Mix Design, Thickness Design, and Construction of Roller-Compacted Concrete Pavement

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ABSTRACT

Roller-compacted concrete pavement (RCCP) is a technology that involves the use of conventional materials and construction equipment in an unconventional application. The result is a savings in time of concrete pavement construction, which ultimately translates into a significant cost savings. Some interesting cause-and-effect relationships based on observations, limited research, and construction of RCCP are presented. In particular these relationships help to identify some of the constraints as well as the guidelines for successful mix design, thickness design, and construction.

In the evaluation of new concepts or technology, judgment may frequently be inhibited by the assumption that unknown phenomena and factors play an important role in function and performance. This is true in many areas of science and engineering and it is true specifically in pavement technology. However, it is not always necessary to invoke new postulates; generally it is a question of recognizing or understanding how prevailing, known phenomena evolve or how the existing factors interact to cause success or failure. The purpose of this paper is to discuss roller-compacted concrete pavement (RCCP) as a new pavement technology by examining its components and the various stages through which the mixture must go to become an effective RCCP, which involves in large part what is already known of a broad area of materials and construction.

In general terms, conventional concrete used in pavements is proportioned to satisfy a design flexural strength and maintain workability within a reasonable water-cement ratio. Other important factors considered in the mix design are durability and economy. Soil-cement is proportioned in large part for durability, with a water content to obtain maximum density as well as overall economy. RCCP mixtures cannot be designed totally as a conventional concrete mixture or as a soil-cement mixture but must be designed on the basis of key features of both these applications of cement in pavement construction. In addition, construction involves the use of asphalt equipment and techniques, which must be taken into consideration.

The expected in situ properties of RCCP are significant in their performance and as a result also to thickness design because of a high flexural strength relative to that of conventional concrete pavements. Increased flexural strength may affect thickness design in one of two ways: first, the increased flexural strength may be included in the selection of a design thickness, and second, existing acceptable thicknesses may be retained by using a factor of safety to reduce the higher RCCP flexural strengths to a value numerically comparable with that of conventional concrete pavement and therefore accommodate the increased strength through an increased confidence level.

Several RCCP projects (1,2) have been built in widely dispersed parts of North America. The geographical spread and varying conditions of the sites may be a fortunate occurrence because the differences provide the basis for some conclusions about the design, construction, and performance of RCCP.

The following projects are used as sources of information:

1. Fort Stewart, Georgia;
2. Fort Hood, Texas; and
3. Vancouver and Caycuse Camp, Cowichan, British Columbia, Canada.

The range in climate at these three locations is important. Fort Stewart is in a climatic region that is wet and hot with high humidity. The climate at Fort Hood is dry and hot with low humidity. In contrast, the British Columbia sites are wet and cold with high humidity. Certainly from a climatic point of view the design of the experiment is not satisfactory, but questions of cause and effect related to some major factors can be addressed because variation in climate is well represented.

In addition to the major climatic differences of the referenced RCCP sites, the following items of interest can be associated with the individual sites and are partly addressed in the balance of the paper.

1. Fort Stewart:
   a. Dowels
   b. Moist-sand cure
   c. Sawing
   d. Compaction
   e. Flexural strength
   f. Transportation
   g. Durability
2. Fort Hood:
   a. Burlap cure
   b. Spray cure
   c. Compound cure
   d. Sawing
   e. Unsound concrete
   f. Uncontrolled cracking
   g. Coarse aggregate
   h. Field compaction
   i. Laboratory compaction
   j. Quality control
   k. Transportation
   l. Laboratory durability

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3. British Columbia:
   a. Spray cure
   b. Spacing of uncontrolled cracks
   c. Thickness comparison and heavy loads
   d. Field durability

The foregoing list of factors is not complete but presents several points that form the basis for meaningful discussion.

MIX DESIGN AND PROPERTIES

As previously mentioned, roller-compacted concrete (RCC) must pass through several transitional stages to become an effective pavement. These stages include features of conventional concrete, soil-cement, and asphalt.

The basic mix design procedure is analogous to that for conventional concrete and is outlined in American Concrete Institute (ACI) Standard 207.5R-80 (Roller Compacted Concrete, 1983). However, there are several points that need to be emphasized. First, quality of the portland cement concrete (PCC) will be determined by the quality of its components, for example, cement, coarse aggregate, and fine aggregate. In general, because a PCC mix is used for RCCP does not bring any new and unknown reactions or phenomena into consideration. The differences in application of a conventional concrete and an RCC will come in the form of a lower water-cement ratio and higher density of the RCC. Both of these properties would generally be expected to have a beneficial effect on concrete properties. Careful note should be made of the word "generally," because the use of a minimum water-cement ratio in a hot, dry, and windy environment may prove inadequate for early hydration. The observations and consequences of this problem will be addressed in the following discussion.

Durability

Early laboratory freeze-thaw tests at the U.S. Army Engineer Waterways Experiment Station (WES) of field RCCP samples from Fort Stewart indicated inadequate durability; however, these laboratory results did not agree with the satisfactory durability demonstrated by RCCP in British Columbia over a several-year period. This difference in laboratory and field results was interesting and suggested the need for a close look at the type and amount of air existing in a concrete mixture that is compacted externally to a high density. In addition, cognizance should be taken of the development of the laboratory freeze-thaw test for a supersaturated condition and the potential for mitigation of a supersaturated condition first in a PCC with high density and second in a pavement structure. Current laboratory tests at WES in which more attention was given to achieving durability indicated satisfactory results. Also, prototype accelerated freeze-thaw tests being completed at the U.S. Army Engineer Cold Regions Research and Engineering Laboratory indicate satisfactory durability.

Gradation

The maximum aggregate size influences several aspects of RCCP. Larger maximum aggregate will result in greater segregation, which could result in honeycombed areas of the pavement. In addition, because construction utilizes asphalt laydown and handwork techniques, the larger maximum aggregate sizes will make handwork details difficult.

An impervious surface with a nominal macrotexture similar to that of an asphalt concrete is desired for RCCP. This type of surface can be achieved on asphalt concrete by both reducing the maximum size aggregate and requiring a dense- (well-) graded gradation. A 3/4-in. maximum aggregate size has provided an acceptable macrotexture for asphalt pavements. Using a denser gradation in RCCP will compensate somewhat for lack of a fluid paste and at the same time will contribute to increased density. The smaller maximum aggregate sizes may increase costs; however, material costs are only marginally significant in the economics associated with RCCP.

Laboratory Consolidation and Compaction

Laboratory compaction techniques affect determination of consistency, amount of water for compaction, and target density for field compaction. Consistency for conventional concrete can be evaluated with the Vebe apparatus, and with some modification this device can be used to evaluate RCCP mix consistency (ACI Standard 207.5R-80). Optimum moisture content and density for soil-cement can be determined with AASHTO Standards T 99 and T 134. For a dense-graded aggregate mixture such as that proposed here for RCCP, AASHTO T 180 is recommended in lieu of T 99 and T 134. Subsequent required field density can be set as a percentage of the laboratory standard density.

Once the cement or pozzolan proportions or both have been selected, water content can be adjusted within a reasonable range of water-cement ratio to achieve consolidation with the modified consolidation technique for the Vebe apparatus. This process is used to arrive at a consistency within the cement paste for efficient compaction. The cement paste is analagous to the soil binder in base, subbase, or other granular construction materials and the asphalt mastic in asphalt mixtures.

Density of PCC achieved through consolidation is desired for quality, durability, and strength. PCC consolidation is a one-time process, after which the PCC physical characteristics (density and thickness) are expected to remain constant. Soil-cement is compacted for generally the same reasons, except that effective utilization of soil-cement for stabilization and strength is related to achieving an optimum density for a given soil-cement combination. The optimum density is achieved by varying the soil-cement binder consistency by adding water. Asphalt-concrete strength and binder content are also tied to the compaction. However, unlike PCC and soil-cement, asphalt concrete will continue to densify under the compactive effect of traffic.

The laboratory compactive effort adopted for soil-cement is related to the constructability or density that can be achieved with certain types of compaction equipment (3,p.30) (e.g., a tamping roller). On the other hand, laboratory compaction for asphalt concrete was initially selected on the basis of density achieved in test sections trafficked with prototype traffic, although the percentage of the laboratory (standard) density was adopted on the basis of ability of field equipment available at the time (the 1940s) to achieve compaction (4-6). The factors related to selecting a target density for RCC are similar to those for soil-cement because once the compacted concrete has been cured, traffic will not induce additional changes. Therefore, selection of a laboratory compactive effort should be related to constructability and achieving a uniform density. However, the density achieved by a vibratory roller used to compact RCC should be evaluated in light of the soil-cement standard compactive effort based on a tamping roller and an expected difference in compactability of the dense-graded aggregate mixture of RCCP.

PLANT PROCESS

Desired long-term performance of pavements, including RCCP, will be achieved first by use of quality materials and construction. Second, consistency in materials and the production process must be maintained. The reason for addressing this second point is generally obvious, but if the recommendations by Pittman and White (1) discussed earlier in this paper are accepted, denser aggregate gradation and a smaller maximum aggregate size than that normally found in concrete mixtures will be used. Some components of an asphalt plant process can aid in achieving efficiency of mixing and the necessary volume of RCC production to support paving operations.

Prior recommendations on gradation were made based on experience with asphalt mixtures; however, in production of asphalt mixtures even a 3/4-in. maximum size aggregate tends to segregate unless care is taken in stockpiling, feeding, and handling. Effective control of gradation for a 3/4-in. dense-graded asphalt mixture generally involves use of three cold bins for the coarse aggregate, fine aggregate, and sand. Mineral filler, if required, is fed from a separate, enclosed hopper. It is anticipated that with multiple stockpiles, a greater portion of which will be fine aggregate as compared with that used in the usual concrete mixture, potential exists for high water-content variations. Stockpile water contents must be monitored because the water content of RCC is lower than that of the usual cement, so any variations in water will be accentuated.

Once the mixing process has started in normal PCC mixtures and a paste has been developed, segregation of the aggregate is inhibited. A paste, or binder of asphalt or mineral filler or both in asphalt mixture, also functions to inhibit segregation. However, the low water content in RCC restricts development of a paste and consequently segregation is a potential problem. Care must be exercised in the transportation, laydown, and handwork associated with constructing an RCCP to maintain homogeneity in the finished product.

CONSTRUCTION

The approach to construction of RCCP must begin with consideration of the use to which the pavement will be put and the expectation for performance. In addition, some limitations exist because of the equipment used for hauling, placement, and compaction.

Transporting

If RCC material is mixed and transported in ready-mix trucks, the drums of those trucks should be in good condition and clean. Even when these conditions are met, unloading is slow, but not meeting these conditions will result in even greater difficulty. Large paving projects are best served by using dump trucks (or the equivalent) to haul the paving mixture rather than using ready-mix operations. In fact, at this point the construction process can be compared with that in an asphalt paving project; the only problem, as mentioned earlier, is segregation, because of a lack of paste. Truck bed covers may be required to retain moisture under extreme conditions of temperature and humidity in the same way that a cover is required to maintain temperature of an asphalt mix in cool weather.

Laydown

The laydown, finish, and compaction processes are the key to the economy of RCCP because only a fraction of time is required for them as compared with those in conventional concrete pavement. For example, in lieu of forming or slipforming individual lanes of conventional concrete pavement, which require setup and preparation time for each paving lane, an RCCP is paved with a highly mobile asphalt laydown machine that generally is only constrained by mix production and number of trucks available for hauling. The time for construction of an RCCP is in the range of 30 percent of that required for a conventional concrete project.

Handwork associated with the laydown operation utilizes most of the same tools used for asphalt, including lutes, rakes, and shovels. However, the work requires more effort because the mix is not as plastic as either conventional concrete or asphalt and is more analogous to working with a soil binder and gravel mixture that has been partially compacted.

Joints

Two types of joints will naturally occur as a result of the construction: longitudinal and transverse. Transverse joints will occur as a result of long delays or at the end of a day's paving. These joints can be handled like transverse joints in asphalt paving, the only difference being that the RCC pavement thickness is significantly greater. Longitudinal joints fall into two categories: fresh and cold. If multiple pavers or short paving lanes are utilized, longitudinal joints are not a great problem. In these cases the joints can be ameliorated. However, delays in construction that would allow hydration to proceed beyond the point when adequate bond occurs will result in a cold joint with poor bond.

An important consideration for RCC pavements is the approach to be adopted for sawing joints. Concrete pavement sawing is normally expected to take place after there has been sufficient hydration to prevent the concrete from raveling and spalling during the sawing action. Because the water content of RCCP is marginal for hydration, external climatic conditions such as high temperature, low humidity, and wind can reduce the already low moisture content, resulting in retardation of surface hydration, which delays a strength gain adequate to accommodate sawing. The delay can result in uncontrolled cracking, which precludes the benefit of sawing a regular joint pattern. Additional moisture may be lost in the region of the crack in addition to the amount required for hydration, resulting in unsound concrete around the crack. The critical nature of adequate moisture for hydration in RCC pavement mixtures was demonstrated through experience at Fort Hood, where conditions of high temperature, low humidity, and wind existed during construction. At this RCCP project there was initially some sawing, but because a slow gain in strength, raveling and spalling, and uncontrolled cracking occurred in spite of the sawing, a decision was made to discontinue the practice. Before the pavement was opened for operations, a steel bar was used to sound the concrete on either side of both the uncontrolled cracks and the sawn joints. Results indicated that unsound concrete existed on both sides of all uncontrolled cracks but none was found at sawn joints. The conclusion that can be drawn is that water from the sawing operation completed the hydration process around the sawn joints. It is possible that raveling from sawing would be less of a problem at the uncontrolled cracks than future spalling of unsound concrete. The decision to stop sawing at Fort Hood because of raveling and appearance of random cracks appears to have been made without consideration of the basic remedies.

When uncontrolled cracking occurs in concrete pavement in spite of sawing, it is common to balance options of sawing sooner or making a deeper saw cut. Because RCC gain in strength is slow, sawing sooner would not be a remedy; however, sawing deeper would be appropriate to ensure a weakened plane to control cracking. In retrospect the initial saw cut at Fort Hood was a minimum T/6 and the subsequent cracking adjacent to saw cuts should have come as no surprise. Other logical reasons for sawing deeper are that the strength gain would be faster and lower in the pavement because of a higher moisture content and that sawing deeper would have ensured an adequate weakened plane.

Although laydown with an asphalt paving machine can be string or wire controlled for elevation and alignment, subsequent compaction leaves a free edge with a variable alignment and unless multiple laydown machines are used or very short lanes are paved, the resulting juncture of two paving lanes will be a discontinuity that will result in an irregular crack. Except as noted, sawing will not eliminate formation of this longitudinal crack.

Concern with cracks versus use of joints is predicated on accelerated deterioration and maintenance that are associated with such cracks in concrete pavements. In two-lane pavements some control can be exercised through use of two paving machines and sawing. However, in broad areas of pavement such as parking areas or loading docks, longitudinal cracks will be a problem.

Curing

The effects of various types of curing have been significant in helping to understand the observations of RCC pavement construction and performance. Curing types include membrane, burlap, water spray, and wet sand. A membrane cure does not appear to supply the extra moisture for early surface hydration, particularly at cracks. Some coordination problems have been encountered when burlap is used. Water spray is the most common type, apparently because of the ease of use. The water spray cure does supply water for hydration but care must be used to keep from eroding the surface with excess water or the force of the spray. Excess surface water may also saturate adjacent construction areas. A wet-sand cure, used at Fort Stewart as an expedient because of the lack of curing compound, apparently supplies adequate moisture for early hydration as indicated by successful sawing of joints. The wet-sand cure may be an overlooked technique.

Smoothness and Texture

Smoothness and texture of RCCP have been partly addressed. Smoothness, although not given a great deal of attention, has not been a particular problem, and driving at 45 mph diagonally across the parking area paving lanes at Fort Hood could be described as no rougher than driving across some recently constructed concrete highway pavements. The Fort Hood project was paved without using a stringline for grade control of the asphalt paver.

The larger the maximum aggregate size, the more segregation will occur in the mix and the more pronounced will be the surface texture. An aggregate gradation, already discussed, closer to a dense asphalt gradation can reduce segregation and reduce the coarseness of the surface texture. A rubber-tired roller has also been used to knead together surface cracking caused by a vibratory steel-wheeled roller. The resulting surface texture resembles that of an asphalt pavement.

DESIGN

Pavement thickness design criteria are generally based on an envelope of failures recorded in pavement test sections or performance observations of prototype pavements. In some cases, design criteria have been modified as a result of laboratory testing. However, incorporation of laboratory data into design criteria has been infrequent because of an inability to directly compare field performance and laboratory test results; for example, there is a shift function that is not generally apparent. Consequently, when new pavement technology or materials are considered without field performance, a great deal of uncertainty develops in its subsequent application. Such a situation exists with RCCP.

In pavement design the flexural strength is a significant design factor (1). Laboratory flexural strength tests of pavement samples indicate that RCCP can develop a 25 percent higher flexural strength than a conventional concrete pavement. In large part, this higher flexural strength will come from a higher density achieved from the compaction applied during construction. Taking advantage of this higher strength hinges on being able to achieve the necessary density uniformly from construction practices. Secondary consideration must be given to the question of whether the higher-density, higher-modulus concrete mixture will have a different fatigue relationship from that of conventional concrete. A related, secondary consideration is the minimum thickness required for the RCCP to maintain its integrity.

Adequate mix design, uniformity of materials, and moisture and density control will ensure a desired flexural strength for design. It is doubtful that significant differences in fatigue properties will exist for RCCP, because too many other factors affecting the quality and performance of the concrete will predominate. Performance of RCCP related to loading has been very satisfactory. In British Columbia a conventional 24-in. concrete pavement has shown severe structural distress, whereas a 17-in.-thick RCCP subjected to the same loads for the same length of time has not (2). The minimum thickness required to ensure that RCCP will maintain its integrety has only been addressed recently through construction of thinner test sections (1).

One measure of concrete pavement performance is the amount of cracking. Cracking of conventional concrete pavements is minimized through proper spacing of sawn joints. Unless the same approach is adopted for RCCP, uncontrolled cracking will occur with discontinuities that would lead to further undesired cracking. This would be a natural and not unexpected phenomenon, and increased thickness may be required to compensate for such occurrences.

Foundation strength is less significant in concrete pavement thickness design than flexural strength, but in the case of RCCP two considerations highlight the need for foundation strength and quality. Functionally, a strong foundation (subgrade modulus greater than 200 psi) will result in less working of cracks because of better pavement support. The effect will be less spalling and additional cracking. From a practical consideration, compaction on a weak resilient foundation may result in low density. Also vibratory compaction directly on a weak wet foundation could result in the foundation material's pushing into and contaminating the

TABLE 1 Thickness Using AASHTO Interim Guide Method for Highways (7)

	M_R (psi)	Working Stress (psi)	E (psi)	Traffic (vehicles/day)	k (pci)	Thickness (in.)
Conventional concrete	600	457	4.2×10^6	8.4×10^6	300	9.5
RCC	750	564	4.2×10^6	8.4×10^6	300	8.5

TABLE 2 Thickness Using COE/AF Method for Storage Areas (8)

	M_R (psi)	Traffic (vehicles/day)	Traffic Category	Design Index	k (pci)	Thickness (in.)
Conventional concrete	600	100	VII	10	300	9.7
RCC	750	100	VII	10	300	8.3

TABLE 3 Thickness Using PCA Method for Industrial Floors on Grade (9)

	M_R (psi)	Factor of Safety	Working Stress (psi)	Stress per 1,000 lb	Thickness (in.)
Conventional concrete	600	2.0	300	7.5	9.0
RCC	750	2.0	375	9.4	7.8

RCC mix. A layered foundation with an adequately compacted subgrade and granular base course similar to an asphalt pavement would provide an adequate foundation for compaction as well as a high-strength pavement foundation. Characteristics of the base course should also mitigate erosion and pumping.

The question of design philosophy as pointed out in the introduction revolves around whether to apply the higher flexural strengths directly into existing design procedures or to apply a factor to reduce the flexural strength to a value associated with conventional concrete before the design procedures are involved.

The effect on thickness of using a high flexural strength for RCCP is examined in a specific example by using three thickness design sources--those of AASHTO (7), U.S. Army Corps of Engineers and Air Force (COE/AF) (8), and the Portland Cement Association (PCA) (9,10). The following assumptions are made:

Single-axle forklift load = 40,000 lb,
Wheel spacing = 50 in.,
Contact area = 200 in.^{2},
Total forklift operations = 300,000,
Modulus of subgrade reaction (k) = 300 pci,
Modulus of rupture (M_R), conventional concrete (CC) = 600 psi, and
Modulus of rupture (M_R), roller-compacted concrete (RCC) = 750 psi.

Although not directly applicable, the AASHTO Interim Guide (7) was used to estimate thickness requirements by using a factor of 1.33 to compute working stress, a concrete modulus (E) of 4.2×10^6 psi, and a slab thickness (D) of 10 in., which results in an equivalent load factor of 27.91 with a terminal serviceability (p_t) of 2.5. The resulting thicknesses are shown in Table 1.

A more direct thickness design method for storage areas is available in TM 5-822-6; AFM 88-7 (8,Ch.1). The specifications used in the design include the 40,000-lb single-axle forklift, 64 vehicles per day, traffic category VII, and a design index of 10. The results are shown in Table 2.

The PCA thickness design procedure for industrial concrete floors was applied by using the axle load of 40,000 lb, single-wheel spacing of 50 in., a 200-in.^{2} single-wheel contact area, and a factor of safety (FS) of 2.0 (10). These thicknesses are shown in Table 3.

As a point of interest the new PCA thickness design procedure for highways was invoked and the allowable load repetitions were checked for both fatigue and erosion assuming a condition of shoulders, aggregate interlock joints, load safety factor of 1.0, and thickness of 9.5 in. and 8.5 in. for conventional concrete and RCC, respectively. The results of this analysis are shown in Table 4.

In general, the 25 percent higher flexural strength is translated into a 1-in. reduction in thickness. It was not the purpose of the example to compare the different thickness design methods and for the assumptions there is little difference between the methods. The COE/AF design procedure may be classified as more conservative than the PCA method as a result of the combination of several factors related to traffic and loading. The PCA method is less conservative because the procedure is more specific as to design input factors and the required design thickness can be more narrowly focused. Perhaps the greatest difference underscored is the effect of considering erosion in the new PCA highway design procedure. The allowable repetitions,

TABLE 4 Thickness Using PCA Method for Highways (10)

	M_R (psi)	Thickness (in.)	Stress Ratio	Allowable Repetitions	Erosion Factor	Allowable Repetitions
Conventional concrete	600	9.5	0.245	340,000	2.36	270,000
RCC	750	8.5	0.227	1,700,000	2.48	120,000

considering erosion, are less than the assumed traffic for the design used to arrive at the 9.5-in. and 8.5-in. thicknesses. However, the allowable repetitions are adequate if dowels are considered.

CONCLUSIONS

During mix design and construction, RCCP must be treated as a transitional material, which requires consideration of portland cement concrete, soil-cement, and asphalt-concrete technologies. It is perhaps unusual to draw from such diverse technologies but also interesting that when basic questions of materials, construction, and performance are arrayed against existing knowledge, cause and effect are easily explained. In the future, with wider application, RCCP will not appear to be an unknown technology but will be applied without hesitation.

Confusion about RCCP durability because of laboratory test results should no longer exist. On the other hand, density from the standpoint of a laboratory standard or field constructability has not been fully defined. The crux is what density can be achieved with existing compaction equipment and what the relation of this field density is to a laboratory standard.

Hydration in concrete is assumed to take place, but under certain climatic conditions, RCCP is characterized by marginal water content, which may be critical for hydration. Experience with different curing techniques has determined that use of a curing compound is not adequate because discontinuities in the membrane can allow loss of the marginal moisture. On the other hand, water spray and wet sand are adequate because a positive moisture condition is maintained at the RCCP surface for hydration. Wetted burlap will accomplish the same purpose but coordination has yet to be worked out for application, maintenance, and conflicts with paving operations.

Allowing uncontrolled cracking is an expediency that may result in decreased performance and increased maintenance. Sawing can be accomplished for control of crack patterns in two-lane pavements and may help control transverse cracking in broader pavement areas. However, longitudinal cracking in broad paved areas will be difficult to control.

Increased flexural strength of RCCP translates into approximately a 1-in. reduction in design thickness. A minimum RCCP thickness for the pavement to maintain its integrity has not been defined. Defining this minimum thickness will involve evaluation of climatic stresses, load stresses, and effects of naturally occurring and constructed discontinuities that would lead to an abbreviated pavement life.

Smoothness of RCCP has been acceptable and may be expected to be even better when the full capability of asphalt laydown equipment is utilized.

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Publication of this paper sponsored by Committees on Rigid Pavement Construction and Rehabilitation and on Soil-Portland Cement Stabilization.