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Disruption factor of asphalt mixtures

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Disruption factor of asphalt mixtures

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Typically, aggregate gradation is selected to meet Superpave mix design specification; however, many Superpave mixtures have exhibited deficient field performance. The porosity of the dominant aggregate size range (DASR), which is the primary structural network of aggregates, has been extensively validated as a tool to evaluate coarse aggregate structure of laboratory and field asphalt mixtures. Mixtures identified by the system as having poor or marginal gradations resulted in poor rutting resistance. This study focused on how asphalt mixture performance is affected by changes in interstitial component (IC), which is the material between DASR particles. Laboratory testing clearly showed that IC characteristics may have a significant effect on rutting and cracking performance of mixtures. The disruption factor (DF) was developed to evaluate the potential of IC aggregates to disrupt the DASR structure. DF satisfactorily distinguished poor performing mixtures; therefore, it may eventually be used in combination with DASR porosity as a design parameter for rutting and cracking resistant asphalt mixtures.

Keywords: aggregate; gradation; asphalt; DASR; disruption; performance

1. Introduction

1.1 *Background*

Roque *et al.* (2006) established a theoretical approach to evaluate coarse aggregate structure based on packing theory and particle size distribution. They developed a physical model to describe an asphalt mixture in terms of two basic constituents: dominant aggregate size range (DASR), which is the primary structural network of aggregates, and interstitial component (IC), which includes particle sizes smaller than the DASR and binder; the volume of IC was referred to as the interstitial volume (IV). They also concluded that the porosity of DASR is a key parameter to correlate aggregate structure and rutting performance of asphalt mixtures.

Kim *et al.* (2006) presented the methodology for identification and assessment of DASR. The DASR porosity criterion has been extensively validated as a tool for predicting rutting performance of laboratory and field asphalt mixtures (Roque *et al.* 2006, Denneman *et al.* 2007, Kim *et al.* 2008, 2009, Steyn *et al.* 2008, Greene *et al.* 2011). Roque *et al.* (2006) also found that DASR porosity may be linked to Hot Mix Asphalt (HMA) cracking performance.

Even though, laboratory results and field data clearly indicated that mixtures identified by the DASR porosity criterion as having poor or marginal gradations resulted in poor rutting performance; there is still a strong need to better understand the effect of the IC on rutting and cracking mixture performance.

The Bailey method (Vavrik *et al.* 2002) for gradation design of mixtures takes a similar approach by requiring the density of the coarse aggregate in the compacted mixture to be between 95% and 105% of the loose density of the coarse aggregate as determined in the laboratory. However, use of a criterion based on calculated DASR porosity would preclude the need for laboratory compaction of coarse aggregate and also assures that the particles are interactive.

1.2 *Objectives*

This work was focused on the development of a conceptual and theoretical approach to evaluate in a more comprehensive manner the IC. The main purpose of this study was to enhance understanding of how asphalt mixture performance is affected by changes in IC; this may serve as the basis for the development of guidelines and/or specification criteria for design of rutting and cracking resistant asphalt mixtures. Detailed objectives of this research work were as follows:

- Identify key characteristics of IC gradation that may likely control asphalt mixture rutting and cracking performance.
- Perform laboratory tests to evaluate the effect of changing IC gradation and IV characteristics on

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*Corresponding author. Email: alvaro.guarin@abe.kth.se performance-related mixture properties for a given DASR porosity.

- Develop a theoretical approach to evaluate the susceptibility of the DASR structure to be disrupted by the IC.
- Identify guidelines for IC characterisation for mixture design purposes.

1.3 *Scope*

To evaluate the effects of IC gradation and IV distribution on rutting and cracking performance of asphalt mixtures, two mixtures with known good rutting performance were selected as a reference and then modified to assess a broad range of IC gradations from very coarse IC to very fine IC; more specifically; one reference mixture was considered per aggregate type (Florida limestone and Georgia granite). Asphalt binder PG 67-22 was used for all tests. Filler gradation (particles passing 75 μm sieve) was kept constant for each aggregate source.

Laboratory tests were performed to assess the effect of different IC gradations on the mixture rutting and cracking resistance. Superpave indirect tensile test (IDT) was performed at 10°C in order to get resilient modulus (MR), creep compliance and tensile strength; also Asphalt Pavement Analyser (APA) was used to estimate rutting susceptibility of the mixtures.

It should be noted that the approach developed in this study was based on packing theory of spherical particles of multiple sizes. Consequently, the criteria developed are probably most applicable to aggregates that are not flat or elongated. However, the authors see no reason why it would not be possible to extend the concepts and theoretical calculations developed to particles that are not spherical. In addition, it is recognised that aggregate angularity and texture can affect the quality of aggregate interlock and these factors were not dealt with in this study. However, gradations that result in better interlock are beneficial regardless of the aggregate angularity or texture.

Furthermore, the DASR porosity criterion, which was also developed assuming spherical particles, has been an effective tool to distinguish asphalt mixtures with poor rutting performance, even without considering surface texture and aggregate angularity (Roque *et al.* 2006, Denneman *et al.* 2007, Kim *et al.* 2008, 2009, Steyn *et al.* 2008, Greene *et al.* 2011). That being said, further research and evaluation in the future may allow for modified criteria based on measurable characterisation of shape, angularity and texture of aggregates.

It is also recognised that DASR porosity and DF alone would obviously not ensure good mixture performance, which will also depend on the characteristics and properties of the finer components of the mixture, including filler and binder, as well as adhesive and cohesive bond between binder and aggregates, but it would help to eliminate mixtures that will not perform well, regardless of the quality of these other components.

2. Asphalt mixture model

According to the proposed model, the two key constituents of asphalt mixtures are DASR and IC. DASR forms the primary structural network of aggregates; while the IC includes particle sizes smaller than the DASR along with binder and will serve to fill the void space between the DASR. Due to their small proportion, particles larger than the DASR will have minimum to no interaction with other stones; therefore they will simply float in the aggregate matrix and will not play a major role in the aggregate structure. Figure 1 shows DASR and IC for Stone Matrix Asphalt (SMA) and dense asphalt mixtures.

2.1 *Dominant aggregate size range*

It is a well-known fact in soil mechanics that the porosity of granular materials in the loose state is approximately constant between 45% and 50%, regardless of particle size or distribution (Lambe and Whitman 1969, Freeze and Cherry 1979). This implies that the porosity of an assemblage of granular particles (e.g. the aggregate within

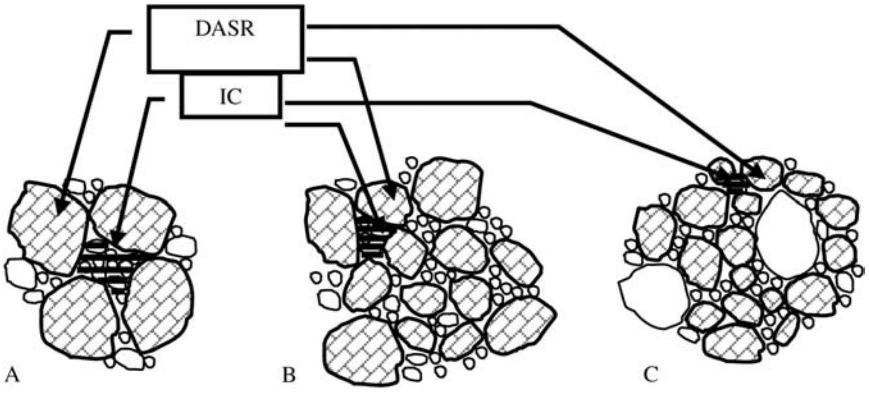

Figure 1. DASR and IC representation. (A) SMA mixture, (B) coarse dense mixture and (C) fine dense mixture (Roque *et al.* 2006).

an asphalt mixture) must be no greater than 50% for the particles to be in contact with each other. This also implies that one can use porosity as a criterion to assure contact between large enough particles within the mixture to provide suitable resistance to deformation. Calculations performed for gradations associated with typical dense graded mixtures indicated that the porosity of particles retained on any single sieve was significantly greater than 50%, even for gradations associated with the maximum density line. Since many dense-graded mixtures are known to provide suitable resistance to deformation and fracture, then there must be a range of contiguous coarse aggregate particle sizes that form a network of interactive particles with a porosity of less than 50%.

A theoretical analysis procedure was developed to calculate the centre-to-centre spacing between specific size particles within a compacted assemblage of particles of known gradation (Kim *et al.* 2006). Calculations performed with this procedure indicated that the relative proportion of two contiguous size particles, as defined by the standard arrangement of Superpave sieves, can be no greater than 70/30 in order to form an interactive network. Thus, the 70/30 proportion can be used to determine whether particles on contiguous Superpave sieves can form an interactive network of particles in continuous contact with each other. The range of particle sizes determined to be interactive was referred to as the DASR and its porosity must be no greater than 50% for the particles to be in contact with each other.

The DASR may be composed of one size or multiple aggregate sizes. Gap-graded gradations such as SMA have a very distinct DASR, because only one size aggregate makes up most of the mixture volume; however, determination of the DASR is less clear for dense-graded mixtures. In consequence, an interaction diagram was developed based on spacing analysis between particles on the interstitial surface to determine which contiguous sizes are interacting as a unit to constitute the DASR (Kim *et al.* 2006).

2.2 *Interstitial component*

This is the material (asphalt, aggregate and air voids) that exists within the interstices of the DASR. The properties of the IC, as well as the IV distribution, will strongly influence the rutting and fracture resistance of mixtures. Therefore, a deeper understanding of the DASR voids structure is absolutely required in order to quantify the susceptibility of the DASR structure to be disrupted by the IC.

3. Porosity

3.1 *DASR porosity*

The principles associated with the calculation of porosity of the DASR are presented below. The voids in mineral aggregates (VMA) in asphalt mixtures, which is the volume of available space between aggregates in a compacted mixture, is analogous to void volume in soils.

$$\mathrm{VMA} = V - V_{\mathrm{Agg}} \tag{1}$$

If one assumes that an asphalt mixture has certain effective asphalt content and air voids for a given aggregate gradation (i.e. VMA), then the porosity can be calculated for any DASR.

For example, the porosity of the DASR can be calculated by subtracting the volume of particles larger than DASR from the total volume of the asphalt mixture as shown in Figure 2.

$$V_{\mathrm{T(DASR)}} = V_{\mathrm{TM}} - V_{\mathrm{Agg>DASR}} \tag{2}$$

where $V_{\mathrm{T(DASR)}}$ is the total volume available for DASR particles, V_{TM} is the total volume of mixture and $V_{\mathrm{Agg>DASR}}$ is the volume of particles larger than DASR.

The volume of voids within the DASR includes the volume of IC aggregates, as well as the volume of effective asphalt plus the volume of air (i.e. the VMA of the mixture).

$$V_{\mathrm{V(DASR)}} = V_{\mathrm{ICagg}} + \mathrm{VMA} = \mathrm{IV} \tag{3}$$

where $V_{\mathrm{V(DASR)}}$ is the volume of voids within DASR, V_{ICagg} is the volume of IC aggregates and IV is the interstitial volume.

The DASR porosity (η_{DASR}) is then calculated as follows:

$$\eta_{\mathrm{DASR}} = \frac{V_{\mathrm{V(DASR)}}}{V_{\mathrm{T(DASR)}}} = \frac{V_{\mathrm{ICagg}} + \mathrm{VMA}}{V_{\mathrm{TM}} - V_{\mathrm{agg>DASR}}} = \frac{\mathrm{IV}}{V_{\mathrm{TM}} - V_{\mathrm{agg>DASR}}} \tag{4}$$

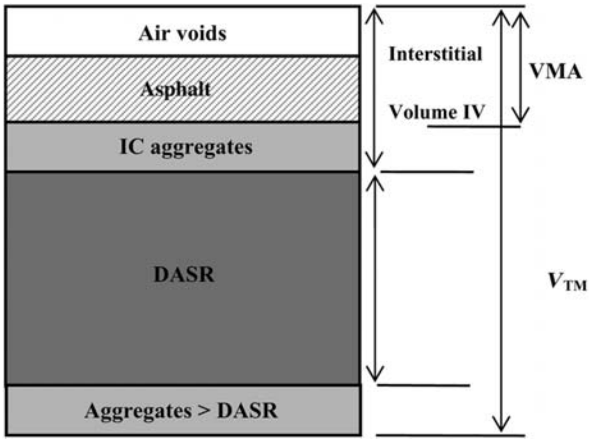

Figure 2. Mixture components for DASR porosity calculation (Roque *et al.* 2006).

It should be emphasised that volume of IC aggregates is the only IC factor required to calculate DASR porosity; consequently, further research on other fundamental IC parameters that may affect asphalt mixture rutting and cracking performance was clearly required to continue the development of the DASR–IC gradation analysis system.

3.2 *Spheres system porosity*

There are six possible regular arrangements of single-sized spheres: simple cubical, hexagonal loose, orthorhombic, tetragonal, face-centred cubical and hexagonal close. A relevant fact is that the porosity of different sphere packing arrangements, which is presented in Table 1, is independent of the particle size (Herdan 1960).

Thus, the densest possible packing of single-sized spheres is the hexagonal close (26% porosity), while the loosest possible arrangement of equal spheres is the simple cubical (47.6% porosity). It should be noted that Roque *et al.* (2006), Kim *et al.* (2008, 2009) and Greene *et al.* (2011) have evaluated an extensive range of asphalt mixtures including laboratory mixtures, Superpave monitoring projects, National Center for Asphalt Technology (NCAT), Westrack, heavy vehicle simulator (HVS) sections, among others; and they found DASR porosity values ranging from 30% to 48% when stone-to-stone contact was guaranteed.

Interestingly enough, in the two scenarios: single-sized spheres and asphalt mixtures (DASR), the range of porosity values is virtually the same, even though porosity of asphalt mixtures is affected by diverse factors such as particle arrangement, size, shape, gradation, asphalt content and air voids. This seems to indicate that type of packing of the DASR structure may be inferred from the DASR porosity (Table 2).

In general, cubical packing is less stable than the hexagonal close structure. The cubical arrangement is relatively easy to disrupt either by IC particles larger than the DASR void or when there are too many IC particles smaller than the DASR void, especially under loading. Conversely, if the IC disruptive range includes few and small particles, then the DASR structure may experience considerable disruption since the IC aggregates will take minimal or no forces, thereby the rutting resistance of the mixture may be diminished (see Figure 3).

Table 1. Porosity values for single-sized sphere arrangements.

Packing arrangement	Porosity (%)
Simple cubical	47.6
Hexagonal loose	39.5
Orthorhombic	39.5
Tetragonal	30.2
Face-centred cubical	26.0
Hexagonal close	26.0

Table 2. DASR packing in function of DASR porosity.

DASR porosity (%)	DASR packing
≈ 48	Simple cubical
≈ 30	Hexagonal close

Hexagonal close structures (Figure 4) may be disrupted even by a modest amount of intermediate IC particles. On the other hand, very fine or a very small amount of IC particles may not be a problem since the DASR structure is already close and does not need any contribution from the IC aggregate structure to provide adequate resistance to shear.

4. DASR voids structure

A deeper knowledge of the DASR void structure (void type, size and number) is essential to understand and predict how the IC will fit into those voids and consequently determine if the DASR structure may be disrupted by the IC. This assessment is essential because when the DASR structure is disrupted, the asphalt mixture rutting and cracking resistance may be dramatically reduced.

An approximated determination of the DASR voids structure can be made by applying particle packing theory, assuming a system of spheres, which may be organised in either regular packing or random arrangement. For regular single-sized sphere systems, the voids structure (type, size and number of voids) can satisfactorily be estimated by mathematical means as a function of the type of packing and it is independent of the sphere size. Conversely, the void structure in a random packing of equal spheres is difficult to calculate. Determination of the voids structure of asphalt mixtures in the laboratory is an accurate but expensive alternative; moreover, it also would be a significant limitation for implementing a practical methodology to analyse aggregate structure.

SMA mixtures, which usually have a single particle size DASR, may be simulated by a single-sized system of spheres. When the DASR includes different particle sizes, like dense-graded mixtures, the weighted DASR average particle size (D_{AVE}), based on the number of particles for each DASR fraction, should be calculated as follows:

$$D_{\mathrm{AVE}} = \frac{\sum(D_i^* N_i)_{i=1}^n}{\sum(N_i)_{i=1}^n} \tag{5}$$

where D is the particle diameter, N is the number of particles, and n is the number of DASR fractions.

Since D_{AVE} is calculated on the number of particles per sieve size, generally it is close to the smallest DASR particle size. Actually, this could be an advantage of the system, considering that the most conservative approach to

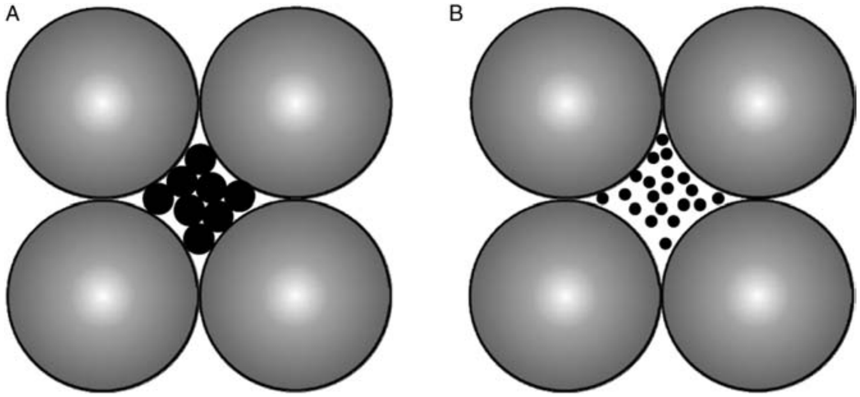

Figure 3. Cubical packing. (A) Too many IC particles smaller than the DASR void and (B) excessively fine IC particles.

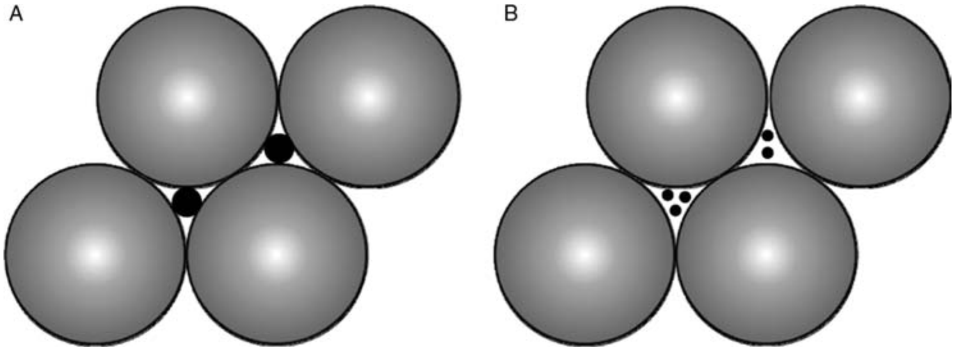

Figure 4. Hexagonal close packing. (A) Relatively large IC particles and (B) excessively fine IC particles.

evaluate DASR voids structure is to assume D_{AVE} equal to the smallest DASR particle size, thus the predicted DASR void size would be the smallest possible.

4.1 *Void types*

Two types of voids can occur in close packing: tetrahedral and octahedral. If a triangular void has a sphere above it, then the resulting void will have four spheres around it; these spheres are the corners of a tetrahedral void (Figure 5).

If a triangular void pointing up is covered by a triangular void pointing down in the next layer, then the resulting void will be surrounded by six spheres; these spheres are the corners of an octahedral void, as shown in Figure 6.

When the aggregate particles are arranged in a simple cubical structure, the resulting void will be surrounded by eight spheres, which constitute the corners of a cubical void (Figure 7).

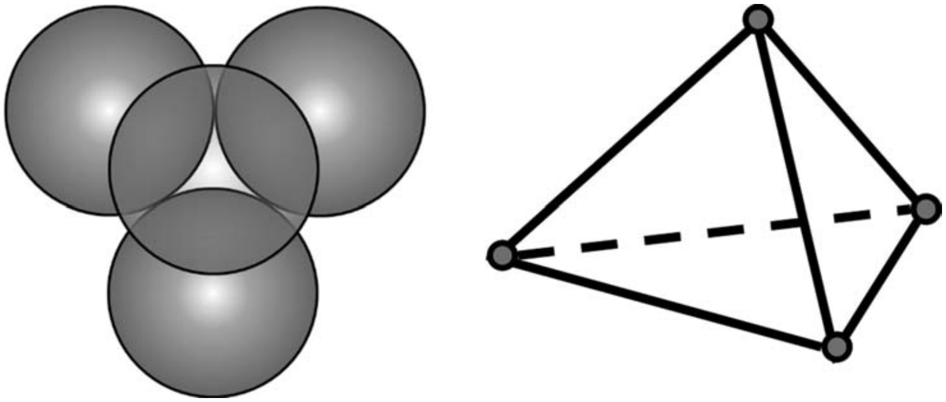

Figure 5. Tetrahedral void.

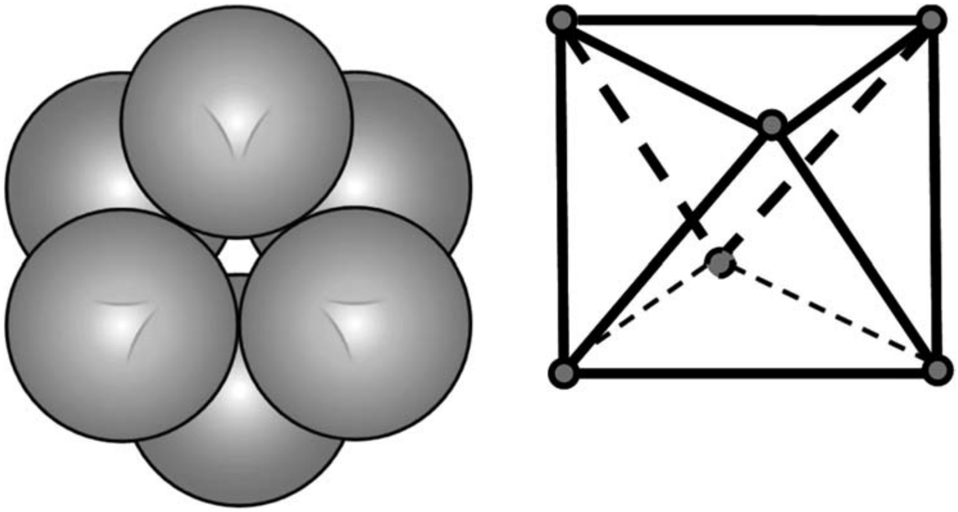

Figure 6. Octahedral void.

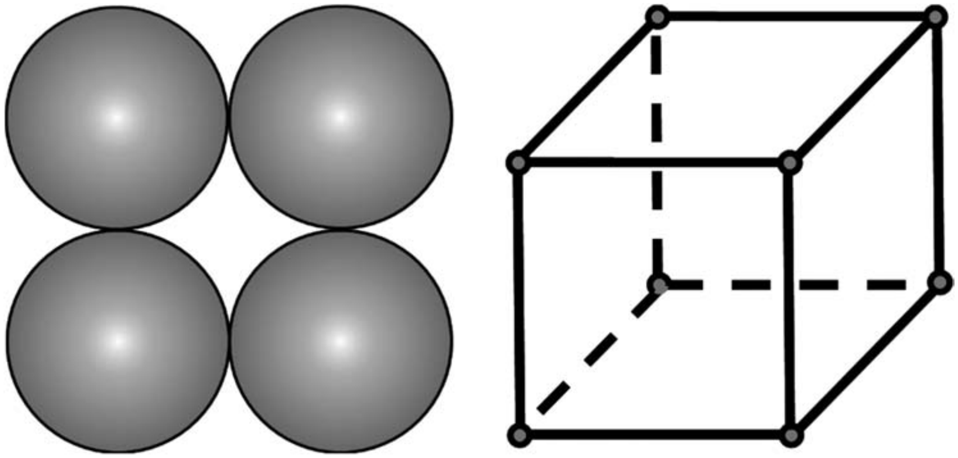

Figure 7. Cubical void.

4.2 *Size and number of voids*

Once the type of DASR packing is selected depending on the DASR porosity; the type, size and the number of voids can be estimated. As mentioned before, a simple cubical structure will have only cubical voids; while a hexagonal close system will have both octahedral and tetrahedral voids. Table 3 summarises the type, size and number of voids as a function of the type of DASR arrangement (Tareen and Kutty 2001).

5. DASR disruption

5.1 *Local DASR disruption*

Local disruption is related to the effect of just one IC particle larger than the DASR void; this local DASR disruption in a close packed arrangement of equal spheres in a plane is represented in Figure 8.

5.2 *Global DASR disruption*

In order to evaluate the overall stability of the DASR structure it is very important to know not only the type, size and number of voids but also the volume of IC particles larger than the DASR voids, since these particles will eventually disrupt the entire DASR structure.

Figure 9 provides a good conceptual representation of the effect that an increasing number of disruptive IC particles l have on the stability of the DASR structure. In accordance with this simple model, there are six available voids between DASR particles. It should be noted that if there are no disruptive IC particles, then the DASR structure has 12 contact points (highest global shear resistance); but if only two IC disruptive particles are placed, then the number of contact points is reduced by 50%. This demonstrates the significant effect that the

Table 3. Voids structure for different sphere arrangements from packing theory.

DASR packing	Void type	Void size	Number of voids
Simple cubical	Cubical	0.732D	One void per particle
Hexagonal close	Octahedral	0.414D	One void per particle
	Tetrahedral	0.225D	Two voids per particle

Note: D = DASR particle diameter.

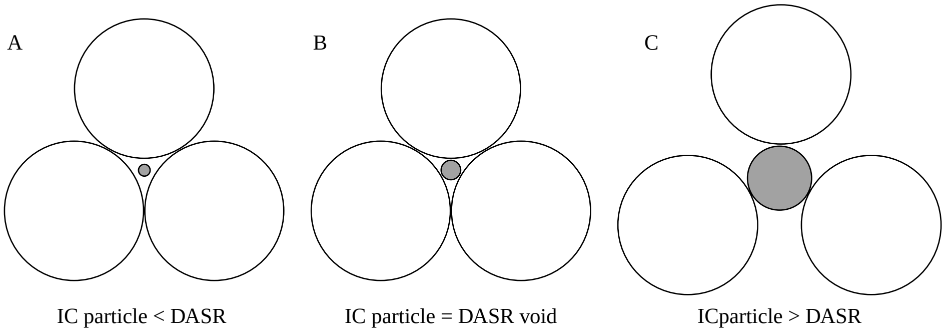

Figure 8. Local DASR stability criteria. (A) Stable, (B) critically stable and (C) disrupted.

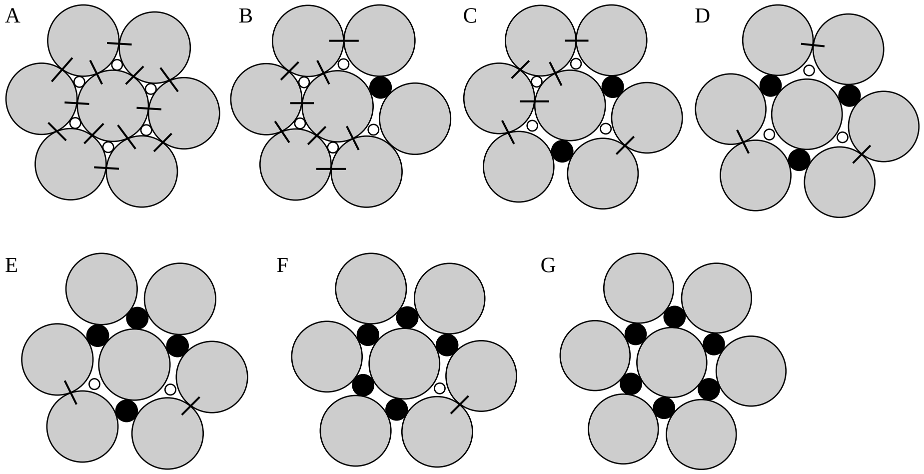

Figure 9. Global DASR disruption. (A) No disruptive IC particles, (B) one disruptive IC particle, (C) two disruptive IC particles, (D) three disruptive IC particles, (E) four disruptive IC particles, (F) five disruptive IC particles and (G) six disruptive IC particles.

number of disruptive IC particles may have on the overall stability of the DASR structure.

5.3 *Potentially disruptive range*

Considering both local and global DASR disruption, the potentially disruptive range (PDR) must include all IC particles larger than the DASR void. For instance, in a cubical structure the PDR should include IC particles larger than 0.732D, while for hexagonal close arrangement, the PDR should involve IC particles larger than 0.225D; this is consistent with Bailey method which also uses this ratio to separate coarse and fine aggregate fractions.

It was hypothesised that IC particles smaller than DASR void have little or no potential to disrupt the DASR structure, considering their small size and relative proportion compared with the DASR; however, additional research is strongly recommended on this issue. Figure 10 illustrates the PDR concept. For example, if the DASR for an SMA mixture includes particles from 9.5 to 4.75 mm; then average void size sieve is 1.18 mm (assuming hexagonal close DASR structure).

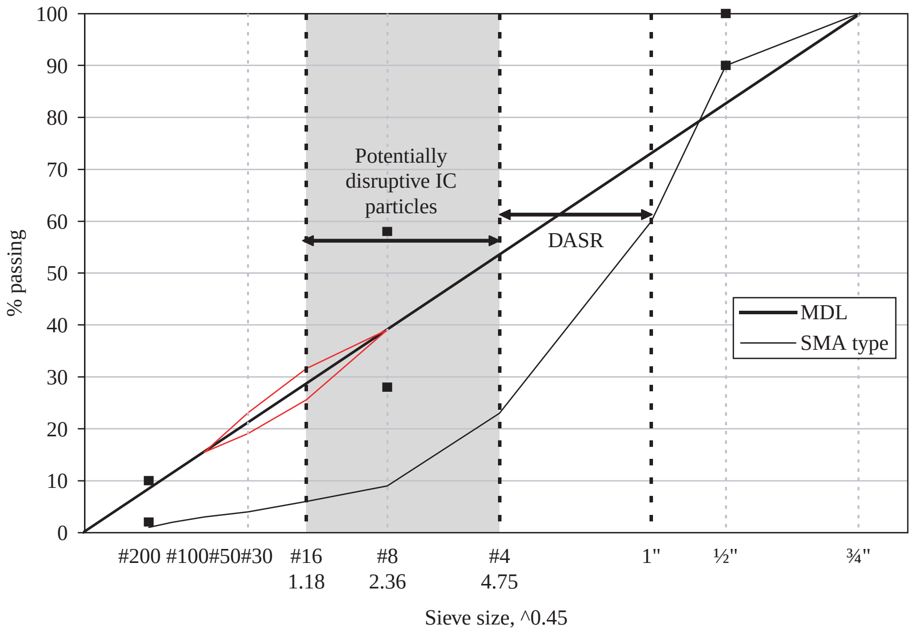

Figure 10. Determination of PDR.

5.4 *Disruption factor*

The disruption factor (DF) was conceived to evaluate the potential of IC aggregates to disrupt the DASR structure:

$$DF = \frac{\text{Volume of potentially disruptive IC particles}}{\text{Volume of DASR voids}} \quad (6)$$

Figure 11 illustrates the DF concept. If DF is low, then the IC aggregates will not be significantly engaged in transferring load between DASR particles, thereby the DASR structure will take minimum or no advantage of the potential benefit that could be provided by IC aggregates. Conversely, if DF is high, then the DASR will be disrupted by the IC aggregates, therefore mixture rutting and cracking resistance will be dramatically reduced. Therefore, an optimal range for DF could be established; this is when IC aggregates assist DASR particles in resisting shear stresses to optimised mixture rutting and cracking resistance.

The expected relationship between DF and mixture rutting and cracking performance is depicted in Tables 4 and 5, respectively.

The optimal DF range should be affected by diverse parameters such as DASR, DASR packing, aggregate source, binder category and mixture type among others; therefore additional validation of this concept, as well as the relationship between DF and mixture rutting and cracking performance, is strongly recommended. However, DF as well as DASR porosity may eventually be used as a design parameter for rutting and cracking resistant mixtures. In any case, another benefit of the DASR–IC model is that it provides a very practical tool to visualise and understand the relationship between aggregate particle size distribution and the mixture performance.

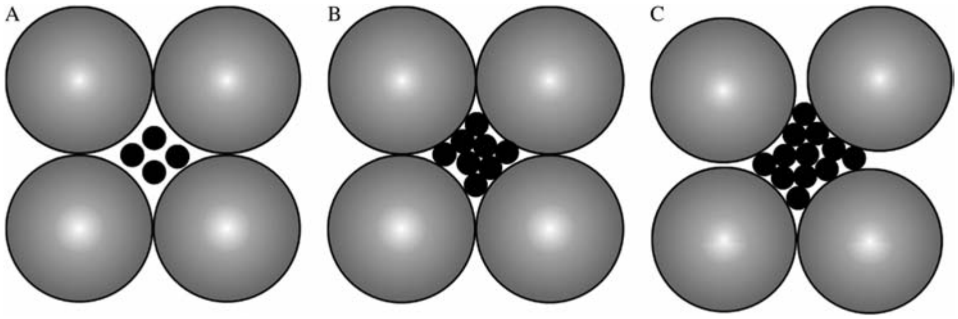

Figure 11. DF representation. (A) Low DF, (B) optimal DF and (C) high DF.

Table 4. Effect of DF on mixture rutting performance.

DF	Mixture rutting performance
Low	DASR structure will take minimum or no advantage of the potential benefit that could be provided by IC aggregates; then, the rutting resistance of the mixture may be reduced.
Optimal	IC aggregates will assist DASR particles in resisting shear stresses; therefore, the mixture will be more rutting resistant.
High	IC aggregates will disrupt the DASR structure; consequently, the rutting resistance of the mixture will be diminished.

Table 5. Effect of DF on mixture cracking performance.

DF	Mixture cracking performance
Low	Low IC stiffness and greater mixture microdamage due to lack of IC aggregates; then, the mixture cracking resistance may be reduced.
Optimal	Optimal IC stiffness; therefore, better fracture resistance.
High	High IC stiffness, brittle mixture; consequently, lower mixture cracking resistant.

6. Laboratory evaluation

One known mixture for each aggregate type (Georgia granite and Florida limestone) was modified so that the DASR porosity was kept constant while the IC was changed from a very coarse gradation ICc to a very fine gradation ICf to evaluate the disruption of the DASR. A total of six asphalt mixtures were designed according to Superpave methodology and then tested in the laboratory. The same type of binder PG 67-22 and amount and gradation of material passing the #200 sieve were used in all mixtures to minimise additional effects.

6.1 *Aggregate gradations*

The reference mixture chosen for Georgia granite mixtures was GA Good. GAICc has a very coarse IC while GAICf has a very fine IC. The DASR for these mixtures included particles from 9.5 to 1.18 mm. Figure 12 shows the gradations for the three granite mixtures.

Florida limestone mixtures were designed in a similar manner as the Georgia granite mixtures. FL Good, FLICc and FLICf gradations are shown in Figure 13. The DASR for these mixtures included particles from 4.75 to 1.18 mm.

6.2 *Mixture design*

The mixtures were designed to meet Superpave requirements for a traffic level C mixture, which corresponds to a design traffic level of 3 to 10 million equivalent single axle loads. Gyratory compaction levels corresponding to traffic level C are 115 gyrations for N_{max}, 75 gyrations for N_{design} and 7 gyrations for N_{initial}. All mixtures were designed to have a compacted air void content of 4.0% at N_{design}. As mentioned earlier, a PG 67-22 asphalt binder was used for all mixtures. Table 6 presents asphalt content (AC) and VMA for the mixtures.

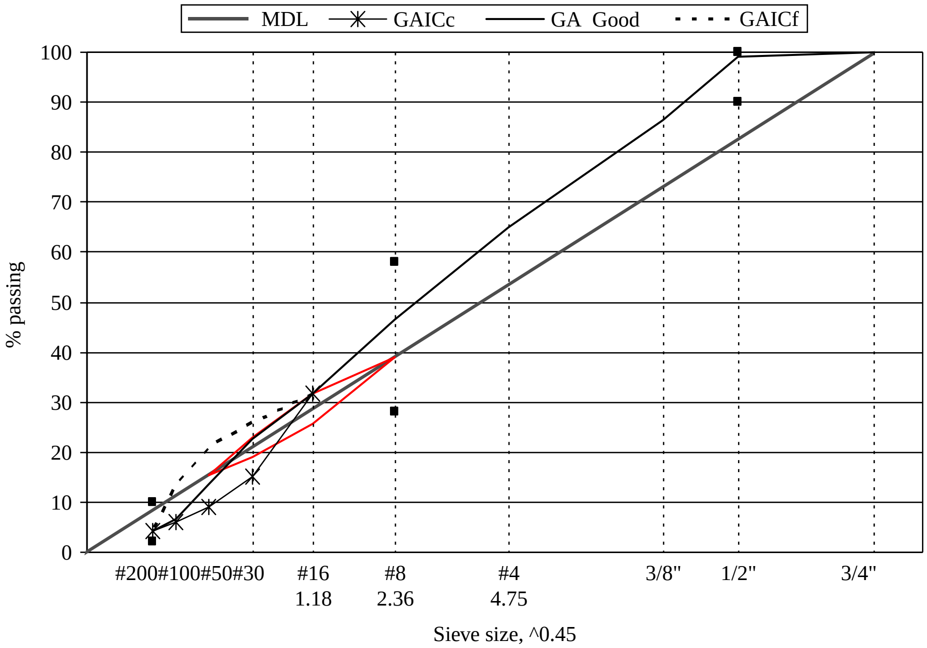

Figure 12. Gradations for GA granite.

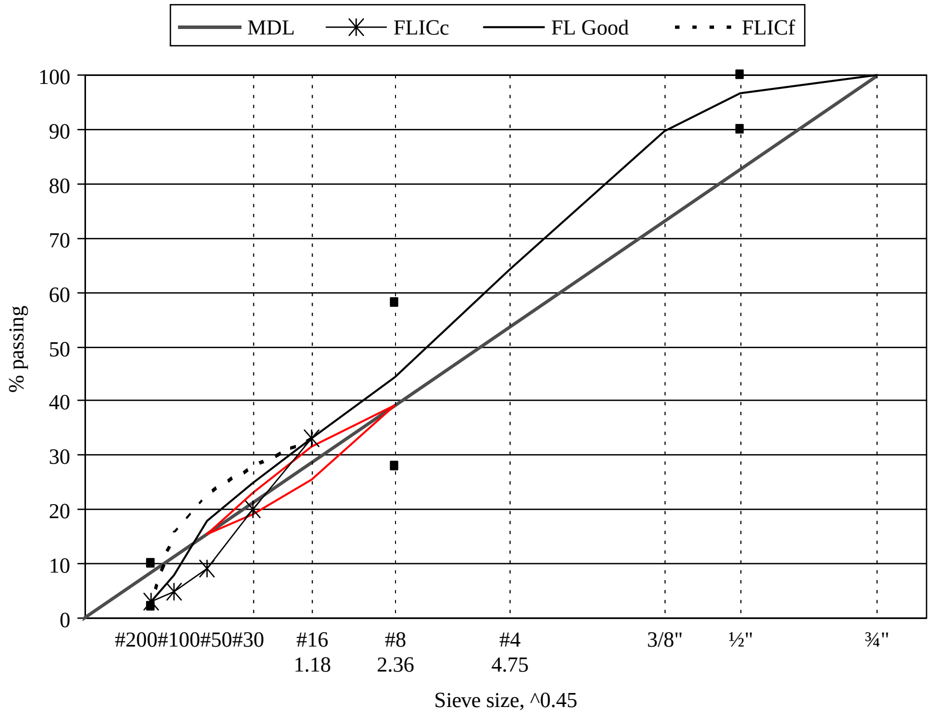

Figure 13. Gradations for Florida limestone.

Remarkably, the IC gradation had major impact on the optimum AC; for both aggregate types, the ICc mixture required much more binder than the fine IC one. This effect was more notable in the Georgia granite gradations, where the ICc mixture required 2.1% higher AC than the ICf mixture. ICf gradations are denser and have more material acting as filler than ICc gradations; this may reduce the optimum AC required for ICf mixtures.

According to the Superpave method, for 12.5 mm nominal maximum aggregate size mixtures, the minimum VMA required is 14%. For both aggregate types, ICf mixtures did not meet this criterion. Most likely, these mixtures have low VMA values due to their high aggregate surface area. Even though ICf mixtures did not meet minimum VMA, they were produced and tested to determine if the DASR–IC model can be better related with the performance of the mixtures.

Table 6. DASR and IC parameters for Georgia granite mixtures.

Mixture	AC (%)	VMA (%)
FLICf	5.2	12.0
FL Good	6.6	13.6
FLICc	6.6	15.0
GAICf	3.9	11.7
GA Good	4.8	14.9
GAICc	6.0	16.4

6.3 *Performance tests*

6.3.1 *Asphalt pavement analyser*

The APA is equipment designed to test the rutting susceptibility or rutting resistance of HMA. Rut performance tests are performed by means of a constant load applied repeatedly through pressurised hoses to compacted test specimens at 60 °C; the cylindrical test specimens are 150 mm in diameter by 75 mm thick. The profiles were measured by the contour gauge system developed by Drakos (2003).

6.3.2 *Superpave IDT*

The Superpave IDT was used to evaluate the mixtures' resistance to cracking. This test was performed to obtain the mixture properties such as MR, creep compliance [$D(t)$], m-value, D_1, tensile strength, fracture energy and dissipated creep strain energy (DCSE) to failure (Roque *et al.* 1997). Figure 14 presents the schematic of the Superpave IDT test configuration and determination of DCSE to failure based on the MR test and indirect tensile strength test results.

The energy ratio (ER) is the most important parameter to evaluate the cracking potential of asphalt mixtures;

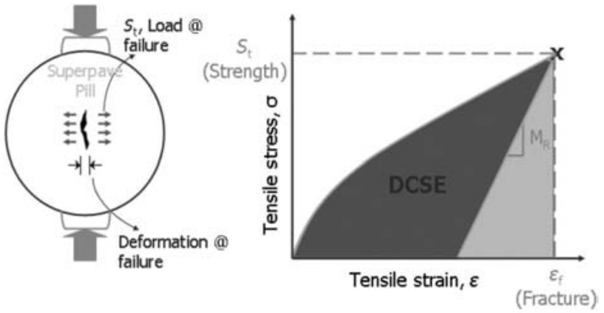

Figure 14. Schematic of Superpave IDT test and determination of DCSE to failure.

ER is defined as the DCSE threshold of a material ($DCSE_f$) divided by the minimum DCSE ($DCSE_{min}$) needed, which is calculated from IDT results as follows (Roque *et al.* 2004):

$$ER = \frac{DCSE_f}{DCSE_{min}} \tag{7}$$

The $DCSE_{min}$ is a function of material properties and the pavement structure

$$DCSE_{min} = \frac{m^{2.98n} D_1}{A} \tag{8}$$

where, m and D_1 are the creep compliance power law parameter.

Parameter 'A' accounts for the tensile stresses in the pavement structure and the tensile strength of the material.

$$A = 0.0299\sigma^{-3.10}(6.36 - S_t) + 2.46 \times 10^{-8} \tag{9}$$

where, σ is the applied tensile stress, S_t is the tensile strength.

6.4 *DF validation*

Rutting potential was evaluated based on the APA test results, whereas cracking resistance was assessed in terms of tensile strength, creep rate and ER. For instance, the Florida limestone mixtures can be classified as cubical structures based on their DASR porosity. DASR porosity, DASR structure type and DF for the Georgia granite and Florida limestone mixtures are summarised in Tables 7 and 8, respectively.

Table 7. DASR and IC parameters for Georgia granite mixtures.

Mixture	DASR porosity (%)	DASR packing	DF
GAICf	40.1	Cubical	0.49
GA Good	42.0	Cubical	0.77
GAICc	43.4	Cubical	1.41

Table 8. DASR and IC parameters for Florida limestone mixtures.

Mixture	DASR porosity (%)	DASR packing	DF
FLICf	45.5	Cubical	0.48
FL Good	46.0	Cubical	0.75
FLICc	47.4	Cubical	1.21

Figure 15 presents APA rut depth as a function of DF; ICf and 'Good' mixtures exhibited very similar performance. Interestingly enough, ICc mixtures were clearly the most rutted, about twice the rut depth of the ICf and 'Good' mixtures. FL limestone mixtures showed better rutting resistance compared to GA granite mixtures. This might be due to the characteristics of the aggregate, such as surface texture, angularity and shape.

Interestingly enough, coarse IC mixtures, which meet Superpave VMA requirements, performed poorly in terms of rutting resistance, whereas fine IC gradations, which did not meet Superpave VMA specifications, performed almost as well as the 'Good' mixtures.

As expected, gradations with DF higher than 1, such as ICc mixtures, exhibited poor rutting performance. Both Florida limestone and Georgia granite mixtures appear to show an optimal range of DF values to achieve better rutting performance. This agrees with the hypothesised relationship between DF and mixture rutting resistance.

As mentioned above, fracture resistance of the mixtures was evaluated in terms of parameters obtained from Superpave IDT. Tensile strength does not seem to be significantly affected by changes in IC gradation, even for different aggregate types; however, ICc exhibited lower tensile strength due to high DF values (Figure 16).

'Good' and ICf gradations for both aggregate sources exhibited similar creep response, having significantly lower creep compliance rate than ICc mixtures; this may

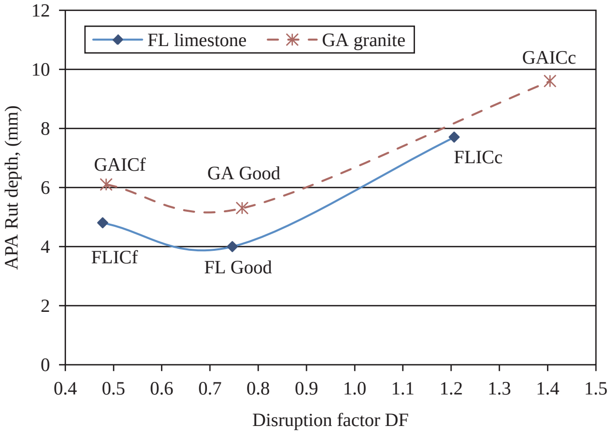

Figure 15. Relationship between APA rut depth and DF.

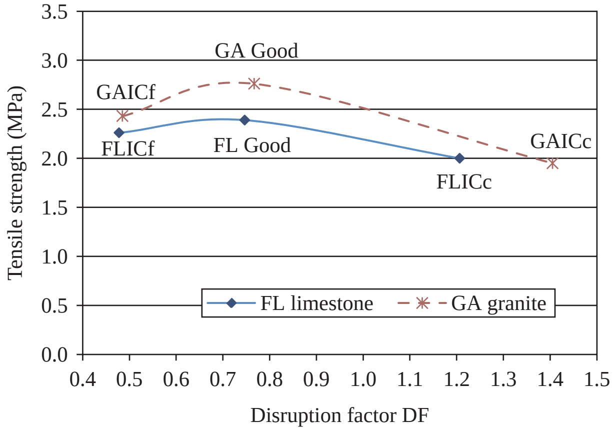

Figure 16. Relationship between tensile strength and DF.

be caused by the disruption of the ICc DASR structures (Figure 17).

Results of ER calculations are presented in Figure 18. As mentioned before, ER is the most important parameter to evaluate the cracking potential of asphalt mixtures. 'Good' mixtures have higher ER than ICc and ICf mixtures probably because the IC aggregates help the DASR structure in resisting shear stresses induced by external loads. ICc mixtures had lower ER than 'Good' mixtures not only because the IC was brittle, but also because the DASR structure was disrupted by IC aggregates. Finally, ICf mixtures exhibited lower ER than 'Good' mixtures due to greater microdamage caused by lack of IC aggregates.

Figure 18 also seems to validate the hypothesised existence of an optimal range for DF in terms of cracking performance. In summary, laboratory tests performed in this research work seem to indicate that DF for cubical DASR structures could be initially estimated to be between 0.65 and 0.85 for optimal rutting and cracking mixture performance. Therefore, DF together with DASR porosity may eventually be used as a parameter to design rutting and cracking resistant mixtures.

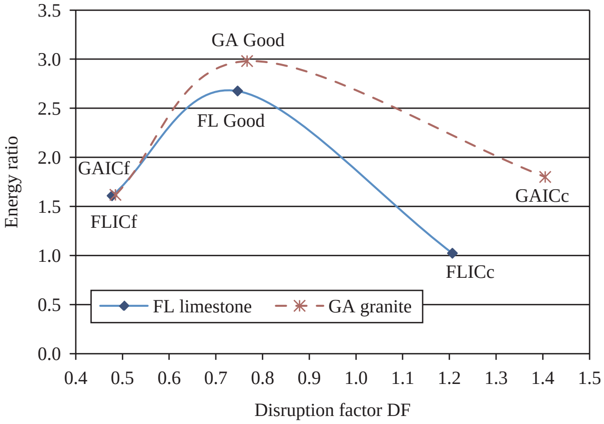

Figure 18. Relationship between ER and DF.

7. Summary and conclusions

This study focused on the refinement of the DASR–IC gradation analysis method. The main purpose was to evaluate, in a more comprehensive manner, the effect of IC on HMA rutting and cracking laboratory performance. Two known good mixtures previously designed according to Superpave methodology, which met the DASR porosity criterion, named FL Good (Florida limestone) and GA Good (Georgia granite), were selected as a reference and

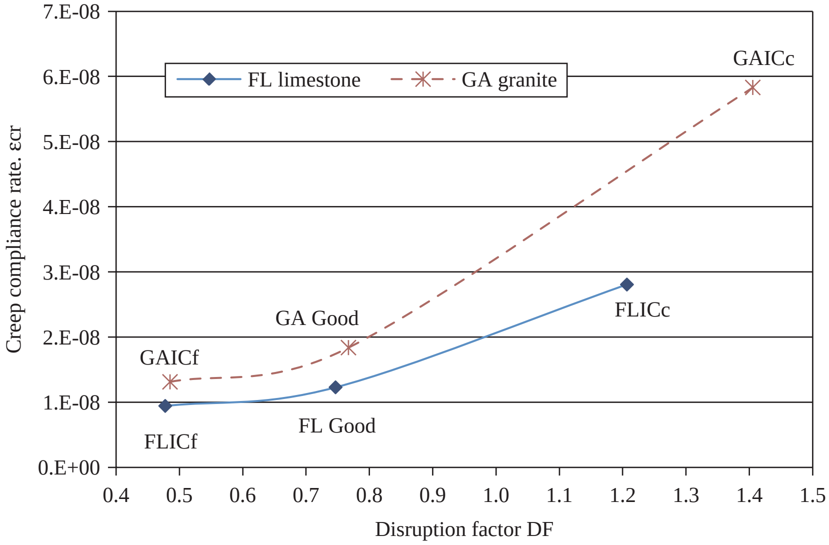

Figure 17. Relationship between creep rate and DF.

then modified to assess ‘extreme’ conditions (either too coarse IC or too fine IC).

Laboratory results from Superpave IDT and APA test clearly showed that IC characteristics may have a very significant effect on rutting and cracking performance of HMA even when both DASR porosity and the percentage passing #200 sieve are kept constant.

Particle packing theory and volumetric properties of the aggregates were applied to calculate the DASR void structure (type, size and number of voids) and the volume of potentially disruptive IC particles. The DF, which is the ratio between the volume of potentially disruptive IC particles and the volume of DASR voids, was calculated for laboratory prepared mixtures and satisfactorily distinguished poor performing mixtures.

It appears that the IC gradation plays a major role in mixture rutting and cracking performance; either too coarse IC or too fine IC may significantly reduce the asphalt mixture rutting and cracking resistance. This suggests that more evenly distributed IC gradations should be used to obtain better mixtures in terms of rutting and cracking resistance.

As expected, laboratory results seemed to validate the existence of an optimal range for DF to achieve better mixture rutting and cracking performance. As a starting point, DF for cubical DASR structures could be recommended to be between 0.65 and 0.85 for optimal rutting and cracking mixture performance.

Coarse IC mixtures (which meet Superpave VMA requirements) performed poorly in terms of rutting resistance; whereas, fine IC gradations (which did not meet Superpave VMA specifications) performed almost as well as the ‘Good’ mixtures.

DASR porosity and DF may eventually be used to develop an effective rutting and cracking performance-based mixture design procedure or guide. An user-friendly software has been developed to calculate both DASR porosity and DF; this is a powerful tool to identify problem gradations and allows the mixture designer to optimise gradations in terms of mixture rutting and cracking performance.

8. Recommendations

Additional validation is required to establish more definitive values for DF optimal range, for both cubical and hexagonal close arrangements; especially for different DASR. Similarly, the relative effects of DF octahedral and DF tetrahedral on the stability of hexagonal close structures, as well as the effect of IC particles smaller than the Disruptive IC range on the asphalt mixture performance should be more extensively evaluated.

Research should continue to further develop and refine this promising approach to establish relationship between gradation parameters and performance-related mixture properties; for instance, the effect of surface texture and aggregate angularity in mixture performance should be properly investigated.

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Notes

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References

Denneman, E., Verhaeghe, B., and Sadzik, S., 2007. Aggregate packing characteristics of good and poor performing asphalt mixes. *In*: *26th annual Southern African transport conference and exhibition*, Pretoria, South Africa: Southern African Transport Conference (SATC), pp. 213–224.

Drakos, C., 2003. Identification of a physical model to evaluate rutting performance of asphalt mixtures. PhD dissertation. University of Florida.

Freeze, R.A. and Cherry, J.A., 1979. *Groundwater*. Englewood Cliffs, NJ: Prentice-Hall.

Greene, J., Kim, S., and Choubane, B., 2011. *Validation of HMA gradation-based performance evaluation method through Accelerated Pavement Testing*. Washington, DC: Transportation Research Board, Paper No 11-0895.

Herdan, G., 1960. *Small particle statistics*. 2nd ed. London: Butterworths.

Kim, S., Guarin, A., Roque, R., and Birgisson, B., 2008. Laboratory evaluation for rutting performance based on the DASR porosity of asphalt mixture. *International Journal of Road Materials and Pavement Design*, 9(3), 421–440.

Kim, S., Guarin, A., Roque, R., and Birgisson, B., 2006. Identification and assessment of the dominant aggregate size range (DASR) of asphalt mixture. *Journal of Asphalt Paving Technologists*, 75, 789–814.

Kim, S., Roque, R., Birgisson, B., and Guarin, A., 2009. Porosity of the dominant aggregate size range to evaluate coarse aggregate structure of asphalt mixtures. *Journal of Materials in Civil Engineering*, 21, 32–39.

Lambe, T. and Whitman, R., 1969. *Soil mechanics*. New York: Wiley.

Roque, R., Buttlar, W., Ruth, B., Tia, M., Dickison, S., and Reid, B., 1997. Evaluation of SHRP indirect tension tester to mitigate cracking in asphalt pavements and overlays. Final Report to the Florida Department of Transportation, 364 pp.

Roque, R., Birgisson, B., Drakos, C., and Dietrich, B. 2004. Development and field evaluation of energy-based criteria for top-down cracking performance of hot mix asphalt. *Journal of Asphalt Paving Technologists*, 73, 229–260.

Roque, R., Birgisson, B., Kim, S., and Guarin, A., 2006. Development of mix design guidelines for improved performance of asphalt mixtures. Florida Department of Transportation, Tallahassee, Fl, BD545-16.

Steyn, W., Denneman, E., and Mahlangu, S., 2008. Comparison between the permanent deformation behaviour of a standard and a rut resistant HMA (hot-mix asphalt). *In*: *27th Southern African transport conference*, Pretoria, South Africa: Southern African Transport Conference (SATC), p. 10.

Tareen, J. and Kutty, T., 2001. *A basic course in crystallography.* Hyderabad, Andhra Pradesh: Universities Press, Sangam Books Ltd, 94–96.

Vavrik, W., Huber, G., Pine, W., Carpenter, S., and Bailey, R., 2002. *Bailey method for gradation selection in HMA mixture design*. Washington, DC: Transportation Research Circular E-C044.