works well in areas with laterally continuous rock units 10 to 15 feet thick, but the economics of selective quarrying become a factor in regions where the rock is thin-bedded (units 2-3 feet thick) and less continuous (Figure 1). For example, the working face at the Baird Quarry (Abilene District) is only 10 feet high and contains thin (1-2 foot) discontinuous limestone beds intercalated with fissile shale and thin sand stringers. Selectively quarrying this material would be extremely difficult and cost prohibitive.

Another important technique for evaluating aggregate quality, with respect to selective quarrying, is to examine natural exposures of the rock outside the quarry because disintegration/natural weathering may not coincide with results of the Sulfate Soundness Test (Loughlin, 1928).

Figure 1. Working Face at the Baird Quarry Shows a Thin (2 foot) Resistant Unit at Top.

Aggregate Sampling and Handling

Aggregate sampling is critical; all tests conducted on an improperly sampled aggregate are meaningless. These test results may result in a HMAC mixture that performs poorly (Roberts et al., 1996). Because of segregation in stockpiles, hot bins, and loaded trucks, the best place to sample aggregate is from a conveyor belt; however, one must be certain to sample the entire width of the conveyor belt because aggregate tends to segregate on the conveyor belt as well (Roberts et al., 1996).

Sampling stockpiles is a problem worldwide. In South African coal mines, a long tube is inserted into a stockpile and a sample is retrieved from the tube at different levels around the stockpile. This works for low-density materials (e.g., coal), but high-density aggregates (limestone/dolomite) make it difficult to push the tube in an adequate depth.

To try to alleviate some of the sampling problems with large stockpiles, the Ohio DOT specifies that the stockpile should not be larger than 2000 tons until the material has been sampled and tested (80 to 100 lb). Then a stockpile may be enlarged, but the enlarged portion must be sampled and tested in the same manner (Jessberger, 2002). The Kansas DOT specifies that aggregates that have been accepted must be stockpiled in layers 1.0 to 1.5 m thick, each layer is bermed so aggregates do not "cone" down into lower layers (Clowers, 1999). The Kansas DOT also specifies that aggregates from different sources, with different gradings, or with a significantly different specific gravity be stockpiled separately (Clowers, 1999).

The type of stockpile constructed makes a significant contribution to size segregation. In 1965 a National Cooperative Highway Research Project (NCHRP) study evaluated size segregation in three different types of stockpiles. The study determined that the type of stockpile had a profound impact on segregation. The cast-and-spread technique produced the least amount of segregation, and stockpiles constructed using the cone technique were by far the most segregated.

Handling aggregates generates fines. The amount of fines generated varies for different aggregates; how the aggregate is handled before being placed also contributes to the fines content. Many aggregate suppliers can give gradations and standard deviations on the belt, stockpile, and truck samples.

Aggregate Laboratory Testing

Many studies have concluded that aggregate performance cannot be linked to a single mechanical or chemical test, but a combination of tests (Fookes et al., 1988; Kandhal and Parker 1998; Little et al., 2001).

Kandhal and Parker (1998) performed an extensive literature review and laboratory evaluation of aggregate tests related to asphalt concrete performance. They concluded that permanent deformation, raveling, popouts, potholing, fatigue cracking, and frictional resistance are all affected by the properties of the aggregates. They identified nine aggregate tests that can be related to HMAC performance; four of the tests are for the fine aggregate only. The five tests they recommend for the coarse aggregate include: sieve analysis (permanent deformation and fatigue cracking), uncompacted void content (permanent deformation and fatigue cracking), flat or elongated particles (2:1 ratio) in coarse aggregate (permanent deformation and fatigue cracking), Micro-Deval (MD) Test (raveling, popouts, or potholing), and Magnesium Sulfate Soundness Test (raveling, popouts, or potholing).

There have been some questions about the utility of the Sulfate Soundness Test. Many researchers and DOT personnel report repeatability problems with the Sulfate Soundness Test (Ed Morgan, TxDOT geologist, pers. comm., 2003). Soundness was defined as an aggregate's resistance to weathering in ASTM-C-88. Forster (1994) points out the pitfalls, resulting in low precision, of the Sulfate Soundness Test when the results are not used in concert with other aggregate test methods and preferably including a prior service record. He concludes that a low soundness loss will "usually" indicate a durable aggregate, but collaborative evidence from other tests should be used.

Researchers at Texas Tech University compared the Micro-Deval to the Magnesium Sulfate Soundness Test (Phillips et al., 2000). They determined that absorption has a significant effect on MSS and MD test results; at a 95 percent confidence interval an aggregate with less than 1.7 percent absorption shows less than 20 percent MSS loss if MD loss is less than 18 percent, and an aggregate with less than 2.1 percent absorption shows less than 30 percent MSS loss if MD loss is less than 25 percent. Phillips et al. (2000) stated that specific gravity did not correlate with performance. They concluded that MD was more repeatable and reproducible than the MSS test.

A research consortium of three different institutions in Texas is collaborating on research dealing with bituminous coarse aggregates. The Texas Transportation Institute (TTI) is the lead agency in this research effort. To date, they have reevaluated many of the tests outlined by Kandhal and Parker (1998) and have concluded that the aggregate tests currently used are not closely related and that the tests monitor independent properties. Therefore, all of these tests may be needed to evaluate aggregate quality, confirming the conclusions of Fookes et al. (1988).

Aggregate Field Testing

The first year of this project focused on identifying and performing simple tests that can be used in the field to identify poor performing aggregate. Two physical properties that indicate poor aggregate performance are (1) extensive capillary pore systems, as reported by the Iowa DOT, and (2) soft aggregate. Most of the engineering tests in the literature require time-consuming laboratory procedures; however, this literature review lists a few simple field tests that may distinguish the poor quality aggregate from the good.

Mielenz (1994) recommends making observations regarding nine properties of aggregate in the field that can be related to aggregate performance. The properties include: (1) friability or pulverulence in the fingers; (2) resonance when struck; (3) ease of fracturing; (4) nature of the fracture surface and fracture fillings; (5) odor on fresh fracture; (6) color and its variation; (7) internal structure, such as porosity, granularity, seams, and veinlets; (8) reaction to water, such as absorption of droplets on fresh fracture, evolution of air on immersion, capillary suction against the tongue, slaking, softening, or swelling; and (9) differential attack by acids or other media.

The Schmidt Hammer, originally developed for nondestructive testing of concrete, has been used to estimate rock strength, mainly at the quarry working face (Katz et al., 2000). Katz et al. (2000) report numerous studies showing good correlation between rebound readings with the Schmidt Hammer and laboratory measured values of Young's modulus, uniaxial compressive strength, and density of the rock. Two drawbacks to this technique are that large blocks are required and that a smooth interface between the tool and rock is required for best results. Therefore, samples in a stockpile cannot be tested with this device.

As stated previously, an important physical property of an aggregate is the ability to absorb moisture. Poor quality aggregates typically absorb more moisture, whereas good quality aggregates absorb very little moisture. Absorption may be regarded as an aggregate property that is a function of aggregate porosity and pore size (Landgren, 1994). Absorption is a simple test that can be performed rapidly in the field.

Because the different physical and chemical properties of calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$] (dolomite is harder and has a higher density), it is desirable to distinguish between these two minerals in a quarry. A simple test is to add several small chips of aggregate to a porcelain spot plate and add a drop of 0.1 percent Alizarin-S solution dissolved in saturated tartaric acid. Calcite causes the solution to turn a purple-red, but dolomite does not react (Jungries, 1985).

One textural and mineralogical property that affects aggregate strength and durability is the formation of stylolites - irregular suturelike boundaries (Figure 2). The stylolites form from insoluble materials (i.e., clay minerals, organic matter, and quartz) that are dispersed in a carbonate sediment becoming concentrated along a thin band due to dissolution of the calcite from increased pressures generated by burial. The stylolites form perpendicular to the principal stress and are generally horizontal in flat-lying limestones. Verhoef and van de Wall (1998) report durability problems with limestone blocks containing stylolites composed of expansive clay minerals (smectite).

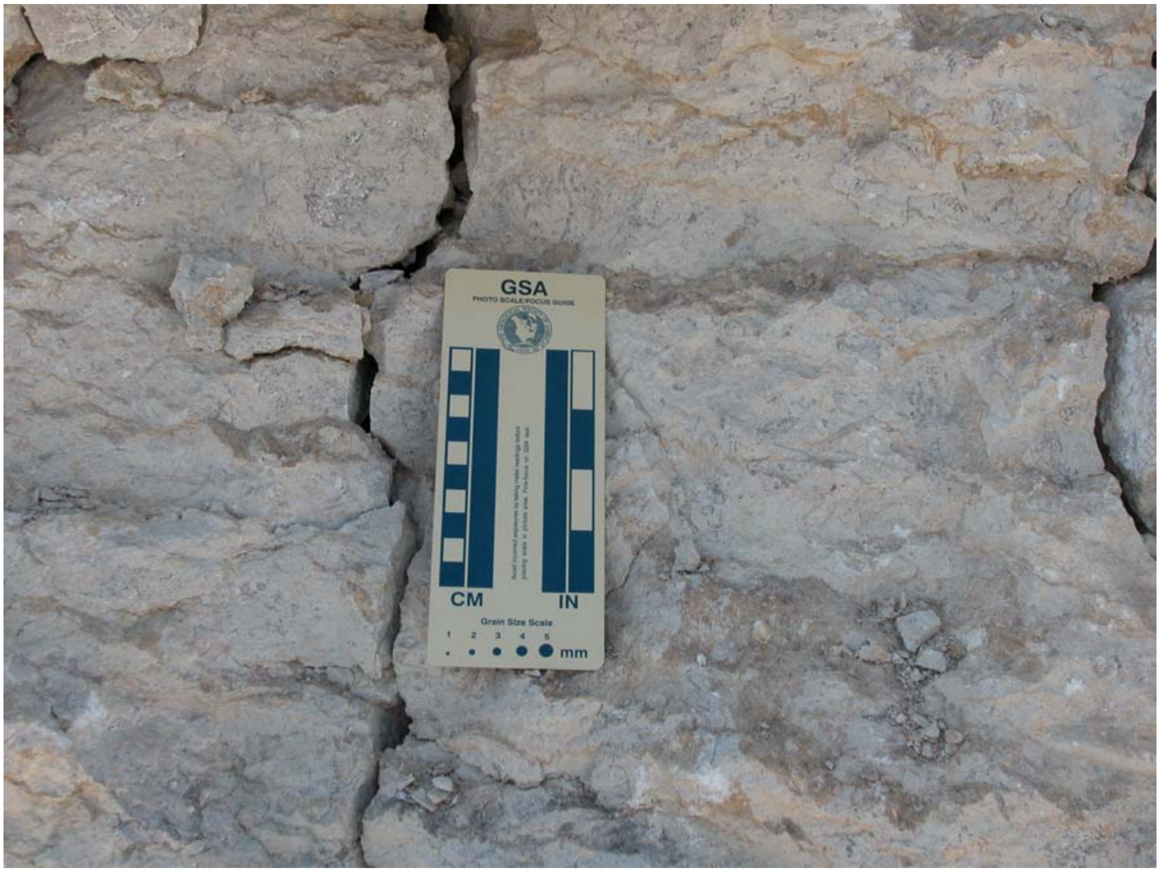

Figure 2. The Semihorizontal Tan Lines in the Top One-Third of the Image are Stylolites from the Black Quarry.

METHODS

To accomplish the goals of this research project, the researchers employed the following techniques to answer fundamental questions about coarse aggregate field performance.

Initially, an extensive literature search was conducted to identify any new field tests that may be used for the identification of poor quality aggregates. Following the literature review, the Project Management Committee (PMC) met with the researchers and identified several districts that may have problems with coarse aggregates in HMAC.

The researchers contacted key personnel in the following districts: Abilene, Atlanta, Bryan, Lubbock, Odessa, Pharr, and San Angelo. Only two districts, Abilene and Lubbock, reported problems related to poor quality aggregates. The Lubbock District sent core samples to the researchers from roads suspected of having performance problems due to low-quality coarse aggregate.

The researchers visited the Abilene District in March 2002 to obtain core samples. The district personnel identified three sections of US-84 in Tyler and Scully Counties that may have problems due to poor quality coarse aggregates. The coarse aggregate quality was questioned because of the presence of fatigue cracking on these highway sections. The researchers also noticed popouts and surface aggregate degradation. Six-inch diameter cores were collected from US-84 in each of the two counties (Tables 2 and 3). The quarry that produced the aggregate used in both sections closed a few years ago. As a result, it was not possible to collect aggregate samples from the quarry to test in the laboratory.

Table 2. Core Description for Northbound Outside Lane of US-84 in Taylor County.

Core No.	Location of Core	Distress
84-1	Center of the lane	Lot of alligator cracks, no rutting
84-2	Center of the lane	Same as above
84-3	Right wheel path (RWP)	Same as above
84-4	Left wheel path (LWP)	Same as above
84-5	Center of the lane	Same as above
84-6	RWP	Same as above
84-7	Left side of the RWP	Some raveling
84-8	Center of the lane	Cracks in the vicinity
84-9	LWP	Lot of alligator cracking
84-10	Center of the lane	No distress
84-11	LWP	Lot of alligator cracks, no rutting
84-12	Center of the lane	Lot of alligator cracks, no rutting
84-13	Left side of RWP	Some alligator cracks
84-14	Center of the lane	Good spot

Table 3. Core Description for Northbound Outside Lane of US-84 in Scully County.

Core No.	Location of Core	Distress
84-S1	Right side of LWP	Low alligator crack around the spot
84-S2	Center of the lane	Very low crack
84-S3	Left side of LWP	Low crack
84-S4	Right side of LWP	Low crack
84-S5	Center of the lane	Popouts
84-S6	Center of the lane	No apparent distress
84-S7	Right side of LWP	Close to huge alligator crack
84-S8	Center of LWP	Close to huge alligator crack
84-S9	Center of the lane	No apparent distress
84-S10	Center of LWP	Low cracks

Sample Locations

The researchers focused on the surface course, but full-depth cores were collected from different locations in the roadway. Cores were collected using TxDOT's mobile coring drill from the northbound outside lane in both counties (Figure 3). Cores were collected from all positions of a lane (e.g., center, left wheelpath, and right wheelpath) and from both damaged and undamaged parts of the lane.

Figure 3. Drilling Cores from US-84.

Once the cores were delivered to the TTI laboratory, they were cut to separate the top layer from the remainder of the core for laboratory testing. Visual inspections were performed before and after sawing.

Mixture Design Data

In 1997, Asphalt Materials, Inc., overlayed a section on US-84 in Tyler County. A type D mixture with PG 64-22 asphalt and limestone from the Parmally Quarry in Abilene was used. The design asphalt content was 5.2 percent. Design data do not show the use of antistripping agent or field sand.

Price Construction constructed the segment of US-84 in Scully County in 1998. A type D mixture with limestone from the Jordan Quarry and PG 70-22 asphalt from Fina was used for the overlay. This mixture also used 7 percent field sand from South Anderson and 2 percent hydrated lime. The design asphalt content was 6.1 percent.

Tests Conducted on the Core Samples

There were five tests performed on the cores retrieved from Abilene. First, each core was visually examined for absorptive aggregates, popouts, cracks, etc. Second, cores were subjected to testing in the Asphalt Pavement Analyzer (APA). The third step was to run a Frequency Sweep at Constant Height (FSCH) on selected cores. The Hamburg Wheel Tracking Device (HWTD) was fourth in the testing sequence. Finally, the Overlay Tester was used to test selected samples. The paragraphs below present brief descriptions of the conditions of each test.

One pair of specimens from each of the two roadway sections was tested with the APA machine. The test was conducted at 147 °F, 100 psi wheel pressure, and 100 lb wheel load. The top 3 inches of selected 6-inch diameter cores was used for this test.

Frequency sweep is a strain-controlled repeated test that measures the viscoelastic behavior of asphalt mixtures. A small magnitude of sinusoidal shearing strain is applied to the specimen at 10 different frequencies, and the stress response is measured. Due to the viscoelastic behavior of an HMA mixture, the specimen's stress response is not in the same phase as the applied strain. The stress always lags behind the applied strain. The ratio between the stress response and the applied strain is used to compute the complex shear modulus, G*. The measured time delay between the strain and stress response is used to compute shear phase angle, *. Higher complex modulus indicates a stiffer mix that is more resistant to rutting, and lower shear phase angle indicates more elastic behavior that is more resistant to rutting (Chowdhury and Button, 2002).

The HWTD is an accelerated wheel tester that has been used as a specification requirement to evaluate rutting and stripping for some of the most traveled roadways in Germany. Use of this device in the U.S. began during the 1990s. Several agencies undertook research efforts to evaluate the performance of the HWTD. Since the adoption of the original HWTD, significant changes have been made to this equipment. A U.S. manufacturer now builds a slightly different device. The basic idea is to operate a steel wheel on a submerged, compacted HMA slab or cylindrical specimen. Recent TxDOT HMAC specifications require that all mixtures pass certain HWTD specifications based on the asphalt grade used in the mixture.

The TTI overlay tester was designed by Germann and Lytton in the late 1970s to simulate the opening and closing of joints or cracks, which are the main driving force inducing reflection crack initiation and propagation (Germann and Lytton, 1979). The key part of the apparatus, as shown in Figure 4, consists of two steel plates, one fixed and the other movable in a horizontal direction, to simulate the opening and closing of joints or cracks in the old pavements beneath an overlay. There are two overlay testing machines at TTI: one is a small overlay tester for a specimen size of 375 mm (15 inch) long by 75 mm (3 inch) wide with variable height; the other is a large overlay tester for a larger size specimen of 500 mm (20 inch) long by 150 mm (6 inch) wide with variable height. Both overlay testers have been successfully used to evaluate the effectiveness of geosynthetic materials on retarding reflection cracking. These applications indicate that the overlay testers have the potential to characterize the reflection cracking resistance of asphalt mixtures.

The overlay tester data include the time, displacement, and load corresponding to a certain number of loading cycles. In addition, the crack length can be manually measured. The overlay tester provides two types of information: one is the reflection cracking life of an asphalt mixture under certain test conditions; the other is fracture parameters of an asphalt mixture. These are discussed below (Zhou and Scullion, 2003).

Three prismatic specimens (6-inch X 3-inch X 2.5 inch) sawed from cores were tested with the TTI overlay tester at 77 °F. The test was performed following the protocol suggested by Zhou and Scullion (2003). Figure 5 shows data typical of the TTI overlay tester.

Figure 4. TTI Overlay Tester.

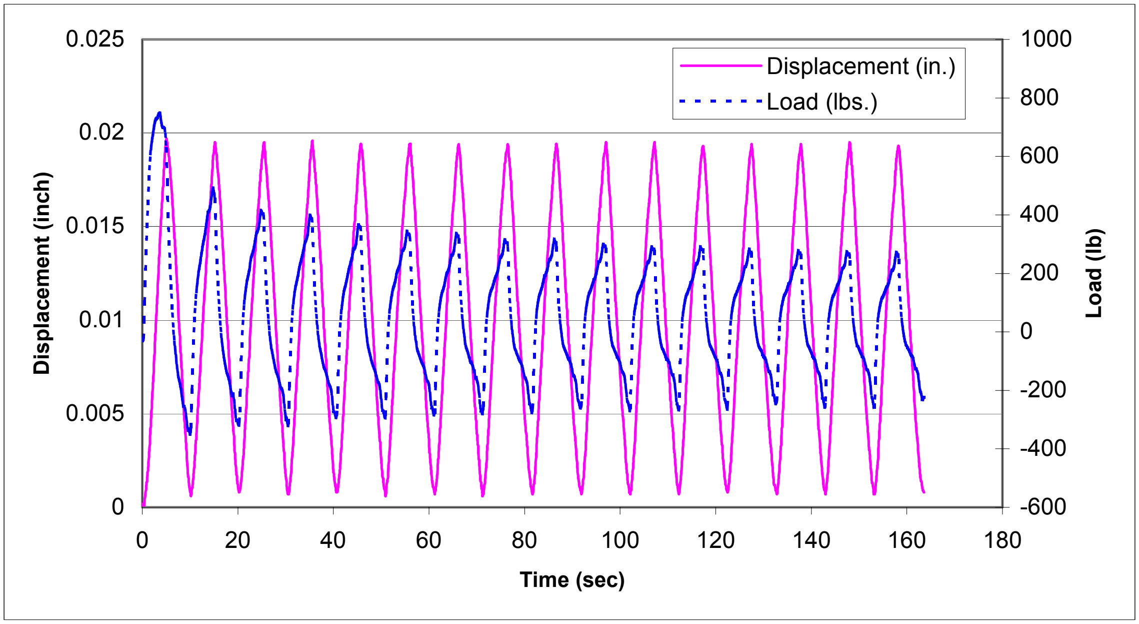

Figure 5. Typical Output of the TTI Overlay Tester.

At the conclusion of the five tests mentioned above, the cores were delivered to Charles Glover, asphalt chemist with TTI. He extracted the asphalt from the aggregate and attempted to identify differences in the fractions serving as binder and the fractions absorbed into the aggregate (see Chapter 2).

After testing of the cores, the researchers visited six quarries in the Abilene, Austin, and San Angelo Districts that had inconsistent MSS and MD results. At each quarry, researchers carefully examined the working face for variations in rock weathering, lithology, fossil content, sedimentary structures, and fractures. Hand samples from distinct beds were collected, and the position was marked in a field notebook. Hand samples were returned to the laboratory for detailed mineralogical analyses.

Stockpile samples were collected at each quarry as well. Some samples were collected using the TxDOT method (Tex-221-F), and others were collected using the one that quarry operators use to compare results for gradation and mineralogical segregation. The TxDOT method involves taking samples from three levels: (1) near the top, (2) in the middle, and (3) near the base. A traverse is made around the entire stockpile, sampling at each level, to try to obtain a representative sample. The quarry operators' technique takes less time and consists of filling the bucket of a front-end loader with aggregate from the side of a stockpile, dumping the material on the ground, and flattening the top of the pile generated by the bucket (Figure 6). Sample bags are then filled with aggregate removed from a trench dug across the top of the flattened pile.

The researchers also talked to quarry operators about techniques used for quarrying/selective quarrying, crushing, and handling (washing and stockpiling) the aggregates. Some operators expressed economic concerns about selective quarrying. The type of crusher selected is also very important. Some crushers work better on soft rocks, for instance, impactors generate nice cubical aggregates in carbonate rocks with less than 5 percent silica. Increased silica results in more wear and higher maintenance costs.

Four simple field tests (visual inspection of rounding, color, and porosity; water absorption; fines content; and hardness/friability in the fingers) were identified and employed at the stockpiles. These tests are simple to perform and give a good indication of properties related to aggregate performance, as outlined in the literature review.

Figure 6. Grade 3 Stockpile at the Baird Quarry in the Abilene District.

RESULTS

Of the seven districts contacted about HMAC problems due to poor quality aggregates, only two districts, Abilene and Lubbock, identified roads that were failing possibly due to coarse aggregate problems. Multiple 6-inch cores were collected from poor performing roads in these two districts and returned to the laboratory for analysis.

Visual Observation

Visual observation of the cores revealed that some of the cores had cracks at the surface that propagated into the lower asphalt layer as well as the base layer. Some of the cores had cracks limited only to the top layer. This suggests the possibility of both top-down cracking (due to a poor surface layer) and bottom-up cracking (due to a poor base). After coring and/or sawing the top layer, the researchers noticed a significant percentage (approximately 5 percent) of absorbent coarse aggregates. Some aggregates absorbed asphalt throughout the entire aggregate (Figure 7).

Figure 7. Sample from US-84 in Tyler County Showing Aggregates with a Lot of Absorbed Asphalt.

APA Test

In the field, the researchers noticed alligator cracking on the roadway. Specimens 84-9 and 84-4 (Tyler County) and 84S-9 and 84S-10 (Scully County) were tested together. The maximum rut depths at the end of 8000 APA load cycles were measured as 0.09 inch and 0.07 inch for the Tyler and Scully County roadway sections, respectively. These rut depths are very low and match field observations. In the field, the researchers found very little rutting.

Frequency Sweep at Constant Height

Researchers tested one sample from each roadway section at two temperatures (68 °F and 104 °F) and 10 frequencies (10 Hz to 0.01 Hz). The Association of American State Highway and Transportation Officials (AASHTO) TP07-01 test standard was followed to conduct this test. Table 4 summarizes the FSCH test results. The specimens from Tyler County exhibit a low shearing modulus at 68 °F.

Table 4. FSCH Test Results.

Specimen No.	Frequency, Hz	Test at 68 °F		Test at 104 °F	
		G* psi	*, degree	G* psi	*, degree
84-3 Tyler	10.0	86,924	19.6	67,078	33.9
	5.0	79,668	16.5	55,206	32.3
	2.0	71,819	16.0	42,041	32.1
	1.0	66,286	14.9	36,656	31.9
	0.5	60,929	16.1	30,980	32.7
	0.2	54,217	16.8	25,498	32.3
	0.1	49,734	18.6	21,264	33.7
	0.05	45,154	19.9	18,475	33.3
	0.02	39,345	21.8	15,135	32.1
	0.01	34,948	24.3	13,117	33.6
84S-4 Scully	10.0	177,512	18.4	66,135	31.9
	5.0	160,549	14.6	53,944	32.0
	2.0	142,442	15.3	41,559	32.3
	1.0	124,146	17.1	34,899	34.1
	0.5	107,949	18.7	28,579	35.8
	0.2	88,049	21.4	21,898	35.1
	0.1	75,177	22.3	17,987	36.7
	0.05	64,416	24.4	14,086	36.9
	0.02	51,565	27.5	10,986	37.5
	0.01	42,920	30.1	9,055	39.8

Hamburg Wheel Tracking Device

Hamburg testing was conducted with 6-inch diameter and 2.5-inch high samples sawed from the top layer of the cores. One pair of specimens was tested from each of the two roadway sections at 122 °F. The cores used for testing were specimens 84-1 and 84-5 together and 84-S2 and 84-S6 together. The final rut depths of the specimens at the end of 20,000 loading cycles were 0.18 inch and 0.13 inch for the Tyler and Scully County specimens, respectively. The relative rut depths are very small and match the results from the APA test. There was no sign of stripping.

Overlay Tester

None of the samples failed by aggregate fracture. All of the samples failed either along the mastic (around the aggregate) or along the interface between the specimen and the horizontal plate. All of the samples failed after very few cycles (Table 5). The tensile force is relatively small, so it is unlikely that the aggregate will break.

Table 5. Overlay Tester Results.

SPECIMEN NO.	NUMBER OF CYCLES TO FAILURE	
	Opening=0.020 inch	Opening=0.040 inch
84-6 (Tyler)	19	13
84-10 (Tyler)	25	-
84-S1 (Scully)	19	-
84-S2 (Scully)	6	-

Aggregate Sampling at Quarries

Sieve analyses of stockpile samples collected using the TxDOT and the quarry operators' methods show virtually identical gradations (Table 6). This consistency indicates that both techniques yield a similar sample with respect to size variation, but texturally and compositionally, the samples can be very different, as illustrated in Figures 8 and 9. Figure 8 shows examples of the different aggregate types found in a single stockpile. The orange gridlines are one inch on a side. Note the differences in angularity of the aggregate grains. The three grains in the lower left corner are chert (microcrystalline quartz) and exhibit conchoidal fracture typical of chert. The chert is also much harder than the other aggregate grains, which are composed of limestone (calcite); therefore, the grains tend to be much more angular because the sharp edges do not break off in processing like they do in the softer aggregates. Another important observation is that the aggregates in the other eight squares of Figure 8 are all composed of limestone. Note how the aggregates become less angular and more spherical toward the upper right of the figure. Although these aggregates have the same mineralogy, textural properties make the aggregates behave and look different.

Table 6. Gradations for Samples Collected by the TxDOT Method and the Quarry Method for the CSA Turner Pit.

Sieve Size	TxDOT Method % retained	Quarry Method % retained
½ inch	41.94	43.43
3/8 inch	51.97	51.02
#4	4.98	4.5
Minus #4	1.11	1.05
TOTAL	**100.00**	**100.00**

Figure 8. Aggregates from the Same Stockpile Showing Variations in Porosity, Angularity, and Mineralogy.

A stockpile of grade 3 aggregate from the Baird Pit in the Abilene District does not show a variation in gradation, but the aggregate type changes drastically from one part of the stockpile to another. The change in aggregate type is obvious by the color variations in this stockpile (Figure 9). The upper left corner of Figure 9 shows a pink, fossiliferrous limestone, and the middle of the image shows a mix of the pink limestone and a gray, more organic rich limestone.

Figure 9. Segregation of Aggregate Types (Gray and Pink) in a Stockpile at the Baird Pit in the Abilene District.

DISCUSSION

Analysis of cores taken from the field for performance problems due to poor quality coarse aggregate provided mixed results. Visual observations indicated a highly absorptive coarse aggregate at both locations.

Results from the HWTD and the APA were very good, indicative of a good performing asphaltic pavement. The FSCH test results indicated a lower modulus than expected. Two reasons can explain the lower modulus: either the asphalt was softer (PG 64-22) or microcracks were present in the specimens before testing. Again, the shearing modulus did not change significantly at higher temperature. On the other hand, shear phase angle increased significantly for both specimens when tested at higher temperature. The increase in shear phase angle is usually due to higher temperatures affecting the viscous properties of the mixture more than its elastic properties. At the higher temperature, both specimens demonstrated similar behavior with respect to shearing modulus.

The Overlay Tester results are indicative of brittle asphalt typically observed in an aged pavement. The aging of asphalt and, hence, mastic (due to overabsorption as observed in Figure 7) made the mastic brittle, which may have caused the loss of tensile strength and resulted in a low number of cycles to failure (Table 5). Results from Charles Glover, reported in Chapter 2, seem to correlate with this interpretation.

Aggregate Sampling and Testing at the Quarry

To assess the utility of simple tests for identifying poor quality aggregates at the quarry, to date the researchers have visited six quarries in the San Angelo, Abilene, and Austin Districts. All six quarries are in Paleozoic to Mesozoic carbonate rocks because the PMC stated that they have not had problems with other aggregate types. The results are skewed toward carbonate rocks since other rock types were not investigated.

One of the major questions of the PMC concerns sampling stockpiles to obtain a representative sample. Engineers generally think of size segregation when sampling stockpiles, but there can also be vast differences in aggregate texture and mineralogy in different parts of a stockpile (Figures 8 and 9). With respect to size segregation, James Bates, TxDOT laboratory supervisor in the San Angelo District (Pers. comm.., 2003) informed the researchers that they do not have size segregation problems with grade 3, 4, or 5 aggregates, but size segregation of base materials is more problematic. Our results in Table 6 seem to corroborate his statement.

With respect to mineralogical and textural variation, Figure 9 illustrates the importance of sampling near the base, in the middle, and near the top, of all sides of a stockpile as outlined in the TxDOT method Tex-221-F. The upper lefthand portion of the image shows a pink-colored limestone, and diagonally from lower left to upper right is a band of more organic rich gray limestone. If one were to sample from a single location, like the quarry operators prefer, then the gray rock may not be sampled at all or it may make a disproportionately large contribution to the sample.

One problem the researchers faced was accessing the entire stockpile to take a sample. Most of the stockpiles were extremely large (Figure 6), so aggregates in the center/core of the stockpile may be totally different from what one has access to around the perimeter. In order to get a representative sample, there are a couple of techniques employed by other state DOTs that the researchers prefer. If one must sample from a stockpile, then a compromise would be to limit the size of a stockpile to 2000 tons or less like the Ohio DOT. Another technique recommended by Shergold (1963) for sampling from a stockpile is to sample a stockpile at intervals as it is being constructed to establish any fluctuations in the product.

The best technique for obtaining a representative sample is sampling from the conveyor belt. Shergold (1963) stated that crushed rock aggregate should be sampled while in motion (e.g., from conveyor belts or at a discharge from bins). He recommends a minimum of eight increments over a period of one day with the weight depending on the size of the material. The increments are then mixed to form a composite and reduced by riffling.

The identification of poor quality aggregates can be accomplished using a few simple tests in the field. The most important of these tests is visual observation. The difficulty is in collecting a representative sample.

Other researchers have identified properties that make a limestone aggregate undesirable. Chief among these properties are microporosity and clay mineral content. Simple field tests that give a good indication of microporosity are water absorption, low density (lightweight), and lack of angularity.

Clay mineral content is more difficult to identify in the field. The easiest identification is made at the working face of the quarry by looking for stylolites (Figure 2) and less resistant units. One simple test for individual aggregates is to place the aggregate into a glass of water to soak. If the aggregate breaks apart or slakes, then there is a potential problem with clay minerals.

Another way to identify clay minerals is to look for highly weathered rocks. Clays often concentrate in these weathered zones. The vertical fracture/joint in Figure 10 is a good example of differential weathering. Along the face of the fracture, there are more fines/clays (grayish orange-pink) that are a product of weathering of the preexisting strata. The pale yellowish brown limestone is the fresh rock. Rock quarried along the fractures will have more deleterious clay minerals and yield a poorer quality aggregate. Soaking the aggregate and use of a washer will help to remove some of the poorer quality material associated with the fractures.

Figure 10. Vertical Fracture at the Price Clements Pit Showing Grayish Orange-Pink Clay Attached to a Pale Yellowish Brown Limestone Block.

The next three figures illustrate good, moderate, and poor quality aggregates, respectively, which are all composed of a single mineral (calcite). The difference in quality is related to the texture. Figure 11 shows textural properties of a good quality aggregate. The top image is a thin-section photomicrograph of a limestone ($CaCO_3$) aggregate from the Vulcan Black Pit: it does not have any visible pores, as evidenced by the lack of blue-dyed epoxy. The fossil fragments (light colored) in this limestone are still preserved. The darker areas are micrite (lime mud) that bind the fossil fragments together. This rock makes a strong, angular, nonabsorptive aggregate as evidenced in the bottom image.

The aggregate represented by the images in Figure 12 is from the Centex Yearwood Pit. It is not as strong as the aggregate in Figure 11 because it has numerous large pores (blue-dyed epoxy) that were generated by the dissolution of fossil fragments. This is called moldic porosity. These pores are not well connected and they are large so there is not a lot of water absorption. The bottom image shows the aggregate. It has more rounded edges than the aggregate in Figure 11 and it also has little pits all over the surface. The pits are the moldic pores observed in the thin-section image above. This rock makes a moderately strong, subangular to subrounded, nonabsorptive aggregate.

The images in Figure 13 are of another aggregate from the Centex Yearwood Pit. This aggregate is also a limestone, composed of the mineral calcite ($CaCO_3$), but the texture is different. The top image shows a limestone with intergranular porosity (pores between the grains) that will absorb a large amount of water or asphalt. This pore network also makes the aggregate very weak. The bottom image shows how the aggregate particle has become well rounded after being crushed and transported. Ed Morgan, TxDOT construction geologist (pers. comm., 2003), concluded that poorer quality aggregates tend to be more rounded based on observations of aggregates from quarries around Texas.

From looking at Figures 11-13, one can easily see how important textural variations are in affecting aggregate quality. Two ways to easily distinguish these three aggregate types are visual observation of aggregate angularity (as observed by Ed Morgan) and absorption of water.

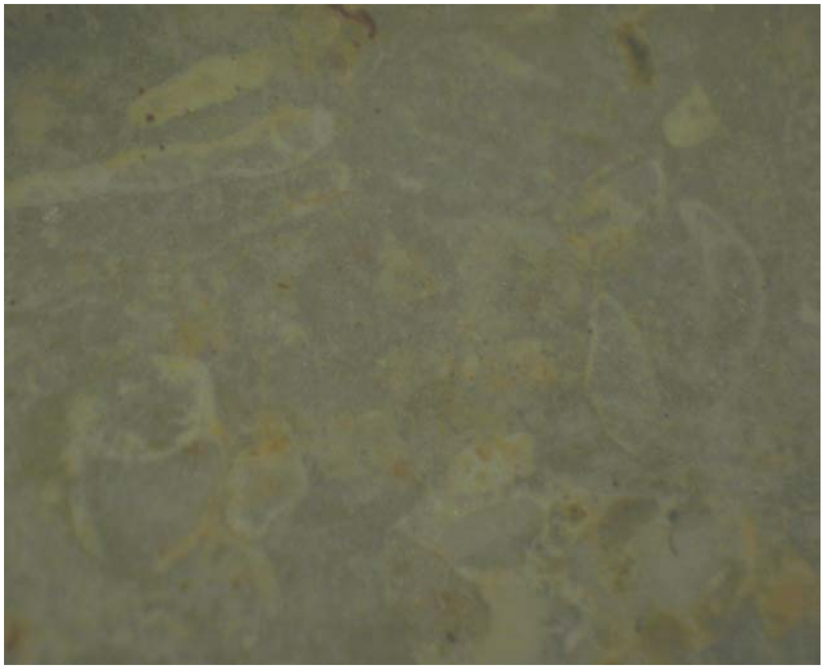

Figure 11. (Top) Thin-Section Photomicrograph of a Limestone Aggregate from the Vulcan Black Pit Showing No Pores. (Bottom) Macroscopic Image of the Same Limestone Aggregate (Note Angularity).

Figure 12. (Top) Thin-Section Photomicrograph Showing Moldic Pores (Blue) in a Limestone Aggregate from the Centex Yearwood Pit. (Bottom) Macroscopic Image of the Same Limestone Aggregate (Note Pits in Surface).

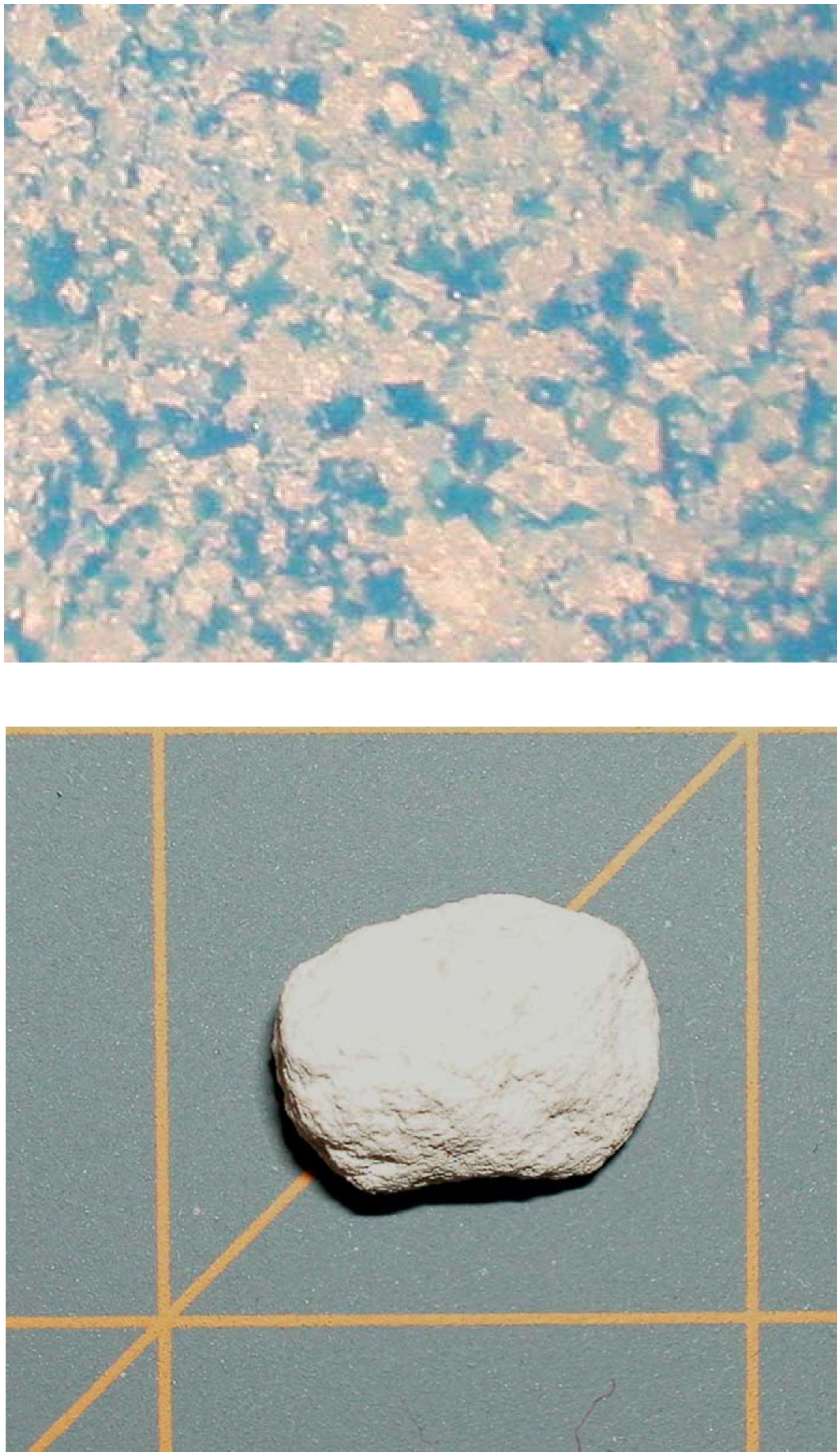

Figure 13. (Top) Thin-Section Photomicrograph Showing Intergranular Pores (Blue) in a Limestone Aggregate from the Centex Yearwood Pit. (Bottom) Macroscopic Image of the Same Limestone Aggregate (Note Roundness).

Definition of Mineralogical Segregation

Mineralogical (*adj*.) for mineralogy is defined as the scientific study of minerals, their characteristics, and their classification. Mineral is defined as naturally occurring, inorganic, possessing a definite internal structure, and a definite chemical composition. Segregation is defined in the American Heritage Desk Dictionary as the act or process of segregating. Segregating is defined to become separated from a main body or mass, separated, isolated. *Mineralogical segregation* would therefore be defined as separation of different minerals in a stockpile. None of the quarries visited as part of this project revealed mineralogical segregation in any of the stockpiles. There was variation in the quality of the aggregate in different parts of stockpiles, but the variation in quality was primarily due to textural differences (i.e., grain shape and grain rounding; Figures 8, 11-13), induration (amount of cementation; Figures 11-13), and degree of weathering in limestone quarries (Figure 10). It is this researcher's opinion that *mineralogical segregation* would more appropriately be termed *textural segregation* for this particular study. Textural (*adj*.), for texture, is defined as the general physical appearance or character of a rock, including the geometric aspects of, and the mutual relations among, its component particles or crystals (e.g., the size, shape, and arrangement of the constituent elements of a sedimentary rock) in the American Geological Institute (AGI) Glossary of Geology. There is a certain amount of bias in this study because it focused predominantly on monomineralic (calcite/limestone) quarries. Perhaps visits to quarries with more diverse mineralogies would yield different results and merit the use of the term mineralogical segregation.

RECOMMENDATIONS FOR SAMPLING AGGREGATES AND FIELD TESTS AT THE QUARRY AND STOCKPILE

- Have a geologist perform a detailed investigation of the aggregate quarry and surrounding area. This may include selecting fresh and weathered samples for thin-section analysis.
- Recommend selecting samples from the conveyor belt to identify different minerals and obtain a better indication of the composition of the stockpile.
- Recommend smaller stockpiles if one has to sample from a stockpile. Ohio specifies a stockpile no larger than 2000 tons.

- Visually inspect how well rounded or angular the aggregates are (more rounded = lower quality).
- Observe reaction to water by absorption on a fresh fracture, evolution of air on immersion, capillary suction against the tongue, slaking, softening, or swelling.
- Determine hardness - friability between fingers. If an aggregate breaks in the hand, then the aggregate is too soft.
- Visually inspect fines content to identify soft aggregates.
- Visually inspect porosity. Big, isolated pores are not a problem, but small, interconnected pores absorb moisture through capillary action and are generally less resistant.

QUARRY RECOMMENDATIONS FOR BETTER QUALITY AGGREGATES

- Selectively quarry the rocks and place in numerous stockpiles for variations in the quality of the materials.
- Utilize water to wash aggregate using a log washer or barrel washer to remove clays and other deleterious materials.
- Have Micro-Deval testing equipment at quarries with inconsistent aggregate quality.
- Use density separation to remove light, porous aggregates from more dense, better quality aggregates.

MISCELLANEOUS

- Design the mix based on the gradation of the mix as it is placed. For example, there is always material loss/generation of fines as an aggregate is crushed, stockpiled, moved to the hotmix plant, mixed with the asphalt, and placed on the roadway. Aggregates from different sources lose different amounts of fines, so one needs to determine what the final gradation will be based upon handling and design the mix based on what the final gradation will be.
- To get more quantitative numbers on aggregate quality, try the new aggregate imaging device made by the French (mlpc VDG 40). It can be attached to a conveyor belt and measures aggregate shape as the aggregate travels over the end of the conveyor belt.

CHAPTER 2
BINDER EVALUATION FOR FIELD CORES FROM ABILENE AND LUBBOCK DISTRICTS

INTRODUCTION

Pavement cracking is a major problem of many asphalt concrete pavements later in their service lives. Such cracking is frequently termed fatigue cracking, implying physical damage to the binder. However, oxidative stiffening of the binder, the result of chemical changes to the binder due to oxidation during the hot summer months, certainly is a significant contributor as well. Other mechanisms of binder stiffening may be possible and prompted this study of binders in pavement cores.

The asphalt concrete in US-84 was in service for approximately 5 years when significant cracking problems were observed. As this is a very short time for age-related cracking failure, further investigation of the binder was conducted to determine the root cause of this cracking.

Several cores were obtained from two sections of US-84. One section was from Scurry County, northwest of Abilene, and the other from Taylor County, the Abilene home county. The Scurry County cores were designated series 84-Sx, while those from Taylor County were labeled series 84-x, where "x" is a number that denotes replicates for each group of cores. From a mixture design perspective, the US-84-Sx cores were 6.1 percent by weight of a Fina PG 70-22 binder, whereas the US-84-x cores were 5.2 percent of a Fina PG 64-22 binder.

From physical observations of the pavement cross-sections, visible in the recovered cores, it was clear that asphalt binder had penetrated past the surface of the aggregate. The researchers suspected that such penetration may have resulted in fractionation of the binder, if, for example, the lighter, more mobile binder components were absorbed preferentially, leaving behind the less mobile and stiffer binder components. It was hypothesized that such fractionation could create a binder that was more susceptible to cracking than was the original design material. This hypothesized, residual binder, we term the "inter-binder."

Objectives

The objectives of this work were threefold:

1. to recover inter-binder and penetrated binder materials and compare their properties,
2. to assess the possibility of binder penetration from the results obtained from objective 1, and
3. to analyze the likelihood of pavement cracking being caused by binder penetration into the aggregate.

EXPERIMENTAL METHODOLOGY

Binder Extraction and Recovery

Extraction

Two methods of binder extraction were used in this study. In each method, a solution of 15 percent by volume of ethanol (ETOH) in toluene was used to extract the asphalt binder from each core. Before extraction, each core was broken into small pieces to increase contact surface with the solvent. After the crushed core was washed with the solvent mixture for 20 minutes, the asphalt solution was separated from aggregate using filtration and centrifugation. This step was repeated until there was practically no asphalt remaining in the aggregate.

For method 1, the asphalt solutions from each wash were combined into one solution, and then passed to recovery process. This method produced a single recovered binder product. This method is called the 1st Method.

For comparison purposes, another extraction method, the 2nd Method, was identical to the 1st Method except that the individual wash solutions were recovered separately to give three recovered binder products.

Normally, three washes were required to remove asphalt binder from the aggregate, so the 1st Method required one recovery step whereas the 2nd Method required three separate recoveries.

Recovery

In the recovery process, a Brinkman rotovap apparatus was used to evaporate all solvent from the asphalt. Asphalt solution was evaporated for about 80 minutes under vacuum and with a nitrogen purge to assist solvent removal. The recovered asphalt binder was then subjected to further chemical and physical analyses.

Extraction/Recovery flow diagrams for both the 1st Method and the 2nd Method are shown in Figure 14.

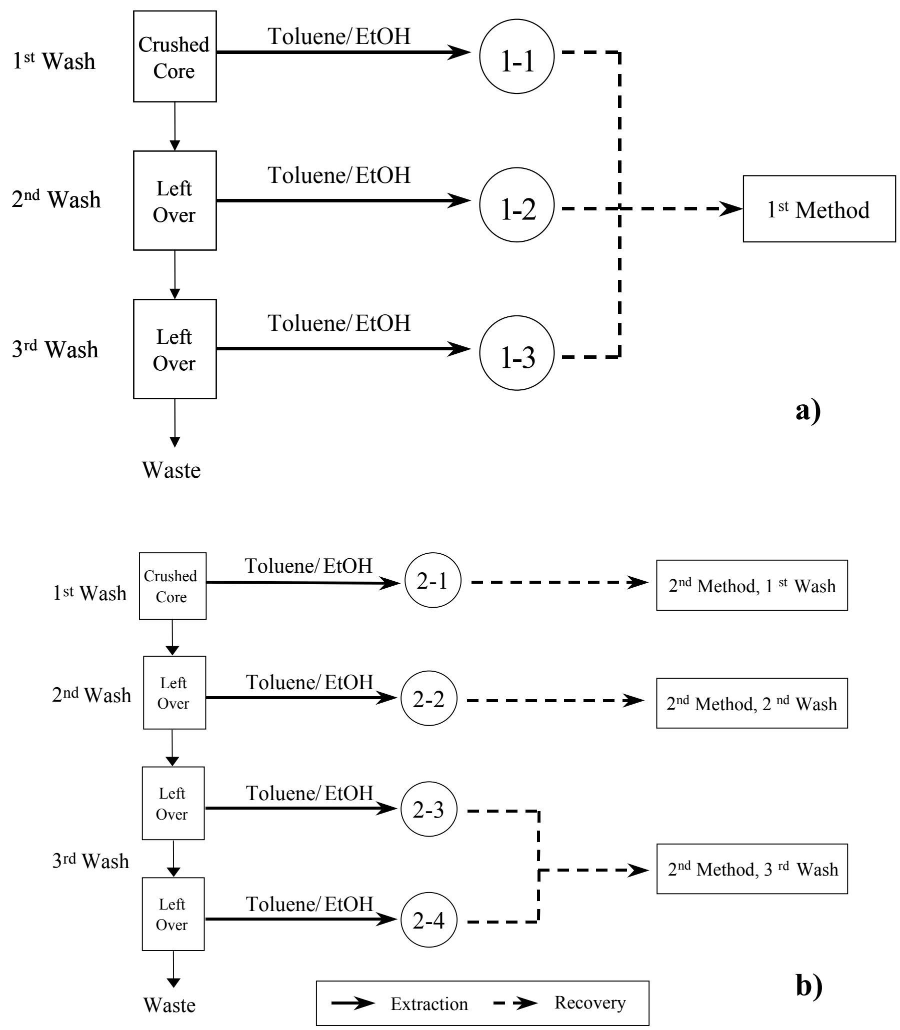

Figure 14. Extraction/Recovery Flow Diagram of (a) 1st Method and (b) 2nd Method.

Size-Exclusion Chromatography

After each recovery process, it is essential to confirm the removal of all solvent from the asphalt binder. Solvent in recovered binder can dramatically distort the rheological properties of the asphalt, making it appear to be much softer than it is, in fact. Using tetrahydrofuran (THF) as a carrier fluid in gel permeation chromatography (GPC), also known as size exclusion chromatography (SEC), a toluene-based solvent can be detected. Also, any other unexpected components in the recovered binder may be observed. SEC conveniently gives a broad perspective of a binder's composition. Components that can be detected and identified from SEC, for example, are the asphaltene-rich fraction of a binder, the maltene-rich fraction, toluene, polymers, and water. Once recovered and binders are found to be free from the extracting solvent, properties of the binder can be confidently measured. The shape and relative size of the asphaltene and maltene peaks can also be used as "fingerprinting," along with other methods, to establish that different binders have been used in different pavement sections or to establish that two binders are likely the same.

Dynamic Shear Rheometer

Two types of rheological property data were obtained from dynamic shear rheometry (DSR) measurements: the viscosity master curve at 60 ^oC and an estimated ductility of the asphalt binder. A 2.5 cm diameter parallel-plate geometry with a 500 μm gap was used for the measurements. To acquire the viscosity master curve at 60 ^oC reference temperature, complex viscosity measurements were obtained in a controlled-stress mode by performing two frequency sweeps at 60 ^oC and 90 ^oC over a frequency range of 100 to 0.1 rad/s. Then, a shift factor was used to adjust frequency range, moduli, and viscosities at 90 ^oC to match with the 60 ^oC reference data. As a result, a single master curve with a wider range of frequency at 60 ^oC can be constructed. After this procedure, also called a time-temperature superposition, a viscosity master curve at 60 ^oC should have a frequency range of 100 to 0.001 rad/s. At the lower end of the frequency range, the viscosity approaches a low shear rate limiting viscosity (also termed the "zero-shear" viscosity), a useful characteristic of the binder. An estimate of the binder's ductility at 15 ^oC and 1 cm/min extension rate can be calculated from DSR G' and G" at 44.7 ^oC and 10 rad/s (Ruan et al., 2003). The DSR function relationship is shown below:

$$DSR\ Function = \frac{G'}{\left(\eta' / G' \right)} = \frac{G' * \omega}{\tan \delta}$$

$$
\begin{aligned}
&where \quad \eta' = \frac{G''}{\omega} \; and \; \frac{G''}{G'} = \tan\delta \\
&\omega = Angular\ Frequency\ (rad/s) \\
&\delta = Phase\ Angle\ (degree)
\end{aligned}
$$

Then, G' vs. (η'/G') can be plotted on the map with a constant ductility curve to identify calculated ductility of each asphalt binder.

Fourier Transform-Infrared Spectrometer

The Fourier Transform Infrared (FT-IR) spectrometer used in this study is a Mattson 5020 Galaxy spectrometer. The infrared spectrum of asphalt binder coated on a zinc selenide prism was collected and analyzed over wavenumbers of 1800 to 700 cm^{-1}. From the data, we define the band from 1820 to 1650 cm^{-1} as the carbonyl area of asphalt binder, which is used to indicate the level of oxidation that a binder has reached. Differences between inter-binder and penetrated binder oxidation were evaluated using this method.

Hardening Susceptibility

Each asphalt has a unique linear relationship between logarithm of viscosity (low-shear rate viscosity at 60 ^{o}C), ln(□), and carbonyl area. The slope of such a relationship is defined as the hardening susceptibility, and it has been found to be independent of oxidation temperature but is a function of oxidation pressure. This parameter was used to assess whether binders from each wash were likely of different composition on the basis that if different they would yield different values of the hardening susceptibility.

Results and Discussion

In this study, four cores of asphalt mixture were analyzed which included specimens 84-S9, 84-S2, 84-6, and 84-S6. Each core was extracted/recovered and then the measurement methods, as described above, were performed. The material from 1st Method represents the weighted average of all three washes from the 2nd Method, which separates the different parts of asphalt binder. Although every core was washed with solvent three times during the 2nd Method, the 84-S9 core was washed only twice because of limited material. Hence, specimen 84-S9 has only two washed data points.

From the 2^{nd} Method, the 1^{st} wash represents the majority of the inter-binder of the asphalt pavement. The 2^{nd} wash is a transition mixture between the inter-binder and penetrated binder, and the 3^{rd} wash is mostly remaining penetrated binder on the aggregate surface. ***From this point, the 1^{st} and 3^{rd} washes will be referred to as inter-binder and penetrated binder, respectively, for ease of understanding.***

First, SEC was used to detect any solvent left behind in the asphalt binder from the extraction/recovery process. Figure 15 shows that all asphalt binders were free from solvent. If

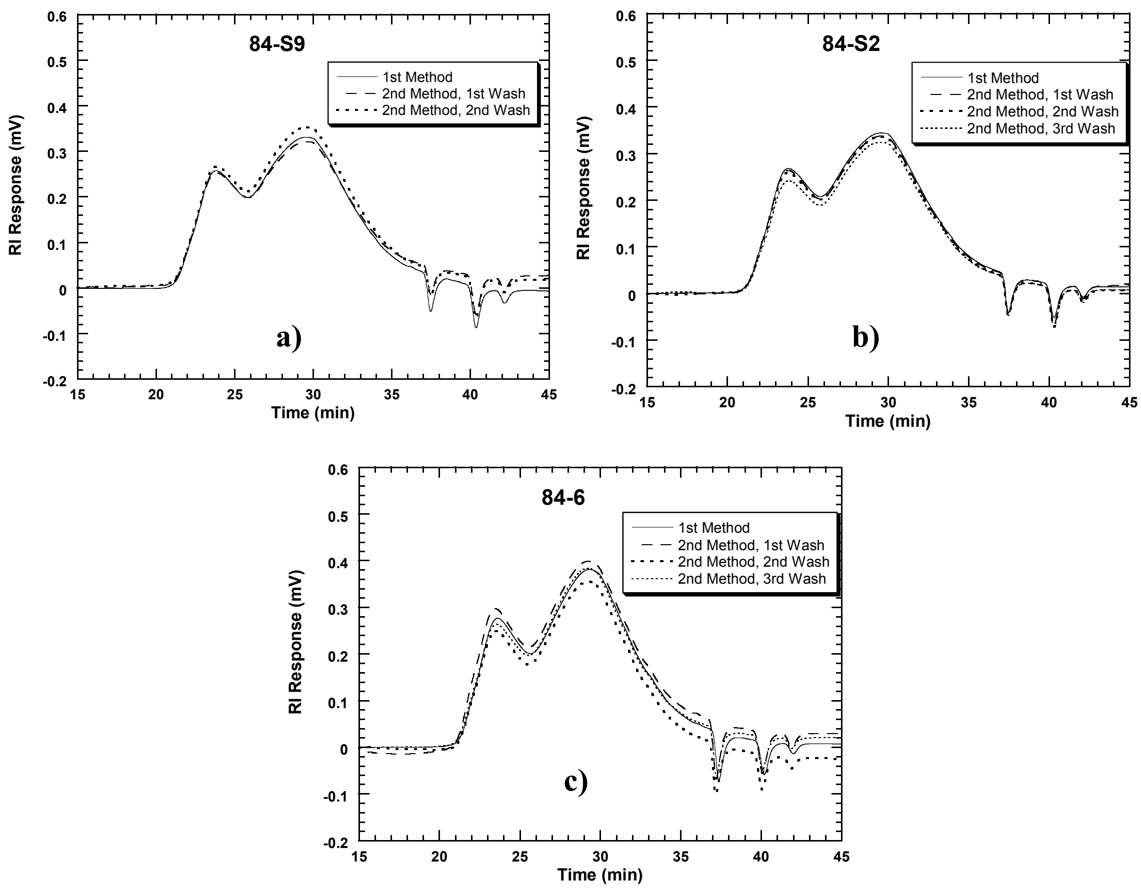

Figure 15. Refractive Index (RI) Response from Size Exclusion Chromatography of (a) 84-S9 (b) 84-S2 (c) 84-6.

there was any solvent present in the binder, a solvent peak appeared at 38 minutes retention time. With these results, accurate property measurements can be assured.

According to the DSR measurements each wash from each core has different zeroth viscosities, as shown in Figure 16. However, every core from the 2^{nd} Method illustrates the same tendency of decreasing viscosity, from the 1^{st} wash to the 3^{rd} wash. This phenomenon indicates that penetrated binder has a better flow property than the inter-binder, to some degree. In addition, it can be seen that specimen 84-S6 had the highest overall viscosity while specimen 84-6 had the lowest, one meaning it had less flow resistance associated with the binder. In fact, specimen 84-6 also had relatively low overall viscosity compared to specimens 84-S9 and 84-S2. From mixture design information, specimen 84-6 is based on PG 64-22 and the rest of the S-series cores are based on PG 70-22 asphalt binder. The difference based on asphalt binder could very well be an important factor for explaining flow behavior of asphalt in each series.

The oxidation level of an asphalt binder is a crucial factor in pavement failure. FT-IR carbonyl area is directly related to the oxidation level of asphalt binder. Figure 17 illustrates the carbonyl area for each core from the different washes. Again, each core demonstrates a similar trend in carbonyl area, decreasing from the 1st wash to the 3rd wash, like viscosity in the previous discussion. The penetrated binder has a lower oxidation level, possibly because it has less contact area with oxygen. On the other hand, inter-binder, which is in the open mixture, has more surface area to oxidize. Nevertheless, overall oxidation levels of each core are evidently the same, regardless of the huge differences in the viscosity of each core. Within the same pavement, oxidation conditions - climate, temperature, pressure, and air void - are basically identical. As a result, indistinguishable conditions lead to similar results in the overall oxidation level of each core. Note that in Figure 17 carbonyl area data are plotted starting at a value of 0.5 instead of 0. Because typical unaged asphalt binder has an initial carbonyl area of around 0.48 to 5.5, 0.5 is a viable starting point. When starting at 0, the difference in carbonyl area between each wash is quite hard to determine.

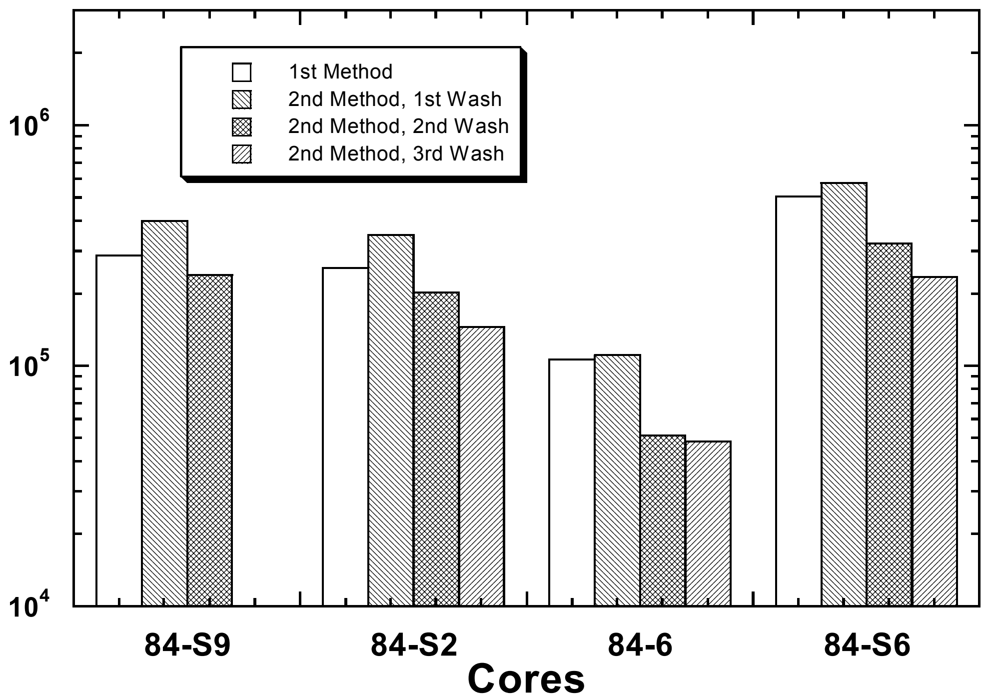

Figure 16. Zeroth Viscosity (η_o^*, poise) of Recovered Asphalt Binder.

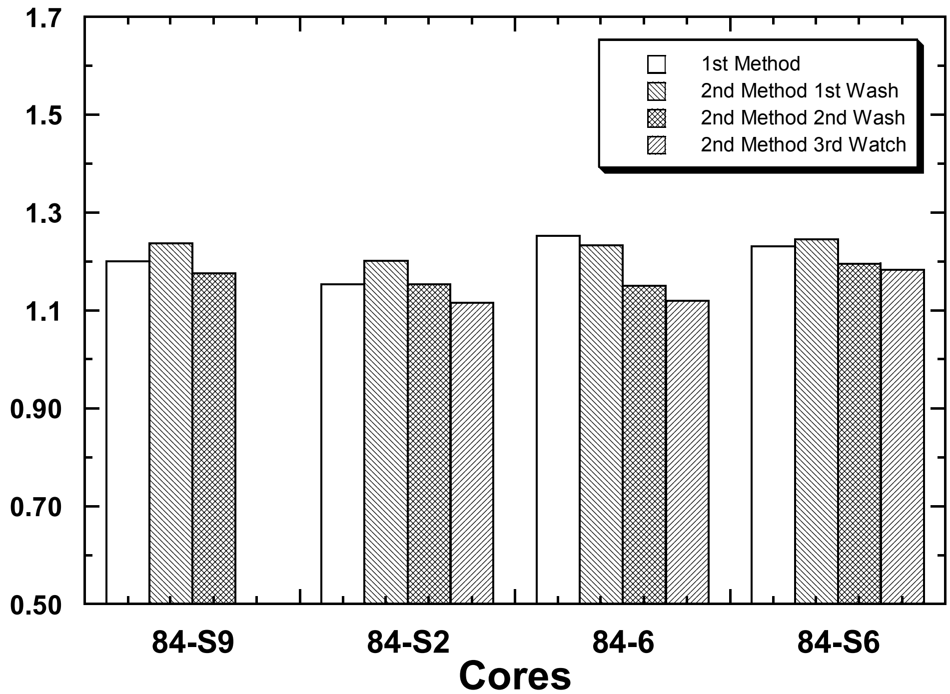

Figure 17. Carbonyl Area of Recovered Asphalt Binder.

In order to examine the performance of a pavement, the calculated ductility of the asphalt binder needs to be considered. In a normal case, a pavement would fail if its ductility were as low as 3 to 5 cm. Figure 18 is a DSR map of the calculated ductility of each asphalt binder. Figure 18 (a) contains data for specimens 84-S9 and 84-S2, whereas 18 (b) contains data for specimens 84-6 and 84-S6. These calculated ductility data show that, for all cores, penetrated binders have higher calculated ductility than inter-binders. Moreover, ductilities of the 84-S series are shorter than those of the 84. These data correspond very well to viscosity data from Figure 16 in terms of flow characteristics such that specimen 84-S6 has the stiffest binder and specimen 84-6 has the softest binder. Another interesting point from this map is that the 84 series has a larger ductility difference between penetrated binder and inter-binder, around 5 cm, whereas the 84-S series has a difference of only about 1 cm. This result, once again reinforces the importance of base asphalt on pavement performance. In addition, from a service life standpoint, this pavement is still too stiff for a 5-year-old pavement.

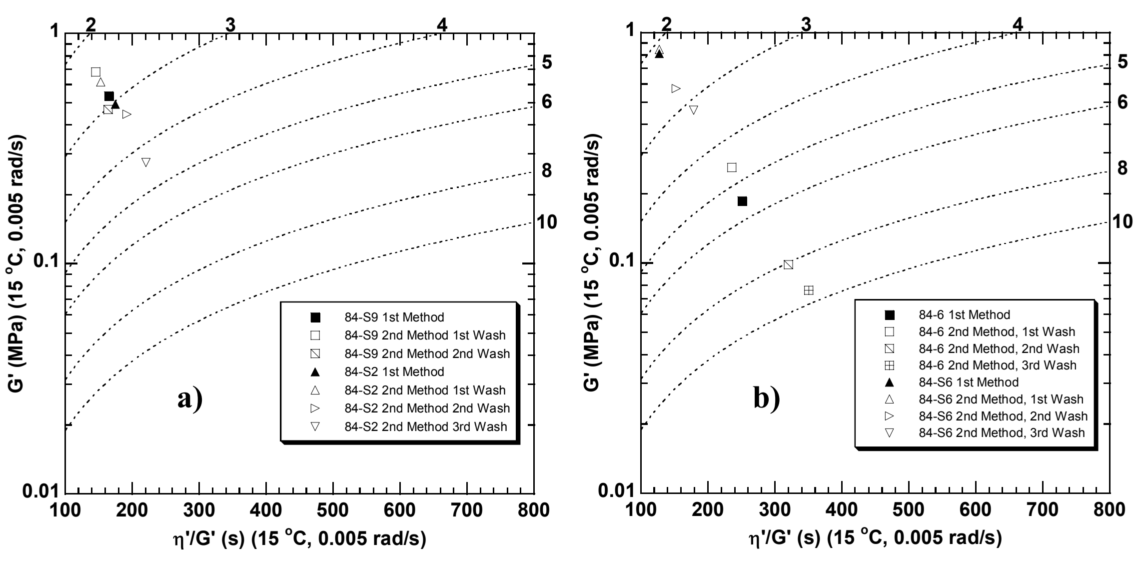

Figure 18. DSR Map of Calculated Ductility of (a) 84-S9 and 84-S2 and (b) 84-6 and 84-S6.

Up to this point, the results show that physical properties of inter-binder and penetrated binder are somewhat different. The next question is what is the difference in composition between those two binders. To answer this question, the concept of hardening susceptibility was used to verify differences in composition of each binder. Since each binder has a unique linear relationship between logarithm of viscosity (ln η) and carbonyl area, a plot of carbonyl area versus ln η should highlight inconsistencies, if any, between the asphalt binders. Figure 19 was constructed to ascertain whether there is a linear relationship for asphalt binders from each core. From the hardening susceptibility perspective, no matter at what temperature and how long asphalt binder is aged, a linear relationship should still hold. As can be seen from Figure 19, data from each core form an acceptable linear relationship, as indicated by R-value. With this information, the overall composition of penetrated binder and inter-binder are not significantly different from each other.

Other evidence that can confirm composition differences between inter-binder and penetrated binder is refractive index response from SEC. Figure 14, shows the refractive index response of each wash for the same core is consistent in terms of curve shape. Any inconsistency would cause the curve to be different in shape, as illustrated in Figure 20. Because the 84-S series and the 84 series were designed based on different asphalt binders, refractive index responses for these two series are quite distinguishable. The refractive index response of the 84 series is shifted slightly to the left of that of the 84-S

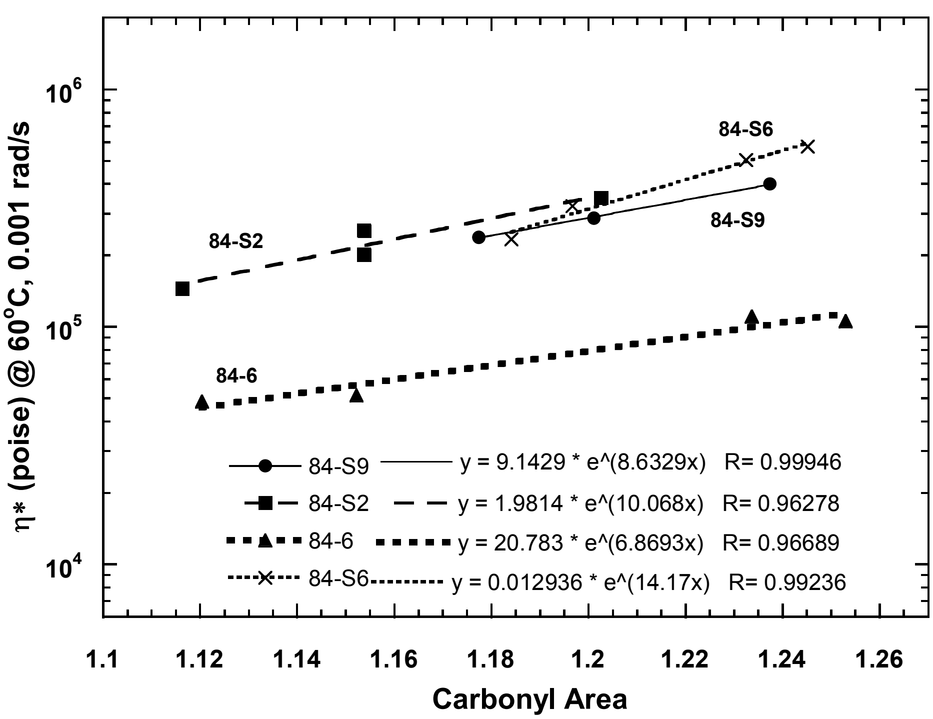

Figure 19. Hardening Susceptibility of US-84 Cores.

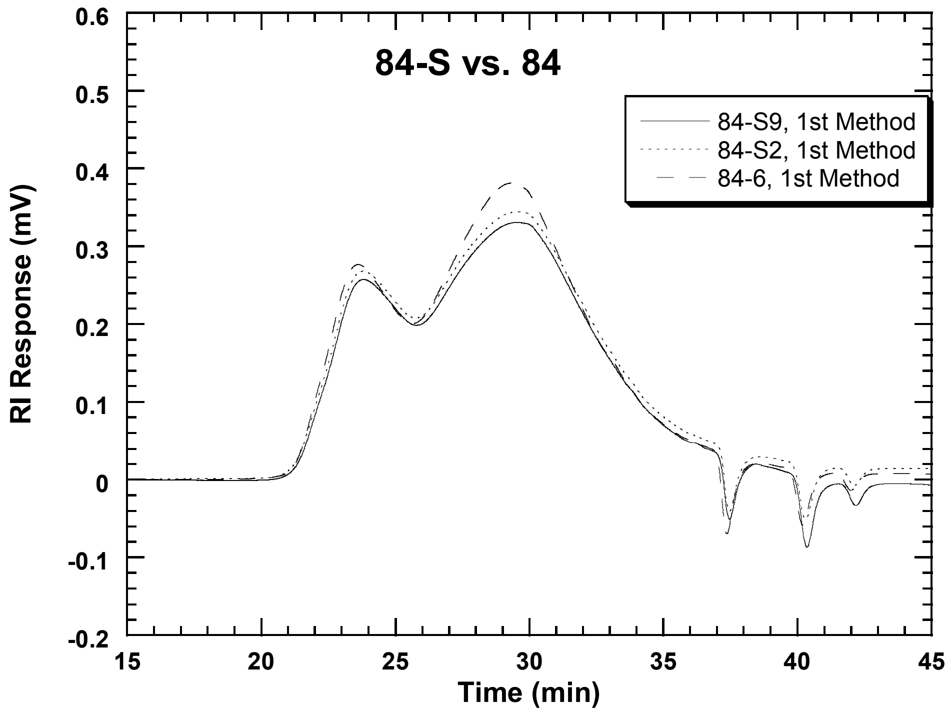

Figure 20. Comparison of RI Response between 84-S Series and 84 Series.

series. This refractive index disparity indicates that the 84 series has larger molecular size than 84-S series asphalt binder.

In this study, physical properties and composition consistency between penetrated binder and inter-binder from US-84 were investigated. Between these two binders, there are some differences in flow characteristics and oxidation levels. The composition differences between penetrated binder and inter-binder cannot be clearly detected, however. Hardening susceptibility displays linear relationships between ln η and carbonyl area for all cores, which assures consistency in composition of the two binders. However, further study is needed to support the results of this project. In the future, more pavement cores from US-84 can be taken from the same locations then similar methodology can be applied. With more experimental data points, hardening susceptibility will obviously become more accurate. Moreover, one could separately construct a hardening susceptibility plot of penetrated binder and inter-binder for better understanding of the hardening behavior of these two asphalt binders.

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