

Study of Compaction in Hot-Mix Asphalt Using Computer Simulations

Kasthurirangan Gopalakrishnan, Naga Shashidhar, and Xiaoxiong Zhong

Abstract—During the process of compaction in Hot-Mix Asphalt (HMA) mixtures, the distance between aggregate particles decreases as they come together and eliminate air-voids. By measuring the inter-particle distances in a cut-section of a HMA sample the degree of compaction can be estimated. For this, a calibration curve is generated by computer simulation technique when the gradation and asphalt content of the HMA mixture are known. A two-dimensional cross section of HMA specimen was simulated using the mixture design information (gradation, asphalt content and air-void content). Nearest neighbor distance methods such as Delaunay triangulation were used to study the changes in inter-particle distance and area distribution during the process of compaction in HMA. Such computer simulations would enable making several hundreds of repetitions in a short period of time without the necessity to compact and analyze laboratory specimens in order to obtain good statistics on the parameters defined. The distributions for the statistical parameters based on computer simulations showed similar trends as those of laboratory specimens.

Keywords—Computer simulations, Hot-Mix Asphalt (HMA), inter-particle distance, image analysis, nearest neighbor

I. INTRODUCTION

MORE than 94 percent of the paved roads in the United States is covered with Hot-Mix Asphalt (HMA). A typical HMA pavement is made of 86% by volume of aggregates bound with about 10% by volume of asphalt cement and incorporates 4% of air-voids. The binder is a product of oil refining and its function is to glue the aggregate particles together. These individual materials and components have different physical and mechanical properties and behavior that have a significant effect on the performance of HMA mixes [1].

Compaction is the process in which aggregates coated with asphalt cement are brought together by pressure and kneading action with or without vibration while reducing the volume of air trapped within it. Thus, the internal structure of HMA,

which refers to the content and the spatial and directional distribution of air-voids, aggregates and asphalt cement as well as the chemical and physical interactions among these constituents [2], evolves during the process of compaction. It has been well recognized that the internal structure of HMA plays a significant role in the mechanical properties of HMA and in the resistance of HMA pavements to major distresses [3,4].

Thus, compaction is a crucial step in the construction of HMA pavements. It is usually defined in terms of density or percent air-voids. During the process of compaction the volume of the mass reduces by 15-20%. Also the aggregates are brought closer to one another, which raises the key question— Is it possible to study the degree of compaction in HMA by studying the inter-particle distances?

The study of the inter-particle distances would also enable determination of compaction in different directions, comparison between different compaction techniques and perhaps even non-homogeneities in HMA specimens.

Over the last decade, several researchers have used two-dimensional (2-D) and three-dimensional (3-D) image analysis techniques to quantify the effect of compaction on the internal structure of HMA [4-9].

Masad et al. [4] used image analysis techniques in studying the difference in internal structure of HMA specimens compacted with the Superpave Gyrotory Compactor (SGC) and the Linear Kneading Compactor (LKC) in the laboratory. Tashman et al. [6] investigated the relationship between aggregate orientation and compaction effort using imaging techniques. Hunter et al. [10] investigated the internal structure of HMA created by different laboratory compaction methods (gyrotory, vibratory, and slab) and compared it with mechanical performance. As a part of Federal Highway Administration's (FHWA) SIMAP (Simulation, Imaging, and Mechanics of Asphalt Pavements) program, Gopalakrishnan et al. [11] quantified the degree of compaction in LKC compacted HMA specimens using image analysis techniques.

In studies such as these, it is advantageous to simulate the HMA internal structures in the computer and measure all the parameters. Such simulations would enable making several hundreds of repetitions in a short period of time without the necessity to compact and analyze laboratory specimens in order to obtain good statistics on the parameters defined. The low noise in such simulated measurements due to the many repetitions would enable us to identify the true behavior of the parameters. Furthermore, several different mix designs can be

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tested to determine the robustness of the parameters.

In this paper, computer simulation techniques are used to study and understand the effect of compaction on HMA internal structure in terms of inter-particle distances.

II. COMPUTER SIMULATION OF HMA: BENEFITS

In computer simulations, the gradation information of the HMA is input into the computer. The computer then packs the aggregate particles into a compact. The aggregates are typically modeled as hard spheres for simplicity. An advantage of studying computer-simulated models as opposed to physical models is that the geometrical properties of the internal structure can be accurately determined, as the particle coordinates are precisely known to the machine accuracy of the computer. Since the exact locations of these particles are known, the number of contacts, the coordination number of these contacts and other characteristics of the compact can be estimated. It is possible to use mathematical descriptors for particle shape and surface texture, introduce flat and elongated particles, and thereby study their effects on HMA properties.

Also, the computer could be programmed to find the optimized gradation that would yield a mix with desired properties. In this loop, the computer would start with an initial gradation and calculate the characteristics of the compact. It could then vary the inputs and check the characteristics of the compact in a closed loop until the desired characteristics are achieved.

Perhaps, the most significant benefit is that computer simulations cost less and take less effort than conducting real experiments. It is admitted that it takes effort to develop the computer code, theory and validate the code. But, once developed, several simulations can be run in short time. For instance, if the effect of different gradations on the density of HMA were to be evaluated, the aggregates have to be sieved and batched. They have to be heated, mixed with hot asphalt, compacted, and cooled, and then the specific gravity has to be measured in the laboratory. The whole process could take as long as a day to test one sample. If, however, a computer simulation technique has been developed, the complete testing for a given gradation can be done in few minutes.

Furthermore, the variability in measured properties would be much higher than what could be obtained through computer simulation techniques. Sometimes the real differences between properties may not be detected by physical testing since the noise level is so high. In simulation, it is possible to achieve much lower coefficient of variation. Multiple simulation runs can further reduce the coefficient of variation.

If an anomalous result is obtained by computer simulation, one can examine the resultant compact to determine if there was anything unusual in the compact. However, in a physical sample, it is extremely difficult to pinpoint the cause of such anomalies unless one has access to techniques like X-ray computed tomography.

An important benefit of modeling and simulations is that they increase our understanding of the mechanism behind

certain phenomena. For instance, when the permeability of concrete was higher than it should have been, several tests were conducted. Scanning Electron Microscopy (SEM) of the concrete indicated the cement matrix to contain more air-voids adjacent to the aggregate particles. Computer modeling of diffusion [12] was able to show that the increased air-voids could indeed increase the diffusion rate. By knowing this information, low-permeability concrete could be designed.

III. QUANTIFYING COMPACTION IN HMA

During the process of compaction, two pre-dominant mechanisms happen. One is the change in orientation of the aggregates in order to pack more efficiently and the other is the decrease in distance between aggregate particles. The aggregate gradation typically used in HMA range from 19.0 mm to less than 0.075 mm, a span of 2.5 decades. However, previous research studies have shown that studying the distribution of large aggregates (greater than 2.36 mm in size) will adequately describe the changes in internal structure during compaction. Including the smaller sized aggregates would make the process unwieldy as the number of data points increase exponentially using more computing resources with little added benefits. A two-dimensional cut section of a laboratory compacted HMA specimen (revealing the large aggregates in brighter shade and asphalt in black) is shown in Fig. 1 for illustration.

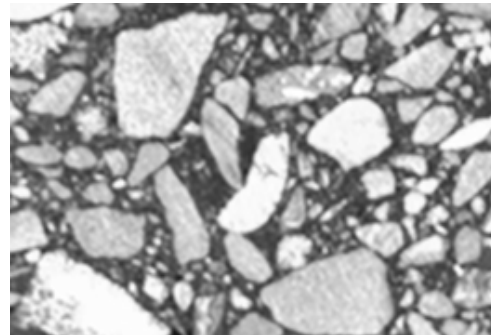


Fig. 1 Two-dimensional cut-section of HMA specimen

IV. SIMULATING HMA COMPACTION IN COMPUTER

A three-dimensional packing program was written in the Visual Basic (VB) programming language to simulate the HMA internal structure using the HMA mixture design information. Aggregate particles in HMA have different shapes, surface texture and friction, and orientations, and therefore are hard to model. Until now, a vast majority of research studies related to micromechanical modeling of HMA internal structure has been limited to two-dimensions because of computational constraints [13]. The three-dimensional packing algorithm used in this study is described in detail by Shashidhar and Gopalakrishnan [14]. The goal was to pack the aggregates in a three-dimensional compact based on the HMA mix design aggregate gradation and volumetrics and then to obtain the two-dimensional cross-sections by choosing imaginary slices at random locations.

The overall steps followed in the simulation process is shown in Fig. 2.

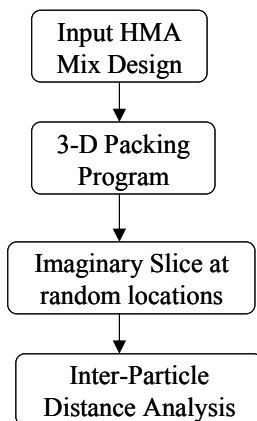


Fig. 2 Overall steps in HMA simulation analysis

The aggregates were randomly placed in the area to be analyzed starting from the biggest aggregates. Only aggregates larger than 2.36 mm were considered as justified previously. The smaller aggregates, asphalt cement and the air-voids were considered as the matrix. A random generator was used to vary the sizes of the particles such that the total area of particles within two sieve sizes would correspond to the weight retained in that sieve. Thus, a continuous size range similar to that obtained in a cross section of asphalt concrete was simulated. A screenshot of the VB program output showing the randomly placed aggregates in the two-dimensional cross-section of the HMA specimen is displayed in Fig. 3.

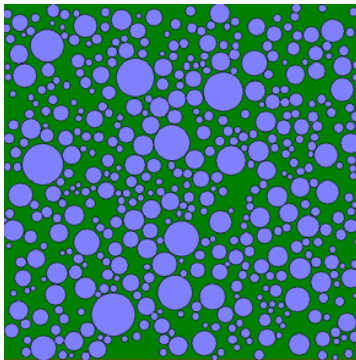


Fig. 3 Computer simulation of HMA cross-section

The level of air-voids was used to control the degree of compaction in the simulations. A higher air-void content increased the relative area of the matrix and made the aggregates further apart. A 4% air-void content increased the area of the box by 4%. Since the width of the box was held constant, the height increased by 4%. The aggregate area was held constant in all the simulations. Since each simulation used random sizes but conformed to the gradation, the number of aggregates varied but the total area in each sieve size was held constant. The particle size distributions of four different aggregate gradations considered in this study are shown in

Fig. 4.

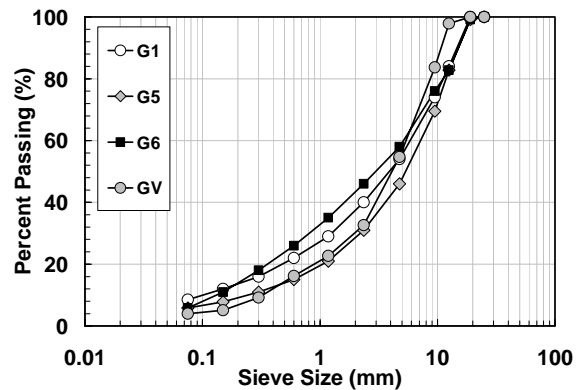


Fig. 4 HMA aggregate gradations considered in this study

Six different compaction efforts were considered in the simulations in terms of air-void levels: 0%, 4%, 8%, 12%, 16%, and 20%. As the compaction effort increases, the air-void in the HMA decreases. Thus, as the air-void level decreases from 20% to lower values, the inter-particle distances are expected to decrease. The statistical parameters that were used to quantify the changes in inter-particle distance as the HMA undergoes compaction are described in the next section.

V. INTER-PARTICLE DISTANCES

In a two-dimensional simulated cross-section of a compacted HMA specimen, the centroids of the particles define the location of the particles in x-y coordinates. The centroids can be joined in a pattern known as Delaunay triangulations. These triangles define the distances between neighboring particles. Delaunay triangulation is a surface triangulation scheme that is popular in many fields of engineering and science and have been used extensively in analyzing spatial distributions. It is considered to be a mathematically rigorous method to define the nearest neighbors.

The edges of these triangles give the edges between the centroids of the particles. We shall refer to this distance as D1. Part of D1 lie on the aggregates themselves and part of it lies in the matrix. It is possible to measure only the length of this distance that lie in the matrix, which we shall call D2. D2 is expected to be a more sensitive measure of change than the distance D1. Also the area enclosed by the triangle A1 can be measured. In a manner similar to the D2, the area within the triangle that lies in the matrix, A2, can also be measured. This area is expected to be more sensitive to compaction. These parameters are illustrated more clearly in Fig. 5. Also the ratio of the lengths and areas are considered. By considering a ratio such as $A2/A1$, the triangles (or lengths) are normalized.

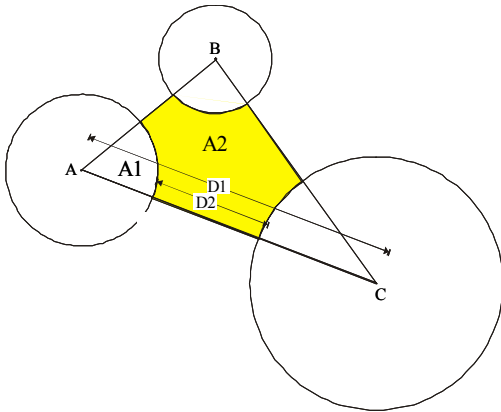


Fig. 5 Nearest neighbor statistical parameters

In the construction of the Delaunay triangulations we assume periodic boundary conditions. The area under study is repeated periodically in both x and y directions. This assumption was necessary to avoid the skewed data due to edge effects.

A. Delaunay Triangulation Algorithm

A Delaunay triangulation of a point set is a triangulation of the point set with the property that no point in the point set falls in the interior of the circumcircle (circle that passes through all three vertices) of any triangle in the triangulation [15]. Many types of Delaunay triangulation algorithm, from simple and/or slow to sophisticated and/or fast exist. For this study, the fastest algorithm ($O(n^2)$), was used to construct the Delaunay triangles [16].

The first step in this algorithm is to find the two closest points within a point set A and connect them as the first edge. Then, a circumcircle is drawn through the end points of the first edge and the first available point in A to the left of the first edge. If any of the points in A to the left of the first edge lie inside this circumcircle, a new circumcircle is drawn through this new point and the endpoints of the first edge. This procedure is continued until no point is caught in the circumcircle. Then, the endpoints of the first edge and the last point that has been checked are connected into a Delaunay triangle. The whole procedure is repeated on the right side of the first edge by interchanging the endpoints of the first edge. After the triangles on each side of the very first edge are found, the procedure is repeated on each of the new edges until all points in A have been triangulated. Periodic boundary conditions were also included as a part of the algorithm. Thus, for each aggregate centroid, its nearest neighbors and the centroid-centroid distances ($D1$) between it and its nearest neighbors are calculated. A schematic of the HMA aggregate centroids connected through Delaunay triangulation pattern (from the Visual Basic program output) is displayed in Fig. 6.

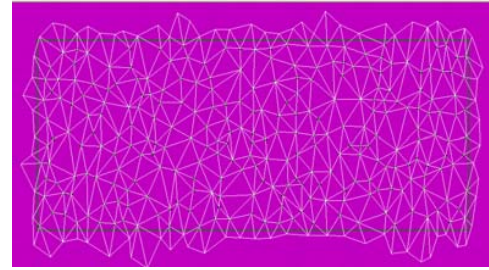


Fig. 6 HMA aggregate centroids connected through Delaunay Triangulation

In summary, the following statistical parameters were considered for quantifying the changes in HMA internal structure during compaction: (1) Centroid-to-centroid inter-particle distances ($D1$), (2) Edge-to-edge inter-particle distances ($D2$), (3) Area of triangles (whole) ($A1$), and (4) Area of triangles in matrix ($A2$).

As mentioned previously, the simulation process generates two-dimensional cross-sections by slicing the three-dimensional simulated HMA compact at desired locations. The area of each cross-section was $150 \times h$ mm² and the height, h , depends upon the air-void content in the specimen. Four typical HMA design aggregate particle size distributions were considered: G1, G5, G6 and GV. Six different air-void levels, representing different degrees of compactions, were considered for each gradation: 0%, 4%, 8%, 12%, 16% and 20%. In each simulated compact for a given HMA mix design at specified air-void level, five cross-sectional slices were generated and the inter-distance statistical parameters, $D1$, $D2$, $A1$, and $A2$ measurements and their ratios were accumulated.

VI. RESULTS AND DISCUSSION

Since the aggregates are placed randomly in the simulation process, it is not possible to keep track of how a given length or area changes with compaction. Instead, what we observe are a series of distributions. The distributions for $D1$, $D2$, $A1$, and $A2$, respectively, are shown in Fig. 7 to Fig. 10 for the GV HMA mix. The distributions are shown as histograms. The distributions of area and lengths are somewhat broad and as the sample gets compacted, the distribution gets narrower and tends to move to the shorter lengths/areas. The changes in the parameter $A2$ and $D2$ were more sensitive to compaction than $A1$ and $D1$, respectively.

The magnitudes of $D1$ and $D2$ have a wide distribution that is almost a Gaussian shape in a semi-logarithmic plot. This could be because the gradation of aggregates is on a logarithmic scale of sizes.

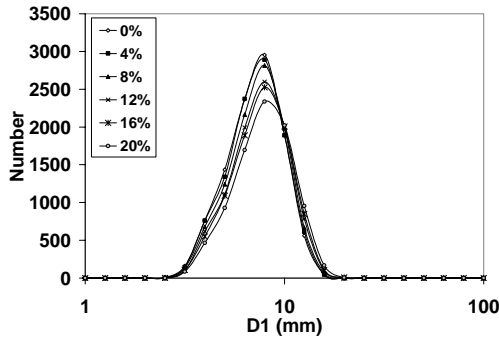


Fig. 7 Distributions of D1 for GV HMA mix

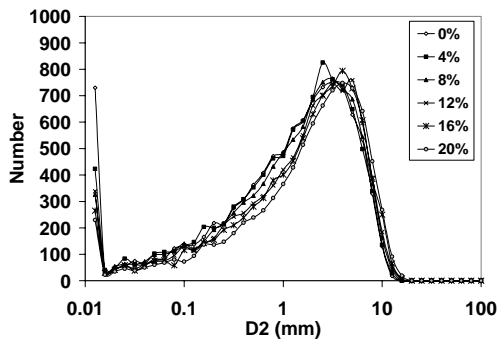


Fig. 8 Distributions of D2 for GV HMA mix

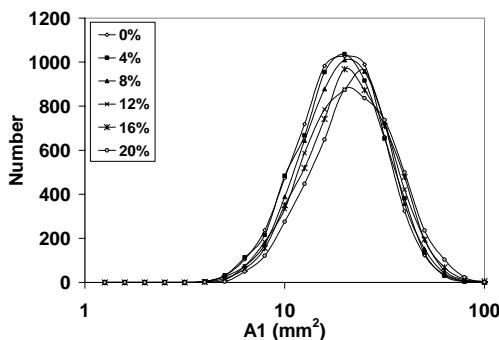


Fig. 9 Distributions of A1 for GV HMA mix

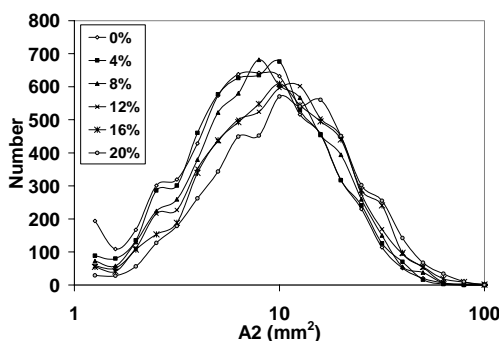


Fig. 10 Distributions of A2 for GV HMA mix

The distribution for D2 is skewed with the degree of skewness increasing with compaction. It can be seen that as the percent air-void decreases, the distribution shifts to smaller lengths. This shift is more obvious in D2 than in D1. This is understandable since it is the matrix that shrinks and not the

aggregate. By considering matrix alone (D2) the changes in lengths are more obvious. Similarly, the distributions of A1 and A2 show similar trends. The distribution shifts to smaller areas when the mix is compacted. The results are shown only for GV mix, but similar trends were observed for other mixes considered in this study.

A fit of a linear equation arithmetic means of these distribution were calculated. The changes in these means (D1, D2, A1 and A2) with percent air-voids are shown for Fig. 11 to Fig. 14.

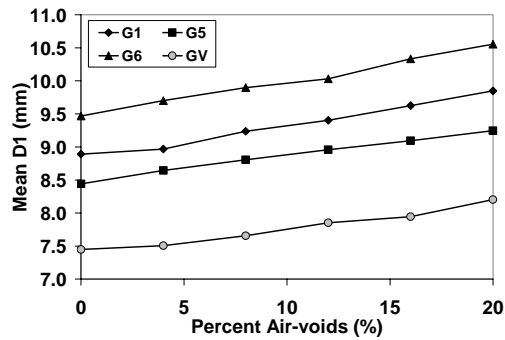


Fig. 11 Variation in mean D1 with percent air-voids

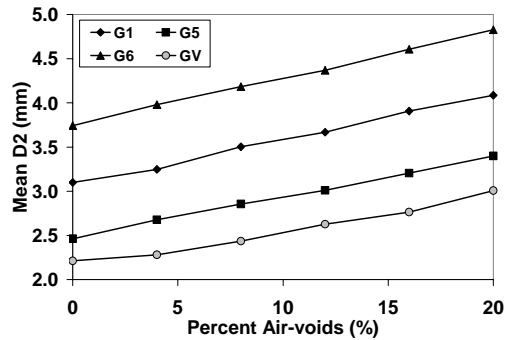


Fig. 12 Variation in mean D2 with percent air-voids

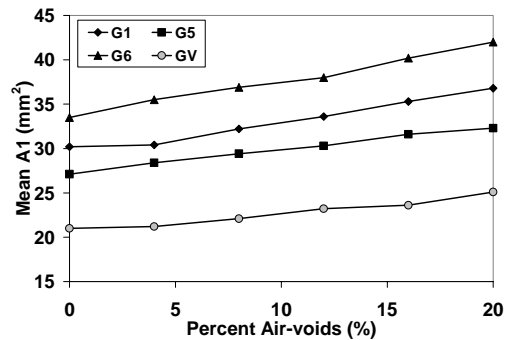


Fig. 13 Variation in mean A1 with percent air-voids

These means vary linearly with air-voids such that a straight line can be fit to these data points. The coefficients of the linear equation (slopes and intercepts) that fit these points could be easily obtained. If the moment for any of the quantities can be calculated from a simulated two-dimensional cross-section of HMA specimen, then the percent air-voids, or the degree of compaction can be estimated from that section

and by repeating this for different gradations and by validating the results, a master calibration curve could be developed to predict the degree of compaction simply from the HMA mixture design information.

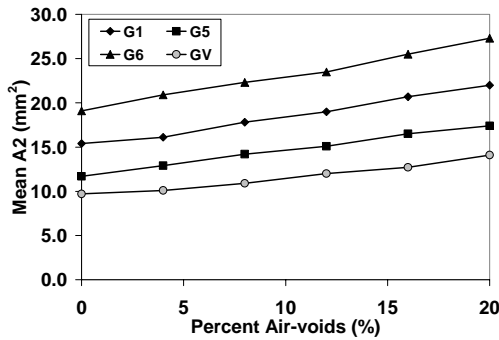


Fig. 14 Variation in mean A2 with percent air-voids

It would have been desirable for the distribution of lengths and areas to be narrow such that significant differences due to the air-void could be determined. Due to the wide distribution in lengths/areas, standard statistical analyses such as t-tests could not be used in this instance. The results showed that regardless of what parameter is chosen the distributions of the values are rather broad.

However, the mean or any of the moments for these inter-distance parameters vary linearly with percent air-voids (degree of compaction). The correlation coefficient, R^2 , for these curves were rather high (above 0.97) for all cases, but are not reported here due to space constraints. Based on these R^2 values, the most appropriate parameters for determination of compaction level is either arithmetic or geometric mean of the inter-particle distances.

Next, the simulation results were compared with the results obtained on actual laboratory compacted HMA specimens. For this, HMA specimens were fabricated in the laboratory using the GV HMA mix design with a Linear Kneading Compactor (LKC). Four samples with four different air-void levels (4%, 9%, 16%, and 18%) were prepared. Five slices from each sample were sawed for studying the inter-particle distances.

The inter-particle distance analysis on the actual lab specimens were conducted using two-dimensional image analysis techniques. Cross-sectional digital images of slices from each sample were captured using a high resolution camera (see Fig. 1). Macros were developed using the Image-Pro Plus software to analyze the changes in inter-particle distances based on Deluanay triangulation scheme. The details of the imaging study are discussed in detail by Gopalakrishnan et al. [11]. A screenshot from the Image-Pro Plus software during the inter-particle distance analysis on actual lab compacted HMA cross-sectional slice is displayed in Fig. 15.



Fig. 15 Inter-particle distance analysis on lab compacted HMA cross-sectional slice

The distributions for the inter-particle distance statistical parameters for lab specimens (based on image analysis) showed similar trends as those of computer simulation results. The changes in the arithmetic means of these parameters with percent air-voids using lab results are compared with the computer simulation results in Fig. 16 and Fig. 17. Naturally, the R^2 values were higher for simulations. The differences in the magnitudes of results between the two methods may be due to different causes such as artifacts during the image analysis, aggregate shape (sphere versus irregular shape), type of compaction (three-dimensional packing algorithm versus LKC compaction), etc. However, it is interesting to note that the trends are very similar.

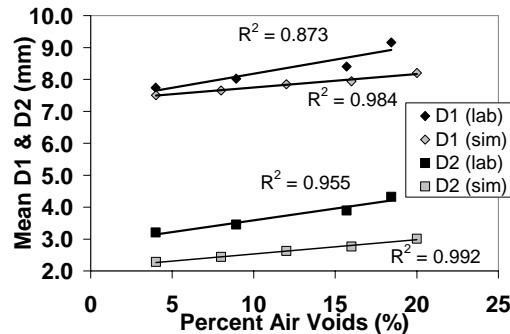


Fig. 16 Comparison of simulation (sim) results with lab specimen results for GV HMA mix (D1 and D2)

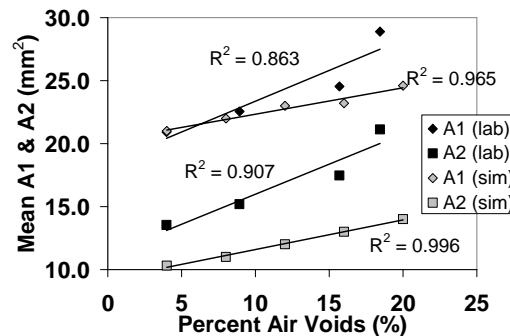


Fig. 17 Comparison of simulation (sim) results with lab specimen results for GV HMA mix (A1 and A2)

Thus, an attempt has been made to quantify the variation in HMA internal structure as the HMA undergoes compaction using computer simulation techniques. By measuring the mean of the distance between the centroids of the neighboring particles, the degree of compaction expressed as air-void content in the HMA sample can be estimated by using a calibration curve developed through computer simulations. This calibration curve can be estimated using computer simulation technique when the HMA mixture design is known. The computer simulation technique randomly places the particles approximated by spheres in a volume equal to the sum of aggregate, asphalt and air-void volumes. The simulation results were compared with the results obtained using image analysis techniques on real laboratory compacted HMA specimens. Good agreement was found between the laboratory results and simulation results. The authors believe that the application of computer simulation concepts to the study of HMA internal, in conjunction with the recent advances in imaging techniques and micromechanical modeling of HMA have tremendous potential to help us to develop a deeper understanding of the HMA internal structure, develop and optimize the various parameters that describe the internal structure and relate them to the performance of HMA pavements in a scientific way.

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