Reduction of Joint Seepage and Cross-Grouting in Bridge Segments

Nur Yazdani, Ph.D., P.E.
Professor of Civil and Environmental Engineering
Florida A&M University-Florida State University
College of Engineering
Tallahassee, Florida

Moussa Issa, Ph.D., P.E.
Chief Structural Engineer
T.Y. Lin International
Chicago, Illinois

Epoxy is normally used to seal segment joints in precast/prestressed concrete bridges. Historically, it has not always been possible to create a good seal at the joint faces. Two new epoxy applications were tested in this study; a top strip recess at the joint, and a recessed annulus groove around the duct that provides a distinct guide for the proper amount of epoxy application. Eight segmented beams were fabricated with various combinations of epoxy-face applications, top strip and annulus. The beams were post-tensioned with a minimum required prestress force. Tanks placed above the joints were used to measure the seepage of water and joint permeability comparisons. Pressurized water was used to detect cross-grouting between ducts. The top strip provided slightly more seepage resistance than that provided by the current one-face epoxy application technique. This feature also improved alignment problems, segment defects, and epoxy application procedures. The practice of one-face application performed well in both tests, but problems occurred in providing the proper epoxy thickness and clearances. Both features performed well and assisted the epoxy application process in producing a reliable joint equivalent to solid concrete.

The use of precast/prestressed concrete members in bridge construction is increasing in popularity due to many factors including ease in erection and control of casting quality. The segmental bridge method uses precast concrete, typically box girders, to create large spans while reducing the complex construction problems.

A chemical epoxy adhesive is normally applied to the segment joints prior to post-tensioning. The American Association of State Highway and Transportation Officials (AASHTO) specifies that epoxied joints be utilized for all bridges having internal and/or external tendons, and for all bridges exposed to severe climatic conditions where freeze-thaw cycles are encountered or deicing chemicals are used.[1]

The primary functions of the epoxy are to provide a watertight seal at the joint in order to prevent the intrusion of water and deicing salts and to prevent the grout from bleeding at the joint. The epoxy can be manipulated, in conjunction with other materials, to change the alignment of the structure.[2]

The joints between precast units are vulnerable where ducts are not continuous and a relatively easy passage for water exists. Water penetrating into the joints and ducts may freeze and expand. In addition, the penetrating water may contain contaminants such as salt, automobile fluids, and deicing chemicals.[3]

All these substances can increase the corrosion rate of the internal tendons. If problems arise later due to the deficiency of the joints, costly repairs may be needed or a catastrophic structural failure may occur.

Recently, a few externally post-tensioned Florida bridges experienced tendon failures due to corrosion from grout voids in vulnerable locations. Among these bridges were the Mid-Bay Bridge in the Florida Panhandle and the Niles Bridge in the Florida Keys. The damaged external tendons were easy to remove and replace. The same would not necessarily be true for internal tendons.

Guidelines have been established for the amount of epoxy, area where epoxy should be applied, and removal of excess epoxy from the edges and ducts. Due to the popularity of segmental bridges in Florida, the guidelines for epoxy application set by the Florida Department of Transportation (FDOT) are generally accepted as the standard.

The current FDOT guidelines for epoxy jointing include provisions whose success heavily depends on the quality of the work and judgment of the contractor.[5,6] The quality of this bond is essential to the success of the epoxy, but is undetectable after the joint is closed.

At the time of this study, it was normal practice to apply epoxy to one face of the segments. The 1999 FDOT Segmental Manual identifies soft epoxy as a frequently occurring problem in segmental construction.[6]

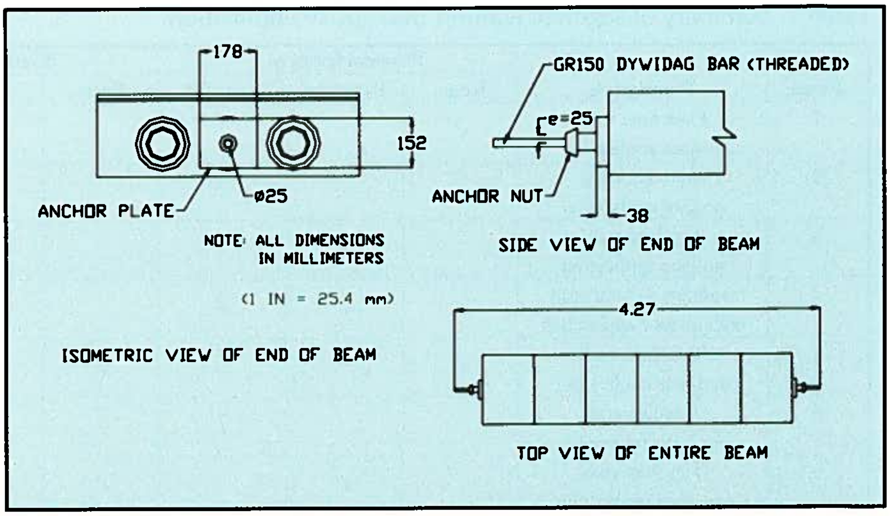


Fig. 1. Dimensions of test segment showing various cross sections of beam.

The study reported herein was developed to investigate the seepage resistance of the current epoxy jointing technique for segmental construction, and to compare it with two new epoxy features. These features are intended to improve the water seepage resistance of segmental joints against water seepage and cross-grouting, assist in proper alignment of segments, and provide distinct and convenient locations of epoxy application.

EXPERIMENTAL PROCEDURE

The experimental portion of this study involved the use of a top strip and an annulus feature with a typical model segmental structure. The experimental program was divided into three phases:

1. Segment Production Phase: The construction of necessary formwork and the casting of the precast concrete beam segments.

2. Beam Erection Phase: The assembly and erection of the beams, including the epoxy application and the post-tensioning operations.

3. Experimentation Phase: The testing of the beams for seepage quality.

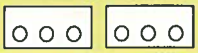
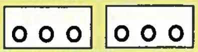
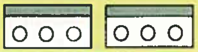
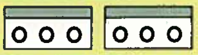
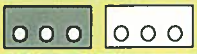
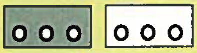
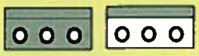
A test segment representing the top flange section of a typical segmental box girder was selected, as shown in Fig. 1. The model test segment was 610 mm (24 in.) long with a cross section 813 mm (30 in.) wide and 254 mm (10 in.) deep. Three ducts were equally spaced across the cross section of the segment at 200 mm (7.88 in.) spacing. These ducts had a diameter of 100 mm (4 in.) and were centered 150 mm (6 in.) below the top surface of the segment.

Three annuli were provided on the face of some of the segments. The male component of the annulus was a half-torus shaped ring, while the female component was a groove in the concrete with the same shape as the ring. The annulus had an inside diameter of 134 mm (5.28 in.) and an outside diameter of 172 mm (6.78 in.) with a width of 19 mm (0.75 in.) and a 45-degree chamfer.

In order to evaluate the effectiveness of the top strip, the annulus, and the face epoxy application, various combinations of these features were tested. The four different types of segments tested were: plain face, with annulus only, with top strip only, and with annulus and top strip. Six segments were cast for each beam following the short-line casting method. These segments were assembled, epoxied, and post-tensioned into eight separate beams, as shown in Table 1.

Beams 1 through 4 had no face epoxy application, while Beams 5 through 8 had one-face epoxy application. The beam with plain faces had no epoxy on any of the joints and served as the control in each group. Beams 1 through 4 were used to isolate the top strip and annulus features and test their individual effects, while Beam 5 represents the previous method used in typical segmental construction.

Table 1. Summary of segment features and epoxy application.

Beam	Description	Physical features			Epoxy application			Diagram
		None	Top strip	Annulus	Face	Top strip	Annulus	
1	Plain face with no face application	√						
2	Annulus with no face application			√			√	
3	Top strip with no face application		√			√		
4	Annulus and top strip with no face application		√	√		√	√	
5	Plain face with one-face application	√			√			
6	Annulus with one-face application			√	√		√	
7	Top strip with one-face application		√		√	√		
8	Annulus and top strip with one-face application		√	√	√	√	√	
		KEY: Duct ○		Annulus ◎		Top Strip ▭		Epoxy ▨

Material Properties

The concrete specified by the FDOT standards for most segmental bridge projects is typically a Class IV mix design.[8] Twenty-six gauge galvanized metal 100 mm (4 in.) diameter pipes were used for the 610 mm (24 in.) long post-tensioning ducts. The casting cells were coated with a common form release liquid before the concrete was poured. The Burke Clean Lift 90 was used as a bond breaker for the match casting operation.

Bearing grease was used in the grooved areas for bond breaking. The grease was thoroughly removed afterwards by using a paint thinner. The Kure & Seal curing compound was applied to the concrete segments after the forms were removed.

The Sikadur 31 segmental bridge adhesive used in this study is a high-modulus, high-strength, moisture insensitive epoxy with an open time of 60 minutes. Eight pieces of 25 mm (1 in.) diameter Grade 150 threaded Dywidag bars were used for post-tensioning. The steel bars were anchored by 152 x 178 x 37 mm (6 x 7 x 1.5 in.) plates and held by 25 mm (1 in.) anchor nuts, as shown in Fig. 2.

Preparation, Setup, and Casting

Wood forms were used in which the female groove was routed and the male ring was attached. In order to construct the top strip, a piece of wood was cut to dimensions that are half that of the top strip and attached to the respective bulkheads. The actual casting cells, shown in Fig. 3(a), consisted of three boards and one bulkhead bolted together and screwed down to a single sheet of plywood for the first pour. The match cast segment replaced the second bulkhead.

To eliminate the possibility of cracking from transportation or thermal effects, a layer of welded wire mesh was placed in the upper section of the cells. PVC pipes, 25 mm (1 in.) in diameter, were attached vertically to the end of the post-tensioning ducts in the first and last segments in each beam to simulate grout inlet/outlet pipes. The segments were fabricated during November-December 1996. The compressive strength of concrete varied between 41 to 56 MPa (5.95 to 8.12 ksi) with an average of 47.8 MPa (6.93 ksi) for the various segments.

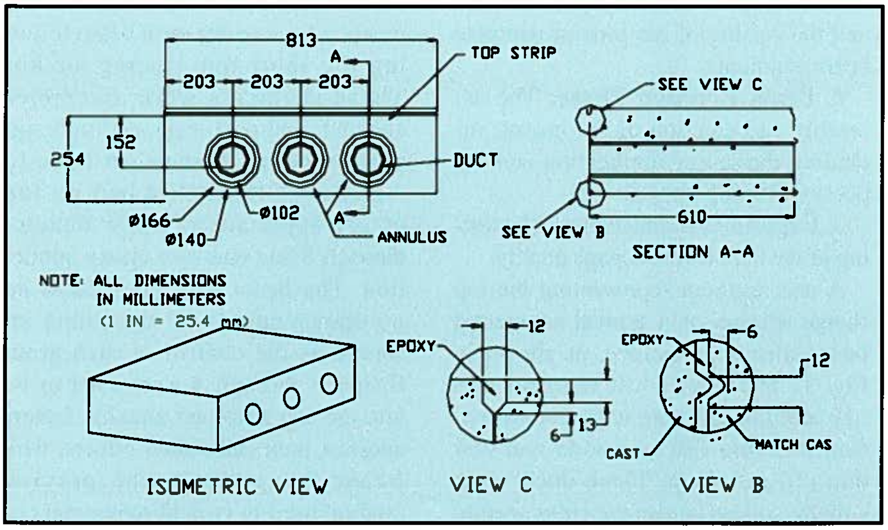


Fig. 2. Detail of post-tensioning anchorage.

Epoxy Jointing

The segment assembly method used herein resembled the span-by-span technique of utilizing a support truss to assemble the segments of the span, including epoxy application and post-tensioning. The segments were spaced at a 300 mm (12 in.) distance to allow access to the faces for the application of epoxy, as shown in Fig. 3(b).

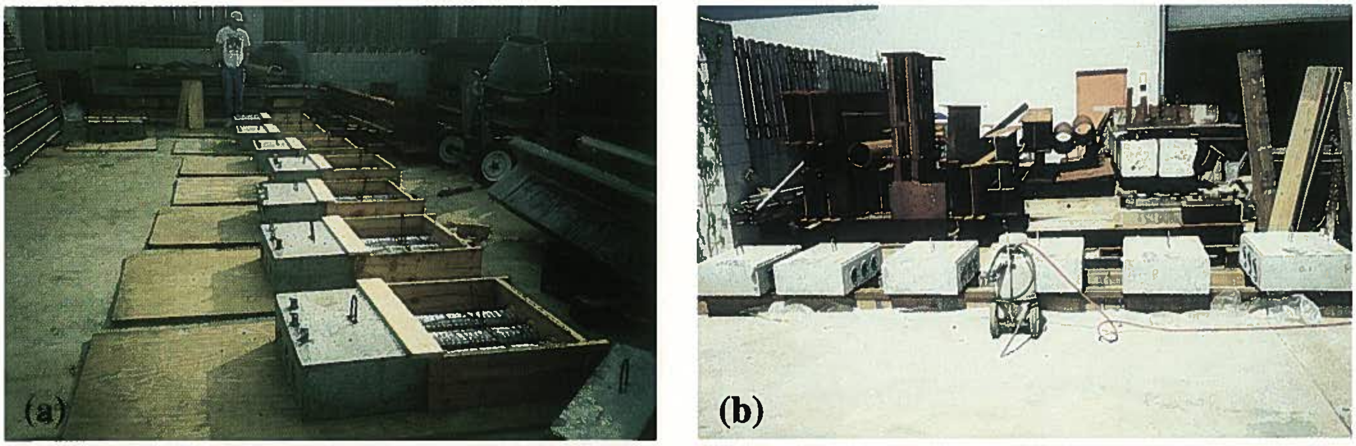


Fig. 3. Details of test setup: (a) Layout of casting cells in yard; (b) Assembly setup for the model segmental beams.

Following manufacturer instructions, approximately one to two minutes was needed to apply the epoxy for each joint. In the test samples requiring epoxy application to the annulus, the annuli were completely filled flush with epoxy. The thick consistency of the epoxy made it difficult to fill the grooves perfectly, but a satisfactory application was made. The interlocking of the annulus was very helpful in aligning the segments in their proper positions. After the beam was post-tensioned, the ducts were swabbed to remove any excess epoxy.

In order to simulate field conditions, the joint faces of Beam 5 were coated with epoxy at an estimated average thickness of 2 mm (0.075 in.), with 12 mm (0.5 in.) edge clearance and 25 mm (1 in.) duct clearance. A large amount of extruded epoxy was observed on the edges and inside the ducts in Beam 6 after post-tensioning. Figs. 4(a) and 4(b) show the application of epoxy on the face and annuli, and on the top strip, respectively.

Even with the presence of the annuli, top strip, and epoxy face application (Beam 8), only a few minutes for epoxy application in each joint and 25 minutes for the entire process were needed. The key-like action of the annuli made it easier for the matching of segments in the beams with annuli.

Post-Tensioning

The post-tensioning force was designed to provide a minimum compressive pressure of 0.3 MPa (43.51 psi) across all joints to set the epoxy.[7] Simple support conditions were assumed due to the eccentric tendons and expected camber. The actual section moduli for the beam section were found to be adequate with respect to ACI allowable tensile and compressive stresses.[8]

It was determined that a minimum effective prestress force of 120 kN (27 kips) was needed to achieve the minimum compressive pressure needed at the critical location (bottom of midspan joint) for epoxy setting. Only one bar was used in the middle duct, leaving the other two ducts accessible for examination. In practice, the temporary post-tensioning steel is located outside of the main internal ducts, leaving them accessible for swabbing. The erected beam and support conditions are shown in Fig. 5(a).

Joint Seepage Test

The joint seepage test was undertaken to evaluate the seepage resistance of the eight beams with various combinations of epoxy application. Plastic tanks filled with water were positioned above each joint to determine the extent of water seepage through the joints, as shown in Fig. 5(b). The inner dimensions of each

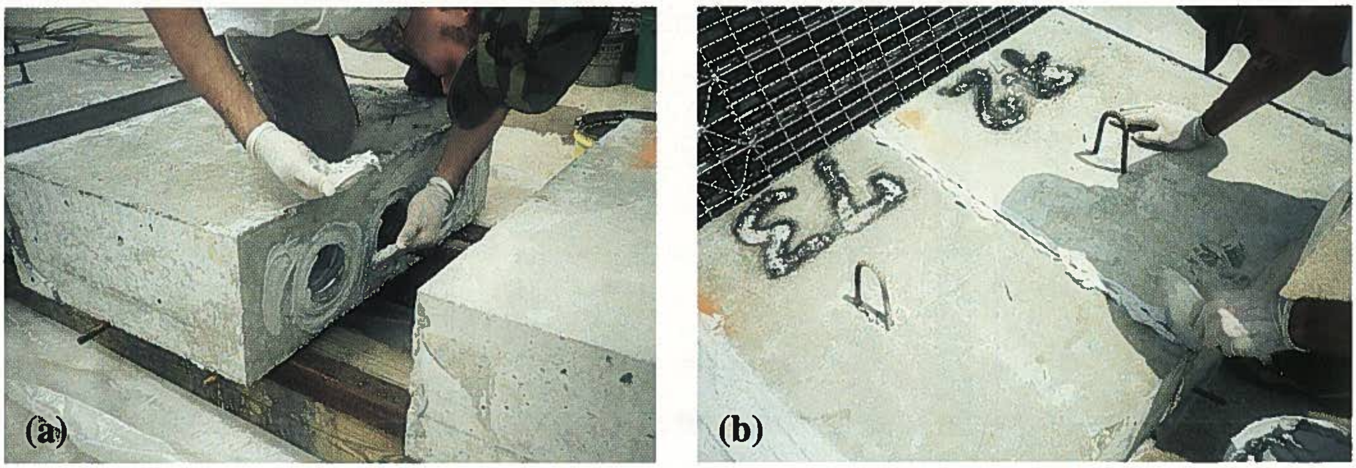


Fig. 4. Details of epoxy application: (a) Epoxy application on annulus and one face; (b) Epoxy application in a typical top strip.

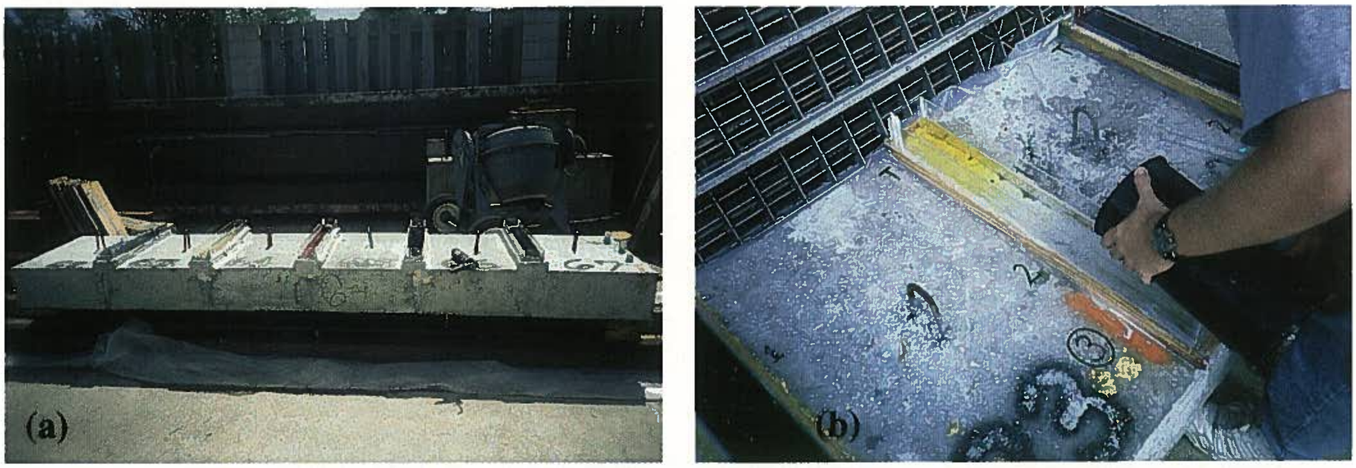


Fig. 5. Photographs of beam test: (a) Erected beam with simple supports; (b) Joint seepage test in progress.

tank were 100 mm (4 in.) wide, 762 mm (30 in.) long, and 100 mm (4 in.) high. Plastic rulers were fastened to the sides of the tanks for water drop measurements.

An additional tank was placed on one of the segments in Beam 1 to act as the control tank for the first group of Beams 1 through 4. This control tank was used to account for water loss due to evaporation and the porosity of the concrete. For the second group of beams (Beams 5 through 8), a separate control tank was placed on Beam 5.

Each control tank was placed on the solid concrete surface, not over a joint. The tanks were filled with dyed water to a depth of roughly 50 mm (2 in.). The tanks were covered with polythene sheets to minimize water loss due to evaporation. Readings of the water depth in the tanks were taken daily over a two-week period. The ducts were swabbed near each joint to check for seepage of the dyed water.

An additional seepage test on Beam 1 was performed, in which the post-tensioning force was increased in increments of 30 to 40 kN (6.74 to 8.99 kips). The changes in tank water depth were recorded for each prestress level. This test was expected to provide a relationship between joint stress and water seepage.

Cross-Grouting Test

The cross-grouting test consisted of filling the ducts with water along the beams and pressurizing them to force the water through any openings at the joints. Because water has a lower density than grout, the pressurized water test provided a more critical evaluation of the joints.

Using PVC pipe fittings, an apparatus that contained a one-way air valve and an air gauge was devised. This apparatus was connected to the grout inlet pipe embedded in concrete during casting. Ducts were capped at the ends and epoxied at the edges to create the necessary airtight seal. All detectable leaks were patched during the numerous trial runs of this test. The ducts were then filled with air to an initial pressure of 0.2 MPa (29 psi) and the loss of pressure with time was recorded.

The amount of pressure maintained after 1.5 hours, when actual grout generally begins setting, was the focus for

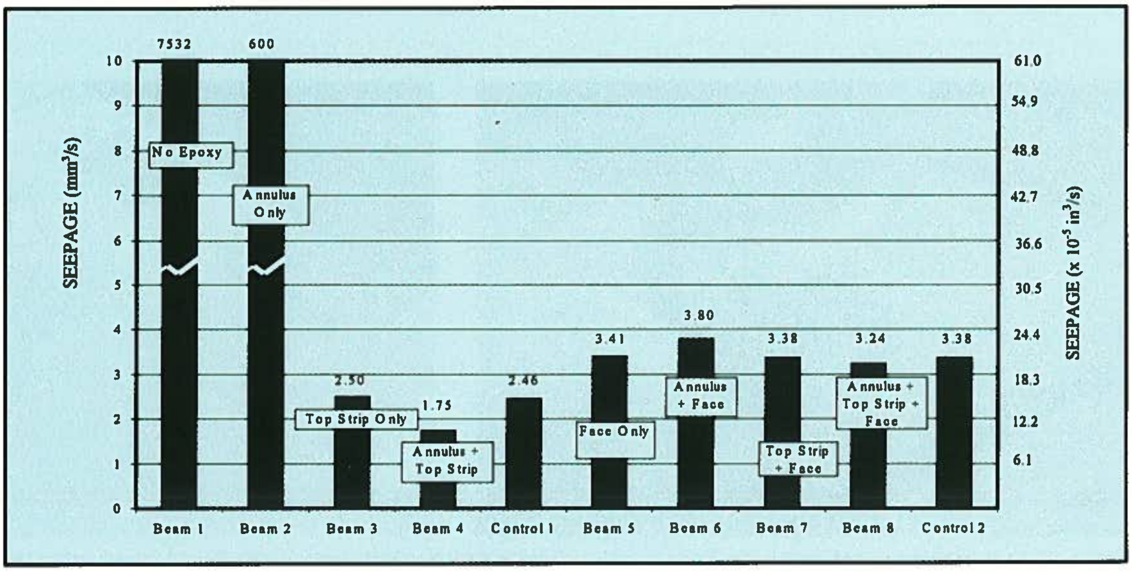


Fig. 6. Average joint seepage for all beams and controls.

this test. The joints were examined for water leakage during this time. Upon completion of these tests, the ducts were pressurized over 0.4 MPa (58 psi) of air pressure, the maximum reading on the gauge, or until the plugs on the ducts failed.

Table 2. Stress at joints in Beam 1 due to prestress force.

Prestress force (kN)	Stress (MPa)					
	Joint 3 (Midspan)		Joints 2 & 4		Joints 1 & 5	
	Top	Bottom	Top	Bottom	Top	Bottom
121.9	–0.98	–0.33	–0.89	–0.43	–0.62	–0.72
151.1	–1.06	–0.58	–0.97	–0.68	–0.69	–0.97
188.8	–1.16	–0.90	–1.06	–1.00	–0.79	–1.29
234.7	–1.27	–1.29	–1.18	–1.39	–0.91	–1.68
274.0	–1.38	–1.63	–1.28	–1.72	–1.01	–2.01
315.1	–1.48	–1.98	–1.39	–2.07	–1.12	–2.36
356.6	–1.59	–2.33	–1.50	–2.42	–1.22	–2.71

Note: 1 MPa = 145 psi; 1 kN = 224.8 lbf.

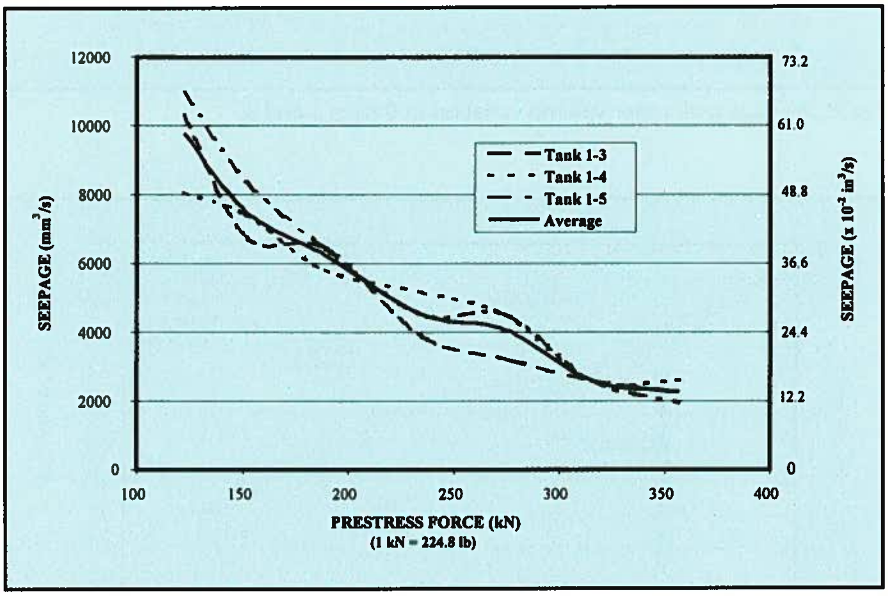


Fig. 7. Effect of prestress level on joint seepage for Beam 1.

Failure Test

Segments from all the beams, except for Beams 1 and 3, continued to be attached by the epoxy after the post-tensioning was removed. Each beam was lifted and dropped in a way to produce a high impact load from its own self-weight. This test was performed to examine the surfaces for stains from the testing dye and epoxy coverage.

TEST RESULTS AND DISCUSSION

Results from each of the three tests performed in this study are presented in the following. Discussion on the obtained test results are also included.

Joint Seepage Test

The seepage rate is defined herein as the volume of water lost per second (mm^3/s). Beam 1 provided a demonstration on the performance of dry joints in a beam. From Fig. 6, the high seepage in Beam 1 is clearly demonstrated. The swabbing of each duct produced evidence of a significant amount of dyed water in the ducts.

The prestress forces and resulting joint stresses for the additional test on Beam 1 are presented in Table 2. Fig. 7 shows that the joint seepage rate decreased by about 770 percent as the post-tensioning force increased about three times.

It appears that if the joints were subjected to tensile stresses due to a large prestress force or eccentricity, the seepage would greatly increase in dry joints, such as in Beam 1. Therefore, it is essential to develop a good bond between the epoxy and concrete faces.

In reality, bridges built with dry joints usually have some detail to seal the joint — such as a neoprene strip inset in a recess between the faces across the top slab, or a thick sealant face application prior to closing or an epoxy filled groove (as in Beam 3). Also, AASHTO required that segmental dry joints be used only with external prestressing tendons. In these bridges, the external tendons are protected independently against corrosion. In 2002, AASHTO removed the provision of dry joints from its specifications.

Only the annuli in Beam 2 were epoxied in order to isolate and test the capability of the annulus feature. As seen in Fig. 6, the average seepage rate of 600 mm^3/s (0.037 in.^{3}/s) in Beam 2 was considerably less than that of 7532 mm^3/s (0.46 in.^{3}/s) for Beam 1. It was evident from the amount and location of the excess squeezed epoxy in Beam 2 that the joint faces were only partially covered, as expected.

The average seepage for Beam 2 was well above the control seepage rate of 2.46 mm^3/s (0.000150 in.^{3}/s). The swabbing of the ducts for Beam 2 produced no traces of dyed water. Because the gaps between adjacent annuli were not sealed with epoxy, some seepage would naturally occur through the gaps. This is why the seepage from Beam 2 was higher than that of all the other epoxy sealed beams.

The effectiveness of the top strip feature was tested through its exclusive use in Beam 3. No water was visible below the joints and no stains were found from swabbing the ducts throughout the testing period for this beam. The average seepage rate for Beam 3 was 2.49 mm^3/s (0.000150 in.^{3}/s), only 1.26 percent more than the control tank seepage. Beam 4 was a combination of Beams 2 and 3.

Fig. 6 shows an average seepage of 1.75 mm^3/s (0.000107 in.^{3}/s) for Beam 4, 29 percent less than the control rate. This demonstrates that the joint was virtually impenetrable to water, and

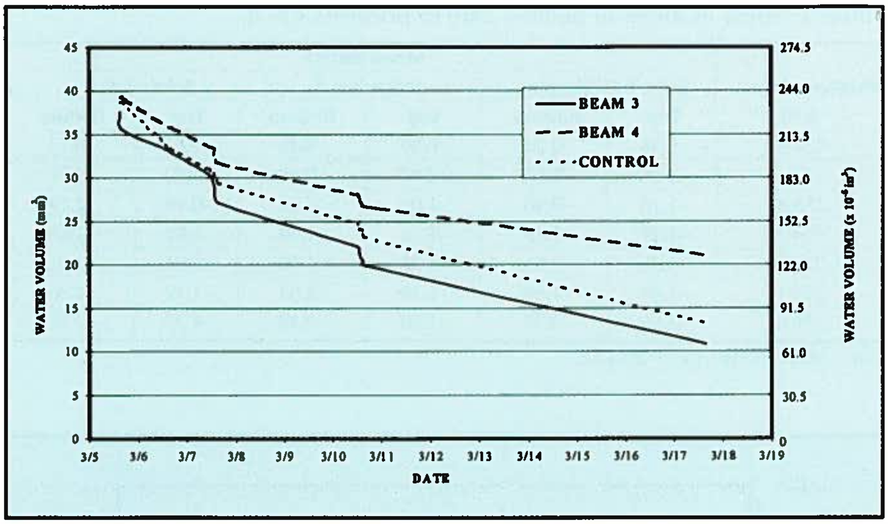


Fig. 8. Average tank water volume variation in Beams 3 and 4.

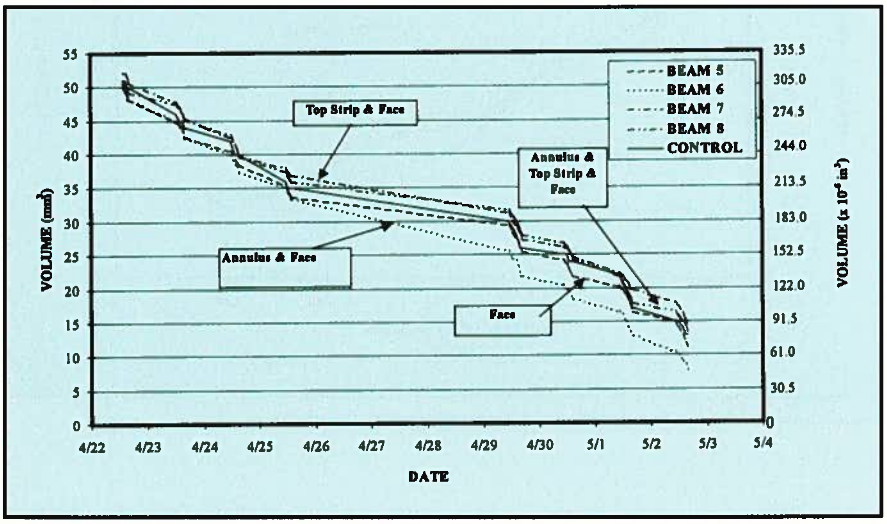


Fig. 9. Average tank water volume variation in Beams 5, 6, 7, and 8.

that the effects of the concrete porosity were reduced by the epoxy in the top strip.

Fig. 8 compares the average seepage behavior of joints from Beams 3 and 4 in terms of the change in tank water depth. Seepage lines for both beams are nearly linear, which means that the seepage ratios were generally constant. The sudden drops in the seepage lines represent increased evaporation when the tanks were uncovered to take water depth readings.

In terms of the joint seepage, Beams 3 and 4 were virtually identical, because the top strip is likely to be the main resistance to water seepage. The lower seepage rate for Beam 4 demonstrates that the joints were virtually impenetrable, and that the effects of the concrete porosity were reduced by the epoxy.

As previously mentioned, Beam 5 represents the practice of epoxy application on one face of the joint with proper clearance. During the epoxy application process, the required excess epoxy bead lines formed at all joints, which indicated that the epoxy squeezed out evenly at all edges.

Fig. 6 shows that the average rate of seepage for Beam 5 was 3.41 mm^3/s (0.000208 in.^{3}/s) and only 1 percent higher than the control seepage. Swabbing of the ducts in Beam 5 produced no traces of dyed water seepage from the tanks.

Beam 6 included the annulus feature with one-face application of epoxy. From Fig. 6, it is observed that the average seepage for Beam 6 was 3.80 mm^3/s (0.000232 in.^{3}/s), 12.6 percent greater than the control seepage. No water was detected inside the ducts or around the joint edges for Beam 6.

Beam 7 included the top strip along with one-face application of epoxy. Theoretically, if the top strip performed as expected, that face application of epoxy would be redundant. The average seepage rate for Beam 7 was 3.55 mm^3/s (0.000217 in.^{3}/s), only 5.3 percent higher than the control seepage. In Beam 7, no water was detected inside the ducts or around the joint edges. In Beam 8, the annulus was added to the top strip and one-face epoxy application.

As seen in Fig. 6, the average seepage for this beam was 3.24 mm^3/s (0.000198 in.^{3}/s), 4.1 percent lower than the control seepage of 3.38 mm^3/s (0.000206 in.^{3}/s). No water was found in the ducts or around the joint edges for Beam 8.

The average variation of tank water depth with time in Beams 5, 6, 7, and 8 are presented in Fig. 9. Beams 7 and 8 are found to hold more water above the joints than the control tank or Beams 5 and 6. Although the seepage line representing Beam 6 shows slightly more seepage towards the end, the overall trends of all the lines are almost identical.

The slight drops in all the lines verify the earlier assumption about the evaporation increase during the time of readings. These drops occurred for all beams and affected the results similarly.

It is very significant that the seepage rates for epoxy filled joints from Beams 3, 4, 5, 6, 7 and 8 are very similar to the results from Controls 1 and 2. The differences are not significant. This demonstrates that properly applied epoxy can create a seal equivalent to solid concrete.

Cross-Grouting Test

The absence of epoxy on the joint faces of Beams 1 and 3 prevented the ducts from maintaining any amount of internal pressure. For both beams, the air pressure applied to the ducts resulted in water flowing from one outer duct to the other outer duct. This "cross-grouting" of ducts brought a significant volume of water to the empty duct.

Due to the openness of the joints in these beams, established in the joint seepage test, water that did not accumulate in the duct escaped through the near edges of the joints. In the Beam 3 test, the top strip blocked the water from escaping through the top edge of the joint.

The lowest pressure drops of the multiple tests for each beam are illustrated in Fig. 10. The pressure drop lines for the beams are fairly linear, indicating constant pressure losses with time. All of the beams, except for Beam 5, maintained over 75 percent of initial pressure after one-and-a-half hours and over 50 percent after three hours.

The data for Beam 5 demonstrated that the ducts maintained 50 percent of the initial pressure for at least one hour. The water pressure in Beam 6 remained at 21×10^{-2} MPa (30 psi) for the entire three-hour test period. This beam indicated that the use of annuli with a one-face application created a watertight seal across all of the joints, demonstrating that single-face application with a filled annulus functions well. Excluding Beams 1 and 3, no water leakage from the joint edges of any beams was detected.

As mentioned previously, water was used instead of actual grout in the testing for convenience and practicality. Because the water was not as dense as grout, the performances of these joints were intentionally underrated. Even with this conservative approach, no cross-watering was evident for the beams with epoxied faces and/or epoxied annuli.

Failure Test

The high bonding strength of the epoxy was evident when Beam 5 failed through the middle of the first segment rather than at a joint. This strong epoxy quality limited the number of separated joints to about two for each beam. The separated joint below Tank 8-4 is shown in Fig. 11.

The following characteristics were noted from inspection of the separated joints after the failure tests:

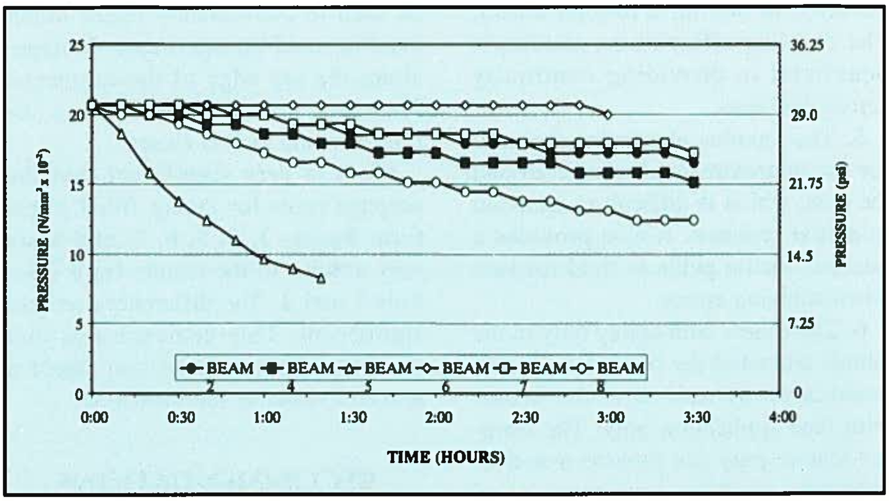


Fig. 10. Pressure variations in beams.

Fig. 11. Joint separation for failure test.

1. For most of the joints, the segments separated either just to the left or to the right of the epoxy layer.

2. None of the joints had any dye stains.

3. The excess epoxy from the annuli at a Beam 2 joint covered nearly two-thirds of the face, but did not distribute at an even distance from the annuli.

4. The bond strength of the annuli and top strip of a Beam 4 joint caused the beam to separate approximately 100 mm (4 in.) away from one joint.

5. In a Beam 6 joint, the interior duct that was not swabbed had an adequate amount of excess epoxy around the entire duct.

6. In a Beam 7 joint, the interior duct that was not swabbed had excess epoxy only halfway around the duct.

CONCLUSIONS

Based on the results of this investigation, the following conclusions can be drawn:

1. Careful and immediate attention is needed with the swabbing of ducts after segment joint closure. Blockage in the ducts due to epoxy may be as harmful as blockage due to cross-grouting.

2. The practice of one-face epoxy application performed well in this study when it was applied properly.

3. Creating the annulus in a segment is simple and may be achieved by the match cast process. It requires no significant extra time during the epoxy application procedure.

4. The annulus provides a duct coupling that resembles the function of a rubber gasket, but eliminated the complication of adding a foreign object. The coupling effect of the annulus is beneficial in providing continuity across the joints.

5. The annulus eliminates the need for the approximate clearance around the duct, which is difficult to maintain in actual practice. It also provides a positive, tactile guide to field workers when applying epoxy.

6. The beams with epoxy only in the annuli protected the ducts from water penetration as well as in the beams with face application only. The annulus feature may not provide a noticeable joint seepage improvement as compared to the typical face application, but it will provide an auxiliary resistance.

7. The annulus provided a watertight seal for over four hours. In practice, the dense grout material is unlikely to flow between the ducts with the annuli application before it sets.

8. The application of epoxy only in the top strip was more effective in resisting water penetration than the typical one-face application. This demonstrates that the epoxy just needs to act as a fill in the top strip to prevent water penetration. This detail may help with retrofitting when shims are used.

9. The top strip allows the use of epoxy to make corrections to the segment alignment problems if necessary, and elimination of the required edge clearance. The strip can conveniently collect excess epoxy squeezed out from the faces. The top strip can also be used to conveniently repair minor handling and transportation damages along the top edge of the segments. The strip can be filled with epoxy any time after the joint is closed.

10. It is very significant that the seepage rates for epoxy filled joints form Beams 3, 4, 5, 6, 7, and 8 are very similar to the results from Controls 1 and 2. The differences are not significant. This demonstrates that properly applied epoxy can create a seal equivalent to solid concrete.

RECOMMENDATIONS

The following recommendations are made based on the conclusions of this study:

1. Proper swabbing of the ducts after joint closure should be practiced to remove excess epoxy squeezed out into the ducts.

2. At a minimum, the practice of one-face epoxy application should be continued. Total epoxy coverage is needed in the joint to prevent the penetration of water that may pass through the concrete.

3. It is recommended that the circular annulus and top feature strips for epoxy application in segmental construction be utilized by state highway departments.

4. A reliable and simple mechanical applicator should be adopted for convenient application of epoxy in the annulus feature.

5. Practical input from the construction industry should be sought prior to instituting the recommended changes.

6. Further investigation of other more efficient annulus shapes is needed. The investigation may include rectangular shapes and combined annulus around several ducts. The proper shape and configuration may eliminate the need for epoxy application around the ducts on both faces. Shims and joint tension found in precast balanced cantilever construction should be investigated in future tests. The effect of increased compressive stresses on seepage reduction at epoxy joints should also be studied. The performance of the "Foam Donut" system of sealing the duct opening needs to be compared with the proposed annulus system.

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