A Look at the Bailey Method and Locking Point Concept in Superpave Mixture Design

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This study analyzes the physical and performance characteristics of asphalt concrete mixtures with aggregate structures designed using the Bailey method of aggregate gradation evaluation. Three aggregate types—limestone, sandstone, and granite—were considered in this study. Three different aggregate structures of 12.5-mm nominal maximum particle size were designed for each aggregate type. Mixtures were designed for high traffic levels. The binder type selected was performance grade 76-22M. The compaction characteristics of the mixtures were analyzed using data from the Superpave gyratory compactor. Locking points and compaction indices were defined and determined for all the mixtures in the study. Simulative (Hamburg wheel tracking test) and fundamental (semicircular fracture and IT strength) tests were conducted to determine laboratory performance properties and evaluate the mixtures under different loading and environmental conditions. The design number of gyrations (N_{des}) recommended by Superpave was compared to the locking points obtained from this study. The data indicate that the current N_{des} level recommended by Superpave is much higher than the locking points of the mixtures and may subject the mixtures to high compaction energy for an extended period of time. Selected mixtures were designed using the locking point as the design number of gyrations instead of the recommended Superpave N_{des}. The data presented in this paper suggests that mixes with dense aggregate structures can be designed using their locking point instead of the recommended N_{des}. The designed mixtures maintained good resistance to permanent deformation and maintained an adequate level of durability.

The behavior of hot-mix asphalt (HMA) depends on the properties of the individual components and how they react with each other in the system. Several mixture design methods have been developed over time, in an effort to create a mixture that is capable of providing acceptable performance based on a certain predefined set of criteria. The most recently developed mixture design method is the Superpave method. It includes several processes and decision points. The Superpave system employs gyratory compaction to fabricate asphalt mixture specimens. The level of compaction in the Superpave gyratory compactor (SGC) is based upon the design traffic level. In summary, the design compaction levels are established, and then materials are selected and characterized. Afterwards, mixture specimens are prepared and laboratory test results are compared to criteria. Those criteria are purely volumetric and do not employ any mechanical properties, i.e., strength or stiffness, to evaluate mixture performance.

Although aggregate constitutes approximately 95% by weight of asphalt mixtures, the aggregate specifications in the Superpave system were developed based on experience from a number of experts in the field. The group did no research on aggregates but they did build on prior studies and recommendations of many researchers who came before them and the expertise of many practitioners. From this previous research, they developed rules and recommendations for the Superpave system.

As a result of the lack of research conducted to develop the aggregate specifications, those specifications and requirements can still be improved, especially in terms of designing the aggregate structure to improve mixture stability. For example, the current Superpave system lacks guidance for the selection of the design aggregate structure and understanding the interaction of the aggregate structure with mixture design and performance. Furthermore, the trial and error nature of the conventional process of formulating the gradation curve, and the use of weight instead of volume when blending aggregates, make it imperative to implement a more rational approach to design the aggregate structure based on sound principles of aggregate packing.

The SGC is generally used to measure only volumetric properties such as density or air void content as a function of compaction gyrations. However, several attempts have been made to analyze the densification curve obtained from the SGC in order to evaluate an asphalt mixture's workability and resistance to permanent deformation. The value of $N_{initial}$ and the slope of the initial portion of the SGC compaction curve have been hypothesized to reveal certain mixture properties such as tenderness of the mixtures and the strength of aggregate structure (*1*).

Bahia et al. (*2*) suggested that the current method of interpretation of the results from the SGC and the design criteria are biased toward performance under traffic and do not adequately consider the constructability of mixtures. He proposed the use of the SGC curve to evaluate the constructability of the mixtures as well as their resistance to traffic loading. He introduced the concept of compaction and traffic indices. The compaction energy index (CEI) and the traffic densification index (TDI) are used to relate to construction and in-service performance of HMA mixtures. Bahia suggested that controlling these indices is expected to allow optimization of HMA construction and traffic requirements.

Mallick (*4*) found that the gyratory ratio, the ratio of the number of gyrations required to achieve 2% voids and 5% voids, was suitable for characterizing HMA. He stated that a gyratory ratio of 4 can be used to differentiate between stable and unstable mixes and, further, that mixes with a gyratory ratio less than 4 may be unstable.

Vavrik et al (*5*) suggested the evaluation of mixture compaction characteristics based upon the locking point or the point during compaction at which the mixture exhibits a marked increase in resistance to further densification. Alabama Department of Transportation (DOT) (*6*) is adopting the locking point mix design concept. They define the locking point as the point where the sample being gyrated loses less than 0.1 mm in height between successive gyrations. Georgia DOT uses the concept of locking point in designing HMA mixtures. They define the locking point as the number of gyrations at which, in the first occurrence, the same height has been recorded for the third time (*7*). For Georgia, typical locking points are reported to be in the range of the low 60s to high 80s measured with Superpave gyratory compactor.

An important control parameter in asphalt mixture volumetric design is the percentage of voids in the mineral aggregate (VMA). However, several researchers and highway agencies have reported that difficulties exist in meeting the minimum VMA requirements (*8, 9, 10*). Under current specifications, many otherwise sound mixtures are subject to rejection solely on the basis of failing to meet the VMA requirement. Studies (*11*, *12*) also show that a VMA requirement based on nominal maximum particle size (NMPS) does not take into account the gradation of the mixture, ignores the film thickness of the asphalt binder and, thus, is insufficient by itself to correctly differentiate between good-performing and poor-performing mixtures.

OBJECTIVE AND SCOPE

The objective of this study was to incorporate an analytical gradation design and evaluation method into the Superpave mixture design procedure and to analyze the compaction and performance characteristics of the resulting asphalt concrete (AC) mixtures. The Bailey method of aggregate gradation and evaluation was used to design and evaluate the aggregate structures for all the mixtures in the study. The compaction characteristics of the mixtures were analyzed using data from the SGC. Locking points and compaction indices were defined and determined for all the mixtures in the study. The performance of the designed mixtures was evaluated using both simulative and fundamental laboratory tests. Gradation parameters were used to analyze the effect of gradation on compaction and performance properties of asphalt mixtures.

Three aggregate types commonly used in Louisiana were studied. These are limestone, sandstone, and granite. For each type, three aggregate structures (coarse, medium, and fine) were designed using the Bailey method of aggregate gradation evaluation. All the asphalt mixtures were 12.5-mm (1/2-in.) NMPS mixtures and were designed for high-volume traffic [greater than 30 million equivalent single-axle loads (ESALs)]. A performance grade (PG) 76-22M binder was used for all the mixtures. Laboratory simulative and mechanistic tests were conducted, including the Hamburg wheel tracking test and semicircular notched fracture test, respectively.

MATERIALS

The asphalt binder used in this study was a styrene–butadiene (SB) polymer-modified asphalt binder meeting Louisiana PG specifications (*13*) for PG 76-22M. Table 1 presents the laboratory test results on the selected binder. Different aggregate stockpiles from each aggregate type were used. Natural coarse sand was used whenever necessary in the final design blends.

TABLE 1 Louisiana Department of Transportation and Development PG Asphalt Cement Specification and Test Results

Binder Grade	PG 76-22M	
	Specification	**Test Results**
Original Binder		
Rotational viscosity 135˚C, Pa*s	3.0-	1.68
Dynamic shear, 10 rad/s G*/sin δ, kPa	1.00+@76˚C	1.29
Flash point ˚C	232+	305
Solubility %	99.0+	99.5
Force ductility ratio (f2/f1, 4˚C, 5 cm/min, f2 @30-cm elongation	0.30+	0.49
Tests on Rolling Thin-Film Oven		
Mass loss %	1.00-	0.08
Dynamic shear, 10 rad/s, G*/sin δ, kPa	2.20+@76˚C	2.84
Elastic recovery, 25˚C, 10-cm elongation %	60+	70
Tests on Pressure-Aging Vehicle Residue		
Dynamic shear, 10 rad/s, G*sin δ, kPa, 25˚C	5000-	2297
Bending beam creep stiffness, Smax, MPa, tested at –12˚C	300-	195
Bending beam creep slope m value, min, tested at –12˚C	0.300+	0.327

AGGREGATE STRUCTURE DESIGN

The main aim of this task was to design the aggregate structures using an analytical aggregate gradation method that will allow a rational blending of different sizes of aggregate to achieve an optimum aggregate structure for better mixture performance. The Bailey method for aggregate gradation evaluation was utilized for this purpose. The Bailey method is a comprehensive gradation evaluation procedure to provide aggregate interlock as the backbone for the aggregate skeleton (*14*, *15*). In this method, the definition of coarse and fine aggregate is not based on the conventional No. 4 sieve. Coarse aggregates are defined as the large aggregate particles that, when placed in a unit volume, create voids. Fine aggregates are aggregate particles that can fill the voids created by the coarse aggregates. The sieve that separates the coarse and fine aggregates is called the primary control sieve (PCS) and is dependent on the NMPS of the aggregate blend. The PCS is mathematically defined as 0.22 of the NMPS based on two- and three-dimensional analysis of the packing of different-shaped particles. Furthermore, the aggregate blend below the PCS is divided into coarse and fine portions and each portion is evaluated.

The method provides a set of tools that allows the evaluation of aggregate blends. Aggregate ratios, which are based on particle packing principles, are used to analyze the particle packing of the overall aggregate structure. The coarse aggregate (CA) ratio is used to characterize the packing and size distribution of the coarse portion of the aggregate blend. The coarse portion of the fine aggregate is evaluated using the fine aggregate ratio of the coarse portion (FA_c), and the fine portion of the fine aggregate is evaluated using the fine aggregate ratio of the fine portion (FA_f). The details of the method are available in other publications (*14, 15*).

Three aggregate structures were designed for each aggregate type (coarse, medium, fine). The structures were designed to meet the recommended ranges of the Bailey method parameters. Table 2 shows the design gradations and their Bailey method evaluation parameters for each aggregate type. For granite aggregate, only two aggregate gradations (medium and fine) were designed. Reasonable separation was maintained between the aggregate gradations within each type of aggregate in order to capture the variation in performance (if any) within the same nominal maximum size of aggregate (NMSA) for each type of aggregate. This separation is quantified by the decrease in the volume of CA in the structure when moving from the coarse to fine gradations. A great effort was made to maintain the number of stockpiles used for each aggregate blend as practical as possible. A maximum of four different stockpiles of readily available, commonly used aggregates in Louisiana were used.

MIXTURE DESIGN

Mixture design was performed for all the aggregate structures using the Superpave mixture design method. All the mixtures were designed for high-volume traffic (N_{des}=125 gyrations at 1.25° angle of gyration). The optimum asphalt content was determined as the asphalt content required to achieve 4.0% at N_{des}. Table 2 presents the results of the mix designs conducted on all the mixtures considered in this study. Optimum asphalt contents ranged from a low of 3.5% to a high of 5.1%. The coarse mixtures had higher optimum asphalt contents for all the aggregate types considered. This is explained by the higher VMA values for the coarse mixtures compared to the others, which created more room for the asphalt binder to be added and hence increased the optimum asphalt content.

TABLE 2 Aggregate Structures and Mixture Design Data

Mixture Name	LS Coarse	LS Medium	LS Fine	SST Coarse	SST Medium	SST Fine	GR Medium	GR Fine
Mix Type	12.5 mm Bailey Designs							
Aggregate Blend	42.2% #78 LS 14.3% #8 LS 36.7 % #11 LS 6.8% Sand	44.3% #78 LS 44.5 % #11 LS 11.2% Sand	41.0% #78 LS 23.6% #10 LS 20.2 % #11 LS 15.2% Sand	59.4% #78 SST 21.4% #11 SST 19.2 % #11 LS	49.8% #78 SST 43.6% #10 LS 6.6% Sand	41.3% #78 SST 48.4% #10 LS 10.3% Sand	48.3% #78 GR 29.7% #11 GR 15.4 % #10 LS 6.6% Sand	36.5% #78 GR 30.2% #11 GR 22.4 % #10 LS 10.9% Sand
Metric (U.S.) sieve								
19 mm (¾ in.)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12.5 mm (½ in.)	97.1	97.0	97.2	96.0	96.6	97.2	97.7	98.3
9.5 mm (⅜ in.)	80.3	80.2	81.7	80.7	83.8	86.5	82.5	86.8
4.75 mm (No. 4)	46.9	55.2	59.8	48.6	57.6	64.7	54.4	65.0
2.36 mm (No. 8)	31.5	39.6	46.1	32.8	41.6	48.4	39.5	49.0
1.18 mm (No. 16)	21.8	27.9	34.7	22.2	31.5	36.9	27.8	35.4
0.6 mm (No. 30)	15.3	19.7	25.6	16.2	23.7	27.8	19.7	25.5
0.3 mm (No. 50)	9.3	11.1	14.4	12.1	15.9	17.7	11.7	14.6
0.15 mm (No. 100)	6.6	7.4	9.3	6.7	11.2	12.1	7.4	9.0
0.075 mm (No. 200)	5.5	6.0	7.2	4.2	8.4	9.1	5.4	6.5
CA Volume	56.0	46.4	41.0	56.0	47.8	40.8	48.1	38.3
CA Ratio	0.612	0.706	0.797	0.627	0.765	0.792	0.694	0.728
FA_c Ratio	0.487	0.374	0.361	0.493	0.471	0.435	0.377	0.352
OAC, %	5.1	4.0	3.5	5.1	3.6	3.9	4.5	4.3
VTM	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
VMA	11.0	11.3	9.4	13.1	8.4	8.5	11.3	10.9
VFA	64.8	62.7	58.5	69	50.0	54.0	62.4	60.6
$\%G_{mm}$ at N_{ini}	85.1	86.2	88.0	86.6	86.4	88.0	87.3	87.1
$\%G_{mm}$ at N_{max}	97.2	97.4	97.3	97.0	97.1	97.4	97.2	97.0
Effective film thickness, microns	8.7	5.5	3.4	8.8	2.5	2.5	6.0	4.5
Dust/P_{beff}	1.3	2.0	3.1	1.1	4.7	4.7	1.7	2.3

LS: Siliceous limestone, SST: Sandstone, GR: Granite, VFA: voids filled with aggregate.

VMA values ranged from a high of 13.1 % to a low of 8.4%. The sandstone medium and fine mixtures had the lowest VMA values. The VMA values for all the mixtures were below the minimum requirement of the current Superpave system for 12.5-mm (1/2-in.) NMPS mixtures. It is noted that mixtures with similar NMPS have different VMA values. This observation supports the concern about the validity of the current VMA requirements based on the NMPS. It is evident that VMA is sensitive to aggregate gradation within the same NMPS. All the mixtures met the Superpave requirements for $\%G_{mm}@N_{ini}$ and $\%G_{mm}@N_{max}$.

The average effective binder film thicknesses ranged from 8.8 microns for limestone and sandstone coarse mixtures to as low as 2.5 for medium and fine sandstone mixtures. For most medium and fine mixtures, the calculated film thickness was below the generally reported range of 6.0 to 8.0 microns.

ASPHALT MIXTURE COMPACTIBILITY

The compactibility of the designed asphalt mixtures was evaluated using results from the SGC. The densification curves obtained from the SGC were used to evaluate mixture resistance to the compaction energy applied by the SGC.

In this study, the following terms will be used in the analysis of the results from the SGC:

- SGC locking point. The SGC locking point is the number of gyrations after which the rate of change in height is equal to or less than 0.05 mm for three consecutive gyrations (Figure 1*a*).
- SGC compaction densification index (CDI). The area under the SGC densification curve from N = 1 to the SGC locking point (Figure 1*b*). This index is hypothesized to be related to compactibility of asphalt mixtures. Higher values of this index are associated with mixtures that are difficult to compact.
- SGC traffic densification index (TDI). The area under the SGC densification curve from the SGC Locking Point to N at 98% G_{mm} or the end of compaction, whichever comes first (Figure 1*b*). This index is hypothesized to be related to the mixtures stability under traffic loading. Higher values are supposed to be indicative of better mixtures stability.

The locking point data from the SGC suggest that coarse mixtures take a higher number of gyrations to reach to the locking condition. This indicates that it takes more energy to densify coarse mixtures compared to the medium and fine mixtures. As the aggregate gradation becomes finer, the compactibility of the mixtures improves except for the fine granite mixture in which locking point was slightly higher than the medium gradation. It is worth noting that the locking points are much lower than the design number of gyrations recommended by the current Superpave system. The highest locking point is less than 70% of the recommended design number of gyrations for the heavy traffic category (N_{des} = 125). The fine limestone mixture had the lowest locking point (57 gyrations).

The concept of energy indices was first introduced by Bahia (*2*) in 1998. In his study, Bahia calculated the energy indices using the region from N = 8 to N at 92% G_{mm} of the densification curve for the CEI (later renamed CDI as used in this study) and from N at 96% G_{mm} to N at 98% G_{mm} for the TDI. He assumed that the first eight gyrations represent the constant compaction energy applied by the paver screed. In this study, however, the densification curve is divided into two main regions: the densification region from N = 1 to the locking point, which is used to calculate the CDI, and the post-densification region from the locking point to N = 205, which represents the terminal densification of the mixture at the end of service life and is used to calculate the TDI. Figure 1*c* shows the energy indices calculated for all the mixtures in the study.

The compaction densification index CDI from the SGC had notable variations across the different gradations within the same NMPS, indicating that it is sensitive to the size distribution of blends having the same NMPS. For example, for limestone mixtures, the fine mixture required about 48% lower energy to reach the locking condition than the coarse mixture. The sandstone had lower variation in CDI across the different gradations. The fine sandstone mixtures took

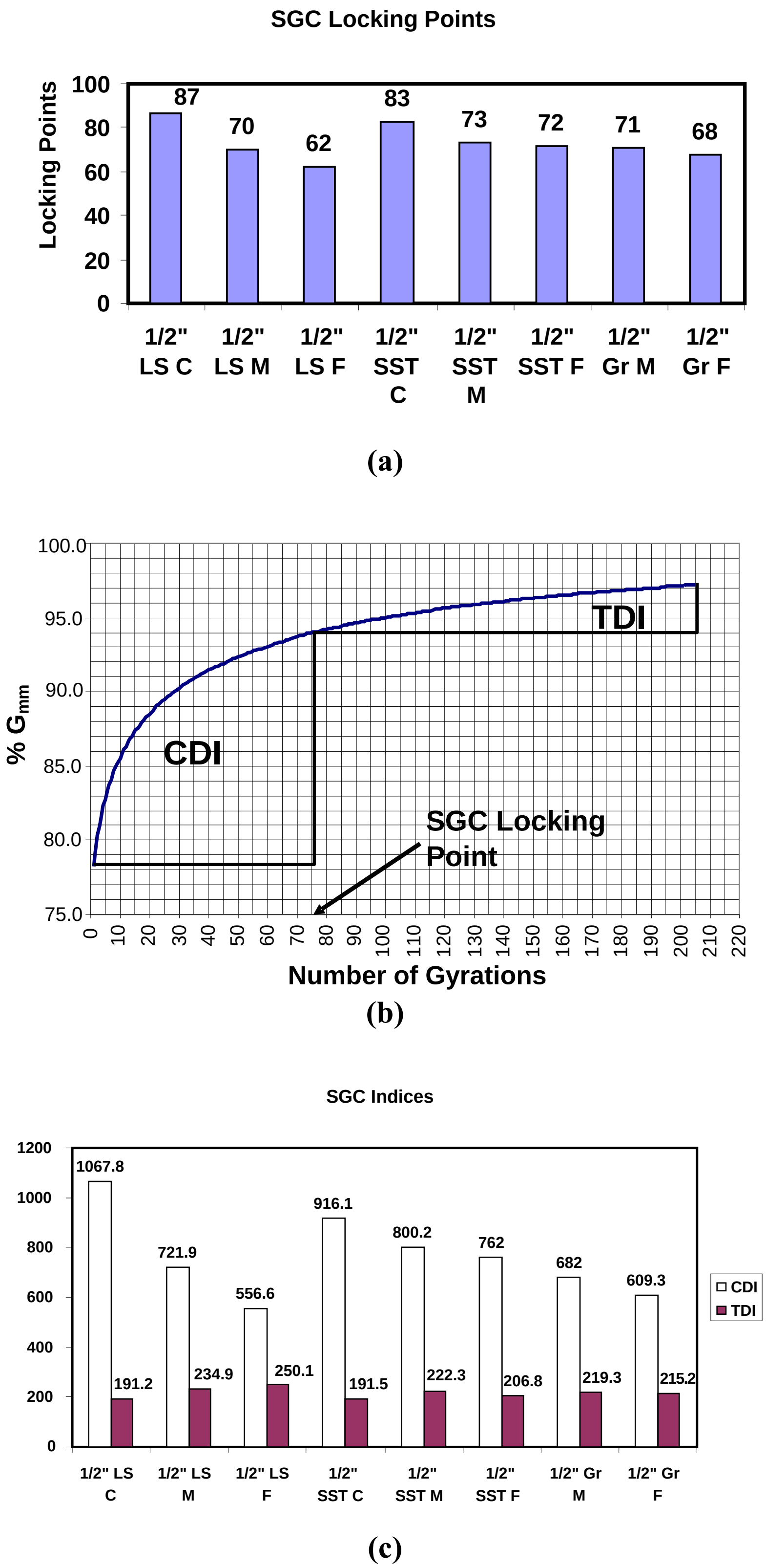


FIGURE 1 Compaction parameters of asphalt mixtures.

about 17% less compaction energy than the coarse one to reach to the locking condition. There was about an 11% difference in compaction energy between the medium and the fine granite gradations. The data, therefore, suggests that it will take more energy to compact coarse mixtures in the first region of the densification curve, indicating that those mixtures might be less desirable for construction and more likely to have compactibility problems.

The aggregate resistance to further densification from traffic loading was explored using the TDI from the SGC. The variation of this index, although still existent, is less than that observed with the CDI. This was expected since the behavior of the mixtures beyond their locking points was relatively similar with very small rates of change in mixture densification.

RESULTS AND DISCUSSION

Gradation Parameters and Mixtures Volumetrics

The effect of aggregate gradation on mixture volumetrics was investigated using the gradation parameters obtained from the Bailey method. Two parameters were used in this investigation. These are the CA ratio and the FA_c ratio. The third Bailey parameter, FA_f, is not calculated for fine mixtures having 12.5-mm NMPS or lower (*15*). Figure 2 illustrates the relationship of the Bailey parameters with mixture's volumetric and other physical properties. It should be noted that all the mixtures were subjected to the same type and amount of compaction energy (SGC Compaction, N_{des}).

CA ratio, which is predominantly a function of the coarse aggregate blend by volume, seems to have the strongest correlation with the mixture volumetrics. As the CA ratio increases, the smaller size particles in the coarse portion of the aggregate structure become more dominant, and that had an inverse effect on the main volumetric parameters such as VMA and VFA. A strong correlation was obtained between the CA ratio and the effective film thickness (R^2 = 0.946).

Mixture volumetrics seem to be less sensitive to the change in the FA_c ratio. A parabolic type of relationship was obtained between FA_c ratio and both VMA and VFA. The minimum value occurred around an FA_c value of 0.435. As the volume of fines exceeds the voids in the coarse part of the fine portion of the blend (that is, moving right from the dip), the VMA in the overall fraction increases. In contrast, as the volume of the coarse part of the overall fine fraction increases (that is, moving left from the dip), the VMA in the overall fraction increases. No relationship could be established between the FA_c ratio and effective film thickness or dust/P_{beff} ratio.

Gradation Parameters and Mixture Compactibility

It was established earlier that compaction characteristics were different for mixtures with different aggregate gradations. In order to quantify the effect of aggregate gradation on the compactibility of the mixtures, the gradation parameters from the Bailey method were utilized. Figures 2*i* and 2*j* describe the relationship between mixture compactibility, as represented by the SGC compaction densification index CDI, and those parameters from the gradation analysis. CDI clearly does respond to a change in the gradation parameters, indicating that those parameters describe the actual gradation characteristics of the mixtures and that the

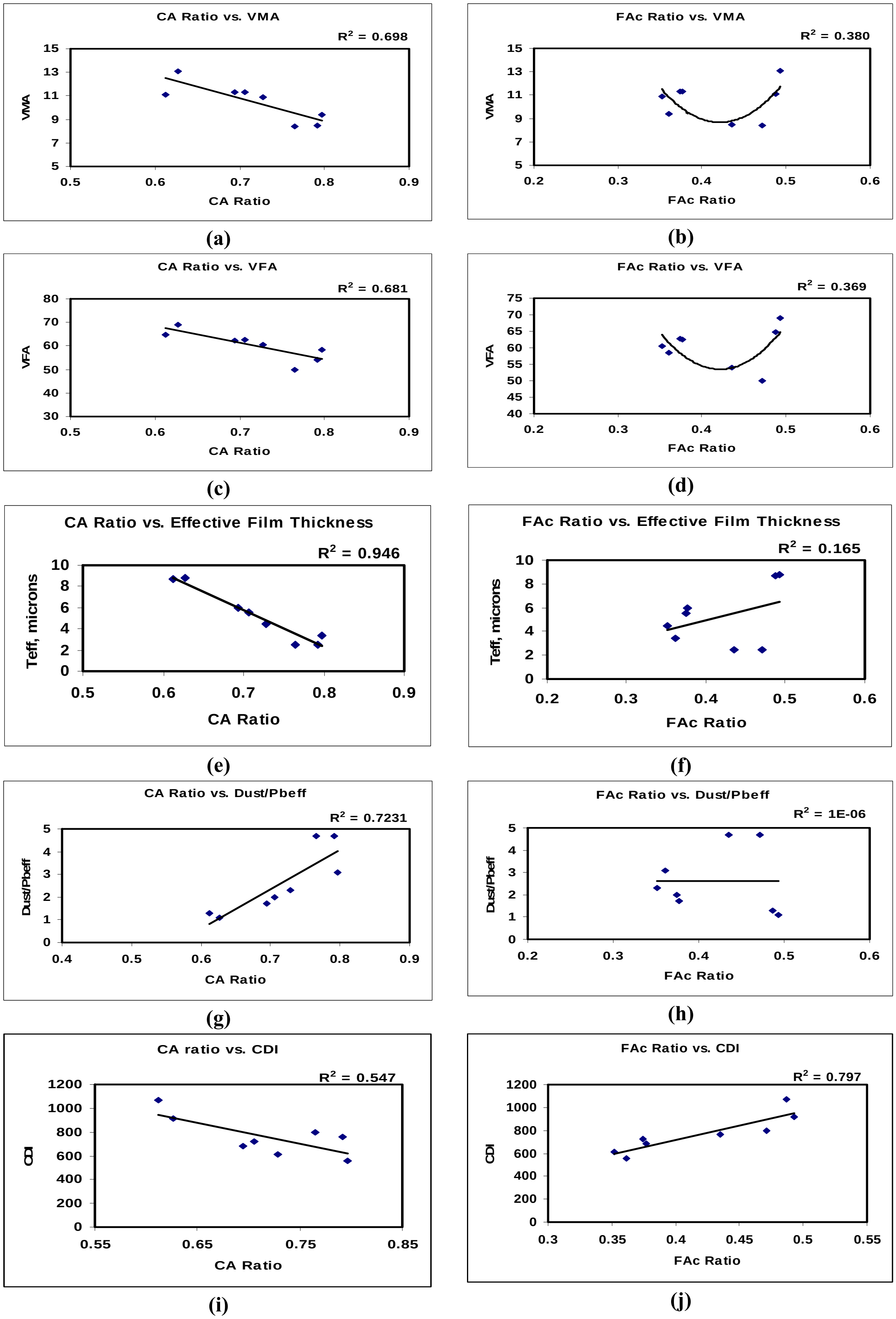


FIGURE 2 Bailey method gradation parameters and mixture physical properties.

compactibility of the mixtures is a function (among other factors) of the particle size distribution as measured by those parameters. FA_c ratio had the best correlation with the CDI. This parameter describes the coarse portion of the fine region in the aggregate gradation curve.

MIXTURE PERFORMANCE

Hamburg Wheel Tracking Test

The designed mixtures were evaluated for their performance under severe load and environmental conditions using the Hamburg wheel tracking (HWT) test. This is a torture test to determine a mixture's resistance to rutting and moisture damage. The HWT device measures the combined effects of rutting and moisture damage by rolling a steel wheel across the surface of an asphalt concrete slab 260.8 mm wide by 320.3 mm long and 40.0 mm thick (for surface course mixtures) that is immersed in hot water at a temperature of 50°C. Two slabs per mixture were tested simultaneously. The slabs were compacted to 7.0 ± 0.5% air voids. A fixed load of 685 N was applied at a rate of 56 wheel passes per minute. A load cycle in this test is equivalent to two passes. All the tests were run for 20,000 cycles.

Figure 3*a* presents the mean rut depths for all the mixtures in the study together with their statistical grouping. Mixtures with the same letter are not significantly different in their performance. All the mixtures had superior performance with a maximum rut depth of 3.7 mm after 20,000 cycles for the limestone coarse mixture. No signs of stripping were found at the end of the test period. The best performing mixture was the sandstone medium mixture with only 1.5-mm rut depth after 20,000 cycles.

The effect of aggregate gradation on HWT results was evaluated using the parameters obtained from the Bailey method as shown in Figures 3*b* and 3*c*. The gradation parameter describing the coarse portion of the gradation curve (CA ratio) had good correlation with the HWT data with an R^2 of 0.769. The trend indicates that there might be optimum values for this parameter for better rutting resistance under HWT test conditions of load and environment. The FA_c ratio had a weaker correlation with HWT results.

The results from the HWT test were also analyzed using the traffic densification index, TDI, obtained from the SGC. It was expected that the higher the TDI, the lower the rut depths obtained from the HWT test, if this index truly provides an indication of a mixture's stability. The data, however, showed an unexpected increase in the rut depth after a certain value of TDI as shown in Figure 3*d*. This raises a question of the suitability of this energy approach to highlight plastic instability of asphalt mixtures. The inability of this index to capture that can be attributed to the fact that the mixture is contained within the rigid walls of the compaction mold and the equally rigid top and bottom platens, which prevent any of the lateral flow that constitutes the basic mechanism of permanent deformation in asphalt pavements.

The effect of VMA on the rutting performance of asphalt mixtures, as measured by the HWT test, is shown in Figure 3*e*. A trend of increasing rut depth with higher VMA values is observed. The correlation however, is not statistically significant.

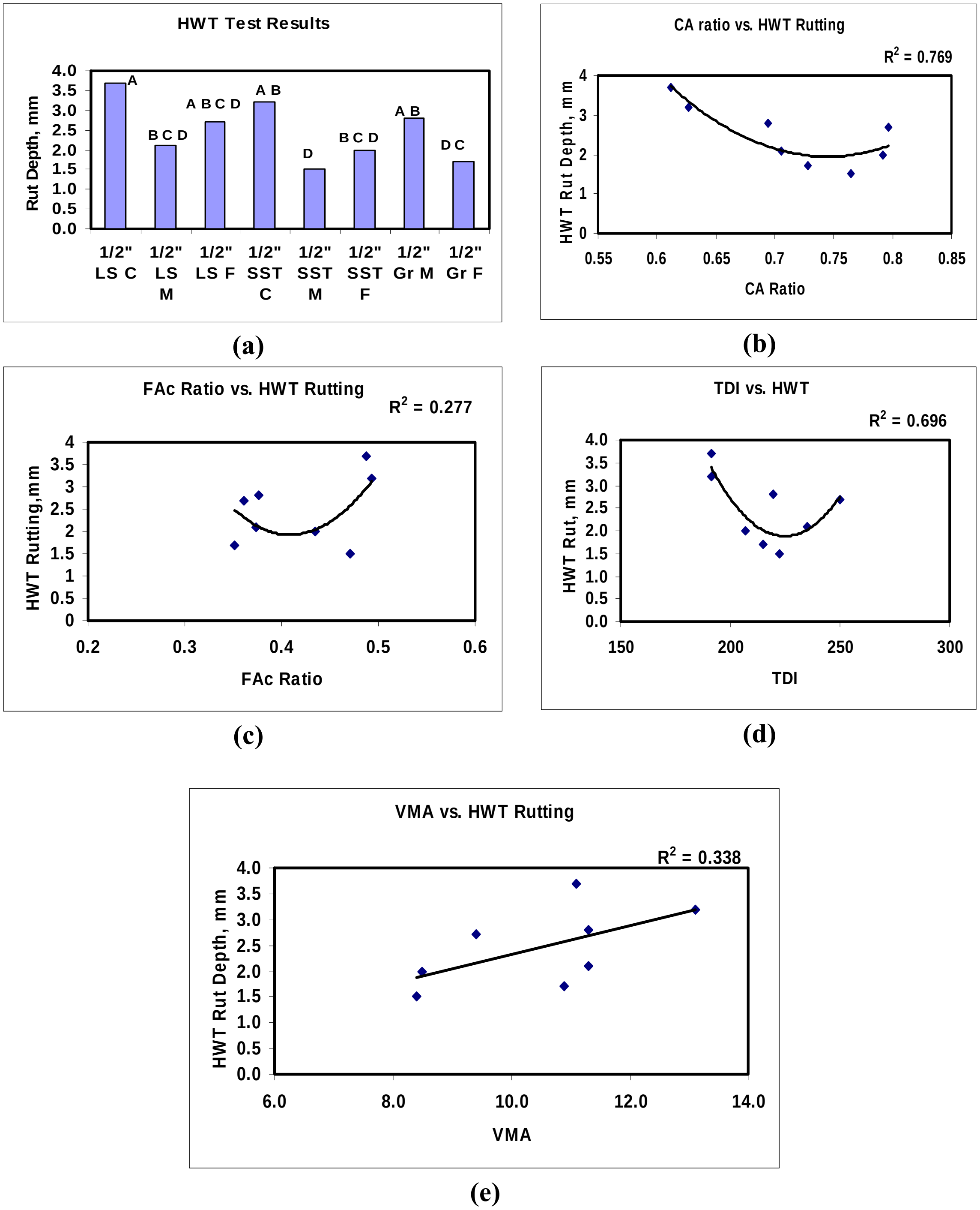


FIGURE 3 Analysis of the HWT test results.

Semicircular Fracture Energy Test

The fracture resistance of the mixtures designed in this study was investigated using the J-integral approach. This approach is gaining popularity for characterizing heterogeneous materials such as asphalt mixtures. The method accounts for flaws represented by a notch, which in turn, reveals the material's resistance to crack propagation or what is called fracture resistance (*16*).

Three notch depths were used: 25.4 mm, 31.8 mm, and 38.0 mm. Two specimens per notch depth were tested. SGC specimens 150.0 mm in diameter by 57.0 mm thickness were compacted to 7.0 ± 0.5% air voids. The specimens were then sliced perpendicular to the central axis to obtain semicircular test specimens. Air void measurements were made again on the cut specimens to ensure that air void level was still within the targeted range. The test specimens were then loaded monotonically at a rate of 0.5 mm/min in a three-point bending load configuration as shown in Figure 4*a*.

The load deflection curve was recorded and the fracture resistance was determined as follows:

$$J_c = -\left(\frac{1}{b}\right)\frac{dU}{da}$$

where *b* is the specimen thickness, *a* is the notch depth, and *U* is the total strain energy to failure, i.e., the area up to fracture under the load-deflection plot as presented in Figure 4*b*. The test temperature was 25°C. Figure 5 presents the results of the calculated fracture resistance from the semicircular notched fracture test for all the mixtures. Within each aggregate type, coarser mixtures had higher fracture resistance compared to the medium and fine ones. The highest fracture resistance was obtained for the sandstone coarse mixture, which was about 79% higher than that obtained for coarse limestone mixtures and 38% higher than the medium granite mixture. A good correlation was obtained between the fracture resistance and the mixtures' effective film thicknesses (R^2 = 0.620) in which the fracture resistance increased with thicker binder films around the aggregates, as clearly shown in Figure 6*a*.

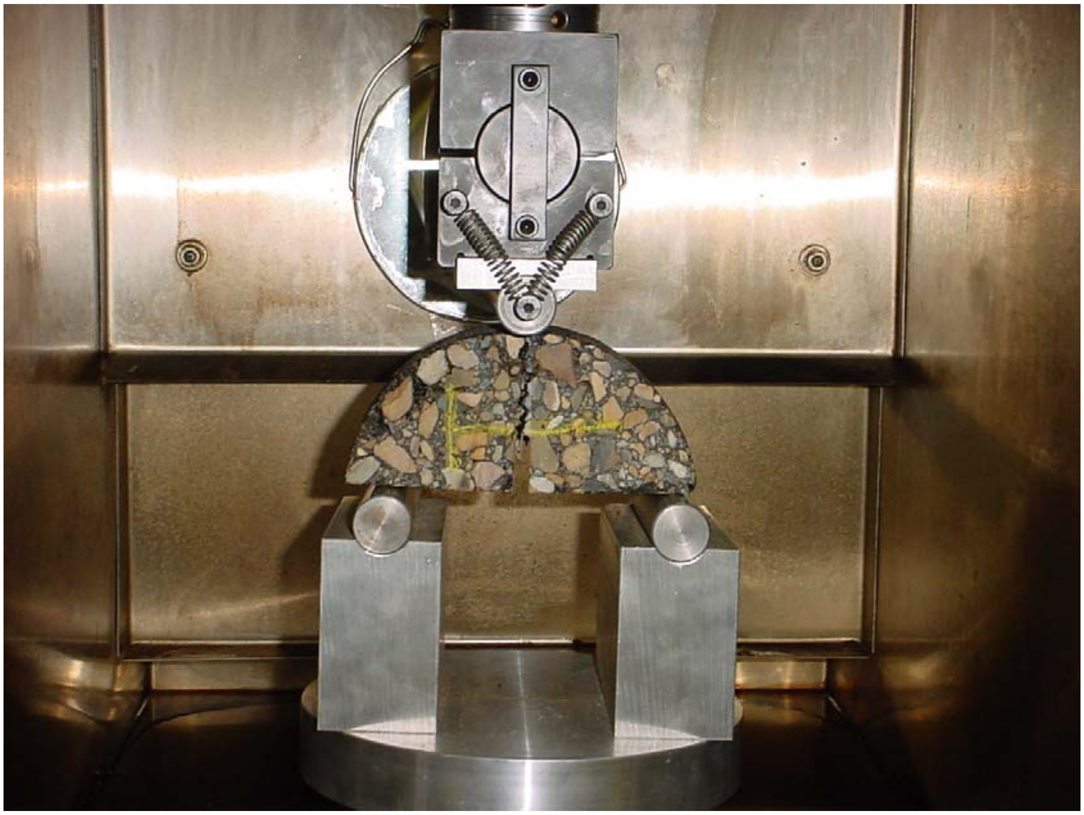
The sensitivity of the fracture energy to VMA is clearly demonstrated in Figure 6*b*. Mixtures with higher VMA values tended to have better fracture resistance than those with relatively lower VMA values.

The relationship of the gradation parameters to the fracture resistance is shown in Figures 6*c* and 6*d*. A trend of decreasing J_c with higher CA ratio (finer gradation) is observed. No trend could be established between FA_c ratio and J_c.

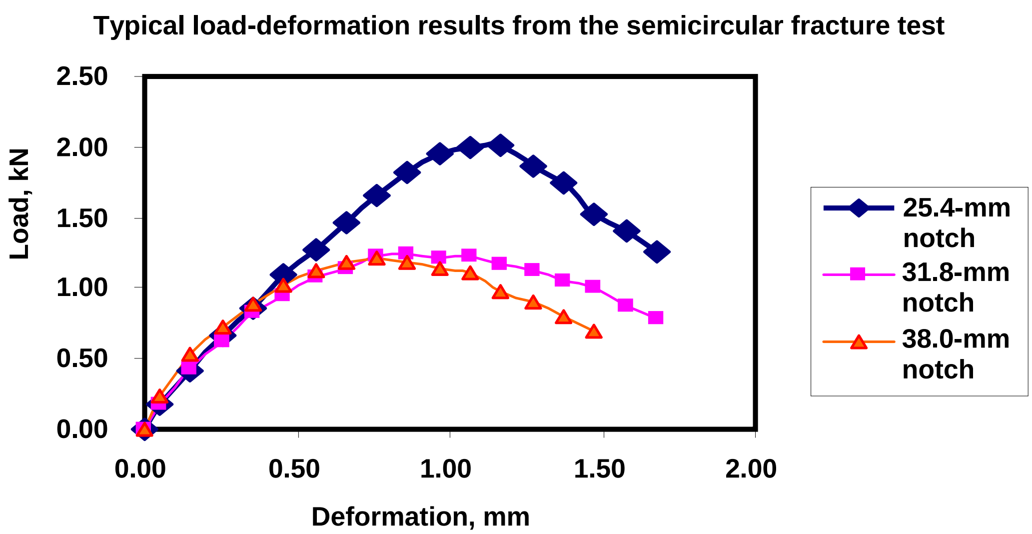
The energy data were also analyzed using the traffic densification index defined earlier, as shown in Figure 6*e*. No correlation could be established between this parameter and the fracture resistance of the mixtures. This index was mainly developed to assess a mixture's resistance to densification under traffic and hence it is not expected to describe the fracture resistance as measured by the *J*-integral test.

Mixture Design Based on Variable Compaction Level

It was clearly evident from the results discussed in the previous section of this paper that neither VMA nor the design number of gyrations is the same for mixes with different aggregate types and structures. Different mixes responded differently to the applied compaction energy, which makes the current approach of specifying the same design number of gyrations to all different



(a)



(b)

FIGURE 4 Semicircular test setup and typical output.

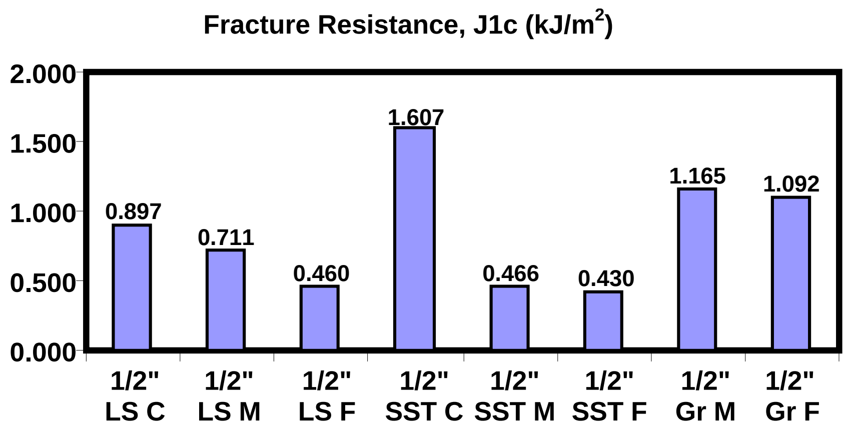


FIGURE 5 Semicircular fracture energy test results.

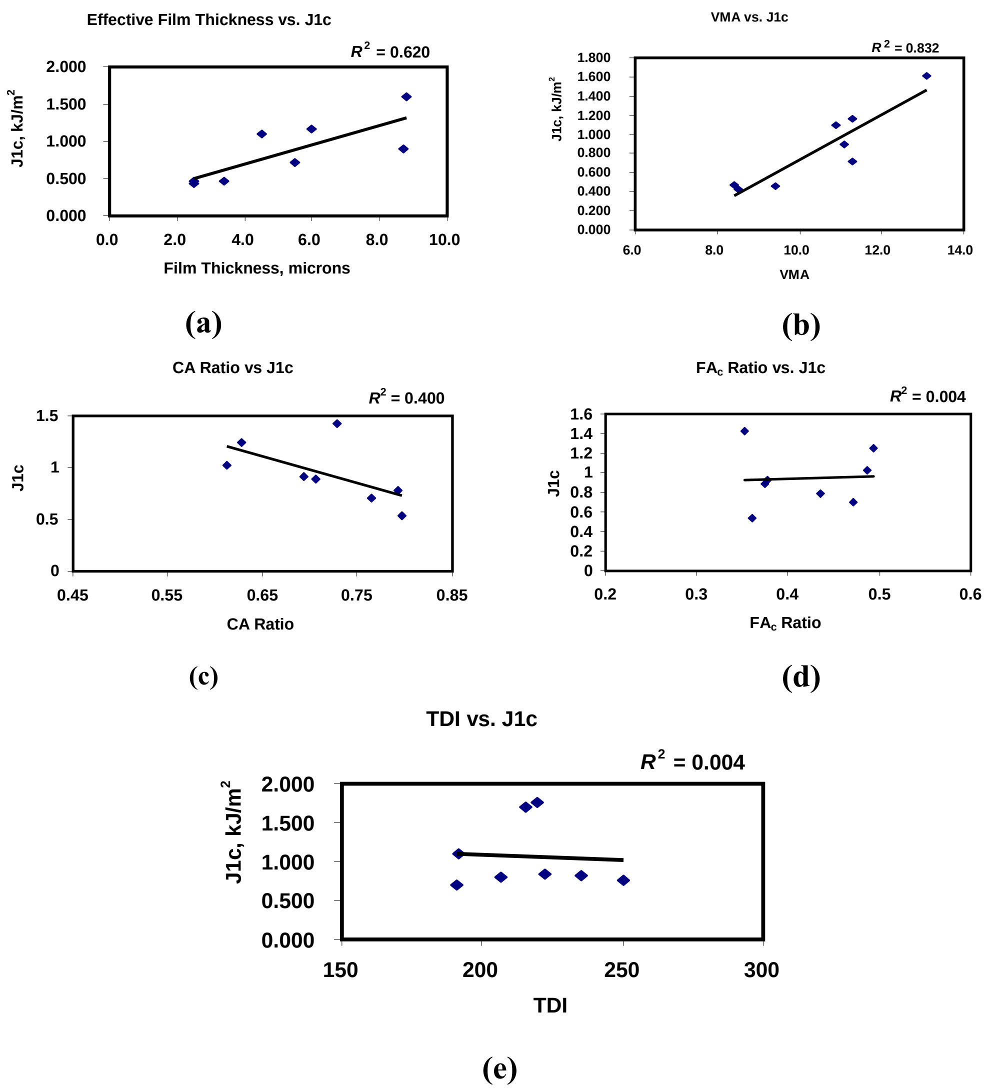


FIGURE 6 Mix physical properties and semicircular fracture energy test results.

mixes in the same traffic level questionable. Therefore, a test plan was developed to determine if it is appropriate to design asphalt mixtures by using a number of gyrations that is mix-specific and lower than that recommended by the current Superpave system. The premise was that using a lower number of gyrations will increase the design asphalt content and hence improve durability. The suggested approach was to utilize the concept of locking point in specifying the design number of gyrations. It was shown that the locking points of all the mixtures designed in this study were different and lower than the currently specified single N_{des} for all the mixes in the traffic level considered. A limited number of mixtures designed in this study were selected for mixture design using the locking point concept as opposed to the traditional Superpave N_{des}. The selected mixtures were as follows: fine granite, fine limestone, coarse limestone, and medium sandstone.

Graphical comparisons of the physical properties of mixtures designed using the locking point, together with their properties from $N_{des,}$ are presented in Figure 7. As anticipated, compacting mixtures to their locking point yielded higher design asphalt contents than those obtained when N_{des} was used. The design asphalt content ranged from 4.1% to 5.4% with the locking point, compared to 3.5% to 5.1% for the same mixtures compacted using N_{des}. It is worth noting that, except for the coarse limestone mixture, there was about a 0.6% increase in asphalt content for all other mixtures when the mixtures were designed using their locking points at the same 4.0% air void level.

The VMA values were about 1.1% to 1.2% higher with the locking point, except for the medium sandstone mixture in which there was a 0.8% increase. Again, this finding clearly indicates that VMA is compaction dependent and specifying it based on NMPS only as currently adopted by the Superpave design system is questionable.

Higher asphalt contents naturally resulted in higher VFA, lower Dust/P_{beff} ratio, and hence higher effective film thicknesses for the mixtures considered.

For comparison and determination of relative performance, the selected mixtures were evaluated using a similar testing suite conducted in phase one, mainly HWT, indirect tensile (IT) strength test (ITS), and fracture resistance using the notched semicircular fracture energy test (Jc).

The performance of the mixtures in the HWT test is shown in Figure 8. There was a slight increase in the amount of rutting for mixtures designed using the locking point partly due to higher asphalt contents used. The highest rut depth was 4.0 mm for 12.5 mm (1/2 in.) coarse limestone. The results however, are still within the range of good performing mixtures indicating that stability was not compromised by designing the mixes using lower compaction levels.

The cohesion characteristics of the mixtures were determined using the ITS and strain test to determine the tensile strength and strain of the mixtures. This test was conducted at 25°C in accordance with AASHTO T245. Each test specimen was loaded to failure at a 50.8 mm/min (2 in./min) deformation rate. The loads and deformations were continuously recorded. Aged samples were conditioned using long-term oven aging in a force draft oven at 85°C for 5 days following the protocol recommended in AASHTO PP2 (1994).

Three parameters from this test were used in the analysis: aged IT strength, aged IT strain, and toughness index (TI). Tensile strength values were slightly lower than those obtained for the mixtures compacted at N_{des}. The strength values ranged from 168.3 for the 12.5 mm (1/2 in.) coarse limestone mixture to 325.0 psi for the 12.5-mm (1/2-in.) medium sandstone mixture (Figure 9). The highest reduction in strength was observed for the 12.5-mm (1/2-in.) fine limestone mixture which had a strength value of 27.8% lower than that obtained for the same

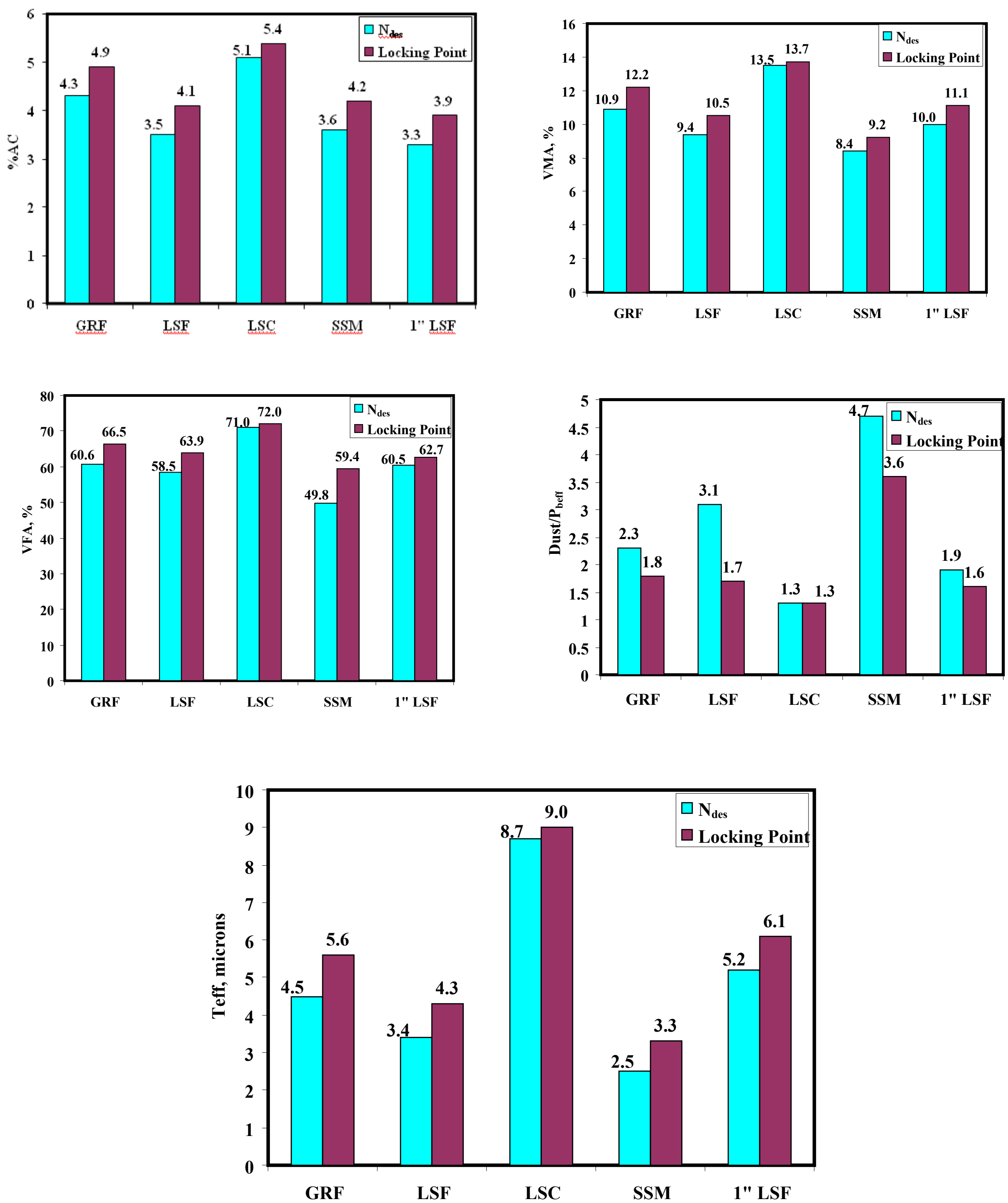


FIGURE 7 Comparison of mixtures' physical properties.

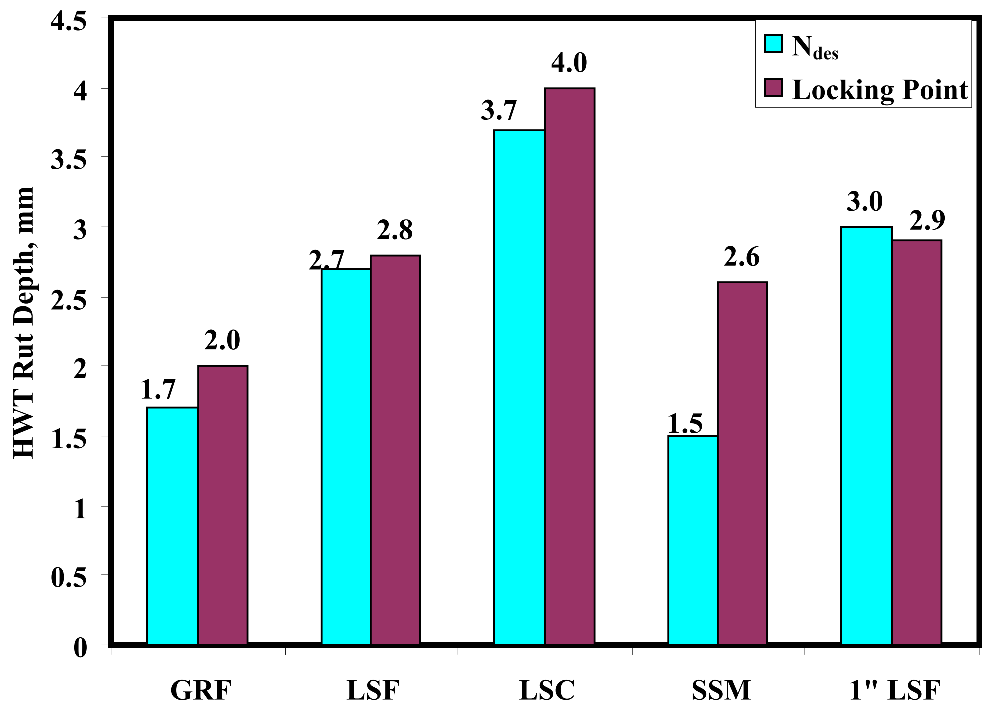


FIGURE 8 HWT results comparison.

mix designed using the Superpave recommended N_{des}. The lowest change in strength was observed for the one inch fine limestone with only 4.1% reduction in strength.

Analyzing the strain data presented in Figure 9 clearly indicates that the mixtures now exhibit higher IT strain values at failure, which implies that they will retain more flexibility over time compared to the phase one mixtures and that makes them relatively less prone to pre-mature failure due to aging.

TI data are also presented in Figure 9. The TI is a parameter describing the toughening characteristics in the post peak region. It compares the performance of a specimen with that of an elastic perfectly plastic reference material, for which the TI remains a constant at one. For an ideal brittle material with no post-peak load carrying capacity, the value of TI equals zero.

The lowest toughness index was obtained for the medium sandstone mixture, followed by the fine limestone. Those two mixtures had the lowest effective film thickness and the highest dust/P_{beff} ratio. Their TI values, although still not considered low (>0.5), are exhibited than those of the other mixtures, which makes them less favorable in terms of their ability to resist aging over time. It should be noted that all the mixtures showed better toughness properties at their locking points than at Superpave N_{des}.

Figure 10 presents the calculated *J*-integral from the semicircular notched fracture test. The test was conducted on mixtures that were aged for 5 days in a forced-draft oven at 85ºC. All the mixtures exhibited an increase in their fracture resistance when designed using the locking point. The granite fine mixture showed the same fracture resistance under both N_{des} and locking point and was the highest among the mixtures tested. The biggest improvement in fracture resistance was observed for the coarse limestone mixture for which there was about 49%

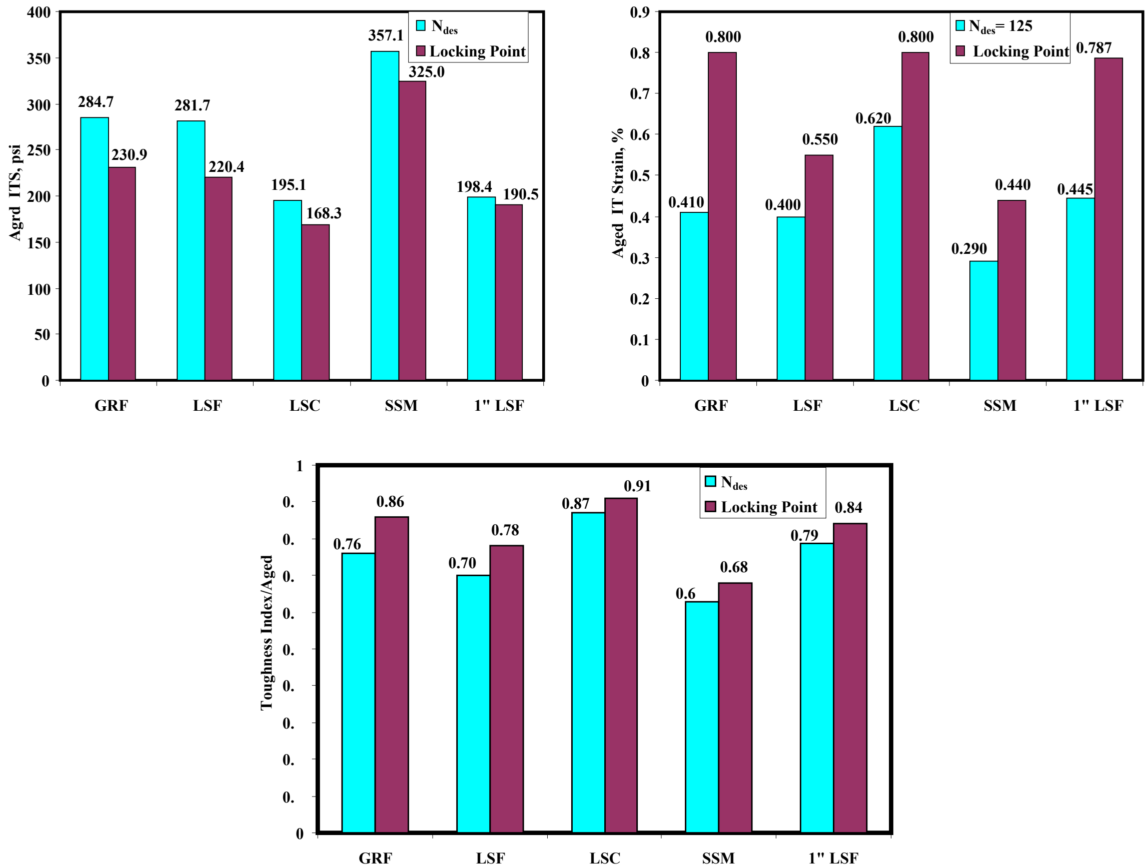


FIGURE 9 ITS results comparison.

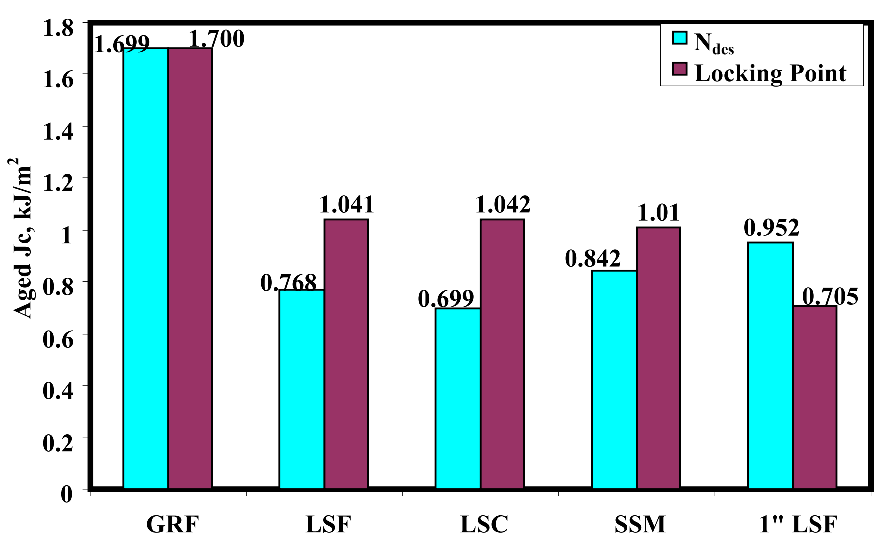


FIGURE 10 Semicircular fracture resistance test results comparison.

increase in J_c when designed using the locking point, followed by the fine limestone mixture which had about 35% increase in J_c. The 12.5-mm (1/2-in.) medium sandstone mixture gained about 20% in J_c.

SUMMARY AND CONCLUSIONS

The compaction and performance characteristics of asphalt mixtures with aggregate structures designed using an analytical gradation method were evaluated through a series of laboratory tests and aggregate gradation analyses. Eight mixtures were evaluated. Aggregate structures were designed using the Bailey method of aggregate gradation evaluation. The compactibility of the mixtures was evaluated using the data from the SGC. Laboratory tests performed on the designed mixtures included the HWT, semicircular fracture test and the indirect tensile strength test. Aggregate gradation analysis was conducted using the parameters from the Bailey method. This type of analysis provides a tool that correlates gradation parameters to mixture performance properties.

The findings of this study are summarized as follows:

- The Bailey method provides a rational approach to aggregate blending and evaluation.
- Adhering to the recommended Bailey ratios produced satisfactory results in terms of volumetrics for coarse mixtures. Fine and medium mixtures however, had lower VMA values than the current Superpave recommendations.
- The data from the SGC suggest that coarse mixtures are more difficult to compact compared to medium and fine ones.
- The compaction data also suggest that the current recommended Superpave design number of gyrations is too high and subjects the mixtures to unnecessarily high compaction loads for a long period of time, which might have an adverse effect on the final mixture volumetrics. The highest locking point in this study was under 70% of the recommended design number of gyrations for the heavy traffic category.
- The CA ratio, which is predominantly a function of the coarse aggregate blend by volume, seems to have the strongest correlation with mixture volumetrics. Mixture volumetrics seem to be less sensitive to changes in the FA_c ratio.
- A strong correlation was obtained between the effective film thickness and CA ratio (R^2 = 0.946).
- CDI does respond to changes in the gradation parameters, indicating that these parameters do describe the actual gradation characteristics of the mixtures and that the compactibility of the mixtures is a function of the particle size distribution as measured by the Bailey gradation parameters (among other factors). The FA_c ratio had the best correlation with the CDI.
- All the mixtures had good performance in the HWT test with a maximum rut depth of 3.7 mm after 20,000 cycles for the limestone coarse mixture. No signs of stripping were found at the end of the test period.
- The results showed that the performance of the mixtures in the HWT test was sensitive to the CA ratio used to analyze the coarse portion of the aggregate gradation in this study.

- The results from the HWT test were not sensitive to changes in the traffic densification index, TDI, from the SGC densification curve.
- Coarser mixtures tended to have higher fracture resistance compared to the medium and fine ones.
- A good correlation was obtained between the fracture resistance and the mixture effective film thickness (R^2 = 0.620) in which the fracture resistance of the mixtures increased with thicker binder films around the aggregates.
- High VMA seemed to improve the fracture resistance of the asphalt mixtures.
- The gradation parameter CA ratio had a statistically significant correlation with Jc. The higher this parameter (finer gradation), the lower the fracture energy obtained.
- No correlation could be established between the TDI and the fracture resistance of the mixtures.
- The data presented in this paper suggest that mixes with dense aggregate structures can be designed using their locking point instead of the recommended N_{des}. The designed mixtures maintained good resistance to permanent deformation and an adequate level of durability.

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