Experimental Testing and Finite-Element Modeling to Evaluate the Effects of Aggregate Angularity on Bituminous Mixture Performance

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Abstract
This study evaluates the effects of aggregate angularity in bituminous mixtures. Previous studies have predominantly focused on the effects of aggregate angularity on the resistance to permanent deformation, while little work has investigated the role of aggregate angularity related to mixture volumetrics and fatigue fracture performance. To investigate the effect of aggregate angularity on mixture performance and characteristics, five mixes with different combinations of coarse and fine aggregate angularity are evaluated by performing the uniaxial static creep test and the indirect tensile fracture energy test. The asphalt pavement analyzer test is also performed with five-year field project mixtures. Fracture energy test results are then incorporated with finite-element simulations of virtual specimens produced to explore the detailed mechanisms of cracking related to the aggregate angularity. Rutting performance test results indicate that higher angularity in the mixture improves rut resistance due to better aggregate interlocking. The overall effect of angularity on the mixtures' resistance to fracture damage is positive because aggregate blends with higher angularity require more binder to meet mix design criteria, which mitigates cracking due to increased viscoelastic energy dissipation from the binder, while angular particles produce a higher stress concentration that results in potential cracks. Finite-element simulations of mixture microstructure support findings from experimental tests.

Keywords: aggregates, asphalts, mixtures, experimentation, aggregate angularity, bituminous mixture, performance, finite-element method, cohesive zone

Introduction

Since aggregates make up between 80% and 90% of the total volume or 94% to 95% of the mass of bituminous paving mixtures, the quality of the aggregate significantly influences pavement performance. Aggregate geometry consists of three independent characteristics, namely, form, angularity (or roundness), and surface texture. Aggregate angularity, which can be defined as the measurement of the sharpness of the corners of a particle, has been recognized as a critical property of bituminous mixtures and is one of the primary aggregate properties described in the Superpave specifications (Witczak et al. 2002). Moreover, angularity is often mentioned as having the potential to influence aggregate and mixture performance through significant interactions with other mixture and material properties. Therefore, the effects of aggregate angularity on mix design characteristics and mixture performance should be appropriately established based on scientific rigor.

Of the various tests for measuring aggregate angularity, the current Superpave mix design method uses the standard "number of fractured faces" testing method (ASTM D5821 2006) for coarse aggregates and the "uncompacted void content" method for fine aggregate (AASHTO 2008). The National Cooperative Highway Research Program (NCHRP) Research Report No. 557 (White et al. 2006) indicates that current Superpave testing to assess coarse aggregate angularity is empirical and has not been directly related to pavement performance. Based on extensive literature reviews and various testing results, the report found that the uncompacted void content in aggregates reasonably predicts the rutting performance of hot-mix asphalt (HMA) mixtures better than the current Superpave angularity testing method [i.e., ASTM D5821 (2006)]. In addition, it was specified that an attempt should be made to suggest appropriate testing methods that are more objective, scientific, and reliable to quantify aggregate angularity. For example, the Aggregate Imaging System (AIMS) has been investigated by numerous state highway agencies and researchers. Based on the analysis of two-dimensional images of aggregates, AIMS characterizes angularity by monitoring the difference in the gradient vector measured at various edge points of the aggregate's image. Interesting correlations have been found between aggregate angularity quantified by AIMS and mixture performance (Masad 2004).

Thus far, a number of studies have been conducted to analyze the effect of aggregate angularity on bituminous mixtures and pavement performance. In their study on the effect of crushed gravel in dense mixtures, Wedding and Gaynor (1961) showed that the use of crushed gravel increased the stability of the asphalt mixture when compared with asphalt mixtures containing uncrushed gravel. Moreover, several studies have indicated that the effect of fine aggregate angularity (FAA) is more significant than that of coarse aggregate an-

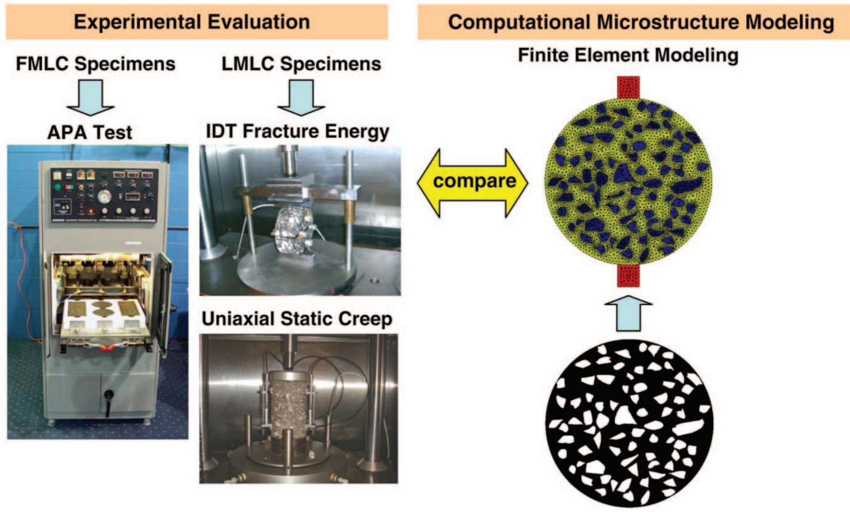

Figure 1. Research method employed for this study (images by L. Souza)

gularity (CAA). Foster (1970) studied the resistance of dense-graded asphalt mixtures by comparing mixes containing different degrees of crushed and uncrushed coarse aggregates. Although pavement test sections showed similar performance results obtained by the mixes with crushed coarse aggregate and those with uncrushed aggregate, the effect of using fine aggregate was more significant. Cross and Purcell (2001) used mixtures containing natural sand and limestone and showed that increased FAA results in improved rutting performance. Stiady et al. (2001) evaluated the effect of FAA using the Purdue Laboratory Wheel Track Device (PURWheel) and showed, based on the evaluation of 21 mixtures, that FAA correlated fairly well with performance, although mixtures produced with an FAA higher than 48% did not necessarily perform better than those with an FAA equal to 45%.

Most of the relevant literature has focused on the effect of aggregate angularity on the resistance to permanent deformation and skid resistance (Mahmoud 2005); however, few studies have examined the role of aggregate angularity related to mixture volumetric characteristics and fatigue fracture performance. Compared to the relatively clear benefit of angular particles in rut resistance, mechanical characteristics and related mechanisms on cracking, such as fatigue damage, are not yet fully understood. Furthermore, conflicting results have been reported regarding the effect of the properties of aggregates on the fatigue life of flexible pavement. For example, Huang and Grisham (1972) reported that the geometric characteristics of coarse aggregates were not significant in the fatigue behavior of asphalt mixtures. By contrast, Maupin (1970) performed a constant strain mode fatigue test and showed that mixtures containing uncrushed gravel yield better fatigue resistance than mixtures containing crushed limestone or slate.

Therefore, a better and more scientific understanding of the effects of aggregate angularity is necessary, given that the minimum angularity requirements for bituminous mix design significantly affect both mix production costs and long-term pavement performance. Thus, the refinement of aggregate angularity criteria is crucial for state highway agencies and pavement/materials contractors.

Study Objectives

The primary objective of this study is to evaluate the effect of aggregate angularity on the mechanical performance and volumetric characteristics of bituminous mixtures. To this end, laboratory test results were incorporated with numerical simulations of mixture microstructure. Specific objectives of this study are the following:

- To conduct appropriate laboratory tests providing performance behavior of asphalt mixtures related to the characteristics of aggregate angularity;
- To pursue a computational microstructure modeling that is capable of better identifying local behavior related to the aggregate angularity of heterogeneous asphalt concrete mixtures; and
- To explore the detailed damage mechanisms related to the aggregate angularity through the integrated experimental-computational approach.

Research Method

Figure 1 briefly illustrates the process of the research method employed for this study. The effect of aggregate angularity on mixture performance was investigated by conducting three laboratory performance tests: the uniaxial static creep test and the indirect tensile (IDT) fracture energy test of five laboratory-mixed, laboratory-compacted (LMLC) mixtures that are designed with five different combinations of coarse and fine aggregate angularity, and the asphalt pavement analyzer (APA) test of various field-mixed, laboratory-compacted (FMLC) mixtures that have been applied to actual asphalt projects paved in Nebraska. Since the APA test has been conducted for field-mixed mixtures, it is limited solely to investigating the effects of aggregate angularity, although useful insights can be found from the APA test results. However, test results from the LMLC mixtures can be used to better identify the mechanical effects of aggregate angularity, since they are artificially manufactured by controlling material types, aggregate gradation, and angularity values to achieve better comparisons between mixtures. The APA specimens have been produced with different aggregate gradations, mixture constituents, and angularity values.

The uniaxial static creep test and the APA test were performed to investigate the rutting resistance of HMA mixtures and the IDT fracture energy test was performed to investigate fatigue resistance. In particular, the IDT fracture energy test employed two different asphalt mixtures: the asphalt concrete mixture to evaluate both CAA and FAA effects and the fine aggregate matrix (FAM) mixture for solely evaluating the effect of FAA. Results from the IDT fracture energy test were

Table 1. Mixtures Used in This Study and Their Volumetric Characteristics

Mixture	Coarse aggregate angularity (%)	Fine aggregate angularity (%)	Air voids (%)	Voids in mineral aggregates (%)	Voids filled with asphalt (%)	Gravimetric binder content (%)	Dust/binder ratio
Laboratory-mixed, laboratory-compacted							
Mix 1	97	45.5	3.7	14.6	74.3	6.0	0.90
Mix 2	90	45.5	4.2	14.4	70.9	5.7	1.02
Mix 3	75	45.5	5.2	14.3	66.7	5.4	1.04
Mix 4	90	43.5	4.1	14.0	70.6	5.0	0.99
Mix 5	75	43.5	4.5	13.8	67.8	4.7	1.05
Required	–	–	4 ± 1	> 14	65–75	–	0.7–1.7
Field-mixed, laboratory-compacted							
SP-2	> 65	> 43	4 ± 1	> 14	65–78	–	0.7–1.7
SP-4S	> 85/80	> 45	4 ± 1	> 14	65–75	–	0.7–1.7
SP-4	> 85/80	> 45	4 ± 1	> 14	65–75	–	0.7–1.7
SP-5	> 95/90	> 45	4 ± 1	> 14	65–75	–	0.7–1.7

then incorporated with microstructure finite-element simulations of virtual specimens that were produced, at least in a qualitative manner, to explore the detailed mechanisms of cracking related to the aggregate angularity. Finally, simulation results were compared with laboratory test results.

Materials, Mixture Design, and Volumetrics

Five types of Superpave mixtures were designed to conduct the IDT fracture energy and uniaxial static creep tests of LMLC specimens. To evaluate the effect of aggregate angularity on the asphalt mixture performance, three CAA values (75%, 90%, and 97%) based on ASTM D5821 (2006) and two typical FAA values (43.5% and 45.5%) based on AASHTO T-304 (2008) were selected to produce five combinations, as presented in Table 1.

The selection of angularity values was based on the analysis of field asphalt pavement projects carried out over the last decade in Nebraska. The chosen values were the most common angularity values used in the field. Each mixture was designed with the same gradation of aggregate blends presented in Figure 2 to find its optimum asphalt content until all volumetric parameters of the mixtures met the required Nebraska Superpave specifications. Aggregate blends with higher angularity typically required more binder to meet mix design criteria. Volumetric parameters of each mix and the required specifications are shown in Table 1.

As presented in Table 1, the five asphalt concrete mixtures were produced to achieve the 4% ±1% air voids requirement, and for that reason, different percentages of binder content were necessary for each mixture. This indicates that two variables, aggregate angularity and binder content, are involved in the analysis of asphalt concrete performance test results, which may mislead the understanding of the pure effect of aggregate angularity on mixture performance. Thus, to obtain mixtures where the same binder content is maintained but different angularity values are applied, two FAM mixtures targeting the two typical FAA values (43.5 and 45.5) were also produced. The FAM mixture is defined herein as the combination of asphalt binder and aggregates passing through sieve no. 16 (mesh size of 1.18 mm). As illustrated in Figure 2, the FAM mixture gradation was obtained from the original mixture gradation shown in the same figure, excluding the aggregates larger than 1.18 mm (i.e., retained on sieve no. 16). Since the FAM mixtures contain only fine aggregates, volumetric characteristics, such as air voids, between two mixtures were not significantly different, even if the same amount of asphalt binder (6.0% in this study) was used. This implies that the effect of FAA on mixture performance can be observed in a much more efficient way than using asphalt concrete mixture results. The amount of binder, 6.0%, was determined as an appropriate value that guarantees complete coating of aggregates with no bleeding on the completion of mixture compaction. As noted earlier and presented later with test results, the FAM mixtures were tested only for the IDT fracture energy in order to enhance understanding of the effects of aggregate angularity on fracture-related performance characteristics.

For the APA test to assess the rutting potential of mixtures with different angularities, four different mix types (designated as SP-2, SP-4, SP-4S, and SP-5) often used for asphalt field projects in Nebraska were considered. SP-2 and SP-4S are mixes used to support low traffic volume. SP-4 is a mix used in pavement for medium traffic volume, while SP-5 is a mix used to support high traffic volume. The number of specimens tested was 11, 90, 24, and 21 for SP-2, SP-4, SP-4S, and SP-5, respectively. Asphalt field mixtures were compacted in the laboratory to produce APA testing specimens, 150 mm in diameter and 50 mm high. This approach might be somewhat limited to provide a direct relationship between the aggregate angularity and the mixture's rutting potential, because many other variables are involved in the process; however, a simple statistical analysis of the APA test results is expected to produce at least some useful insights into the role of aggregate angularities in the mixtures' rutting performance. Table 1 presents the required mixture characteristics and material properties of each mix type considered.

Laboratory Tests and Results

In the uniaxial static creep test, cylindrical specimens were subjected to static axial loads, and the applied stress and strain responses were recorded throughout the test. The test procedure followed was that described in the NCHRP report no. 465 (Witczak et al. 2002). A Superpave gyratory compactor was used to produce the cylindrical samples with a diameter of 150 mm and an approximate height of 170 mm. The samples were then cored and sawn to produce testing specimens with a 100-mm diameter and 150-mm height.

The static creep test was conducted on three replicates of each type of mixture at 60°C. A constant pressure of 207 kPa (30 psi) was applied to the specimens, and the vertical deformation (in compression) was monitored with three linear vari-

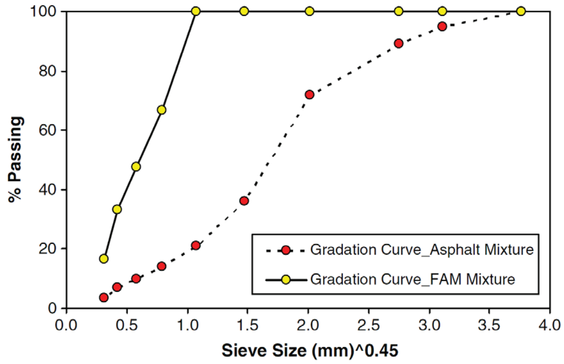

Figure 2. Gradation curves of the asphalt mixtures and the FAM mixtures

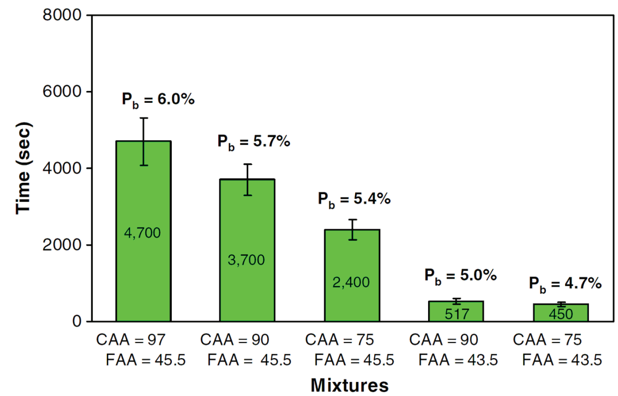

Figure 3. Uniaxial static creep test results

able differential transducers (LVDTs) mounted onto the surface of the specimen at 120° radial intervals with a 100-mm gauge length. The failure point due to plastic flow was determined at the transition stage from secondary creep to tertiary creep. The starting point of the tertiary zone was defined as the flow time and is considered a good evaluation parameter of the rutting resistance of asphalt concrete mixtures. Figure 3 shows the average flow times obtained from three specimens of each mixture and its standard deviation in the form of an error bar. As shown in Figure 3, there was an increasing trend in the resistance to rutting as increasingly angular aggregates were placed in the mixtures. This was an expected phenomenon since higher angularity produces better aggregate interlocking. This improved interlocking can increase the rutting resistance of the asphalt mixtures, as has been indicated in other studies (Wedding and Gaynor 1961; Pan et al. 2005; Huang et al. 2009). The contribution of angular aggregates to rutting resistance becomes even more obvious when the binder content (P_b) of each mixture is considered. As shown in Figure 3, mixtures with higher binder content were more resistant to rutting, which contradicts a typical observation, namely, that the increase of binder content decreases the rutting resistance. Thus, the effect of angular particles is clearly a factor in the resistance of rutting.

In addition to the uniaxial static creep test, the APA test was performed following the AASHTO TP-63 (2007) to assess the rutting potential of the mixtures with different angularities. Asphalt field mixtures were compacted in the laboratory. The hose pressure and wheel load were 690 kPa and 445 N (100 psi and 100 lb), respectively. All tests were performed at 64°C. Figure 4 presents the test results (rut ratio versus number of fractured face in percentage). Instead of using the APA rut depth (in mm), the test results are presented with a different quantity: rut ratio. The rut ratio serves as a replacement for the rut depth and is simply calculated by dividing the total rut depth by the corresponding number of loading cycles and multiplying the obtained value by 100. Rut ratio was employed in this study because the APA test stopped automatically when the wheel loading reached 8,000 cycles before a 12-mm rut depth had been reached or when the total rut depth exceeded 12 mm before 8,000 cycles had passed. Therefore, rut ratio was calculated to provide an identical measure of a mixture's rut potential for any case. The number of fractured face was obtained following the most widely used standard method to date: ASTM D5821 (2006) for quantifying CAA values of aggregate blends.

As can be observed in Figure 4, APA test results generally present a high testing variability, which is due to the fact that many other variables, such as aggregate gradation and properties of mixture constituents, are also involved in the process in addition to the effect of angularity. Consequently, analysis of the APA test results might be somewhat limited to provide a direct relationship between the aggregate angularity and the mixture's rutting potential. However, for all mixtures, the simple linear regression implies that the increase of CAA improved the rutting performance, which supports the results from the uniaxial static creep test.

To evaluate the effects of aggregate angularity on fatigue damage resistance, the IDT test was performed on LMLC specimens. As presented in several studies (Kim et al. 2002; Wen and Kim 2002; Kim and Wen 2002), the IDT test was performed on specimens 100 mm in diameter and 38 mm thick by applying constant crosshead rate loading (0:833 mm=s) to failure at 20°C. Horizontal and vertical strains were measured over a 50-mm gauge length in the center of the specimen on both faces. Test results are plotted in a stress-strain curve, where the fracture energy can be calculated as the area under the stress-strain curve until peak stress. Kim et al. (2002) have shown that fracture energy can be a good indicator for field performance. In their study, the ranking of the mixtures with respect to this parameter agreed with that of the mixtures in the field, with respect to the percentage of fatigue cracking. They validated the use of fracture energy by testing actual pavement cores; that is, the field-mixed-field compacted specimens and fracture energy were able to distinguish between the performance of mixtures with different gradations, asphalt contents, and air void contents. Based on these observations, the IDT test was employed in the present study. In addition, the IDT test is easy to perform and can significantly reduce testing efforts. Typical fatigue tests require long testing times, and test results are usually not repeatable.

Figure 5 presents test results with average fracture energy and its standard deviation (in the form of an error bar) obtained from three replicates of each mixture with the binder content (P_b) for each mixture. As can be seen in Figure 5, mixtures with a higher CAA value produced greater fracture energy, which corresponds to their better resistance to fatigue cracking. In addition, mixtures with different FAA values but the same CAA value showed similar values of fracture energy.

Since two variables (binder content and aggregate angularity) are involved in the test, both variables can affect test results. It is generally known that an increase in the binder content of a mixture increases the mixture's fatigue resistance (Epps et al. 1998) because the binder helps dissipate viscoelastic energy, which results in the stress relaxation of the mixture. On the other hand, the presence of angular particles in the mixture may result in higher stress concentration at the sharp corner of particles than mixtures with round-shaped particles. This has been observed from many other particulate composites including cement concrete mixtures.

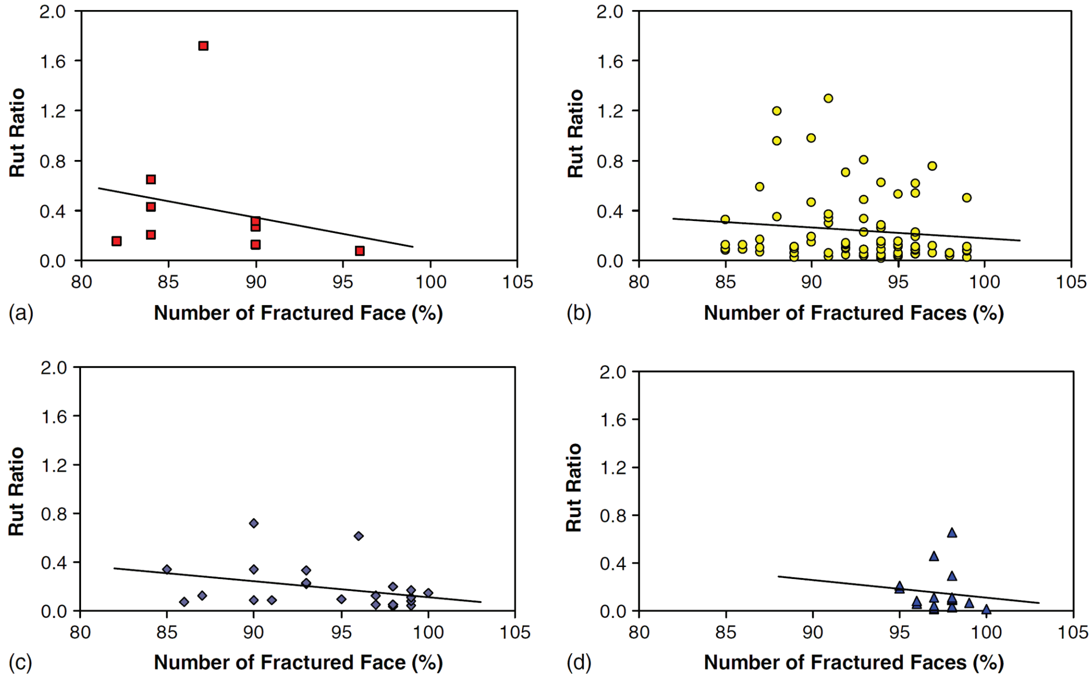

Figure 4. APA test results: (a) SP-2; (b) SP-4; (c) SP-4S; (d) SP-5

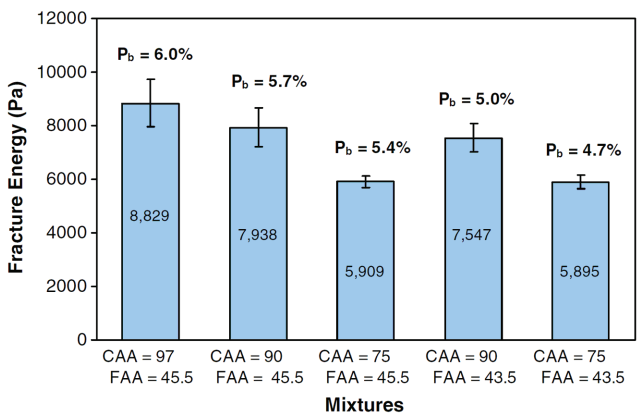

Figure 5. IDT fracture energy test results from asphalt concrete specimens

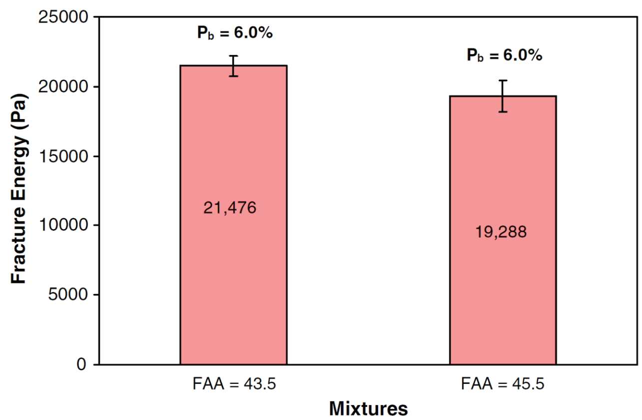

Figure 6. IDT fracture energy test results from FAM specimens

From the results of the IDT test for the mixtures with different CAA values but identical FAA values, the effect of CAA on mixture fracture potential is somewhat unclear to identify, since the test results are related with two variables (angularity and binder content). Although it is premature to make any definite conclusions at this time with the limited test results, it can still be inferred from the figure that the role of the binder might be more significant than the effect of the CAA, which is in good agreement with a study by Huang and Grisham (1972). They found that the geometric characteristics of coarse aggregates were not significant in the fatigue behavior of asphalt mixtures. However, further investigation and supporting test results are needed to fully verify this finding.

As for FAA, an examination of the mixtures with identical CAA values but different FAA values in Figure 5 shows that the effect of FAA was equivalent but opposite to that of the binder content, which resulted in similar fracture energy between the mixtures. To further investigate the aforementioned inference, the IDT test was performed with FAM mixture specimens to analyze only the effect of angularity. The FAM was produced by mixing aggregate particles less than 1.18 mm. Two matrix mixtures with different FAA values (43.5% and 45.5%) but the same amount of binder content were produced for comparison. Since the matrix mixtures were very dense, varying the angularity did not significantly alter the internal volumetric characteristics even when the same amount of binder (6.0%) was used. Three specimens of each mixture were tested, and test results are presented in Figure 6. As can be seen in the figure, the inference can be supported to a certain extent, as higher angularity increases potential cracking due to stress concentration around the particles.

Finite-Element Modeling of IDT Fracture Testing

Some visible findings and related inferences as described in the previous section were obtained from the results of the indirect tensile test that used two types of asphalt mixture (asphalt concrete and fine aggregate matrix); however, the global

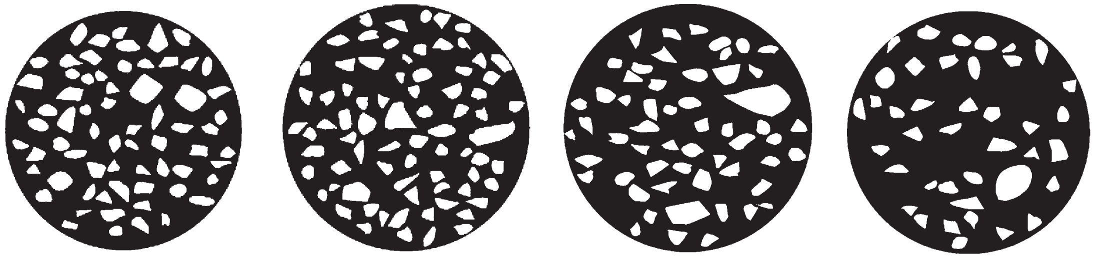

Figure 7. Virtual IDT specimens produced by the virtual microstructure generator: (a) 2,633 AIMS and 75% V_b; (b) 2,935 AIMS and 75% V_b; (c) 2,935 AIMS and 80% V_b; (d) 2,935 AIMS and 85% V_b

behavior observed from the laboratory test was not sufficient to address the detailed local events occurring in the specimens. Angularity, a material-level (aggregate) design variable, is one of the critical properties of bituminous mixtures and is regarded as having the potential to influence mixture performance through a significant level of interactions with other materials such as binders. Thus, the effects of aggregate angularity on mixture performance would be better identified by certain approaches that can provide insights into detailed local behavior and interactions among materials.

Recently, a microstructure-based computational modeling approach has been actively pursued to account for the effects of individual mixture constituents (e.g., aggregates and asphalt binder) on overall mixture performance. Some studies (Masad et al. 2001; Papagiannakis et al. 2002; Dai and You 2008) have proposed finite-element (FE) method-based models to characterize the damage performance of asphaltic composites. The discrete-element method (DEM), an explicit numerical technique, has also been employed by several researchers (Abbas and Shenoy 2005; You and Buttlar 2006; You et al. 2009). These computational approaches allow engineers to better understand the mechanical effects of small-scale design variables (such as asphalt mastic film thickness, air voids in the mixture, size/shape/distribution of aggregates, mineral additives in the mixture, volume fraction of asphalt mastics, etc.) on overall damage-associated responses and the lifetimes of mixtures.

To this end, the microstructure FE simulation was conducted in this study to investigate in greater detail the effect of angularity on asphalt mixture fatigue performance. Modeling and simulations were carried out using an in-house code that has been employed to model various composite materials and structures (Kim et al. 2006a, 2006b, 2007). The code is based on the FE method and incorporates elasticity, viscoelasticity, and nonlinear fracture. Since asphalt mixtures consist of elastic aggregates and viscoelastic asphalt and typically present nonlinear viscoelastic fracture, all of these features are essentially necessary for the modeling of asphalt mixtures. The IDT fracture energy test was simulated using this code. The same loading condition (a constant displacement rate of 0:833 mm=s) was applied to all modeled specimens.

To accomplish microstructure FE modeling, it is necessary to construct and mesh the internal microstructure of the specimen. For this study, the inner microstructure of the specimens was artificially generated by a newly developed virtual microstructure generator (Souza 2009). Due to its virtual mixture fabrication and laboratory testing, the virtual microstructure generator allows the experimental effort to be considerably reduced. The current working (beta) version of the virtual microstructure generator can produce the microstructure of mixtures with known basic geometric properties of aggregates (i.e., gradation, angularity, elongation, and orientation) and mixture volumetric parameters (such as volume fraction of each phase). In particular, the angularity characteristic is controlled by its input aggregate imaging system (AIMS) value. AIMS is an automated system used to characterize geometric properties of aggregates. Angularity (both CAA and FAA) is one of the geometric properties obtained from AIMS by monitoring the difference in the gradient vector measured at various edge points of two-dimensional images of aggregate particles. Consequently, angularity values quantified by AIMS are strongly related to other angularity measurements obtained from different approaches such as ASTM D5821 (2006) for CAA and AASHTO T-304 (2008) for FAA. The virtual microstructure generator has been validated as far as its capability to address the various geometric factors (virtual microstructure generator inputs) by comparing its produced artificial microstructures and actual microstructures obtained from digital images of asphalt concrete cross sections (Souza 2009).

In an attempt to incorporate laboratory test results, four virtual IDT specimens were generated, as presented in Figure 7. It should be noted that the virtual specimens considered for this study present very simple mixture microstructures that do not represent actual asphalt concrete microstructure, which is extremely complicated, since the purpose of the simulation was only to capture the qualitative effects of the angularity and volume fraction of individual phases with a reasonable amount of simulation time and efforts.

The first specimen [Figure 7(a)] was generated with an angularity value of 2,633 (in AIMS), while the second specimen [Figure 7(b)] targeted a higher angularity (2,935). Aside from angularity, all other variables stayed the same so that simulation comparisons between two specimens would purely produce the effect of aggregate angularity on cracking behavior. To evaluate the effect of binder content, the third [Figure 7(c)] and fourth [Figure 7(d)] specimens were generated by varying their binder volume fraction (V_b) to 80% and 85%, respectively, but keeping the angularity constant (2,935 in AIMS) in the second specimen.

Triangular elements were used for the FE meshing, as exemplified in Figure 8 [FE meshing of Figure 7(b)]. It can be noted that a higher degree of refinement was intended around the aggregates to capture more accurately any detailed mechanical behavior related to angularity. In addition, studies of mesh and time step convergence were performed to minimize numerical errors. Analysis results indicate that a time step of 0.01 s and a mesh with 15,000 elements were adequate to guarantee a reasonable degree of convergence.

Figure 8 also presents the constitutive relationship of each phase for the FE modeling. As shown in the figure, aggregates and metal blocks (loading strips) were modeled as linear elastic materials. The linear elastic constitutive relationship can be

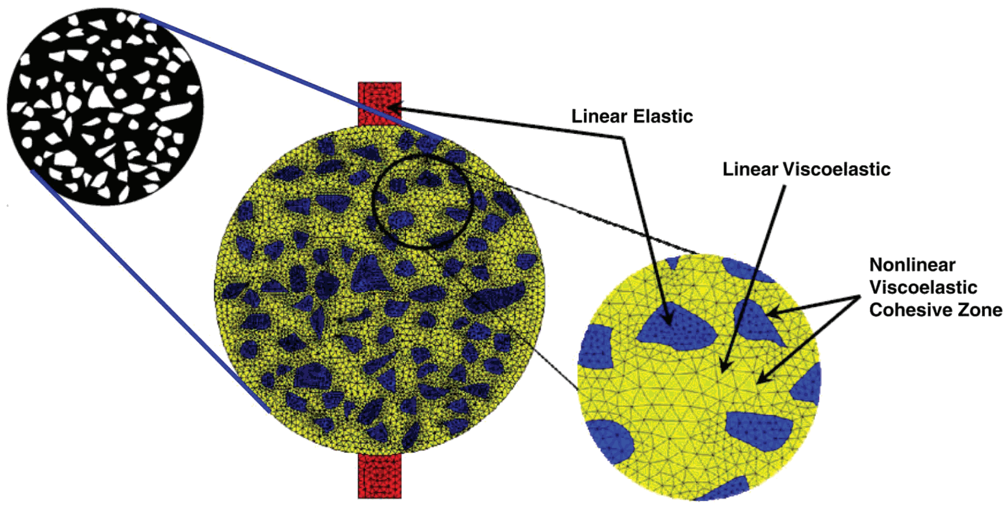

Figure 8. Finite-element mesh of the virtual specimen (2,935 in AIMS and 75% V_b)

expressed as

$$\sigma_{ij}(x_m, t) = C_{ijkl;E}\,\varepsilon_{kl}(x_m, t) \qquad (1)$$

where $\sigma_{ij}(x_m, t)$ = stress as a function of space and time; $\varepsilon_{kl}(x_m, t)$ = strain as a function of space and time; $C_{ijkl;E}$ = elastic modulus, which is not time-dependent; x_m = spatial coordinates; and t = time of interest.

The time-independent elastic modulus consists of elastic material properties. If the individual particle of aggregates and the metal loading strips are assumed to follow simply isotropic linear elastic behavior, only two independent material constants among Young's modulus (E), shear modulus (G), and Poisson's ratio (ν) are required.

The constitutive behavior of the asphalt phase surrounding aggregates can often be represented by the following linear viscoelastic convolution integral:

$$\sigma_{ij}(x_m, t) = \int_0^t C_{ijkl,VE}(t-\tau)\frac{\partial \varepsilon_{kl}(x_m, \tau)}{\partial \tau}d\tau \qquad (2)$$

where $C_{ijkl;VE}(t)$ = linear viscoelastic time-dependent stress relaxation modulus and τ = time-history integration variable.

The linear viscoelastic relaxation modulus of the asphalt phase is often represented by a mathematical form such as a Prony series based on the generalized Maxwell model. The linear viscoelastic stress relaxation modulus by a Prony series can be expressed as

$$C_{ijkl,VE}(t) = C_{ijkl,\infty} + \sum_{p=1}^{q} C_{ijkl,p}\exp\left(-\frac{t}{\rho_{ijkl,p}}\right) \qquad (3)$$

where $C_{ijkl;\infty}$ and $C_{ijkl;p}$ = spring constants in the generalized Maxwell model, $\rho_{ijkl;p}$ = relaxation times in the generalized Maxwell model, and q = the number of dashpots in the generalized Maxwell model.

To simulate cracking and fracture failure, the cohesive zone concept was implemented in the modeling. Fracture behavior can be modeled in many different ways, and one of the well-known approaches is to use the cohesive zone. Cohesive zone approaches regard fracture as a gradual phenomenon in which separation takes place across an extended crack tip, or cohesive zone (fracture process zone), and where the fracture is resisted by cohesive tractions. Cohesive zone models are well-established tools in classic fracture mechanics developed

Table 2. Material Properties Used for the Finite-Element Simulations

Properties of materials (intact state)				
Elastic aggregates		Asphalt phase and Cohesive zone		
E (GPa)	55.2		ν	0.35
ν	0.15	p	E_p (MPa)	ρ_p (sec)
		∞	3.51E +01	—
Elastic metal strips		1	1.23E +03	3.00E −05
E (GPa)	200	2	2.11E +03	3.00E −04
ν	0.29	3	2.00E +03	3.00E −03
		4	1.26E +03	3.00E −02
		5	3.45E +02	3.00E −01
		6	1.13E +02	3.00E +00
		7	3.91E +01	3.00E +01
		8	1.73E +01	3.00E +02
Fracture properties (cohesive zone parameters of asphalt and asphalt-aggregate interface)				
δ_n (m)			0.01	
δ_t (m)			0.01	
Σ_n (MPa)			2.0	
Σ_t (MPa)			15.0	
A			50E +05	
m			2.0	

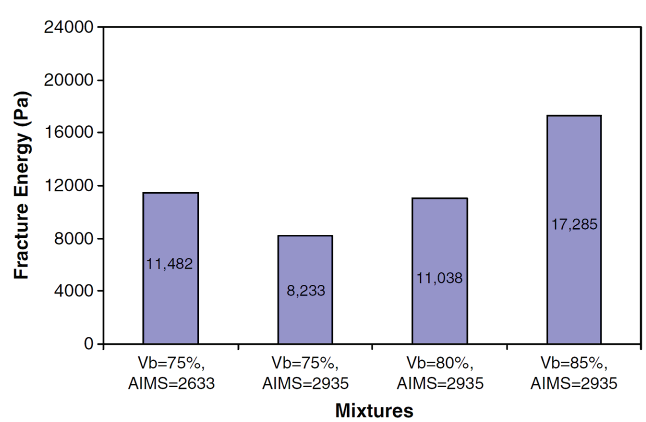

Figure 9. Finite-element simulation results of the IDT fracture energy test

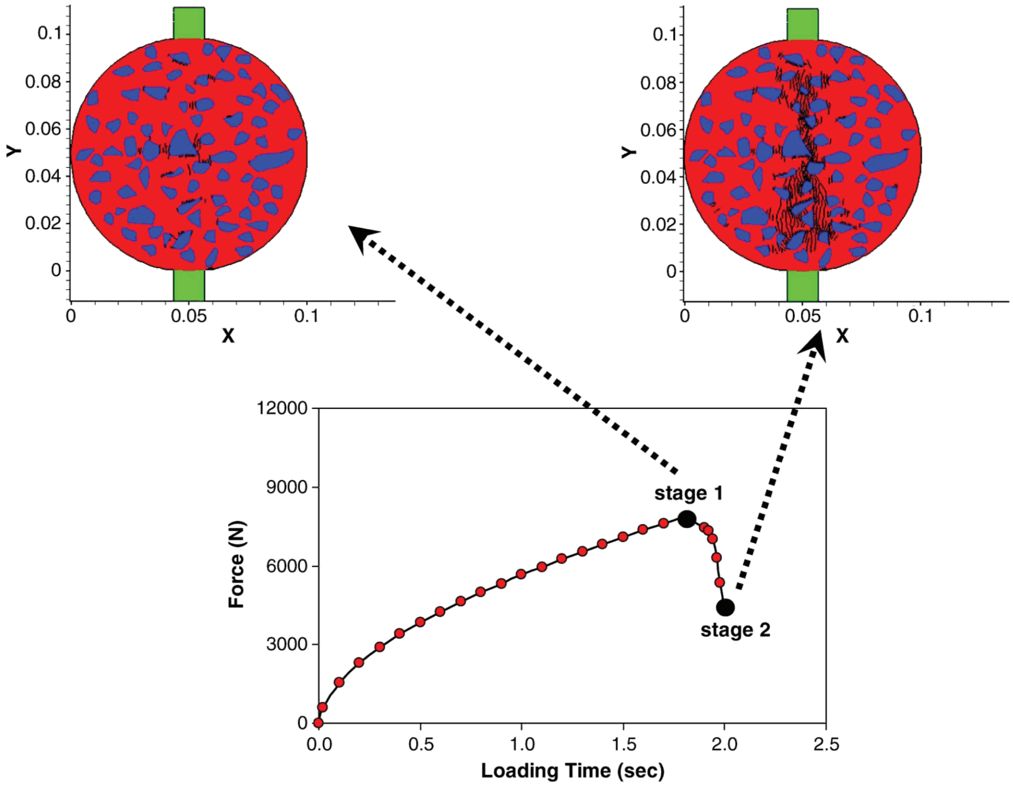

Figure 10. Deformation and crack growth simulation of the specimen [shown in Figure 7(b)]

to remove stress singularities ahead of crack tips. Recently, the cohesive zone concept has been employed in several studies, most of which attempted to simulate crack-associated fracture damage of asphalt concrete mixtures (Song et al. 2006; Kim et al. 2007). Among the various cohesive zone models available, the present study used a cohesive zone model developed by Allen and Searcy (2001), because the model can reflect nonlinear viscoelastic damage growth in the asphalt mixtures. Furthermore, the model can predict damage evolution, microcracking, corresponding postpeak material softening, and eventual fracture failure of highly inelastic asphalt mixtures. The general two-dimensional traction-displacement relationship for the nonlinear viscoelastic cohesive zone model is as follows (Allen and Searcy 2001):

$$T_i(t) = \frac{1}{\lambda(t)} \cdot \frac{u_i(t)}{\delta_i} \cdot [1-\alpha(t)] \cdot \left[\Sigma_i + \int_0^t E^c(t-\tau)\frac{\partial \lambda(\tau)}{\partial \tau} d\tau\right] \quad (4)$$

where i = n (normal) or t (tangential); T_i = cohesive zone traction; u_i = cohesive zone displacement; δ_i = cohesive zone material length parameter; $\lambda(t)$ = Euclidean norm of cohesive zone displacements, which is $[(u_n/\delta_n)^2 + (u_t/\delta_t)^2]^{1/2}$; $\alpha(t)$ = microscale damage evolution function; Σ_i = requisite stress level to initiate cohesive zone; and $E^c(t)$ = stress relaxation modulus of the cohesive zone.

As presented in Equation (4), the cohesive zone damage evolution is characterized by the internal state variable, $\alpha(t)$. It can be noted from Equation (4) that when $\alpha(t)$ reaches the value of unity, the crack face traction decays to zero, thus resulting in crack extension. The damage evolution law can be determined by performing fracture tests to represent the locally averaged cross-sectional area of damaged material in a cohesive zone. Alternatively, a phenomenological form of the damage evolution can also be employed to represent rate-dependent fracture. In this study, the following simple phenomenological form has been selected, since it is sufficient to evaluate mixtures designed with different aggregate angularities. Parameters A and m are microscale phenomenological material constants that govern damage evolution behavior

$$\dot{\alpha} = A[\lambda(t)]^m, \quad \text{when } \dot{\lambda} > 0 \text{ and } \alpha < 1 \quad (5)$$

$$\dot{\alpha} = 0, \quad \text{when } \dot{\lambda} \leq 0 \text{ or } \alpha = 1 \quad (6)$$

Cohesive zones are placed between continuum elements to represent the progressive separation of a material. The cohesive zone effectively describes the material resistance when material elements are being displaced. In this study, cohesive zone elements were embedded within asphalt phase elements and along boundaries between aggregates and asphalt. No cracking was allowed inside the aggregates. As for the simulation, the material properties of each phase have been reasonably assumed and/or obtained by referring to previous studies (Kim et al. 2006a, 2006b, 2007), since the purpose of the simulation was only to capture the qualitative effects of the angularity and volume fraction of each phase. Table 2 presents material properties used for the FE modeling.

Model Simulation Results and Discussion

Simulation results are presented in Figure 9 in the form of a bar chart representing fracture energy. The fracture energy of each specimen was calculated from stress-strain curves predicted by the model. As shown in the figure, fracture energy increased as the angularity of the mixture decreased and the asphalt content increased. This is consistent with the IDT test results, as asphalt content positively affects a mixture's fatigue

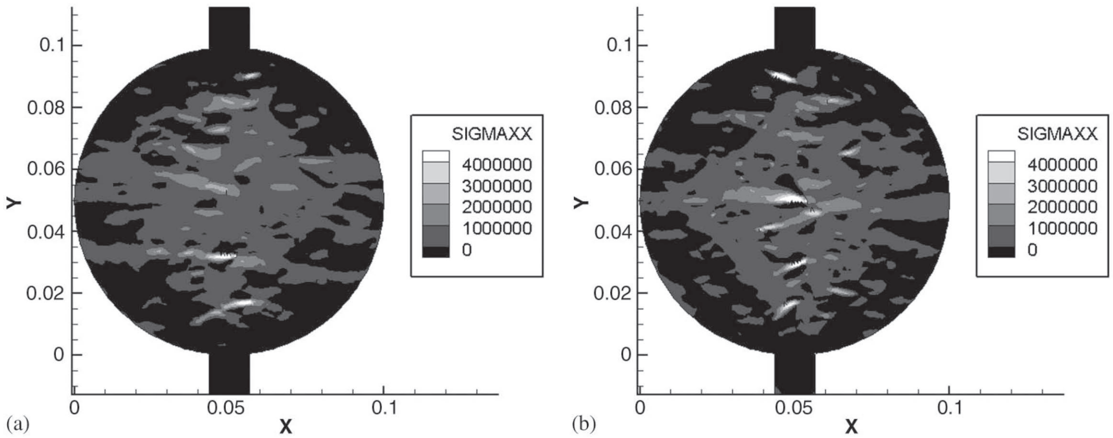

Figure 11. Comparison of elemental stress contour plots: (a) specimen shown in Figure 7(a); (b) specimen shown in Figure 7(b)

resistance, while angularity lowers resistance to cracking due to sharp corners that cause higher stress concentration.

Figure 10 shows the deformation of the specimen [Figure 7(b)] and the adaptive insertion of cohesive zones (crack initiation and growth) that are represented by solid lines in the specimen at two different loading stages (at the peak force and near failure) selected from the force-time curve. Clearly, the deformation of the specimen is increasing due to the accumulated viscoelastic elemental deformation and material cracking. Some cracks develop within the asphalt phase, and others are located at the boundaries between the aggregate and asphalt phases. Further loading after the occurrence of peak force illustrates the development of numerous macrocracks in the specimen, which can be observed by the large decrease in load-bearing capacity.

Along with the result shown in Figure 9, the elemental stress contour plots in Figure 11 confirm the inferences made from the laboratory IDT test, namely, that the sharper corners of the higher angularity aggregates tend to concentrate stresses, thus yielding crack formation and propagation at earlier stages. Figure 11 gives a comparison of the stress contour plots between two specimens [Figures 7(a) & 7(b)] at the same loading level. As can be observed, the specimen with higher angularity presents a higher intensity of stress concentration (represented in lighter color), which results in lower fracture energy (see Figure 9).

Summary and Conclusions

This study investigated the effect of aggregate angularity on rutting and fatigue performance through experimental tests and microstructure finite-element simulations. Based on this study, the following summary and conclusions can be made:

- The analysis of rutting performance showed the same trend in the static creep test and the APA test. That is, increased CAA and FAA in a mixture improved the mixture's resistance to rutting.
- Test results and analyses of fatigue performance data allowed the inference that CAA produces a less significant effect in the fatigue fracture behavior of asphalt mixtures than binder content, while FAA produces an almost equivalent but opposite effect to that of binder content. However, it is premature to make any definite conclusions with the limited test results obtained from this study. Further investigation with supporting test results would be necessary to fully verify the observation and inference.
- The effect of FAA on fatigue fracture performance could further be evaluated with the test results using FAM mixtures. The increase in FAA was observed to decrease the mixture's resistance to cracking.
- Experimental results were supported by microstructure finite-element simulations, which intended to investigate in greater detail the effect of microstructure characteristics on fatigue fracture performance of entire asphalt mixtures. The use of the virtual specimens produced by varying angularities and asphalt volume fractions demonstrated clear effects of mixture components and interactions among components on the overall fracture-related mixture performance.
- Model simulations and experimental results indicate that the asphalt binder content positively affects mixture fatigue resistance, while angularity lowers resistance to cracking due to sharp corners, which cause a higher stress concentration.
- Although angular particles develop a higher stress concentration, which can result in cracks, the overall effect of angularity on the mixtures' resistance to fatigue damage is positive in practice, because aggregate blends with higher angularity typically require more binder to meet mix design criteria. Consequently, thicker binder films in the mixture mitigate cracking due to increased viscoelastic energy dissipation from the binder.

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References

AASHTO. (2007). "Standard method of test for determining the rutting susceptibility of asphalt paving mixtures using the asphalt pavement analyzer (APA)." *AASHTO TP-63*, Washington, DC.

AASHTO. (2008). "Standard method of test for uncompacted void content of fine aggregate." *AASHTO T304*, Washington, DC.

Abbas, A. M., and Shenoy, A. (2005). "Modelling asphalt mastic stiffness using discrete element analysis and micromechanics-based modes." *Int. J. Pavement Eng.*, 6(2), 137–146.

Allen, D. H., and Searcy, C. R. (2001). "A micromechanical model for a viscoelastic cohesive zone." *Int. J. Fract.*, 107(2), 159–176.

ASTM. (2006). "Standard test method for determining the percentage of fractured particles in coarse aggregate." *ASTM D5821*, West Conshohocken, PA.

Cross, S. A., and Purcell, E. M. (2001). "Effects of fine aggregate angularity on VMA and rutting of Kansas HMA mixtures." *ASTM STP 1412*, West Conshohocken, PA.

Dai, Q., and You, Z. (2008). "Micromechanical finite element framework for predicting viscoelastic properties of asphalt mixtures." *Mater. Struct.*, 41(6), 1025–1037.

Epps, J. et al. (1998). "Performance of HMA test sections at WesTrack." *J. Assoc. Asphalt Paving Technol.*, 67, 738–782.

Foster, C. R. (1970). "Dominant effect of fine aggregate on strength of dense-graded asphalt mixes." *Special Rep. 109*, Highway Research Board, National Research Council, Washington, DC, 1–3.

Huang, B., Chen, X., Shu, X., Masad, E., and Mahmoud, E. (2009). "Effects of coarse aggregate angularity and asphalt binder on laboratory-measured permanent deformation properties of HMA." *Int. J. Pavement Eng.*, 10(1), 19–28.

Huang, E. Y., and Grisham, D. A. (1972). "Effect of geometric characteristics of aggregates on the fatigue response of bituminous paving mixtures." *ASTM STP 508*, West Conshohocken, PA.

Kim, Y., Allen, D. H., and Seidel, G. D. (2006a). "Damage-induced modeling of elastic-viscoelastic randomly oriented particulate composites." *J. Eng. Mater. Technol.*, 128(1), 18–27.

Kim, Y., Allen, D. H., and Little, D. N. (2006b). "Computational model to predict fatigue damage behavior of asphalt mixtures under cyclic loading." *Transportation Research Record 1970*, Transportation Research Board, Washington, DC, 196–206.

Kim, Y., Allen, D. H., and Little, D. N. (2007). "Computational constitutive model for predicting nonlinear viscoelastic damage and fracture failure of asphalt concrete mixtures." *Int. J. Geomech.*, 7(2), 102–110.

Kim, Y. R., Daniel, J., and Wen, H. (2002). "Fatigue performance evaluation of WesTrack asphalt mixtures using viscoelastic continuum damage approach." *Final Rep. No. FHWA/NC/2002-004*, Federal Highway Administration, Washington, DC.

Kim, Y. R., and Wen, H. (2002). "Fracture energy from indirect tension testing." *J. Assoc. Asphalt Paving Technol.*, 71, 779–793.

Mahmoud, E. M. (2005). "Development of experimental methods for the evaluation of aggregate resistance to polishing, abrasion, and breakage." M.S. thesis, Texas A&M Univ., College Station, TX.

Masad, E. A. (2004). "Aggregate imaging system (AIMS): Basics and applications." *TTI Rep. 5-1707-01-1*, Texas Transportation Institute, College Station, TX.

Masad, E., Niranjanan, S., Bahia, H., and Kose, S. (2001). "Modeling and experimental measurements of localized strain distribution in asphalt mixes." *J. Transp. Eng.*, 127(6), 477–485.

Maupin, G. W. (1970). "Effect of particle shape and surface texture on the fatigue behavior of asphalt concrete." *Highway Research Record 313*, Highway Research Board, National Research Council, Washington, DC.

Pan, T., Tutumluer, E., and Carpenter, S. H. (2005). "Effect of coarse aggregate morphology on the resilient modulus of hot-mix asphalt." *Transportation Research Record, 1929*, 1–9.

Papagiannakis, A. T., Abbas, A., and Masad, E. (2002). "Micromechanical analysis of viscoelastic properties of asphalt concretes." *Transportation Research Record 1789*, Transportation Research Board, Washington, DC, 113–120.

Song, S. H., Paulino, G. H., and Buttlar, W. G. (2006). "Simulation of crack propagation in asphalt concrete using an intrinsic cohesive zone model." *J. Eng. Mech.*, 132(11), 1215–1223.

Souza, L. T. (2009). "Investigation of aggregate angularity effects on asphalt concrete mixture performance using experimental and virtual asphalt samples." M.S. thesis, Univ. of Nebraska, Lincoln, NE.

Stiady, J., Hand, A., and White, T. (2001). "Quantifying contribution of aggregate characteristics to HMA performance using PURWheel laboratory tracking device." *ASTM STP 1412*, West Conshohocken, PA.

Wedding, P. A., and Gaynor, R. D. (1961). "The effects of using crushed gravel as the coarse and fine aggregate in dense graded bituminous mixtures." *Proc., Association of Asphalt Paving Technologists*, Vol. 30, St. Paul, MN, 469–492.

Wen, H., and Kim, Y. R. (2002). "Simple performance test for fatigue cracking and validation with WesTrack mixtures." *Transportation Research Record 1789*, Transportation Research Board, Washington, DC, 66–72.

White, T. D., Haddock, J. E., and Rismantojo, E. (2006). "Aggregate tests for hot-mix asphalt mixtures used in pavements." *NCHRP Rep. 557*, National Cooperative Highway Research Program, National Research Council, Washington, DC.

Witczak, M. W., Kaloush, K., Pellinen, T., Basyouny, M. E., and Quintus, H. V. (2002). "Simple performance test for superpave mix design." *NCHRP Rep. 465*, National Cooperative Highway Research Program, National Research Council, Washington, DC.

You, Z., Adhikari, S., and Kutay, M. E. (2009). "Dynamic modulus simulation of the asphalt concrete using the X-ray computed tomography images." *Mater. Struct.*, 42(5), 617–630.

You, Z., and Buttlar, W. G. (2006). "Micromechanical modeling approach to predict compressive dynamic moduli of asphalt mixtures using the distinct element method." *Transportation Research Record 1970*, Transportation Research Board, Washington, DC, 73–83.