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Superpave and the Aggregate Industry

ABSTRACT: The Superior Performing Asphalt Pavement (Superpave) mix design system was developed under the Strategic Highway Research Program (SHRP), which was completed in 1993. Superpave consists of new methodologies for evaluation and selection of hot mix asphalt (HMA) material constituents along with new laboratory compaction protocols. During Superpave development, significant research focused on the performance grade (PG) asphalt binder system and gyratory compaction development. In contrast, very little research was performed to determine those aggregate properties and specification requirements most closely related to HMA mix performance.

In 2000, the aggregate industry prepared a white paper for, and at the request of, the Transportation Research Board (TRB) Expert Task Group (ETG) on Superpave Mixtures and Aggregates. The paper focused on discussion of aggregate related issues that presented challenges to the implementation and use of Superpave. Since the white paper was written, Superpave has undergone modifications (specifications and general use or practice) based on completed research and general knowledge obtained. Many Superpave modifications were addressed in varying degrees in the white paper, and it is now important to discuss the impact of these modifications on HMA performance and the aggregate industry.

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In addition, other aggregate related issues are presented and discussed, including inconsistent fine aggregate definition, influence of minus 0.075 mm sieve material on fine aggregate specific gravity determination, aggregate production and particle shape, and the influence of aggregate on dynamic modulus.

KEYWORDS: Superpave, aggregate, hot mix asphalt, specific gravity,

Background and Introduction

The Superior Performing Asphalt Pavement (Superpave) mix design system was developed in 1993 as part of the Strategic Highway Research Program (SHRP). Superpave consists of new methodologies for hot mix asphalt (HMA) material constituent (asphalt binder and aggregates) selection, aggregate gradation blend requirements, and a new laboratory compaction protocol. While extensive research was performed during SHRP on asphalt binder and laboratory compaction, no research was conducted to determine those aggregate properties most closely related to HMA performance. However, aggregate specifications and blend gradation requirements were desired as part of the Superpave system. Therefore, in lieu of a structured research program, a limited number of pavement "experts" participated in a modified Delphi procedure to recommend aggregate specifications and gradation requirements. These experts were surveyed to determine which aggregate properties and gradation requirements were most influential on performance. Afterwards, consensus and source aggregate properties, with associated specification requirements, along with blend gradation requirements were developed [1].

Consensus properties are those that; theoretically, a supplier can modify depending upon processing protocols. Among these consensus properties are coarse aggregate angularity, fine aggregate angularity, sand equivalent, and flat and elongated. Source properties are properties considered to be "source" or inherent, and consist of Los Angeles abrasion, sodium or magnesium sulfate soundness, and clay lumps and friable particles. In contrast to consensus properties, source property requirements are established by local specifying agencies [1].

Superpave also attempted to unify gradation specification methodology. A 0.45 power gradation chart and “universally” used definitions for maximum, nominal maximum, and nominal aggregate sizes were provided. The maximum density line was drawn from the zero originate through the maximum size of the aggregate blend. Control points were established and placed on the nominal maximum size sieve, an intermediate size sieve (either the 2.36 mm or the 4.75 mm size), and the 0.075 mm sieve [1].

Also present in the initial Superpave specifications was the restricted zone, which was represented by a gradation envelope or band through which aggregate blend gradings were “restricted”. Restricted zone gradation boundaries varied based on the blend nominal maximum aggregate size, but were located on intermediate sieves [(4.75 mm or 2.36 mm), 1.18 mm, 0.6 mm and the 0.30 mm]. The purpose of the restricted zone was to limit ‘humped” gradation resulting from use of excessive natural sand. Gradations violating the restricted zone were believed to possess weak aggregate skeletons that would exhibit less resistance to shear deformation [2].

Influence of Superpave on the aggregate industry has been significant. Aggregate specification and gradation requirements have in some cases resulted in substantial modifications to production equipment and procedures. Production has often slowed due to particle shape requirements. In many cases production of coarse aggregate with the required particle shape has resulted in fine aggregate with less likelihood of passing specification requirements for fine aggregate angularity.

In July 2000, a summary of aggregate issues of importance and concerns related to Superpave was documented in “White Paper on Superpave Issues of Concern to the Aggregates Industry” [3]. This paper was written per request of the Superpave Mixtures and Aggregate

Expert Task Group (ETG) by individuals within the aggregate industry under the direction of Chuck Marek of Vulcan Materials Company.

Since the white paper was written, Superpave has undergone modifications based on completed research and knowledge obtained. Many Superpave modifications were addressed in varying degrees in the white paper. It is now important to discuss their impact on HMA performance and the aggregate industry. In addition, other aggregate related issues are presented and discussed, including inconsistent fine aggregate definition, influence of minus 0.075 mm sieve material on fine aggregate specific gravity determination, aggregate production and particle shape, and the influence of aggregate on dynamic modulus.

Objective and Scope

The primary objective of this paper is to discuss the impact of Superpave related issues on the aggregate industry. Discussion will focus Superpave's evolution from inception to present day along with items of concern for the future.

Review and Discussion of 2000 Aggregate Industry White Paper

The "White Paper on Superpave Issues of Concern to the Aggregates Industry" [3] contained eighteen recommendations. Each recommendation will be presented followed by a discussion or update of related activities. Some of the discussion will be very brief, while other discussion will be more substantial. In the white paper, recommendations were classified as informational, regional issues, standard changes, or needed research.

Informational (2 Recommendations)

<u>Recommendation 1: "The ETG should request an immediate fast track effort by TRB to synthesize all published and currently on-going research on aggregate properties and aggregate</u>

acceptance criteria for use in Superpave. This review and compilation should be performed by an *independent* source."

National Cooperative Highway Research Program (NCHRP) Project 9-35: Aggregate Properties and the Performance of Superpave Designed Hot Mix Asphalt was completed in October 2004 by the National Center for Asphalt Technology (NCAT). Report findings are summarized in *NCHRP Report No. 539* [4]. Significant reference will be made to the work conducted in NCHRP 9-35 as it pertains to various items discussed. The project objective was to review literature to determine the consensus, source, or other aggregate properties that most significantly influence HMA performance. To complete the objectives, researchers conducted a state of the practice review with regards to aggregate properties, surveyed on-going research projects, surveyed various agencies for specification requirements and performance, and reviewed performance data from field test sections and full-scale testing facilities.

While there were many important findings and conclusions reached in the NCHRP study, one key conclusion was that interactions from aggregate properties, gradation and mixture volumetric properties make it very difficult to isolate an individual property's influence on HMA performance. Therefore, development of a HMA performance test is of critical importance for proper mix performance evaluation.

Recommendation 2: "Aggregate producers must perform more frequent tests on aggregate products produced for Superpave mixtures. The ETG should encourage aggregate producers to develop appropriate testing and quality control plans to provide accurate information for use in Superpave mixture design."

For the most part, aggregate producers and suppliers have strengthened their quality control (QC) program with increased testing frequency being one result. In many respects it is the overall desire of aggregate producers to improve their QC program, not just Superpave, which has resulted in QC program improvements. Some increase, in certain areas, has been in response to a reduction in quality assurance (QA) testing being conducted by State DOTs.

Without question, customers have become more demanding and knowledgeable about aggregate's role in final HMA performance. Tighter control of produced materials is necessary to provide customers with more consistent products. More testing and tighter control by aggregate producers means less potential problems for HMA producers due to better gradation controls and reduced variability. Increased testing has resulted in more expense (increase technicians, equipment, etc.), but is necessary in a marketplace where customers are demanding more consistent products. Most aggregate producers simply see increased testing as part of an overall philosophy of striving to be better than the competition and meeting customer expectation. Increased testing alone will not necessarily improve quality. Results should be used in an overall statistical analysis and process control management program to optimize production efficiency and quality.

Regional Issues (2 Recommendations)

<u>Recommendation 1: "Some source properties, such as LA degradation (abrasion), have not been related to the performance of a Superpave mixture, and therefore, the validity of state DOT acceptance criteria is questioned. Research on source properties for various geologic aggregate types used in HMA should be supported and recommended by the ETG. In particular, the influence of LA degradation (abrasion) loss on asphalt mixture performance should be evaluated and current guidelines and/or acceptance criteria should be validated or revised."</u>

Prowell [4] conducted an analysis of the Superpave source properties of LA abrasion and revealed that LA abrasion was specified by 96 percent of respondents with 40 percent loss being the most commonly specified maximum value. However, background and development of the specification value remains in question. Work conducted during *NCHRP Project 4-19*, as reported in *NCHRP Report 405*, *"Aggregate Tests Related to Asphalt Concrete Performance in Pavements,"* [5] concluded that LA abrasion results were not related to pavement performance.

Some states specify different LA abrasion requirements based on traffic level. Using traffic level dependent requirements may appear logical; however, the majority of aggregate breakdown occurs during production and placement, not during service. This theory is backed by Prowell [4], who reports that there appears to be no relationship between LA abrasion of the aggregate and the long-term abrasion loss of the pavement surface.

Another issue is source property variation as a function of crushing operations. Source properties, by definition, were intended to be independent of aggregate production procedures. However, there is a question as to whether LA abrasion is a "true" source property. By nature of the test action, edges are "rounded off" of aggregate particles. As a result, there may be considerably lower loss for cubical particle when compared to more flat and elongated particles of the same parent rock type. Differences up to 5 percent have been shown between particles crushed by impact crushers relative to jaw crushers. Substantially lower soundess values may also be recorded when testing aggregate produced in impact crushers relative to jaw crushers [6].

<u>Recommendation 2: "Use of locally available aggregates should be encouraged if they will not adversely impact the performance of the Superpave mixture. Engineering judgment should be permitted in Superpave mixture design to avoid excessive transportation costs for materials that will be incurred when the local materials are not within the acceptance criteria."</u>

Many agencies have different aggregate property requirements based upon historical performance. It is crucial that agencies continue to be conscious of locally available materials and the resulting economic impact of their use. If field performance or laboratory performance testing indicates good HMA performance using locally available materials, then local materials should be allowed.

Standards Changes (5 Recommendations)

Recommendation 1: "The ETG should recommend to AASHTO Subcommittee on Materials (SOM) that the basic definitions used by all state DOTs in the Superpave mix design system be standardized. In addition, the proliferation of aggregate test procedures by state DOTs should be discouraged. The ETG should support and recommend that the *best test methods* (ASTM or AASHTO methods if good, or some other method if better than ASTM/AASHTO) for aggregate properties be adopted and used by all state DOTs without modification and without tweaking."

Agencies continue to designate Superpave gradation in different manners. For example, the Alabama Department of Transportation (ALDOT) [7] specifies mixes based upon maximum aggregate size, while most other states use nominal maximum aggregate size. The maximum density line (MDL) specified in the SHRP research was to be drawn on the 0.45 power chart from the zero origin through the maximum aggregate size. Today, differences exist in how agencies specify the MDL. For example, the Mississippi Department of Transportation (MDOT) specifies the MDL as a straight line plot on the 0.45 power chart extending from the zero origin through the plotted point of the combined aggregate gradation curve on the nominal maximum sieve size [8]. Inconsistent terminology and definitions can and have lead to confusion in understanding specified or designed mixes and in evaluating the performance of these mixes.

Perhaps Superpave's major inadequacy is the lack of a reliable and easily implementable HMA performance test. Without such a test there will continue to be substantial guesswork involved in mix design and construction. Lack of a performance test has lead to increased efforts to characterize materials with varying degrees of success. In some cases, characterization methods may have made their way in to specifications without necessary supporting data.

Specification proliferation clearly emphasizes the need for a universally accepted performance test. Without a performance test, specification proliferation will continue to be an issue. Making specifications tougher or adding more specifications do not always result in a better product. Many times, "new" test procedures are developed to take the place of existing procedures. However, in some cases, the new procedure may be placed in specifications in addition to the existing procedures. This is especially critical if two procedures are not correlated, which can make it extremely difficult for certain materials to meet both or all specification requirements. One example of this is LA abrasion and micro-deval testing. Specifications need the necessary lab and preferably field performance data to support their use and implementation. Specification redundancy is also evident with one example pertaining to fine aggregate specifications. Prowell [4] reports 46 percent of responding states placed limitation on natural sands with 79 percent of those states also having FAA requirements.

One of Superpave's goals was to have one set of aggregate requirements; however, this obviously has not or will not happen. Even if a performance test is developed that will accurately predict HMA field performance, agencies must then implement it into specifications. Care must be taken because a likely tendency will be to implement a performance test while at the same time maintaining existing or new aggregate property or gradation requirements. The ultimate goal should be a performance based specification with minimal features of a method or "recipe" specification.

Recommendation 2: "The ETG should recommend consideration and acceptance of aggregate blends that meet Superpave requirements that are anywhere within the grading control points. The Restricted Zone should be eliminated. The ETG should encourage State DOTs to consider blends that are on the fine side as well as on the coarse side of the band. Consideration and use of fine-graded Superpave mixtures and mixtures having gradings that pass through the restricted zone should be encouraged."

While the restricted zone concept seems logical, it prohibited the use of "dense" or well-graded crushed aggregate blends with proven histories of good field performance in many states. *NCHRP Project 9-14: Investigation of the Restricted Zone in the Superpave Aggregate Gradation Specification* was completed in July 2001, with results published in *NCHRP Report 464* [9]. It was concluded that the restricted zone was not necessary for satisfactory mix performance when the fine aggregate angularity and volumetric mix criteria were achieved. Researchers recommended the restricted zone be eliminated from Superpave specifications. Since research completion, it has been reported that the restricted zone has been removed from more current Superpave specifications [4].

During the initial years of Superpave it was a commonly-held belief that coarse-graded mixes held the most potential to resist permanent deformation or rutting. Because of this, many agencies specified blend gradations to be on the coarse-side or below the restricted zone. Not all HMA mixes need to be coarse-graded. While coarse-graded mixes may be appropriate for some applications, fine-graded mixes also can be utilized. In some instances, mixes designed above the restricted zone (i.e., fine-graded mixes) performed equal to or better than coarse-graded mixes. It was concluded from the initial performance evaluation of the NCAT test track that coarse-graded and fine-graded mixes had approximately the same rutting performance [10].

Additionally, because of the "rocky" grading of coarse-graded mixes, compaction may be more difficult to achieve, thus leading to permeability problems. Even if fine and coarse-graded mixes are compacted to the same field density, air voids of the coarse-graded mix will likely be larger and thus there is a greater tendency for interconnected voids. The result will be increased permeability resulting in oxidation and premature cracking [11].

Increased demand for coarser mixes has required fractionalization of coarse aggregate materials to meet grading requirements, production of more fines, more plant wear, reduced production rates, and increased quality control efforts [3]. Increased fines generation is evident in many areas. In South Carolina, for example, the continued specification of coarse-graded mixes has, in part, resulted in large quantities of fines being produced and stockpiled. To illustrate the production of fines, consider that in a typical aggregate plant the production of 1 ton of No. 789 stone yields 1.5 tons of screenings. South Carolina HMA mixes used to be 50 percent No. 789 and approximately 25 percent each of manufactured sand and screenings. Today, those "same" mixes utilize around 65 percent No. 789, 10 percent screenings, and 25 percent manufactured sand [12]. Without an outlet for these fines, aggregate production is either slowed or the cost per ton is increased. In some applications with Superpave-driven increased coarse aggregate demand, high performance crushers have been installed. While these crushers will increase production, increased dust generation also occurs and this is a major concern. Increased costs are now incurred to handle the dust material through pond systems, belt presses, etc.

Some states are beginning to modify specifications to require more fine-graded mixes. For several years now, the Alabama Department of Transportation (ALDOT) has required all wearing (surface) and upper binder (below wearing) layer mixes to be designed either through or on the fine side (above) of the restricted zone [7]. This is in response to observed permeability issues with coarse-graded Superpave mixes.

Recommendation 3: "The ETG should encourage development of proper corrections and adjustments to aggregate gradings used in the laboratory design process (to account for changes that may occur during handling, transport, and mixing), and encourage state DOTs to permit use of the adjusted gradings in the design process."

The reasoning behind this recommendation is to account for potential breakdown in materials during production activities. Doing so would potentially enable the mix designer to complete a design with aggregates that have undergone breakdown through production. This could decrease the number and magnitude of mix adjustments required during production. While this is a good concept, there are concerns about the time and effort required to dry-run the aggregates through the HMA plant. Further, the amount of breakdown will be greater without the addition of the asphalt binder. In actuality, most mix designers have a good idea of the breakdown anticipated from various aggregate materials. Therefore, some accounting for this can be done during the design phase, even while using "stockpile" gradations.

Recommendation 4: "Significance of test method precision should be recognized, and the inherent variability of each test should be properly reflected in Superpave mixture acceptance criteria. The ETG should recommend that state DOTs incorporate test method precision into their specifications and acceptance criteria."

Test precision is a tremendously important issue related to specifications, especially with the advent of percent within limit (PWL) specifications. Realistic estimates of testing variability must be utilized in such specifications to insure fairness to the producer and owner agency.

While there are several specifications where variability is an issue, without question, the flat and elongated test has the highest test variability and most limited data documenting its precision. Currently, *ASTM D4791 Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate* [13] does not have a precision statement. Prowell [4] summarized work conducted to determine precision of D4791. Among the research cited was work conducted by the AASHTO Materials Reference Laboratory (AMRL) in which over 120 laboratories participated in a precision study for flat and elongated particles. Results for 5:1 testing showed extremely high variability with D2S multi-laboratory values ranging from 119.2 to 151.0 percent. It was also reported that flat and elongated testing at 5:1 is subject to erratic variations even at low levels of flat and elongated particles [4].

Fine aggregate angularity precision is of great importance. For fine aggregate angularity *(ASTM C1252 Standard Test Methods for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading), Method A)*, [14] the D2S limit for single-operator and multi-laboratory are given as 1.61 and 2.12 percent, respectively. Therefore, if a fine aggregate angularity (FAA) test result of 45 percent is determined in one laboratory, and another result on the same material in a different laboratory of 43 percent is obtained, both results should be acceptable, even though the specifications require a minimum FAA value of 45.

Especially critical with FAA testing is the proper measurement of fine aggregate bulk specific gravity (G_{sb}). Prowell [4] suggests research be conducted to improve fine aggregate G_{sb} measurements to lower FAA testing variability. ASTM C1252 specifies determining the G_{sb} of the minus 4.75 mm material and to use this gravity unless some size fractions differ by more than 0.05 from the specific gravity typical of the complete sample. If specific gravity differences exceed 0.05, determine the specific gravity of the individual 2.36 mm to 0.150 mm sizes for use with Method A or the individual size fractions for use with Method B either by direct measurement or by calculation using the specific data on gradings with and without the size fraction of interest. It is also stated that a change in G_{sb} of 0.05 will result in about a 1 percent change in the calculated void content [14]. A change in FAA of one percent is highly significant and may be the difference in meeting or not meeting specification requirements. A more appropriate solution is to determine the G_{sb} on the size fraction being tested. This should substantially improve the accuracy and precision of the FAA test.

Recommendation 5: "Differences will be experienced between the grading of the aggregate components used in the laboratory design of Superpave mixtures and the grading of each aggregate in stockpiles at the asphalt plant. Specifying agencies should allow the contractor to modify the mixture design (adjustment to the aggregate blends) in the field to account for these differences. The ETG should encourage field verification of a mix and adjustment as necessary without penalty, to insure that the mix will perform as designed."

Aggregates can breakdown to varying degrees during shipment from the production facility to the HMA plant site. This breakdown can be attributable to a variety of reasons including aggregate shape and durability, transport type, handling amount, etc. Ideally, the mix designer would use the gradations from the stockpile as it exists on the plant yard. However, in the vast majority of cases the mix design is completed in advance of material delivery. Therefore, with the job mix blend percentages, the blend gradation is likely to deviate from the design blend and will likely result in differences in mix volumetrics. Also, it is likely that the gradation of aggregates used for a given mix will vary between the time the materials were sampled for mix design preparation and the time for production. This will require some level of adjustment by the HMA producer.

Needed Research (9 Recommendations)

Recommendation 1: "The ETG should recommend and promote development of valid performance measures and related tests. A performance measure and test will allow the mix designer to use available aggregates to their best technical advantage to achieve cost effective HMA pavements for each application."

It is disappointing and frustrating that a mix performance test has not been developed and implemented for use in the Superpave system. Whether the test is a "simple" or "complex" performance test, is less of an issue than it being a "good" test that will alleviate the substantial guesswork involved in the design and construction of HMA mixes. As mentioned earlier, this guesswork has lead to increased efforts to characterize aggregate and mixes with varying degrees of success. An HMA performance test should be developed and implemented so HMA can be engineered to meet a certain level of expected performance. For example, not all mixes require a coarse aggregate grading with 100 percent crushed particles. Given a performance test industry and agencies can better optimize mix constituents (asphalt binder, aggregate, etc.) to provide the most economical mix possible given the target application.

Recommendation 2: "Use of the fine aggregate angularity (FAA) test and current FAA acceptance criteria should be reexamined. The ETG should recommend that research be performed on the test method a) to establish the validity and applicability of the method, b) to establish the sensitivity of the method and the results to specific test parameters (size of sample, size of orifice, height of free fall, size of collection cylinder, etc.), and c) to validate current

<u>acceptance criteria. Since 100 percent crushed sands perform well in asphalt mixtures, the ETG should support and recommend acceptance of use of 100 percent crushed, angular, sharp edged aggregate products in Superpave mixtures without a FAA requirement."</u>

The fine aggregate angularity (FAA) test procedure continues to be a major source of debate within the HMA and aggregate industry. In August 2002, a white paper on fine aggregate angularity [15] was presented and discussed at the Superpave Mixtures and Aggregate Expert Task Group (ETG) meeting in Minneapolis. Extensive review of literature pertaining to the fine aggregate test and subsequent performance was conducted. Due to the fact that a separate white paper was prepared specifically for FAA, substantial discussion will be presented from that paper.

Some of the significant conclusions presented in the FAA white paper are given below. Readers are encouraged to review the complete white paper for specific information [15].

1) *ASTM C-1252 test procedure is a poor test for characterizing fine aggregate and the method as currently defined has several shortfalls. Use of uncompacted voids content to measure the properties of shape, grading, and surface texture must be approached with caution.*

2) *Superpave specifications should allow use of 100% crushed fine material irregardless of the FAA value that is measured for the fine aggregate. Some highly cubical fine aggregates will have FAA values just under 43. Some natural fine aggregates will have FAA values above 43. Grading differentiates these materials and is why crushed materials perform well in pavements.*

3) *Superpave technically does not allow fine aggregates with FAA values below 45 to be used in high traffic situations. However, several states waive the FAA requirement altogether, or have reduced FAA acceptance criteria, to permit use of locally available fine aggregates.*

4) *"Shape" of a fine aggregate determined by ASTM C 1252, Method A should not be a basis for acceptance or rejection of fine aggregate since quality mixtures can be made with fine aggregate of many different shapes.*

5) *Standard sample grading used in ASTM C 1252, Method A to determine the FAA value contains no material in the "minus 4.76 mm to 2.36 mm" size fraction, and is therefore not representative of all of the material typically defined as fine aggregate. A more appropriate FAA value can be determined when the minus 4.76 to plus 2.36 size fraction is included in the measurement, or in the calculated FAA value.*

6) *Several factors influence ASTM C 1252 test results. These factors include: sample size, sample drop height, funnel orifice size, and receiving container size. The information derived from ASTM C 1252 needs to be analyzed in conjunction with the results from other tests that isolate surface texture.*

7) *The FAA Test Method does not consistently identify angular, cubical aggregates as high quality aggregates***.** *Cubical shaped particles, especially from impact crushers and even with 100 percent fractured faces, usually will not meet the FAA requirement for high traffic volume. The current Superpave FAA method cannot consistently distinguish between cubical aggregates that perform well and rounded aggregates*

that perform poorly. The method appears to lose the ability to discriminate angularity among aggregates when the uncompacted voids are more than 43 percent.

Recommendations from the white paper were presented as follows:

1) *Eliminate the Superpave FAA requirements for 100 percent crushed aggregate.*

2) *Alternately, recommend that state DOT's modify specifications to permit evaluation of crushed fine aggregates with FAA values less than 45 percent. Currently, the Superpave specifications of some state DOT's prohibit use of fine aggregate with FAA less than 45 percent, and these aggregates are eliminated from further consideration at the mixture design stage. Mixtures made with crushed aggregate should be made and evaluated for mixture performance (using a simple performance test system) and use of the aggregate should be permitted if the mixture passes the mixture performance tests.*

In NCHRP 9-35, Prowell [4] found that 85 percent of surveyed states specified either AASHTO T304 or ASTM C1252 for fine aggregate angularity. While *AASHTO M323 Standard Specification for Superpave Volumetric Mix Design* [16] specifies fine aggregate angularity testing in accordance with AASHTO T304, Method A, five states do not require any test for FAA, but instead place limitations on natural sand ranging from 0 to 15 percent. Texas and California currently use other test procedures in lieu of the FAA test.

Other agencies that specify FAA testing have modified their specifications based on local materials and experience. According to Prowell [4], 49 percent of agencies surveyed did not follow the specifications for FAA set forth in AASHTO M323. Additionally, some agencies continue to maintain different requirements for aggregate blends used in non-wear and wearing surfaces. Also interesting was that 46 percent of the responding state agencies continue to place limitation on natural sand.

Prowell [4] recommended further analyzing aggregate with a FAA below the minimum of 45 percent, but with good field performance under high traffic. One possible test procedure listed for possible use was the compacted aggregate resistance (CAR) test.

<u>Recommendation 3: "The ETG should recommend that the minimum VMA required for a given Superpave design be a function of aggregate grading, not just nominal maximum size of the aggregate."</u>

As mixes become finer within a given nominal maximum aggregate size classification, the amount of intergranular void space and aggregate surface area increases. Coarse and fine-graded mixes with the same VMA will likely have dramatically different film thickness. Therefore, the concept of having VMA requirements as a function of aggregate gradation is one that makes sense.

Recall earlier that the Alabama Department of Transportation (ALDOT) requires all upper binder and wearing layer mixes to be designed either through or on the fine side (above) of the restricted zone [7]. For those mixes, ALDOT requires one percent higher VMA than for mixes designed below the restricted zone (coarse-graded). Whether exactly one percent more VMA is required is not known, but it is ALDOT's belief that fine-graded mixes should require more VMA than coarse-graded mixes.

National Pooled Fund Study No. 176 [17] was conducted to, in part; provide answers to several issues pertaining to the Superpave VMA versus nominal maximum aggregate size relationship. Research concluded that minimum VMA requirements alone are not adequate to delineate between stable and unstable mixes. Minimum VMA requirements for various nominal maximum aggregate sizes are not independent of fine aggregate angularity values. Mixes with fine aggregate having high FAA values generally had higher VMA values. Researchers also concluded mixtures with high FAA values (e.g., 50) did not necessarily perform better in regards to permanent deformation than mixes with typical FAA values (e.g., 44). Authors recommended the use of a typical FAA value for acceptable rutting performance, rather than a very high FAA value, which may lead to an over-asphalted mix and rutting problems.

NCHRP 9-25: Requirements for Voids in Mineral Aggregate for Superpave Mixtures is currently being conducted and is focused on developing recommended mix design VMA criteria. This research is evaluating the influence of mix nominal maximum aggregate size on required VMA.

A separate issue of concern is inconsistency in the methods agencies use to calculate VMA. Some agencies use the aggregate effective specific gravity (G_{se}) while others use the bulk specific gravity (G_{sb}). Prowell [4] reports 89 percent of responding agencies use G_{sb} for VMA calculation with 9 percent using G_{se}. One agency was reported to use the apparent specific gravity (G_{sa}) for VMA calculation. Because of time and testing issues with determining the G_{sb} some agencies determine the G_{se} and back-calculate a G_{sb} through the use of an offset or correction factor. While there are arguments for both sides of the issue, a universally accepted method for VMA calculation should be developed and used.

<u>Recommendation 4: "Proposed limits for flat and elongated particles at 3 to 1 should be thoroughly researched, and the impact of F&E on mixture performance should be determined, prior to a change of Superpave acceptance criteria."</u>

Flat and elongated is a consensus aggregate property that is the characteristic represented by the percentage by weight of coarse aggregates that have a maximum to minimum dimension of greater than five [2]. Superpave specifications in AASHTO M323 [16] specify a maximum of 10 percent flat and elongated particles at a 5:1 ratio. Some states have more stringent flat and elongated specifications. Prowell [4] concluded that seven states specify a 3:1 ratio for flat and elongated, with five states using a 20 percent maximum limit. It was further reported that research has not established a difference in performance of HMA made with aggregate having flat and elongated between 20 and 40 percent 3:1. By definition, consensus aggregate properties were intended to be applied to the proposed aggregate blend, not individual components. However, one state, Virginia, applies the flat and elongated requirement to each coarse aggregate material used in a blend. This can obviously eliminate many aggregate sources which otherwise could be used in varying degrees with other materials to meet the intended consensus source requirement.

In response to proposed modification of the flat and elongated specification requirement from a maximum of 10 percent 5:1 to a maximum of 20 percent 3:1, a large flat and elongated evaluation was undertaken. Under the guidance of David Jahn, at the time employed by Martin Marietta Materials, flat and elongated data from 563 stockpiles representing 15 states were analyzed. Jahn reported that if the flat and elongated specification was changed to 20 percent maximum at 3:1, 52 percent of the stockpiles measured would fail. Jahn concluded based on the study results that modifying the flat and elongated requirement to 20 percent maximum 3:1 would be cost prohibitive to the industry and the consumer. Estimates for plant modifications to modify particle shape ranged from $500,000 to $2 million per plant. This expenditure would obviously decrease the potential for other improvements and lead to increased repair and maintenance cost and ultimately higher aggregate costs [18].

In recent years significant research has been conducted on imaging analyses for determination of aggregate particle shape. Among the promising techniques is the Aggregate Imaging System, which allows for a more detailed particle analysis using three-dimensional quantifying of aggregate particle shape and texture. Imaging is likely the technology of the future for analysis of particle shape as well as HMA mix composition, including particle orientation and packing arrangement. Prowell [4] recommended research be conducted to correlate digital imaging techniques for aggregate angularity, texture, and particle shape to HMA field performance.

Recommendation 5: "Significance of a 2 or 3 percent difference in coarse aggregate crush count (change from 97 to 100 percent) on the performance of Superpave mixtures designed for high traffic levels using a crushed gravel aggregate should be researched."

Extensive literature review by Prowell [4] led to the already known fact that increased fractured faces provide increased rutting resistance. However, the review found little research supporting the need for greater than 95 percent fractured faces. It was stated that 95 percent two crushed faces appear to be a reasonable target for high traffic volume pavements (i.e., greater than 30 million ESALs).

Achieving a very high crushed face percentage with some gravel aggregate can be difficut to impossible. Mississippi DOT is one agency that has recognized this fact. Due to relatively small size of the Mississippi native gravel aggregate, it is almost impossible to achieve 100 percent two crushed faces. Therefore, MDOT specifies a maximum of 90 percent crushed faces for 12.5 mm NMS and smaller mixes [8].

Recommendation 6: "Use of the Superpave criteria of fixed air voids at 4 percent should be carefully reexamined."

While most in the HMA industry would agree that the adoption of Superpave has been successful in reducing rutting, premature cracking has been a significant problem. Some have attributed this cracking to lower asphalt binder contents of Superpave mixes relative to historical mixes. As a result, *NCHRP 9-31: Air Void Requirements for Superpave Mix Design* is currently being conducted to determine how variations in design air void content influences HMA stability and durability performance. The project is being coordinated with *NCHRP 9-25: Requirements for Voids in Mineral Aggregate for Superpave Mixtures.* NCHRP is currently awaiting the final reports from both projects.

In the interim, some agencies are taking steps to increase the asphalt binder content of Superpave mixes. One method of increasing asphalt binder content is to lower the number of design gyrations. Excessive gyrations can result in aggregate breakdown; therefore, some states have investigated a "locking point" concept, which is the number of gyrations required to result in some minimum change in sample height (i.e., density). In Alabama, for example, the "locking point" gyration is the second of two consecutive gyrations with no change in sample height. Alabama DOT has established a minimum design gyration level of 60. If the locking point occurs at less than 60 gyrations, the locking point is 60. Locking points greater than 60 results in that number of gyrations utilized. Locking point utilization has resulted in 0.2 to 0.4 percent higher asphalt binder contents and mixes with less permeability and improved durability [19].

The Virginia DOT utilizes an N_{design} level of 65 gyrations for all Superpave mixes at all traffic levels [20]. Again, this will typically result in slightly higher asphalt binder contents relative to the recommended N_{design} values set forth in AASHTO M323.

Another method being used to increase asphalt binder contents is to lower the design or production air voids from 4 percent. For some mixes, Colorado DOT (CDOT) allows production air voids down to 3 percent with the goal being increased asphalt binder. Reports show increases in asphalt binder from 0.1 to 0.3 percent. Maryland DOT allows design air voids of 3.5 percent which may result in increased binder contents [19].

One important item to note is that research is currently underway to verify the correct N_{design} levels for Superpave mixes. The National Center for Asphalt Technology (NCAT), as part of *NCHRP 9-9(1): Verification of the Gyration Levels in the N_{design} Table*, is conducting an extensive field study of pavements throughout the country to determine relationships between gyration level and traffic. This study will hopefully provide a final answer to the question of what is the N_{design} level for a given traffic level. As a result, caution should be undertaken by agencies in reducing the design or production air voids as the "correct" N_{design} level may not be currently used or known.

<u>Recommendation 7: "Tests for aggregates identified in *NCHRP 4-19 Aggregate Tests Related to Asphalt Concrete Performance in Pavements* should be validated, and the ETG should support and recommend adoption and use of those tests that are valid and relate to pavement performance."</u>

NCHRP 4-19(2) Validation of Performance-Related Tests of Aggregates for Use in Hot-Mix Asphalt Pavements was initiated in March 2000 by Purdue University. The study objective is to validate the recommended aggregate tests from *NCHRP 4-19* and reported in *NCHRP Report 405* [21] through accelerated loading or field research. Research is scheduled to be completed in 2005, but a final report was not available at the time of this paper.

<u>Recommendation 8: "Validity of the moisture sensitivity test, AASHTO T 283, is of concern to aggregate producers and others. The ETG should continue its efforts to support research of this test, or to develop an alternate test that more accurately relates to mixture performance."</u>

The HMA industry has recognized the need for modifications to AASHTO T283 to insure better moisture susceptibility prediction for Superpave mixes. *NCHRP 9-13: Evaluation of Water Sensitivity Tests* was completed in 2000 with the research findings published in *NCHRP Report 444: Compatibility of a Test for Moisture-Induced Damage with Superpave Volumetric Mix Design* [22]. Research focused on evaluating AASHTO T283 with recommendations made to make T283 more compatible with the Superpave system. However, research work was entirely focused on the T283 procedure. Today, many are of the opinion that T283 does not adequately predict HMA moisture susceptibility potential. Therefore, several national studies are currently being conducted evaluating other methodologies for conditioning and moisture susceptibility evaluation.

NCHRP 9-34: Improved Conditioning Procedure for Predicting the Moisture Susceptibility of HMA Pavements is being conducted with the primary objective being development of an improved environmental conditioning procedure system (ECS) for moisture susceptibility evaluation. This conditioning procedure will be used along with the simple performance test (SPT), from *NCHRP 9-19: Superpave Support and Performance Models Management,* for HMA mix design and quality control/assurance testing.

AASHTO T283 and perhaps the ECS with the SPT offer the ability to evaluate, to varying degrees, the moisture susceptibility of HMA mixes. Other research is focusing on the mechanisms of asphalt binder to aggregate bonding through surface energy theory. Surface energy theory consists of determining the surface energy of asphalt binder and aggregate and ultimately the bond strength, as determined by bond energy, in the presence of moisture. *NCHRP Project 9-37 Using Surface Energy Measurements to Select Materials for Asphalt Pavements* is currently being conducted (scheduled completion December 2005) with an objective of developing and validating surface energy measurement methodology for characterization of aggregates, asphalt binders, and additives. The ultimate goal will be to develop the surface energy concept such that it can be used for optimum selection of HMA material constituents.

NCHRP Project 9-37 is a step forward in moisture susceptibility research. Use of past test procedures for moisture susceptibility evaluation have evaluated the end-result HMA mix, many times without clear thought of the constituent interaction. Surface energy and other technologies will hopefully allow users to evaluate different material components in a logical, stepwise, scientifically-based process that will result in a more engineered HMA product.

<u>Recommendation 9: “The ETG should recommend research pertaining to Multiple Ratio Analysis for characterizing aggregate shape. It should also encourage determination of particle shape and then optimum grading, rather than vice versa, to minimize the requirement of a uniform particle shape for all geologic aggregate types. Further, video imaging systems have demonstrated a capacity to readily distinguish aggregate shape and grading changes quickly and accurately.”</u>

Certainly, a distribution of aggregate particle shape instead of one percentage determined at one F&E ratio would better characterize an aggregate for use in HMA. This can possibly be accomplished with multiple ratio analysis (MRA) and/or imaging techniques. Multiple Ratio Analysis (MRA) can be used to define an aggregates shape on five maximum to minimum dimension ratios: less than 2:1, 2:1 to 3:1, 3:1 to 4:1, 4:1 to 5:1 and greater than 5:1. MRA can be used to obtain a more complete view of particle shapes for a given aggregate, not just information at the 5:1 ratio [23].

Imaging analysis work continues to be conducted with promise. Imaging research has been conducted for many years with *NCHRP Projects 4-30 and 4-30A: Test Methods for Characterizing Aggregate Shape, Texture, and Angularity*. *NCHRP 4-30* primary project objective is to develop and test methods for determining aggregate shape, texture, and angularity characteristics that influence HMA performance. In *NCHRP 4-30A* researchers are charged with taking the results from Project 4-30 and developing test methods for particle shape, texture and angularity characteristic determination.

Results of the studies have not been published at this time. Hopefully, a certain particle will not be recommended as the “only” particle shape to use for good performance. Perhaps, imaging analysis could be conducted initially to determine what aggregate shape corresponds to good and bad performance. Then, as mentioned previously, HMA mixes could be engineered to make the best use, if possible, of a wide range of aggregates with varying particle shape and mineralogy.

While the issues presented in the white paper are of critical importance, there are several other issues of importance. Several of these issues are discussed below.

Inconsistent Fine Aggregate Reference

Today differences exist in how agencies reference fine aggregate in their specifications and the size fraction specified for specific gravity determination. Specifications for fine aggregate specific gravity in ASTM and AASHTO only reference the fine aggregate being tested. *AASHTO T84 Specific Gravity and Absorption of Fine Aggregate* [24] specifies in

Section 6.1 to "Obtain approximately one kilogram of the fine aggregate……" *ASTM C128 Standard Test Method for Density, Relative Density, (Specific Gravity), and Absorption of Fine Aggregate* [14] specifies in Section 7 "Sample the aggregate in accordance with Practice D75. Thoroughly mix the sample and reduce it to obtain a test specimen of approximately 1 kilogram."

If one reviews the definitions for fine aggregate provided in ASTM and AASHTO there are some differences. *ASTM C125 Standard Terminology Relating to Concrete and Concrete Aggregates* [14] provides the following fine aggregate definitions and discussion:

> *"(1) aggregate passing the 3/8-inch (9.5 mm) sieve and almost entirely passing the 4.75-mm (No. 4) sieve and predominantly retained on the 75-μm (No. 200) sieve; or (2) that portion of an aggregate passing the 4.75-mm (No. 4) sieve and retained on the 75-μm (No. 200) sieve.*
>
> *Discussion - The definitions are alternatives to be applied under different circumstances. Definition (1) is applied to an entire aggregate either in a natural condition or after processing. Definition (2) is applied to a portion of an aggregate. Requirements for properties and grading should be stated in the specifications."*

AASHTO M29 Standard Specification for Fine Aggregate for Bituminous Paving Mixtures [25] specifies fine aggregate as passing the 9.5 mm (3/8 in.) sieve and almost entirely passing the 4.75 (No. 4) sieve.

Obviously, there is some vagueness in the definitions resulting from the use of "predominantly" and "almost entirely". Furthermore, upon a review of state agency specifications there exist more confusion as given in the following examples. The Alabama DOT [7] defines fine aggregate in their HMA specification as material passing the 4.75 mm (No.

4) sieve; however, bulk specific gravity determination is specified in accordance with AASHTO T84 [24], which defines fine aggregate as passing the 9.5 mm (3/8 in.) sieve. Florida DOT, FM 1-T 084, [26] states to "sieve the material to remove the portion retained on the 4.75 mm (No. 4) sieve. If the fine aggregate contains more than 10 percent of the material retained on the 4.75 mm(No. 4) sieve, separate the material coarser than the 4.75mm (No. 4) sieve, and test the coarser material according to FM 1 T-085 [27] (i.e., coarse aggregate specific gravity test procedure)."

Consistent fine aggregate definitions and specific gravity procedures are needed. Significant misunderstanding and differences in specific gravity determination can result.

Influence of Minus 0.075 mm Material on Specific Gravity and Absorption

One issue of importance stemming from the differences in defining fine aggregate and specifying the size fraction for specific gravity testing is how to handle the minus 0.075 mm (No. 200) material (i.e., dust). AASHTO T84 [24] and ASTM C128 [14] both specifically state that after required covering of the fine aggregate sample with water to "decant excessive water with care to avoid loss of fines." Glass and Rogers [28] showed significant differences in bulk relative density when the fine aggregate was tested with and without the dust present. Specific gravity was found to decrease as the dust content of fine aggregate material increased. Absorption, on the other hand, was found to increase with increased dust content. Differences in G_{sb} for diabase and limestone screenings of 0.106 and 0.085, respectively, were reported. This corresponds to an absorption difference for the two materials of 1.23 and 1.62 percent, respectively. Dust contents for the diabase and limestone screenings were 10.9 and 11.5 percent, respectively. In contrast, sand with 1.1 percent dust was tested and yielded a difference in G_{sb} and absorption of 0.006 and 0.08 percent, respectively. It was concluded that the difference in

G_{sb} and absorption was a function of both the amount and nature of the dust material. Researchers concluded that the dust material form clumps creating "artificial" aggregate particles which have a porosity and density that are not close to that of the parent rock. The authors point out that C128 was developed in the 1930's for concrete sands, and was not intended to be used for fine aggregate with high fines content. It was recommended that for proper measurement of fine aggregate density, dust should be removed by washing prior to testing.

A substantial impact from conducting the specific gravity without the dust present is a higher G_{sb} and thusly a higher voids in the mineral aggregate (VMA). Results, shown in Table 1, [29] clearly indicate substantial increases in G_{sb} and decreases in absorption for screenings and field sand with minus 0.075 mm removed. The 0.075 mm material amounts for the screenings and field sand were 13.4 and 11.1 percent, respectively. As expected, the minus 0.075 mm material had only a slight impact on apparent specific gravity (G_{sa}). Impact of G_{sb} change is further evident in an example VMA calculation using an example HMA mix design blend. This blend utilized 50 percent coarse aggregate, 40 percent screenings, and 10 percent natural sand. With this blend, a VMA change of approximately 1.4 percent (11.8 and 13.2 percent with and without minus 0.075 mm material respectively) would result by using the different blend G_{sb} values (2.638 and 2.680 with and without minus 0.075 mm material, respectively).

TABLE 1 - Aggregate Specific Gravity Comparison Data [29]

Aggregate	Test Fraction	Gsa	Gsb_{ssd}	Gsb	Abs. (%)	% Blend
Sand	Minus 4.75 mm	2.646	2.606	2.582	0.94	10
	4.75 mm x 0.075 mm	2.647	2.631	2.622	0.37	
	Difference	-0.001	-0.025	-0.040	0.57	
Screenings	Minus 4.75 mm	2.788	2.658	2.585	2.82	40
	4.75 mm x 0.075 mm	2.775	2.714	2.679	1.30	
	Difference	0.013	-0.055	-0.093	1.52	
Coarse Agg.	Max Size x 4.75 mm	2.797	2.730	2.694	1.37	50

Aggregate Production and Particle Shape

In NCHRP 9-35, Prowell [4] concludes the aggregate industry is challenged with divergent requirements for particle shapes and that changing the shape of a product for one application may be detrimental to its use for another and/or could change the shape of other products produced at the same time. In the Superpave system, cubical, crushed coarse and fine aggregate are deemed to be "better" aggregates. It is extremely difficult, if not impossible, to have distinctly different particle shapes for coarse and fine aggregate during the same production operation. In many respects, aggregate producers are being asked to do the impossible: provide cubical coarse aggregate while at the same time produce a fine aggregate with a high FAA value. Prowell [4] states that production of cubical coarse aggregate yields more cubical fine aggregate, resulting in lower uncompacted voids. This is an extremely important point because FAA is stated to insure a high degree of internal friction and rutting resistance [2]. However, cubical, crushed particles tend to have lower FAA values than more flat and elongated fine aggregate.

There is no question that particle shape influences HMA mix performance. The obvious question is what particle shape is best? Most research has stated that a cubical, crushed particle will provide the best performance for a given mix. Particle shape influences many mix parameters including shear strength, compactibility, permeability, etc. Additionally, as particles become more cubical for a given gradation, the amount of surface area will be reduced, resulting in lower VMA values.

Aggregate Role in Dynamic Modulus Determination

The “new” Mechanistic-Empirical Pavement Design Guide (M-EPDG), will provide users with the ability to analyze and design pavement structures through a combination of empirical and mechanistic principles. When fully completed, it is hoped this Guide will be adopted by AASHTO as the design guide for the future.

In the Guide, there are three levels of design: levels 1, 2, and 3. Design level selection depends upon several factors, but generally on the desired level of reliability and availability of the required design traffic loading and material characterization inputs. Based on past research, including recent findings from NCHRP 9-19, the dynamic modulus test is considered to be one of the best indicators for rutting and fatigue cracking of HMA mixes. Dynamic modulus is also being considered as the simple performance test method for Superpave mix design. For level 1 designs, dynamic modulus, or complex shear modulus (E*), must be determined for the specific mixes proposed for use. However, for design levels 2 and 3, an empirically determined relationship can be used to estimate E* for the selected HMA mixes [30]. For level 2 and 3 estimation of dynamic modulus, the Witczak Predictive Equation (equation 1 below) will be utilized in the new design guide. This equation has been developed through the testing of hundreds of HMA mixes comprised of a wide range of asphalt binders. [31]

$$\log E^* = -1.249937 + 0.02923\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a$$
$$-0.82208\frac{V_{beff}}{V_{beff}+V_a} + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.00547\rho_{34}}{1+e^{(-0.603313-0.313351\log(f)-0.393532\log(\eta))}} \quad (1)$$

where,

E* = dynamic modulus, 10^5 psi

η = asphalt viscosity at the age and temperature of interest, 10^6 Poise (use of RTFO aged viscosity is recommended for short-term oven aged lab blend mix)

f = loading frequency, Hz

V_a = air void content, percent

V_{beff} = effective asphalt content, % by volume

ρ_{34} = cumulative percent retained on 3/4 in (19 mm) sieve

ρ_{38} = cumulative percent retained on 3/8 in 9.5 mm sieve

ρ_4 = cumulative percent retained on No. 4 (4.75 mm) sieve

ρ_{200} = percent passing No. 200 (0.075 mm) sieve

Inputs to the predictive equation include binder viscosity and volume, mix air voids, and aggregate gradation on four sieves. However, there are no inputs pertaining to any aggregate property required in the Superpave mix design procedure. As developed, the predictive equation is not sensitive to aggregate properties, other than grading.

Birgisson, et al [32] conducted a study for the Florida DOT focused on evaluating the dynamic modulus test for 29 typically used mixes. It was concluded that the dynamic modulus was sensitive to binder viscosity, but was insensitive to changes in aggregate structure for a given asphalt binder. The authors state the dynamic modulus test does not relate to mixture properties that cause rutting. Therefore, it is stated that the dynamic modulus should be used with caution in predicting rutting in HMA mixtures.

Kim [33] evaluated over 40 HMA mixes in North Carolina to develop a database of dynamic modulus results. It was concluded that aggregate source and gradation do not seem to have a significant effect on the HMA dynamic modulus. Furthermore, it is concluded that binder source, binder PG, and asphalt content seem to affect the dynamic modulus. Kim suggests the relatively low strain levels (50 to 75 microstrains) used in the dynamic modulus test are not adequate to determine the effect of aggregate displacement and reorientation. In his words *"the test more or less tickles the mastic"*. A concern is expressed whether the dynamic modulus test alone can be used to predict the rutting performance of HMA mixes because the major factors which influence rutting are also related to the aggregate characteristics.

In Kim's report, separate research by Underwood [34] is referenced. In Underwood's work the influence of anisotropy is evaluated in a variety of testing, including dynamic modulus. Underwood [34] concluded that inherent HMA mix anisotropy did not affect the dynamic modulus results most likely due to the small strains during testing. A further conclusion was that HMA mixes do exhibit different responses in horizontal and vertical directions during compression testing, and that these differences must be accounted for in any permanent deformation model.

Clearly there is an issue with whether the dynamic modulus test captures the aggregate's contribution to performance. Remember, dynamic modulus is one of the key properties selected to characterize HMA mixes, but yet aggregate properties such as coarse and fine aggregate angularity, particle shape, texture, toughness, and soundness are not included in the equation. The question then becomes why are the properties important enough to be evaluated during "mix design", but not influential enough for inclusion in the prediction equation for a major design input for HMA layer thickness design and analysis for the new pavement design guide? The aggregate industry believes this is a question that must be addressed.

Conclusions

The Superpave mix design system represents a significant step forward for the HMA industry. Since inception, Superpave has undergone significant and continued modification. Many changes have been the result of learned experiences and knowledge obtained through research and field experiences. The fact that Superpave has changed does not make it an inferior product, nor does the current system insure success. On the contrary, past and continued evolution is necessary to insure the best HMA mix design system can be obtained. This evolutionary process should not be limited to any one part of the system. If research data or field data suggest that changes or modifications should be made to the system, then the changes must be made. Several important NCHRP research projects will be completed in the near future and may provide supporting evidence for Superpave modification.

Continued specification addition and tightening of specification requirements will not necessarily lead to better performing mixes. Therefore, a reliable performance test for Superpave mix evaluation during design and production must be developed and universally implemented. Steps must be taken to develop Superpave mixes more into "engineered" products to insure the most cost effective mixes are designed and placed. The fact that extensive aggregate property specifications are utilized during design and production of HMA mixes, but similar properties are not used to estimate HMA dynamic modulus and predict HMA performance is a major cause for concern. Why should specifications contain numerous aggregate characterization specifications, while the new flexible pavement design guide predictive equation for dynamic modulus and performance prediction only contains parameters corresponding to aggregate blend gradation, without direct consideration of aggregate angularity, particle shape, hardness, etc?

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