(2-in) overlay. Hence it can be concluded that, solely from the standpoint of cost, overlay is not cost-effective. Further, neglecting inconvenience and safety during patching operations, a cost-effective means would be to merely let breakups occur and to patch them as needed.

Undersealing also halted further deterioration and was done at a cost of $1020/100 m, which was less than the cost of maintaining the control sections. Hence it was concluded that this was the most cost-effective means of maintaining this pavement. The primary mode of distress for this pavement was pumping caused by high deflections and an impervious subbase. Undersealing effectively corrected this defect.

For this analysis it was assumed that all breakups would be repaired during the next summer if the failure had occurred during the winter or spring or during the same summer if the failure had occurred during the summer. It is known that all the breakups were not patched by using concrete. In some cases, temporary measures were taken, and the breakup still exists on the test pavement. Hence the economic analysis reported here is conservative.

As in any engineering project, the decision relative to type of maintenance to be applied must consider all factors and not merely cost. For this particular pavement the question of the desirability of expending large sums of money for complete removal of the possibility of further distress is moot.

Perhaps the primary conclusion to be reached from studies of this type is that, to be effective from the point of view of both performance and cost, maintenance procedures must be evaluated in the light of the defects that are to be corrected and planned accordingly. It is axiomatic that in an energy-constrained environment, design and maintenance should be carefully evaluated and based on sound engineering principles.

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Patching Jointed Concrete Pavements

K.H. McGHEE

The experiences of the Virginia Department of Highways and Transportation in the repair of jointed concrete pavements over the past 10 years are summarized. Persons involved in pavement repair are cautioned to give careful consideration to pavement geometrics and dynamics. Also emphasized is the need for proper consolidation, adequate quality-control procedures, and care in the selection of repair materials. The conclusion is that serviceable repairs to concrete pavements can be achieved if these factors are given full consideration.

In the repair of jointed concrete pavements, the choice of the procedure to be used must include a consideration of how the pavement responds to its environment. The two major components of this environment are traffic loadings and climatic conditions.

The response of the pavement to traffic loadings is within the purview of the design activity and will not be considered at length here. It is evident, however, that when a pavement no longer provides the service for which it was designed, the selected maintenance procedure should restore it to the original level of service. For example, when pavement support conditions change so that wheel loads become more destructive, the maintenance engineer must attempt to restore the original support conditions through undersealing, slab-jacking, and improving the drainage.

The response of the pavement to climatic conditions also is treated in the design analysis, in which curling, warping, and joint movements are considered. Maintenance personnel, however, generally seem to be much less aware than designers are that the pavement is more or less in constant motion and that service conditions and repair techniques must make allowances for this motion. As a result of this lack of awareness, one often sees repairs that are incompatible with service conditions, e.g., unjointed patches on jointed pavements.

Instances in which pavement movement of one type or the other must be accommodated will be pointed out in succeeding sections of this paper. For now, it is sufficient to emphasize that pavements are dynamic and that, whether one is dealing with design, construction, or maintenance, those dynamics must be considered. From the standpoint of pavement repairs, one can state simply that the repair must be geometrically compatible with the dynamic pavement system.

DISTRESS MECHANISMS AND MANIFESTATIONS

Joint failures of various types probably lead to the necessity for much more maintenance than do problems with the slabs. Numerous factors can contribute to joint failures, and the failures can be manifested in several ways. Because the repair procedure to be used is often dependent on the nature of the distress, some of the mechanisms and manifestations of joint failures are discussed below.

Metal Inserts

Tubular metal inserts were used to form transverse contraction joints in many of the concrete pavements constructed in the early 1960s. Placed in the fresh concrete, these devices provided a weakened vertical plane at which contraction joints would occur. After the concrete had hardened, the inserts were crimped downward and a poured sealant was introduced.

A survey of these metal joint inserts in 1968 by the Virginia Highway and Transportation Research Council (VHTRC) found their condition to be fair to rusted and badly rusted after four to six years of service. Because the inserts were anchored by small flanges that extended into opposing faces of concrete at the contraction joints, they created weakened planes that were later aggravated by corrosion products. Weakened planes of this type, not initially evident on the surface, propagate under repeated wheel loadings and eventually intercept the pavement surface at 6-12 in from the joint face (Figure 1).

Figure 1. Semicircular spall caused by corrosion of insert.

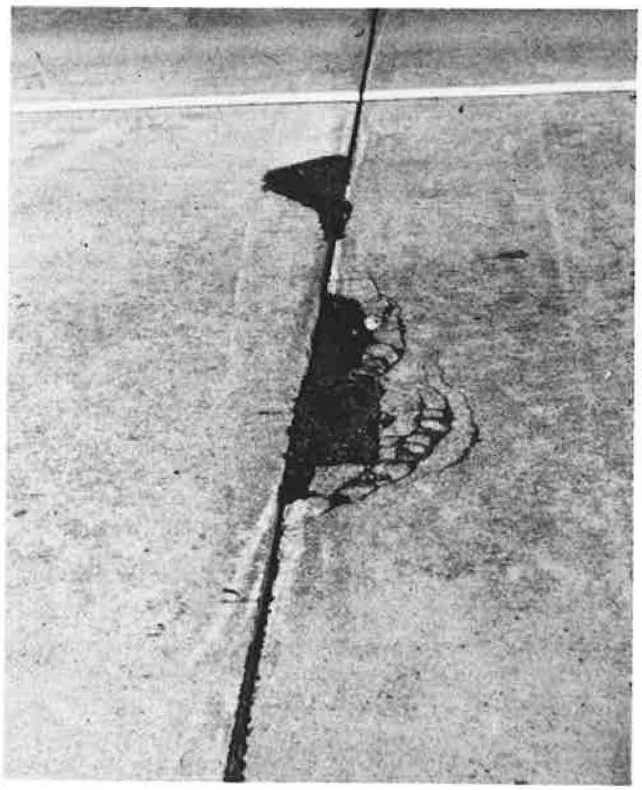


Figure 2. Conditions prior to blowup.

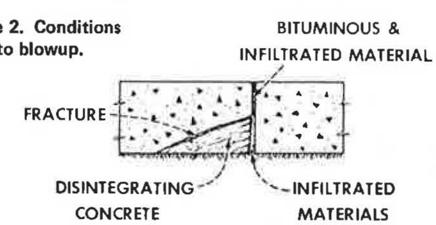
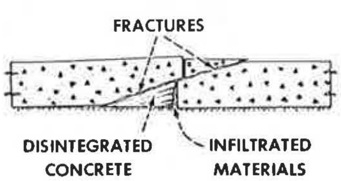


Figure 3. Blowup in which characteristic fractures and pavement uplift are shown.



Subbase and Shoulder Materials

Most surface water can be expected to find its way to the underside of pavement slabs through the edge joint, which is difficult to seal. Recent studies have shown that 70 percent of the surface water that flows over a crack that is only 1/32 in wide will enter the crack and proceed to the lower pavement layers (1). Depending on the permeability of the subbase and shoulder materials, this water may remain for significant periods of time after rainfall has ceased.

As wheel loads cross the joint, pressures on trapped water are reduced under the approach slab and increased under the leave slab. A net deposition of soil particles is caused under the approach slab by this pumping action. The accompanying faulting produces a less satisfactory pavement from the standpoint of rideability but, more important, it causes increased stress at the joint. Pumping may result in a migration of fine, incompressible material into the contraction joints from their outer edge and bottom portions. Unchecked, the reservoir can extend toward the pavement centerline while progressively undermining the structure and infiltrating the remaining bottom portion of the transverse joint. Early indications of pumping are soil staining of the shoulders and, later, faulting of transverse joints.

Joint Sealants

The infiltration of incompressible materials, water, and deleterious chemical agents such as deicers into the longitudinal and transverse joints of a concrete pavement promotes conditions that hasten the need for repair, reduce the riding quality, and generally shorten the useful life of the pavement.

Incompressible materials restrict the free movement of the joint (expansion and contraction), which results from variations in temperature and moisture, and give rise to localized high compressive stresses that may cause blowup of the pavement.

A widely accepted theory of the development of blowups was given by Giffin in 1943 (2). The first stage of failure occurs when compressive stresses become high enough to fracture the concrete below the surface but no distress is evident on the pavement surface. This condition is shown schematically in Figure 2 [adapted from Giffin (2)], in which it may be seen that disintegrating concrete at the lower joint corner forms an inclined plane with the undamaged concrete above. As the compressive stresses increase, the situation changes to that indicated in Figure 3 [adapted from Giffin (2)], in which one slab has moved up the inclined plane with sufficient force to shear the corner of the adjacent slab. In this manner, the observed blowup characteristics of one slab that is overriding the other are generally explained.

The succeeding sections of this paper deal with the repair procedures used in Virginia. All procedures used fall into two broad classifications--partial depth and full depth. Procedures in both classifications have evolved over approximately the past 10 years, primarily as the result of trial and error but with a good deal of attention to engineering requirements.

PARTIAL-DEPTH REPAIRS

Successful partial-depth repairs depend to a great extent on the type of material used in patching.

Many concretes can be used in partial-depth, cast-in-place pavement repairs on the basis of satisfactory laboratory evaluations. For the successful employment of any concrete in the field, however, there are numerous procedural factors that, if ignored, can adversely affect the service life of a patch. These procedural factors are encountered during the preparation of the pavement for patching and during the installation of the repair concrete. The modification of repair procedures to eliminate the destructive effects of these factors has resulted in durable patches that have service lives that currently exceed five years and have a reasonable expectation of a number of years of additional service.

Other factors that affect the service life of pavement patches are traffic intensity and weather conditions. Requirements dictated by these factors can normally be satisfied by selecting concretes on the basis of satisfactory performance in laboratory evaluations of strength and durability.

Location of Unsound Concrete

A visual survey can provide a reasonable initial estimate of the extent of needed repairs on a roadway. However, the actual extent will always be greater, since a plane of rupture extends beyond the visually identified limits of joint spalls and in the early stage of spall formation the weakened plane may exist even though there are no visible indications.

The technique that has been used to identify the total area affected by spalls relies on hammer soundings. A ball peen hammer is tapped on the pavement surface; areas that issue a clear ringing sound are judged to be serviceable, whereas those that emit a dull sound are considered to be weakened by ruptures and are marked for removal.

Joint spalls usually affect an area that extends 6-12 in from the transverse joint; however, experience has shown that it is advisable to remove the concrete for a minimum of 12-18 in from the joint. The areas removed along the joint are typically 1-3 ft in width; however, the area may extend along the full width of the lane.

Sawing

A saw cut that has a minimum depth of 1 in should be made along the perimeter of the pavement area to be removed. The area removed should be rectangular to provide a vertical face against which to cast the repair concrete, to give an aesthetic appearance to the finished patch, and to prevent feather edging and resultant raveling of the repair concrete along the perimeter.

Removal

The partial-depth removal of the designated pavement areas can be accomplished quickly by using jackhammers. The removal can be started by using an 80-lb hammer but should be finished by using a 20-lb hammer to allow removal of all loose concrete in the area and prevent damage to the underlying and surrounding concrete.

The depth to which the concrete is removed typically varies from 1 to 4 in and averages approximately 3 in over the majority of the patch areas. Removal of the concrete by this technique provides a very irregular surface that is ideal for achieving mechanical interlock between the cast-in-place repair concrete and the existing pavement.

The occurrence of spalls in areas adjacent to partial-depth patches has been practically eliminated since inspectors and maintenance supervisors have implemented the above procedures for locating, sawing, and removing unsound concrete.

Occasionally in partial-depth patching, the full depth of the slab may be removed. This is particularly true for spalls that occur at the corner of the slab adjacent to the shoulder material (3). However, if full-depth removal is consistently needed to eliminate unsound concrete in this and other areas of the transverse joint, a full-depth repair technique is probably needed for the roadway (4).

Patch Installation

Regardless of the type of cast-in-place concrete to be used in a patch, the installation must be made in similar logical steps. In the following paragraphs these steps are discussed and, when appropriate, examples are cited to demonstrate the problems encountered if the steps are not performed properly.

Concrete Production

The volume of concrete required for partial-depth patches may vary up to several cubic feet. The use of ready-mix trucks for the supply of fresh concrete is therefore not desirable, since the maximum allowable mixing times for specified temperature ranges would be exceeded, even with normal type 2 cement concrete, after only a small portion of the batch was used.

An increasingly popular method of preparing concrete for partial-depth repair operations is to use a continuous mixer in which the materials are continously batched by volume. The auger feed on such a mixer can be stopped when the correct amount of concrete has been discharged, and a minimum of concrete is wasted. The guidance provided by ASTM C685 is helpful when a continuous mixer is used. This equipment will not always be available, however, and the size of the job may not be sufficient to effectively utilize its capacity.

In such instances, small portable mixers of about 2-ft^3 capacity have been effectively used, particularly with prepackaged patching materials in which water is the only ingredient to be added on the job (5).

Forming

Prior to the placement of repair concrete in a prepared area, it is important that all needed forms be in place. The three locations that require attention are the centerline and transverse joints and the shoulder.

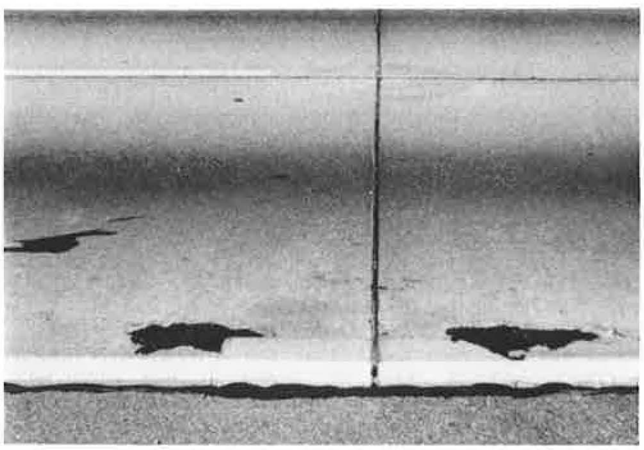
The centerline joints between pavement lanes are provided to prevent warping stresses. The patch shown in Figure 4 was cast directly against the adjacent slab at the centerline joint, and raveling and minor spalling resulted from movement at this location due to normal warping stresses. This problem can be overcome by inserting a polyethylene strip along the centerline joint prior to casting the repair concrete.

A large number of partial-depth patch failures have resulted from using no forming or inadequate forming at the transverse joint. Figure 5 shows two patches cast together across the transverse joint. Before the transverse joint could be sawed and sealed, the slab movements had disrupted the patches.

Studies have shown that many patch failures have resulted from failure to form the total depth of the

Figure 4. Raveling and minor spalling of partial-depth patch cast without forming at pavement centerline.

Figure 5. Spalling of adjacent pavement that resulted from compressive stresses transmitted through patches.



patches at the transverse joints. The lower portions of the partial-depth patches were therefore in contact with the adjacent slabs and the patches were subjected to the destructive effect of hydrothermal slab movements (Figure 5).

If shoulder material adjacent to the pavement is removed by erosion or disturbance during removal of the concrete, a vertical form should be placed parallel to the shoulder to prevent the repair concrete from filling the void and forming a key into the shoulder. Otherwise, the normal hydrothermal movements of the slab can cause the patch to be disrupted by resistance from the stationary shoulder.

Consolidation and Bonding

In order for repair concrete to become an integral portion of a slab, it must fill the space created by the removal of deteriorated concrete, and it must develop an adequate bond to the existing hardened concrete. Both requirements are related to the consolidation of the fresh concrete, since adequate consolidation should produce a patch that has maximum density and should provide the greatest amount of contact between the fresh and existing concrete for development of bond and for mechanical interlocking.

Consolidation of concrete is the process of removing randomly occurring volumes of entrapped air. The remaining mass, which contains uniformly distributed entrained air volumes, approaches a theoretical maximum density that can be determined by the volumetric proportions of the constituents.

Methods employed in Virginia to consolidate concretes in partial-depth patches have been manual rodding and tamping and the use of vibrating screeds or internal vibrators. Each of these methods has advantages and disadvantages, which will not be discussed here except to state that, of these methods, internal vibrators have given the most uniform and best-quality consolidation. Also, since standard models of internal vibrators seem to be more readily available among contractors than are the small versions of vibrating screeds, the trend in Virginia has been to encourage the proper use of internal vibrators for the consolidation of concretes in pavement patches.

Figure 6 shows a core drilled from the central portion of a patch that emitted a hollow sound when struck with a hammer. The large void in the zone between the repair concrete and the underlying old concrete is clearly indicative of inadequate consolidation. This patch and others that emitted a similar hollow sound when struck failed by cracking and spalling after being in service for less than one year. These patches were installed by using the manual rodding and tamping method of consolidation.

It has been demonstrated that the elimination of visible voids at the interface between the repair concrete and the existing pavement can readily and consistently be accomplished by using an internal vibrator. An internal vibrator that has a head diameter of 1 in has been successfully used for consolidating repair concretes. After a patch area has been overfilled with enough fresh concrete to allow for a reduction in volume during consolidation, the vibrator is held at a small angle (15-30°) from the horizontal and moved through the concrete in such a way that the full patch is vibrated. The speed at which the vibrator is moved is determined by observing the surface of the concrete. Adequate consolidation is indicated when there is no further reduction in the concrete depth, the emergence of air bubbles ceases, and a smooth layer of mortar occurs on the surface. A typical core section from a patch that received this treatment is shown in Figure 7, in which it may be observed that the irregularities along the interface with the existing concrete are completely filled and that the repair concrete is not segregated.

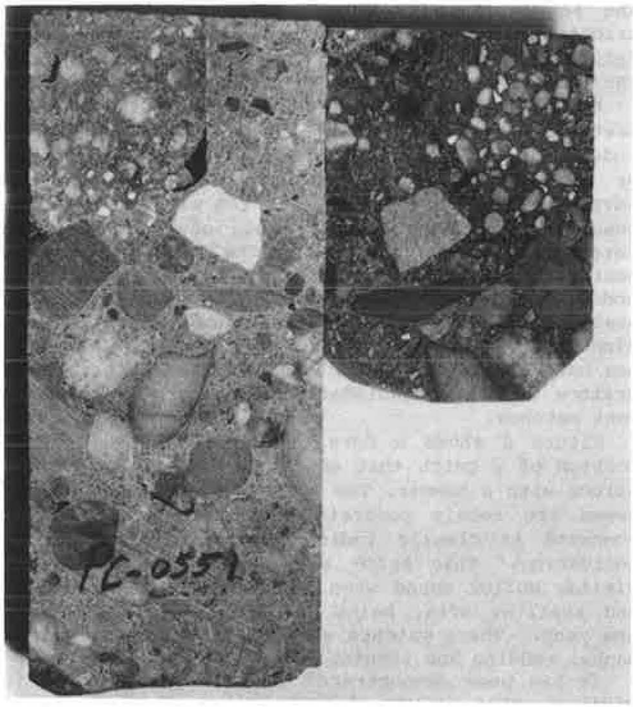
Shear-bond tests of four systems used in Virginia yielded the results given in Figure 8. The resulting strength may be interpreted on the basis of published data that show that strengths of 200 psi are adequate for good performance. Note that all four systems had developed excellent bond by the age of 25 days; however, only cement slurry had adequate bond at 24 h of age.

Screeding and Finishing

Cast-in-place patches can be manually screeded to the proper grade by using a stiff board. The small size of the patches normally allows space for the board to rest on the adjacent surface of the slab being repaired so that the screed can advance in a direction perpendicular to the transverse joint. If large sections of the transverse joint are being repaired or if repairs are being made on both sides of the joint, the patch can be screeded across the joint by using appropriate precautions to avoid disturbing the form inserted in the transverse joint.

Hand troweling of the patch surface removes any

Figure 6. Incomplete consolidation in vertical section of core (core dimensions, 4x9 in).



remaining irregularities and, most importantly, provides a good finish for the edge of the patch adjacent to the transverse joint into which a sealant must be installed after hardening of the concrete. A textured finish can easily be applied to the patches by using a broom that has stiff bristles so that the patches will have a texture similar to that of the surrounding concrete.

Curing

The application of curing materials to the surface of patches is important, because moisture losses can occur quickly from the relatively large surface of these shallow placements. Moist burlap and polyethylene must be removed when the roadway is opened to traffic, and the sudden drying can cause shrinkage cracks. The most effective cure can be provided under hot-weather conditions by using a white-pigmented curing compund, since that reflects radiant heat, allows the heat of hydration to escape, and can provide curing protection for several days until it has been worn away by traffic. When patching is done under cold-weather conditions, the loss of heat can be reduced by the addition of insulating materials such as blankets, straw, sand, or burlap or heat may be supplied from an external source if conditions are severe.

Performance of Partial-Depth Repairs

Studies on one heavily traveled toll road on which several thousand partial-depth repairs had been installed by using the procedures described above showed that more than 80 percent of the repairs were in excellent condition five years after installation. In this instance, five rapid-curing materials (including $CaCl_2$-accelerated conventional concrete) were used successfully, and lanes were reopened after about 6 h of curing. However, inspection and quality control were very stringent on this project, so that one can conclude that under nearly ideal conditions good repairs can be realized by using a variety of materials.

On most projects, quality control and success have been less dramatic, and up to 50 percent of the repairs have failed in about two years. Most failures have been related to (a) poor quality control of concrete, (b) poor consolidation, (c) failure to remove all unsound concrete, and (d) geometric incompatibility between the repair and surrounding pavement features.

FULL-DEPTH REPAIRS

Full-depth repair of portland cement concrete (PCC) pavement as addressed in this paper refers to one of two procedures:

1. Full-depth restoration, in which the existing pavement joints (which includes load-transfer devices) are restored in their original positions, and
2. Full-depth replacement, in which no effort is made to restore the original transverse joints, two transverse joints are provided, and load transfers may or may not be restored. In this case, both cast-in-place and precast repairs have been used effectively. Only cast-in-place methods will be discussed.

Cast-in-Place Restoration

Virginia pavements that have a small number of joint failures have been repaired by restoring the transverse joints along with the placement of cast-in-place concrete.

Concrete Removal

Transverse saw cuts approximately 1.5 in deep are made along the two limits of the repair parallel to the transverse joint. Jackhammers are used to remove the concrete to the full pavement depth. This procedure allows ties to be made to the existing reinforcing fabric located at the 2-in depth, and it further produces irregular faces against which the repair material can be cast to provide load transfer through aggregate interlock. About 6 in of the protruding steel is left in place to provide a tie-in with the repair concrete.

Repair Concrete

Both high-alumina cement (HAC) concrete and high-cement-factor type 3 PCC have been used successfully in these repairs. However, experience has shown that HAC concrete does not perform as well as had been hoped because of the destructive effects of the very high early heat evolution and subsequent cooling. Conventional concrete that has high early strength is now the preferred mixture.

Installation

The precut steel-fabric reinforcement and prefabricated dowel assembly used in this type of repair are shown in Figure 9. The reinforcement is tied to the existing reinforcement that protrudes from the slab. The dowel assembly is fixed to the subbase and includes a bituminous-impregnated felt strip to form the contraction joint through the full slab depth.

Placement of the cast-in-place concrete includes planned considerations for consolidation, finishing, and curing. Finished repairs are ready for opening to traffic in 6-8 h. The darker-colored repair concrete can be observed in Figure 10. Most of the repairs do not exceed 8 ft in length and present an

Figure 7. Typical core section from patch in which internal vibration was used.

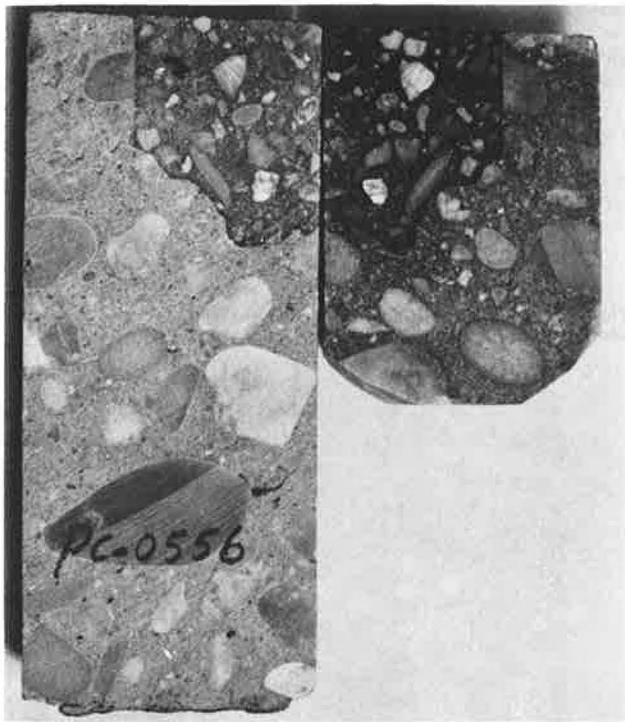
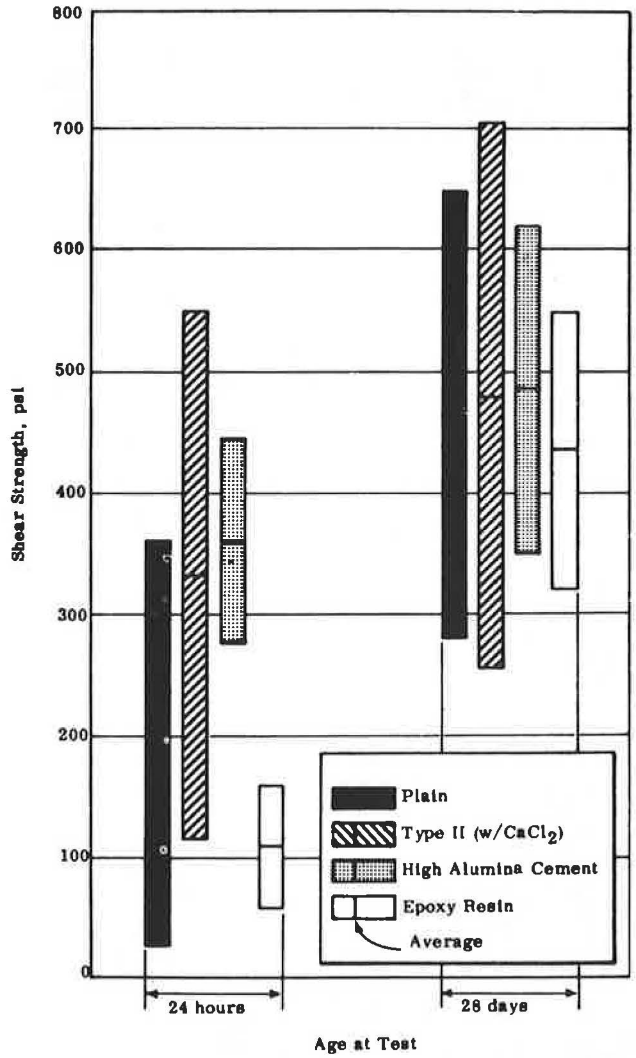


Figure 8. Shear-bond test results for four bonding systems.



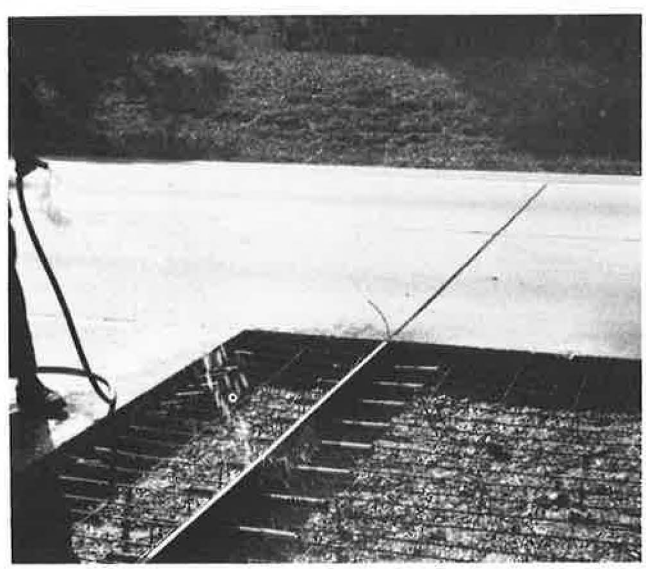
acceptable appearance from a moving vehicle.

Performance

Thirteen initial repairs of the type shown in Figure 10 have performed satisfactorily for more than four years. The functioning of the restored transverse joints and the proper tie-in at the construction joints between the repair concrete and existing pavement slabs were studied. Movements in several of the restored contraction joints and construction joints were instrumented by using gage plugs and monitored to determine whether they were functioning as they should. Deviations from expected behavior would have served as an early warning that the repair procedure needed modification. Movements of the restored contraction joints average approximately 10 times those in the construction joints at each of the repairs. The movement of the construction joints compared well with that of original construction joints on similar pavements. The tightness of the construction joints can be attributed to the careful tie-in of reinforcement mesh between the old pavement and the repair concrete. The vertical section of a core drilled down through the construction joint revealed the overlapped transverse bars of the mesh as seen in Figure 11. The excellent potential for load transfer can be seen in the mechanical interlock between concretes in that figure. The favorable irregular face in the old pavement was created by the concrete-removal technique described earlier, and good bonding was achieved at the construction-joint interface by adequate consolidation following the application of a bonding slurry.

Although, as indicated above, the cast-in-place restoration has performed well, it has fallen into disfavor because of its expense, which is primarily associated with restoring the dowel assembly. For this reason, cast-in-place replacement, as discussed below, is the most frequently used full-depth repair procedure. Bid experience has shown that the former

Figure 9. Precut steel-fabric reinforcement and prefabricated dowel assembly in place.



is about 50 percent more costly than the latter.

Cast-in-Place Replacement

The cast-in-place replacement procedure used for most full-depth repairs at transverse PCC pavement joints is depicted in Figure 12. This approach has become commonly known as the inverted-T method.

Load Transfer

It can be observed in Figure 12 that the traffic loadings for this repair situation are transmitted directly from the existing pavement slabs on either end of the repair area to the repair concrete through the inclusion of 6-in undercuts in the subbase material. The volume of the undercuts is filled along with the volume created by removal of the deteriorated concrete and approximately 6 in of the subbase material. The resultant monolithic mass of repair concrete serves to carry traffic loadings directly on its surface and from the adjacent slabs.

In some instances, in which cement-stabilized subbases underlie the pavement to be repaired, no undercut is feasible and repairs have been placed at full depth without the reestablishment of load transfer. In these cases, a repair that is a minimum of 6 ft long is provided on the assumption that the more-massive repair will be less subject to displacement under wheel loads. Surprisingly, the problems associated with this type of repair are those of upheaval due to pumping action of the adjacent slabs rather than those of depression under load. A contract now being developed will use a nonvertical saw cut on either side to provide approximately a 1-in undercut of adjoining slabs so those slabs will tend to rest on the repair concrete.

Concrete Removal

The 2-ft minimum length for concrete removal on either side of the existing transverse joint indi-

Figure 11. Core from construction joint between HAC repair concrete (left) and old pavement (right).

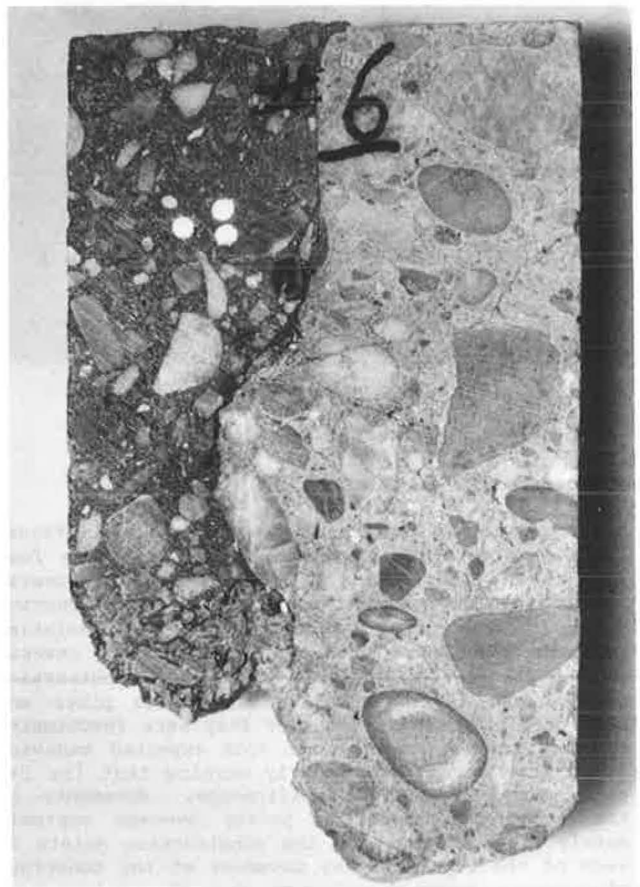


Figure 10. Hardened cast-in-place restoration made by using HAC concrete.

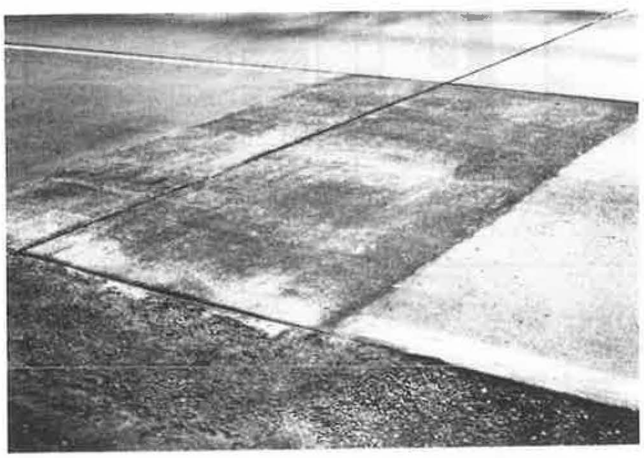
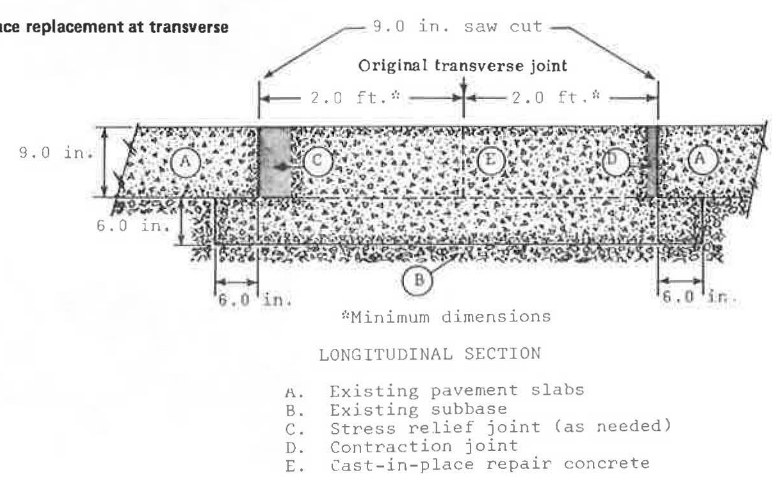


Figure 12. Typical details of cast-in-place replacement at transverse joint.



cated in Figure 12 is based on field experience. It has been observed that subsurface fractures of the joint face that may not be visually detected from the pavement surface can extend more than 1 ft into the slab before they intersect the subbase interface (3). It is therefore appropriate to designate minimum limits for pavement removal for this and other procedures for full-depth pavement repairs.

The pavement-removal technique described was also used in this procedure. Following removal of the subbase material, no further preparation of the area was necessary since the cast-in-place concrete could conform to irregularities in the subbase.

Repair Concrete and Joints

The concrete mixtures described earlier for cast-in-place restoration are used in this method of repair. Transverse joints are treated as if they were contraction joints on new construction. Essentially, this means that they are resawed and sealed by using a preformed seal or a good-quality poured sealant that has the appropriate shape factor.

Performance

Repairs of this type number more than 1000 and have been in service for up to five years. In some contracts, most are in excellent shape; in others, up to 50 percent have failed, sometimes in less than six months. Most failures have been attributable to one of the following causes:

1. Use of HAC concrete, which becomes excessively hot and results in shrinkage cracks that later spall;
2. Inadequate consolidation in the undercut area, which triggers early failure of the load transfer so that adjoining slabs become depressed and sometimes fail;
3. Failure to underseal the adjoining pavement so that it fails outside the limits of the repair; and
4. Poor quality control of concrete, particularly with mobile mixers in which water control is by judgment or slump only and is highly variable.

CONCLUSION

In conclusion, it may be stated that Virginia experience has shown that durable repairs to jointed concrete pavements can be achieved if the engineering requirements of the repair and the engineering characteristics of repair materials are properly accommodated in the chosen repair procedure. Accordingly, most failures have been seen to occur when the above factors did not receive due consideration or when quality control of repair activities was lacking. Such failures are enormously expensive because of the costs for traffic control associated with repairs. For this reason, it behooves the highway engineer to ensure that repairs are carefully planned and that the best inspection and quality control possible be provided on repair activities.

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Highway Pavement Repairs by Using Polymer Concrete

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As traffic, particularly truck traffic, has increased on the primary highway system, the need for rapid repair methods has increased. Polymer concrete (PC) has been used effectively for rapid repair of portland cement concrete pavements, both jointed and continuously reinforced. Basic formulations for PC are presented and both user-formulated and prepackaged systems are described. Methodology for the repair of cracks, joints, spalls, and punchouts is illustrated. The results of several PC repairs are presented. Deflection measurements that illustrate the restoration of structural integrity, which means a prolonged pavement life, are given.

Many high-volume highways in the United States were constructed by using portland cement concrete (PCC) as the pavement surface. Now that traffic and allowable axle loads have increased, many of these facilities are approaching the limits of their design life, which usually means increased maintenance. The need for rapid, permanent types of repairs has led to the development of polymer concrete (PC) as a repair material.

The use of PC is not new to highway repairs. It