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Rubblization of Portland Cement Concrete Pavements

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Rubblization of Portland Cement Concrete Pavements

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Foreword

Rehabilitation of existing pavements is a top pavement priority facing transportation agencies. Hot-mix asphalt (HMA) overlays on asphalt pavements is an accepted option by all transportation agencies for restoring rideability, improving functional pavement performance, and increasing the structural capacity of the existing pavement system. HMA overlays can also be considered for application to an existing, deteriorated portland cement concrete (PCC) pavement providing measures are taken to eliminate reflection cracking emanating from the cracks and joints in the PCC pavement through the HMA overlay. One such measure is to rubblize the existing PCC pavement.

This process was discussed in a two-part session on rubblization of portland cement concrete pavements at the 2005 Annual Meeting of the Transportation Research Board. The papers in this document were written following the session and are based on the presentations. The papers in this Circular have not undergone peer review.

Appreciation is expressed to Dale S. Decker for his efforts in developing this Circular.

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Design and Construction of HMA Overlays on Rubblized PCC Pavements
State of the Practice

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Rehabilitation of existing pavements is a top pavement priority facing local, state, and federal transportation agencies. The use of hot-mix asphalt (HMA) overlays presents a long-term and economical solution to the pavement rehabilitation problem. HMA overlays restore rideability, improve the long-term functional pavement performance as well as increase the structural capacity of the existing pavement system. Due to the expense, time and traffic delay involved in concrete pavement restoration (CPR) and reconstruction, resurfacing of portland cement concrete (PCC) pavements with an HMA overlay is a very appealing option for many agencies.

However, existing, worn-out PCC pavements present a particular problem for rehabilitation due to the likelihood of reflection cracking when an HMA overlay is placed. The reflection cracking problem must be addressed in the HMA overlay design phase if long-term performance of the overlay is to be achieved.

The objective of rubblization is to eliminate reflection cracking in the HMA overlay by the total destruction of the existing slab action of the PCC pavement. This process is normally achieved by rubblizing the slab into fragments. Temperature and/or reinforcing steel, if present in the PCC pavement, is generally fully debonded from the concrete by this approach. The rubblization process is applicable to all types of existing PCC pavements.

The objective of this paper is to provide an overview of current design and construction guidelines specific to the PCC rubblization process. A procedure is presented for determining the required thickness of an HMA overlay placed over rubblized PCC slabs as well as guidelines for construction.

INTRODUCTION

Rehabilitation of existing pavements is the greatest pavement priority facing local, state, and federal transportation agencies. The use of HMA overlays presents a long term and economical solution to the pavement rehabilitation problem. HMA overlays restore rideability, improve the long-term functional pavement performance as well as increase the structural capacity of the existing pavement system.

In many respects, the rehabilitation of pavement systems is a more complex engineering task than the design of new pavement systems. Rehabilitation is generally considered to be actions taken that significantly extend the service life of an existing pavement. On the other hand, routine maintenance is considered actions that preserve the existing pavement in order to accommodate present traffic loadings.

Pavement rehabilitation requires significant engineering judgment in the evaluation process. The engineer must define the problem, develop potential problem solutions and then select the preferred solution. Rehabilitation of PCC pavements can be done by concrete pavement restoration, reconstruction and by resurfacing. Due to the expense, time and traffic delay involved in CPR and reconstruction, resurfacing of PCC pavements with an HMA overlay is a very appealing option for many agencies.

However, existing, worn-out PCC pavements present a particular problem for rehabilitation due to the likelihood of reflection cracking when an HMA overlay is placed. Horizontal and vertical movements occurring within the underlying PCC layer cause reflection cracking. Reflection cracking can occur at any PCC joint or crack. The reflection cracking problem must be addressed in the HMA overlay design phase if long-term performance of the overlay is to be achieved.

The objective of rubblization is to eliminate reflection cracking in the HMA overlay by the total destruction of the existing slab action of the PCC pavement. This process is normally achieved by rubblizing the slab into fragments. Temperature and/or reinforcing steel, if present in the PCC pavement, is generally fully debonded from the concrete by this approach. The rubblization process is applicable to all types of existing PCC pavements.

The best way to control reflection cracking in an HMA overlay over a PCC pavement is to fracture the slabs prior to placement of the HMA overlay. “Slab Fracturing” techniques have proven to be an excellent strategy for preparation of the PCC pavement prior to overlay with HMA. The National Asphalt Pavement Association’s publication IS-117, “Guidelines for Use of HMA Overlays to Rehabilitate PCC Pavements” (*1*), based on a comprehensive national study performed by PCS/Law, provides an exhaustive review of all slab fracturing techniques. Slab fracturing can be accomplished by crack/seat, break/seat and rubblization processes.

The objective of this paper is to provide an overview of current design and construction guidelines specific to the PCC rubblization process. A procedure is presented for determining the required thickness of an HMA overlay placed over rubblized PCC slabs as well as guidelines for construction. The design procedure is based on the use of PerRoad Software, a mechanistically based procedure for the design of flexible long-life pavements.

REFLECTION CRACKING

Reflection cracking can occur in an HMA overlay over any joint or crack in the PCC pavement. The current state-of-the-technology does not provide accurate methods to predict the occurrence and growth of the reflection crack. Figure 1 schematically Illustrates reflection crack distress in an HMA overlay placed over a joint or crack of an existing PCC slab. Figure 2 illustrates the mechanism through which the crack develops and propagates in the HMA layer.

PCC slabs expand and contract with seasonal changes in temperature. This movement causes the development of forces at the bottom of the HMA layer as shown in Figure 2*a.* The combination of forces at the bottom of the HMA overlay will eventually cause the development of a microcrack at the bottom of the HMA overlay as shown in Figure 2*b*. With time, this microcrack will grow and eventually reflect upwards to the surface of the HMA overlay as shown in Figures 2*c* and 2*d*. As temperature and loading cycles continue, multiple cracks will form and eventually result in significant deterioration of the HMA surface as shown in Figures 2*e* and 2*f*. Figure 3 illustrates a distressed reflection crack area in an HMA overlay over an existing PCC pavement.

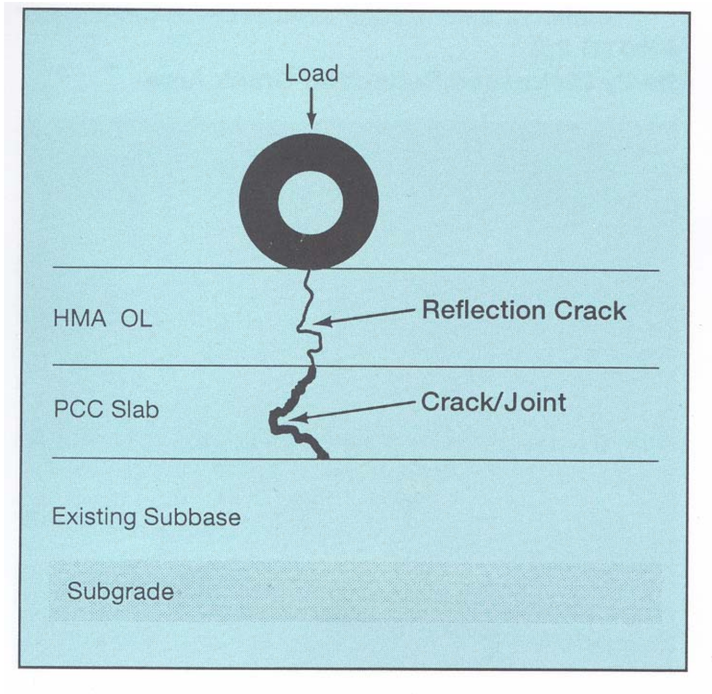

FIGURE 1 Schematic of reflection cracking (*1*).

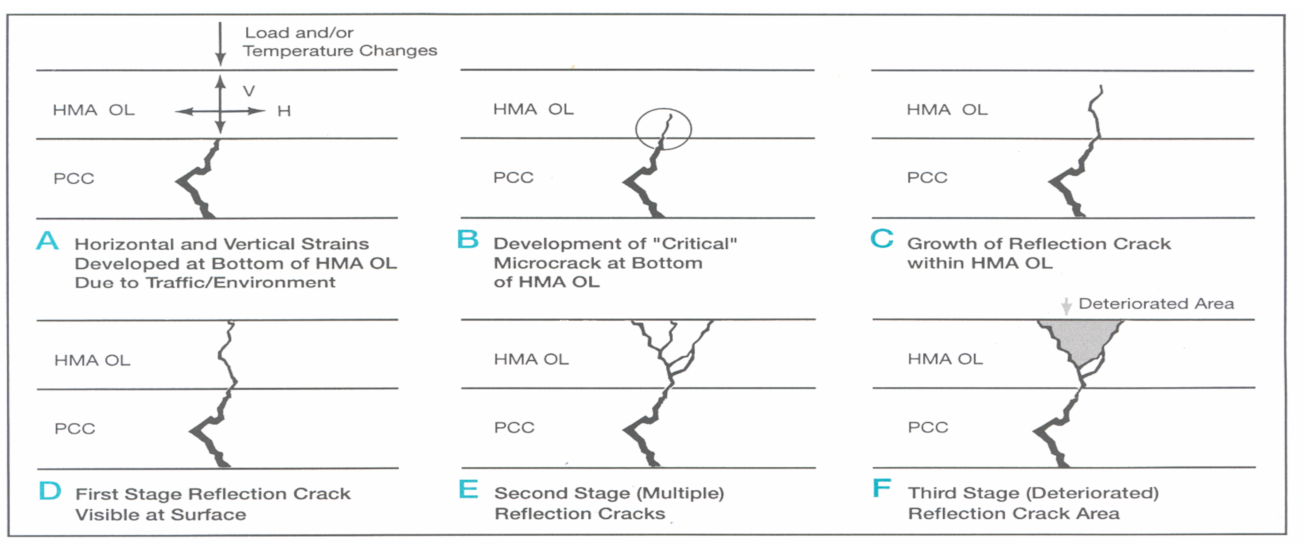

FIGURE 2 Growth of reflection cracks (*1*).

FIGURE 3 Reflection cracking in HMA overlay over PCC pavement. (Photo courtesy of Antigo Construction.)

A variety of techniques have been used over the years in an attempt to eliminate reflection cracking in HMA overlays. These approaches include: saw/seal the HMA overlay; use of thick HMA overlays; installation of crack relief layers (including stress absorbing interlay materials); selection of modified asphalt HMA overlay materials; and slab fracturing prior to HMA overlay.

Of the slab fracturing techniques, rubblizing has proven to be one of the most economical and successful ways to eliminate reflection cracking of HMA overlays placed on existing PCC pavements. The underlying principle of this approach is to significantly reduce the effective slab length of the PCC pavement by fracturing the slab into small fragments. The reduction of the effective slab length will result in minimal horizontal movements of the slab joints and cracks due to seasonal temperature changes. This greatly minimizes the tensile and shear forces normally occurring at the bottom of the HMA overlay.

The modulus of a fractured PCC slab is an extremely important parameter for the successful performance of HMA overlays on rehabilitated PCC systems. The greater the degree of slab fracturing and/or steel-concrete debonding achieved in the construction process, the lower the effective slab modulus will be. Thus, the effective modulus of a fractured slab is a function of the nominal fragment size or crack spacing actually achieved in the rubblization process.

The fractured slab modulus has a significant impact on functional distress caused by reflection cracking through the HMA overlay as well as on structural requirements of the HMA overlay to eliminate distress caused by inadequate structural capacity of the existing rubblized slabs. As the PCC modulus decreases (slab becomes more intensely fractured), the likelihood of having reflection crack problems in the HMA overlay is significantly reduced. However, as the PCC modulus decreases, the likelihood of having insufficient structural capacity also significantly increases. The ultimate goal is to reduce the effective slab modulus value to a minimum or critical value such that reflection cracking will not occur, but not reduce it to so low a value that the existing capacity of the fractured slab is reduced to a point where an excess HMA overlay thickness is required (*1*).

Rubblizing has been used extensively by many agencies in the last 20 years (*15, 17, 19, 20, 21, 22, 23, 24*). In general, field performance of HMA overlays on rubblized slabs has been found to be good to excellent. The field-proven success and growing use of this rehab approach indicates that this technique no longer needs to be considered as research or experimental in nature.

RUBBLIZATION PROJECT EVALUATION

Every rough, worn-out PCC pavement may not be a candidate for rubblization with an HMA overlay. A structural evaluation of the existing pavement, traffic, subgrade, and environmental conditions must be performed. These steps are imperative to determine if the specific pavement is an appropriate candidate for rubblization. Condition surveys of the existing pavement are important to understand the foundation material for the overlay. It is important to understand the soil and moisture conditions for the pavement system prior to making a decision on the rehabilitation type. However, most PCC pavements can be rubblized in an appropriate manner and overlaid with HMA.

Evaluation of the Existing Structure

As with any pavement overlay project, it is important to know the existing condition of the pavement. It may be that existing conditions are so poor that nothing short of removal and replacement is appropriate. These are decisions that must be made by the design engineer, given an appropriate engineering evaluation of the project.

The key elements of the evaluation are:

- Perform a distress survey of the existing pavement:
  - Cracking,
  - Joint deficiencies,
  - Surface defects, and
  - Miscellaneous distresses;
- Evaluate existing pavement structure:
  - Layer types,
  - Layer thickness,
  - Shoulder condition; and
- Determine soil conditions:
  - Soil types,
  - Bearing value, and
  - Moisture condition.

Distress Survey

Using the *Distress Identification Manual for the Long-Term Pavement Performance Project* (*2*), evaluate the condition of the existing pavement. Each type of distress should be identified, along with the relative severity of the distress. In order to evaluate long term performance of the pavement system, it is critical that the pre-construction condition be known.

Existing Pavement Structure

Through a process of either coring or trenching or a combination of both, evaluate the existing pavement structure. The thickness of each existing layer, the material type, and condition should be determined. These data are quite important for the design of the new pavement system.

A sampling plan must be developed that will provide an appropriate overview of the pavement section to be rehabilitated. As a minimum, two core samples should be randomly sampled per lane mile. Core locations should be in representative cut and fill locations and staggered between lanes. Any areas of obvious structural distress should be evaluated and, if necessary, removed and replaced.

The condition of the pavement shoulder must also be evaluated. Traffic will need to be routed off the existing pavement during the rubblization process. The shoulders will need to be able to carry the traffic loading during the construction process.

As an example of evaluation criteria, Wisconsin Department of Transportation considers the rubblization process when one or more of the following conditions are met:

- Greater than 20% of the concrete pavement joints are in need of repair;
- Greater than 20% of the concrete surface has been patched;
- Greater than 20% of the concrete slabs exhibit slab breakup distress; and
- Greater than 20% of the project length exhibits longitudinal joint distress greater than 4-in. wide (*9, 10, 11*).

Soil Conditions

After the coring or trenching has been completed, testing on the soil should be performed to determine the structural adequacy of the foundation material. Tests such as dynamic cone penetrometer (DCP) and field California Bearing Ratio (CBR) have been used to characterize the materials. Moisture content of the in-situ soil materials shall also be determined. From the field data, typical values for the project can be developed.

The Illinois Department of Transportation (IDOT) recommends splitting the top twelve inches of the subgrade into two equal layers, determining the DCP for each layer, and using the average of the two values to determine the type of rubblization method to be used (*3,4,5*). The selection of rubblization method will be discussed later in this paper.

The soil condition survey will provide the designer with data to make decisions regarding the rehabilitation process. If very soft subgrades are noted, it may be necessary to limit the extent of the rubblization or in some cases, change the processing to another rehabilitation technique such as Break and Seat or Crack and Seat.

Project Evaluation Report

In addition to the information discussed above, the project evaluation report should include comments on the material conditions at the time of sampling, clearances for overhead items for the project, location of utilities and culverts in the pavement, location of any buildings within 50 feet of the pavement to be rubblized and the location and condition of any underdrains in the pavement.

HMA OVERLAY THICKNESS DESIGN

Overlay thickness design can be based on either the AASHTO Pavement Design Guide or mechanistic theory. Some agencies are successfully using mechanistic approaches to pavement design. The process requires a significant validation and refinement process to account for material properties in a specific area as well as calibration of the performance prediction models. Currently, most agencies are using the AASHTO design procedure.

The AASHTO Guide is based on the structural capacity deficiency approach. This approach requires the design engineer to calculate the required future structural capacity and determine the existing structural capacity. The structural number of the overlay is then determined by calculating the difference between future required structural number and the existing structural number. IS-117 (*1*) presents a thorough discussion of this process.

The overlay thickness design process for this paper is based on the PerRoad mechanistic software. PerRoad was developed at Auburn University and is based on the Waterways Experiment Station Layered Elastic Analysis (WESLEA) approach. Development of this software was funded by the Asphalt Pavement Alliance and is available for free download at www.asphaltalliance.com/library (*25*).

PerRoad allows the rubblization designer to evaluate existing conditions and to develop an appropriate overlay thickness. The PerRoad Software has been used by NAPA to develop design charts which are presented in Information Series 132 (*27*). The NAPA publication provides the rubblization designer with the tools necessary to determine the overlay thickness required. Figures 4 and 5 illustrate the graphic design charts that were developed with PerRoad.

Figure 4 shows the overlay thickness versus subgrade modulus for a 7-in. rubblized PCC pavement with a subbase structural number of 0.4. For example, consider a subgrade modulus of 8 ksi. It can be observed that the overlay thickness varies from 6 to 12 in. for traffic counts from 5 to 100 MESAL. The figure also indicates minimum overlay thicknesses. These values were established to ensure adequate prevention of reflection cracking for a specific structural requirement. Figure 5 illustrates the same ideas but with a subbase structural number of 1.6. It is noted that with the better subbase material, the required overlay thickness is reduced. Note again the 8 ksi subgrade modulus. Until you reach approximately the 50 MESAL traffic level, the minimum overlay requirements are in effect. But at even the highest traffic level of 100 MESAL, the overlay thickness is only 9 in.

RUBBLIZATION EQUIPMENT

Rubblization requires the use of highly specialized equipment to break the concrete down to a specified maximum particle size. There are two basic types of self-contained, self-propelled devices for rubblizing PCC pavements.

Multi-Head Breaker

The Multi-Head Breaker (MHB) has sixteen 1,200- to 1,500-lb drop hammers mounted laterally in pairs with half the hammers in a forward row and the remainder diagonally offset in a rear

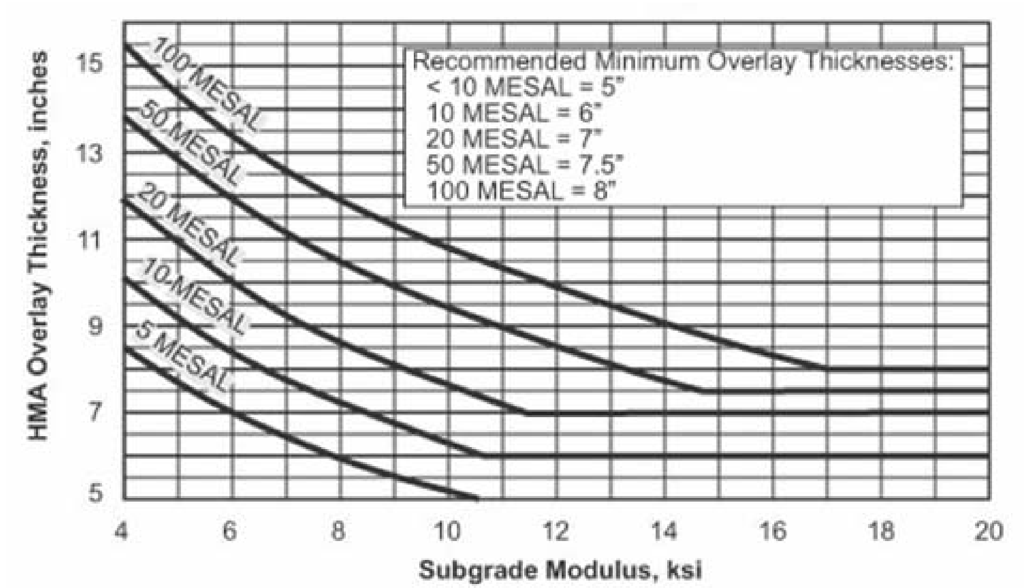

FIGURE 4 HMA overlay thickness versus subgrade modulus (7-in. rubblized PCC, SN_{sb} = 0.4). (*27*)

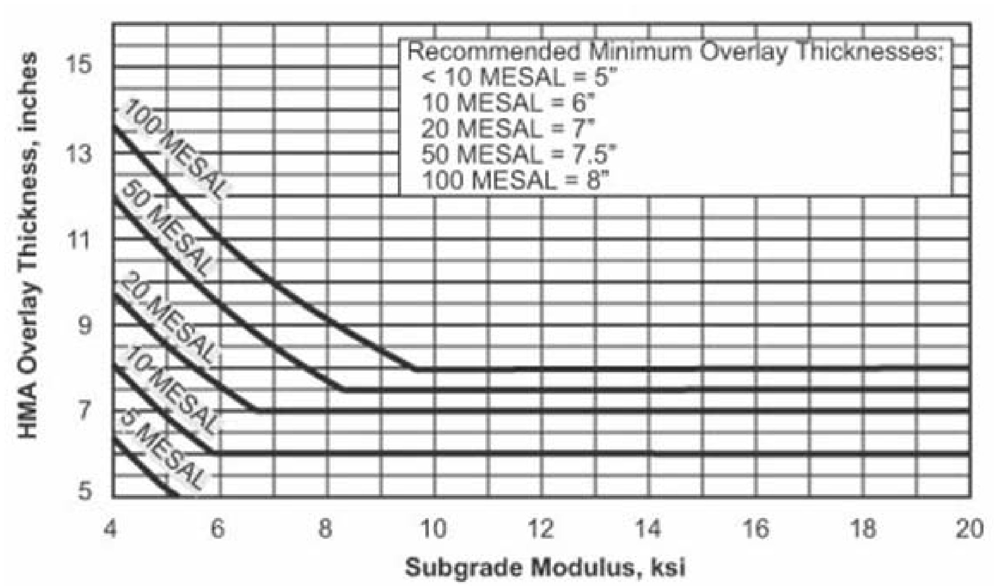

FIGURE 5 HMA overlay thickness versus subgrade modulus (7-in. rubblized PCC, SN_{sb} = 1.6). (*27*)

row. This hammer configuration ensures there is continuous breakage from side to side. Each pair of hammers is attached to a hydraulic lift cylinder that operates as an independent unit. Each pair of hammers develops between 1,000 and 8,000 ft-lb of energy depending upon the lift height selected and cycles at a rate of 30 to 35 impacts per minute. The drop height of each pair of hammers can be adjusted during production to control the amount of breaking energy that is transferred to the PCC pavement. The 8-ft wide machine carries 12 hammers 8 in. in width. A wing, carrying two 1,500-lb hammers, can be added to each side for a total breaking width of up to 13 ft. Due to individual control of each lifting cylinder, breaking can be as narrow as 2.67 ft or increased in increments to as wide as 13 ft. The MHB is capable of rubblizing a full lane width of the pavement in a single pass.

Figure 6 illustrates the MHB. The MHB is manufactured by Badger State Highway Equipment, Inc., Antigo, Wisconsin (www.antigoconstruction.com) (*12*).

Resonant Frequency Breaker

The Resonant Frequency Breaker (RFB) is a self-propelled device that utilizes high frequency, low amplitude impacts with a foot force of 2,000 lbs. The foot is located at the end of a pedestal that is attached to a beam and counter weight. The force applied to the pavement is achieved by vibrating the large steel beam connected to the foot. The foot is moved along the concrete surface at the front of the machine. The breaking principle is that low amplitude, high frequency, resonant energy is delivered to the concrete slab, resulting in high tension at the top. Since concrete has low tensile strength, the slab fractures on a shear plane through the pavement. The foot, beam size, operating frequency, loading pressure and speed of the machine can be varied.

Using the RFB, the breaking begins at the centerline and proceeds to the outside edge of the pavement. The breaking pattern is approximately 8 in. wide, thereby requiring approximately 18 to 20 passes to break a 12 ft wide lane. The RFB is generally required to operate at a maximum amplitude of one inch to avoid disruption of base and prevent damage to underground structures. The RFB encroaches about 3 to 5 ft onto the adjacent lane to rubblize near the centerline of the pavement. Since the RFB has wheel loads of 20,000 lbs and a total weight of 60,000 to 70,000 lbs, the fractured pavement, shoulder and subgrade must be adequate to support multiple passes of the equipment (*6*).

FIGURE 6 MHB for PCC rubblization. (Photo courtesy of Antigo Construction.)

Figure 7 illustrates the RFB, manufactured by Resonant Machines, Inc., Tulsa Oklahoma (www.resonantmachines.com).

CONSTRUCTION OPERATIONS FOR RUBBLIZATION

This section will present guidelines for construction operations for the rubblization process (*3, 6, 7, 11, 13, 14, 16, 18*). The topics include:

- Surface preparation,
- Drainage issues,

FIGURE 7 RFB for PCC Rubblization. (Photo courtesy of RMI.)

- Location of utilities and underground structures,
- Selection of rubblization equipment,
- Rubblization recommendations,
- Compaction after rubblization,
- Troubleshooting rubblizing operations, and
- Quality control issues for rubblization.

The RFB can also be fitted with high flotation tires, thereby allowing operation on pavement sections that are thinner or have soft subgrades.

Other Equipment

Other types of pavement breaking equipment have been used to rubblize PCC pavements and are discussed in NAPA's IS-117 (*1*). However, recent experience in the U.S. has shown that the MHB and RFB are the two most successful approaches for rubblizing PCC.

Surface Preparation of the Existing Pavement

Experience has shown that any existing HMA overlay should be removed prior to the rubblizing the PCC. A relatively clean surface allows better transmission of the rubblization energy into the underlying concrete. Due to possible deviations in the surface of the existing concrete from faulting and variations in the milling operation, thin layers of HMA may be present and should present no problems with the rubblization process.

Any loose materials on the surface should be removed. This might include loose patching material, joint fillers, and expansion material. Some agencies wait until after the rubblization to remove any loose materials, in case the rubblization process creates any additional materials that should be removed. Full depth concrete joint repair is not necessary prior to rubblization.

The Engineer must evaluate an appropriate course of action relative to patches on the existing PCC surface. If the patch is PCC, it can be rubblized along with the rest of the pavement. If the patch is HMA and is relatively small and sound, it can remain in place. If the HMA patch is large and unsound, it should be replaced. The replacement material can be HMA binder mix or aggregate (#57 is often used).

Before rubblizing begins, all load transfer devices in the existing PCC pavement that are adjacent to PCC that will remain intact must be severed with a full-depth saw cut. This process isolates the rubblized area. Sawing jointed pavements at an existing joint has proved to be successful. Examples of this situation are exit ramps that are not to be rubblized and beginning and end of the project.

Drainage

Underdrain systems should be installed and functioning before rubblizing begins. In areas of weak subgrade or high water table, the drainage system should be functioning as far in advance of the rubblizing as possible to allow for the subgrade to be as stable as possible. The drainage system also serves to remove rainwater from the rubblized concrete layer, base layer and subgrade during construction. During the rubblizing operation, a steady flow of water in the drainage system is often observed.

Location of Utilities and Underground Structures

Underground utilities and structures must be clearly marked prior to rubblization of the pavement. Special attention should be given to identifying any covers or shutoffs that are not exposed at the surface. When necessary, the breaking energy should be reduced in the proximity of sensitive utilities to avoid damage. The rubblization specification may also allow the contractor to remove the pavement over and around utilities and backfill with aggregate.

Selection of Rubblization Equipment

The Illinois DOT specification uses the graph shown in Figure 8 for selection of the rubblization technique (*3, 4, 5*). Method I in the graph is for use of the MHB. Method II is for the RFB with high flotation tires, thereby allowing operation on pavement sections that are thinner or have soft subgrades. Method III also makes use of the RFB with some limitations as shown in the figure. Method IV allows the use of any of the previous methods or other breaking devices with no restrictions regarding subgrade support, traffic, staging or structures.

Rubblization Recommendations

As a general rule, the smaller the crack spacing and/or fragment size achieved, the greater the likelihood that reflection cracking will be eliminated in the HMA overlay. Of course, the smaller the crack spacing the lower the structural layer coefficient and therefore a greater thickness of overlay is required.

The rubblization process is begun at a free edge or the centerline of the pavement. Typical rubblizing specifications require the breaking of the concrete down to specified maximum particle dimensions while giving the engineer the discretion to direct or allow larger maximum particle dimensions. These specified particle dimensions are what can be expected when rubblizing over a fair to good base/subgrade. The particle sizes that can be achieved are directly related to the condition of the base/subgrade, the slab thickness, seasonal variations, reinforcement type and the operation of the rubblization equipment.

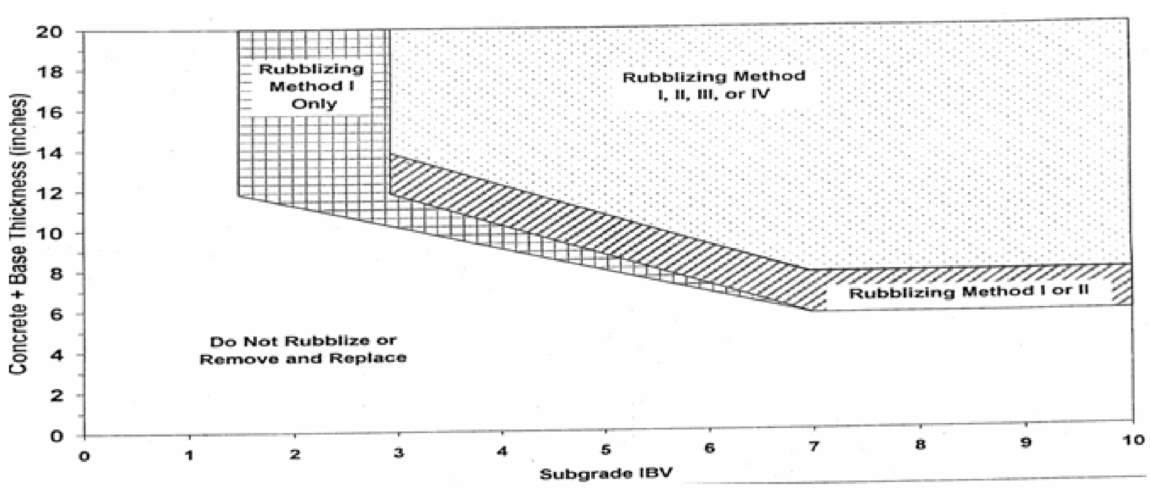

FIGURE 8 Illinois DOT rubblization type selection guide (*3–5*).

A firm and stable base/subgrade will allow for the production of smaller particle sizes than when working over a less firm and stable base/subgrade. Engineering judgment must be used when evaluating the rubblizing process, keeping in mind that the intent of rubblizing is to produce a structurally sound base which prevents reflective cracking by obliterating the existing pavement distresses and joints. The intent is not to meet a gradation requirement.

It must be remembered that the rubblized layer must provide a working platform for paving operations and a stable foundation for the pavement overlay. If isolated areas of weak subgrade exist, appropriate actions must be taken to repair these areas. In some cases, adjustment of the rubblizing process is appropriate. Modifying the rubblization process to induce less energy into the subgrade may be necessary and appropriate.

Traffic should not be allowed on the compacted rubblized slab, due to the risk of "unseating" the particles of the rubblized pavement. There may need to be an exception for cross traffic at intersections. The amount and weight of construction traffic on the rubblized surface should also be minimized, especially in areas with weak subgrade.

Light to moderate rainfall does not impact the rubblization operation. Work might need to be stopped for safety reasons if heavy rain and/or lightning occur. Rubblized PCC drains well, especially if the edge drains are functioning properly. Therefore, paving operations can usually begin shortly after the rain has stopped. If however, the rubblizing is being performed over a moisture-sensitive subgrade, the rubblizing/paving operations should be coordinated to minimize exposure of the subgrade to excessive moisture. Generally, it is recommended that the HMA overlay over a properly compacted rubblized PCC pavement should occur within a 24 hour period from the compaction process.

Some contractors use water to control dust until the HMA overlay is placed.

Consideration must be given to the effect of vibration and impact on buildings in close proximity to the project where rubblization is being performed.

Rubblization has been successfully performed on PCC pavements ranging from local roads to interstate highways to airfield pavements. Using either MHB or RFB, the contractor must determine an optimum operation to successfully rubblize the slabs. It may be necessary to use multiple pieces of equipment to accomplish adequate fracturing of the PCC. As an example, a guillotine breaker has in some cases been used, followed by the rubblizer. Multiple rubblizing devices are also used to improve productivity of the operation.

Regardless of the equipment used, typical production for the rubblization operation is approximately one lane mile per work day per machine (*26*).

Compaction After Rubblization

The purpose of compacting the rubblized pavement surface is to ensure adequate seating of the rubblized segments and to provide a compacted surface upon which the HMA overlay can be placed. A vibratory roller is normally used to compact and prepare the rubblized surface for placement of the HMA overlay.

The MHB and RFB have slightly different compaction requirements. For the RFB, a 10-ton tandem vibratory roller is used in low amplitude and high frequency settings. A typical HMA roller is used. The operation is very similar to compacting about 2 in. of HMA. Some agencies use an 8- to 10-ton pneumatic roller to smooth up the surface prior to placement of the overlay. Louisiana requires the pneumatic roller to make one pass after the initial pass with the vibratory roller. Two additional passes of the vibratory roller are made after the pneumatic pass (*14*).

Compaction of the rubblized surface by the MHB is usually accomplished using a vibratory roller that has been fitted with a “Z” or Elliott grid as shown in Figure 9. The purpose of the Z grid is to further pulverize the broken concrete particles at the surface.

In either compaction scenario, it may be necessary to reduce the vibratory amplitude to prevent damage to the subgrade or underground utilities. This is particularly true in areas of weak or wet subgrade.

Observation of the compaction process is an effective method to determine the stability of the rubblized layer. Proof rolling with a loaded tandem-axle truck after compaction is a quick and effective way to determine the stability of the rubblized layer. This would generally be done if the engineer has concerns about the stability of the rubblized section after the compaction is completed.

Troubleshooting Rubblizing Operations

Rubblization is not for every pavement. As an example, thin PCC pavements (say less than 7 in.) on poor subgrade with high moisture content may not be possible to properly rubblize. Other slab fracturing techniques such as crack/seat, or break/seat (*1*) may be more appropriate in such conditions.

For some PCC pavement conditions, both the RFB and MHB may apply too much load to the pavement. Examples have been observed where the rubblizing device has broken through the structure. This may be the result of an inappropriate project evaluation or of changed conditions since the time of the evaluation.

With the RFB device, if the vibratory response in the pavement is too much for the existing PCC, the foot can punch through the concrete or cause extreme vibration in the equipment.

FIGURE 9 Roller with Elliott Grid. (Photo courtesy of Antigo Construction.)

Quality Control Issues for Rubblization

The quality control/quality assurance (QC/QA) process used to ensure that proper fracturing has occurred in the rubblization process is a very important consideration for the ultimate success of the project. Unfortunately, controlling the process is a very complex and difficult aspect to properly evaluate. Relying on a visual surface crack survey to enforce specifications may not be entirely reliable as surface cracks may not be a true indication of the effectiveness of the rubblization process.

Test holes are generally excavated to verify the efficiency of the rubblization process as shown in Figure 10. At the beginning of the project, several test holes may be excavated to confirm the process. Once the engineer has verified the specification requirements are being met, the digging of test holes is not usually continued throughout the project. The test holes are usually about 3 ft square and are dug during the first day of rubblizing. The test holes must be repaired with replacement material and compacted.

A typical specification requires less than 9- to 10-in. size particles on the surface and a maximum of 12-in. particle size in the lower half of the broken pavement. However, Arkansas DOT requires that the maximum particle size be 8 in. with the majority of particles being in the 1-to 3-in. range (ADOT specifies the RFB only). If the rubblization process does not achieve these maximum particle size requirements, the contractor must repeat the process, use other equipment to achieve the requirements or remove and replace the materials (*13*). Experience has shown that segments of 12 to 18 in. in the lower half of the slab do not adversely impact the effectiveness in reducing reflection cracking.

FIGURE 10 Rubblization test hole. (Photo Courtesy of RMI.)

FIGURE 11 Exposed reinforcing steel after rubblization. (Photo Courtesy RMI.)

Reinforcing steel in the rubblized pavement can be left in place unless any steel is exposed on the surface as shown in Figure 11. Any exposed steel should be removed by cutting below the surface. The steel should be removed from the site.

PLACING THE HMA OVERLAY

The paving of an HMA overlay on a rubblized and compacted PCC surface is very similar to paving on a prepared crushed aggregate base (*6, 15, 17, 24*). Care must be taken to maintain the compacted condition of the rubblized surface up to the time of paving. A vibratory steel roller may be used to recompact the rubblized surface if local and/or construction traffic have loosened the rubblized surface. Of course, the best plan is to not allow traffic on the rubblized surface.

After the rubblization process is completed, asphalt overlays are placed to accommodate the structural requirements for the traffic, subgrade and environmental conditions. As with most paving operations, traffic will be placed on the intermediate HMA lifts to accommodate construction scheduling. This situation presents a different set of circumstances than for a conventional overlay that is being placed on a pavement that is already carrying traffic.

Through the rubblization process, the PCC has been reduced to the load carrying capacity of unbound base course. As a result, consideration must be given to the thickness of the first lift of HMA that is to be placed on the rubblized surface. The first lift of HMA must be thick enough to adequately cover the rubblized PCC surface and carry traffic temporarily until the additional lifts are paved. The number of large trucks and the type of base determine the minimum thickness needed to carry traffic. If the project includes making cross slope corrections with the first lift, there could be a variable thickness of the lift placed. If this is the case, attention must be paid to maintaining an adequate thickness not only at the centerline but also at the edge of the pavement. In areas of low base/subgrade support, additional thickness of the HMA may also be required.

Experience has shown that traffic should not be allowed on the rubblized surface until the minimum HMA thickness for the type of facility has been placed.

If the thickness of the HMA overlay is decreased when approaching a bridge or overpass, rubblizing should stop at the point where the thickness of the overlay begins to decrease. The designed thickness of the overlay should be maintained over all rubblized areas.

If a yielding subgrade is identified in the operation, the first course of action is to remove such materials if at all possible. If it is not possible to remove the materials, an HMA leveling course may be used to stabilize the area. The HMA leveling course adds greater strength to the section over a yielding subgrade than would filler aggregate and may also facilitate achieving smoothness of the HMA overlays.

USER BENEFITS TO PCC RUBBLIZATION AND CONCLUSION

Agencies are looking for quick, cost effective means to rehabilitate PCC pavements. Despite claims to the contrary, concrete roads do not last forever. Across the U.S., concrete pavements are in need of rehabilitation to meet both structural and functional requirements.

Rubblization is a process whereby the existing worn-out PCC pavement is converted into a high quality aggregate base. This rubblized base layer is the perfect starting point to build a perpetual Hot Mix Asphalt pavement.

Rubblization Advantages

The advantages that rubblizing offers to the owner/agency are as follows:

- Elimination of reflection cracking.
- Improvement in smoothness with the placement of HMA as the new surface.
- Elimination of alkali silica reactivity (ASR) problems with the existing PCC.
- Dramatic decrease in construction time relative to PCC reconstruction
- Improved maintenance of traffic.
- Reduction in length of time traffic is in a two-way situation compared to PCC reconstruction and/or PCC overlay.
- Reduction in cost versus reconstruction of PCC pavement.
- Reduction in cost versus CPR.
- Increase in service life of the HMA overlay.
- Improved public relations due to decrease in construction time and work zone delays.

Rubblization Performance

Performance of pavements that have been rubblized has been excellent. The PCS/Law study involved 118 actual pavement sections throughout the United States. Performance of the rubblized sections was better than any other rehabilitation technique. The Ksaibati report (*22*) was done for the Florida Department of Transportation as an evaluation of the rubblization process. The study conducted a nationwide survey of DOT's to determine the use of rubblization. Twenty-one states reported experience with rubblization. The report states "…it is clear that most states are highly satisfied with rubblization as a good means for eliminating reflected cracks. Only a few states indicated problems with rubblization, mainly due to weak subgrade."

As a specific example, the Illinois 10-year study (*18*) indicates that performance has been better with rubblization than with other techniques which they tested side-by-side. Arkansas has over 300 miles of rubblization either completed or in progress with similar excellent results. (*13, 15, 17*). Michigan, Wisconsin, Louisiana, and Nevada have also reported excellent performance results. (*8, 15, 17, 21,22*) The bottom line is that rubblization has been successfully used in many states.

CONCLUSION

As agencies continue to look for cost-effective methods to rehabilitate PCC pavements, it is clear that rubblization offers an excellent tool to the pavement engineers. The pavement engineer is able to rehabilitate an existing deteriorated PCC pavement into a long-life HMA pavement very quickly and with minimal disruption to the traveling public. In addition, costs are kept to a minimum. The process is no longer experimental. Rubblization of PCC with an HMA overlay works and can provide excellent pavement performance.

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Rubblization Using Resonant Frequency Equipment

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Asphalt Institute

Since the early 1980s, resonant rubblization has evolved from a process used to prepare existing portland cement concrete (PCC) pavement for removal to a technique for converting PCC pavement into an unbound base or subbase. The original equipment, developed by Mr. Ray Gurries (1) in Nevada, uses a vibrating steel beam to apply high frequency, low amplitude loads through a breaking shoe that contacts the surface of the concrete pavement as the equipment moves along the pavement. The PCC fractures throughout its thickness and breaks the bond between any distributed steel and concrete, making the process of removal and hauling much more efficient than traditional methods using drop hammers. While this equipment was originally developed to expedite the removal of PCC pavement, resonant rubblization is now used mostly as a technique for preparing an existing PCC pavement for overlay with hot mix asphalt (HMA). Slab movement that causes reflection cracking in HMA overlays is eliminated, and a stable foundation for construction of a new HMA pavement is created without having to remove or further process the existing material.

In 1986, the New York State Department of Transportation was the first agency to use resonant rubblization as a method for preparing failed PCC pavements for overlaying with HMA. Since then, resonant rubblization has been successfully used in the rehabilitation of jointed plain, jointed-reinforced, and continuously reinforced PCC pavements ranging from city streets to Interstate highways, and on military and commercial airports. Resonant rubblization has been used in 37 U.S. states and is now being used in two Canadian provinces and several countries in Asia, Europe, and South America.

EQUIPMENT AND MECHANICS OF RESONANT RUBBLIZATION

The equipment originally developed by Mr. Gurries was less sophisticated than modern resonant pavement breakers (RPBs), but the concept for initiating fissures through the entire slab thickness established at that time is the same. A counter-weight ranging in mass from 5,450 to 9,100 kg (12,000 to 20,000 lbs) rests above the forward end of a steel beam, on which a 200 to 275 mm (8 to 11 in.) wide steel breaking shoe is attached (Figure 1). Impact loads, applied through a steel breaking shoe induce diagonal cracks through the depth of the PCC slab (Figure 2). The steel beam is oscillated through eccentric shafts at a frequency of 42 to 46 Hz, resulting in closely spaced impacts to the PCC surface as the machine moves forward. The amplitude (vertical movement) in the breaking shoe is less than 25 mm (1 in.), typically between 12.5 and 25 mm (0.5 to 1.0 in.), with the lowest end of the range corresponding to the lowest frequency.

The mechanics of how the concrete fractures have not been reported in detail, but the cracking resembles "shear-compression" failure described by Ferguson (*2*) for reinforced concrete beams. In this mode of failure, diagonal cracks may "initiate approximately a 45-degree crack," followed by crushing on the surface as the crack propagates up through the concrete.

FIGURE 1 Resonant pavement breaker (courtesy RMI, Inc.)

This can be observed in a resonant broken PCC pavement in Figure 3. According to Ferguson, this mode of failure is most likely to occur when the shear span (distance from the load to the edge of the beam) is less than four times the depth of the beam. The resonant pavement breaker is always operated at the edge of an intact slab or on the boundary with previously broken material, resulting in the short shear span required for this mode of failure.

The close spacing (<50 mm, 2 in. apart) of the impact loads results in the generation of a series of cracks that intersect throughout the depth of the PCC slab. The pieces formed by the intersecting fissures increase in size as the fracture lines are spaced farther apart, thus the largest pieces are at the bottom of the rubblized concrete. Near the surface, the broken concrete pieces are much smaller due to the crushing of the PCC that occurs under the breaking head.

Since the original resonant pavement breakers were developed in the early 1980s, there have been significant modifications and improvements to the equipment that have extended the successful application of this technique to extremely thick (>600 mm, 24 in.) PCC airport pavements. Electronic feedback allows current equipment to vary the frequency of the resonant beam and the amplitude (vertical movement) of the breaking head as the machine moves along the pavement. The forward speed of the machine depends on the concrete slab thickness, the stiffness of the PCC, and the relative support provided by the subbase. The equipment is

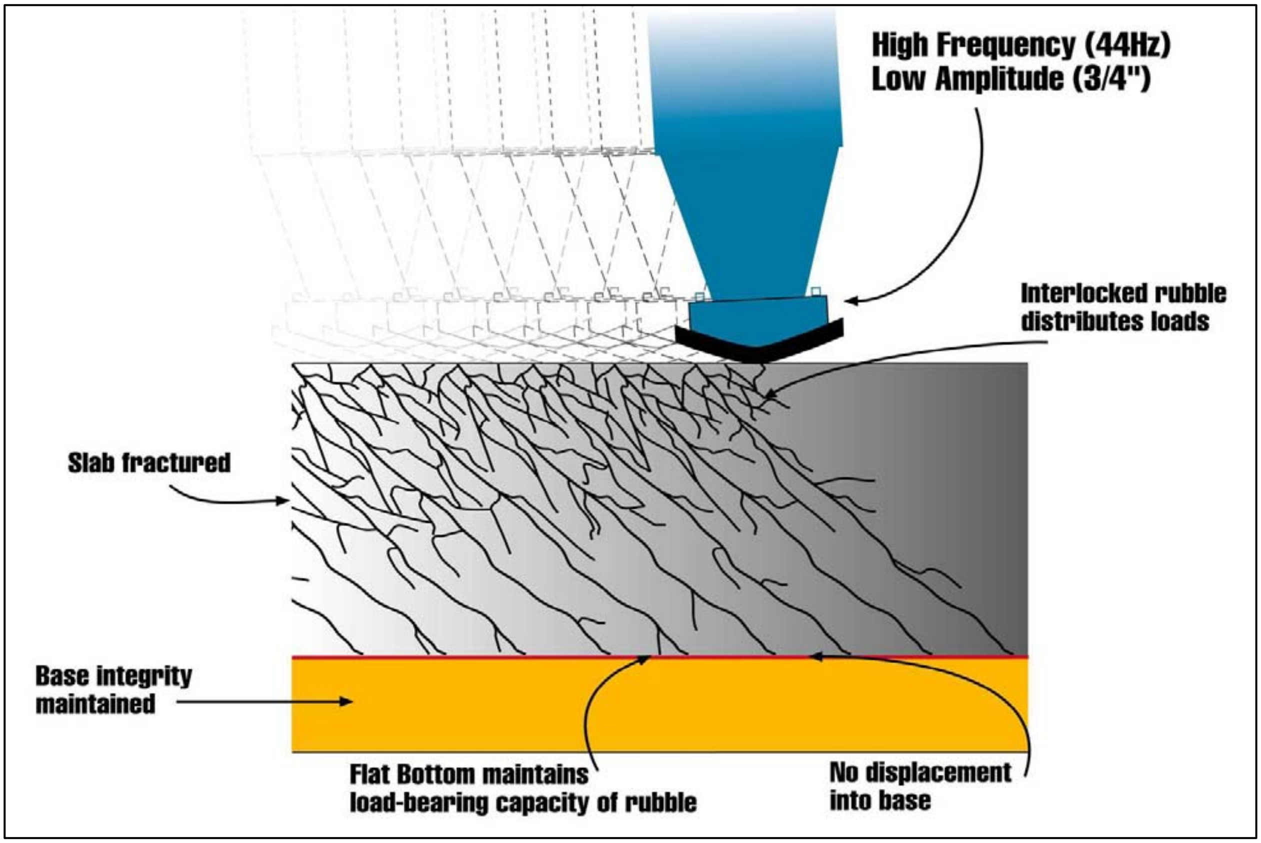

FIGURE 2 Illustration of PCC fracturing resulting from Resonant Rubblization (*1*).

operated at a forward speed of less than 8 km/h (5 mph) to generate the close impact spacing desired.

The production rate (area rubblized per unit time) depends on the operational speed of the equipment, the number of patches or other anomalies that have to be avoided during operation, traffic control requirements, and the number of RPBs being used on a given project. For estimating purposes, one machine can be assumed to be able to rubblize from 4,180 to 8,360 m^2 (5,000 to 10,000 yd^2) per workday shift.

The RPB weighs from 27,200 to 31,750 kg (60,000 to 70,000 lbs), and operates on pneumatic tires. For soft conditions, the RPB may be fitted with wide "flotation" tires to reduce the pressure applied to the fractured concrete and avoid excessive deformation in the underlying foundation.

CONSTRUCTION PROCEDURE

The Asphalt Institute (*3*) suggests the following sequence for rubblizing PCC pavements using either a resonant or a multiple head breaker:

- Remove any existing overlay.
- Install the drainage system 2 weeks (minimum) prior to rubblizing the pavement.
- Saw-cut the full thickness of the pavement adjacent to remaining sections.

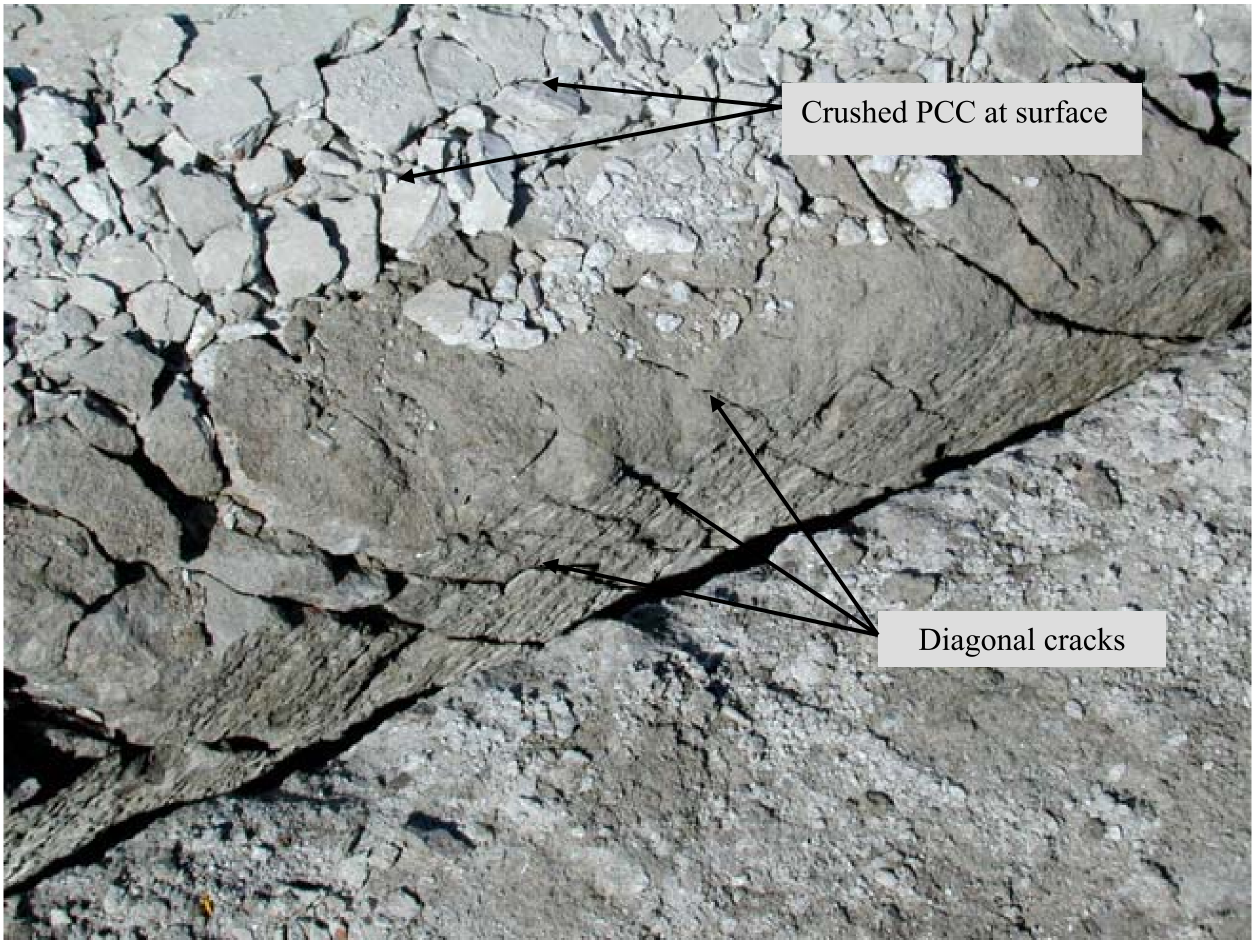

FIGURE 3 Resonant broken PCC pavement.

- Rubblize the PCC pavement.
- Cut and remove exposed steel reinforcement.
- Proof roll fractured PCC.
- Remove and replace soft areas.
- Roll the rubblized PCC at least three passes.
- Place the HMA leveling course and overlay.

Removal of any existing overlay is necessary to assure consistent fracture of the concrete pavement by allowing the breaking head to directly contact the PCC. This is normally done by cold milling immediately before edge drains/shoulder reconstruction begins for convenience and to avoid excessive drop-off between the lane and shoulder since traffic will usually have to be routed onto the existing traffic lanes at least temporarily during construction.

For many projects where resonant rubblization is specified, poor subsurface drainage is a strong contributing factor to the structural deterioration of the existing PCC pavement. Since the ability to fracture the concrete without dilating the broken particles at the bottom of the PCC layer depends on having a stable platform to work against, deficient subsurface drainage conditions must be corrected before resonant rubblization. RMI suggests (*4*) that subsurface drainage should be installed or replaced at least one week ahead of rubblization for typical Interstate highway conditions where the existing pavement is well drained and has an improved subbase. For pavements built at-grade or directly on the subgrade, drainage improvements should be made 30 to 60 days in advance. Originally, many believed that the rubblized concrete fractured using a RPB was relatively permeable and would function as a drainage layer. While the upper 50 mm (2 in.) of the rubblized concrete is porous, particularly before it is rolled, the remainder of the rubblized concrete does not appear to be highly permeable, since the broken concrete has not been dilated by the breaking process or the repeated passes of the RPB.

It is important to design the edge drainage system to collect and dispense excessive moisture immediately under the rubblized concrete and at the interface between the HMA and rubblized PCC, particularly in rolling terrain. Conventional trench/pipe/backfill systems have been most commonly used, although prefabricated geotextile edge drains have also been used. Where geotextile edge drains are used, it is important to locate them where they can remove water from under the PCC pavement and any that collects in the upper 50 mm (2 in.) of the rubblized concrete. A typical edge drain detail is illustrated in Figure 4. Any existing edge drains should be inspected carefully and repaired as necessary if they are to be left in place.

Resonant rubblization has also been performed on projects where lanes were being added to increase the capacity of the existing highway. Where this is performed, either an aggregate base or permeable asphalt base is placed directly against the PCC lane to be rubblized.

Any adjoining concrete pavement that is to be left intact must be physically separated by full-depth sawcut before rubblization. The sawcut minimizes load transfer so the RPB does not damage the concrete on the unloaded side of the sawcut. On highways, this is normally done where there are connecting roadways such as entrance and exit ramps, and has also been done before and after approaches to overpasses and underpasses where the overlay thickness required

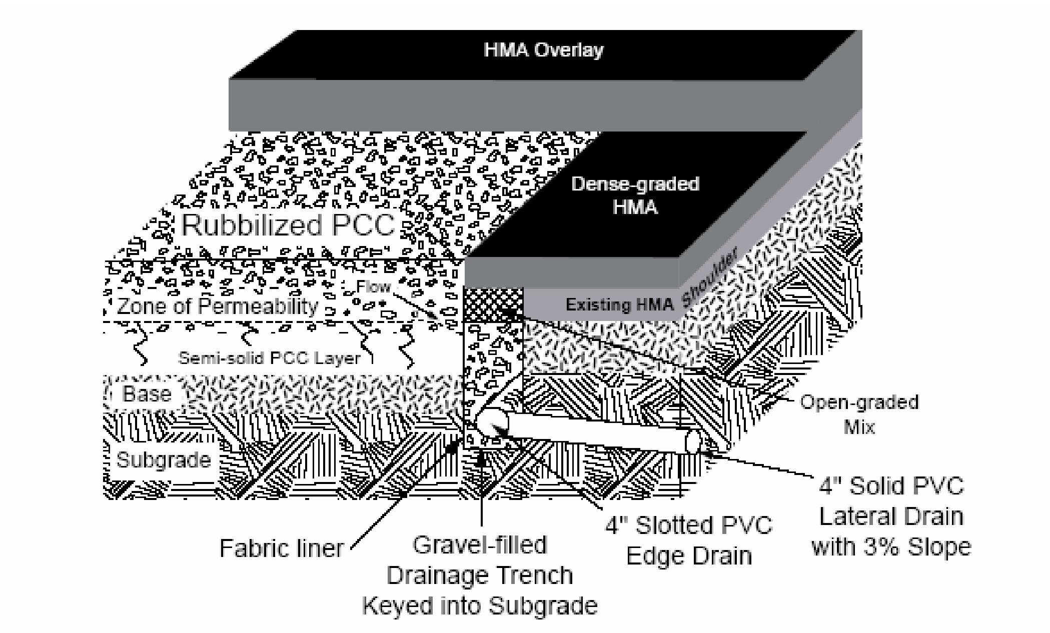

FIGURE 4 Longitudinal edge drain system for rubblized PCC pavement (*3,* Figure 15–2).

was too great to maintain vertical clearance. Where the PCC pavement is left in place, it is usually overlayed with less than 100 mm (4 in.) of HMA due to vertical clearance and/or other geometric constraints. To minimize distress associated with reflection cracking, either an interlayer is place or the overlay is sawcut and sealed directly over the joint. In either case, it is necessary to replace any panels with working cracks and any joints with insufficient load transfer. Rubblization has been used in this case to hasten the removal of deficient concrete pavement panels. An alternative to this is to rubblize the PCC pavement for removal, replacing it with an appropriate asphalt pavement structure that more closely matches the response and performance of the rubblized and overlayed pavement.

Resonant rubblization is performed in successive passes, beginning at the edge of pavement (Figure 5) or at a full-depth sawcut down the length of the pavement for a prescribed distance, preferably at least 1,000 m (3,000 ft). Note that the adjacent pavement (new HMA) on the shoulder is not damaged by the first pass of the RPB (Figure 6). The machine returns to the beginning point adjacent to the previous pass and proceeds down the pavement, repeating this to work across the pavement surface, resulting in a loose fractured surface as shown in Figure 7. As described before, the breaking head must be close to an edge of the PCC pavement to have a short shear span and cause the diagonal cracking to occur. To minimize airborne dust, the PCC surface is often moistened before operating the resonant breaker.

On wide airport runways and taxiways, it was originally thought necessary to cut a relief trench through the PCC pavement to allow for expansion to occur as the concrete is fractured. There was concern that the confinement provided by the fractured concrete in a wide expanse of pavement would affect the ability to fracture the concrete. This has not proven to be necessary on several recent airport projects, particularly with the large machine (PB-500) developed specifically for rubblizing thick PCC pavements up to 650 mm (26 in.) thick.

As mentioned before, resonant rubblization has also been performed on residential streets. The major constraint for this is the recommended (*3*) minimum overlay thickness (125 mm/5 in.) that creates practical problems with adjustments to driveways, intersecting streets and surface drainage systems. Where it is practical to rubblize on urban streets, an advantage to this technique compared to other fractured slab methods is that shallow utilities and adjacent structures are not damaged if they are not tied to the existing PCC pavement.

The production rate of the RPB depends mostly on the thickness and stiffness of the PCC pavement and the support conditions under the concrete, as well as detour plans, traffic control requirements, etc. Where feasible, it is preferable to route traffic away from the construction area rather than work adjacent to live traffic. Long runs without impedance from traffic or other construction activities are preferred for resonant rubblization due to improved efficiency and the lack of potential safety hazards to the equipment operators, other construction workers, or traffic.

When planning to stage the project where traffic will be using the lane adjacent to the resonant rubblization process, it is important to consider the condition of existing shoulder pavements. Construction equipment and traffic must use the shoulder, at least temporarily, during construction in this case. Installation of edge drains provides an opportunity to reconstruct or improve the structural condition of the shoulders without further inconvenience to traffic or construction operations. Rubblization is extended at least 150 mm (6 in.) beyond the width of the HMA course placed directly over the rubblized PCC. This allows the remaining concrete to be rubblized once traffic is moved to the overlayed pavement.

As the RPB fractures the concrete, it invariably moves across material that had been previously rubblized. By doing so, it effectively “proof rolls” the rubblized concrete. On thin

FIGURE 5 Resonant rubblizing starting from pavement edge.

FIGURE 6 Rubblized surface adjacent to shoulder.

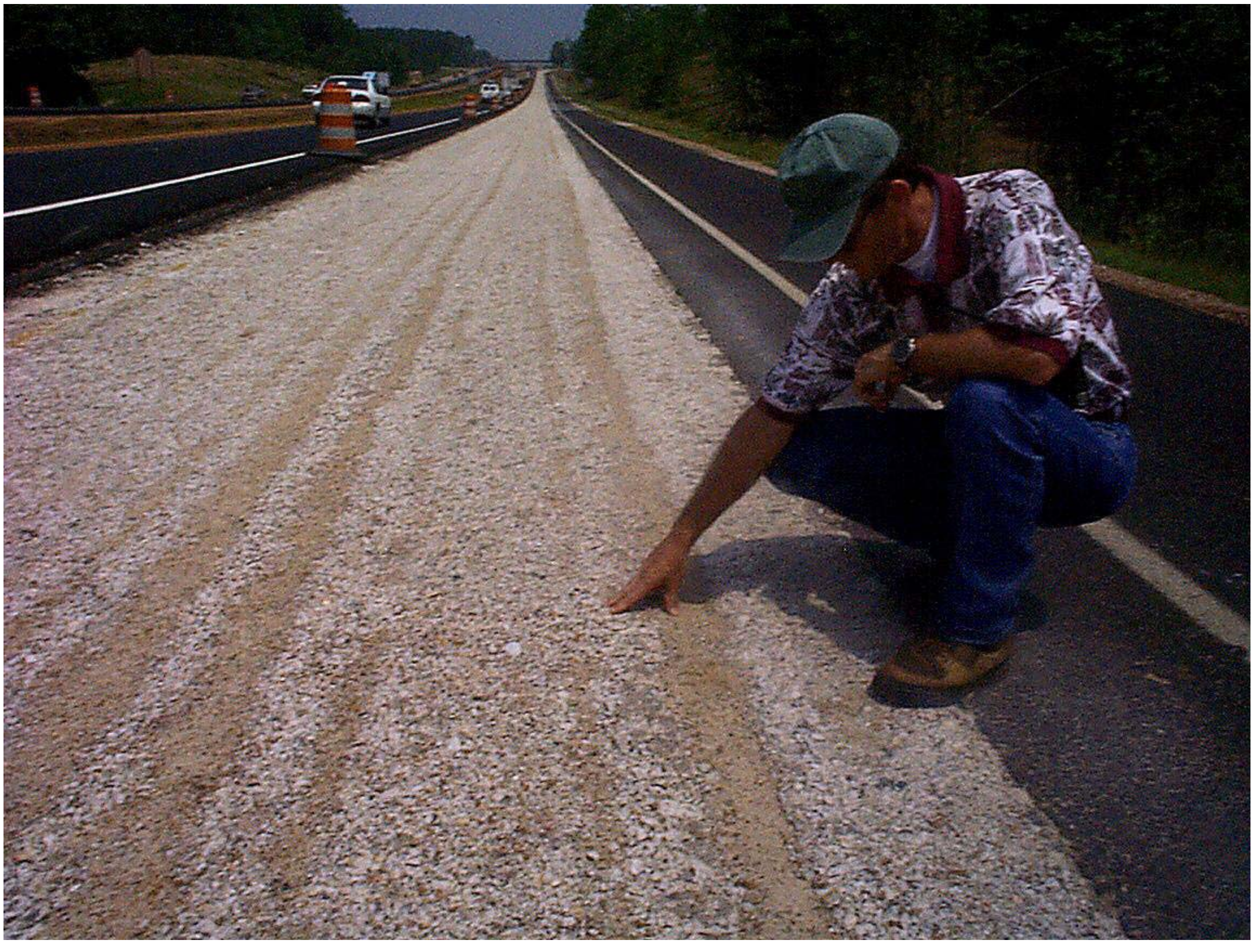

FIGURE 7 Resonant rubblized PCC, before rolling.

concrete pavements or those with weak or saturated foundation conditions, permanent deformation can occur due to excessive vertical compressive strain on the subgrade. RMI suggests that areas with ruts greater than 50 mm (2 in.) should be undercut. Such areas are usually excavated and replaced with suitable material such as crushed stone or HMA while providing for subsurface drainage. To reduce the likelihood of this, RMI uses flotation tires to reduce the contact pressure applied to the fractured concrete during construction.

Any reinforcing steel or wire mesh that emerges above the surface during rubblization is removed by cutting with a welding torch flush with the surrounding surface unless the pavement is being rubblized for removal. Removing of the steel from rubblized concrete that is to remain in place would disturb particle interlock and will raise the profile in the affected area. When rubblization is performed prior to removing the concrete pavement, the steel is usually removed using rippers, cut and hauled away. The shattered concrete can then be removed using front end loaders and transported efficiently off site.

Dowel bars, assemblies, or other joint load transfer devices are less likely to appear at the surface of resonant rubblized concrete. If they do so, they must be carefully removed to minimize disturbance of the broken concrete particles. Joint sealant materials such as rubberized asphalt and low modulus silicone are normally loosened during rubblization, but they are often left in place.

Most specifications require the excavation of a 1.2 by 1.2 m (4 by 4 ft) test pit to assure that the PCC has been fractured throughout its entire thickness and that the bond between any distributed steel and concrete has been broken. Most highway specifications have particle size requirements for resonant broken PCC, usually 150 mm (6 in.) nominal maximum size and 200 mm (8 in.) maximum particle size. The test pit is usually excavated using a backhoe or similar equipment. The test pit is patched using crushed stone or HMA as for repairing soft spots.

Rolling the surface is performed to prepare the surface for placing the overlay. The operational characteristics and mass of the RPB, moving up and back over the pavement surface provide any proof rolling or seating of material at areas where voids developed under the slab such as at faulted transverse joints or punchouts. As mentioned before, the rubblized PCC is loosened superficially by the resonant breaker, with the remainder of the material intact except for fissures that extend through the concrete. Tandem vibratory rollers (min. 9000 kg, 10 tons) operating at the highest frequency setting available are required by specification, as are pneumatic-tired rollers in some states. Two to four passes of the tandem vibratory roller, depending on how the material responds to rolling, are normally applied, with the roller operating at a forward speed that results in at least 33 impacts/meter (10 impacts/ft). It was originally thought that the rolling should occur while the material was in a dry state—this has changed over time with experience. As with rolling any unbound material, moisture lubricates particle surfaces and facilitates particle reorientation. Figure 8 shows a rubblized and rolled surface ready to be paved.

FIGURE 8 Resonant rubblized PCC, after rolling. (Photo courtesy of RMI, Inc.)

Some early rubblizing specifications required the use of a heavily ballasted (31,750 to 45,350 kg, 35 to 50 ton) pneumatic tired roller, similar to what has been used when cracking and seating or breaking and seating PCC pavements. This is not recommended for resonant rubblized PCC, particularly on sites with questionable foundation conditions. As with vibratory rollers, the same pneumatic rollers used for rolling HMA are suggested for rolling rubblized PCC.

After any soft areas have been patched and rolling is complete, the surface is ready for HMA paving operations. There is disagreement on the necessity of applying a tack or prime coat to the surface of the rubblized PCC. On one project observed by the author where a diluted, slow-setting asphalt emulsion was applied, there were places where construction traffic marred the surface by picking up conglomerations of fine particles and asphalt. While this did not appear to cause major problems with the HMA paving operation, it was inconvenient and some areas had to be filled and tamped with aggregate materials or HMA ahead of the paving machine. There is no known reference describing performance problems in rubblized and overlayed pavements attributed to the use or lack of use of a tack or prime coat material.

Once the PCC pavement has been rubblized and rolled, construction proceeds in the same manner as for a new or reconstructed thick asphalt pavement structure. Placement of the HMA overlay is usually performed in two or three lifts, depending on the overlay thickness and traffic control requirements. The most notable difference is in the placement of the HMA base course directly over the rubblized PCC, since there is more variance in the profile of rubblized PCC than there usually is for a finished aggregate base course. The finished grade of the prepared rubblized PCC is also slightly higher than the original profile; this should be taken into account when developing profile elevations of the finished surface and plan quantities for the HMA overlay.

Traffic is not usually routed over the rubblized surface until it is covered with HMA. This is mostly for safety and to avoid loosening surface particles. Where rubblization has been performed on relatively thin PCC pavements or soft supporting conditions, allowing traffic onto the rubblized pavement should be avoided until there is sufficient overlay thickness to avoid subgrade deformation under traffic. For Interstate highways, it is most common to place at least 150 mm (6 in.) of HMA before moving traffic onto the rubblized pavement. The total overlay thickness required depends on the subgrade support, thickness of the rubblized concrete, and projected traffic. Total HMA thickness for Interstate highway projects typically ranges from about 200 mm to 350 mm (8 to 14 in.).

PROBLEM AREAS

There have been some projects where the concrete pavement failed through punching shear under the breaking head, resulting in large (>250 mm/12 in.) blocks of concrete that were pushed into the underlying foundation material. This is usually caused by a combination of having a relatively thin (≤ 175 mm, 7 in.) PCC slab and a weak, usually saturated, foundation. In one case, the contractor had been instructed to wait until after the PCC pavement had been rubblized before placing the edge drains. In another case, the PCC pavement had been placed directly over a clay subgrade. Another sign that the PCC pavement is too weak to rubblize is if the rubblized PCC is severely (>50 mm, 2 in.) rutted by the tires of the RPB. While use of flotation tires might remedy this in some cases, engineers should closely evaluate the drainage and support conditions on the project to determine if drainage corrections will result in the support necessary to successfully rubblize the pavement without having subbase/subgrade failures.

There have been instances where these problems have occurred under temporary conditions, such as when rubblizing has been attempted during thawing conditions in colder climates. In these cases, rubblizing should be postponed until the subbase/subgrade has drained sufficiently.

To date, no engineering criteria have been defined to identify when a PCC pavement is too weak to be rubblized with a resonant pavement breaker. This should be investigated as more agencies seek to apply resonant rubblization to older, thinner pavements not on the Interstate highway system.

SUMMARY

Resonant rubblization has evolved from a procedure used to expedite removal and processing of existing PCC pavement into proven technique for converting PCC pavements into stiff, unbound base courses for new HMA pavements. A resonant pavement breaker is used to generate intersecting diagonal cracks extending through the entire thickness of the PCC, slab thicknesses over 600 mm (24 in.) thick have been successfully rubblized.

After rubblizing, the shattered PCC is rolled using compaction equipment common for HMA construction. After rolling is completed, the rubblized PCC is ready for overlaying with HMA.

Edge drains or other methods to achieve adequate subsurface drainage should be installed well before resonant rubblization to facilitate the resonant rubblization process. Caution is advised in areas with poor drainage that cannot be adequately corrected, since weak support of the existing PCC pavement is the primary cause for problems during resonant rubblization.

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Rubblization Using Multi-Head Breaker Equipment

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A comprehensive nationwide National Asphalt Pavement Association (NAPA) study published in 1991 indicated that rubblization was the most effective procedure for addressing Hot-mix-asphalt overlay (HMA OL) reflective cracking in portland cement concrete (PCC) pavements. In recent years, rubblization has also been effectively utilized to rehabilitate PCCs showing D-cracking and ASR (alkali-silica-reaction) distresses.

Since the late 1980s and early 1990s, PCC rubblization has gained favor and rubblization equipment and construction procedures have been considerably improved. Rubblization is currently the most-widely used PCC slab fracturing technique.

A prototype lane-width/one-pass multi-head breaker (MHB) developed by Badger State Highway Equipment, Inc., Antigo, Wisconsin, (MHB Badger Breaker®) was first utilized by Antigo Construction, Inc. (Antigo) in the 1995 construction season. This paper documents the development, capabilities, and effective utilization of the MHB for rubblizing PCC.

INTRODUCTION

NCHRP Synthesis of Highway Practice No. 144 (*1*) summarized Breaking/Cracking/Seating (B/C/S) practice and technology for PCC pavements. The primary goal of B/C/S was is to reduce (hopefully eliminate) HMA OL reflective cracking. The *NCHRP Synthesis* (*1*) considered B/C/S performance based on the monitoring reports of several agencies. In general, the techniques retarded but did not eliminate HMA OL reflective cracking. The delay period typically varied from 3 to several years, and longer delays were achieved with the thicker HMA OLs. B/C/S specifications that required smaller-sized B/C/S PCC segments typically displayed better performance.

At the time of the NCHRP Synthesis, rubblization applications were not as widespread as B/C/S, but several states had utilized the procedure. A comprehensive nation-wide National Asphalt Paving Association (NAPA) study published in 1991 (*2, 3*) indicated that rubblization was the most effective procedure for addressing reflective cracking. Rubblization destroys PCC slab continuity and eliminates transverse joints and the associated joint opening/closing which cause reflective cracking. Rubblization breaks the concrete into pieces that are substantially debonded from any reinforcement. In recent years, rubblization has also been effectively utilized to rehabilitate PCCs showing D-Cracking and ASR distresses.

Since the late 1980s and early 1990s, PCC rubblization has gained favor and rubblization equipment and construction procedures have been considerably improved. Rubblization is currently the most-widely used PCC slab fracturing technique.

The Resonant Pavement Breaker (RPB) was a particularly significant early (mid-1980s) development. A prototype lane-width/one-pass MHB developed by MHB Badger Breaker was first utilized by Antigo in the 1995 construction season. This paper documents the development, capabilities, and effective utilization of the MHB.

DEVELOPMENT OF MHB BADGER BREAKER®

The MHB is a rubber-tired, self-propelled unit that carries hammers mounted laterally in pairs with half the hammers in a forward row and the remainder diagonally offset in a rear row. Thus, there is continuous breakage from side to side. Each pair of hammers is attached to a hydraulic lift cylinder that operates as an independent unit, develops varying energy depending upon drop height selected, and cycles at a rate of 30 to 35 impacts per minute. The 8-ft (2.44-m) wide machine carries 12 hammers 8 in. (200 mm) in width. A wing, carrying two hammers 12 to 15 in. (300 to 381 mm) in width, can be added to each side for a total effective breaking width of up to 13 ft (3.95 m). The breaking energy is applied to the pavement via 1.5-in. (38-mm) wide steel strike bars welded to the bottom of the hammers. Breaking widths can be as narrow as 3 ft (0.91 m) or increased in increments to as wide as 13 ft (3.95 m). The operator adjusts the travel speed of the MHB to match the conditions encountered throughout the project. Adjustments in hammer drop heights and travel speed are made to maintain the optimum breaking pattern. These adjustments allow the MHB to produce a wide range of breaking patterns. Larger-sized PCC segments provide increased "load-carrying" capacity (decreased falling weight deflectometer deflections and basins).

The prototype MHB (Figure 1) was built on an existing Bomag MPH100 chassis and first used in 1995. It was outfitted with 1,000-lb (4.4-kN) interior hammers and 1,500-lb (6.6-kN) wing hammers. The maximum hammer drop height was 48 in. (1.2 m). A second MHB prototype was built in 1996 on an existing Wirtgen concrete breaker chassis with the same hammer specifications as the first MHB. After operating these two MHBs for 2 years, a standard design was developed and the third and fourth MHBs were manufactured from the ground up and went to work in 1997 with the same hammer specifications as the prototypes. Figure 2 shows a current MHB model.

FIGURE 1 The "prototype" MHB (1995).

FIGURE 2 A recent model MHB.

These MHBs were effective rubblizing 6- to 9-in. (150- to 225-mm) thick concrete in Wisconsin and neighboring states. In 1998, Antigo rubblized a 14-in. (356-mm) thick PCC pavement on a section of the East–West Tollway (Interstate 88) in DeKalb County, Illinois. It was determined that more breaking energy was required to rubblize the thicker concrete while maintaining the desired production rate of 1 lane-mile (1.6 lane-km) per shift. The weight of the interior hammers was increased to 1,200 lb (5.3 kN) and the maximum drop height of all hammers was increased to 60 in. (1.52 m). This configuration was used effectively on all MHBs for several years.

Two 2002 projects led Antigo to increase the maximum breaking energy. A project at Selfridge Air National Guard Base near Detroit, Michigan, included the rubblization of a concrete runway with two layers of concrete with a total thickness of 21 in. (533 mm). Another project on I-495 in Massachusetts had very high strength concrete that caused a significant reduction in the hourly production rate. By increasing the front row hammers to 1,500 lb (6.6kN) and the wing hammers to 1,750 lb (7.7 kN) the MHB was able to maintain its production rate even when rubblizing very thick and/or very hard (high strength/high modulus) concrete. Wings with 2,000 lb (8.8 kN) hammers were also developed and are used on the occasional project that requires the extra breaking energy. A one-hammer style of wing is available for those conditions where a narrower pass is required. Another option Antigo has utilized is to pre-break thick PCCs with a single hammer, 12-kip (53.3-kN), guillotine-style breaker before completing the rubblization with the MHB. That option was used on the Selfridge project.

To date, 18 MHBs have been built. The combination of hammer weights varies across the machines. Some have all 1,200 lb (5.3 kN) hammers, some have all 1,500 lb (6.6 kN) hammers, and others have a combination of the two weights. The appropriate MHB and wing set-up are chosen depending on project job conditions.

PRODUCTION CAPABILITIES

Typical MHB production rates are 500 to 600 ft/hour (152 to183 m/hour) when rubblizing a typical 9-in. (225-mm) PCC. Production rates will vary depending on the strength/modulus of the concrete and underlying base/subbase/subgrade conditions. As many as four MHBs have been operated together to meet aggressive project HMA OL production schedules.

TRUCK-MOUNTED MHB

The most recent MHB development was the introduction in 2003 of a truck-mounted MHB (MHBT) shown in Figure 3. This is an 8-ft (2.44-m) wide MHB mounted on a truck. The operator can drive the truck from project to project and operate it in the same manner as the conventional chassis MHB. In order to meet maximum axle weight rules, the MHBT carries 1,200 pound (5.3 kN) hammers but the front row hammers have a maximum drop height of 72 in. (1.83 m). The higher drop height compensates for the lesser weight hammers when compared to the current standard 1,500-lb (6.6-kN) hammers on the chassis MHBs. The MHBT utilizes a wireless remote control that allows the operator to control it from the best vantage point.

FIGURE 3 The MHBT.

SUMMARY: MHB DEVELOPMENT

With the increased hammer weights and maximum drop heights, the MHB can effectively/efficiently rubblize thicker and stronger/higher modulus concrete pavements. A variety of fractured slab specifications (from rubblization to B/C/S) can be met with the MHB. However, the primary advantage of the MHB has not changed since the first one was built in 1995—the ability to vary drop heights across the machine and vary travel speed to produce an optimum breaking pattern while rubblizing a full lane-width in a single pass.

MHB BADGER BREAKER WHEEL LOADS

Wheel loads and loading conditions are important factors to consider in selecting rubblization equipment. MHB wheels only load the unfractured PCC slab. Only one machine pass is required since the MHB has lane-width capability. These factors are particularly important when

1. Rubblizing thin PCCs;
2. Base/subbase layers are thin and/or unstable; and
3. The subgrade is weak (low strength and modulus). The MHB considerably reduces (frequently eliminates) operational problems associated with the factors presented above.

The MHB Badger Breaker has two modes of operation. The base machine carries 12 8-in. (200-mm) wide hammers for a breaking width of 8 ft (2.44 m). Wings carrying two wider hammers can be added to each side for a breaking width of up to 13 ft (3.96 m). The 13-ft (3.96-m) wide mode is typically used when rubblizing on highways and airport pavements. The 8-ft (2.44-m) wide model is typically used when rubblizing urban streets. There usually are manholes and other utility items that must be avoided on urban projects and the narrower mode is better suited for this type of work.

The weight of the MHB in the 8-ft (2.44-m) wide mode is approximately 47,000 lb (207 kN). When the two wings are added the weight increases to approximately 58,000 lb (255 kN). The weight is carried on three axles: the steer axle (5 kips/22 kN), drive axle (43 kips/185 kN) and trailing wheels [total on two wheels is 10 kips (44 kN)]. The steer and drive axle widths are narrower than the 8-ft (2.44-m) wide breaking width and the breaking takes place at the rear of the machine, thus these wheels do not travel over the rubblized concrete. To help stabilize the machine, the trailing wheels are mounted behind the hammer cage. When necessary, two hydraulic cylinders mounted between the chassis and hammer cage can be extended to lift the trailing wheels off the rubblized pavement thus transferring all of the machine's weight to the unbroken pavement. Though slightly less stable, the MHB still operates effectively in this mode.

CRACK/BREAK AND SEAT WITH THE MHB BADGER BREAKER

The MHB Badger Breaker has been used primarily to rubblize concrete pavement prior to an HMA overlay. However, some specifications for fractured PCC result in fractured slab segments that could be characterized as coarse rubblization or small-sized B/C/S. Kentucky's Breaking and Seating specification requires that 80% of the PC segments be less than 24 in. (600 mm).

The ability to achieve a variety of fracture patterns with one machine is advantageous. The MHB has also proven to be effective as a crack/break and seat machine. The MHB has two types of operational controls: the hammer drop height and the machine's travel speed. The hammer drop height determines the amount of breaking energy that is applied to the concrete pavement. Each pair of hammers is attached to an individually controlled hydraulic cylinder and the drop heights can be varied across the width of the concrete being broken. The travel speed determines the hammer strike spacing.

When rubblizing concrete to meet a typical specification the hammer drop heights and the travel speed are set to break the concrete into particles with a maximum dimension of 2 in. (50 mm) at the surface of the slab and 9 to 12+ in. (225 to 300+ mm) at the bottom of the slab. Typical MHB operating settings for rubblizing a highway pavement are 5-ft (1.52-m) drop height and 3- to 4-in. (75- to 100-mm) strike spacing.

When cracking/breaking concrete to meet a typical specification the hammer drop heights and travel speed are set to produce visible, full-depth breaks in the concrete that produce broken pieces of concrete with a maximum dimension of between 12 and 24 in. (300 and 600 mm) depending on the particular specification. Surface spalling is kept to the minimum possible while still achieving full-depth breaking. The MHB operating settings are adjusted to meet the specification and are adjusted as necessary throughout the project to account for varying pavement and base conditions. The first step is to determine the minimum drop height that adequately breaks the concrete full depth. This may vary across the pavement being broken. Once this has been determined, the travel speed is set so as to produce the segment sizes required. If the specification calls for 12-in. (300 mm) size segments, the strike spacing is usually in the 10- to 12-in. (250- to 300-mm) range. The strike spacing is increased to produce larger PCC segments.

In summary, the operating settings of the MHB can be adjusted to provide concrete breaking patterns across the complete spectrum from total rubblization to light cracking. This flexibility allows for the use of the appropriate fractured slab technique to match each project's particular requirements. This flexibility is particularly valuable when unexpected conditions are encountered on a project as it allows for an immediate response to those conditions.

DISTINCTIVE FEATURES (ADVANTAGES)

Some distinctive features that contribute to MHB utility are

- The MHB is a lane-width/one-pass machine.
- The MHB can operate close to the pavement centerline/edge (traffic is frequently diverted to the adjoining shoulder lane/shoulder during construction) and traffic barriers without unduly interfering with traffic (Figure 4).
- By varying MHB operating characteristics (hammer weights, number of hammers, hammer drop heights, and travel speed) the MHB can produce a wide range of fracture patterns to accommodate individual project conditions such as
  - Differing specifications (rubblization to B/C/S),
  - Variable support (PCC thickness/concrete quality, base/subbase) conditions, and
  - Subgrade strength/modulus.
- Drop height and travel speed can be adjusted by the MHB operator "on the fly."

FIGURE 4 The MHB operating working close to a barrier.

- The MHB is particularly well adapted to "assembly line/tightly spaced" construction (PCC rubblization/compaction/HMA OL paving) since lane-width/one-pass rubblization is achieved. On a typical project, all of the operations can be observed within a short length.
- On many projects, rubblization is started only a few hours prior to HMA paving. More than one MHB can be utilized to achieve desired production rates and/or to rubblize more than a lane width.
- The MHB is very reliable. Due to the simple nature of its operation—hammers being lifted and dropped—it is able to perform hour after hour, day after day, with only minimal time required for maintenance and repair.

TYPICAL CONSTRUCTION SEQUENCE

A typical MHB construction sequence [per the current Illinois Department of Transportation (IDOT) rubblization specification] is

- Install (if specified) the underdrain system.
- Remove any existing HMA overlay(s).
- Repair/replace any "unsound" PCC patches (either concrete or HMA).
- Rubblize the PCC to meet specification. (The surface of the MHB rubblized PCC is typically "flaky" in nature—see Figure 5).

FIGURE 5 Note the "flaky" rubblized PCC surface.

- Compact the rubblized slab with a Z-pattern roller to reduce the size of "flaky" particles (Figure 6).
- Compact the rubblized PCC with a vibratory roller. (IDOT requires four passes.)
- Compact the rubblized PCC with a pneumatic-tired roller. (IDOT requires two passes.)
- Immediately prior to constructing the HMA OL, compact the rubblized PCC with two passes of a vibratory steel-wheeled roller. A typical finished rubblized PCC surface (ready for HMA paving) is shown in Figure 7.

Note: Compaction specifications for other agencies may vary. Some agencies eliminate the pneumatic-tired rolling and vary the number of required roller passes.

REPRESENTATIVE PRICES

MHB bid prices typically include rubblizing and compaction with the z-pattern roller. They may also include additional compaction operations. Typical bid prices for MHB rubblization are \$1.50/yd^2. The price varies depending on the requirements of the rubblizing specification and the size and phasing of the project. As an example, the weighted average bid price on Wisconsin DOT projects (1998–2004) is \$1.56/yd^2 (\$1.86/m^2).

FIGURE 6 A vibratory Z-grid roller followed by a vibratory steel-wheeled roller.

FIGURE 7 The final rubblized and compacted PCC surface.

MHB PRODUCTION STATISTICS

The MHB was first used in 1995 and since then MHBs have rubblized over 15 million square yards (13.8 million square meters) of concrete pavement on highways, streets and airfields in 25 states and provinces, the United Kingdom, China, and Afghanistan. For the years 1996–2004, the MHB was used in the United States to rubblize about 2,178 lane-mi (3,485 lane-km) of PCC. The projects included 1,950 lane-mi (3,129 lane-km) of highway pavement, 183 lane-mi (293 lane-km) of city streets, and the equivalent of 45 lane-mi (72 lane-km) of airfield and other miscellaneous pavements. The peak year was 345 lane-mi (552 lane-km) in 2001. The states with the most projects are Wisconsin (150), Michigan (61), Iowa (29), and Illinois (17).

PERFORMANCE DATA

Antigo has conducted performance surveys (per the *Distress Identification Manual for Long-Term Pavement Performance Project,* SHRP-P-338) on its MHB rubblization and HMA OL projects since 1999. During 2003–2004, 178 MHB rubblization projects constructed in 14 states were surveyed. The projects were constructed from 1997–2003 (as many as 7 years of service). The projects were from a wide geographical area, with a range of PCC thickness and subgrade/base/subbase conditions, and variable HMA OL thicknesses [many less than 5 in. (125 mm)]. Many roadway types are represented, including interstates with a high number of trucks to lightly traveled residential streets. More than 1,300 lane-mi (2,080 lane-km) were surveyed. These data are available upon request from Antigo Construction, Inc. (P.O. Box 12, Antigo, WI 54409; telephone 715-627-2222).

The performance of the surveyed projects has been excellent. The only pavement distresses typically found are those that also occur in HMA pavements built on aggregate base course. These include low-severity transverse and longitudinal cracks, low-severity surface raveling, and low-severity rutting and bleeding. Of the projects surveyed, 75% had no transverse cracks. It is difficult to determine if a transverse crack is a reflective crack. In none of the projects with transverse cracking was there any indication of “repetitive” transverse crack spacings/patterns. It is concluded that there has been “little to no” apparent reflection cracking. There were no longitudinal cracks in 80% of the projects. Most of the projects had rutting less than 0.25 in. (6 mm). Only one project showed initial signs of low severity block/alligator cracking.

The Antigo MHB performance data base documents the excellent performance of rubblized PCCs with HMA OLs and validates the effectiveness of rubblization in preventing reflective cracking.

SUMMARY

Since the late 1980s and early 1990s, PCC rubblization with HMA OL has gained favor as a PCC rehabilitation process. Rubblization equipment and construction procedures have been considerably improved. Rubblization is currently the most-widely used PCC slab fracturing technique.

The lane-width/one-pass MHB developed by MHB Badger Breaker was first utilized by Antigo in the 1995 construction season. This paper documents the development, capabilities, and effective utilization of the MHB for rubblizing PCC.

ACKNOWLEDGMENT

The help and cooperation of MHB Badger Breaker in providing inputs to this paper are gratefully acknowledged.

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Rubblization of Airfield Pavements

State of the Practice

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With the airlines reporting passenger numbers returning to pre-September 11, 2001, levels, demand for more aircraft operations at the nation's airports is continuing to grow. This growth will continue to stress the nation's older concrete airport pavement infrastructure that has already served beyond its design and service limits for which it was constructed. As a result, a major portion of these concrete airport pavements will require rehabilitation in the very near future.

Traditionally, concrete pavement restoration (CPR) procedures have been employed to maintain these pavements in a fair to good condition. With growing demand and rapidly aging pavements, these CPR procedures are becoming more costly and less effective as the present pavement condition ratings are reaching a critical point where major rehabilitation is required.

Rubblization and repaving with hot-mix asphalt (HMA) is quickly becoming the portland cement concrete (PCC) pavement rehabilitation technique of choice for old deteriorated PCC airfields. In the past 7 years, well over one-half million square meters of PCC had been rubblized in place, resulting in a stiff unbound granular base layer for new HMA pavements.

With the FAA's recently published guidance and specification for rubblizing airfield PCC, the use of rubblization should continue to grow on both civilian and military airfields. The same benefits that highway agencies realize with rubblization are now being recognized by airfield agencies. This is vital as our airfield pavement infrastructure, much of which is PCCP, continues to age beyond the point of restoration.

This paper presents the concepts associated with the process of rubblization, equipment development, specification criteria and in-service performance for rubblizing airfield pavements. The focus of this paper is the application of rubblization technology to airfields, designed for both light loads and heavy loads. Discussion items include

- **Rubblization process;**
- **Characteristics of state-of-the-practice equipment for rubblizing airfields;**
- **Specifications for rubblizing airfield pavements, including recent FAA guidance;**
- **Recent projects that demonstrate the ability to successfully rubblize heavy load airfield concrete pavement up to 26 in. thick;**
- **Recent and upcoming rubblization projects on airfields in the United States; and**
- **Design/ construction issues unique to airfields.**

INTRODUCTION

Rubblization is the process of fracturing the existing PCC pavement in-place into small, interconnected pieces that serve as a base course for a new HMA overlay. Because there are no hauling or disposal costs and none of the existing pavement system is discarded, rubblization is a very cost-effective rehabilitation method. Since the rubblization process fractures the existing PCC pavement into small pieces, the underlying slab integrity that would cause reflective cracking is eliminated. All existing pavement layers remain to serve as critical structural support layers for a new HMA overlay. The net effect of rubblizing is to convert a deteriorating rigid pavement system into a new and well-serving flexible one.

The most common procedure for PCCP rehabilitation since the early 1990s has been rubblization. From 1994 to 2002, highway agencies in the northeastern, southern, and midwestern United States have rubblized and placed HMA over more than 41 million square meters (50 million square yards) of highways. The number of rubblization projects each year continues to grow.

While rubblization technology and equipment was initially developed for highway pavements, there is a tremendous need to rehabilitate aging airfield pavements as well. Airfield PCC pavements often have significantly greater thicknesses compared to highway PCC pavement. Within the FAA Integrated Airport System airfield infrastructure and the U.S. Department of Defense airfield inventory, there are more than 83 million square meters (100 million square yards) of PCC pavement greater than 33 cm (13 in.) thick and more than 35 years old. These aging pavements will likely need major rehabilitation within the next 10 years. Traditionally, CPR procedures (including sub-sealing, full-depth patching, partial-depth patching, load transfer reconstruction, diamond grinding, and joint sealing) have been employed to maintain these airfield pavements in a fair to good condition. The CPR procedures are becoming less effective today as the pavement condition ratings reach a critical point where major rehabilitation is required.

RUBBLIZATION PROCESS

Rubblizing PCC pavement means the complete destruction of any slab action before applying a HMA overlay. The concrete-to-steel bond is broken in jointed reinforced concrete pavements (JRCP) and continuously reinforced concrete pavement (CRCP). Rubblization effectively reduces the existing concrete pavement to an in-place crushed aggregate base with a high degree of particle-to-particle interlock. The rubblized base eliminates inherent distresses (such as reflective cracking, D-cracking, or alkali silica reaction) and provides a sound base for the HMA.

Rubblization saves natural resources, expedites construction, and is environmentally friendly as a rehabilitation technique. The old PCC pavement stays in place and becomes the base for the new HMA pavement, thereby reducing or eliminating the need for new virgin aggregates. Weather delays are minimized since the subgrade is never opened up and exposed to the elements. Rubblization eliminates the need to remove and dispose of the old PCC pavement, reducing air pollution (truck exhausts and fugitive dust) and saving landfill space.

The procedural steps in the rubblization technique are essentially the same for airfields as they are for highways. They are

- Mill and remove any existing asphalt;
- Install a side drain system;
- Isolate any adjacent sections with full-depth sawcut;
- Rubblize the concrete pavement;
- Cut off and remove any exposed steel reinforcement;
- Remove exposed joint sealing material;
- Roll the rubblized concrete pavement;
- Remove and patch any unstable areas;

- Place asphalt HMA leveling course/HMA overlays;
- Pave transitions to existing pavement surfaces; and
- Adjust shoulders grades as necessary.

There are two basic types of rubblization equipment, the resonant pavement breaker (RPB) and the multi-head breaker (MHB). These two machine types are described below.

RESONANT PAVEMENT BREAKER

Various models of the RPB exist. All are self-contained, self-propelled units that vary in size and weight. The largest model is the RB-500 (Figure 1), which is a sixth generation machine developed to rubblize heavy load PCC pavement (greater than 13 in. thick). A 447-kW (600-HP) diesel engine that weights from approximately 30,000 kg (68,000 lbs) powers the RB-500. The breaking unit produces low amplitude 12.5 to 25 mm (1/2 to 1 in.), high frequency (42 to 46) impacts per second (hertz) through a massive steel beam. This vibrating beam is 3.8 m (12.5 ft) long and has been described as a "giant tuning fork."

The vibrating foot rubblizes the concrete pavement in narrow strips as the machine moves forward along the free edge or unfractured edge of the existing pavement. The forward speed of the machine depends on the size of the machine, slab thickness, the stiffness of the PCC, and the support provided by the subgrade. Generally, one machine can be expected to rubblize from 5000 to 7000 m^2 (6,000 to 8,000 yd^2) per workday shift, with thick airfield pavement work being on the low end of this range. For critical projects, multiple machines can be employed to expedite the process.

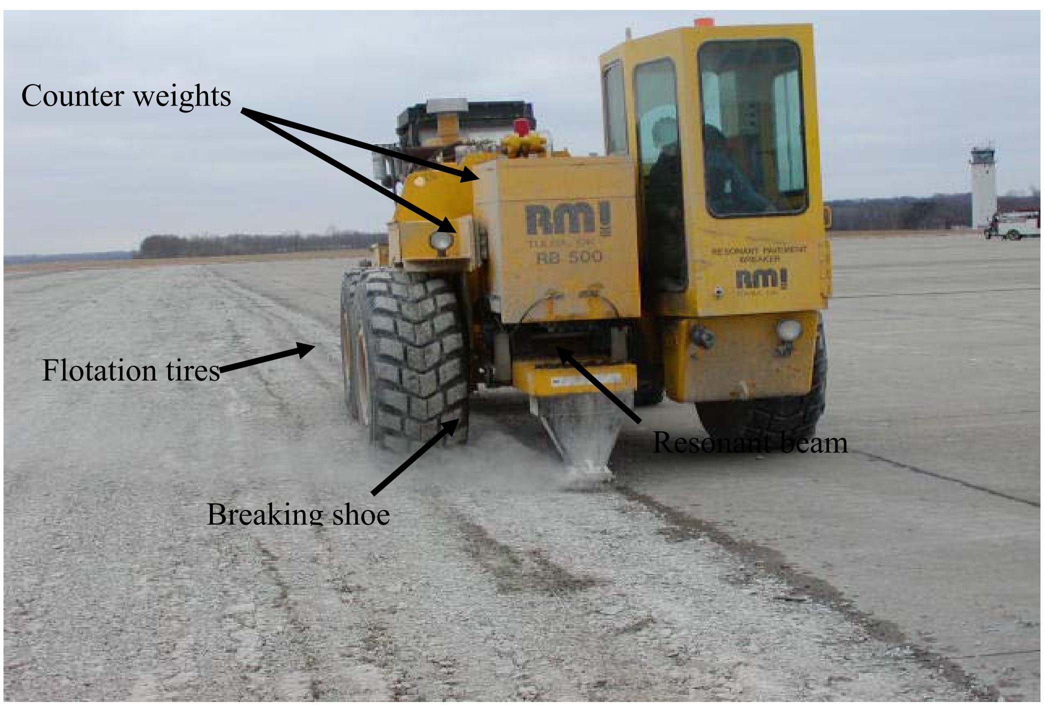

FIGURE 1 Resonant concrete pavement breaker.

Light load airfield PCC pavement, typically found on general aviation (GA) airfields, can be as thin as 6 in. It is important to protect the freshly rubblized material from being overloaded by the repetitive operations of the RPB. For light load PCC pavement with soft subgrades or high water tables, special flotation tires (lower tire pressures) may be required to avoid damaging the rubblized and underlying layers.

Rubblization of airfield pavements using an RPB must start at a free or unfractured edge and continue with successive passes until it has moved transversely across the width of the pavement (Figure 2). This makes the process self-regulating. Any attempt by the operator to move too far into the pavement transversely and away from the free edge results in less and less fracturing of the pavement until finally the machine can no longer fracture the pavement. When this happens, breaking energy is no longer absorbed by the pavement but is reflected back into the machine itself producing a noticeable “hammer and anvil” affect where the hammer merely bounces off the pavement surface and very little breaking is accomplished.

As RPBs work along the unfractured edge of an existing PCC pavement, a small amount of horizontal and vertical expansion takes place (Figure 3). Early airfield rubblization projects required relief joints (Figure 4) to be cut full-depth through the pavement at fix intervals to take up the horizon expansion that accumulates as large areas are rubblized. Recent advancements in RPB design and technology, including significant horsepower increases, have all but eliminated the need for cutting relief trenches in the pavement prior to rubblization. However, certain combinations of older and smaller breakers and thicker pavement sections can result in situations where relief trenches are still necessary. The need for relief trenches will show up in the form of the “hammer and anvil” effect as described above and reduced breaking effectiveness.

FIGURE 2 Starting from free edge.

FIGURE 3 Vertical displacement prior to rolling.

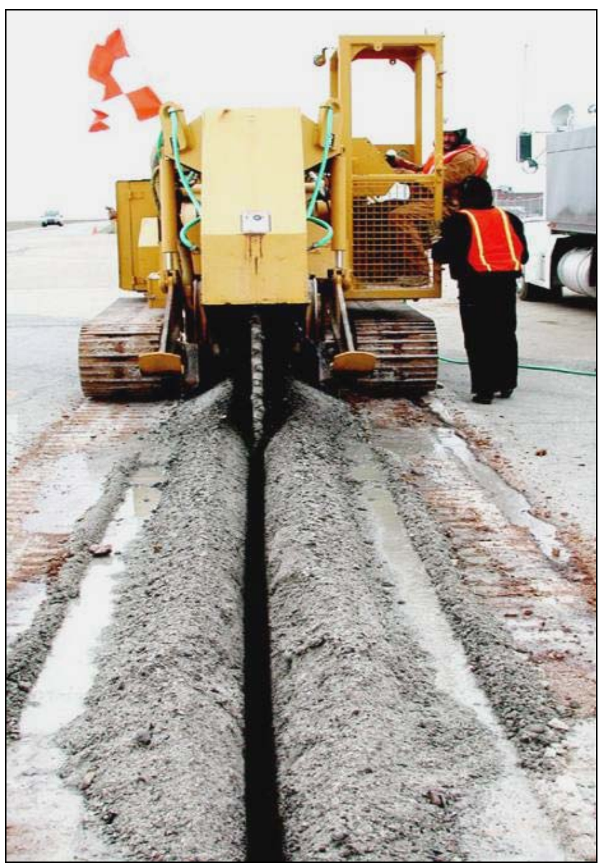

FIGURE 4 Relief trench cut with a wheel saw.

MULTIPLE-HEAD PAVEMENT BREAKER

The MHB is a rubber-tired, self-contained, self-propelled unit (Figure 5). It consists of six pairs of 544 kg (1,200 lbs), 20-cm (8-in.) wide hammers mounted laterally in pairs with half the hammers in a forward row and the remainder diagonally offset in a rear row so that there is continuous breakage from side to side. Wing units, carrying two 680 kg (1,500 lb) hammers, can be added to each side for a total breaking width of up to 4.0 m (13 ft). In the 16-hammer configuration, the MHB weighs 25,855 kg (57,000 lbs). Each pair of hammers is attached to a separate hydraulic lift cylinder with an adjustable drop height from 0 to 1.5 m (60 in.). Each pair operates as an independent unit, and develops between 1,355 to 10,800 joules (1,000 and 8,000 ft-lbs) of energy depending upon the drop height selected, and cycles at a rate of 30 to 35 impacts per minute.

By controlling the individual lift cylinder for each pair of hammers, the MHB can rubblize in 0.6 to 4 m (2 to 13 ft) widths at a production rate of approximately 418 to 1254 m^2 (500 to 1500 yd^2) per hour. This allows the multiple-head breaker to rubblize a 3.8 m (12.5 ft) wide lane while traveling at a speed ranging from 0.11 and 0.32 km/h (.07 to .20 mph). Production rates are comparable to the RPB, and depend upon the strength and thickness of the slab and the underlying subgrade.

Rubblization using a MHB requires a single pass over an area to be rubblized. The tractor or power unit travels on the unbroken slab as it moves forward and tows the breaking unit behind. Because it is a single pass technique, there is no need for the MHB to travel on the rubblized surface. Fracturing of the slab is controlled by a set combination of drop height, frequency of the impacts and the forward speed of the machine as determined by a test strip/pit.

FIGURE 5 MHB.

For heavy-duty airfield pavement (greater than 14 in. thick), it may be necessary to utilize a guillotine pavement breaker prior to an MHB to expedite the rubblization process. This type of breaker (Figure 6) has rubber tires, is self-propelled, and generally weighs about 5,440 kg (12,000 lbs). The drop height of the hammer is adjustable up to 9 ft. The guillotine breaker makes the initial pass and pre-fractures the existing pavements, allowing the MHB to complete the rubblization. Another situation that may require the teaming of both a guillotine breaker and an MHB is if there exists an interface within the PCC pavement, such as with an un-bonded or partially-bonded rigid overlay. The interface between the two lifts creates a shear plane that absorbs some of the breaking force, requiring the PCC pavement to be pre-broken to insure the bottom lift is adequately rubblized.

PROCESS DIFFERENCES

The two types of rubblization equipment just described operate in completely different modes to achieve the required rubblization of the PCC pavement. The RPB is a high frequency, low amplitude process while the MHB is a low-frequency, high-amplitude process. Research is currently underway to document the effects of the different equipment types on the underlying subgrade integrity, rubblized layer permeability, and effective modulus.

The size of rubblized particles is dependant upon the amount of rubblization energy put into the pavement, the strength of the pavement itself, and the amount of support provided by the subgrade. The size distribution of particles is confirmed by digging test pits through the rubblized pavement, then visually inspecting to confirm project specifications are being met.

FIGURE 6 Guillotine style breaker.

On light-load airfield pavements, soft spots within the subgrade can be detected by noticing a change of particle size, assuming the rubblization energy and PCC pavement thickness/strength remains constant. When soft or unstable subgrade areas are detected, a solution must be worked out. The solution may be as simple as allowing additional time for the underdrains to work, putting floatation tires on the RPB or changing the drop height of the MHB. More extreme cases may require undercutting and backfilling with suitable material.

PREPARATION OF THE PAVEMENT SURFACE

For the rubblization equipment to work properly and transmit the optimal amount of energy to the existing PCC pavement, all HMA overlays must be removed prior to rubblizing the underlying concrete.

Adjacent pavements that are not to be rubblized must be isolated from the rubblized pavements. This is best accomplished by cutting a relief trench with a wheel saw (Figure 4), or by utilizing two parallel full-depth diamond blade saw cuts approximately 6 in. apart. Either method allows the rubblizing equipment to work up to the project limits without damaging the structural integrity of the pavement that is to remain in place.

Underground structures, utilities, and in-pavement fixtures must be identified as needing protection during the rubblization process. Specifications are then written that requires the contractor to operate his equipment in such a manner as to not damage these existing features. In-pavement features on airfields, such as drainage inlets, electrical fixtures and conduits must be noted during design. Isolation or removal and replacement may be required during the rubblization process. Provisions also must be made to raise all in-pavement features to the grade of the new HMA pavement.

INSTALLATION OF UNDERDRAINS

Experience has shown that a key element to a successful rubblization project is the installation of a properly designed underdrain system. Underdrain systems serve two purposes. Prior to the rubblization process, underdrains dry out and stabilized the subgrade and during the service life of the new pavement they prevent water from becoming trapped inside the different layers of the pavement structure.

During the rubblization process, water trapped in the subbase or subgrade will sufficiently weaken the subgrade and cushion the impacts from the pavement breakers. This loss of subgrade support will substantially reduce the amount of pavement fracture and increase the overall size of the rubblized particles. To insure proper subgrade drainage, rubblization specifications require underdrains to be installed a set period of time prior to commencing rubblization. In most specifications this is a minimum of 2 weeks.

During the service life of the pavement, the underdrain system must have sufficient capacity and depth to collect and carry the water being discharged from the subgrade, the old permeable base, and the top or “permeable zone” of the rubblized layer (Figure 7). The trench depth must be deep enough to accomplish the intended drainage function. It is recommended that the trench depth be deep enough to allow the top of the pipe to be located a minimum of 5-cm (2 in.) below the bottom of the permeable base material. The filter fabric and trench backfill

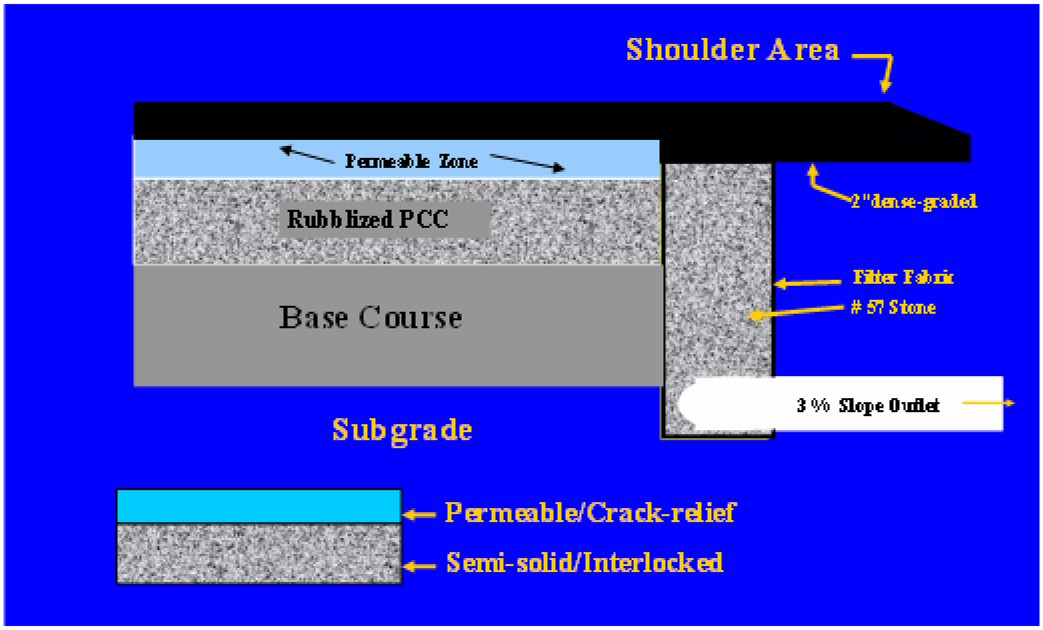

FIGURE 7 Typical side drainage system.

material must also be designed with sufficient capacity to handle the outflow from the new pavement structure. Erosion of fines into the side drain system should not pose any problem as the base, or rubblized concrete, should not contain erodable fines that would tend to clog the system.

Polyethylene tubing used in agriculture and thin "fin" style drains as used along highways do not have sufficient strength or capacity to handle the outflow and should not be used for airfield underdrains. Pipe underdrains such as rigid corrugated polyvinyl chloride (PVC) with smooth interior walls are recommended because of their strength, high flow capacity, and their configuration for easy maintenance.

Installation of the outlet pipe is critical to the edge drainage system. It is recommended that a metal or rigid (PVC) non-perforated pipe be used for the outlet pipe for its strength and capacity. A grade of at least 3% is recommended so that the pipe will continue to drain if there is a light variance of the pipe grade. Since the purpose of subsurface drainage is to remove water as quickly as possible, it is recommended that the outlet spacing be a maximum of 75 m (250 ft). The edge drainage design should be coordinated with surface drainage to handle removal of all sources of water.

PREPARATION OF THE RUBBLIZED SURFACE

After rubblizing the PCC pavement and prior to placing the HMA overlay, the surface of the rubblized material must be given one of the following rolling treatments. The purpose of the rolling is to tighten the surface by seating loose particles as well as smoothing the surface in preparation for repaving. This rolling is not intended to achieve additional densification of the rubblized material or underlying layers. Excessive rolling could actually destroy particle interlock and cause a weakening of the rubblized layer.

Generally, rubblization produces very little fugitive dust. The small amount (Figure 8) that is produced is usually not a problem on closed areas of an airfield. However, where traffic is maintained on nearby parallel runways, taxiways or aprons, dust control may become an issue. Water as a dust palliative should be applied sparingly and only as needed to control fugitive dust.

After Rubblizing with the RPB

Roll the crushed concrete with at least two passes of a smooth vibrating steel wheel roller weighing a minimum of 9,000 kg (10 tons) for surface smoothing and further alignment of the fractured concrete pieces.

After Rubblizing with the MHB

Roll the crushed concrete with two passes of a vibratory steel drum roller fitted with a special "Z" pattern grid on the drum face. The grid roller should weigh a minimum of 12,700 kg (14 tons). This provides a uniform surface and reduces the size of the surface pieces. The grid roller is followed by a 22,680-kg (25-ton) pneumatic-tired roller for final seating.

Leveling Course

Rubblized surfaces cannot be trimmed or fine graded like conventional granular surfaces. Larger pieces will be disturbed by the fine grading equipment resulting in the loss of particle interlock and an overall reduction in the strength of the rubblized layer. Leveling courses may be necessary to accommodate grade and profile corrections. Leveling courses have included Item

FIGURE 8 Dust generated during rubblization.

P-209 (FAA's aggregate base specification) or Item P-401 (FAA's HMA specification). Aggregates manufactured from recycled PCC pavements that have been removed and processed to meet the requirements of P-209 have also been used successfully as leveling courses.

Traffic Control

Heavy construction vehicles on a rubblized surface can destroy particle interlock and reduce the overall strength of the rubblized layer. Construction traffic on the rubblized surface should be minimized until the first layer of HMA has been applied.

PERFORMANCE SPECIFICATIONS FOR RUBBLIZING

Rubblization specifications, especially for heavy-load airfield PCCP, should be written as performance based to include requirements on the size of pieces through the full depth of the rubblized concrete. Recent developments with both equipment types have resulted in different techniques for accomplishing a satisfactory product. Projects described in the next section (Wright–Patterson Air Force Base and Selfridge Air National Guard Base) demonstrate that rubblizing heavy-duty airfield PCC pavement can be successfully achieved with either type of equipment.

In February 2004, the FAA adopted and published *FAA Engineering Brief No. 66, Rubblized Portland Cement Concrete Base Course*, which includes guidance and specifications for rubblizing existing PCC pavement. The publication of EB 66 will facilitate even more use of the rubblization technology on airfields. For a designer to use EB 66 on an FAA project—a "modification to standards"—must still be submitted through proper approval channels. In writing EB 66, the FAA consulted the Asphalt Institute, rubblization equipment manufacturers, the U.S Air Force and others in the industry. The guidance and performance related specification in EB 66 represents state of the practice for rubblizing airfield pavement and is recommended for use.

It is recommended that specifications for rubblizing airfields contain the following items as a minimum.

- Scope of work for rubblizing and rolling as shown on the plans.
- Submittals, including a description of the rubblizing and rolling equipment.
- Preparation of the pavement, including removal of all asphalt layers and full-depth saw cutting to isolate the pavement being rubblized.
- A test strip: Using the proposed equipment, rubblize a test section 3.7 m (12 ft) by 46 m (150 ft) in the outer extremity of the project.
- Test pit excavation and inspection: At no additional cost, contractor shall provide adequate equipment and excavate a test pit within the test strip area. All test pit excavations shall extend completely through the rubblized PCC pavement and remove any steel reinforcing that may be present to expose completely the subgrade. The user agency will inspect the test pit for particle size and debonding of steel reinforcing.
- No rubblization will be allowed outside of a test strip area until the rubblization process has been approved.
- Test pits should be required whenever the pavement cross section changes or every 30,000 to 40,000 m^2 (35,880 to 47,840 yd^2), depending on the size of the project.

- Particle size criteria: EB 66 requires the rubblized PCCP to have at least 75% (as determined by visual observation) particles smaller than 75 mm (3 in.) at the surface and 300 mm (12 in.) in the bottom half. For reinforced PCCP, the reinforcing steel shall be substantially debonded from the concrete and left in place, unless protruding above the surface. Concrete pieces below the reinforcing steel shall be reduced to the greatest possible extent, and no individual piece shall exceed 380 mm (15 in.) in any dimension.
- Rollers: Depending on the method of rubblizing, the user agency shall specify the roller type, minimum roller weight and number of roller passes per earlier discussion under Preparation of Rubblized Surface.
- Removal of weak areas: Replace with full depth asphalt patches, as required by the user agency. This is considered an additional pay item.

RUBBLIZATION PROJECTS

This following is a list of airfield projects that have been rubblization in the last 7 years along with a partial list of projects scheduled to be rubblized in 2005. The list is compiled as an indication of just how prevalent rubblization as a rehabilitation technique has become over the last seven years. Projects range from heavy load military airfields handling some of the largest aircraft that fly, to local GA airfields that handle the smallest aircraft. Projects also cover a wide range geographically; from Florida to Washington state, from Tennessee to upstate New York. The list is provided to illustrate the extent of projects that have been completed or are scheduled to be completed in the near future and is not intended to be an all-encompassing list of projects that have been completed. In some cases, limited project information was available.

Wright–Patterson Air Force Base, Ohio

The heavy load concrete aircraft parking aprons at Wright–Patterson, near Dayton, Ohio, were more than 40 years old when reconstruction began in 2000. The first parking apron was reconstructed in a traditional manner using a lifting and removing technique that was expensive and time consuming, taking more than 3 months to complete. When the second parking ramp, with thicknesses of 21 to 26 in. of non-reinforced PCC pavement, was scheduled for reconstruction in the summer of 2002, the contractor decided to try rubblization. The resonant breaker RB-500, weighing 31,750 kg (70,000 lbs), rubblized 50,100 m^2 (63,100 yd^2) in 10 working days. While rubblization on this project was to facilitate removal, the PCC pavement was completely rubblized and broken into pieces no larger than 12 in. through the concrete sections. Inspection of the rubblized material proved that the thickest heavy load PCC pavements could be rubblized in place and used as high-quality base material. In terms of removal, rubblization on this project proved to be more economical than traditional methods of removing PCC pavement. The contractor estimated that the rubblized concrete pavement removal was accomplished in one-fifth of the time and one-third of the costs.

Selfridge Air National Guard Base, Michigan

Selfridge Air National Guard Base, near Detroit, Michigan, serves five military branches of service. The air operation utilizes a 2,743-m (9,000-ft), and a 1,524-m (5,000-ft) runway, along with adjacent taxiways and aprons that contain over 836,000 m^2 (1,000,000 yd^2) of paved surface. The original runway, built in 1959, had non-reinforced PCC pavement sections up to 53-cm (21-in.) thick.

By 2002, the pavement was so badly deteriorated it could no longer be maintained in a safe condition. To accomplish the reconstruction in the most economical and expedient manner possible, the old pavement was rubblized and used as the aggregate base for a new HMA pavement. A taxiway was pressed into temporary service as a runway, while the contractor was given only 5½ months to completely rebuild the main runway, or face $15,000-per-day liquidated damages.

By specifications, an extensive underdrain system was installed well in advance of beginning the rubblization process. This system was designed to have a maximum spacing of 250 ft between outlets to insure an adequate amount of drainage. The contractor used a portable crusher on site to recycle the PCC pavement removed from the touchdown zones. This recycled material was used as a 10-cm (4-in.) aggregate leveling course on the rubblized material to adjust grade and crown. The new pavement is 18 cm (7 in.) of HMA.

In May 2002, 79,432 m^2 (95,000 yd^2) of concrete runway was rubblized in 16 days. To meet this specification the PCC pavement was first broken using a guillotine-type concrete pavement breaker and then completely rubblized with the multiple-head breaker in the 16-hammer configuration. A grid roller was then used to further pulverize the concrete particles at the surface and begin the seating process. Final seating was accomplished with a 25-ton pneumatic-tire roller. The contractor was required to prove compliance with specifications before being allowed to continue with full production rubblization.

Recent falling weight deflectometer testing on the 53-cm (21-in.) thick PCC layer at Selfridge shows modulus values ranging from 450 ksi to 750 ksi.

NAVFAC Atlantic Division

- Jacksonville Naval Air Station, Florida.
- Taxiway "A."
- One of the earliest uses of rubblization as a rehabilitation technique on airfield pavements.
- Evaluation in 2003 (Figure 9) shows pavement still in good condition.

Walla Walla Regional Airport, Washington

- 61,314 m^2 (73,300 yd^2).
- Complete rehabilitated of main runway by rubblizing and overlaying.
- Contract time 4½ months.
- 15 to 23 cm (6 to 9 in.) PCC pavement.
- HMA laid 24 to 30 cm (9½ to 12 in.) to reestablish drainage.
- Existing subsurface drainage infrastructure.

FIGURE 9 Jacksonville Naval Air Station taxiway "A" in 2003.

Buffalo Niagara Falls International, Erie County, New York

- PCCP 28 cm (11 in.).

NAVFAC Southern Division

- C-17 Assault Strip, South Carolina.

NAVFAC Southern Division

- Jacksonville Naval Air Station, Florida; portions of main runway.

NAVFAC Atlantic Division

- Willow Grove Naval Air Station, Pennsylvania; reconstruction of 15-33 thresholds.

Rantoul Municipal Airport, Illinois

- Rehabilitation of former Chanute Air Force Base.
- 15 to 20 cm (6 to 8 in.) PCC pavement.
- Convert existing 30-m (100-ft) runways to 23-m (75-ft) wide GA runways.

Memphis International Airport, Tennessee

- 38 cm (15 in.) reinforced PCC pavement.
- Steel reinforcing completely debonded in a single pass (Figure 10).

Indiana Air National Guard, Fort Wayne, Indiana

- 21,120 m^2 (25,258 yd^2).
- 25 cm (10 in.) PCC pavement.

Hunter Army Airfield, Savannah, Georgia

- East ramp taxi lane.
- 15 cm (6 in.) PCC pavement.

Watertown Airport, Codington County, South Dakota

- Rehabilitate main runway:
  - 32,990 m^2 (39,456 yd^2).
  - 20 cm (8 in.) PCC pavement.
- Hanger area:
  - 1,660 m^2 (1,982 yd^2).
  - PCC pavement 15 cm (5.75 in.).

FIGURE 10 Test pit showing complete debonding of steel.

Columbus Airport, Bartholomew County, Indiana

- Overlay taxiway C and west apron taxiway:
  - 20,630 m^2 (24,975 yd^2).
  - 15 cm (6 in.) PCC pavement.
- Taxiway E rehabilitation:
  - 11,350 m^2 (13,572 yd^2).
  - 15 cm (6 in.) PCC pavement.

Ephrata Municipal Airport, Grant County, Washington

- Runway 11/29 and Taxiway B-2 rehabilitation.
- 21,813 m^2 (26,090 yd^2).
- 15 cm (6 in.) PCC pavement.

PROJECTS UNDER CONTRACT AND SCHEDULED TO BE RUBBLIZED IN 2005

Capital Airport, Springfield, Illinois

- Rehabilitation R/W 4 overrun.
- 12,540 m^2 (15,000 yd^2).
- 25 cm (10 in.) PCC pavement.

Buffalo Niagara International Airport, Erie County, New York

- Taxiway A, 18,666 m^2 (2,325 yd^2).
- 28 cm (11 in.) PCC pavement.

Grand Forks Air Force Base, North Dakota

- Rehabilitate main runway.
- 144,230 m^2 (172,500 yd^2).
- 48 cm (19 in.) PCC pavement.
- Rubblize/HMA cross-section chosen using an alternate bids process: award based on past performance trade-off (PPTO) and the best value to the government criteria.
- Contract time is 180 days.

SUMMARY

Rubblization and repaving with HMA is quickly becoming the PCC pavement rehabilitation technique of choice for old deteriorated PCC pavement airfields. In the past 7 years, well over one-half million square meters of PCC pavement had been rubblized, leaving in place a stiff unbound granular base layer ideal for new HMA pavements. The majority of airfield rubblization projects have taken place in the last three construction seasons with more scheduled for the 2005 season. These projects range from heavy load military airfields handling some of the largest aircraft to local GA airfields that handle the smallest aircraft. These projects also cover a wide range geographically; from Florida to Washington state and from Tennessee to upstate New York.

The Wright–Patterson Air Force Base project in 2002 demonstrated that the RPB can successfully rubblize up to 26 in. of PCC pavement, resulting in aggregate particles smaller than 12 in. throughout the concrete thickness. The Selfridge Air National Guard Base project demonstrated that the Guillotine Breaker followed by a MHB can successfully rubblize up to 21 in. of PCC pavement.

With the FAA's recently published guidance and specification for rubblizing airfield PCC pavement (EB 66), the use of rubblization should continue to grow on both civilian and military airfields. The same benefits that highway agencies realize with rubblization are being recognized by airfield agencies. This is vital as our airfield pavement infrastructure, much of which is PCCP, continues to age beyond the point of restoration.

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Nondestructive Testing Results from the Rubblized Concrete Pavement on Interstate 10 in Louisiana

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This paper provides a summary of the nondestructive testing (NDT) results obtained on Interstate 10 (I-10) in Louisiana. The two sections tested were 2 and 3 years old, both consisted of old jointed concrete pavement (JCP) which had been rubblized and surfaced with between 8 to 10 in. of Superpave binder and wearing courses. The NDT consisted of both ground-penetrating radar (GPR) and falling weight deflectometer (FWD) testing. These data were collected in January, 2003 by both the Texas Transportation Institute (TTI) and the Texas Department of Transportation (TxDOT). To date rubblized sections have not performed well in Texas. This evaluation is aimed at determining the in-place strength of the rubblized sections that have perform well under heavy traffic and to assess if the construction practices in use in Louisiana could be used on similar highways in Texas.

As the basics of GPR technology are not widely known, the first phase of this paper will present a summary of the principles of GPR. It will cover what is measured, how the data is processed and reported. This will be followed by a discussion of the results obtained on the two monitor sections on I-10.

The principles of the FWD are well known and the later part of this paper will show the results from FWD data collected on I-10 and processed with MODULUS 6.

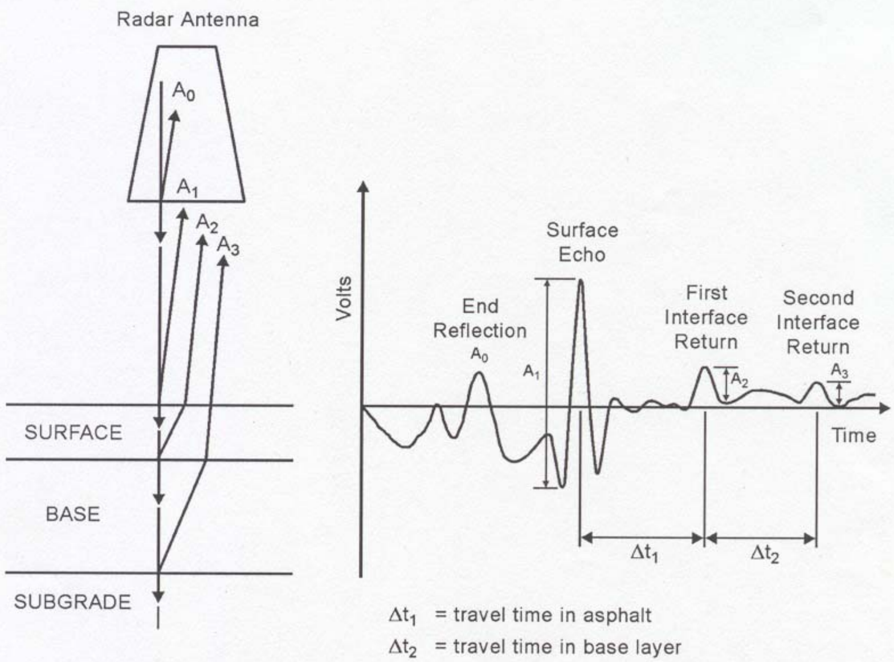
BASICS OF GROUND-PENETRATING RADAR

The Texas Transportation Institute's (TTI's) 1-GHz air-launched GPR unit is shown in Figure 1*a*. This system sends discrete pulses of radar energy into the pavement system and captures the reflections from each layer interface within the structure. Radar is an electromagnetic wave and therefore obeys the laws governing reflection and transmission of e-m waves in layered media. This particular GPR unit can operate at highway speeds (60 mph), transmit and receive 50 pulses per second, and can effectively penetrate to a depth of 2 ft. A typical plot of captured reflected energy versus time for one pulse is shown in Figure 1*b*, as a graph of volts versus arrival time in nanoseconds.

The amplitude of surface echo A_1 is the energy reflected from the surface of the pavement and A_2 and A_3 are reflections from the top of the base and subgrade respectively. These amplitudes of reflection and the time delays between reflections are used to calculate both layer dielectrics and thicknesses (Scullion, 1992). The dielectric constant of a material is an electrical property which is most influenced by moisture content and density. An increase in layer moisture content will cause an increase in layer dielectric and an increase in the amplitude of GPR reflections (Saarenketo, 1995; Scullion, 1997); in contrast an increase in air void content will cause a decrease in layer dielectric.

The examples below illustrate how changes in the engineering properties of the pavement structure would influence the typical GPR trace shown in Figure 1*b*.

(a) TTI GPR Equipment



(b) Principles of GPR. The incident wave is reflected at each layer interface and plotted as return voltage against time of arrival in nanoseconds.

FIGURE 1 GPR equipment and principles of operation.

1. If the thickness of the surface layer increases, then the time interval between A_1 and A_2 would increase. Therefore by collecting data along a highway it is possible to determine layer thickness and identify major changes in subsurface structure;
2. If the base layer becomes wetter, then the amplitude of reflection from the top of the base A_2 would increase,
3. If there is a significant defect within the asphalt layers, then an additional reflection will be observed between A_1 and A_2. This could be caused by variations in density between layers or areas of trapped moisture. If there are no large reflections between A_1 and A_2 then a solid homogenous core will be obtained, and
4. Large changes in the surface reflection A_1 would indicate changes in either the density or moisture content along the section. The variation in surface reflection is used to check segregation within a new hot-mix asphalt (HMA) surface layer, and it can also be used to test the quality of longitudinal construction joints (Saarenketo, 1998).

COLOR-CODED IMAGES OF SUBSURFACE CONDITION

In most GPR projects several thousand GPR traces are collected. In order to conveniently display this information color-coding schemes are used to convert the traces into line scans and stack them side-by-side so that a subsurface image of the pavement structure can be obtained. This approach is used extensively in Texas. A typical display from the Texas system for a thick HMA pavement is shown in Figures 2 and 3. This is taken from a section of newly constructed thick asphalt pavement over a thin granular base. Figure 2 shows a typical single trace from a good quality thick HMA layer. There is a clear reflection from the surface and the top of the base and no major reflections between these peaks.

Color coding consists of converting this trace into a single line scan of different colors where the high positive volts areas are color coded red, the negatives are blue and the areas around zero volts are green. Using the color coding and stacking scheme this data is transformed into Figure 3 which shows a Colormap subsurface image for a 2,500-ft section of highway. The labels on this figure are as follows:

a. Files containing data,
b. Main pull down menu,
c. Button to define the color coding scheme,
d. Distance scale (miles and feet),
e. End location,
f. Default dielectric value used to convert the measure time scale into a depth scale, and
g. Depth scale in inches.

It is noted that the zero on the depth scale is the reflection from the surface of the pavement. The important feature of this figure are the lines marked H, I, and J. These are the reflection from the surface, top and bottom of base respectively. The pavement is homogeneous and the layer interfaces are easy to detect. The variation in surface dielectric is shown at the bottom of the figure. For good quality uniform density HMA this would be almost a horizontal line. Significant areas of high dielectrics would indicate wet areas on the surface. Significant dips in surface dielectric are associated with areas of low density areas in the mat, typically “truck-end” segregation.

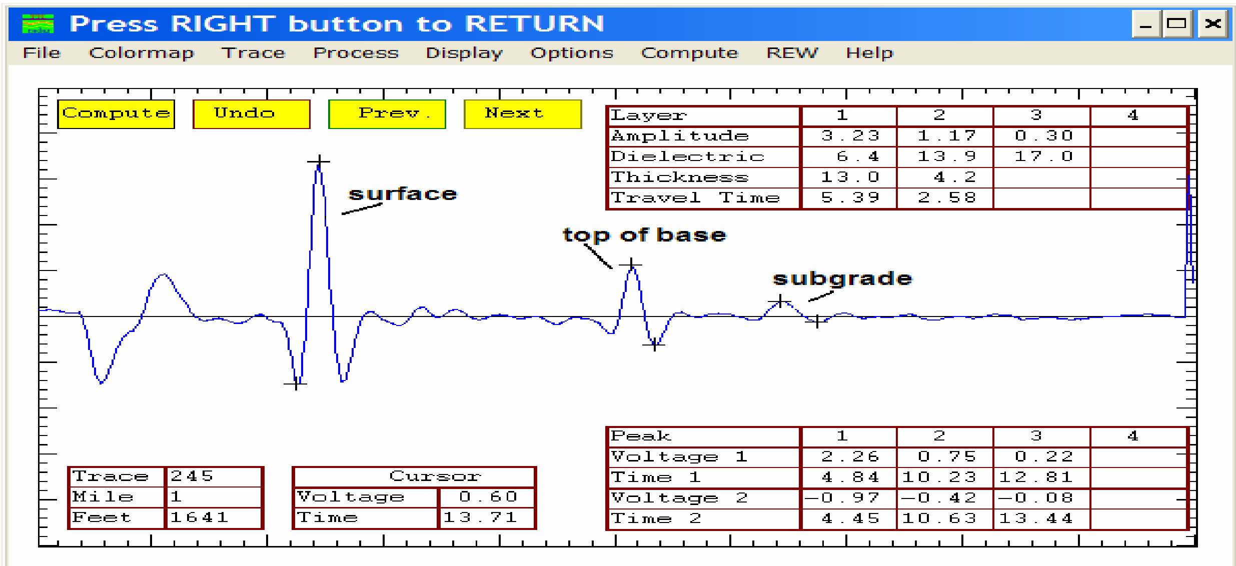


FIGURE 2 One individual GPR trace from a thick HMA pavement.

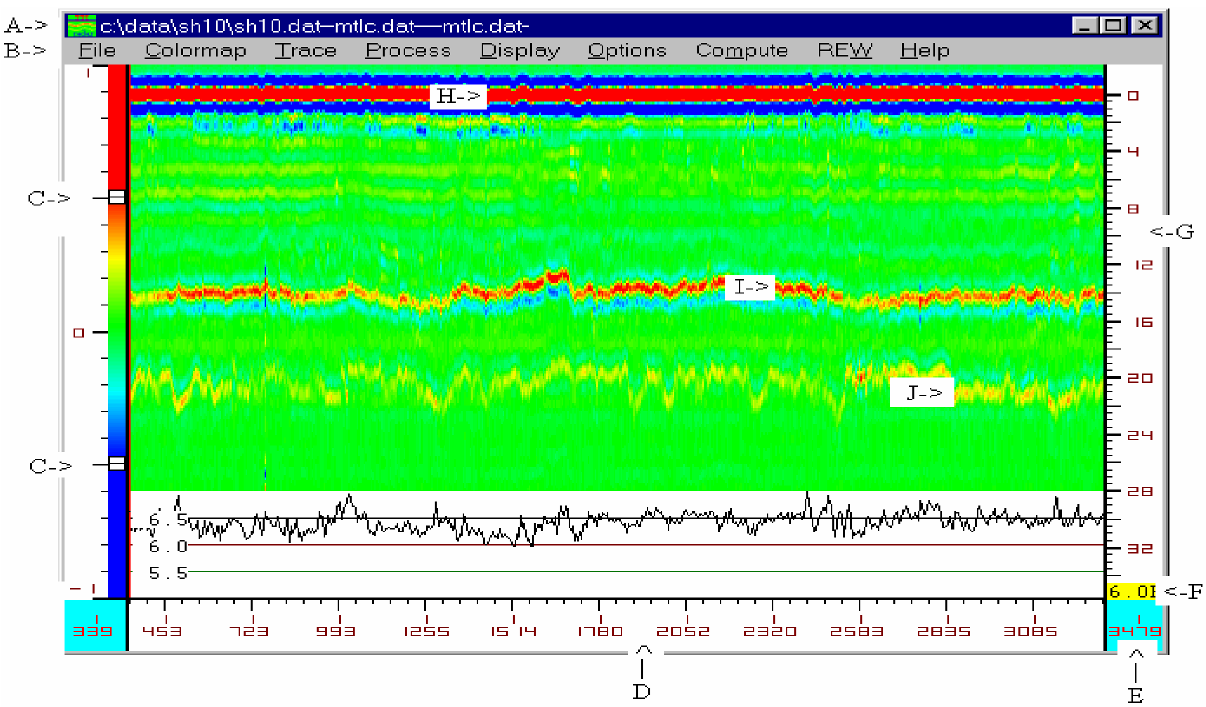


FIGURE 3 Color-coded GPR traces for a 2500-ft section.

When processing GPR data the first step is to develop displays such as Figure 3. From this it is possible to identify any clear breaks in pavement structure and to identify any significant anomalies. The intensity of the subsurface colors is related to the amplitude of reflection. Therefore areas of wet base would be observed as bright red reflections (I).

GPR RESULTS FROM INTERSTATE 10 IN LOUISIANA

GPR testing was conducted on I-10 on January 31, 2003. A GPR unit similar to that shown in Figure 1 was used; data was collected on two rubblization projects. Job 1 was just over a 10-mi section between Mileposts (MP) 82 and 93. Job 2 was also a 10-mi section, from MP 93 to MP 103. Data was collected at 60 mph with one GPR trace taken every 3 ft of travel.

The first run was eastbound (EB) from MP 92 so it included about 1 mi of Job 1 and 9 mi of Job 2. The second run was collected westbound (WB); data was collected continuously for approximately 20 mi. In both runs 1 and 2 all the data was collected in the outside lane/outside wheel path. A third run was made EB on Job 1starting at MP 82. In this run several diagonal passes were made over the pavement to collect data over the longitudinal joints in the pavement.

Figure 4 shows typical data from Job 2 (east of MP 93). This data is judged as ideal. The blue line in Figure 4 is the raw data collected at this location. The distance from the start of the run (7 mi and 943 ft) is shown in the box at the lower left hand corner. Synchronized video was also collected and the same distance information appears on the video tape. The red line superimposed on the blue line in Figure 4 is the resulting trace once the large surface reflection has been removed by TTI's processing software package (Colormap). This "surface removal" technique is useful in exposing small near surface reflections which are typically from the bottom of the last overlay placed. In this case a small peak is detected just to the left of the surface reflection, which is the bottom of the wearing course.

The numbers in the box in the upper right part of Figure 4 are the results of the calculations made on this trace. The amplitudes and travel times between peaks are listed together with the computed layer dielectrics and thicknesses. In this particular case the trace was analyzed to show 2 in. of wearing course, 6.3 in. of HMA base, and 10.2 in. of rubblized concrete. The individual layer dielectrics are 6.2, 7.0, and 8.1. The dielectric for the rubblized concrete is low at 8.1; this is very dry. This number is judged to be ideal for a base layer, if it is less than 10 and it would be a cause for concern if it was greater than 16. Values less than 10 represent dry granular bases; values over 16 would indicate saturated conditions.

Using the color coding scheme described earlier a 1,500 ft of I-10 is shown in Figure 5 below. The scale at the bottom is the distance scale from 5 mi, 810 ft to 5 mi, 2,310 ft. In this case the surface has been moved to the top of the screen. The only significant reflection is a faint yellow line at a depth of approximately 10 in. This is the top of the rubblized concrete layer. No defects are apparent in either the HMA or base layers. The line at the bottom of the figure is the surface dielectric plot. This is an indicator of the uniformity of the surfacing and sudden localized dips would indicate areas of segregation. No significant segregation was found on either job. This implies that the construction techniques are producing a uniform final wearing surface.

There is one small defect areas to the far right of Figure 5. There is a localized strong red/blue reflection at approximately mid depth in the HMA layer. The location and significance of this defect will be discussed later in this paper.

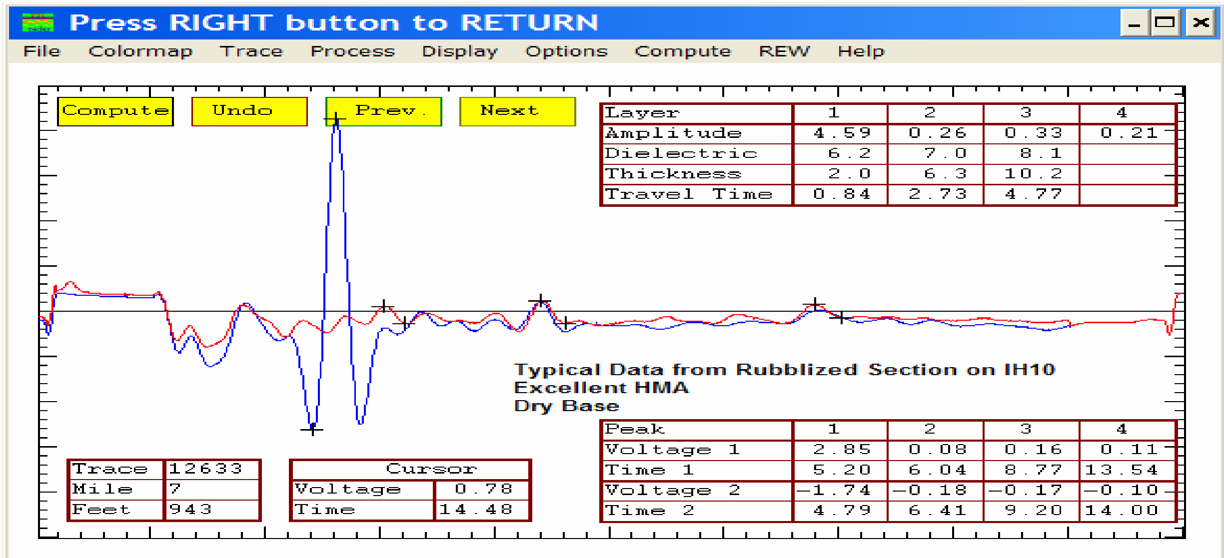


FIGURE 4 Typical trace obtained on Job 2 (ideal case: no defects).

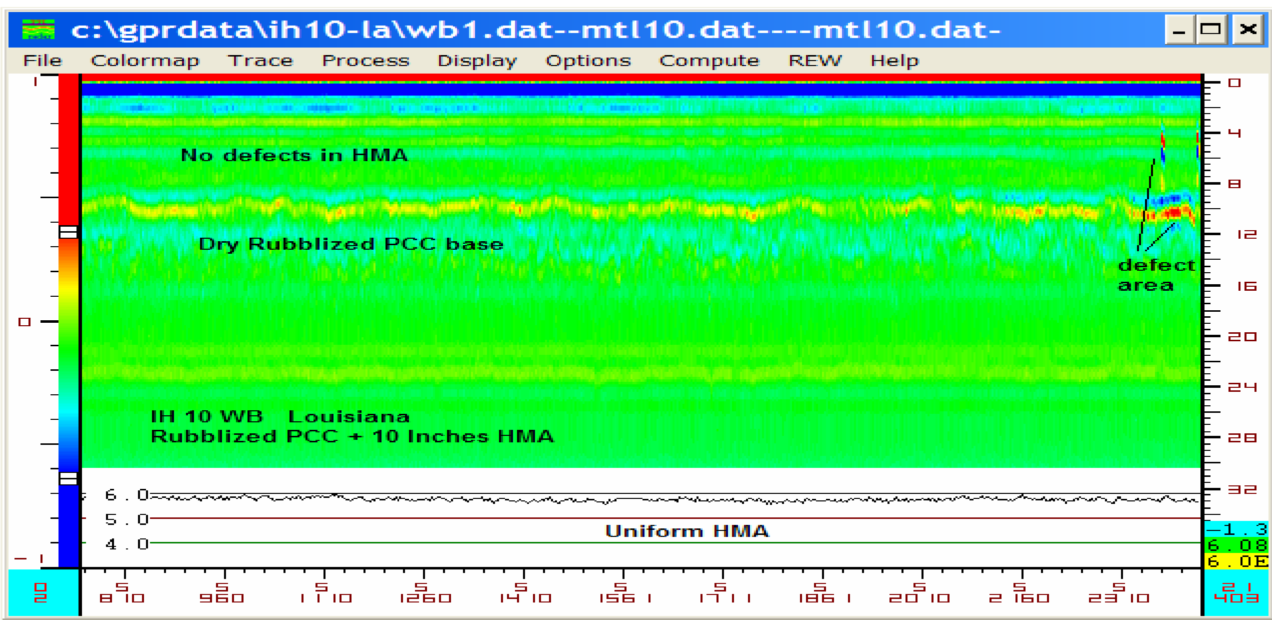


FIGURE 5 Typical Colormap display for Job 2 (ideal case), small defect area at right of display.

Results from Job 1 (West of MP 93)

There are several clear differences between Jobs 1 and 2. Job 2 is judged as ideal data. The transition from Job 2 to Job 1 is shown below in Figure 6. One big difference between the jobs is the interface at the top of the rubblized concrete. As shown below the pattern changes from a faint yellow line to a stronger blue/red line. Two factors could be causing this stronger reflection. The first and most probable are density problems at the bottom of the lower Superpave binder

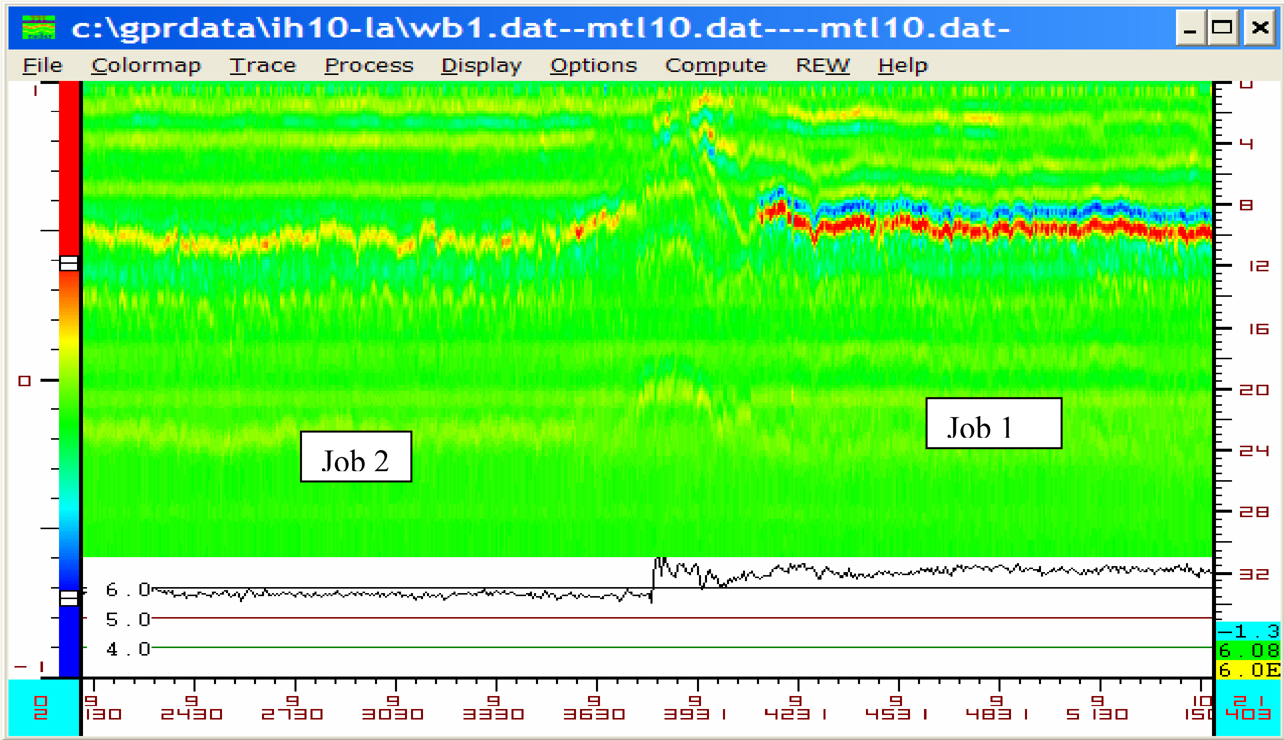


FIGURE 6 Transition from Job 2 to Job 1 WB I-10.

layer. The second contributing factor could be that the Job 1 base is holding more moisture. The dielectric of the Job 1 base is not excessively high but higher than the Job 2 base.

An individual GPR reflection from the EB run of Job 1 shows further evidence of a low-density HMA layer. In contrast to the ideal trace shown above in Figure 4, the trace shown in Figure 7 has an inverted (negative) reflection at the bottom of the HMA layer. The most probable cause is the presence of a low density (honeycombed) layer at the bottom of the first layer of binder course.

Figure 8 shows 1,500 ft of the WB direction of Job 1. In this Colormap display there are significant reflections (blue areas) from several places within the HMA layer. This type of pattern in the past has been found to be associated with segregation or compaction problems. Areas such as shown in Figure 7 and 8 would be good candidates for coring to validate the GPR interpretation.

Overall the data collected on Job 1 was judged as reasonable, but inferior to Job 2 which will be described below. On the positive side the surface dielectrics in the wheel paths were relatively constant indicating that the top layer is uniform. The concern about this job is localized density problems within the HMA mat particularly at the bottom of the first lift.

Results from Job 2 (East of MP 93)

The results from Job 2 are judged as ideal and provide clear evidence that this is a well compacted, top quality, defect free HMA layer. For the entire project the surface dielectric was extremely uniform, the base was dry and the HMA had none of the density problems found in

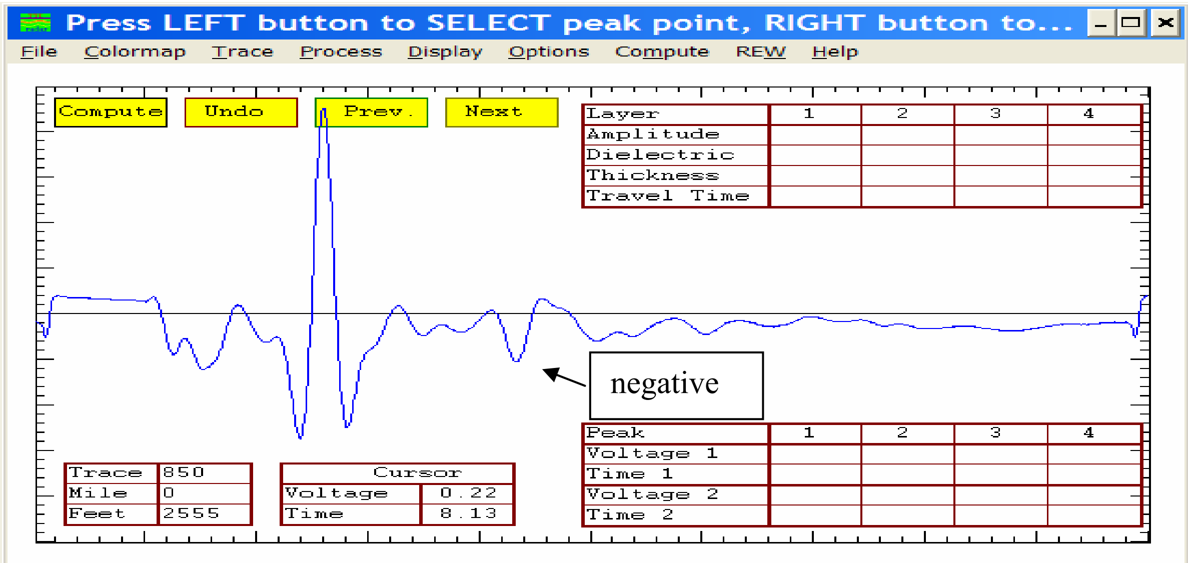


FIGURE 7 Potential defect area in Job 1. Negative or inverted reflection at bottom of HMA indicates potentially poor compaction at the bottom of the binder course.

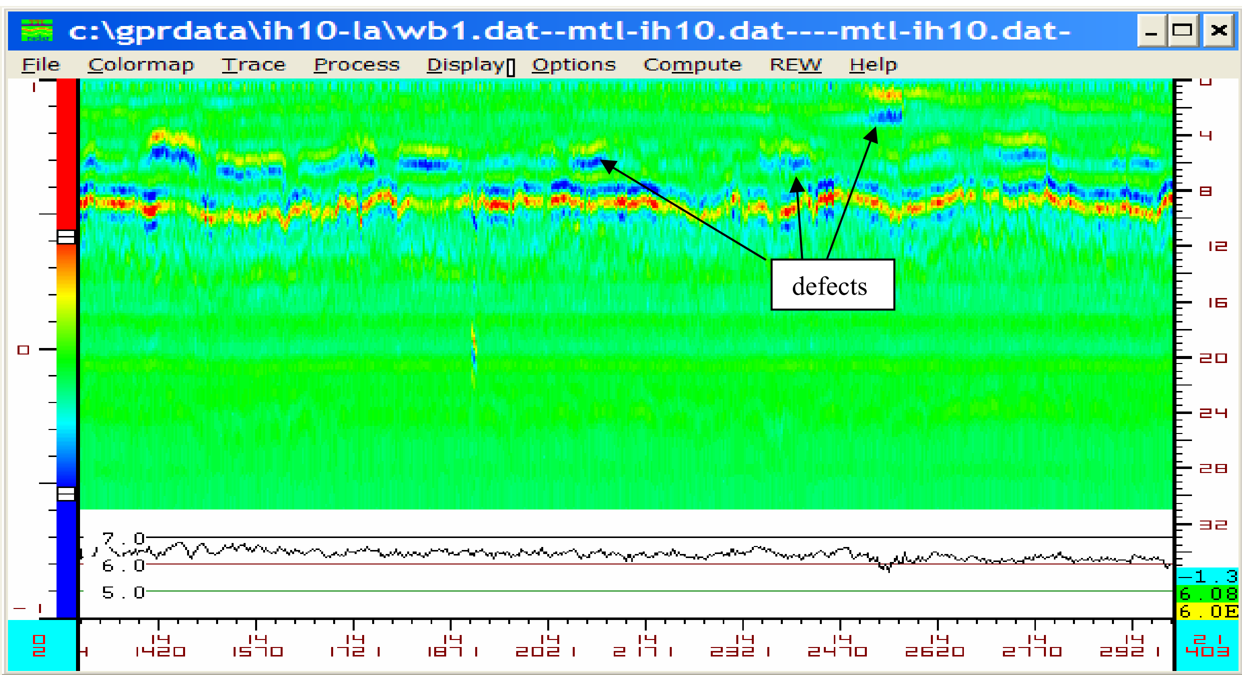


FIGURE 8 WB I-10 Job 1, blue areas in HMA indicate possible localized compaction problems or segregation.

Job 1. However a few localized problems were detected these are illustrated in Figure 9. All of the defects in Job 2 were detected at either on or off ramps.

It appears that the drainage systems may not be functioning where the concrete ramps meets the main lanes. The on and off ramps were not rubblized. The potential problem areas are localized to a few GPR traces. However the reflections in these areas are very high. It was

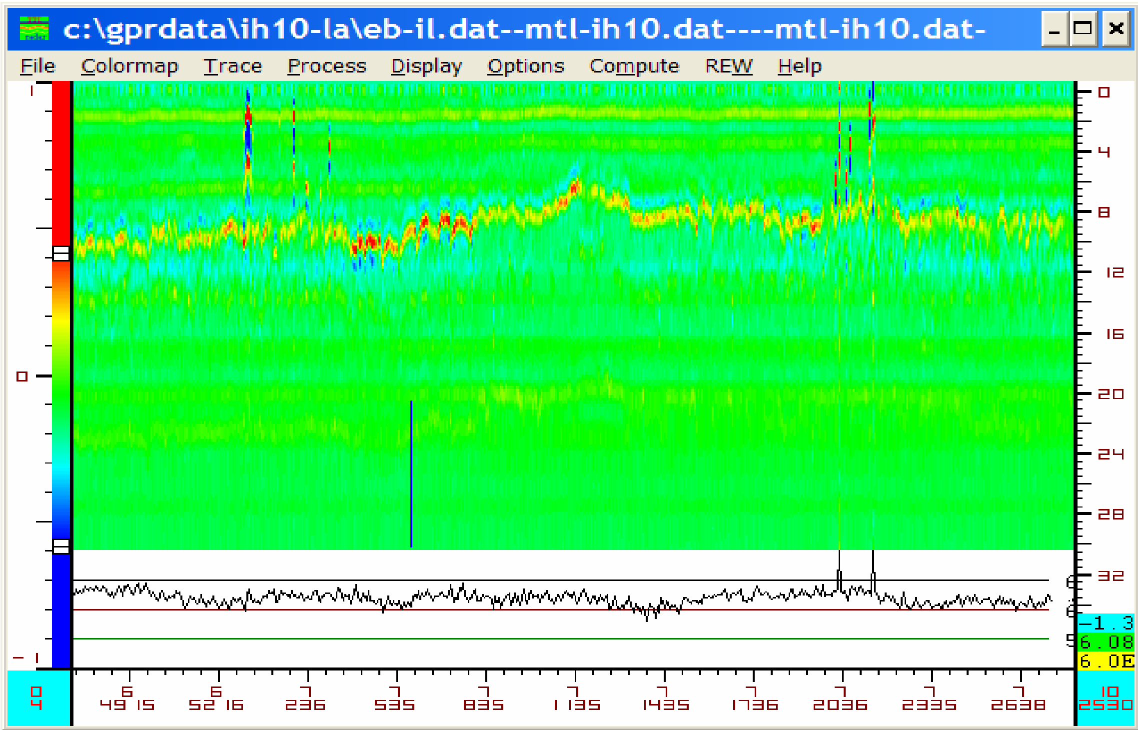


FIGURE 9 Localized potential problems areas in HMA at on/off ramps.

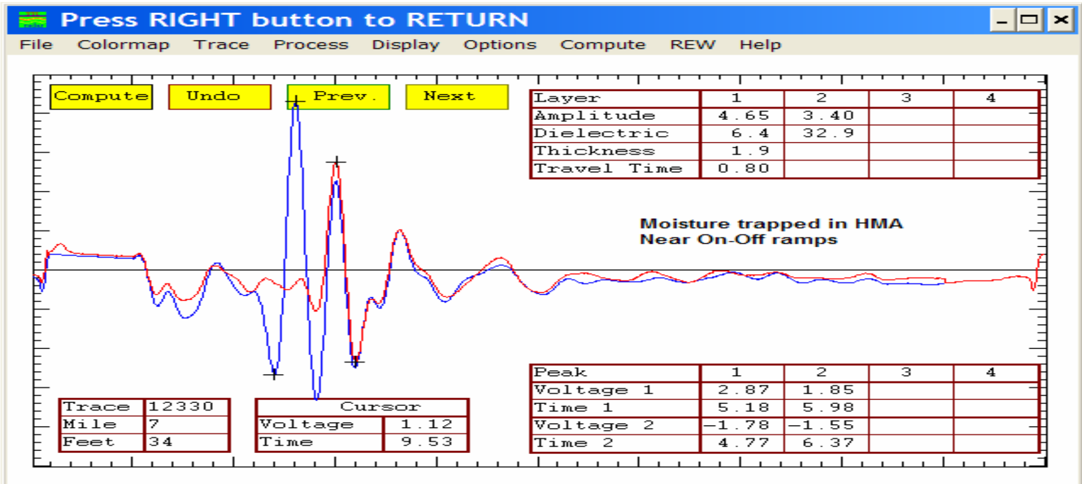
decided to group the GPR reflections from these problems areas into the 3 severity levels shown in Figure 10. At the low severity level it appears that there is a moist layer 2 to 3 in. below the surface, this is not a real cause for concern. The moderate level indicates a very high concentration of moisture at the bottom of the wearing surface. The severe level is a mystery. This is too high for moisture and it is assumed to be related to a metal object beneath the upper HMA layers.

Table 1 shows the location and severity level of all the problem areas identified in both jobs. It was recommended that the moderate and high severity areas should be investigated with limited field coring. It is interesting to note that no problems were found at the on/off ramp in Job 1. Clearly it will be important to identify what different practices were used in these ramp locations.

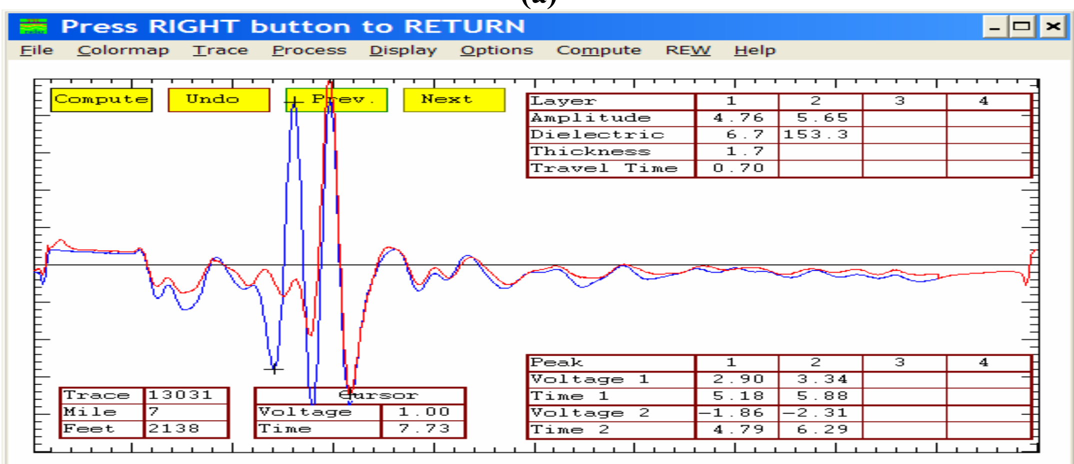
FALLING WEIGHT DEFLECTOMETER RESULTS FROM I-10 IN LOUISIANA

To provide an assessment of the structural strength of the rubblized pavement FWD data was collected on a section of Job 2. The TxDOT FWD is shown in Figure 11. This is the standard structural strength tool used by TxDOT. The FWD data is processed using the MODULUS 6.0 backcalculation program.

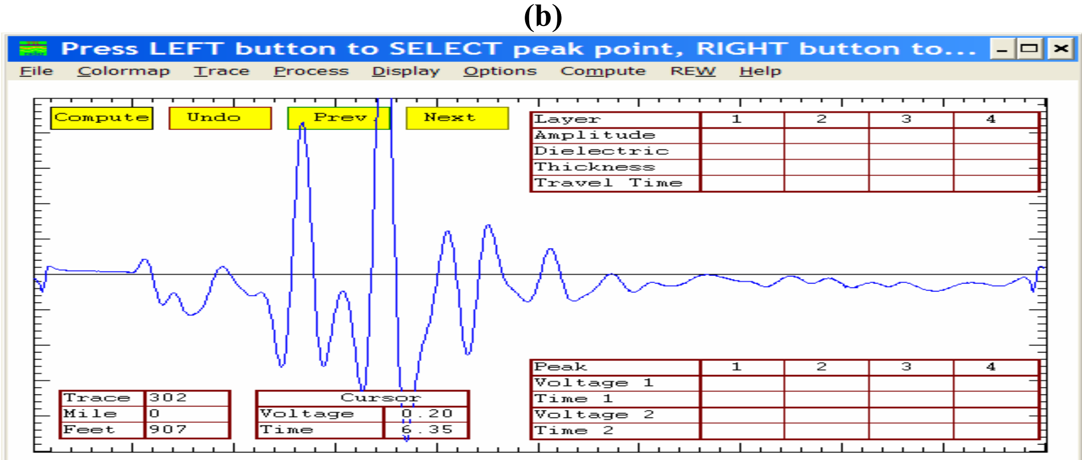
On I-10 the FWD data was collected in the outside lane EB direction starting at MP 94, with data collected at 0.2-mi intervals for approximately 6 mi. The temperature of the HMA layer at the time of testing was measured by drilling a hole to a depth of 2 in. The temperature



(a)



(b)



(c)

FIGURE 10 Different severity of problems detected at on/off ramps on Job 2 EB IH 10: (*a*) low severity—moisture in HMA layer 2 in. below surface; (*b*) medium severity—saturated layer 2 in. down; and (*c*) high severity—unknown cause, perhaps a metallic object, foil, or metal paint 4 in. below surface.

TABLE 1 Potential Defect Areas on the I-10 Testing in Louisiana

No.	Job	Dir.	Distance m + ft	Video min:s	Problem	Sev.
1	1	EB	0+2471	6:14	Wet base (high reflection) + low density at bottom HMA.	M
2	1	EB	0+2555	6:15	Low density at bottom of HMA layer.	L
3	2	EB	4+2926	10:46	Moisture in HMA, 2 in. below surface, not serious.	L
4	2	EB	4+4868	11:10	Major reflection in HMA 4 in. down. Too high for moisture, look for metallic paint or foil.	H
5	2	EB	7+0034	13:27	Moisture in HMA, 2 in. below surface, substantial moisture.	M
6	2	EB	7+2138	13:55	Moisture in HMA, 2 in. below surface, very high reflections—investigate here.	H
7	2	EB	9+1658	15:59	Major reflection in HMA 4 in. down. Too high for moisture, look for metallic paint or foil.	H
8	2	EB	10+1936	17:06	Major reflection in HMA 4 in. down. Too high for moisture, look for metallic paint or foil.	H
9	2	WB	0+0907	17:42	Major reflection in HMA 4 in. down. Too high for moisture, look for metallic paint or foil.	H
10	2	WB	1+2563	19:08	Moisture in HMA, 2 in. below surface, not too serious.	L
11	2	WB	2+5074	20.39	Moisture in HMA, 2 in. below surface, not too serious.	L
12	2	WB	3+1590	21:01	Moisture in HMA, 2 in. below surface, not too serious.	L
13	2	WB	5+4239	23:37	Major reflection in HMA 4 in. down. Too high for moisture, look for metallic paint or foil.	H
14	1	WB	14-1800 15+3500	32:47 34:11	Low density areas within HMA, segregation or compaction problems (core 15 + 3167).	M
15	1	EB	8+4960	50:15	Check longitudinal joint density—major decreases in surface reflection.	L

Key: Sev. = Severity of problem (low, medium, or high)

of the HMA at the time of testing averaged 67°F. This section was over 3 years old at the time of testing.

The FWD data and the results from the MODULUS run on the 6 mi of data are shown in Table 2. The first observation from this data is that the maximum deflections are very low at this load level. The average maximum deflection is 2 mi. The average back calculated moduli for both the surface and base layers are very high with average values of over 1400 ksi and 847 ksi, respectively. Using standard TxDOT temperature correction factors the temperature corrected modulus for the HMA layer would be 977 ksi at the design temperature of 77°F. This is well above the standard HMA design value used in Texas of 500 ksi. This is explained by the use of the stiffer stone-filled mix with high performance gade binder

A second set of deflection data was also collected mid-slab on different section of jointed concrete on I-10 which was about to be rubblized. This was an intact 10-in. thick portland cement concrete (PCC) slab made with gravel aggregates. Figure 12 compares the normalized

FIGURE 11 TxDOT's FWD.

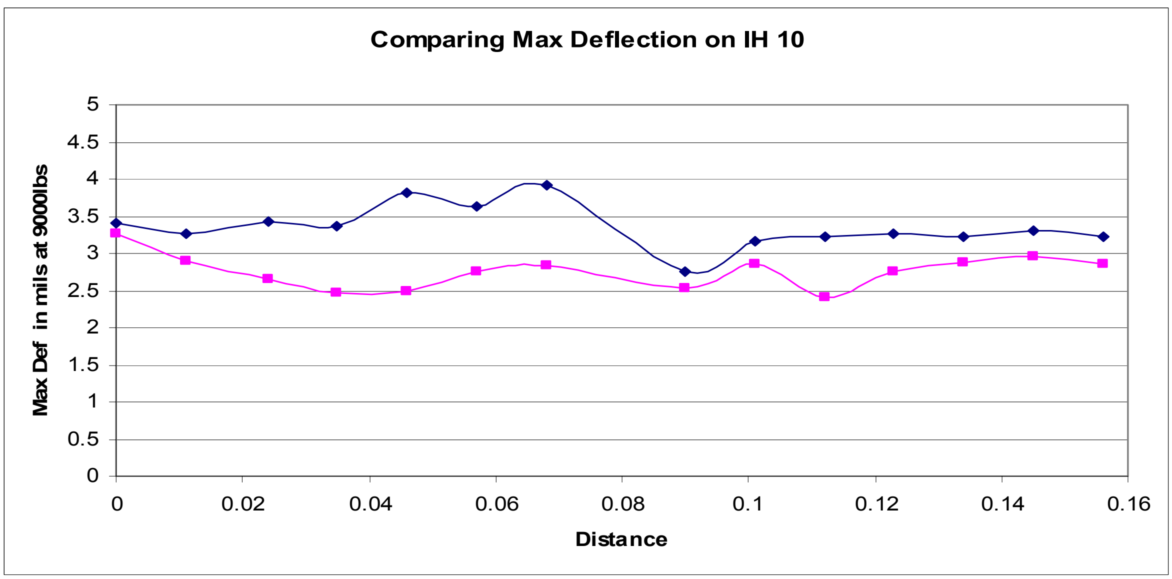


FIGURE 12 Comparing deflection from the rubblized section (Job 2) with an uncracked concrete slab.

maximum deflection data from the rubblized section on Job 2 to the unbroken concrete section. In both cases the data were normalized to 9,000 lbs and both sets of data were collected with a pavement temperature close to 67°F. It is interesting to note that the deflections from the rubblized pavement are very similar to the deflections from the concrete slab. In fact the rubblized section has slightly lower deflections than the uncracked slab.

In summary the structural strength of the rubblized section looks excellent. The rubblized concrete base modulus of almost 850 ksi is well above that traditionally found with Class 1

TABLE 2 TTI Modulus Analysis System Summary Report (Version 6.0)

			MODULI RANGE(psi)		
District: Louisiana		Thickness(in)	Minimum	Maximum	Poisson Ratio Values
County :	Pavement:	10.00	540,000	1,780,000	H1: v = 0.38
Highway/Road: IH 10 EB	Base:	11.00	50,000	2,000,000	H2: v = 0.25
	Subbase:	0.00			H3: v = 0.00
	Subgrade:	234.39(by DB)	15,000		H4: v = 0.40

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (ksi): SURF(E1)	BASE(E2)	SUBB(E3)	SUBG(E4)	Absolute ERR/Sens	Dpth to Bedrock	
0.000	6,907	2.51	2.07	1.81	1.53	1.35	1.18	0.96	1277.6	1008.5	0.0	18.1	1.16	142.1	
0.200	6,506	2.09	1.82	1.58	1.13	1.07	0.88	0.75	1780.0	415.2	0.0	25.8	5.24	300.0	*
0.400	6,407	1.89	1.61	1.41	1.20	1.02	0.86	0.72	1780.0	957.7	0.0	22.6	1.00	300.0	*
0.600	6,323	1.73	1.42	1.28	1.09	0.97	0.83	0.72	1707.3	1532.0	0.0	22.5	0.77	300.0	
0.800	6,303	1.74	1.48	1.32	1.14	1.00	0.83	0.68	1780.0	986.0	0.0	24.0	2.42	132.8	*
1.000	6,256	1.91	1.63	1.44	1.16	1.04	0.87	0.77	1780.0	838.2	0.0	22.3	1.92	300.0	*
1.200	6,212	1.96	1.63	1.46	1.15	1.07	0.90	0.78	1733.3	879.0	0.0	21.5	2.29	300.0	
1.400	6,164	1.74	1.37	1.21	0.98	0.92	0.77	0.67	1240.9	1656.2	0.0	25.0	2.16	300.0	
1.600	6,164	1.95	1.60	1.42	1.18	1.04	0.85	0.74	1630.3	858.7	0.0	22.2	1.14	300.0	
1.801	6,216	1.66	1.35	1.24	1.00	0.90	0.72	0.55	1780.0	1125.2	0.0	26.0	2.30	300.0	*
2.000	6,180	1.89	1.44	1.17	1.01	0.88	0.72	0.68	988.8	1154.3	0.0	28.0	1.80	300.0	
2.401	6,176	1.98	1.54	1.39	1.14	1.04	0.83	0.74	1128.0	1277.3	0.0	22.7	1.94	300.0	
2.600	6,208	2.04	1.68	1.44	1.25	1.05	0.89	0.77	1538.2	809.9	0.0	21.9	0.44	300.0	
2.800	6,164	1.96	1.67	1.39	1.08	1.01	0.82	0.67	1780.0	424.8	0.0	26.5	4.01	300.0	*
3.000	6,156	1.80	1.41	1.18	0.99	0.88	0.73	0.61	1200.1	1164.1	0.0	27.3	1.70	300.0	
3.400	6,240	2.09	1.71	1.44	1.17	1.03	0.86	0.77	1441.4	659.0	0.0	23.8	1.46	300.0	
3.600	6,156	2.42	1.80	1.39	1.05	0.88	0.70	0.61	881.7	313.4	0.0	30.8	2.04	300.0	
3.800	6,113	2.95	2.36	1.83	1.36	1.13	0.87	0.77	1109.8	142.1	0.0	24.4	1.89	300.0	
4.000	6,105	2.37	1.78	1.43	1.13	0.95	0.78	0.70	863.4	458.5	0.0	27.2	1.53	300.0	
4.201	6,117	1.96	1.67	1.40	1.20	1.05	0.89	0.72	1780.0	767.1	0.0	21.6	1.43	127.8	*
4.400	6,180	1.70	1.46	1.20	1.02	0.87	0.72	0.63	1780.0	833.1	0.0	27.3	1.30	300.0	*
4.800	6,133	1.87	1.43	1.18	0.93	0.82	0.68	0.57	1109.3	773.7	0.0	30.8	2.02	300.0	
5.000	6,148	1.92	1.69	1.38	1.30	1.21	1.05	1.00	1780.0	1618.8	0.0	16.2	3.12	300.0	*
5.200	6,141	2.07	1.57	1.27	0.98	0.85	0.67	0.51	1064.7	481.9	0.0	31.3	1.77	300.0	
5.400	6,148	2.12	1.66	1.20	0.87	0.68	0.52	0.37	1445.5	124.8	0.0	41.6	2.14	89.9	
5.600	6,133	1.90	1.56	1.34	1.11	0.98	0.85	0.70	1484.7	985.4	0.0	23.1	1.44	150.1	
5.800	6,109	2.18	1.72	1.48	1.14	0.96	0.77	0.67	1418.5	382.1	0.0	26.6	1.39	300.0	
6.000	6,129	1.89	1.48	1.28	1.06	0.94	0.78	0.71	1199.1	1100.2	0.0	25.1	1.12	300.0	
Mean:		2.01	1.63	1.38	1.12	0.99	0.82	0.70	1445.8	847.4	0.0	25.2	1.89	255.4	
Std. Dev:		0.28	0.21	0.16	0.14	0.13	0.12	0.12	318.1	409.9	0.0	4.8	0.97	117.7	
Var Coeff(%):		13.81	13.18	11.98	12.16	12.97	15.02	17.43	22.0	48.4	0.0	18.8	51.16	46.1	

flexible bases of 70 to 80 ksi. This indicates that the rubblized base is not being reduced to a flexible base it is still retaining many features of a fractured slab. It was commented that the rubblization process rubblized the upper layers but only introduces diagonal cracks in the lower part of the slab. These very high moduli values would support that observation.

The extremely high values for the Superpave mix are also very interesting. This is a modified binder with a large stone aggregate. Field performance to date has been excellent. It is recommended that follow up FWD testing during summer months be conducted to evaluate the impact of high temperatures on the backcalculated moduli value. It would also be worthwhile to conduct laboratory tests on this material to compare the laboratory moduli value with those obtained on traditional dense graded mixes.

CONCLUSIONS

Based on the FWD and GPR results, the Job 2 rubblization project (east of MP 93) is judged to be excellent. The design and construction practices used by the Louisiana Department of Transportation and Development (LADOTD) have produced a sound, defect-free pavement which is judged to be structurally adequate to carry interstate traffic for many years to come. On this project the rubblized concrete has a moduli value over 10 times higher than that of a traditional flexible base and the base is draining well with no evidence of trapped water. The Superpave mixes with the Roadtec shuttle buggy and LADOTD's warranty bond are providing an outstanding HMA surface over the solid rubblized concrete base.

Discussions with the LADOTD pointed out that the following items are critical in ensuring a successful project.

1. The existing mid slab support should be good, otherwise problems will be encountered when rubblizing the slab.
2. Rubblization is preferred over crack and seat when failed/voided joints are present. Crack and seat may simply bridge the joints whereas rubblization will fill the voids.
3. Installing edge drain before rubblization is essential.
4. Design and quality control of the asphalt layers is critical, LADOTD pointed out that the only problems they have encountered in earlier projects was with rutted asphalt layers. The new design and construction techniques have eliminated these problems.

Is this concept transferable to areas in Texas? It should be recalled that subgrade conditions in this area of Louisiana are extremely challenging. The water table is very near the surface and the area receives over 50 in. of rain each year. Furthermore the traffic loadings on I-10 are very high. No rutting or cracking was observed in any of the project tested in this study. The one factor clearly assisting the Rubblization process is the presence of a stiff cement treated base beneath the old JCPs. As many of the old JCPs in Texas were constructed on untreated select fill, the efficacy of this process to work in areas of poor support is yet to be determined.

ACKNOWLEDGMENTS

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Illinois Performance Study of Pavement Rubblization

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The majority of the pavements on state routes in Illinois were originally constructed of portland cement concrete (PCC). Many of these pavements have been rehabilitated or are in need of rehabilitation. Historically, the most common rehabilitation method has been patching of deteriorated areas followed by an overlay with bituminous concrete. Bituminous overlays of PCC pavements usually begin to fail at the reflected joints and patched areas of the old concrete pavement, as well as in areas where the underlying concrete has continued to deteriorate. In 1990, the Illinois Department of Transportation (IDOT) began experimenting with rubblization as a method for rehabilitation of PCC pavements. Rubblization transforms the existing pavement into a high quality aggregate base, thus eliminating joints and cracks that may reflect through the bituminous overlay.

This paper provides a history of rubblization in Illinois, including factors used in project selection, types of rubblization equipment used, and construction sequence. Design details of experimental sections and a summary of each project's performance are described. Twelve projects using the rubblization method have been constructed on state routes in Illinois, eight of which have been closely monitored. To date, all rubblization projects constructed in Illinois have performed as well as, or better than, control sections.

INTRODUCTION

The vast majority of the pavements maintained by IDOT were originally constructed of PCC. Early designs were usually jointed reinforced concrete pavement (JRCP), with some jointed plain concrete pavement (JPCP). After 1965, continuously reinforced concrete pavement (CRCP) became the pavement design of choice for the most heavily traveled routes. On the Interstate system, about 30% of the lane mileage was originally constructed of JRCP. Approximately two-thirds of the system was built using CRCP. Full-depth asphalt pavement was not used to a great extent until the 1990s, and now accounts for about 4% of the interstate network.

Over the last couple of decades, many pavements have undergone rehabilitation. Typical repair includes patching the areas of deteriorated concrete (joints and transverse cracks in JRCP or JPCP, and punchouts in CRCP), followed by an overlay with bituminous concrete. Over three-fourths of the Interstate system had been overlaid at the time of this writing, with about one-third of sections receiving a second overlay, and some a third overlay. It may be possible to overlay a pavement section multiple times, in some cases, and still get adequate performance. However, studies have shown that the life of each successive overlay tends to decline (*1*).

Bituminous concrete overlays of PCC pavements usually begin to fail at the reflected joints and patched areas of the underlying concrete pavement, in addition to areas where the concrete has continued to deteriorate. IDOT has experimented with several types of reflective crack control treatment over the years (*2*). However, these experiments have resulted in limited success (*3–6*), and additional methods continue to be explored.

Pavement rubblization is one of the more promising methods used to prevent the performance problems commonly associated with bituminous overlays. In the rubblization process, specialized equipment is used to essentially transform the existing concrete pavement into a high quality aggregate base. A thick bituminous overlay is then placed on top of the rubblized pavement. Rubblization aims to eliminate reflective cracking in the bituminous concrete overlay at locations of underlying joints and cracks. The construction and performance history of rubblization projects in Illinois are presented in this report.

PROJECT SELECTION

Many factors were considered when selecting projects for rubblization. A variety of routes was chosen to represent different traffic levels and a range of overlay design thicknesses (*2*). A complete evaluation of the existing pavement and subsurface was made to determine if the section was a good candidate for rubblization. Older pavements with severe joint distresses and transverse cracking (in JRCP or JPCP) (Figure 1), or extensive punchouts (in CRCP) are often good candidates for rubblization, due to the cost of conventional patch and overlay methods. Pavements showing signs of durability cracking (D cracking) (Figure 2), a distress related to freeze-thaw expansion of certain types of coarse aggregates, are also ideal candidate projects.

Pavements exhibiting the distresses mentioned above will likely have high patching quantities, and are likely to continue to deteriorate over time. Patching of existing pavements

FIGURE 1 Prime candidate project for rubblization.

FIGURE 2 D cracking distress at transverse crack.

prior to overlay is both costly and time-consuming. Patching quantities greater than 10% to 15% are generally considered to be excessive. When patching quantities reach this level, rubblization is often the best option for rehabilitation, from both a cost and performance standpoint.

A thorough investigation of the subgrade soils on each project was required to determine whether or not the pavement could be rubblized successfully. Weak subgrade soils do not provide ample support and can make the rubblization process difficult to accomplish. The rubblized pavement, subbase, and subgrade must also be capable of providing adequate support for subsequent construction activities. Information on the subgrade soils was also used in the selection of rubblizing equipment, as discussed below. If it is decided that the pavement cannot be rubblized, complete removal and replacement of these areas, or other methods of rehabilitation, will be necessary.

Other factors, such as overhead clearances, transitions to mainline structures, utilities, proximity to buildings or other structures, and location and condition of underdrains were also considered in the selection process. Short sections of pavement removal and replacement may be necessary to maintain adequate clearances at overheads and to meet existing bridge structures.

EQUIPMENT

Two basic types of devices are currently approved by IDOT for use in the pavement rubblization process. These are the multi-head breaker and the resonant frequency breaker. Slight variations of each device exist. Device selection is made based upon the combined thickness of the existing concrete pavement and base and the support of the subgrade soil.

The multi-head breaker (Figure 3) is a self-propelled unit with multiple drop-hammers mounted at the rear of the machine (*2*). The device can break pavement up to 4 m (13 ft.) in width in a single pass. A Z-pattern steel grid roller (Figure 4) must be used in conjunction with the multi-head breaker to complete the breaking process. This roller further breaks flat and elongated material into more uniform pieces (*2*). The production rate for this machine is approximately 2.3 lane-km (1.4 lane-mi) per day, depending on the cross section and integrity of the pavement being rubblized. Use of the multi-head breaker is required when there is any question as to the ability of the rubblized section to support construction equipment. This machine does not encroach into the adjacent lanes, therefore making its use preferred when the roadway is to remain open to traffic.

The resonant frequency breaker (Figure 5) is a self-propelled unit that utilizes a high frequency, low amplitude impact force to fracture the pavement. The force is applied via a shoe located at the end of a pedestal attached to a beam and counter weight. Several passes (18 to 20) are needed to rubblize a 3.6-m (12-ft) lane. The production rate for this machine is slightly less than that of the multi-head breaker at 1.6 lane-km (1.0 lane-mi) per day. The machine has very heavy wheel loads that prohibit its use on softer subgrades or thinner cross sections. A lower tire pressure version of this machine allows usage on many softer soils. The resonant breaker also encroaches 1.0 to 1.5 m (3 to 5 ft) into the adjacent lane when working near the centerline, making it ill-suited for use when the roadway is open to traffic.

FIGURE 3 Multi-head breaker.

FIGURE 4 Z-pattern steel grid roller.

FIGURE 5 Resonant frequency breaker.

CONSTRUCTION SEQUENCE

The general steps in the construction process are as follows:

- Install underdrains if none are present or if existing underdrains are not functioning properly. Underdrains provide drainage during construction and also help prevent moisture-related damage after construction is complete (*2*).
- Remove any existing bituminous concrete overlays (usually by milling).
- Remove and replace any existing unsound bituminous repairs.
- Rubblize the pavement.
- Compact the broken pavement.
- Pave the binder lifts of the bituminous concrete overlay.
- Allow traffic on sections having adequate thickness (if necessary).
- Pave the surface of the bituminous concrete overlay.

PROJECT HISTORY

The first rubblization project in Illinois was constructed in 1990. Two short test sections were constructed as part of a Strategic Highway Research Program (SHRP) SPS-6 experiment. Given the initial success of these experimental sections, a decision was made to move forward with additional experimental projects. These projects typically included a control section (patch and overlay) for comparison purposes. Different rubblization methods and various overlay thicknesses over the rubblized concrete pavement were used to aid in the development of thickness design procedures and construction guidelines.

To date, 12 projects using the rubblization method have been constructed on state-maintained routes in Illinois, seven of which incorporated experimental features (see list below). Five of these seven projects are located on heavily traveled Interstate routes. A recent project, constructed in 2003, was the first rubblizing project designed using a 30-year design period. Although this project does not contain experimental features, it is a unique design that will also be monitored closely. The locations of the eight monitored projects are shown in Figure 6. Details on the construction and performance of these projects are presented later in this report. Performance has been very good thus far, with less reflective cracking than on adjacent patch and overlay sections. None of the projects have required rehabilitation at this point.

- I-57 constructed 1990.
- Illinois Route 38 constructed 1994.
- I-55 Frontage Road constructed 1994.
- I-57 constructed 1996.
- I-70 constructed 1997.
- I-57 constructed 1997.
- I-74 constructed 1999.
- I-70 constructed 2003.

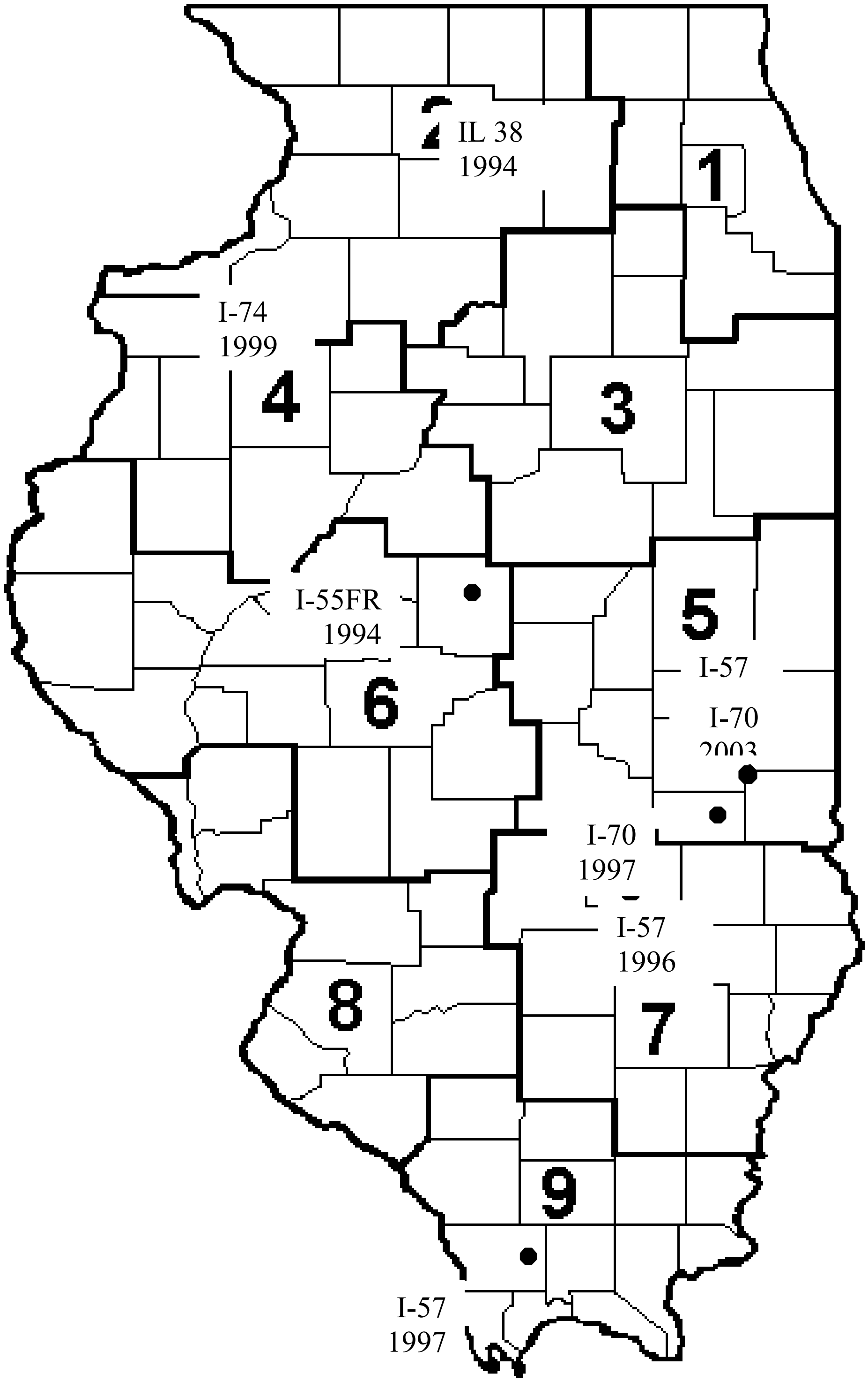

FIGURE 6 Locations and construction year of monitored rubblization projects in Illinois.

PROJECT PERFORMANCE

Outlined below are the design details for the rubblization projects, along with a summary of pavement performance to date. Various measures were used to examine the performance of the different test sections on each project. Much of this information was collected using IDOT's automated data collection vehicles. These vehicles are used to collect International Roughness Index (IRI) and rutting information, and to record digital imagery. The digital images are used to perform visual distress surveys and determine condition rating survey (CRS) values. The CRS is a numerical value from 1.0 to 9.0 that gives an indication of the condition of the pavement surface, with a value of 9.0 representing a pavement with no distress (see ranges below). Detailed manual distress surveys and falling weight deflectometer (FWD) testing were also performed.

- CRS 1.0 – 4.5 = Poor
- CRS 4.6 – 6.0 = Fair
- CRS 6.1 – 7.5 = Good
- CRS 7.6 – 9.0 = Excellent

Interstate 57 Constructed 1990

The first rubblization project in Illinois was constructed on Interstate 57 in 1990. Two 152-m (500-ft) test sections were constructed as part of a SHRP SPS-6 experiment. The existing pavement, constructed in 1965, was 254 mm (10 in.) of JRCP on a granular subbase, with a joint spacing of 30 m (100 ft). A PB-4 resonant frequency breaker was used to rubblize the existing pavement. The 1987 average daily traffic (ADT) was 13,700 vehicles, with 20.5% trucks. In 2003, the ADT for this section was 20,800 vehicles, with 28.4% trucks. Design details for the sections of interest are as follows:

- 83-mm (3.25-in.) bituminous overlay of patched JRCP (control).
- 152-mm (6-in.) bituminous overlay of rubblized JRCP.
- 203-mm (8-in.) bituminous overlay of rubblized JRCP.

The CRS value for the test and control sections in 2003 was 6.5. This rating is still considered good, but the pavement is now at the point where rehabilitation will be needed in the near future. The primary distress in the control section is transverse reflective cracking. Two PCC patches have been placed in this section, along with some small areas of spray injection patching. Both rubblization sections now have extensive transverse and longitudinal cracking (mostly low-severity) that is developing into block cracking. The IRI value for the control section was 1.87 m/km (119 in./mi), compared to 1.40 m/km (89 in./mi) and 1.25 m/km (79 in./mi) for the thin and thick rubblized sections, respectively. Rutting for all sections was similar, with an average of 4.3 mm (0.17 in.).

Illinois Route 38 Constructed 1994

An experimental project was constructed on Illinois Route 38, a non-Interstate route with moderate traffic, in 1994. This project was 12.5 km (7.8 mi) in length. The existing pavement was a 229-mm (9-in.) JRCP with welded wire fabric and a joint spacing of 30 m (100 ft). Rubblization was accomplished using a PB-4 resonant frequency breaker. In 1993, the section had an ADT of 2,500 vehicles, with 8% trucks. The most recent count, from 2003, indicated the same ADT, but a slightly higher truck percentage of 11.4. The following test sections were constructed:

- 178-mm (7-in.) bituminous overlay of rubblized JRCP;
- 102-mm (4-in.) bituminous overlay over 76-mm (3-in.) open-graded base course over JRCP;
- 102-mm (4-in.) bituminous overlay of JRCP with minimal patching; and
- 64-mm (2.5-in.) bituminous overlay of JRCP with standard patching (control).

The CRS value in 2003 for the rubblized section was 5.9 and 5.6 for the other test sections. These values are at the high end of the fair category. Transverse cracking and block cracking are the primary distresses in all sections. Most of the cracks have been sealed. The rubblized section had slightly less cracking than the other test sections. Reflective cracking was apparent in the three non-rubblized sections. Grinding of transverse cracks had been performed on the section with minimal patching, indicating a continued deterioration of the underlying concrete pavement. The rutting values were low for all sections, at less than 2.5 mm (0.10 in.). The IRI values were similar for all sections, with an average of 1.85 m/km (117 in./mi).

Interstate 55 Frontage Road Constructed 1994

Another project was constructed in 1994 on a frontage road to I-55. The existing pavement was a 254-mm (10-in.) JRCP with welded wire fabric and a joint spacing of 30 m (100 ft.). In 1991, the section had an ADT of 1,650 vehicles, with 10% trucks. Rubblization was accomplished using a PB-4 resonant frequency breaker. A 127-mm (5-in.) bituminous overlay was placed on top of the rubblized pavement. No control section was built; however, there is a patch and overlay section immediately to the south of the project constructed the previous year that can be used for comparison.

The CRS value for the rubblized section was 6.3 in 2003. Extensive transverse and longitudinal cracking is now present, which has developed into block cracking in many areas. Some of the cracks are now medium-severity, and there are a few isolated areas of fatigue cracking in the outer wheel path. This section had the thinnest overlay of any rubblizing section. The pavement surface is slightly weathered, and no crack sealing or other maintenance has been performed. The IRI value was 1.89 m/km (120 in./mi). Rutting was low, at 1.8 mm (.07 in.).

The section to the south is performing like most typical patch and overlay projects. Reflective cracking is common at the underlying transverse joints, with some additional transverse and longitudinal cracking. Grinding has been performed at some of the transverse reflective cracks to improve ride. The CRS for this section was 6.1, and the IRI and rutting values were almost identical to the rubblized section.

Interstate 57 Constructed 1996

The first large-scale experimental project on an interstate was constructed on I-57 in 1996. The existing pavement was a 203-mm (8-in.) CRCP that had been previously overlaid. A multi-head breaker and Z-grid roller were used in the rubblization process. The 1995 ADT for this section was 13,600 vehicles, with 30% trucks. The 2003 ADT was 15,800 vehicles, with 34% trucks. The design details for the test sections are as follows:

- 152-mm (6-in.) bituminous overlay of rubblized CRCP;
- 203-mm (8-in.) bituminous overlay of rubblized CRCP;
- 127-mm (5-in.) bituminous overlay of existing CRCP (control); and
- 152-mm (6-in.) bituminous overlay of existing CRCP.

The existing overlay was removed from all sections. The overlays placed on the existing CRCP were thicker than the standard IDOT policy overlay, which was 82.6 mm (3.25 in.) at the time.

The CRS value for this project (all sections combined) in 2002 was 7.4, at the high end of the good range. Mid-lane longitudinal cracking has started to developed in all of the sections. Patching (PCC and bituminous) has been done on the control section, indicating deterioration of the underlying pavement. Mid-lane cracking is also more predominant in this section. The 152-mm (6-in.) rubblized section had an IRI value of 1.74 m/km (110 in./mi), and 4.8 mm (0.19 in.) of rutting. The thicker rubblized section had an average IRI of 1.22 m/km (77 in./mi), and an average rutting value of 4.2 mm (0.17 in.). The IRI value for the control section was 1.36 m/km (86 in./mi), with rutting of 0.12 in. The section with a 152-mm (6-in.) bituminous overlay of existing CRCP had an IRI of 0.92 m/km (58 in./mi), and rutting of 3.8 mm (0.15 in.).

Interstate 70 Constructed 1997

A portion of I-70 was selected for rubblization in 1997. The existing pavement was a 203-mm (8-in.) CRCP that had been previously overlaid. A multi-head breaker and Z-grid roller were used in the rubblization process. The 1997 ADT for this section was 17,500 vehicles, with 40% trucks. The design details for the test sections are as follows:

- 229-mm (9-in.) bituminous overlay of rubblized CRCP;
- 254-mm (10-in.) bituminous overlay of rubblized CRCP;
- 279-mm (11-in.) bituminous overlay of rubblized CRCP; and
- 140-mm (5.5-in.) bituminous overlay of existing CRCP (control).

The existing overlay was removed from all sections. The overlay placed on the existing CRCP was thicker than the standard IDOT policy overlay, which was 82.6 mm (3.25 in.) at the time.

A review of digital images collected in 2004 indicates that the pavement remains in excellent condition. A very small amount of mid-lane longitudinal cracking is present in the 229-mm (9-in.) rubblized section, along with one PCC patch and a few transverse cracks. The 254-mm (10-in.) rubblized section also has a few transverse and longitudinal cracks. The remaining two sections have no visible distress. The 2003 IRI values were low for all sections, with an average of 1.17 m/km (74 in./mi). Rutting was similar on all sections, with an average of 5.1 mm (0.20 in.).

Interstate 57 Constructed 1997

A third project on I-57 was constructed in 1997. The existing pavement was a 254-mm (10-in.) JRCP on a granular subbase. A multi-head breaker and Z-grid roller were used in the rubblization process. The 1997 ADT for this section was 10,400 vehicles, with 39% trucks. The 2003 ADT was unchanged, but the truck traffic had increased to 43%. The design details for the test sections are as follows:

- 229-mm (9-in.) bituminous overlay of rubblized CRCP (standard rubblization); and
- 229-mm (9-in.) bituminous overlay of rubblized CRCP ("coarse" rubblization).

The coarse rubblization section [only 152 m (500 ft) in length] was built to determine if there are any negative effects of using a more rapid rubblization procedure.

A review of digital images collected in 2004 indicates that the pavement remains in excellent condition. Some mid-lane longitudinal cracking was present, along with a couple of bituminous patches and a few small areas of bleeding. The average IRI for both sections was 1.30 m/km (83 in./mi.). Significant rutting occurred on this project within a year of construction. An investigation revealed that the rutting was due to a problem with the bituminous mixtures, and was not related to the rubblization. In 2003, the rutting averaged 9.0 mm (0.35 in.). At this point, there is no difference in performance between the standard and coarse rubblization.

Interstate 74 Constructed 1999

A rubblization project was constructed on I-74 in 1999. The existing pavement was a 178-mm (7-in.) CRCP. A multi-head breaker and Z-grid roller were used in the rubblization process. The 1999 ADT for this section was 12,200 vehicles, with 35% trucks. The 2003 ADT was 13,100 vehicles, with 31% trucks. The design details for the test sections are as follows:

- 279-mm (11-in.) bituminous overlay of rubblized CRCP; and
- 140-mm (5.5-in.) bituminous overlay of existing CRCP (control).

The overlay placed on the existing CRCP was thicker than the standard IDOT policy overlay, which was 82.6 mm (3.25 in.) at the time.

A review of digital images collected in 2004 indicates that the pavement remains in excellent condition.

A few sealed transverse cracks were present in the control section. The centerline and lane-shoulder joint had been sealed on both sections. The 2003 IRI for the rubblized section was 1.34 m/km (85 in./mi), with rutting of only 1.3 mm (0.05 in.). The IRI for the control section was 1.59 m/km (101 in./mi), with rutting of only 2.0 mm (0.08 in.).

Interstate 70 Constructed 2003

A 15.3 km (9.5-mi.) stretch of I-70 was rehabilitated using the rubblization method in 2003. This project was the first rubblizing project designed using a 30-year design period. The existing pavement was a 203-mm (8-in.) CRCP that had been overlaid two times. The 2003 ADT for this section was 19,800 vehicles, with over 50% trucks. The overlay thickness for this project was

445 mm (17.5 in.). A review of the digital images collected in 2004 indicated no distress after one year of traffic.

CONCLUSION

The IDOT experience with rubblization has been a positive one. Rubblization is both reliable and cost-effective. To date, all rubblization projects constructed in Illinois have performed as well as, or better than, control sections. The rubblization process has been used successfully on both interstate and non-interstate routes (*2*). Some of these routes carry very heavy traffic, including high percentages of truck traffic. Experience from early projects has been used to develop thickness design procedures and construction guidelines for future projects.

Rubblization is not yet a standard rehabilitation practice included in IDOT's pavement selection process. Rather, it remains a special design that requires approval from IDOT's Bureaus of Design and Environment and Materials and Physical Research. The main factors to consider in project selection are the condition of the existing pavement and subgrade strength. Care must be taken on very thin pavements to ensure that enough support will be provided for construction equipment after rubblization. Rubblization has been found to often be the most viable option when patching quantities exceed 10% to 15%. Other factors, such as overhead clearances, transitions to mainline structures, utilities, proximity to buildings or other structures, and location and condition of underdrains must also be taken into account.

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