Optimizing Designs of Structurally Stable Open-graded Aggregate Bases (OGAB) in Concrete Pavements

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Abstract: A stable, non-erodible, drainable base layer is crucial to maintain uniform support under concrete pavements and ensure satisfactory performance. This paper presents findings from a recent study aimed at investigating possible improvements in concrete pavement base layers in terms of stability, stiffness, and permeability. Moisture regimes in PCC pavement foundation layers and corresponding predicted pavement performance were first evaluated using different types of base course materials with varying hydraulic and mechanical properties. A previously validated discrete element method (DEM) model was subsequently employed for evaluating the gradation effect on both packing characteristics and load-carrying performance of unbound aggregate materials. The calibrated DEM model has the potential for optimizing the selection of size and shape properties of various types of unbound aggregates to achieve desired shear strength (stability) and drainage characteristics (drainability) for open-graded permeable aggregate base. DEM simulations were performed on different gradations chosen from the current Minnesota Department of Transportation (MnDOT) specified gradation band for unbound permeable aggregate base (UPAB). It was found that depending on the specific gradation and material hydraulic properties, different types of unbound permeable aggregate bases resulted in varying performance improvements. The benefits of maintaining adequate permeability and stability of base course proved to be evident. The DEM model simulation results indicated that a gravel to sand (G/S) ratio of 1.6 yielded the highest coordination number due to the achieved densest packing (indicated by the lowest porosity). Therefore, the optimal G/S ratio of 1.6 also determined previously from experimental results agreed well with the results of DEM simulations, which utilized three-dimensional polyhedral particles with realistic size distributions and aggregate shape properties. The use of such optimal size and shape properties is expected to achieve cost-effective open-graded aggregate base designs for long-life concrete pavements.

Key words: Open-graded Aggregate Base (OGAB), Gradation, Drainability, Structural Stability, Concrete Pavements, Discrete Element Method.

INTRODUCTION

Excessive field moisture content is among the primary causes for concrete pavement deterioration and premature failures due to pumping, slab settlement, joint faulting, and slab cracking. In places like Minnesota where a wide range of in-situ subgrade soil

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conditions exist, concrete pavement design, construction and maintenance face great challenges in terms of heavy and high volume traffic loadings, depletion of high quality aggregate materials, and drastic environmental conditions. Among these challenges, one aspect is to adequately cope with moisture content increases and effects of seasonal spring thaw which requires removing all transient water out of the pavement structure as rapidly as possible before excessive accumulation (Birgisson and Roberson 2000). Such requirements imply the following two objectives of concrete pavement foundation design: (a) proper selection/utilization of base/subbase materials retaining low average moisture contents and/or moisture susceptibility, and (b) efficient subsurface drainage design. Many field forensic studies have demonstrated that good drainage and subsurface grading are essential for long term satisfactory performance (Tutumluer et al. 2015). On the other hand, base/subbase layers below concrete pavements should be properly designed to provide a stable construction platform, uniform slab support, and erosion resistance. Different base/subbase materials have been used under concrete pavements over the years, including dense- and open-graded unbound materials, cement- and asphalt-treated bases (CTB and ATB), lean concrete bases, and the combinations of those layers (sometimes with asphalt concrete interlayer for debonding).

In an effort to study subsurface drainage and stability of a new open-graded aggregate base material (OGAB Special) under construction, PCC pavement test sections (Cells 306 and 406) were constructed by the Minnesota Department of Transportation (MnDOT) on the 3.5-mile mainline interstate roadway segment at the MnROAD test facility in 2011. Both test cells consisted of 6-in thick Portland cement concrete (PCC) slab, 6-in thick OGAB Special layer and 7-in Class 5 (MnDOT traditional dense-graded) unbound aggregate underlain by clay subgrade. However, an extensive cracking pattern was observed in July 2012. To ascertain immediate and remote causes of such early severe cracking occurred, various investigative processes and tests were conducted. It was concluded that mechanical instability of the OGAB layer was the likely cause of this early extensive cracking, and that predictive tests for stability of the aggregate as well as the drainable base needed to be developed (Izevbekhai and Van Deusen 2015). Xiao et al. (2014a) analyzed field instrumentation data and Falling Weight Deflectometer (FWD) test results from MnROAD test Cells 306 and 406 to assess the effectiveness of the OGAB Special layer in controlling subsurface moisture regime and providing structural stability. They concluded from analysis results that the OGAB special layer could not only reduce the subsurface moisture content significantly as compared to traditional dense-graded (Class 5/6) base layers, but could also provide as much stiffness/modulus as traditional dense-graded base layers could possibly do. As contrary to common wisdom, Izevbekhai and Van Deusen (2015) cautioned that compaction and in consequence stiffness was not a guarantee for mechanical stability, and that aggregate type and quality (e.g., abrasion resistance, gradation, and shape) could not be ignored. In drainable bases, strong aggregate-to-aggregate contact is crucial for stability because unstable aggregates are susceptible to movements and widespread movements of unstable aggregates could result in loss of support and therefore in cracking.

Tutumluer et al. (2015) recently conducted a study with the Minnesota Department of Transportation (MnDOT) focusing on possible improvements in concrete pavement base layers in terms of stability, stiffness, and permeability. One of the goals was to engineer unbound aggregate gradation and shape properties through both laboratory testing and micro-mechanics based approaches (e.g., discrete element method, or DEM, modeling) and to recommend performance based material specification guidelines for future implementation. Utilizing the gravel-to-sand ratio (G/S) concept proposed from the preliminary experimental studies for optimizing unbound aggregate gradations for improved shear strength behavior (Xiao et al. 2012), Xiao et al. (2014b) recommended a drainable aggregate base that needed to include a significant amount of recycled PCC to support a new PCC pavement on test sections at the MnROAD test Facility. Furthermore, Wilde et al. (2015) approached the G/S ratio from the pavement performance perspective. They utilized the Mechanistic-Empirical Pavement Design Guide (MEPDG) software, Version 1.1, and a regression model for predicting resilient modulus (M_R) of an unbound aggregate layer to develop several distributions of resilient modulus and the resulting influences on performance. The optimum G/S ratio obtained by this method was reported to range from 0.8 to 1.4 – similar to those obtained by Xiao et al. (2012), only a little lower. The gradations recommended to MnDOT for a new Class 5 unbound aggregate base and a new permeable aggregate base were obtained to balance the stability, stiffness, and permeability requirements by following this method (Wilde et al. 2015).

OBJECTIVES AND SCOPE

The primary objective of this paper is to present an approach to optimize designs of structurally stable open-graded aggregate bases (OGAB) in concrete pavements. The scope followed is twofold. First, the effects of using different base layers, e.g., open-graded ones, on pavement foundation moisture regime and the overall PCC pavement performance are evaluated. The Enhanced Integrated Climate Model (EICM) program version 3.4 is employed to predict the moisture profiles in a PCC pavement system; additionally, the long-term performance trends of PCC pavement sections built with different types of permeable base materials are predicted using the MEPDG software, Version 1.1. The evaluation is based on an extensive use of the mechanical and hydraulic properties of typical base/subbase materials collected from previous MnDOT studies and relevant literature. Secondly, a DEM model packing simulation using different gradations is pursued to evaluate the gradation properties influencing the contact and packing characteristics of aggregate skeleton and to further verify the aforementioned drainable gradations recommended by using the optimal gravel to sand ratio concept.

EFFECT OF THE USE OF PERMEABLE BASE/SUBBASE

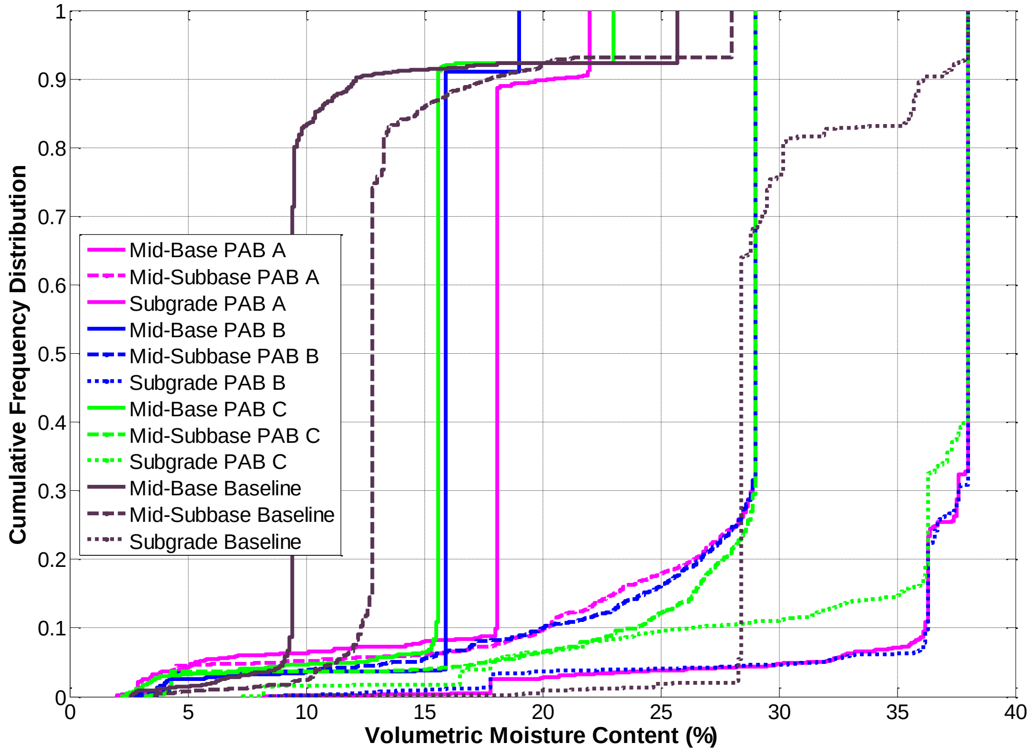
Moisture Regime Prediction

Using permeable base design options, e.g., open-graded aggregate base, cement-treated base (CTPB), and asphalt-treated base (ATPB), has been demonstrated to be effective strategies for improving drainage efficiency and thus pavement longevity. In Minnesota, two main permeable base materials are widely used, i.e., stabilized and unbound (Arika et al. 2012). In addition to maintaining adequate permeability, these layers are also required to maintain stability during construction as well as future rehabilitation activities over multiple life cycle designs. It is a known fact that the mechanical behavior and structural capacity of pavement foundation materials vary seasonally with moisture, i.e., modulus and strength of base/subbase layers decrease and permanent deformation increases with increasing moisture content. Consequently, decreased structural capacity of underlying foundation layers leads to increased magnitudes of critical stresses affecting PCC slabs and thus accumulated damage. Therefore, it is desirable to predict how the moisture regimes within a PCC pavement system change both hourly/daily and seasonally in different climatic regions and then account for the corresponding hourly/daily and seasonal variations of base/subbase stiffness.

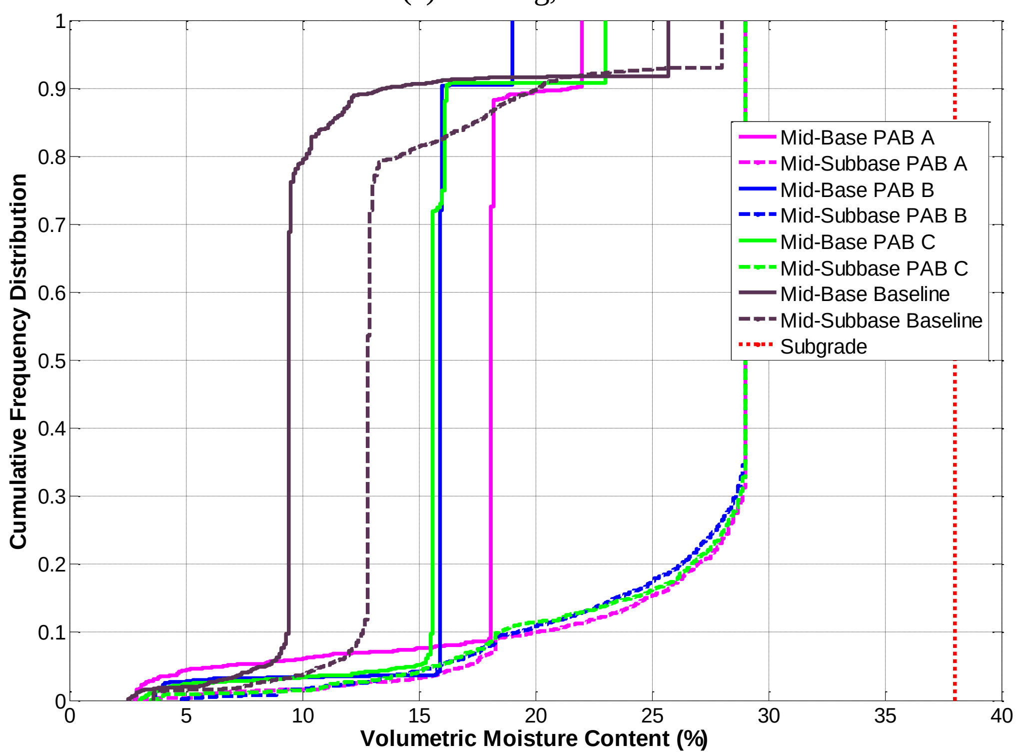
Three different open-graded aggregate base materials typically used in permeable base applications were explored for potential benefits in terms of pavement foundation moisture regime. In order to characterize the base/subbase moisture in different parts of Minnesota, the existing weather stations with climatic data files for the state of Minnesota, were selected from the MEPDG climatic database (Johanneck 2011). The standalone Enhanced Integrated Climatic Model (EICM) was utilized to predict the mid-depth moisture content on a daily interval with the pavement structure and geographical location given as inputs. Using the EICM, base/subbase moisture regimes at different climatic locations were predicted for a baseline long life concrete pavement section which was chosen as a typical design option for Minnesota high performance concrete pavement (HPCP) with a 60-year design life target (Rohne 2009). Multiple pavement structures were generated subsequently by changing the PCC slab and base/subbase layer thicknesses, as well as layer material properties. Note that default values were used for such inputs that are expected to either have minimal effects or be out of the scope of this study. By using the established inputs, the moisture content variations for base, subbase, and subgrade soils were generated on a daily basis within the specified analysis period. The aim was to quantify the effects of design features and site conditions on predicted moisture regimes. For brevity, other details are skipped herein and can be found elsewhere for the interested reader (Tutumluer et al. 2015).

Table 1 lists the corresponding material properties of three representative permeable aggregate bases (PAB) collected from literature (Liang 2007), together with material properties of the baseline MnDOT Class 5 dense-graded aggregate base. Two climatic locations were selected for illustration purpose, i.e., Hibbing and Minneapolis, which have different climatic data and groundwater table depths. Figure 1 shows the cumulative frequency distribution curves for temporal volumetric moisture content variations in both base and subbase courses at both locations. The maximum moisture contents in base course for those three permeable aggregate base materials are all less than the baseline dense-graded base material; while the maximum moisture contents in subbase course and subgrade soils are approximately identical. Overall, the use of permeable base materials increases the moisture contents in underlying subbase and subgrade soils, as evident from the corresponding frequency distribution curves of moisture. Similar trends are observed for both Hibbing and Minneapolis, Minnesota.

Despite greater saturated hydraulic conductivity (k_{sat}) for PAB material C than PAB material B, the use of both PAB materials leads to similar moisture contents in base and subbase courses, as evident in Figure 1 from the cumulative frequency distributions falling close to each other. Therefore, moisture-suction relationship (i.e., soil water characteristic curve or SWCC), in addition to saturated hydraulic conductivity itself, seems to play an important role in controlling the moisture regimes in PCC pavement foundation layers as well, which is probably due to the fact that moisture flow within the pavement foundation layers is unsaturated in nature.



(a) Hibbing, MN



(b) Minneapolis, MN

Figure 1. Cumulative Frequency Distributions for EICM Predicted Moisture with Varying Permeable Aggregate Base Properties in (a) Hibbing and (b) Minneapolis, MN.

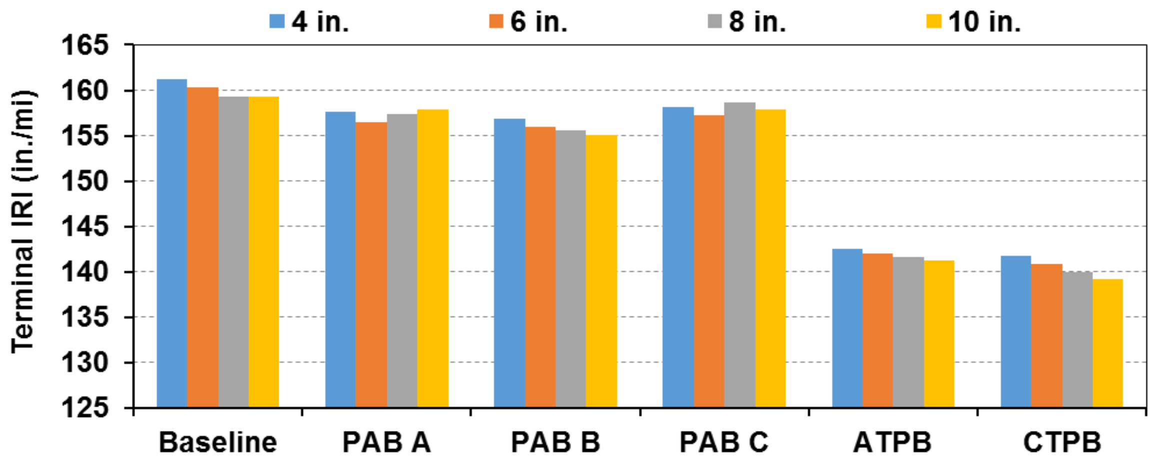
Table 1. Material Properties of Permeable Aggregate Bases (PAB) Used

Material Property		PAB A	PAB B	PAB C	Baseline
Thickness (in.)		4	4	4	4
Porosity		0.22	0.19	0.23	0.257
Specific Gravity		2.6	2.6	2.6	2.786
Saturated Permeability (ft/hour)		159	95	154	0.01
Dry Unit Weight (pcf)		127	128	127	130
Percent Passing #4 Sieve (%)		47	40	28	57.5
Plasticity Index		0	0	0	0
Percent Passing No.200 Sieve (%)		1.2	0.7	1.18	5
Diameter D60 (mm)		12.2	11.9	16.1	2.03
Initial Volumetric water content (%)		17.9	6.7	6.8	15.26
Fredlund & Xing (1994) Model Parameters	a_f	2.05	2.40	1.66	19.26
	n_f	149.17	210.25	15.24	2.71
	m_f	0.41	0.33	0.53	0.31
	h_r	0.11	0.19	2.24	135.66

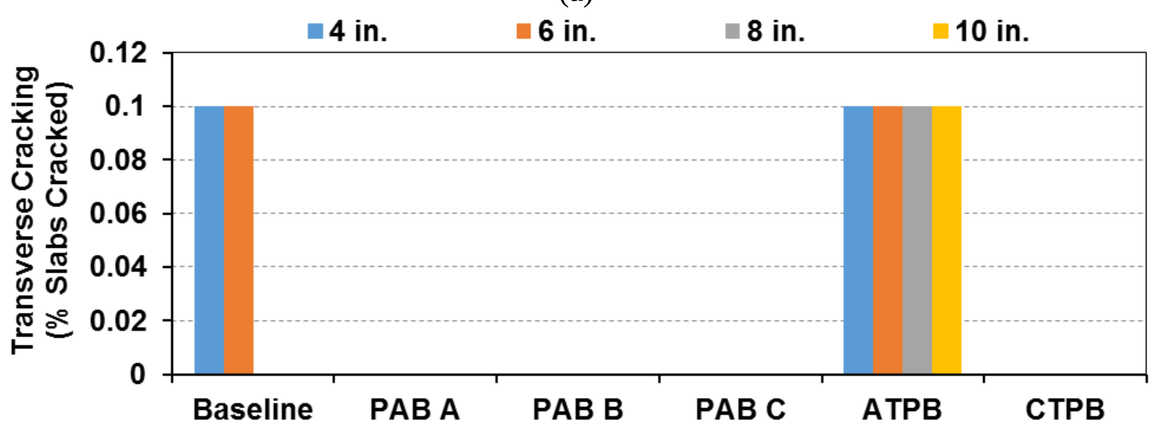
Pavement Performance Prediction

A limited number of sensitivity analyses were performed with the changing variables. The primary objective was to quantify the impact of base material hydraulic properties and modulus values on long-term pavement performance as predicted by the MEPDG. Other MEPDG input parameters that are related to moisture effects were also varied as sub-factors in the sensitivity analyses, including base material type (different saturated hydraulic conductivity k_{sat} and SWCC), base layer thickness, subgrade type, and GWT depth. Various types of base courses, ranging from traditional unbound dense-graded aggregate base (e.g., MnDOT Class 5) to unbound permeable aggregate bases (open-graded PAB), CTPB, and ATPB, were explored in this study for potential long-term performance benefits. With the addition of a stabilizer (asphalt or cement), the gradation of the stabilized material becomes much coarser; whereas unbound materials require higher amounts of finer-sized aggregates to achieve stability through aggregate interlock. This then explains the fact that typical permeability values are 6800 ft/day for stabilized bases and 1000~3000 ft/day for unbound granular ones. Note that subbase type and thickness, as well as subgrade resilient modulus, were assumed to be the same among all the cases analyzed. For illustration purposes, Minneapolis, MN was pre-selected as the geographical location studied. More details are referred to Tutumluer et al. (2015).

Figure 2 shows the effects of different types of base course with varying base thicknesses on predicted distress results. As can be seen from Figure 2, the use of asphalt treated and cement treated permeable bases significantly reduces the predicted pavement distresses, as compared to the baseline dense-graded aggregate base; whereas the extent to which the use of unbound aggregate permeable bases (A, B, and C) reduces pavement distresses is much less profound than treated bases. Depending on the specific gradation and hydraulic properties, different types of unbound permeable aggregate bases result in varying performance improvements. It seems that for unbound permeable aggregate bases, the 8-in thickness yields the best performance, while increasing treated base thickness leads to reduced pavement distresses. The use of permeable aggregate base and stabilized permeable base, as compared to baseline dense-graded aggregate base, significantly reduces predicted transverse cracking. Therefore, maintaining high permeability and modulus values of concrete pavement base course would contribute to improved long-term pavement performance.



(a)



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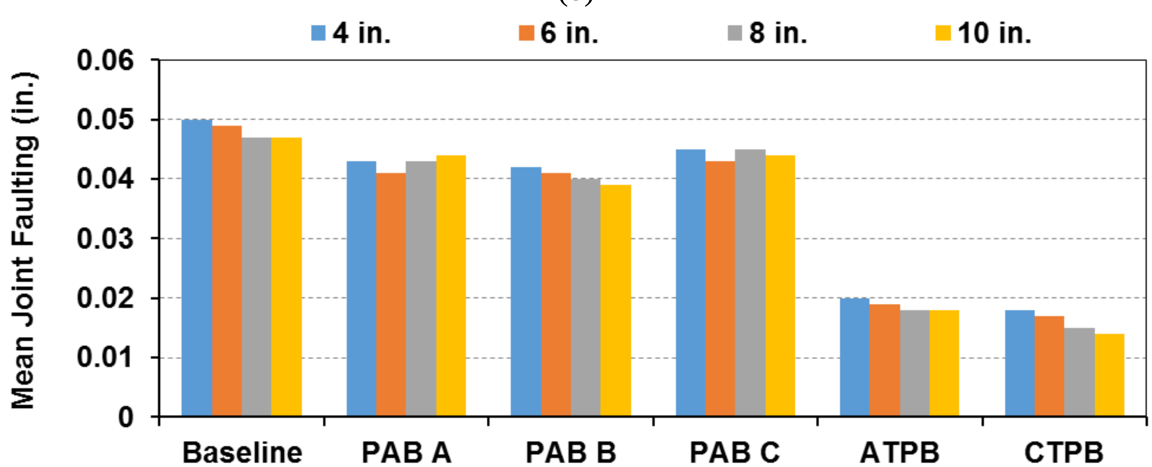

(c)

Figure 2. Effect of Base Type and Thickness on Predicted Pavement Performance: (a) Terminal IRI, (b) Transverse Cracking, and (c) Mean Joint Faulting.

DEM VALIDATION OF THE GRAVEL-TO-SAND RATIO CONCEPT

Unbound aggregates transfer loads through forming an aggregate skeleton, which in turn is dictated by aggregate gradation, shape, texture and angularity. To ensure adequate particle contact for load transfer, proper gradation needs to be designed/selected for unbound aggregates possessing certain shape properties. However, limited analytical and numerical studies have been conducted in the past by considering only the packing and grain size distribution and the aggregate shape, angularity and surface texture were often neglected. There is currently no systematic procedure or guideline available for pavement engineers to study/engineer aggregate gradation and shape so that targeted performance can be achieved.

The DEM model calibrated by Xiao et al. (2014b) for six different aggregate materials has the potential to study the underlying mechanisms of aggregate packing and to engineer the gradations of aggregate base materials, especially permeable (open-graded) ones that require both permeability and long-term stability. By adjusting the percentages of aggregates at different sizes, aggregate gradation can be optimized at the microstructure level for the large enough void space yet remain still adequate for the structural performance (strength and stability) to evaluate the degree of aggregate contact and interlocking. The effect of aggregate angularity and surface texture are considered directly by choosing different particle shape from pre-established shape library.

The process of DEM simulation involves three major steps. First, polyhedron particles retained on the Nominal Maximum Particle Size are generated in the computer according to the target gradation. These particles are added to a square box (0.15*0.15*0.15 m) under a unidirectional gravitational force, as shown in Figure 3.

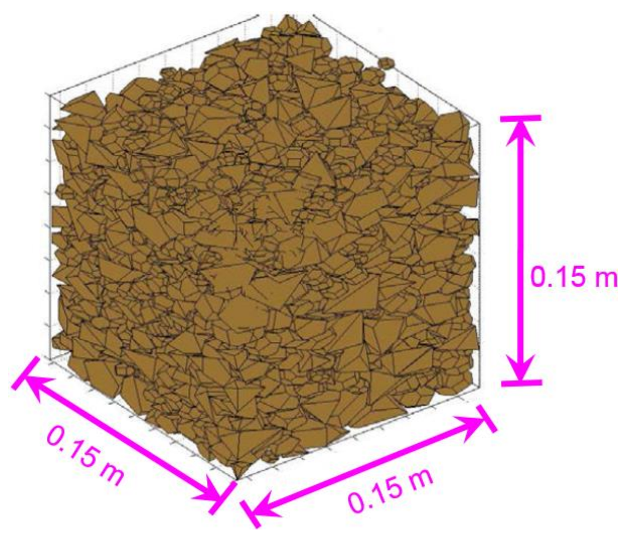

Figure 3. Domain Dimensions for the DEM Particle Simulation.

Secondly, particles are compacted by the assigned gravitational force to its stable position. Finally, the volumetric properties and the mean contact force are calculated. The simulation of a complete aggregate gradation requires adding different sizes of particles to the system sequentially (from large to small) following an iteration process. Once the structure of large size particles are established and their volumetric properties are determined, finer aggregates will then be added into the structure following the same three steps of particle generating – compaction to equilibrium – data calculation. Finally, the corresponding volumetrics and mean contact forces will be determined and compacted with the results for larger size particles to check the change in volume and contact force due to the addition of small size particles.

DEM model simulations were performed for optimum packing based on five different gradations (see Figure 4) that varied the gravel to sand (G/S) ratio values as follows: 1.0, 1.6, 2.0, and 2.5. These different gradations were selected from the current MnDOT specified gradation band for unbound permeable aggregate base (UPAB) and a typical dense-graded aggregate band from Illinois DOT (IDOT) is also shown for comparison. The main objective was to verify if the recommended UPAB gradation (Xiao et al. 2014b) for MnROAD RCA test sections outperforms others in terms of both structural stability (as characterized by coordination number, i.e., average stone-on-stone contact points per particle) and drainability (as characterized by porosity). Intermediate G/S ratio values of 1.2, 1.5, 1.7, 1.8, and 2.2 were also added subsequently into the DEM simulation. Two different aggregate angularity levels, i.e., high and low, were also considered to include the interaction effects of grain size and particle shape. Note that instead of simulating the entire particle size distribution, the minimum particle size simulated in DEM was 2 mm in order to avoid a long run time. Due to space limitations, only the most important results (see Figure 5) are presented herein, while the DEM procedure followed and corresponding results were described elsewhere in detail (Xiao 2014).

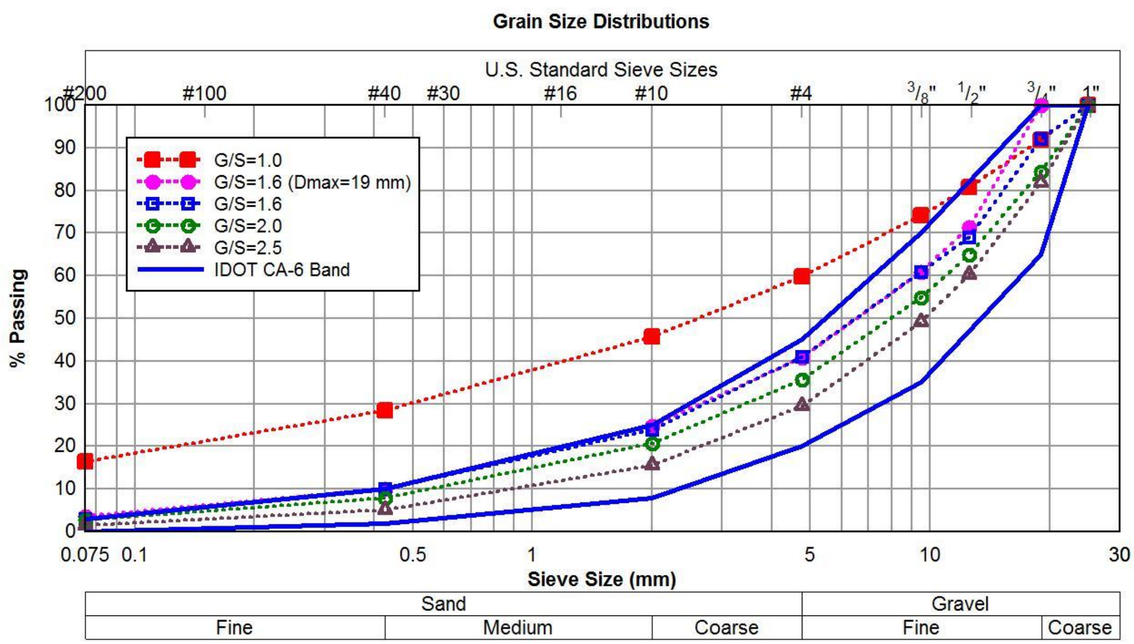

Figure 4. DEM Simulated Gradation Curves with Varying G/S Ratios.

It can be observed from the DEM packing study results presented in Figure 5 that the coordination number (how many contacts one aggregate particle has on the average) increases with increasing aggregate angularity level, whereas the porosity decreases with increasing aggregate angularity level. This indicates that more angular aggregates are expected to have better interlock, and therefore, structural stability (e.g., shearing and rutting resistance) as represented by higher coordination number and lower porosity. Note that, the G/S ratio of 1.6 results in the highest coordination number due to the densest packing (indicated by the lowest porosity). Therefore, the optimal G/S ratio of 1.6 observed by Xiao et al. (2012) from experimental results agrees well with the DEM model simulation results using the three-dimensional (3D) polyhedral particles with realistic aggregate shapes. The recommended optimal gradation for unbound PAB by Xiao et al. (2014b) exhibits better contact and packing characteristics of aggregate skeleton as compared to others; hence, it is expected to yield better structural stability in the field while still satisfying the MnDOT unbound PAB gradation band requirements.

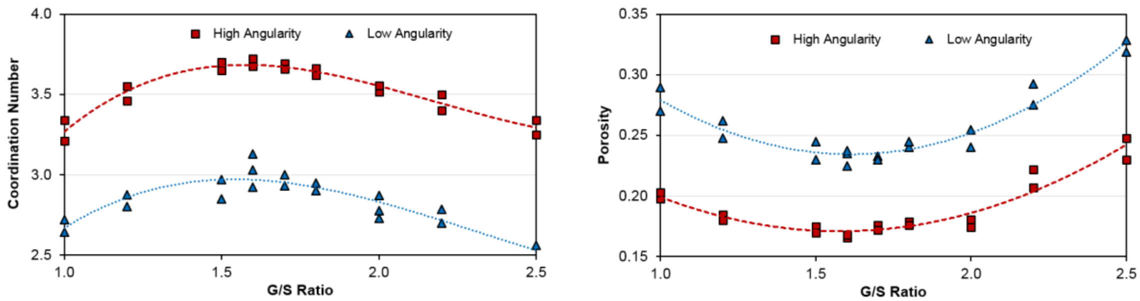

Figure 5. DEM Calculated (a) Coordination Number and (b) Porosity versus G/S Ratio for High and Low Angularity Levels.

SUMMARY AND CONCLUSIONS

This study presented evaluation results of moisture regimes in PCC pavement foundation layers using the EICM program and typical Minnesota HPCP structure. Different types of base course materials with varying hydraulic and mechanical properties were studied for their potential effects of the EICM predicted moisture regimes and MEPDG predicted long-term pavement performances. It was found that the maximum moisture contents in base course for those three PAB materials studied are less than the baseline dense-graded base material; while the maximum moisture contents in subbase course and subgrade soils are approximately similar. Overall, the use of permeable base materials increases the moisture contents in underlying subbase and subgrade soils. Through a limited sensitivity study, the use of asphalt treated and cement treated permeable bases significantly reduces the predicted pavement distresses, as compared to the baseline dense-graded aggregate base; whereas the extent to which the use of unbound aggregate permeable bases (A, B, and C) reduces pavement distresses is much less profound than treated bases. Depending on the specific gradation and material hydraulic properties, different types of unbound permeable aggregate bases result in varying performance improvements. Moisture-suction relationship (i.e., SWCC), in addition to hydraulic conductivity itself, plays an important role in controlling the moisture regime in PCC pavement foundation layers as well, which is probably due to the fact that moisture flow within the pavement foundation layers is unsaturated in nature instead of being saturated. Therefore, it may be postulated that base/subbase hydraulic conductivity and SWCC possibly exist an optimal combination for which significant improvement can be achieved over layer moisture regime, and that changing either hydraulic conductivity or SWCC alone may not be effective in improving layer moisture regime. The benefits of maintaining adequate permeability and modulus of base course were proved to be evident.

A previously validated DEM model was employed for evaluating the gradation effect on both packing characteristics and load-carrying performance of unbound aggregate materials. The calibrated DEM model has the potential for optimizing the selection of size and shape properties of various types of unbound aggregates to achieve desired shear strength (or rutting resistance) and hydraulic conductivity or drainage characteristics (function of aggregate shape and air void distribution) for open-graded permeable aggregate base. Finally, DEM simulations were performed on different gradations with varying gravel-to-sand (G/S) ratio values. The different gradations were all chosen from the current MnDOT specified gradation band for unbound permeable aggregate base (UPAB). The main objective was to verify if the previously recommended UPAB gradation for MnROAD RCA test sections outperforms others in terms of both structural stability (as characterized by coordination number) and drainability (as characterized by porosity). The G/S ratio of 1.6 was found to result in the highest coordination number due to the achieved densest packing (indicated by the lowest porosity). Therefore, the optimal G/S ratio of 1.6 observed by Xiao et al. (2012) from experimental results agrees well with DEM simulation using 3D polyhedral particles with realistic aggregate shape properties.

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