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Three designs for the internal release of sealants, adhesives, and waterproofing chemicals into concrete to reduce permeability

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Abstract

Various types of hazardous wastes need engineered barriers to prevent outflow. Concrete is a brittle and porous material, which changes dramatically over its lifetime. In order to design waste barriers using any type of concrete, the most effective intervention occurs at the time when it is needed during the life of the material and at the location undergoing distress. Internally placed encapsulators containing sealants, adhesives, and waterproofing are designed to release these chemicals where and when they are needed. Optimizing for durability requires an understanding of the timing and location of release. In all of the cases, brittle fibers containing adhesives or sealants release the chemicals where and when the matrix cracks, causing the fiber to crack and release chemicals. Research from over a decade is presented with special emphasis on permeability, cracking, and data and results from field tests. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Permeability; Internal release; Crack detection; Concrete

1. Introduction

Concrete and cement permeability (due to cracking and porosity) and brittleness can be addressed by the incorporation of chemicals in fibers, which are later released. This changes the material matrix properties just in time to prevent damage or to repair it. The conventional method to reduce cracking is fiber reinforcing. Permeability is reduced by sealants and waterproofers or creation of a tighter microstructure of fewer, smaller pores. Our research combines the fibers and sealants/adhesives together for internal release of chemicals from hollow fibers. The sensing of the cracking of a settable material by a chemical, physical, or human sensor starts the activation of a remedial process. It is a distributed system in which sensing and repair occur when and where they are needed. This research, into the development of cementitious matrices that have a self-repairing capability, was done at the University of Illinois Architecture Materials Research Laboratory and at the Natural Process Design.

This research concerns the repair or healing of cracks and filling of voids in cementitious matrices by the internal release of repair chemicals from inside of the fibers or beads into the hardened matrix. One active and two passive mode of activation are discussed in response to different types of cracking that occurs in different locations and at different times in the concrete's history. Active release is in which a human intervention is required, while passive release occurs automatically in response to initiation by the damaging event itself.

It is found that factors in the deterioration of concrete can be divided into two particular times, during the first month and after that. Factors such as cracking due to surface shrinkage, thermal cracking, plastic movement cracking, and settling all occur within the period under 28 days. The second phase in the life of concrete occurs after 28 days. That is when the concrete is considered cured. This period lasts until the concrete is destroyed at the end of its useful life.

The damage and repair location varies as well, the two variables being surface or interior location or a combination of the two. The damage caused by the internal and external environmental events can be reversed by chemicals released from fibers. The release can be done in a sudden manner in response to specific changes or evenly released in response

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Type of Problem	Materials Used	Time in Cement History	Location of Repair/ Im-provement	Active or Passive Release	Slow or Fast Release
Permea-bility	Methylmeth acrylate in fibers coated with polyol	Ususally beyond 28 days	Concrete interior or surface	Active	Fast
Shrinkage cracks	Scored brittle tubes containing sealant/ adhesive	7-28 days	Surface of concrete decks	Passive	Fast
Shear cracks	Brittle tubes containing adhesive	Usually beyond 28 days	Concrete interior	Passive	Fast

Fig. 1. Chart listing the factors involved in each design solution for repair of a particular problem.

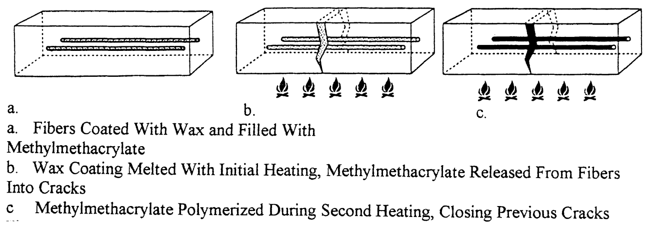

Fig. 2. Design for timed release of polymerizable chemicals to repair cracks and fill pores by melting of the coating on porous fibers.

to slow movement or heat. There are four possible categories of release in either time zone: slow constant release, release in response to a sudden event, and release in response to human impetus, which is either slow or sudden release. The examples of repair that are discussed in this paper and their particular factors are named in the following Fig. 1.

2. Smart materials

The smart materials using time release for each application is made from individual components. These tailor-made smart materials consist of several parts, including (1) an agent of internal deterioration, for instance, dynamic loading, which causes cracking; (2) a stimulus to release the repairing chemical; (3) a fiber or other vessel; (4) a coating or vessel wall, which can be removed or changed in response to the stimulus; (5) a chemical carried inside the fiber; and (6) a method of hardening the chemical in the matrix in the case of cross-linking polymers, or a method of drying the matrix in the case of a monomer.

3. Active mode to reduce permeability in interior of concrete at any time

The active mode design example was the fast release of liquid methylmethacrylate from inside wax-coated, hollow, porous-walled polypropylene fibers into concrete to fill voids, and reduce permeability in the interior. It is done in response to human intervention and is, therefore, an active mode repair. It was done after the cement was 28 days old but could be done earlier.

When low heat is applied to the matrix, wax coating on the fibers is melted, and the methylmethacrylate moves out into the dried matrix. The heat is raised and the methylmethacrylate polymerizes in the cement pores as seen in Fig. 2 [1].

The fiber aspect ratio, material, volume capacity, size of pores, and type of release need to be matched with the volume needed to be delivered. The volume of repair chemical required depends upon aggressiveness of the environment (i.e., pore or crack size), the ability of the chemical to move in the matrix, and the volume of chemical in the fiber for release [1].

3.1. Results in active mode release

Visual assessment was utilized to assess the release of dyed methylmethacrylate from fibers into white cement upon heating. As seen in Fig. 3, the release was successful [1]. Research shows that after the methylmethacrylate polymerizes in the pores and cracks of the concrete, it reduces permeability (see Fig. 4). Permeability tests were done on samples using the apparatus described as "a simple method for measuring water permeability of concrete" [2]. A head of water in a pipette is filled above a cement sample sealed in the apparatus. Measurements are made to determine equilibrium of water flow, and permeability is calculated therefrom.

Tests were done with various volumes of fibers to ascertain any strength deterioration due to these volumes of fibers used. The results showed no deterioration. A comparison of

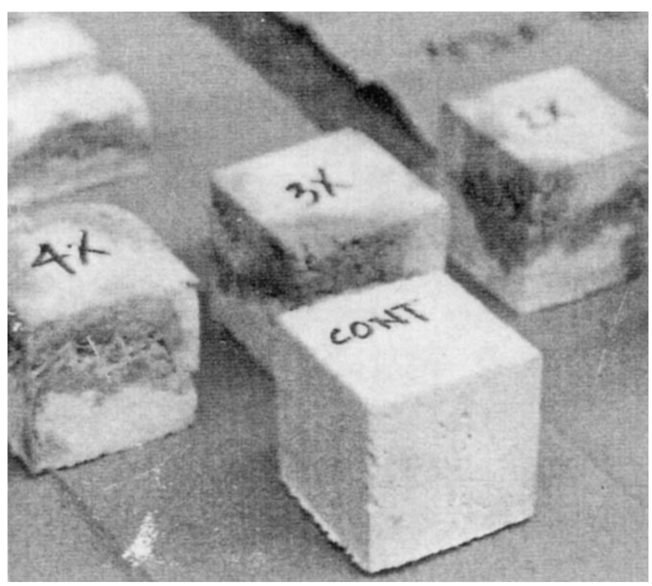

Fig. 3. Photo of samples in which the release of red-dyed chemical (dark areas) from the fiber into the white cement matrix can be seen [1].

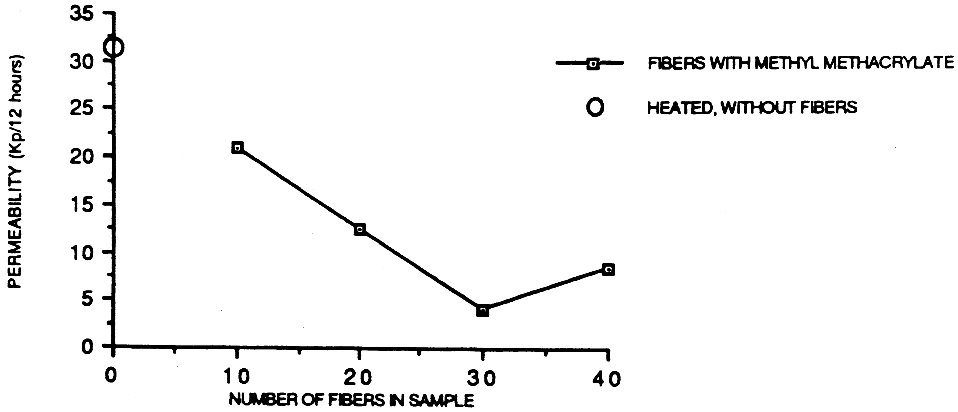

Fig. 4. Permeability of Portland cement containing methylmethacrylate and wax released from polypropylene fibers (samples cured for 7 days, heated to 212°F for 30 min) [1].

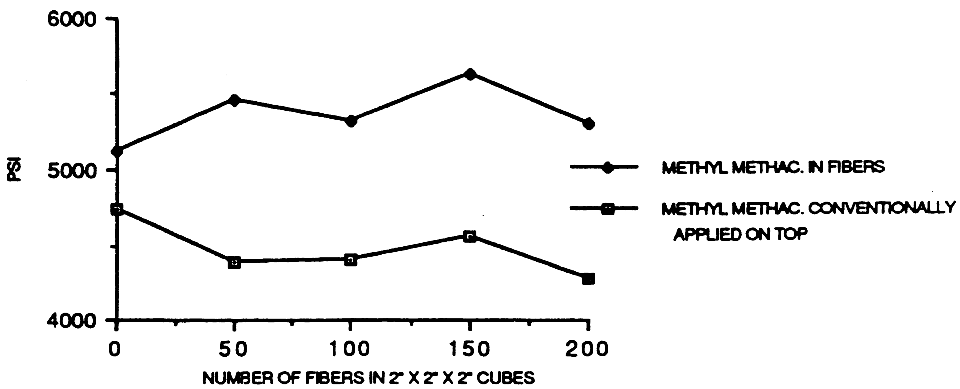

Fig. 5. Effect of internal release of methylmethacrylate and wax from porous polypropylene fibers and internal polymerization against conventional application from the exterior top surface on compressive strength (samples heated to 212°F for 30 min) [1].

internal release vs. exterior application of gravity feed was made. The results showed that samples with internally released chemicals had better compressive strength (see Fig. 5) and less permeability (see Fig. 6) than those using conventional surface application of methylmethacrylate and heating. Research has shown that this interior chemical

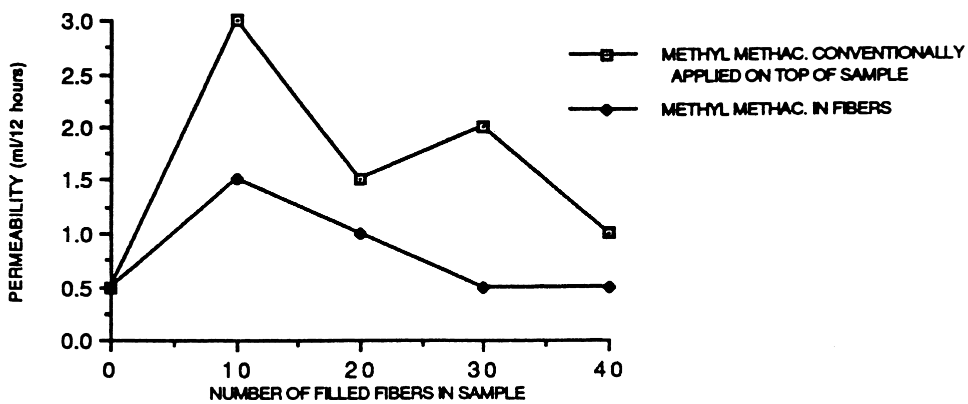

Fig. 6. Effect on permeability of internal release of methylmethacrylate and wax from porous polypropylene fibers and internal polymerization vs. conventional application from the exterior top surface (samples cured for 3 days, heated to 212°F for 30 min) [1].

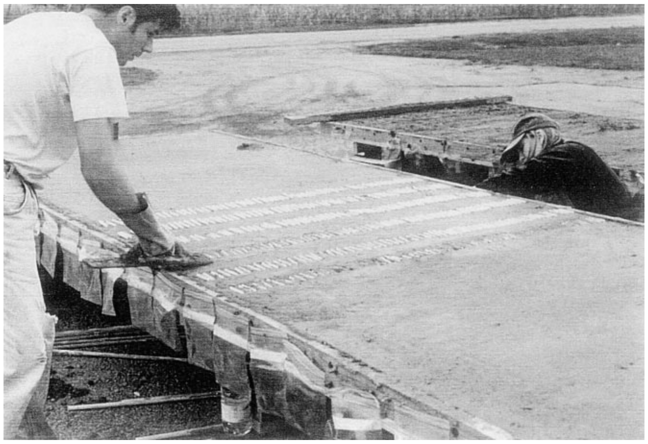

Fig. 7. A photo of the tubes embedded in the top surface of the deck [3].

delivery system works in the sense of delivering chemicals from the outside to inside the matrix [1].

4. Passive mode — repair of surface cracks caused by drying shrinkage within the first 28 days

One passive design investigated is the release of crack-adhering adhesives and sealants into the outer surfaces of concrete from scored hollow glass fibers to fill shrinkage cracks. Drying shrinkage causes stress loading, which causes cracking near the matrix surface to pull the fibers apart at the scored line, which then forms a weak zone in the cement and so create a control joint. The adhesive/sealant flows out from the broken-open tubes and fills the control joint crack. Fig. 7 is a photo of a series of these tubes embedded in the top surface of large-scale bridge decks.

Deck microcracking is a critical concern in bridge design. It allows cracks to form, and later allows water and other elements to enter the concrete matrix of the deck and most importantly to fall onto the supporting structure below [4]. This leads to significant structural damage of that support structure. A field application of this design for an in-situ means of controlling and repairing transverse shrinkage cracking was this design of brittle tubes filled with sealants in the concrete deck later to be broken by drying shrinkage of the concrete. This application can be applied to bridge decks specifically to control the location of transverse shrinkage cracks by creating control joints on the surface as a transverse row of sealant-filled tubes. These tubes broke due to shrinkage strain, thereby focusing the transverse cracks along this line. The repair sealant/adhesive has a low modulus of elasticity, thereby allowing future movement to resist stresses and strains in the deck without additional cracks extending from these shrinkage microcracks.

Four full-scale bridge decks were fabricated with repair-sealant tubes embedded at various locations as seen in Fig. 8.

4.1. Experimental results — passive mode applied to surface cracking

Visual assessment was the primary means used for assessing behavior of the sealant-filled tubes. These adhesive-filled fibers along the deck surface were monitored for breakage beginning immediately after placement and finishing. The sealant/adhesive, VOC, changed color,

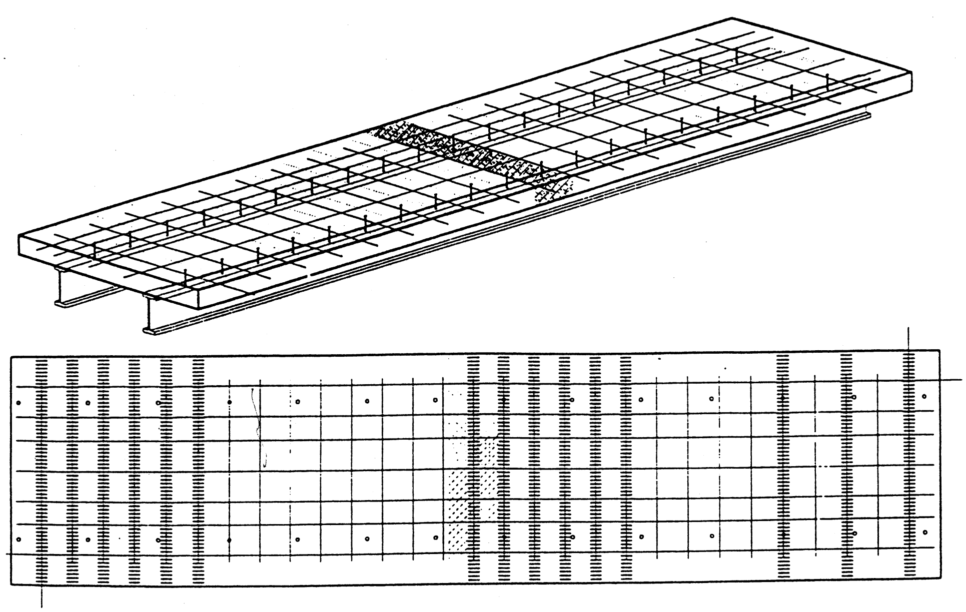

Fig. 8. A drawing of the top surface of the 4 × 20-ft decks into which repair tubes were embedded [3].

first to light blue and then orange when released into contact with the concrete.

It was evident that tubes in the deck surface broke due to transverse shrinkage strain. Results in the first two decks after 1 month of monitoring showed that repair tubes embedded just under the deck's top indeed ruptured due to surface shrinkage and created repair control joints as designed. Repair tubes placed in the deck surface but not totally covered mostly broke after 2 months, while those left totally uncovered did not break. Although these were more exposed to the environment and freezing and thawing weather cycles than the fully embedded ones, the environmental forces did not cause breakage of the fully exposed tubes. As seen in Fig. 9, most of the fully embedded tubes broke by the end of 35 days; the tubes, which were not totally embedded broke within the first 2 months, the typical time dry shrinkage occurs in new concrete and an additional 10% broke later. The other glass tubes, which were not covered account for the approximately 20%, which did not break at all. These readings were taken usually on a weekly basis although the embedded ones were read only at 35 days. The control joints created by the fully embedded tubes could be seen because the released sealant penetrated up through the concrete and stained it, first a light blue color and then orange, as seen in Fig. 10 [3].

During these first several months, the decks were subjected to the extremes of freezing and thawing, yet those tubes fully exposed and not bonded or covered with concrete did not break. The conclusion is that breakage was due to shrinkage tension from the concrete on the scored brittle tubes, which were bonded into the concrete, not from freeze thaw or weather damage. The result was a transverse line of repaired cracks, a control joint [3].

Future testing and monitoring is planned for additional information acquisition. Corrosion monitoring was attempted, but no conclusive data was obtained. Additionally,

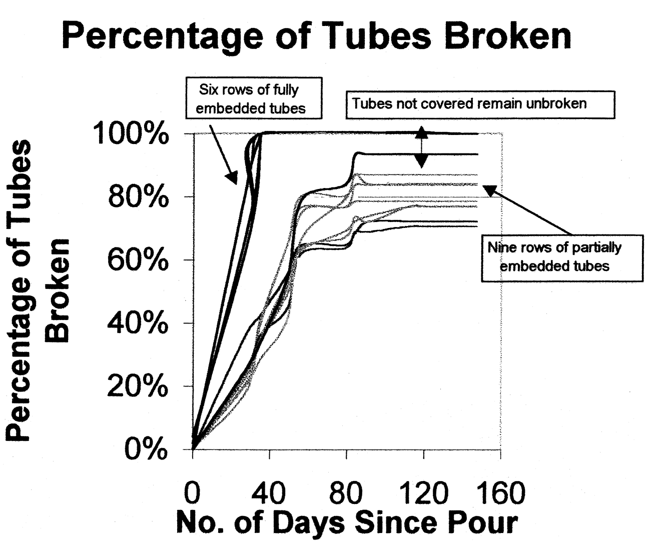

Fig. 9. Chart of the percentage of tubes, which released sealant over time [3].

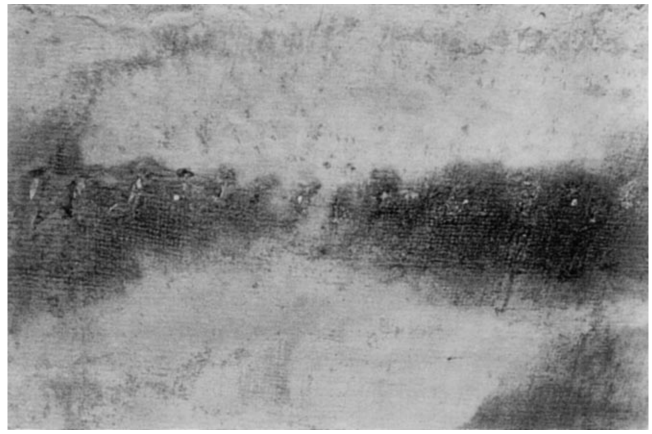

Fig. 10. A photo of the control joint line created by the release of sealant from embedded tubes or fibers [3].

salt water will be ponded on the surface, and leaking due to cracking will be assessed as a change in the voltage potential. The continued corrosion monitoring is expected to give useful information regarding the adhesive/sealant's effectiveness in sealing cracks to prevent water penetration and corrosion. The issue of reduced permeability will be tested at a later date. The small cracks generated by drying shrinkage may take years to become large enough to test in a through thickness flow permeability test.

5. Passive mode — repair of internal shear cracking after 28 days

This research focuses on the repairing of structural load-induced shear cracks after 28 days in the four full-scale bridge decks. Tubular capsules containing stronger, high modulus adhesives were placed below the surface in areas of tension caused by bending, for example, in the top of the section over supports. These structural cracks, which were induced by loading, were successfully repaired as evidenced by higher strength than a tested control deck without adhesives and by the creation of new cracks in some places where the old repaired cracks had not re-opened.

The same four decks that showed a repair system's effectiveness in dry shrinkage crack repair were loaded in bending to study the repair effectiveness on internal structural shear cracking. The bridge decks were loaded three times allowing time in between tests for the repair adhesives to set. From these test results, the strength gain and/or behavioral changes could be assessed. A simple method was devised to induce structural cracking in the decks. The steel I-beams, which were composite with the deck, were sawed through at mid-span to eliminate the additional strength offered by this composite system. However, the top flange was still embedded in the deck, and would therefore offer significant additional tensile reinforcing at the bottom of the slab, if load was applied at the top of the deck. The load was applied upward at the mid-span of the

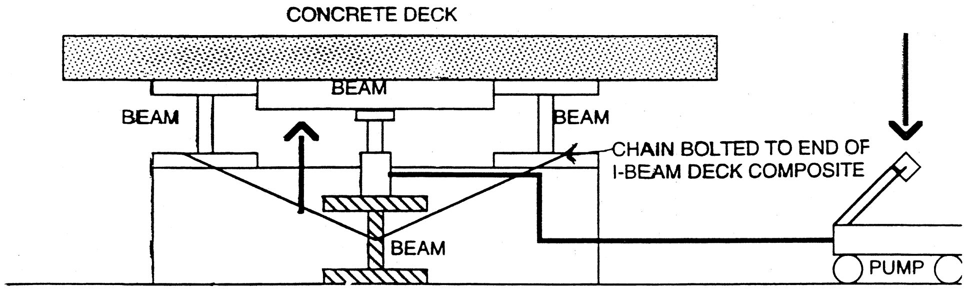

Fig. 11. A diagram of the testing method set-up used to induce structural shear cracking.

deck with a pneumatic jack as seen in Fig. 11. This jack replaced the initial middle support. In most cases, the ends of the deck were tied down to prevent uplift. An 18-in. long steel, T-shaped steel member was placed transversely at the deck mid-span with its flange against the deck bottom and its wide web balance on the 1-in. diameter jack head. The jack supplied an upward load that was measured by the force in the cylindrical base. A 1000-psi pressure converts to 0.785 kips at the deck mid-span.

Based on the deck dimensions and materials, the following behavior was approximately expected: Initially, the deck is only subjected to gravity-causing bending with tension in the bottom of the deck. The upward jacking force is then applied. Once a jacking force of approximately 0.80 kips (1000 psi) is reached, the deck is in equilibrium (no bending). Any force beyond this, put the deck into the opposite bending, causing tension at the top of the deck. The applied loads were recorded in sequence, as were the resultant upward deflections of the mid-span of the deck. Deck cracking was also monitored visually and measured with a crack caliper.

5.1. Experimental results — passive mode applied to shear cracking

All four decks were tested three times each in bending. Deck 1 had VOC embedded at its surface and cyanoacrylate repair capsules through its section. Deck 2 was the control deck, and contained no repair adhesives. Deck 3 has several hundred Tripp-filled capsules embedded randomly through a 2-ft wide section at mid-span of the deck's length. It also has a transverse row of longitudinally aligned capsules with VOC just beneath the top surface of the decks. These are within the tensile zone during load-induced bending. Deck 4 had Tripp on its surface and nothing through its section.

All decks were several months old at first break. The ends of all decks were tied to the ground with a continuous chain before applying the jacking force. The mid-span of the deck was then forced upward. After jacking the mid-span up 1 in. to a pressure of 1000 (0.785 kips), the deck was held in position for 4 min. The mid-span was then jacked further to 1500 psi (1.178 kips), at which point the deck yielded or cracked so that it would no longer take additional loading. The embedded repair adhesive could be seen out through the continuous transverse crack at mid-span on the top of the deck. In Decks 3 and 4, circles of it came to the surface at least every 1/2 in. The deck was held there for another 4–5 min. The deck was then gradually released down to 1100 psi (0.864 kips). More glue released, forming puddles of an average diameter of 1/4–1/2 in., and dried within 4 min. Finally, the deck was released of any loading The data are summarized in Fig. 12.

All four bridge decks were loaded again several months later in October. This would test how much effect the repair adhesives and sealants had on the decks for repairing load-induced cracks. Two of these decks had been poured over 1 year prior (Decks 1 and 2); the other two (Decks 3 and 4) were over 6 months old. All four decks had been loaded to failure previously: Decks 1 and 2 (2 months previously), and Decks 3 and 4 (4 months previously). The concern with these repair chemicals in the field was their longevity, however, even after as long as 1 year, there was still liquid adhesive released during this second loading.

Deck 1 originally broke at 1250 psi (0.982 kips). The crack from the first loading remained closed under this second loading until 900 psi (0.707 kips). At that time, only the eastern 2/3 of the original transverse crack re-opened to 0.007 in., and glue was released. However, the western 1/3 of the original crack, where adhesive had been released during the first test, remained closed. A slight increase to 1000 psi (0.785 kips) widened the eastern 2/3 of the original crack to 0.010 in., while a secondary parallel crack (0.007 in.) opened 7 in. offset form the 1/3 of the original crack that remained repaired. This correlates with results from earlier loading. At that time, glue was seen as it released in the

Deck #	1st Load (kips)	2nd Load (kips)	% change
1	1250	900	-33%
2	1200	750	-37%
3	1500	1100	0%
4	1500	1200	20%

Fig. 12. List of strength results at a crack size of 0.007 in. in two bending tests applied by jack to full-scale decks in the field.

western 1/3 of the transverse crack at mid-span. This glue repaired the original crack in this region, allowing it to gain strength beyond the rest of the concrete matrix. Under a second loading, this repaired portion did not re-open. In fact, it remained closed as the failure was actually diverted to a previously intact portion of the deck. In the re-opened crack, visibly more repair adhesive was released. The new offset cracks showed slight signs of adhesive release.

Deck 2 was the control, and therefore, had no strength gain, as anticipated. After failure from the first loading, additional loading was unable to be held. Whereas, Deck 1 was able to reach 1000 psi (0.785 kips) before cracks re-opened or new ones were formed; cracks in Deck 2 re-opened as soon as the dead load of the deck was overcome by mid-span upward loading. By a loading of 800 psi (0.628 kips), the crack widths were about 0.010 in.

This Deck 3, with VOC at the surface and Tripp through the section, did not appear to repair as well as Deck 1; no portion of the crack remained closed or was diverted under secondary loading. The original transverse crack did not re-open until a load of 1000 psi (0.785 kips), at which time it was measured at 0.010 in. The crack continued to widen under loading. No apparent crack repair occurred in this deck. The re-opened crack did again release VOC under this second loading as it had under its first loading as seen in Fig. 13. Therefore, it seems that the VOC releases as

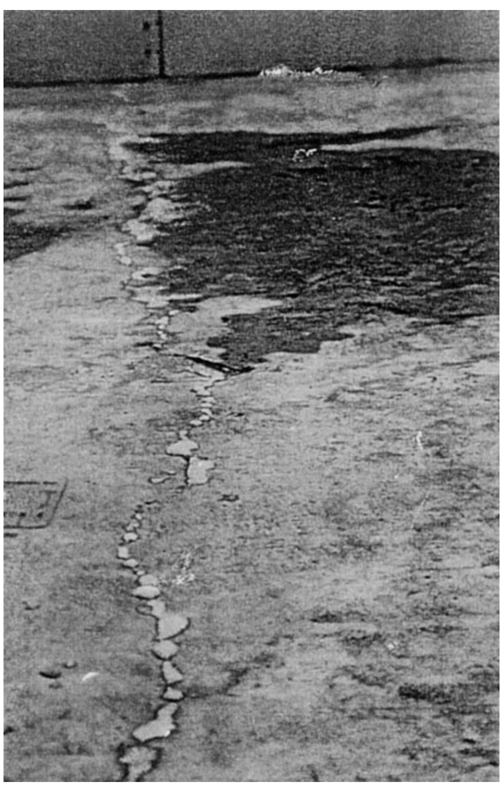

Fig. 13. Photo of release of adhesive into crack on second testing for release of adhesive when subjected to upward bending, Deck 3 with VOC embedded.

Strength Increase

Deck #	1st Load (kips)	2nd Load (kips)	% change	3rd Load (kips)	% change
1	1250	1250	0%	1100	-12%
2	1200	800	-33%	800	-33%
3	1500	1500	0%	1200	-20%
4	1500	1800	20%	1700	13%

Fig. 14. A listing of loads carried at failure point by the four bridges in three bending tests.

necessary, but does not supply desired strength gain properties. The failure is caused by the poor properties of the chemical chosen for release.

Deck 4, which had Tripp repair adhesive embedded just below its surface and nothing through its section, showed more successful signs of structural crack repair than Deck 3. The original crack remained closed under this second loading until a load of 1100 psi (0.864 kips). At this time, the outside 16 in. of the transverse crack re-opened to a width of 0.004 in.; a new 0.007-in. crack opened 6 in. offset from the original crack in the middle 28 in. of the transverse crack. A slight load increase to 1200 psi (0.942 kips) caused the original crack to then re-open in this middle section, to 0.004 in., while the new crack widened to 0.007 in. At this load, the outside edges of the original crack were opened to approximately 0.0101 in.

Three weeks later, all four bridge decks were loaded for a third time to test the effectiveness of the repair adhesives in repetitively repairing load-induced cracks. The results can be seen in Fig. 14. Deck 1 held its strength, much like the previous re-loading. At the east end, the primary crack re-opened and released glue. On the west end, the primary crack re-opened, but the secondary crack remained closed through most of the loading. This seems to indicate that the secondary crack (approximately 7 in. offset from the primary crack) was repaired by the cyanoacrylate embedded in a 2-ft section of the bridge deck. Bridge Deck 3 released a modest amount of new adhesive (dots 1/16 in. in diameter). This was concentrated in the western 18 in. of the transverse width. Deck 4 released adhesive all along its transverse length in this third loading. The primary crack in the middle of the transverse length opened first. The rest of the primary crack and the entire secondary crack re-opened under additional loading. Larger amounts of adhesive (1/4–1/2-in. diameter dots) appeared along the primary transverse crack, with most of it outside the middle third of the crack's length.

6. Conclusions

The specific conclusions are:

1. Tests on active-mode time release of methylmethacrylate revealed an improvement in permeability and no loss of strength due to fiber addition.

2. Tests on the passive-mode example of release of adhesives from glass pipettes to address drying shrinkage crack conditions on the surface revealed:

   (a) Sealant/adhesive-filled scored repair tubes embedded in the concrete surface can create control joints in the deck by controlling the location of cracks caused by dry shrinkage of concrete.
   (b) Sealant/adhesive will be released into the cracks.
   (c) Whether further damage caused by the propagation of cracks to create a crack though the depth of the deck was not be tested in the field at this time.

   This in-situ means of controlling and repairing transverse shrinkage cracking, utilizing brittle tubes with sealants in the concrete deck, is an effective means of repair in actual field testing as predicted by laboratory testing using a different sealing system, the methylmethacrylate one.

3. Tests on the passive-mode example of release in the interior to address shear cracks revealed:

   (a) The most successful evidence of the structural crack repair capabilities of this system are the diverted cracks in the second loadings of Decks 1 and 4. In both cases, original cracks from the first loading were repaired; secondary cracks opened, at least in portions, during the second loadings before the primary cracks did re-open. In both cases, the secondary cracks were offset 7 in. from the original cracks.
   (b) Compared to the second and third loadings of the control deck, Deck 2, which contained no repair adhesives, Decks 1, 3, and 4 all showed signs of bending strength re-gain in their later tests.
   (c) Re-release of repair adhesives in second and third loadings occurred in all of the decks containing repair adhesives, subsequent loadings revealed additional adhesive release all along the re-opened crack. These adhesives survived for over 1 year in field conditions ranging from below freezing to over 100°F.

6.1. Comparison of attributes of release

6.1.1. Timing and location

Timing of release in the cement life is totally related to when the distress appears. The location for release is usually near the site of the damage or area needing improvement. If that is impossible for some reason then force should be used to push the repair chemical the required distance.

6.1.2. Passive and active release modes

The release of methylmethacrylate by melting the wax fiber coating with the subsequent release of chemicals from the fiber wall is activated by human control. This is an active sensor. The timed release of chemicals by fiber breakage is a passive actuation process.

In the passive sensing and activation example, the breakage of the fiber is the sensor that causes the passive activation release to occur. In the example of active mode, the sensor is in active mode. Optimization control studies allow us to compare these modes and predict circumstances when each will be most efficient. In the methylmethacrylate example, the amount of chemical is predetermined, but the timing is left up to human action. In the example of release of adhesives from broken glass fibers, the location of release is predetermined, but neither the amount of chemicals nor the timing is controlled by human intervention. The amount from a fiber at any specific loading with certain fiber wall strength must be calculated and designed ahead of actual use.

The passive sensing and actuation example has the advantages of freedom from external control and an automatic sensing and release of chemical. The cost-savings would be significant especially in terms of reduced maintenance by humans, reduced repair costs as well as a reduced delay in the time to first repair.

The active system gives confidence because humans activate the system. The passive system is cost effective precisely because human maintenance is eliminated. These systems could be combined to give both confidence and reliable maintenance and yet be an economical system.

6.1.3. Speed of release

The speed of release needed partly depends upon the flow rate of the chemical and the distance to be traveled to do the repair. Mainly, it is in response to the type of problem to be addressed. If the problem needs instant repair, such as impact damage, then the force and speed of release must be high; if the problem recurs at a slow rate, such as corrosion, then release can be slow even a constant release.

Acknowledgments

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