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Premature Failure of Concrete Patching: Reasons and Resolutions

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Based on these findings, the study recommended revisions to future special provisions for concrete patching and the VDOT Materials Division Manual of Instructions, Chapter 6.

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FINAL REPORT

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ABSTRACT

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INTRODUCTION

The Virginia Department of Transportation (VDOT) uses full-depth concrete repair to patch hydraulic cement concrete pavement that has distresses such as punchouts, spalls, extensive cracking, and corroded steel in continuously reinforced concrete pavement (CRCP). Such full-depth repair comprises an attempt to ensure load-carrying capabilities by reestablishing the continuity of reinforcing steel through the patched area and replacing the damaged concrete with new high early strength concrete. VDOT has developed a special provision for full-depth repair of concrete pavement (VDOT, 2007).

These repairs are usually more than 6 ft in length and are the width of the full lane, approximately 12 ft. The distressed area is identified, and repair boundaries are marked. The old concrete is removed through saw-cutting and jackhammering, as shown in Figure 1, which is identified as a Type IV patch for CRCP. Full-depth saw-cutting is performed along the longitudinal boundaries of the patch area and at least 12 in outside the transverse boundaries of the failing concrete. This cut piece is pulled and removed in as many large pieces as possible. To avoid base damage, no in-place breaking is allowed. An additional partial depth (2 to 3 in) saw cut is performed, avoiding steel bars on the transverse edges of the repair boundaries at least 18 in from the full-depth saw cuts, and the concrete is removed from the pavement using jackhammers (or any other suitable method). The continuous reinforcement is reestablished by splicing the exposed bar with the new steel before the patch concrete is placed (VDOT, 2007).

The following characterizes the VDOT-recommended practice for identifying the patch limits for Type IV patches (Tate, 2011):

- minimum 6 ft long
- full lane width (12 ft)

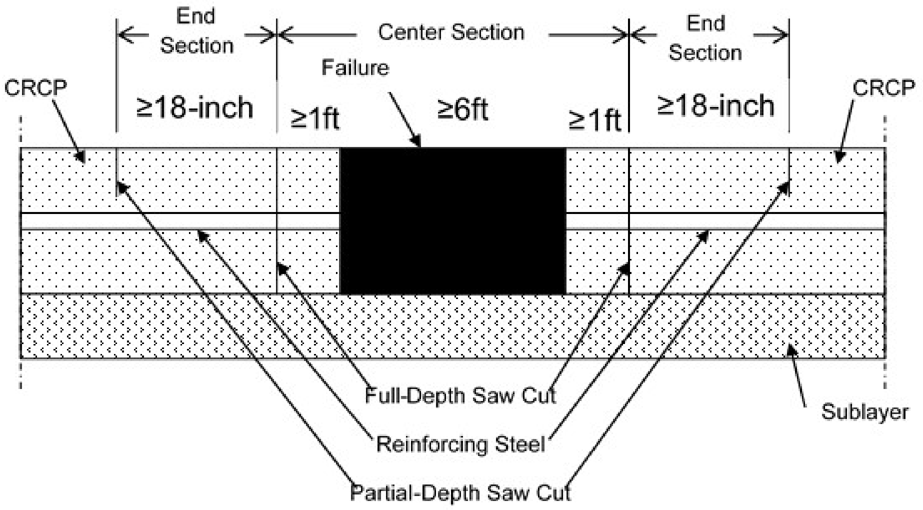
- minimum 1 ft past/beyond distress (punchout, asphalt patch, cluster cracks, Y-cracks, etc.)

- minimum 1 ft past/off existing transverse crack

- minimum 10 ft between patches.

In the 1980s, VDOT recognized problems with patching CRCP. The 36 miles of CRCP on I-64 near Charlottesville constructed around 1968 was failing in different sections because of alkali-silica reactions. Patching was not successful because the concrete failed around the patch within months of the repair. One-sixth of the pavement (east end of the westbound lane) was replaced around 1990 at considerable cost and inconvenience to the traveling public. The other five-sixths of the pavement was overlaid with approximately 5 in of Superpave asphalt around 1995. The pavement performed well for 20 years, with no concrete patching or asphalt resurfacing being required. This experience indicated that overlaying the pavement was a more economical and acceptable alternative to replacing the concrete pavement and that patching was not an acceptable option. It is believed that the overlay option worked well because the overlay reduced moisture infiltration into the concrete, minimized temperature fluctuations, and reduced the stress from traffic in the concrete by increasing the pavement section modulus.

Another example of the benefits of an overlay is I-66 in Northern Virginia. Jointed pavement patches were being replaced in less than 7 years at considerable cost and inconvenience to the traveling public because of the frequent lane closures. A decision was made to overlay the pavement with asphalt, and patching has not been required since the overlay was placed.



NOTES:

1. Longitudinal Tie Bars are necessary for patches greater than 15 ft.
2. The length of the “End Section” shall be 30 times the rebar diameter plus 2 inches with a minimum of 18 inches.

Figure 1. CRCP Patching Diagram (VDOT, 2007). CRCP = continuously reinforced concrete pavement.

Full-depth repair has a mixed performance history in highway agencies. Premature failure has occurred in numerous locations within 1 to 5 years of repair, especially where lane closure was allowed for only a short duration. The main causes of failure were thought to be poor base compaction/preparation under the exposed steel for splicing (20 in along the transverse edge of the patch that hinders the access of compaction equipment), poor quality of the patching concrete, and poor steel overlapping (splicing) practices (Tayabji, 2011).

The following possible causes of repair failure were identified for investigation in this study:

1. failure to remove deteriorated concrete adjacent to the area being patched

2. damage to concrete adjacent to the patch during concrete removal (possibly because of use of heavy equipment)

3. cutting of steel and inadequate splicing of steel

4. inadequate load transfer

5. improper base preparation including lack of provision for drainage when needed

6. poor concreting practice

7. use of high early strength concrete mixtures that are opened to traffic in 5 to 6 hours when the required compressive strength of 2,000 psi is not achieved

8. failure to assess the overall pavement condition that may warrant more substantial rehabilitation such as placing an overlay on the patched pavement to protect the pavement and reduce the level of stress caused by traffic and the environmental changes.

PURPOSE AND SCOPE

The purpose of this study was to identify the causes of early failure of patches and onset of deterioration beyond the repaired area in CRCP. Failed patches and adjacent pavement were evaluated for strength and permeability to help identify failure mechanisms. Selected patching operations were also monitored to document the operations including selection of patch areas, construction of patches, concrete strength at opening to traffic, and final performance.

The appropriate measures to minimize the premature failures are suggested in the form of modifications to VDOT's *Special Provision for Patching Hydraulic Cement Concrete Pavement* (VDOT, 2007) and the VDOT *Materials Division Manual of Instructions*.

METHODS

Four tasks were performed to achieve the study objectives:

1. Investigate the causes of premature failures.
2. Monitor the installation of several reinforcement connection details.
3. Analyze the data.
4. Revise the specifications, and develop best practices.

Investigate Causes of Premature Failures

Concrete patching operations were observed at several locations on I-85 South, SR 288 North, US 58 West, and I-264 East to investigate the causes of premature failures. The location, type of pavement, and age of the pavement are provided in Table 1.

Patching on I-85 was evaluated to explore the causes of premature failure. This evaluation included the following:

- A visual survey was conducted to identify the extent and type of distress in the vicinity of the patching.
- Patching operations were monitored including concrete removal, installation of reinforcement, and placement of concrete.
- At least three cores were obtained from each of the patch areas being evaluated: old concrete removed for patching, new concrete placed for patching, and original undamaged areas in the vicinity.
- Permeability and compressive strength testing on the cores was conducted to allow a comparison of the quality of the concretes.

Patching on SR 288, US 58, and I-264 was evaluated for the quality of patching concrete in terms of early strength at opening to traffic and long-term performance. The evaluation included the following:

- Cylinders were prepared that were temperature matched cured (TMC) with the patches to provide an accurate indication of the strength of the patch over time and when opened to traffic.

Table 1. Patching Locations for Field Investigation

Highway	County	Mile Marker	Pavement Type	Year Constructed
I-85S	Dinwiddie	51.49 to 61.44	8-9-in CRCP	1969
SR 288N	Chesterfield	11.83 to 15.59	8-in CRCP	1988
US 58W	South Hampton	18.3 to 20.9	8-in CRCP + 4-in bonded overlay	2012
I-264E	Norfolk	9.0 to 11.0	Jointed concrete pavement	1967-1972

CRCP = continuously reinforced concrete pavement.

- Thermocouples were placed in the patches to measure the temperature and provide an indication of the maturity of the concrete over time and when opened to traffic. The maturity provides an indication of the compressive strength.

- Cylinders were prepared that were air cured (AC) to provide an additional comparison for the strength of the patching concrete.

Monitor the Installation of Several Reinforcement Connection Details

In addition to the current practice of reestablishing the continuity of the reinforcement, three new reinforcement connection (splicing) details as shown in Figure 2 were tried in the I-85 patching work to determine their effect with regard to the construction of the patches and to provide sites for future performance evaluation. These connections included hose clamps, U-bolts, and six tie wires. Current VDOT patching practice uses only two tie wires with an 18-in overlap, which provides continuity through the development length concept. The experimental mechanical connections were designed to reduce the required development length, which would reduce the quantities of concrete removal and patching material.

Four options for connecting reinforcement were tried:

1. two tie wires with an 18-in overlap (current VDOT practice)
2. ¼-in U-bolt with two plates and one nut at each end with a 9-in overlap
3. hose clamp with a 9-in overlap
4. six tie wires with a 9-in overlap.

Analyze the Data

The data were analyzed and observations synthesized to determine the probable causes of premature patching failure.

Revise the Specifications and Develop Best Practices

Based on the findings, a revision to VDOT's *Special Provision for Patching Hydraulic Cement Concrete Pavement* (VDOT, 2007) was suggested, and best practices for patching CRCP were developed.

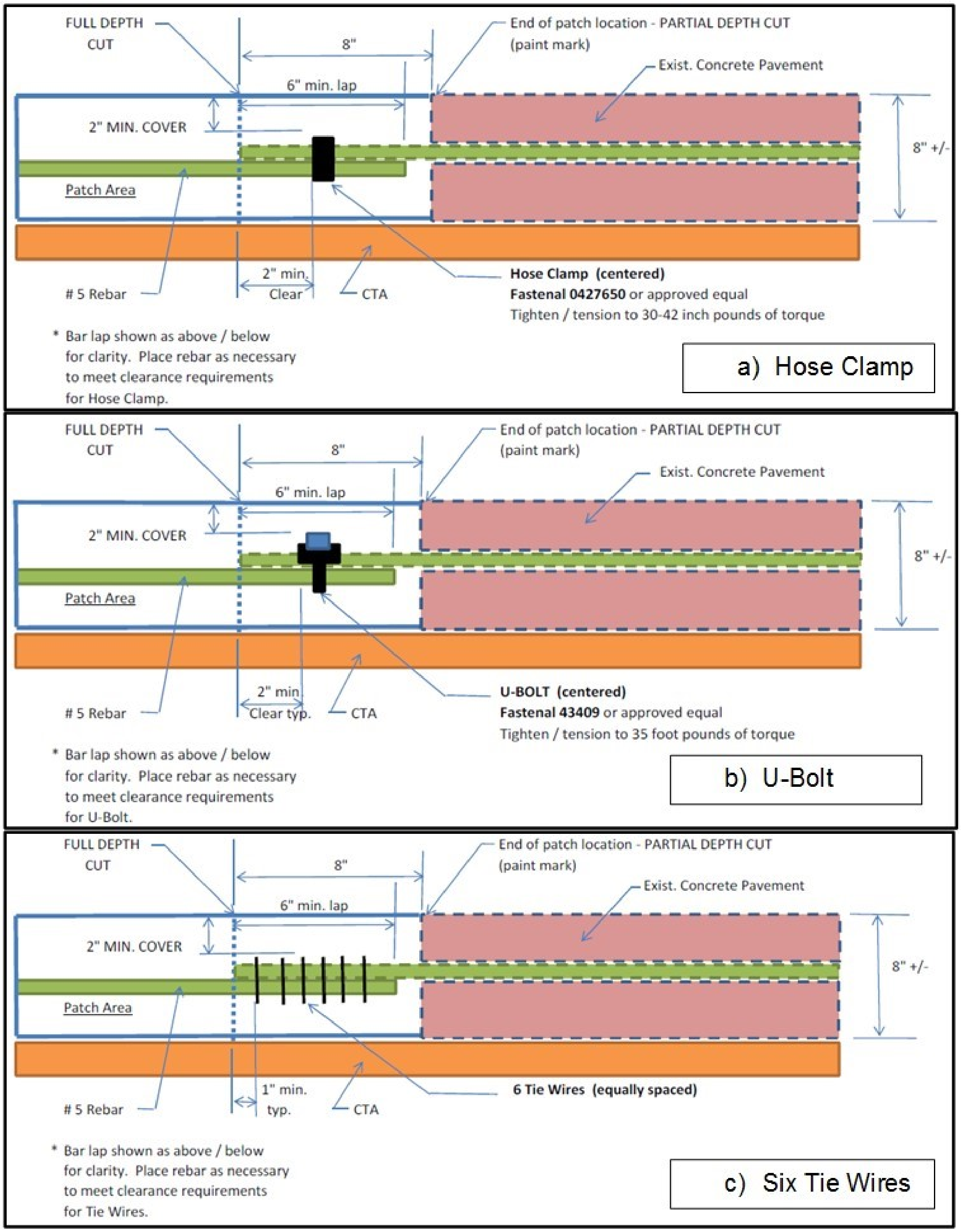


Figure 2. Alternative Splicing Methods: a) hose clamp; b) U-bolt; c) 6 tie wires

RESULTS AND DISCUSSION

Causes of Premature Failures

Patching on I-85

Failure to Remove Deteriorated Concrete Adjacent to Patch

Site visits did not identify this as a cause. Typically, concrete was being replaced that one could argue could be left in place, as shown in Figure 3. The 40-year-old pavement (Figure 3b and 3c) to be removed has fewer and tighter cracks than a recent patch (Figure 3a).

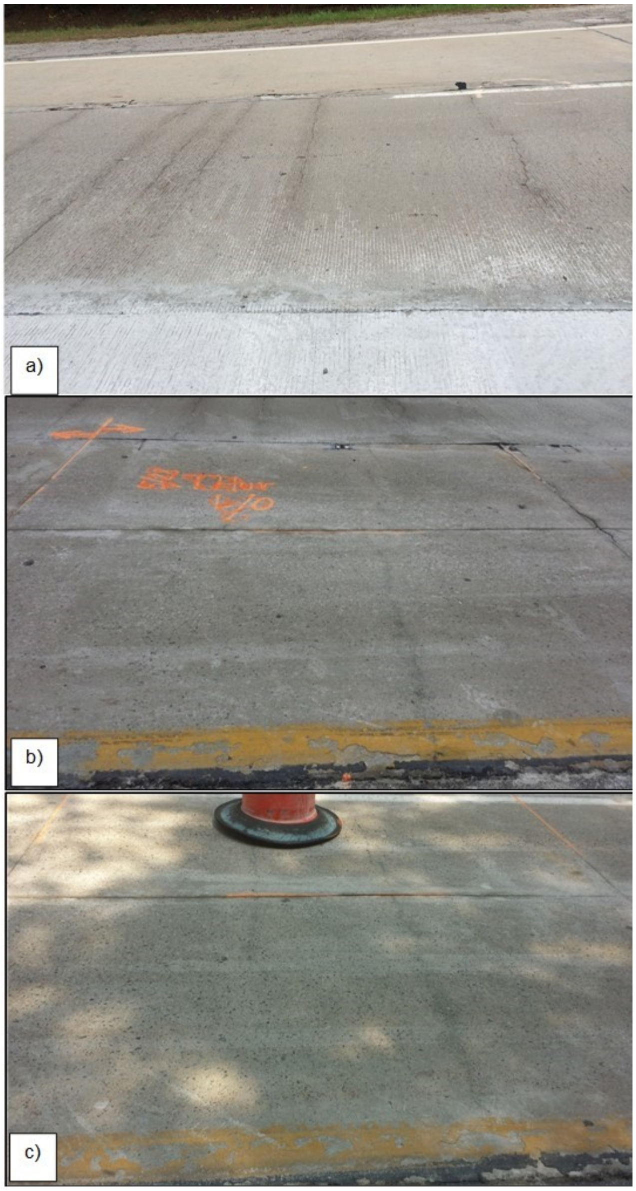


Figure 3. Forty-Year-Old I-85 Pavement That Appears to Be in Good Condition: a) patch a few years old; b) section marked for removal; c) section marked for removal

Damage to Concrete Adjacent to Patch During Concrete Removal (Possibly Because of Use of Heavy Equipment)

Figure 4 shows concrete being removed along the edges of the area to be patched on I-85. The larger hammer shown in Figure 4a removes the concrete faster than the smaller hammer shown in Figure 4b. In theory, the larger hammer has the potential to cause more damage, but this was not verified in this project. Figure 5 shows damage to the pavement adjacent to the patch that was likely caused by poor workmanship during concrete removal.

Cutting of Steel and Inadequate Splicing of Steel

Type IV patching includes cutting the reinforcement in the CRCP. Often, the pavement can be observed to move when the steel is cut because the stresses in the pavement caused by creep, shrinkage, and temperature are no longer restrained. The movement is the greatest when the first cut is made and only one patch is constructed. As the patches become closer together, the movement is less. It appears that cutting the reinforcement causes redistribution of the stresses in the pavement, which may be a factor in premature deterioration, but not enough information could be gathered for this project to confirm such a relationship.

Figure 4. Hammer Breaking Concrete Next to Joint for Patching on I-85: a) larger hammer; b) smaller hammer

Figure 5. New Patch (*right*) Next to 40-Year-Old Pavement (*left*) on I-85. Pavement deterioration next to the patch suggests damage from concrete removal.

After the reinforcement is cut and the concrete is removed, the new reinforcement in the patch is lapped 18 in with reinforcement in the pavement and a tie wire is commonly used to connect the reinforcement. Figure 6 shows the tie wires that were used to connect the reinforcement in the failed patch that was removed. During field visits, the improper splicing of the reinforcement was not evident. It is important to note that when an 18-in lap is used, the continuity of the bar mostly relies on the development length rather than on a mechanical connection between the bars through tying.

Figure 6. Single Tie Wire for Connecting Reinforcement on I-85. The 5-year-old patch that has been removed (*left*) is being replaced.

Poor Concreting Practice

Figure 7 shows that the concrete may not have been consolidated properly in the vicinity of the splice location on the longitudinal steel in the 4-year-old patch (on the right in Figure 7a and on the left in Figure 7b) on I-85. The 4-year-old patch in both cases shows closely spaced cracks, indicating poorly proportioned concrete with a high cement content. It can be argued that the distress was caused by the concrete removal for the new patch on the left.

Figure 7. Joint Deterioration at Patches on I-85: a) new patch (*left*) next to 4-year-old patch (*right*); b) new patch (*right*) next to 4-year-old-patch (*left*)

The damage near the joints in the old patch as shown in Figure 7 could be attributed to the following causes:

- improper consolidation of concrete at the joint because of congestion of reinforcement because of splicing
- damage because of concrete removal during the installation of the new patch
- base erosion near the joint (as shown in Figure 5)
- poor quality concrete (high cement content) and excessive cracks in old patches.

Use of High Early Strength Concrete Mixtures

All Type IV patches observed for this project were constructed with high cement contents (e.g., 800 lb for 5-hour mixture and 752 lb for 8-hour mixture) so they could achieve the 2,000 psi compressive strength needed to be opened to traffic in 5 to 8 hours. Typical mixtures are described in Table 2 along with an improved, more durable mixture. The 5-hour and 8-hour mixtures were used in the I-85 patching project. Similar ingredients were collected from the respective plant, and mixtures were prepared in the laboratory. Figure 8 shows the typical early age compressive strength of these patching mixtures. All cylinders in the laboratory were cured in an insulated chamber to simulate field patching conditions where loss of heat is prevented because of the mass of concrete in a patch. Although the 8-hour mixture achieved the required 2,000 psi strength in 8 hours, the 5-hour mixture did not gain a similar strength in 5 hours. Figure 9 shows the early age compressive strength of improved high early strength patching mixtures that achieved the required 2,000 psi strength in 6.5 hours and hence were named 6.5-hour mixtures. Figure 10 shows the cracking typical of the high early strength mixtures being used. It is believed that a primary cause of the premature deterioration of the patches is the cracking in these mixtures.

Table 2. Pavement Repair Mixtures Prepared in the Laboratory

Components in 1 Cubic Yard	**Current 8-Hour Mix**	**Current 5-Hour Mix**	**Improved 6.5-Hour Mix**
Cement Type I/II (lb)	752	800	750
Fly ash (lb)	0	0	132
Water (lb)	279	275	265
Fine aggregate (lb)	1,156	1,129	1,061
Coarse aggregate (lb)	1,711	1,711	1,676
w/cm	0.37	0.34	0.30
Admixture (oz/cwt)			
Hardening accelerator	---	48	20
Set accelerating	36	---	24

w/cm = water–cementitious material ratio; --- = not used.

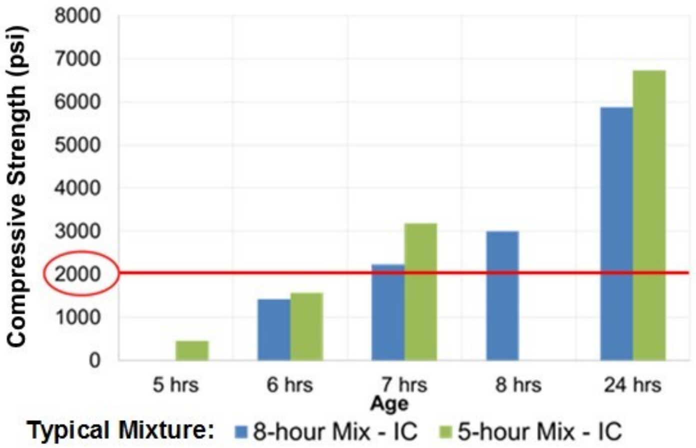


Figure 8. Early Age Compressive Strength of a Typical (VDOT) High Early Strength Patching Mixtures Prepared in the Laboratory. IC = insulated curing.

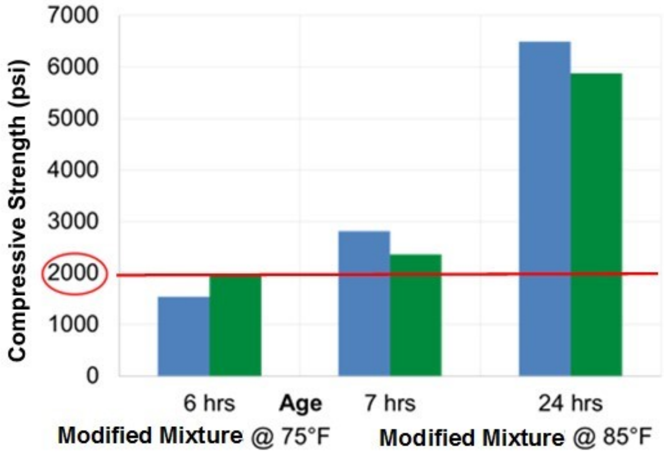


Figure 9. Early Age Compressive Strength of Improved High Early Strength Patching Mixtures Prepared in the Laboratory. Blue = mixing water temperature of 75 °F; green = mixing water temperature of 85 °F; both insulated cured.

Figure 10. Five-Year-Old Patch on I-85 with Cracks Close Together. The cracks were caused by the use of concrete with a high cement content.

The special provisions for all three projects that were part of this study, i.e., I-85, SR 288, and US 58, allowed lanes to be closed from 9 P.M. Sunday night through noon on Friday. However, contractors elected to use the high early strength 5- to 8-hour mixtures. Durable mixtures with less cement and containing fly ash or slag could have been used on Monday, Tuesday, and Wednesday if lanes were closed from Sunday night through noon on Friday. This would have resulted in fewer cracks as high cement content is one of the reasons for closely spaced cracks in a patch; it would also have provided a longer curing time.

Failure to Assess Overall Pavement Condition That May Warrant Overlay/Replacement Instead of Patching

At least three cores were taken from each of the patch areas being evaluated on I-85. Three or more cores were drilled from the concrete removed for patching and from the original undamaged areas next to the patch. Rather than coring of the new patch, cylinders were prepared in the laboratory using the patching mixture. The cores and cylinders were tested for permeability and compressive strength to allow a comparison of the quality of the concretes. The results are shown in Tables 3 and 4. The permeability and strength values were similar for the concrete left in place and the concrete that was replaced. This suggests that the concrete was not failing because of the quality of the concrete but that the shrinkage cracks because of the high cement content and poor curing of the concrete might be aggravating the situation. Replacing the failed concrete with concrete that has a similar strength but more cracks should contribute to early failure of the patches. If a mixture with a high cement content cannot be avoided because of traffic constraints, an improvement of the pavement structure could improve patch performance. This could be accomplished by placing a thicker concrete patch or replacing the base and subbase with stronger materials, but these options are not practical because of design, construction, and traffic issues. A practical option would be placing an asphalt or unbonded concrete overlay. Experience has shown that overlays can be an economical alternative to extensive patching. If VDOT were reconstructing the CRCP to provide a pavement section for today’s traffic loadings, the thickness would be much greater, as shown in Table 5. It is unreasonable to expect a patch and the remaining concrete area that is 8- to 9-in thick to perform well in long run. Eventually, the concrete will crack and spall because the composite section (pavement, base, and subbase) is not structurally adequate for current traffic in those areas. The repair needs to be designed properly for future traffic; e.g., overlaying the entire area, which would add structural capacity.

Table 3. Permeability (C) of Cores and Cylinders From I-85

Type of Concrete	No. of Cores	Average	Std. Dev.
Replaced	37	1936	1086
Left in place	36	2072	1062
New patches	Lab cylinder	2054	---

--- = not available.

Table 4. Compressive Strength (psi) of Cores from I-85

Type of Concrete	No. of Cores	Average	Std. Dev.
Replaced	9	6,298	1,003
Left in place	2	6,135	---
New patches	Lab cylinder	>6,000	---

--- = not available.

Table 5. Design Thickness Considering Current Traffic

Pavement	Location	Traffic			Pavement Thickness (in)	
		Year	AADT	% Trucks	Existing	Design for Next 30 Years[a]
I-85S	MP 48 to MP 53	2016	13,000	18	8-9	11-13
SR 288N	US 360 to SR 76	2017	60,000	5	8	10-12
US 58W	MP 16.0 to MP 20.9	2009	16,000	15	8	11-12

AADT = annual average daily traffic.

[a] AASHTO 1993 design using current traffic.

Figure 11 shows a section of I-85 marked for Type IV patching. The white circles indicate spalls along cracks that were used to justify patching the area. The pavement was in good condition. Placing an overlay would preserve the good condition. Type IV patching with high early strength concrete with many cracks, as shown in Figure 10, would not last as long as the pavement shown in Figure 11, which has fewer cracks. Unless there is a local unique problem with the concrete in the area when the pavement needs to be patched, the pavement should be overlaid to provide a long life.

Figure 11. Section of I-85 Marked for Type IV Patching. White circles indicate spalls along cracks that justify patching the area.

Other Probable Causes of Failure

There was no evidence of inadequate load transfer across cracks in this project. Further, other causes of failure such as a poor base and/or drainage problems were not identified in this project.

Patching on SR 288

CRCP patching was performed on SR 288. Selection of the areas to be patched was based on visual observation. Conditions that influenced the decision to patch included existing temporary patches, spalls, and cracks, especially where the transverse and longitudinal cracks intersected, as shown in Figure 12a and 12b. Removal of old concrete to prepare for patching is shown in Figure 12c.

Figure 12. Patching on SR 288: a) area to be patched with closely spaced cracks; b) area selected for patching; c) old concrete slabs being removed; d) removed concrete slabs

The depth of the removed slabs was mostly 8 in, with some locations as deep as 9 in, as shown in Figure 12d; patches were cast to match the depth of the removed slabs. The observations were mainly focused on the strength development of patching mixtures with time as they are opened to traffic.

On the nights of June 9 and 10, 2014, the patching operation was observed and concretes were tested for fresh and hardened properties. On June 9, patches that were the width of one lane were placed at 10 locations from before the exit sign for Strayer University to the overpass of Genito Road. On June 10, patches were placed at 2 locations; one long patch was placed under the overpass of Genito Road, and a smaller patch was placed right after the exit for SR 76 (Powhite Parkway). The mix design for the patches is shown in Table 6. VDOT No. 57 stone was used for coarse aggregate, and it was a rich mix with 800 lb of cement.

Table 6. Mix Design for Patching on SR 288

Ingredient	Amount
Type II cement (lb/yd^3)	800
Coarse aggregate (lb/yd^3)	1,812
Fine aggregate (lb/yd^3)	1,009
Water (lb/yd^3)	275
High-range water-reducing admixture (oz/cwt)	24/36
Water–cementitious material ratio	0.34
Air (%)	4-9
Accelerator (oz/cwt)	120/280

Each night, a batch of concrete for each of the two patches was tested for fresh and hardened properties: the first batch was tested when placement started, and the second batch (from the final patch) at the end of the day. The strength of the concrete when the road was opened to traffic the following morning at around 7 A.M. was of interest, and tests on the first and last loads indicated the level of strength achieved for the patches for that particular day. The minimum strength required for the concrete was 1,750 psi at the age of 5 hours. The road was closed to traffic starting at 7:30 P.M., enabling work to start at 8 P.M. The deteriorated concrete was removed, and then the new reinforcement was tied to the exposed steel using a machine that facilitated the tying. Each splice had two wire ties.

After the reinforcement was placed in the beginning patch areas, concrete was ordered for delivery to the site at about 10 P.M. (or a little later). On the first night, the first of the 10 patches was so long that the reinforcement had to be tied within the patch as well as at the ends of the patch. Therefore, the second patch, measuring 17 ft 10 in long, was selected for monitoring and Batch 1A was sampled for fresh and hardened concrete testing. The second batch (Batch 2A) was for the tenth patch and was 87.5 ft long. To determine if a sufficient amount of deteriorated concrete had been removed, 3 cores each were taken on the north and south sides of the second and tenth patches at varying distances in the transverse and longitudinal directions, for a total of 12 cores. From visual inspection, the quality of the concrete from these cores looked similar to that of the removed concrete.

On the second night, June 10, only two patches were placed. The first (Batch 1B) was 381 ft 10 in long, and the second (Batch 2B) was 8 ft 8 in long. Figure 13 shows work being done on the longer patch. The first patch (Batch 1B) was under the overpass and did not appear to be in distress, but it was placed so that better quality exposed concrete to maintain the clearance would be present when the rest of the patch areas would be overlaid with asphalt. Core samples from the placement on the second night were taken from only the second smaller patch since the purpose of the first large patch was mainly to maintain the clearance under the bridge deck rather than to correct the damaged concrete pavement. Three cores each were taken on the north and south sides of the second, shorter patch at varying distances in the transverse and longitudinal directions.

Figure 13. Longer of Two Patches on SR 288 Constructed on 6/10/14

For further analysis, six additional pieces of broken concrete were collected on the second night, with three from the long patch and the other three from the short patch. Again, based on the visual inspection of cores, the quality of the concrete was similar to that of the removed concrete.

The fresh concrete properties including slump and air content for the patches from SR 288 are shown in Table 7. Batch 1A was at the site at 11:05 P.M., and its fresh concrete properties were determined at 11:15 P.M. Placement of the tenth patch was completed at 12:53 A.M. Batch 2A, representing Patch 10, was placed approximately 2 hours after Batch 1A. On the second night, the first load, Batch 1B, arrived at 9:58 P.M. and the final load, Batch 2B, arrived at 12:42 A.M. The transportation time for the concrete from the plant to the site was about 25 to 30 minutes. Wet burlap was placed immediately after concrete placement, wetted more, and then covered with additional blankets. All patches were opened to traffic between 6 A.M. and 7 A.M. the next morning.

The compressive strength of the concrete was determined using two curing methods. The first was TMC. A thermocouple was used for temperature monitoring at the mid-depth of the patch; the heated cylinder molds matched the cylinder temperature to that of the actual patch. At each patch, four TMC molds (SURE CURE molds) were used; two cylinders were tested right before opening to traffic and the other two at a later time. In addition, four more cylinders were made and kept near the patch and were designated “AC” (for air cured). Again, two AC cylinders were tested before opening to traffic to show the difference in comparison to TMC. Two of the remaining cylinders were placed in a moist room to be tested for permeability at a later date.

The temperature progression for the first few hours (4 to 6) was collected at three locations: (1) at mid-depth of the patching, (2) in the TMC molds, and (3) in the AC molds. Figure 14 shows the temperature behavior of the concrete patches during the first 5 or 6 hours after placement, detailing temperature fluctuations of the actual patches, air, and cylinders. On the first night, June 9, the generator used to heat the TMC molds for the second batch ran out of gas and was restarted at approximately 4 A.M., when this was discovered. Therefore, the temperature of the second patch on the first night was not available. All three plots show that the patch temperature was much higher compared to the air temperature for the first 6 hours. The TMC mold was able to match the actual patch temperature in the mold. On the other hand, the temperatures of the AC cylinders mostly followed the air temperature and were about 10 °F to 15 °F above it. This difference in curing temperature would also influence the strength gain, as explained later.

Table 7. Fresh Concrete Properties for Patches on SR 288

Property	Patches on 6/9/14		Patches on 6/10/14	
	Batch 1A	**Batch 2A**	**Batch 1B**	**Batch 2B**
Concrete temperature (°F)	86	90	86	85
Air temperature (°F)	76	76	73	70
Density (lb/ft^3)	136.0	137.2	137.2	134.0
Slump (in)	5.5	5.0	6.2	2.8
Air (%)	7.0	6.1	5.9	6.9

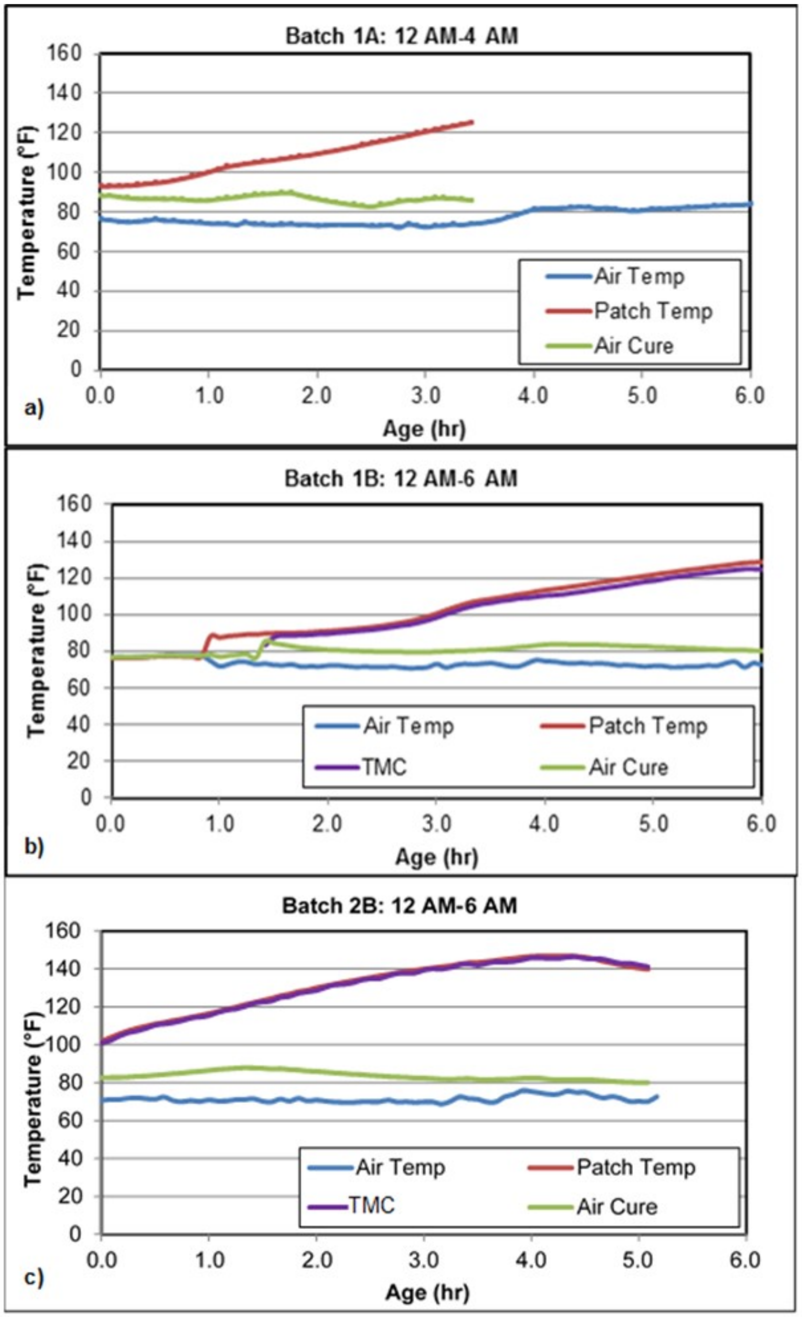


Figure 14. Temperature Variation With Time for Patches, Surrounding Air, and TMC and Air Cured Cylinders on SR 288. TMC = temperature matched cure.

The TMC and AC cylinders were tested at different ages for compressive strength; the results are shown in Table 8. It is obvious that the AC cylinders had much lower strength compared to the TMC cylinders and that they do not represent the actual patch strength at the early age of 4 to 8 hours. The strength of the TMC cylinder would be more representative of the strength of actual patch since their maturity (temperature-time factor) is similar. Thus, verifying the strength for opening to traffic using field AC cylinders would be misleading. The maturity curve would provide a more reliable and representative strength for opening to traffic.

Table 8. Compressive Strength (psi) of Test Cylinders From SR 288 Patches[a]

Patching Date	Batch or Patch No.	Age (hr)	Air Cured	Temperature Matched Cured[b]
6/9/14	1A (first patch)	7.5	---	2,240
		34	3,640	3,180
	2A (last patch)	5.8	---	1,420[c]
		32	3,090	3,300
6/10/14	1B first patch)	8.5	1,020	2,510
		16.5	3,060	3,460
	2B (last patch)	6.5	390	1,660
		16.5	2,530	3,450

--- = not available.
[a] Values are the average of 2 cylinders.
[b] Temperature was matched for only the first 6-8 hours; for the remaining time, the temperature was either the air or lab temperature.
[c] Generator broke; TMC cylinders could not maintain/match patch temperature.

All patches were opened to traffic around 6 A.M. Figures 15 and 16 show the strength gain of the AC and TMC cylinders along with the time of mixing and opening to traffic. During the second night, the AC cylinders were tested right after opening to traffic. It is obvious from Figure 16 that the strength of the AC cylinder did not represent the actual strength of the patch, so using the strength of the AC cylinder for opening to traffic would be grossly inaccurate. The high temperature, hence the high strength, in the TMC cylinder indicates the feasibility of using the maturity method for estimation of strength for opening to traffic. The low value for TMC Cylinders 2A (last patch of the first night) was likely due to the generator stopping and the TMC cylinder not maintaining the temperature in the patch. In addition, the chloride permeability of the concrete cylinder specimens from the first night was measured at the age of 6 months and was above 6000 C, indicating poor durability.

Patching on US 58

For this project, the investigation of the early age concrete temperatures in the patches and the compressive strength development was similar to that of the patches on SR 288. Four patches were monitored, and a number of TMC and AC cylinders (4 by 8 in) were prepared from each patch. Cylinders were tested for strength at various ages. This was also a rich 5-hour mixture with 800 lb of cement.

There was a big difference in the temperature of the air and the patches, as shown in Figure 17; as a consequence, the AC cylinder had a much lower early strength than the actual patch would have. Compressive strengths for TMC and AC cylinders as a function of age are shown in Table 9 and Figure 18. TMC strengths were in compliance with VDOT’s specification except for that for Patch 2PL, which had a 6.0-hour TMC strength of 400 psi.

There was some evidence of poor concreting practice in one of the patches. The first truck of concrete to be delivered to the patching project had zero slump, likely because the quantity of high- and mid-range water reducer added was the same as used in the trial batch, which did not simulate travel time. The concrete should have been rejected, but it was installed with great difficulty. Future inspections of the patch can determine if performance was affected by placing concrete with a zero slump. Subsequent loads had the proper consistency because the ready mix producer used more high- and mid-range water-reducing admixtures.

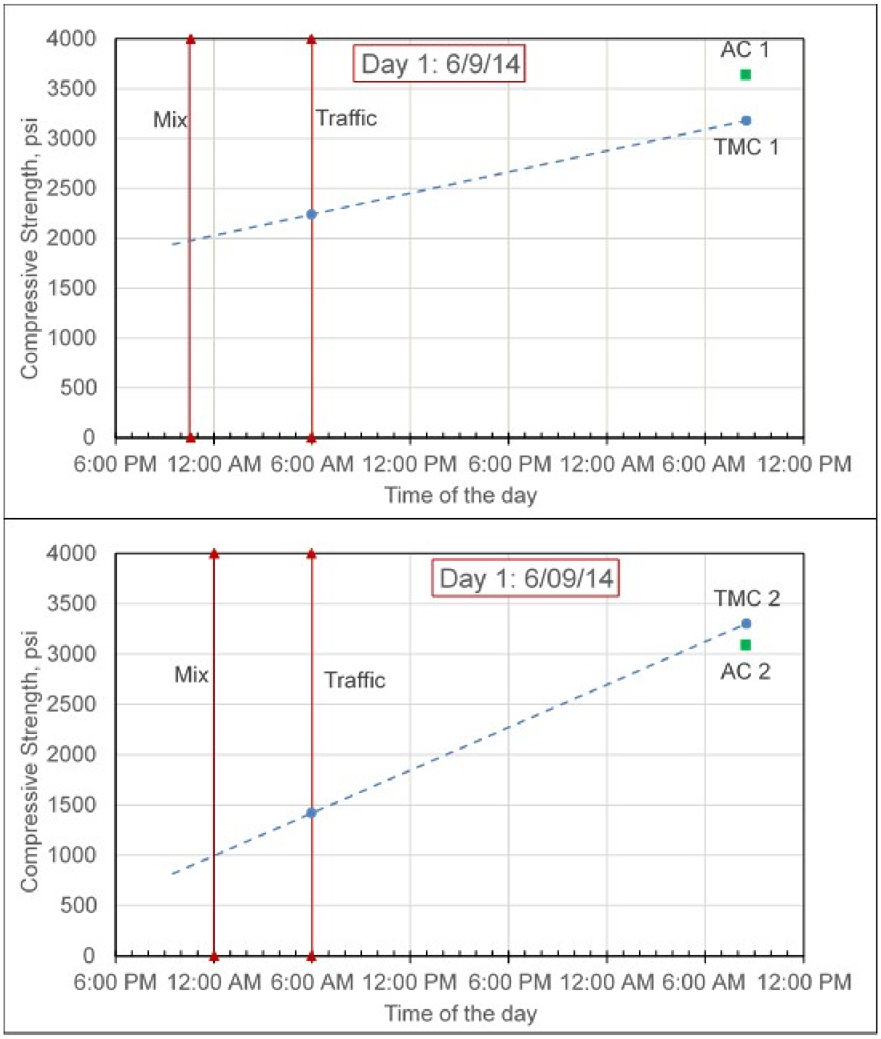


Figure 15. Compressive Strength Development for TMC and AC Cylinders From Patches on SR 288: Day 1 (first day of observation). TMC = temperature matched cured; AC = air cured.

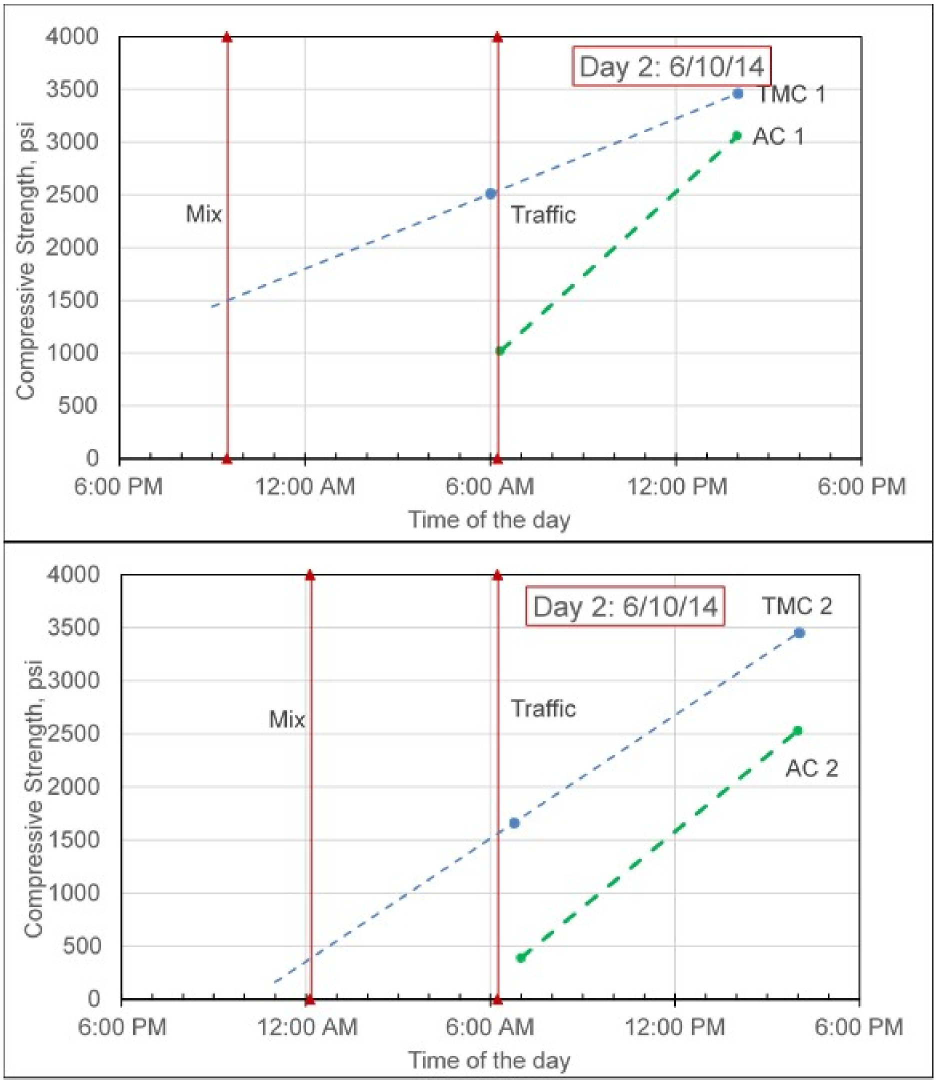


Figure 16. Compressive Strength Development for TMC and AC Cylinders From Patches on SR 288: Day 2 (second day of observation). TMC = temperature matched cured; AC = air cured.

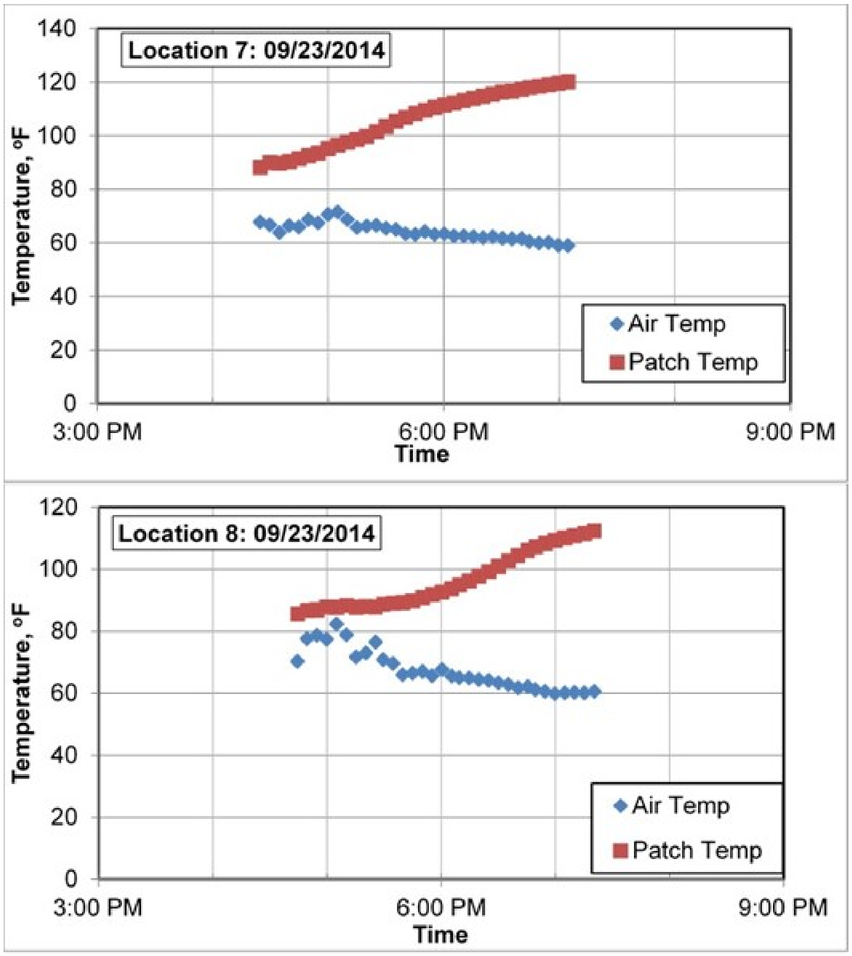


Figure 17. Temperature Variation With Time for Patches and Surrounding Air on US 58

Table 9. Compressive Strength of Test Cylinders (psi) From US 58 Patches

Patching Date	Patch No.	Batch Time	Age	Air Cured	Temperature Matched Cured[a]
9/23/14	7	1:44 P.M.	8.0 hr	1,020	1,770
			10.0 hr	1,630	3,180
			25.0 hr	3,230	4,390
9/23/14	8	2:12 P.M.	8.0 hr	1,110	2,790
			11.0 hr	2,130	3,020
			24.5 hr	4,170	4,500
9/25/14	1	1:08 P.M.	28.0 hr	5,170	---
			28 days	9,910	---
9/26/14	2PL[b]	11:21 A.M.	5.0 hr	100	---
			6.0 hr	---	400
			10.0 hr	1,680	2,790
			24.0 hr	3,260	4,360
			28 days	6,580	6,890

--- = not available.

[a] Temperature was matched for only the first 5-8 hours; for the remaining time, the temperature was either the air or lab temperature.

[b] Temperature matched curing was done by matching the temperature in a 5-gal bucket of patching concrete brought into the lab.

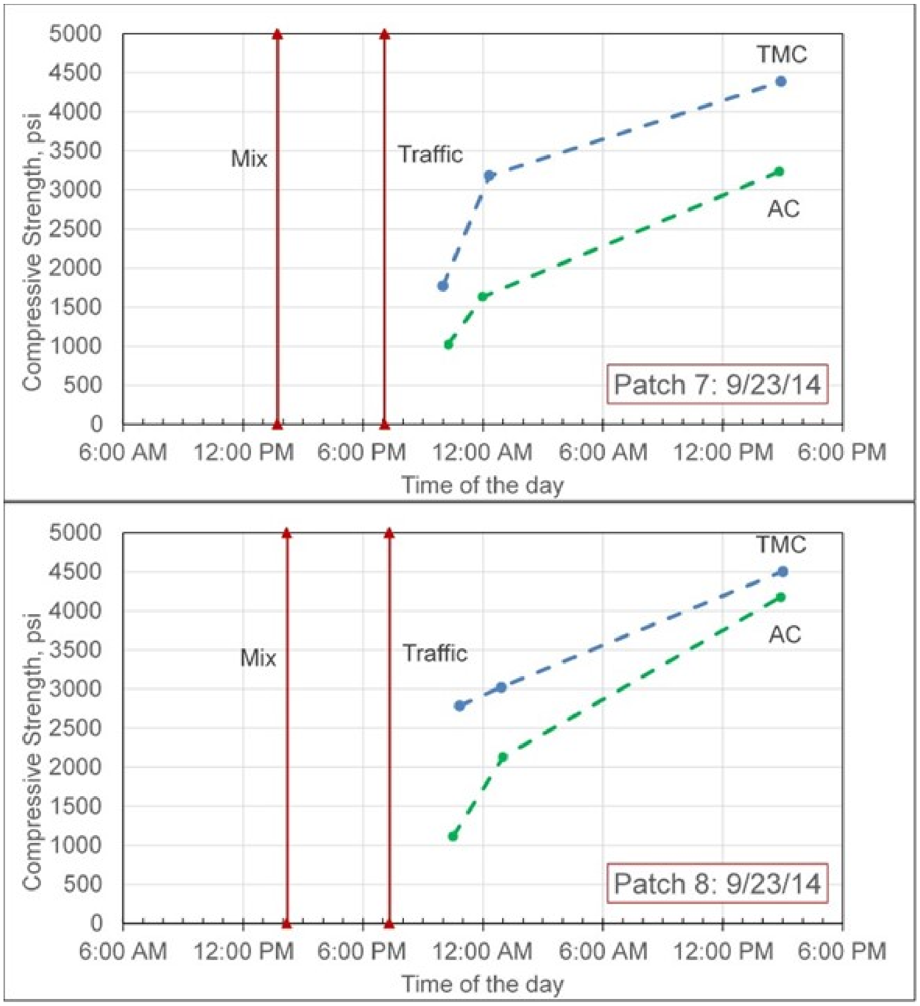


Figure 18. Comparison of Compressive Strength for AC and TMC Cylinders for Patches on US 58. The actual time of opening to traffic was not available and is estimated. AC = air cured; TMC = temperature matched cured.

Patching on I-264

Similar to other patch areas, two patches were monitored on I-264: the first and last batches of a night's work. This was the first project evaluated for this study. This jointed concrete pavement patching was selected because no CRCP projects were available at the start of the study. Only the early age strength behavior of the high early strength patching mixture was investigated. Again, it was also a rich mixture with 800 lb of cement; fresh concrete properties were determined for the first and last patch, which exhibited slumps of 1 in and 3 in, respectively, and air contents of 3.0% and 7.2%, respectively. VDOT No. 57 stone was used for the coarse aggregate. The early age concrete temperatures in the patches and the surrounding air temperatures were recorded for a few hours, and there was a big difference between them, as shown in Figure 19. Eight cylinders (4 by 8 in) were prepared onsite from each patch: four were TMC, and the others were AC. The compressive strengths of the TMC and AC cylinders were determined at different ages and are shown in Table 10 and Figure 20. The results suggest that the mixture satisfied the specification requirement of 1,750 psi at 5 hours in the patch but not in the AC cylinders, since they did not maintain the same temperature as the actual patches.

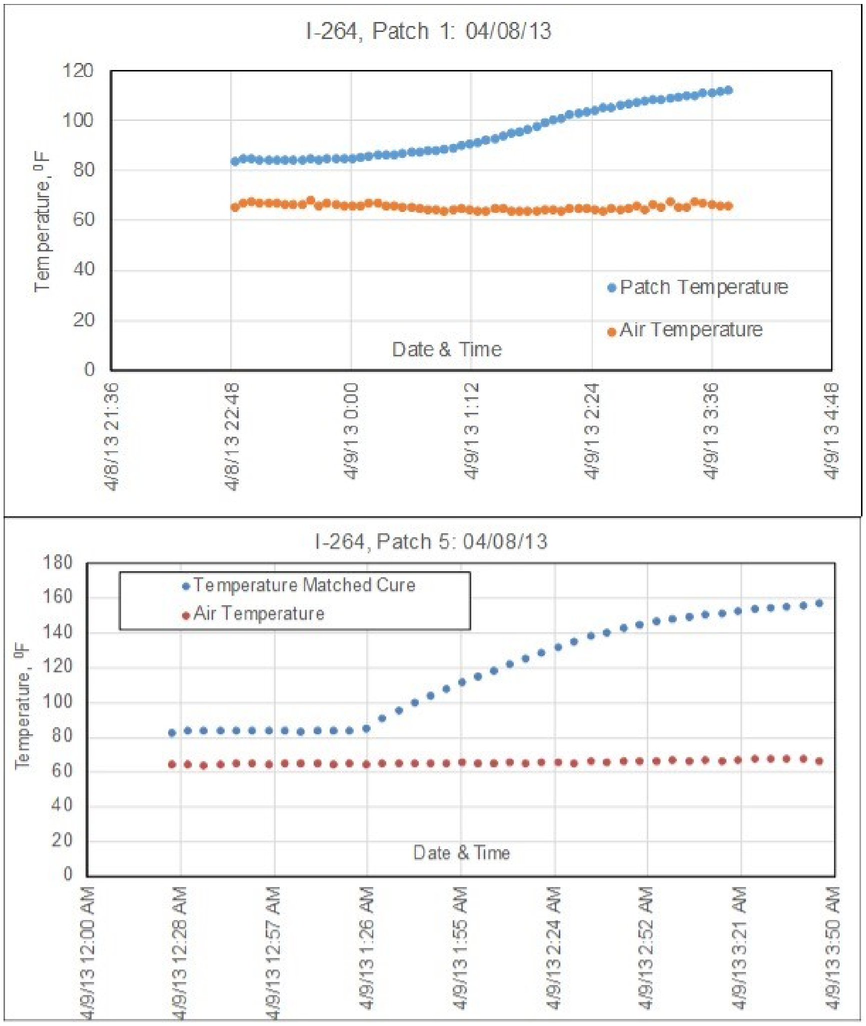


Figure 19. Temperature Variation With Time for Patches, Surrounding Air, and TMC Cylinders on I-264. TMC = temperature matched cured.

Table 10. Compressive Strength (psi) of Test Cylinders From I-264 Patches

Patching Date	Patch No.	Batch Time	Age	Air Cured	Temperature Matched Cured[a]
4/8/13	1	9:06 P.M.	8.0[b] hr	---	2,430
			14.0 hr	---	4,060
			3 days	5,050	5,590
			7 days	6,570	7,200
			7 days	7,040	---
			7 days	7,360	---
4/8/13	5	11:24 P.M.	6.0[b] hr	360	3,200
			12.0 hr	---	4,390
			3 days	4,770	4,890
			7 days	6,270	6,570
			28 days	7,440	---

--- = not available.

[a] Temperature was matched for only the first 5-8 hours; for the remaining time, the temperature was either the air or lab temperature.

[b] Within 30 min of opening to traffic at 4:30 A.M. to 5:00 A.M. the next morning.

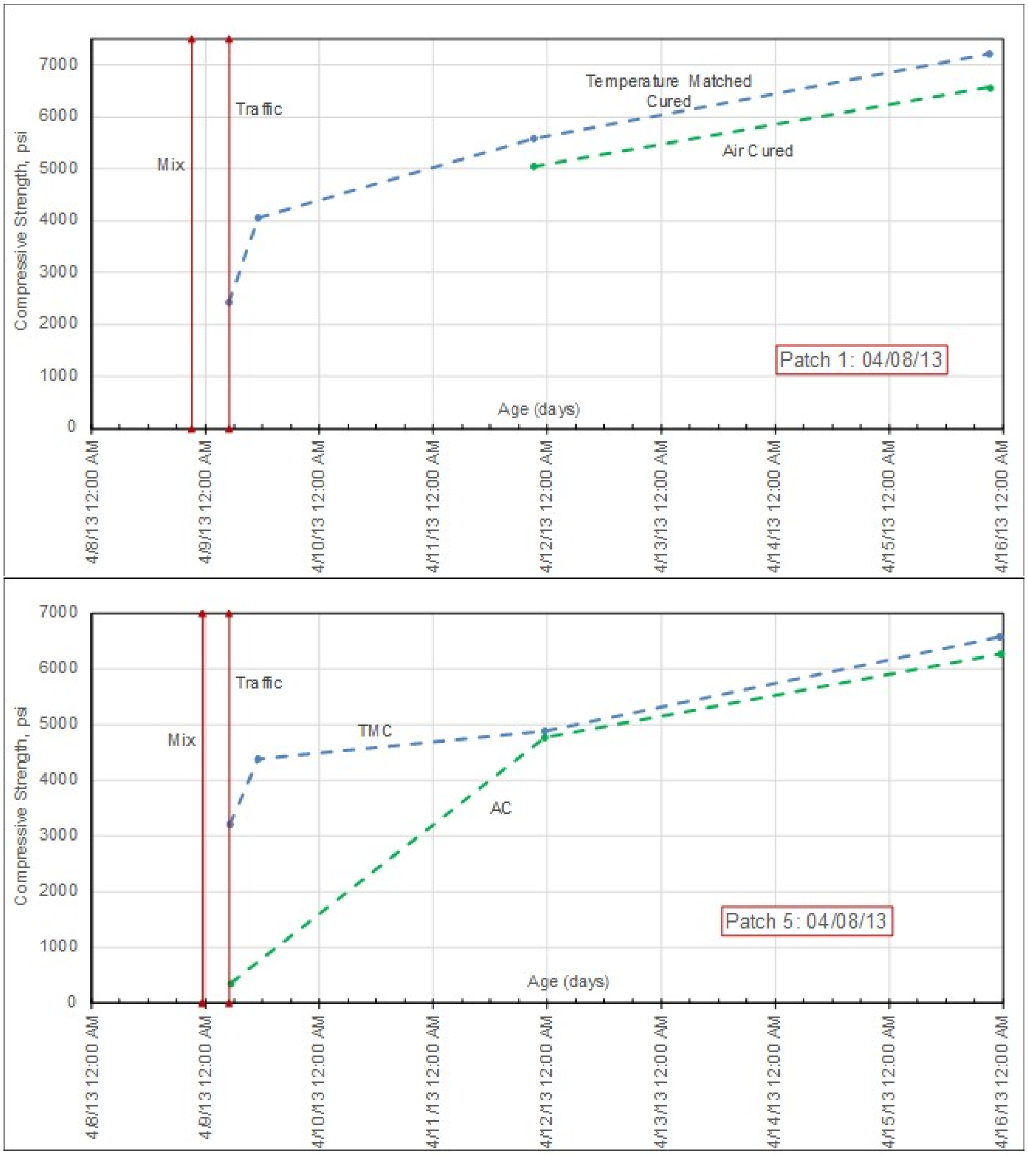


Figure 20. Comparison of Compressive Strength for AC and TMC Cylinders for Patches on I-264. AC = air cured; TMC = temperature matched cured.

A few cores were also collected from the patched area and original old concrete pavements. All appeared to be sound, showing no obvious signs of damage having occurred to the in-place concrete. The cores from the new patches tended to show a relatively high entrained air content. The cores from the original pavement showed some evidence of alkali-silica reaction product but no obvious associated damage to the aggregates or paste.

Installation of Reinforcement Connection Details

At least three new reinforcement connection details were monitored with respect to the construction of the patches, and these sites will be used for future performance evaluations. New connections included hose clamps, U-bolts, and six tie wires.

The hose clamps and U-bolts were tried on SR 288 to determine the feasibility of using these alternatives. Because of the concern that the ties do not provide a fixed continuity for the reinforcement, for the first patch on the first night, June 9, 2014, U-bolts were used for tying the reinforcement; hose clamps were attached in the second patch, as shown in Figure 21, but the splice lap length was not changed.

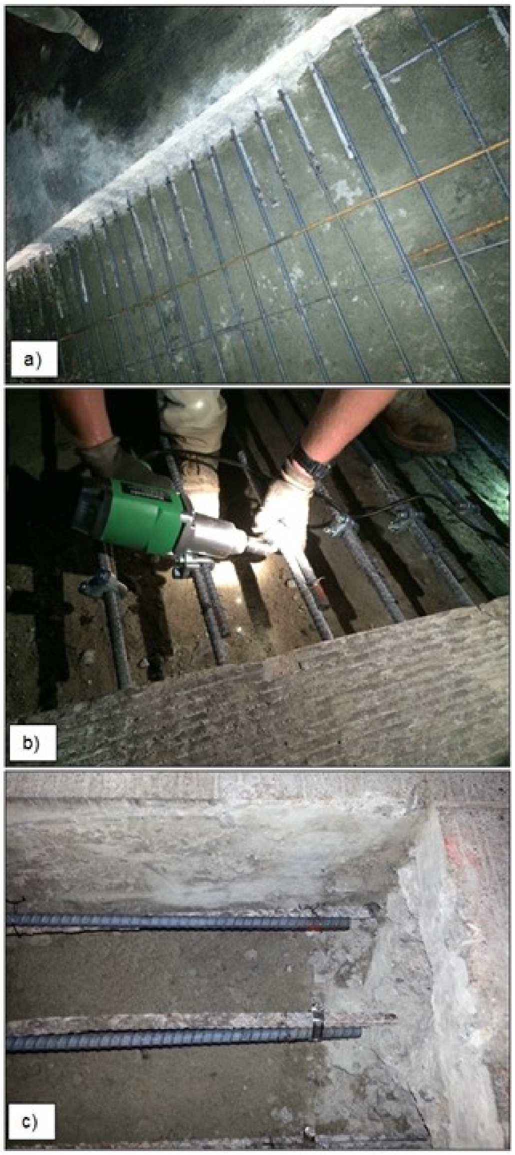


Figure 21. Splicing of Steel in Patches on SR 288: a) conventional method, 18-in overlap with 2 tie wires; b) U-bolts in first patch on the night of 6/9/14; c) hose clamps in second patch on the night of 6/9/14

These trial installations (two locations) on SR 288 were done successfully and did not raise any concern. So experimental installations of all three splicing techniques were done as part of the I-85 patching project. The new splice connections on I-85 are shown in Figure 22 and included six tie wires (Figure 22a), U-bolts (Figure 22b), and hose clamps (Figure 22c). The contractor did not have a problem installing the new connections, although some required more time and material than others. For example, six tie wires required more time and materials compared to two wires. Long-term monitoring may show if the new connections improve performance. The list of patches with different types of splice connections and their respective locations are summarized in Table 11. It is important to note that all of these patches were overlaid with 5.5 in of stone matrix asphalt (SMA) mixtures.

In the cases where the exposed reinforcing bar (rebar) was either missing or too short to be connected to the new rebar, extra steps were taken to ensure the new reinforcements could be firmly secured to the reinforcements exposed in the existing section. Figure 23 shows the results of the extra steps taken to ensure secure attachment of new reinforcement. If the rebar already in place was too short to connect with the newly installed rebar, a short bar was added to the new longitudinal rebar. If the original rebar was missing, a new piece was inserted into the hole and secured with epoxy. If the bar was missing in the existing section, a transverse bar was added.

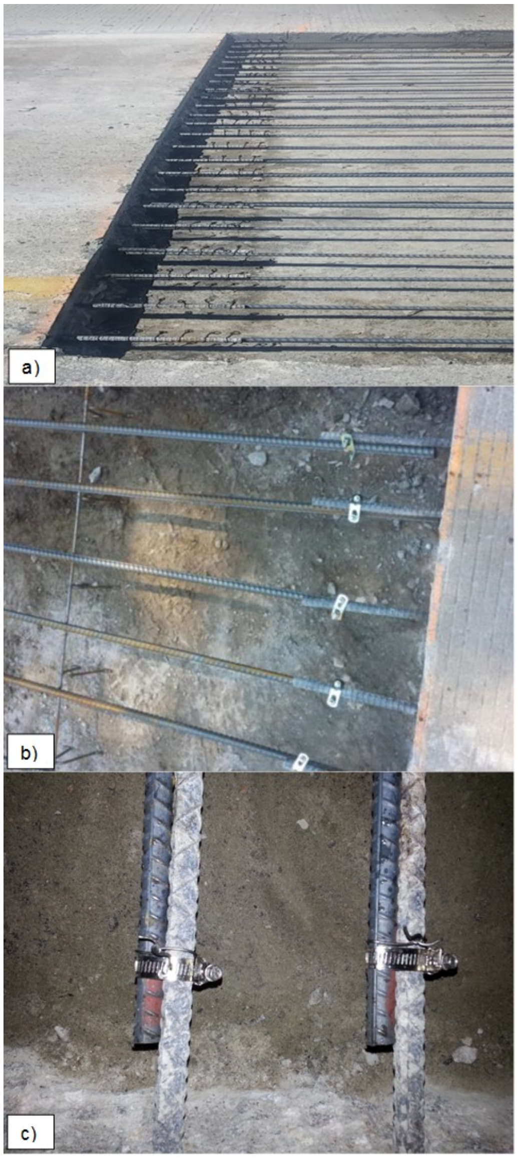


Figure 22. Splicing of Steel in Patches on I-85: a) 6 tie wires; b) 1 U-bolt; c) 1 of 2 hose clamps

Table 11. Patch Locations on I-85 for Different Splicing Methods

Splicing Method	Patch No.	Patch Length (ft)	Southbound Distance From MM 54 or MM 53 (start)	Date of Installation
Six tie wires	1	24.4	44.5 ft south of MM 54	4/29/15
	2	283.8	151.5 ft south of MM 54	
	3	251.8	496.9 ft south of MM 54	5/4/15
	4	129.2	1908.0 ft south of MM 54	5/13/15
	5	173.9	2212.6 ft south of MM 54	
	6	92.0	2459.6 ft south of MM 54	5/14/15
	7	90.3	2574.4 ft south of MM 54	5/18/15
	8	59.3	2789.5 ft south of MM 54	
	9	66.1	3003.4 ft south of MM 54	
Hose clamp	1	103.5	3947.5 ft south of MM 54	5/28/15
	2	160.3	4274.5 ft south of MM 54	
	3	262.1	4414.0 ft south of MM 54	6/1/15
	4	153.1	5000.2 ft south of MM 54	6/8/15
	5	32.5	739.2 ft south of MM 53	6/15/15
	6	132.0	1246.1 ft south of MM 53	
U-bolt	1	41.0	2821.5 ft south of MM 53	6/22/15
	2	76.9	3011.6 ft south of MM 53	
	3	34.3	3225.9 ft south of MM 53	
	4	12.1	3313.4 ft south of MM 53	
	5	22.6	3394.8 ft south of MM 53	
	6	12.0	3723.0 ft south of MM 53	6/29/15
	7	61.0	4017.0 ft south of MM 53	
	8	121.0	4164.0 ft south of MM 53	
	9	292.4	4300.0 ft south of MM 53	6/30/15

Figure 23. Exposed Reinforcement Is Absent or Too Short on SR 288

In the existing pavement, the reinforcement was placed through tubes that did not keep the steel at the desired depth in all cases. When the existing reinforcement was closer to the concrete surface, it was vulnerable to corrosion. In the patch area, continuous chairs were used to keep the reinforcement at the desired depth, as shown in Figure 24. Obviously, at the joints, the new reinforcement was at the same elevation as the existing reinforcement.

In some places, there were two bars present in the existing pavement when an old patch was being patched again; splicing was done with only one bar. Sometimes, existing reinforcement was bent so badly that splicing became difficult and additional transverse bars had to be installed to secure the splicing, as shown in Figure 25 for I-85.

Figure 24. Additional Supports Keeping Steel at Constant Depth on SR 288

Figure 25. Short and Bent Reinforcing Bars on I-85 Patching

Data Analysis

The analysis of the data collected for Tasks 1 and 2 may be summarized as follows:

- *One of the most significant causes of premature failures of patches was the use of high early strength concrete mixtures with high cement contents (as high as 800 lb) that cause excessive shrinkage cracking, as shown in Figures 3a and 10.* The narrow concrete sections between the transverse cracks soon crack in the longitudinal direction, providing weakened concrete sections that are prone to breaking into smaller sections, punchouts, and eventually spalls, typically in 1 to 5 years.

- *The other area of concern is the failure to assess the overall pavement condition, both in terms of what area needs to be removed and what structure is needed for future traffic.* In many cases, the pavement section was not adequate for current traffic, which might have contributed to the original failure. The only practical way to increase the structural capacity of the section is to place an overlay. Fortunately, most concrete patching being done today is followed by the application of an asphalt overlay of the entire section.

- *Other more localized causes of premature failures of patches could be the following:*

  — cutting of the continuous reinforcement, which allows the concrete to move and redistribute the stresses in the pavement

  — re-establishment of the continuity of bars when they are bent or too short or more than one bar is present (i.e., a leftover spliced bar per location from a previous patch) in the existing concrete (e.g., see Figure 25)

  — damage to concrete adjacent to the patch during concrete removal (possibly because of the use of heavy removal equipment) (e.g., see Figure 4a)

  — poor concreting practice with respect to the proper consolidation of the concrete in the vicinity of the adjacent hardened concrete (e.g., see Figure 7)

  — reinforcement in the old concrete being too close to the surface (i.e., not enough concrete cover because of the use of the tube feeding of bars in old pavement) (e.g., see Figure 5).

  Long-term visual observation of these patches is needed to confirm if such failures are occurring, but many of the patches have been overlaid with asphalt.

- *Opening the patches to traffic before the concrete had achieved the specified compressive strength of 2,000 psi (1,750 at 5 hours) was not found to be a problem.* But use of the compressive strength of the AC cylinder for such a determination may be inaccurate; a maturity method or TMC should be employed for estimation of in-place strength before opening to traffic.

- *Three connection details to reduce the splice length from 18 in to 9 in were tried.* However, all the locations have been overlaid with asphalt, so no performance data are available. Long-term monitoring may provide useful information.

Specification Revision and Best Practices

CRCP patching is expensive. Sprinkel et al. (2014), in their report on the construction and evaluation of concrete overlays on US 58, provided useful information on the cost of patching CRCP and the cost of using bonded and unbonded concrete overlays and asphalt overlays (Table 12). The data suggest that the cost to patch about 20% of the CRCP equals the cost to place 5 in of SMA over the entire pavement and the cost to patch about 25% of the CRCP equals the cost to place an unbonded concrete overlay over the entire pavement (Sprinkel et al., 2014). When many patches are failing in 1 to 5 years, an overlay with limited patching is a more cost-effective option. The installation of an overlay provides the pavement with some protection from the elements, increases the section modulus, and reduces the live load stress on the CRCP. Patching should be done when less than about 10% of the pavement (Sprinkel et al., 2014) has localized spalling and intersecting cracks that will likely become spalls in a short time. Because of the increase in traffic volume, the patches should usually be thicker than the original pavement or an overlay should be placed. The cost of the additional concrete to increase the thickness of a patch from 9 in to 13 in is only about \$13 per square yard, or about a 10% increase in the cost of the patch. There would be some additional cost to excavate the 4 in of base.

Table 12. Bid Prices of Materials In-Place for Asphalt and Concrete Overlays

HCC Unbonded Overlay	HCC Bonded Overlay	Asphalt Overlay
Length: 2.2 mi	**Length: 2.6 mi**	**Length: 9.75 mi**
1-in PFC: \$155/ton Cost/yd^2: \$8.53 (110 lb/in/yd^2)	Concrete patch: \$130/yd^2 Actual patched area: 10.6% Cost/yd^2: \$13.74[b]	Concrete patch: \$155.5/yd^2 Actual patched area: 12.4% Cost/yd^2: \$19.28[a]
7-in HCC: \$27/yd^2	4-in HCC: \$19/yd^2	3-in SMA-19.0: \$100/ton Cost/yd^2: \$16.6 (110 lb/in/yd^2)
HCC for profile correction up to 1 in: \$2.61	HCC for profile correction up to 1 in: \$3.38	2-in SMA-12.5: \$105/ton Cost/yd^2: \$11.54 (110 lb/in/yd^2)
Total[b]: \$38.14/yd^2	Total[b]: \$36.12/yd^2	Total[b]: \$47.42/yd^2

Source: Sprinkel et al. (2014).

HCC = hydraulic cement concrete; PFC = porous friction coarse; SMA = stone matrix asphalt.

[a] The cost for the entire surface area of the overlay.

[b] The cost for the maintenance of traffic is not included in the total.

CONCLUSIONS

- *One of the most significant causes of premature failures of patches is the use of high early strength concrete mixtures with high cement contents that cause excessive thermal and shrinkage cracking.*

- *The maturity method or TMC must be employed if flexural or compressive strength needs to be known.*

- *Patching concrete that is failing has strength and permeability that are similar to that of pavement concrete that is not failing, which suggests the failures are caused by factors other than these properties of the concrete.*

- *The existing concrete sections requiring patching had inadequate structure (i.e., thickness) for the current traffic, as indicated in Table 5. It is important to note that these pavements have already exceeded their design life.*

- *The performance of different tying mechanisms to shorten splicing length could not be determined at this time since those patches were overlaid with asphalt; long-term monitoring is needed.*

RECOMMENDATIONS

1. *VDOT's Materials Division and Construction Division should require in future special provisions that concrete patching mixtures include much less cement (as in the regular paving concrete) and include fly ash or slag when longer lane closures can be specified. In a single project, multiple mixture designs with varying cementitious materials could be used for achieving the required strength.*

2. *Chapter 6 of the VDOT Materials Division Manual of Instructions should be revised to indicate that the VDOT districts should require preliminary engineering prior to patching to consider the condition of the existing pavement, future traffic, and the need for patching and placing an overlay to improve the structural capacity.*

IMPLEMENTATION AND BENEFITS

Implementation

With regard to implementing Recommendation 1, VDOT's Materials Division should include the recommendation in future special provisions for patching.

Recommendation 2 has been implemented. It was made a part of Chapter 6 of the VDOT *Materials Division Manual of Instructions*.

Benefits

The benefit of implementing Recommendation 1 is that patches will last longer because they will be less prone to cracking and spalling. The mixtures with reduced cement contents and longer curing times (i.e., longer time to opening to traffic) should be permitted in the contract if maintenance of traffic time could be extended. Thus, multiple mixtures for a given project may be specified. No further implementation is needed.

The benefit of implementing Recommendation 2 is that the patches will have a longer service life and ride quality will be maintained because the increased pavement section can handle the loads imposed by increased traffic for future design life. No further implementation is needed.

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