CRCP IN VIRGINIA
LESSONS LEARNED

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ABSTRACT

This paper presents the lessons learned from the performance of continuously reinforced concrete pavement (CRCP) in Virginia. The approach was to identify the most critical distresses, establish the failure mechanism, and implement the best practice for extended service life with minimal maintenance. Distress included map cracking, localized areas of broken concrete, punchouts, longitudinal cracking, and sags. The failure mechanism of each distress was established using pavement condition surveys, forensic investigations, coring, and shoulder trenching. The experience gained was translated into changes to include using 4.2-m (14-ft) truck lanes, thicker pavement, a higher percentage of reinforcing steel, steel placed on chairs, transverse steel, larger size aggregate, a lower water/cementitious material ratio, mineral admixtures, adequate consolidation, and dense asphalt drainage layer, supported by an effective edgedrain system. These changes were complemented by an emphasis on quality construction and a smoother ride. These changes were implemented on our most recent project with very promising results.

INTRODUCTION

Concrete pavements have been constructed in Virginia since 1913. Initially, plain concrete and then reinforced concrete pavements were built. The first continuously reinforced concrete pavement (CRCP) built by the Virginia Department of Transportation (VDOT) was built in late 1966 and early 1967 on I-64 around Richmond (McGhee, 1969). Most of the concrete

pavements have performed satisfactorily during their intended service life and beyond. However, some have not served for their life expectancy.

The key to attaining a long lasting, safe, and economical CRCP or any pavement is in learning from its performance. Pavement performance is dependent on the characteristics of the materials, the pavement design, and the construction practice used. Therefore, it makes good sense to trace the impact of these elements to identify deficiencies and then to develop a plan of action leading to a high-performing CRCP.

BACKGROUND

Currently, VDOT wearing courses are required to be non-polishing aggregates, which are siliceous. Initially, concrete pavements with 50-mm (2-in) Nominal Maximum Size Aggregate (NMSA) were built. In Virginia, the availability of non-polishing aggregates for pavements has been a concern since most quarries are west of I-95 and only gravel sources are available in the eastern areas. Urban sprawl and interstate construction have either consumed or concealed the gravel aggregates. The larger gravel aggregate has provided good performance, but because of its scarcity, VDOT uses more crushed stone to save money. With the introduction of the slipform paver in the 1960s, a 25 mm (1 in) NMSA was used because the paver could not place larger aggregates. The smaller size also minimized segregation in aggregate stockpiles.

The scarcity of aggregates has affected the thickness of concrete pavements. Initially, CRCP with a thickness of 200 mm (8 in) was acceptable, based on the Portland Cement Association (PCA) design method, if a stabilized base is used, compared to the 225 mm (9 in) of concrete pavements on plain aggregate. However, thicker pavements were later adopted for improved performance.

The use of the radial truck tire with a higher tire pressure in the 1970s and the increase in the legal axle load by the early 1980s increased the stresses in the pavement and resulted in major distress in both new and old pavements. In the 1970s, the high speed of trucks and the use of three lanes or more per direction made water expulsion under tires difficult, creating hydroplaning that resulted in increased wet traffic accidents. To improve drainage, VDOT began grooving its existing pavements. This further reduced the effective thickness of the CRCP, since VDOT was sawing concrete pavements, and further increased the shear stress concentration in the pavement, contributing to delamination at the level of reinforcing steel. This is because shear stresses have parabolic distribution, with the maximum value at the centroid of the section (Popov, 1964).

In early slip form operations, the inability to feed steel through tubes and the interference of the chairs with truck traffic led to two-stage construction. Steel was placed on top of the first layer when concrete was plastic. A delay in the placement of the second layer could result in a cold joint, leading to delamination.

Although specifications allow the use of 335 kg/m^3 (564 lb/yd^3) of cement, contractors have continuously chosen richer mixes for high early strengths to enable the early use of the pavement by haul trucks. Haul trucks have high gross weights and axle weights that stress pavements

unduly at an early age. Rich mixes also contribute to high shrinkage, leading to more cracking. The volumetric changes attributable to temperature and moisture have also contributed to punchouts and delamination (Zollinger, 1999).

The experiences gained in Virginia resulted in new approach to CRCP design and construction. The approach included identifying the most critical distresses, establishing the failure mechanism for each distress, and implementing the best practice to construct CRCP using an improved concrete mix, adequate consolidation, thicker slabs, and a stable yet drainable layer supported with an effective edgedrain system. The implementation required the cooperation of personnel from the materials, research, pavement design, and the paving industry. The reward was a quality CRCP with a promising performance, as confirmed by the initial results.

DISTRESS IDENTIFICATION AND FAILURE MECHANISMS

Distress identification was based on extensive field visits and consistent concrete pavement condition surveys. Only critical distresses that resulted in early failures are noted in this paper. Failure mechanisms were established based on pavement condition surveys, coring, shoulder trenching, laboratory testing, and historical data.

Map Cracking

Map cracking was identified in at least two interstate projects (I-64 and I- 295). For example, on I-64, map cracking totaling 10,241 m^2 (12,248 yd^2) was determined in a 1989 VDOT survey of a 14.5-km (9-mi) section with four lanes. The CRCP was constructed in 1971, had a thickness of 200 mm (8 in), and was supported on 150 mm (6 in) of a cement-treated aggregate base without edgedrains. The crack pattern had a predominant longitudinal direction and was interconnected by finer transverse or random cracks. The cracks might go deeper into the concrete than normal map cracking. The cracks in the wheel paths were the first to crumble, as shown in Figure 1. On I-64 westbound lanes near Charlottesville, VDOT replaced 9.6 km (6 mi) of CRCP because of severe cracking beyond repair. On I-64 in New Kent County and on I-295 near Richmond a total of 37 km (23 mi) were overlaid. All these pavements were close to their 20-year service life but with different levels of distress.

Map cracking with white gel was characterized as alkali silica reaction (ASR). This failure mechanism was challenging since it required an understanding of cement production after the implementation of particular environmental regulations, leading to higher alkalinity in the cement. In addition, the chemical reaction between the reactive aggregate and the high alkalinity cement in the presence of water was not easy to figure out. The cracks stay tight even after the formation of the white gel; the presence of water then leads to its expansion, and the concrete breaks into pieces.

Localized Areas of Broken Concrete

A cluster of closely spaced transverse cracks 200 to 450 mm (8 to 18 in) was evident as shown in Figure 2. The distress was more evident where the cracks intersected, creating a Y shape. The concrete was broken into pieces mainly at the wheelpaths, as shown in Figure 3. For example, in

the 14.5-km (9-mi) section mentioned previously, there was 13,830 m^2 (16,540 yd^2) of spalling and potholes with broken concrete and edge punchouts.

Localized areas of broken concrete were caused by the closely spaced cracks, which had a wide opening (>1.5 mm) (>1/16 in) and spalling. Cracks and spalls were the result of the delamination shown in Figures 4 and 5. Delamination occurred at mid depth of the pavement at the level of the reinforcing steel. The shear stress in slabs has a parabolic distribution, with the highest stress at mid slab, which could explain the delamination. The CRCP in Virginia did not show the large amount of distress until the early 1980s, shortly after radial tires increased the concentration of the load on the CRCP and the legal axle loading increased. The delamination has not been seen in the 225-mm-thick (9-in-thick) jointed reinforced concrete pavement. It became a real problem with the 200-mm-thick (8-in-thick) CRCP. The value of the maximum shear stress is reduced with increased slab thickness. A report from Texas described similar delamination in CRCP 350 mm (14 in) thick (Merritt et al., 2001). Thickness may not be the only issue. The curling action of the concrete because of drying and temperature changes may be the most significant contributor. The selection of ingredients and their proportioning affect the shrinkage and curling. The dissimilarity between the reinforcing steel and the concrete because of thermal and drying shrinkage may be a contributory factor in causing the delamination to be located at the level of the steel. The current design in Texas is for the steel to be in two layers rather than one; this would have the effect of distributing the dissimilarity of the steel and concrete and would take the steel away from the location of highest shear stress. Some of the delamination in Virginia was attributed to early slipform paving in which the concrete was placed in two layers with the steel being placed in between. If the lower layer of concrete was allowed to dry or set before the top layer was placed, the strength of the bond would be very low because of the creation of a cold joint. After the concrete slab has delaminated, it separates into two layers at the reinforcing steel. Now the axle loading is carried by the upper layer making it easy to break mainly in the wheelpath of truck. The presence of closely spaced cracks and large entrapped air resulting from inadequate consolidation causes the concrete to break into pieces without evidence of pumping or staining. Water then infiltrates to the bottom layer causing it to fail in a similar fashion to punchouts.

Edge Punchouts

This distress is similar to the localized areas of broken concrete except that punchouts occur between two transverse cracks spaced at about 450 to 750 mm (18 to 30 in) near the edge joint. These cracks typically start as faulting and slight spalling followed by a short longitudinal crack at the wheelpaths. Eventually, these cracks break down further, and pieces of the concrete punch downward into the subbase and subgrade. Pumping and staining are always present near the edge punchouts, as shown in Figure 6.

Edge punchouts occur under variety of conditions. If there is a lack of subbase, edge support, or drainage, the punchouts can be caused from the bottom up. This is attributable to the presence of voids and water under the pavement. On the other hand, punchouts can be from the top down because of the delamination described previously. Staining and pumping are generally associated with edge punchouts. The seriousness of this failure is that it can expand to adjoining pavement and develop into a very large area if not repaired.

Longitudinal Cracking

Longitudinal cracks are typically parallel with the centerline of the pavement, mainly on ramps wider than 4.5 m (15 ft). They start as hairline cracks and eventually develop into spalling and faulting, as shown in Figure 7. In the 14.5 km (9 mi) of CRCP on I-64, 1,700 m (5578 ft) of longitudinal cracking was found during the survey.

Longitudinal cracking was investigated in two cases, which resulted from improper construction of longitudinal joints. In one case the crack is within a normal lane width of 3.6 meters (12 ft) in a 7.2 meter (24 ft) wide concrete placement. In this case either the plastic tape at the centerline joint did not perform its intended function, or got cut off during construction, or the sawing of the center joint was delayed, causing the concrete to crack randomly in the longitudinal direction. The second case occurs on ramps with width > 4.5 meters (> 15 ft), without longitudinal joint, so concrete creates its own joint by cracking randomly. The observed distresses are the same in both cases, which include spalling, eventual faulting, and infiltration of water causing further damage to the sub-layers. Also combination of heavy load repetition, loss of support, and curling and warping stresses can cause this distress.

Sags

Sags are depressions up to 100 mm (4 in) varying in length from about 10 to 30 m (30 to 100 ft), where the concrete surface is lower than that of the surrounding pavement as shown in Figure 8. Water ponding after rain is usually present under these conditions. Eventually, severe cracking and settlement of the pavement occur. These conditions are mostly located near culverts and bridge approach slabs, especially at high fill embankments. For example, on I-295, near Chickahominy Swamp, sag occurred and CRCP was replaced on both sides of the culvert, which was supported on piles. A similar problem occurred in the CRCP on both sides of a culvert on Route 60 near Sandston, while on I-295 south of Route 60 a fill settlement resulted in sag.

Sags develop because of inadequate compaction, the continuing consolidation of the sub-layers, or lack of drainage in the area. In severe cases, all three factors were present, as was noticed near the bridge approach slabs. These areas were compacted at the end of the project (after the back-wall was constructed) using small vibrating plates. In addition, the lack of a stringent requirement for density and the lack of adequate compaction testing lead to loose placement of the backfill and densification of the fill during the CRCP service life, causing the sag. As the roughness increases, bounce increases by the heavily loaded trucks, causing severe cracking.

These distresses were well documented in a 1979 FHWA survey, and their failure mechanisms are explained here.

VIRGINIA'S PLAN OF ACTION

Virginia's plan of action was formulated using all the available talent in several areas, including pavement design, materials selection and testing, research, and the concrete industry. The collective effort resulted in a better understanding of the failure mechanisms and the interaction among the several factors involved in constructing high-performing CRCP.

Pavement Design Changes

To construct durable pavements, attention should be paid not only to materials and mix design but also to structural design, environment, and construction practices. Therefore, several changes were made as follows:

a. Use of a wider travel lane of 4.2 m (14 ft) while keeping the delineating white line at 3.6 m (12 ft). This approach provides an economical way to provide edge support equal to a full width tied shoulder without the joint, and it reduces the chances for punchouts.
b. Use of thicker slab that reduces the shear stress at the steel attributable to the bending action during loading. In estimating the axle loading, each axle of trucks was assumed to be fully loaded, resulting in higher equivalent single axle loading (ESAL). This, in turn, resulted in thicker pavement. In one case, the thickness went from 250 to 300 mm (10 to 12 in).
c. Increasing the amount of reinforcing steel from 0.65% to 0.70% to improve the crack spacing and using two-layer reinforcement with smaller diameter bars for future consideration. The goal is to have the transverse cracks spaced at 1.2 to 1.8 m (4 to 6 ft) while having tight crack opening.
d. Using transverse steel spaced at 1.2 m (4 ft) to support the longitudinal steel and to keep the longitudinal cracks tight in the event of their occurrence.
e. Use of an asphalt layer 75 mm (3 in) thick that provides stability and drainability under the slab. An intermediate mix was selected, with an NMSA of 19 mm (3/4 in). It is essential to provide stability first and drainability second to obtain a stable yet dry condition under the CRCP.
f. Modifying Virginia's edgedrain standards to provide an effective drainage system. This is very important when using drainage layers under the slab. An edgedrain inspection program was established using video camera to ensure that the system will function during the pavement service life.
g. Dealing with sags at the bridge approaches, VDOT modified the requirement for constructing the backfill behind the backwall of bridges. The depth of select material used behind the footing must provide a minimum 1.8 m (6 ft) under the pavement end of the approach slab. Select material Type I, with a minimum CBR of 30 must be used. In addition, the minimum compacted dry density of the select material must be 100% in the top 0.9 m (3 ft), 98% from 0.9 to 1.8 m (3 to 6 ft), and 95 % below 1.8 m (6 ft).
h. Changing the two plain jointed slabs spaced at 6 m (20 ft) to one reinforced concrete slab with a tapered depth from 375 mm (15 in) to a depth matching the CRCP in the mainline. Two expansion joints, one on each side of the reinforced slab, are used. This change in addition to the compaction requirements will provide a bridging effect in the presence of inadequate support in the bridge approach area.

i. Long sags resulting from inadequate consolidation of a thick and soft subsurface layer is avoided by requiring the primary consolidation of the fill to be complete, before the pavement placement.

Materials Selection and Testing

Aggregate Maximum Size and Grading

VDOT is interested in minimizing the crack width and increasing the spacing of cracks in the CRCP. Moisture loss causes shrinkage and temperature drop contraction, which, when restrained by the base and the reinforcing steel, result in cracking. In the two new CRCP paving projects in Richmond and Lynchburg, use of the larger NMSA of 50 mm (2 in) is planned. The Richmond pavement is under construction. With larger size aggregates, a reduction in the water and paste contents is expected, which will lead to reduced shrinkage. One other important issue with the aggregates is the grading. Present VDOT specifications separate the aggregate into coarse and fine and require that each meet a certain grading requirement. When such aggregates are combined, a lack of intermediate sizes is evident. In the current CRCP projects, an attempt is being made to look at the combined aggregate grading. The goal is to achieve a uniform grading that enables the use of a large amount of aggregate with a minimal paste content, reducing the shrinkage potential. In the Lynchburg project, to encourage the use of a uniform grading, the contractor is given the option of reducing the cementitious material content to 318 kg/m^3 (535 lb/yd^3) rather than the usual 335 kg/m^3 (564 lb/yd^3). Larger aggregate is also expected to provide better aggregate interlock. If cracks form, a vertical movement between two sides is not expected because of the bridging of the larger aggregates. Old pavements in Virginia with 50 mm (2 in) NMSA have performed well, which supports the soundness of the increasing the aggregate top size.

Pozzolans/Mineral Admixtures

Since early 1990s, VDOT has been specifying pozzolans (Class F fly ash) and slag to inhibit ASR. Pozzolans also reduce the permeability of concrete. Concrete exposed outdoors is subjected to severe conditions because of the intrusion of harmful solutions: either just water, or chloride, or sulfate solutions. Concrete with low permeability resists such intrusion. CRCP naturally has cracks that may facilitate the intrusion of solutions. However, if the crack width is narrow or does not exist near the reinforcement, corrosion concerns are diminished. Even if corrosion occurs, it is expected to be in isolated small anode locations at the cracks.

Alkali Silica Reaction

ASR has been somewhat of a problem in Virginia. We replaced about 9.6 km (6 mi) of pavement on I-64 near Charlottesville because of ASR in the late 1980s. We have many miles of pavement and many structures showing evidence of ASR, though they have not progressed to total failure.

Factors required to get ASR are a reactive aggregate, alkalis, and moisture. All three must be present for distress to occur. The methods of determining the reactivity of the aggregates are not

totally reproducible, which can cause identical aggregates to show up as reactive for one and nonreactive for the other. Preparing and performing the tests take a very long time. The 9.6 km (6 mi) of pavement on I-64 was replaced because of reactive aggregate, even though the aggregates met the specifications at the time, which are unacceptable by current limits. Since most of the aggregates in Virginia have some of the reactive components, VDOT decided to arbitrarily declare all aggregates reactive.

Most of the available alkalis come from the cement. The amount of alkali has increased over the years because of environmental restrictions. The cement mills have had to collect dust from the stacks, which must be wasted, recycled, or reused. The manufacturing of cement was forced to change, with the oil embargo in the 1970s, from the use of oil to coal and from slurry blending to dry blending; pre-heaters are used to reduce the amount of energy. The change to coal also increased the amount of alkalis in the cement. Cement kiln dust is much higher in alkalis than the raw feed and, when mixed with raw feed ingredients, raises the alkali of the cement. The availability of the alkalis is much higher because of the much higher fineness of the cement. In the old days, the alkali could be buried deep in the cement grain that was going to be hydrated in a century or more. Today's finenesses allow nearly complete hydration in a very short time, making the alkalis available almost immediately. The amount of alkali that VDOT found to cause an excessive expansion is 0.45%. ASTM C 150 recognizes 0.60% as the dividing line for low-alkali cement. The difference is probably attributable to the changes in fineness over the years. Others have also found that an alkali limit of 0.60% does not provide protection in all cases (Lane, 1994).

Moisture is always present in pavements. If it is not coming from above, it is wicking from below. Drainable bases may reduce the amount of available moisture from the bottom, as long as they work, but exterior concrete is subject to cooling and heating, condensation, and evaporation, maintaining a relatively high relative humidity in the concrete.

There is another way to prevent ASR, which is to use supplementary cementitious materials, such as Class F fly ash, slag, silica fume, metakaolin, or similar types of products (Lane and Ozyildirim, 1999a). In Virginia, because of the difficulty of eliminating aggregate sources or finding low-alkali cements, we have opted for the use of supplemental cementitious material, which is highly effective and improves the overall durability of concrete.

The amount of supplementary cementitious materials is determined by the amount necessary to limit the expansion of the mortar bars in accordance with ASTM C441, which uses Pyrex glass as the reactive aggregate. VDOT has data that show the expected expansion for particular types of materials at different concentrations and through interpolation, have maximum alkali levels that can be used with certain percentages of cement replacement (Lane and Ozyildirim, 1999a,b).

Strength Tests

The flexural strength of concrete is used in design of the pavement. However, flexural strengths are seldom determined in actual concrete pavements. Beams are bulky and exhibit a lot of variability. Currently, VDOT is establishing a relationship between compressive strength and

flexural strength before the beginning of a project. The acceptance tests are then based on the compressive strength of the concrete.

Construction Issues

One concern has been with the ability of slipform pavers to place a 50 mm (2 in) NMSA. VDOT present projects have shown that slipform pavers can satisfactorily place concrete with large aggregate. Test results show that satisfactory strength and durability are obtained (Ozyildirim, 2001).

Construction issues of concrete placement, consolidation, and curing are important for satisfactory performance. Adequate concrete consolidation is essential to attain the strength and durability desired. In VDOT present project, the frequency of the vibrators will be continuously monitored. Cores taken from the pavement will be tested for air void system to determine the adequacy of consolidation. Good curing will be emphasized. A section of a concrete pavement is planned for curing with wet burlap rather than the usual curing compound. Proper curing ensures that the desired properties are achieved and that the volumetric changes that result in cracking are minimized.

Placing the longitudinal reinforcing steel on continuous runner chairs with clips attached at planned widths rather than using the feed-tube system. The chairs provide the proper positioning of the steel in the slab, and serve as the horizontal reinforcement. It also allows for the slab to be poured monolithically, which reduces the probability for cold joint at the reinforcing steel, that have resulted from pouring two layers in the feed tube system.

Monitoring the supply of concrete with continuous quality control during mixing, hauling, placing, and finishing. Concrete delivered must be workable with an adequate time of setting. Early stiffening of the concrete can lead to difficulties in placement and finishing (Gress, 1997).

The paving process must provide uniform quality of concrete, delivery and placement, and head of material in the paver to ensure uniform forces in front of and under the paver.

Initial saw cutting of the longitudinal joints needs to be done as soon as the concrete slab can support saw equipment and the cut can be made without undue raveling. The use of tape in the longitudinal joint is still allowed in Virginia, but not for slabs greater than 225 mm (9 in).

Requiring a smoother ride, with incentive and disincentive as part of the contract. The use of stringline is recommended. VDOT has been using a profilograph to test concrete smoothness for many years, but now efforts are underway to specify the use of a non-contact lightweight profiler. This will enable a contractor to find out how smooth the concrete is and to take the necessary steps to adjust the operation if needed.

The implementation of the plan of actions involved the pavement design engineers, materials engineers, researchers, and the industry. Their collective efforts complement one another, and a sound product is expected. VDOT has already implemented these actions on a project underway on Route 288 in Chesterfield County, with 250-mm (10-in) CRCP, and plans are underway for

another project at the Madison Heights Bypass in Lynchburg, where a 300-mm (12-in) CRCP will be used. The early results on Route 288 are promising.

RECOMMENDATIONS

1. Use an analytical approach and benefit from the lessons learned to extend the service life of CRCP with minimal maintenance.
2. Use consistent pavement condition surveys that aid VDOT in identifying critical distresses.
3. Establish the failure mechanism for each distress before starting pavement rehabilitation or making any changes to improve CRCP performance.
4. Reach the most logical failure mechanism by understanding pavement design, concrete mix design, the factors affecting concrete production, the interaction between the concrete components and environmental conditions, and construction practices.
5. Adopt and implement changes to improve CRCP.
6. Monitor and provide feedback to measure the effectiveness of the changes made.
7. Establish cooperation among pavement design engineers, materials engineers, researchers, and the industry to implement changes.

ACKNOWLEDGMENT

Special thanks go to the employees of VDOT and the FHWA who through design, construction, testing, and research continuously strive to improve the performance of concrete pavements in Virginia.

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Figure 1. Map cracking as a result of ASR



Figure 2. Cluster of closely spaced cracks leading to localized distress



Figure 3. Localized broken concrete advanced condition under wheelpath



Figure 4. Separation at the steel as a result of delamination



Figure 5. Broken concrete attributable to traffic loading and advanced delamination



Figure 6. Pumping, staining and severe damage as a result of punchouts



Figure 7. Longitudinal cracking near outer edge, due to tape failure



Figure 8. Pavement depression measurement as a result of sag on I-295