Development of a Crack-Resistant Rubber-Modified Cementitious Repair Material

From compatibility concepts to the field

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Rehabilitating concrete infrastructure is one of the most significant challenges in civil engineering today, as more than 50% of the repairs performed on concrete structures have been found to show signs of premature failure within 5 years after completion.[1] Concrete repair is not just a simple bandage for a structure experiencing damage; rather, it is a complex engineering task that presents unique challenges that differ from those associated with new concrete construction. For a repair project to be successful, it must adequately integrate new materials with old concrete, forming a composite system capable of enduring exposure to service loads, ambient and enclosed environments, and the passage of time.

The premature deterioration and failure of concrete repairs in service is a result of a variety of physicochemical and electrochemical processes. Among the most serious causes is cracking in the repair material. Cracking may result in a reduction in the effective cross-sectional area of the repaired structure and always substantially increases permeability, which leads to premature corrosion and deterioration.

Cracks generally interconnect flow paths and thus increase effective permeability of the repair material. The resulting chain reaction of cracking → more permeable repair → corrosion of reinforcement → more cracking may eventually result in irreversible deterioration and failure of the repair. Some 50 years ago, Valenta[2] observed that "continuous cracks linking into wider cracks originating from the concrete surface play the biggest role in increasing permeability." Figure 1 schematizes a model of repair failure caused by cracking.

Problems associated with premature failure of repairs have to a certain extent worsened in recent years, notably due to the increasing use of high-strength (or "high-performance") repair materials. These materials can be prone to early age cracking sensitivity, especially in the restrained movement conditions typical of repairs. It is beyond the scope of this article to provide a critical review of the theoretical and mechanistic considerations of cracking in brittle composites such as cement-based materials. In what follows, only specific aspects of cracking in concrete repairs comprising hydraulic cements will be emphasized.

Concrete Repair Failure

The composite repair system results from the setting and hardening of a semiliquid substance—the freshly mixed repair material—placed against a rigid concrete substrate. A bond starts to develop in the contact area with the substrate as soon as the chemical reaction initiates in the repair material cement paste. As hydration proceeds, the repair material matures, and, after a limited period of moist curing, the repair material is exposed to the ambient air. Through these processes, the new material is subject to thermal deformations, autogenous shrinkage, and drying shrinkage. Because of the bond, free movement of the repair layer is restrained by the rigid substrate, leading to the development of significant stresses that may at some point overcome the material's tensile strength and cause cracking and/or debonding of the repair (Fig. 2).

Shrinkage-induced stresses are often considered to be the main cause of premature failure of a repair. The issue is not easily addressed, as the consequences of differential shrinkage depend on factors that include the age and quality of the concrete substrate, temperature and moisture gradients, boundary conditions (restraints), magnitude of induced stresses, and strain capacity of the repair material; and many of these are time-variant parameters. The primary significance of deformations caused by moisture content changes in cementitious materials is whether their occurrence would lead to cracking. Here, the magnitude of the restrained shrinkage strain is the most dominant one, but it is not the only one governing the sensitivity to cracking. The other relevant material properties are:

- Tensile strength—the risk of cracking decreases as this parameter increases;
- Modulus of elasticity (MOE)—the elastic tensile stress induced by a given shrinkage strain decreases as this parameter decreases; and
- Creep—stress relaxation increases and the shrinkage-induced tensile stress decreases as this parameter increases.

While it may appear that designing the repair material to have greater tensile strength is a straightforward solution to cracking, cement-based materials are inherently brittle and exhibit sudden failure characteristics when the ultimate stress is reached.

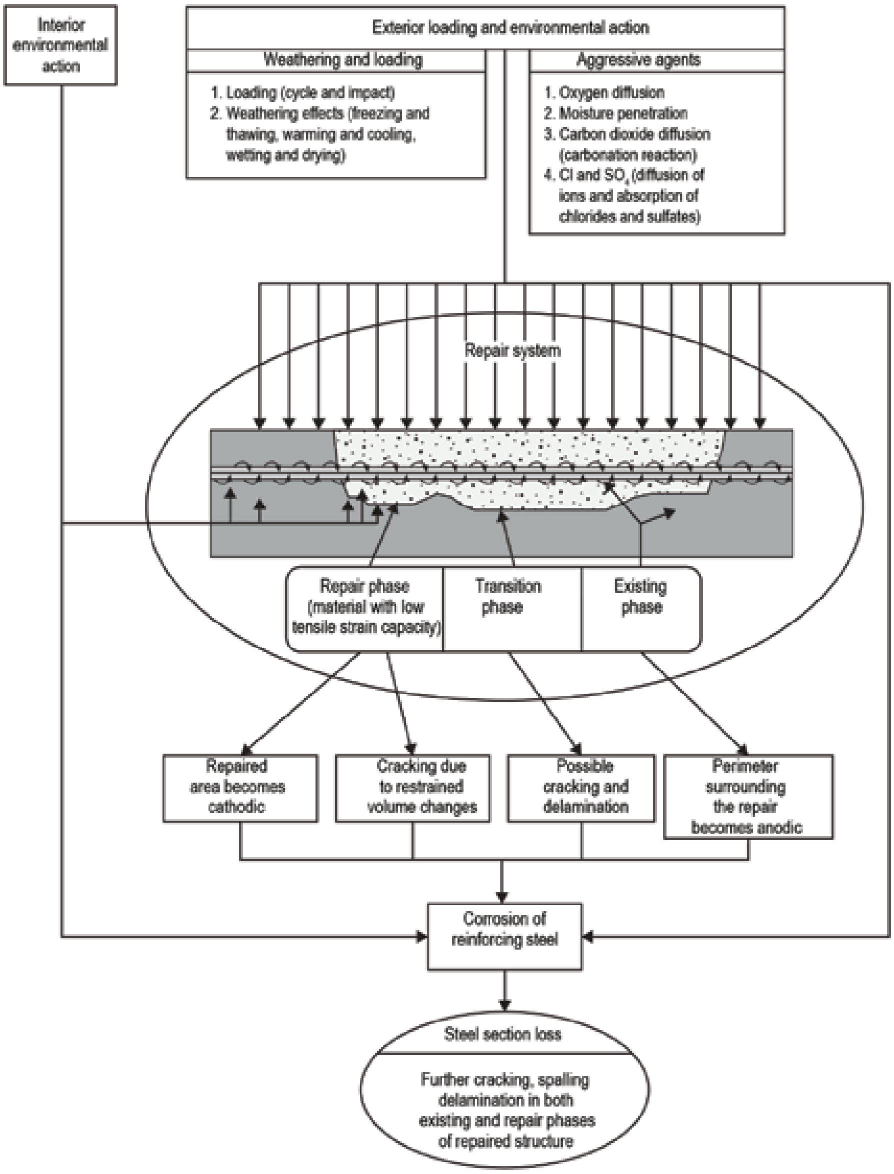


Fig. 1: Model of repair failure caused by cracking[3]

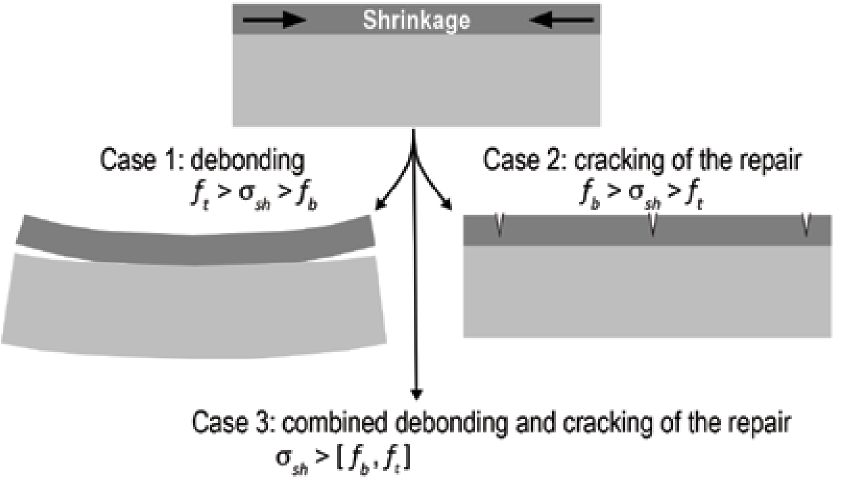
The MOE significantly influences the tolerance of a material to restrained shrinkage without cracking. The factors affecting the MOE of a cement-based material are related to compressive strength and density. Thus, factors that affect strength, such as water-cementitious materials ratio (*w/cm*); aggregate type, size, and grading; curing conditions; and age often similarly influence the MOE. An overview of the various parameters that influence the MOE of cement-based materials is presented in Fig. 3. Reducing the MOE of a repair material can lead to a lower stress buildup due to restrained drying shrinkage and/or thermal strains at the interface between the repair material and the existing concrete substrate provided that the overall volume changes are not amplified as much.

Creep reduces tensile stresses from restrained drying shrinkage and thus reduces cracking in the repair material. Therefore, material with high creep, particularly during the early age, is desirable. Material with early high creep will typically have relatively lower compressive strength and slower strength development. Conversely, materials with high or very high early strength development will exhibit low creep behavior and thus have a greater risk of cracking. The biggest complexity in practical design of mixtures with increased creep can be attributed to the significant correlation between creep and drying shrinkage. The same factors that assist in achieving higher creep also lead in a number of cases to higher drying shrinkage. Unfortunately, the higher stress induced by drying shrinkage may in some cases more than offset the advantages of stress relaxation achieved by increased creep.

Durability of Repair Material

Over the last three decades, substantial progress has been achieved in improving the quality and versatility of concrete repair materials. Durability has been enhanced through the use of plasticizing admixtures, supplementary cementitious materials, air-entraining agents, and corrosion inhibitors.

It is often perceived that a densified microstructure is one of the most effective means for enhancing durability, as a dense microstructure generally leads to increased mechanical strength and lowered permeability, and reduced diffusivity of the material. This perception has led to the development of a handful of sophisticated and expensive high-strength repair materials with low bulk permeability. However, many of these materials are prone to early age cracking, due to significant volume changes, high elastic modulus, low creep deformation, and overall more brittle behavior.[6] Very few solutions have been targeted at the brittle nature of cement-based materials, which make them inherently sensitive to restrained volume changes. The main objective of the project described in this article was to develop a cement-based repair material with reduced brittleness and improved resistance to cracking. A complementary goal was to make this material more environmentally friendly**.**



f_t = repair material tensile strength
f_b = tensile bond strength between the repair material and the substrate
σ_{sh} = shrinkage-induced stress

Fig. 2: Damage mechanisms in concrete repair systems (adapted from Luković et al.[4])

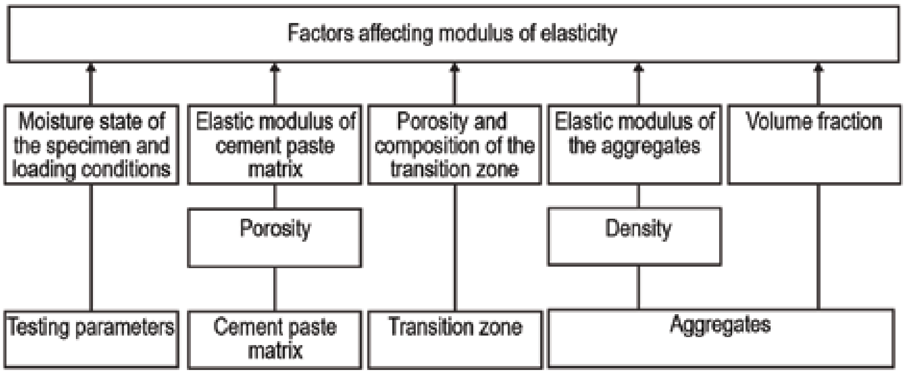


Fig. 3: Overview of parameters that influence the MOE of cement-based materials[5]

Recycled Waste Rubber

Over the last 30 years, several research projects have been focused on the properties and performance of rubber concrete and other rubberized cement matrix composites. Rubber obtained from waste tires and other waste rubber sources attracted interest for its natural ductility, energy absorption capacity, and low density. Recycled waste rubber is generally divided into two particle size categories: chipped rubber (3/4 to 1-1/4 in. [20 to 30 mm] particles) and crumb rubber (1/8 to 3/8 in. [3 to 10 mm] particles). Chipped rubber can be used to replace part of the coarse aggregate, whereas rubber crumbs can be used as fine aggregate.

When used to replace aggregates in cement-based materials, rubber particles induce significant variations in material properties. Numerous studies demonstrate that the partial replacement of aggregates with rubber negatively affects the strength properties of cement-based composites proportionally to the replacement rate.[7] Partial replacement of aggregates also lowers the MOE (Fig. 4).

Using an instrumented steel ring to conduct restrained shrinkage tests, Kiang and Jiang[8] found that the addition of

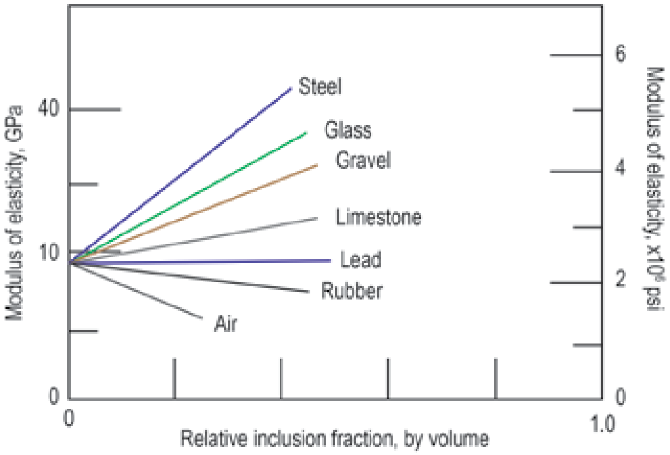


Fig. 4: Effect of various materials on MOE of concrete[5]

rubber particles leads to reductions in both tensile strength and shrinkage stress of paste and mortar specimens. They observed that when the rubber fraction is less than 20% by volume of mortar, the reduction of shrinkage stress is more than that of tensile strength, so cracking time is retarded.

Although much research has been conducted thus far on the use of recycled rubber in cementitious composites, no study has been reported yet on such materials specifically intended for concrete repairs. Due to the ability of the rubber to withstand large tensile deformations, the particles act in cement-based systems as miniature springs distributed throughout the material's matrix, halting very effectively the development of microcracking. At the macroscale, this results in enhanced ductility and significantly reduced sensitivity to restrained-shrinkage cracking.

One major drawback of rubberized cement-based composites is reduced compressive strength. There are many reasons for the lower strength of these materials:

- Low stiffness of rubber particles. Under a given strain, the particles draw very low stresses, and the other components in the matrix must carry most of the load—an effect that has been termed "reduction of the effective surface of concrete" by Eldin and Senouci[9];
- Weak adhesion of rubber particles and cement paste. The hydrophobic character of rubber results in the formation of a weak paste-rubber aggregate interfacial transition zone (ITZ)[10];
- Entrapment of air. The hydrophobic character of the rubber particles causes air entrapment during mixing, which is known to affect directly the compressive strength[11];
- Reduced sand content in the matrix. Fine aggregates play an important role in the material's strength,[12] and the replacement of a fraction of the sand with crumb rubber results in a weakened matrix; and
- Excessive amounts of rubber particles. A high concentration of rubber in the mixture leads to increasing rubber-to-rubber contacts within the matrix. These can carry very little stress, aggravating further the "reduction of the effective surface of concrete."

MOE

MOE is a key property of cementitious repair materials because it impacts the ability to resist both restrained shrinkage-induced cracking and debonding from the substrate. The MOE is closely related to the stiffness of the aggregate makeup of the mixture. The elastic modulus of mineral aggregates used in concrete is typically of the order of 7.25×10^6 psi (50 GPa), while that of rubber is less than 1450 psi (0.01 GPa), so the MOE of rubberized cement-based materials is inevitably lower than that of ordinary cementitious materials.

From the viewpoint of developing crack-resistant mixtures, favorable modifications with regard to the MOE offer quite a complex task. On the one hand, using low-modulus aggregates, increasing the paste content, and using lower-strength material reduce the MOE, and as such reduce restrained shrinkage stresses. On the other hand, these same factors generally increase shrinkage.

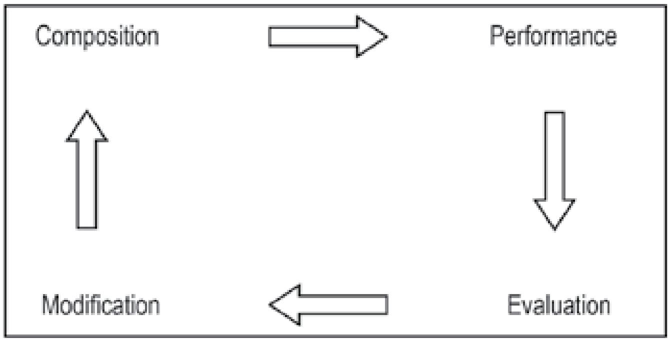


Fig. 5: A material development approach[5]

Crack-Resistant Repair Material

Research and development efforts reported herein were aimed at developing a crack-resistant cement-based material for structural and protective repairs. The goals were to meet the performance requirements of ACI 546.3R-14[13] and to satisfy environmental and economic requirements. The repair material was developed using the general approach shown in Fig. 5. Guiding parameters in the design process included:

- Mechanical characteristics for crack resistance:
  - Moderate 28-day compressive strength of 4000 psi (27.6 MPa),
  - Moderate to low early strength,
  - Low early MOE; and
- Composition for environmental friendliness:
  - Type II cement,
  - Pozzolan (fly ash),
  - Low amount of silica fume, and
  - Low-modulus recycled rubber aggregate.

Developing a repair material in accordance with these parameters was intended to balance repair performance needs and environmental considerations. The first category of requirements relates to the repair material's engineering properties. These mainly concern the final, hardened state characteristics, such as strength, permeability, and the properties governing the sensitivity to cracking—drying shrinkage, tensile strength, and MOE. In addition, fresh state properties such as workability, pot life, rheology, and the ability to "wet" the substrate are primary considerations in the formulation of repair materials. Also, it is important to evaluate how the material properties are affected by variations in ambient temperature and humidity during placement, curing, and service.

Laboratory experiments

Previous research has shown that it is challenging to produce a homogeneous mixture with an even distribution of rubber. Previous work has also shown that a potentially significant reduction in strength limits the rubber content achievable in practice. Hence, screening tests were conducted to estimate the maximum rubber content practically achievable. The basic requirements set out at the beginning of the design process were a *w*/*cm* value of 0.40 and a 28-day compressive strength of 4000 psi. Mixtures developed for the screening tests were prepared with ASTM Type I/II cement, Class C fly ash, silica fume, fine and coarse mineral aggregates, fine rubber crumb aggregates, a high-range water-reducing admixture (ASTM C494/C494M Type F), a defoaming agent, and water. The mineral aggregates met the requirements of ASTM C33/C33M, “Standard Specification for Concrete Aggregates.” The coarse aggregate was a 3/8 in. granite pea gravel, with specific gravity of 2.48 and absorption of 1.93%. The coarse aggregates used in the tests were dry. The specific gravity of fine aggregate was 2.65 and absorption was 1.01%. Crumb rubber was used as a fine aggregate replacement, with the amount varying from 0 to 30% by volume of sand. The crumb rubber was clean, without cord (steel belting). It had a specific gravity of 1.2 and adsorption was insignificantly low. The particle size ranged from 1/32 to 1/8 in. (0.75 to 3.5 mm).

Mixture proportioning was performed in accordance with the absolute volume method per ACI 546.3R-14. A series of preliminary “trial-and-error” tests were conducted. Batches were produced with various proportions of constituents, all with *w*/*cm* = 0.40. The mixtures were optimized to satisfy the guiding parameters discussed earlier and to exhibit adequate workability, minimum bleeding, and the absence of rubber segregation. Screening test results revealed that to meet ordinary strength requirements, rubber replacement rates could hardly exceed 20%. From the extensibility and crack resistance point of view, a higher fraction of rubber crumb substitution might have been desirable, but the amount of rubber was limited by practical strength requirements and other compatibility requirements.

Five candidate mixtures were then designed for sensitivity to cracking and chloride permeability. Based on the preliminary test results and considering the information from previous investigations, a nominal rubber substitution rate of 20% by volume of the sand was selected for further optimization and fine-tuning to meet the objectives of the project. To compensate for compressive strength reduction resulting from the presence of rubber particles and at the same time to provide improvements in the material

microstructure, silica fume was added to the candidate mixtures. The silica fume was also used to provide a relatively cohesive paste, with the additional benefits of:

- Improving the bond between rubber aggregate and cementitious matrix. It is known that the bond between cement paste and aggregate particles increases with the consistency of the paste; and
- Preventing segregation. The low specific gravity of the rubber particles relative to the replaced sand (1.2 versus 2.48) makes rubber aggregates highly sensitive to gravitational segregation.

A defoaming agent was added to minimize the amount of entrapped air caused by the addition of rubber aggregate to the mixture. For each mixture, several adjustments were made by varying the dosage in fly ash, silica fume, water-reducing admixture, and ultimately rubber to meet the requirements for compressive strength while achieving the desired workability (6 in. [150 mm] slump), preventing rubber segregation and excessive bleeding, and minimizing the entrapped air content.

The optimized mixtures ended up with 17% in rubber substitution for sand by volume. They all had a satisfactory rubber particle distribution.

Testing

Specimens were tested in compression in accordance with ASTM C39/C39M, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," at 28 days of age. Resistance to cracking was tested in accordance with ASTM C1581/C1581M, "Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage," with ring specimens being monitored daily for evidence of cracking. The test results are summarized in Table 1.

Table 1:
Compressive strength and cracking resistance test results

Mixture identification	Compressive strength per ASTM C39/C39M, psi (MPa)		Resistance to cracking per ASTM C1581/C1581M
	7 days	28 days	
C5-1	3660 (25)	4540 (31)	Crack at 21 days
C5-3	2540 (18)	3740 (26)	Crack at 32 days
C5-4	2680 (18)	3880 (27)	> 90 days
C5-5	3580 (25)	4680 (32)	> 104 days
C5-7	4010 (28)	4760 (33)	> 55 days

Based upon these results, two mixtures, C5-5 and C5-7, were selected for a more comprehensive characterization. Several standard test methods and one nonstandard test method were used. In addition to the two tests performed in the previous round of tests, the selected mixtures were tested for splitting tensile strength (ASTM C496/C496M, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens"), MOE (ASTM C469/C469M, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression"), length change or free shrinkage (modified ASTM C157/C157M, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete"), and chloride permeability (ASTM C1202, "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration"). The "Baenziger Block" test, a nonstandard procedure, was also conducted to evaluate the performance of the two materials with respect to shrinkage-induced cracking in a representative repair layout situation. The results of the second series of tests are summarized in Table 2.

Table 2:
Additional characterization of mixtures C5-5 and C5-7

Property/Test	Age, days	C5-5	C5-7
Splitting tensile strength, psi (MPa)	7	447 (3.1)	397 (2.7)
	28	399 (2.8)	365 (2.5)
MOE, psi (GPa)	7	2.63×10^6 (18.1)	2.46×10^6 (17.0)
	28	3.03×10^6 (20.9)	3.05×10^6 (21.0)
Length change, $\times 10^{-6}$	7	40	40
	28	410	370
Rapid chloride permeability, coulomb	28	1976 (low permeability)	1583 (low permeability)
Baenziger Block	90	No crack	No crack

The results of tests performed on mixtures C5-5 and C5-7 demonstrated that both mixtures satisfied the established criteria. However, based on the results of the ring test (ASTM C1581/C1581M) and slightly "friendlier" constructability properties, mixture C5-5 was selected as a prototype mixture for further experimental repair application under controlled field conditions.

Field experiments

Experimental field repairs were carried out on U.S. Navy concrete structures selected by officials with the Naval Facilities Engineering Systems Command, Port Hueneme, CA, USA. The experiments consisted of a formed vertical repair and a trowel-applied horizontal repair. The field-testing program included mixing, placing, curing, and monitoring of the repair. In addition, tensile bond strength tests were carried out on-site and petrographic examinations were performed on core specimens extracted from the aged repairs. The repair material was manufactured and packaged in accordance with ASTM C387/C387M, “Standard Specification for Packaged, Dry, Combined Materials for Concrete and High Strength Mortar,” by a manufacturer of conventional repair products.

The horizontal repair was located on a pier deck slab (Fig. 6(a)), and the vertical repair was located on a slab that was rotated to the vertical (Fig. 6(b)). The repair dimensions were chosen to be representative of the geometrical proportions and the surface-area-to-volume ratio of typical surface repairs made on Naval facilities. Formwork for the vertical repair was constructed using plywood in accordance with the applicable provisions of ACI 347R-14,[14] and it included two chutes (“bird mouths”) on the top for concrete placement.

The prepared concrete surfaces of the cavities were water saturated for 16 hours prior to repair applications to produce saturated surface dry (SSD) conditions at the time of repair material placement. After mixing, the repair material was placed in horizontal repairs using a shovel and in vertical repairs directly from buckets. For both repair types, the repair material was consolidated using an internal vibrator. The formwork for the vertical repair was also vibrated using an external vibrator. Weather conditions at the time of placement were favorable to plastic shrinkage with full sun, wind gusts up to 21 mph (35 km/h), and a relative humidity in the low 50%. Immediately after finishing, the horizontal repairs were covered with wet burlap and plastic sheet, and they were moist cured for 72 hours. For the vertical repairs, curing was performed in the formwork for one week, with water sprinkled from the top twice during the first 48 hours. Repairs were monitored for cracking for

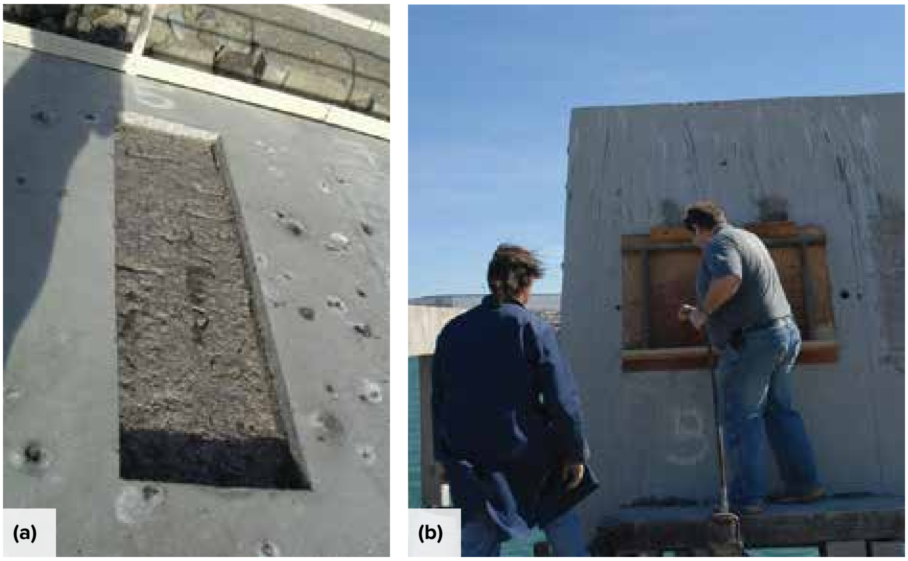


Fig. 6: Repair areas selected for field experiments at the U.S. Navy facility in Port Hueneme, CA, USA: (a) horizontal, on the pier, 73.5 x 19.5 in. (1840 x 490 mm) and 3 in. (75 mm) deep; and (b) vertical, on an existing slab installed upright next to the selected pier, 48 x 36 in. (1200 x 900 mm) and 3.5 in. (88 mm) deep[5]

10 months and sounded with a hammer for voids and delaminations. Over the monitoring period, no cracking was observed on any of the repairs, and the sounding did not reveal any voids, nor delamination.

Using the results from the testing program, a comprehensive material data sheet was developed based on the protocol set out in ACI 364.3R-09[15] (shown in Table 3).

Field Applications

The performance of the repair material is being evaluated in several concrete rehabilitation projects. Two of these projects are described herein to provide examples of typical applications where the characteristics of the repair material can be advantageously exploited. One project is the repair of a deteriorated parking garage deck in Utica, NY, USA, completed in 2016. The rubber-based repair material was selected for its lower shrinkage-cracking sensitivity. The job involved patch repairs and then resealing of the exposed areas. As shown in Fig. 7, the patches had somewhat unusual geometries. The repairs were also shallow in some areas, and the exposed reinforcement was generally not undercut. Even so, no debonding, cracking, or bond line shrinkage have been observed after 4 years in service.

The second case study is the restoration of a 500 ft (152 m) tall, 40-story office building in Philadelphia, PA, USA, in 2016. The building was erected in 1974, and it is the tallest reinforced concrete building in the city. The rubber-based material was chosen for horizontal application, including long form-and-place repairs at the parapets, as well as vertical application. In addition to low cracking sensitivity, the other main parameters influencing the material selection by the specifier were the compressive strength, which had to match

Table 3:
Prototype material data sheet per ACI 364.3R-09[15]

Property	Standard	Data		
Physical characteristics:				
Bulk density (after immersion)	ASTM C642	2.25		
Absorption (after immersion), %	ASTM C642	7.2		
Voids (permeable pore space), %	ASTM C642	15.6		
Mechanical strength and behavior:		**1 day**	**7 days**	**28 days**
Compressive strength, psi (MPa)	ASTM C39/C39M	1525 (10.5)	3427 (23.6)	5574 (38.4)
Flexural strength, psi (MPa)	ASTM C78/C78M	382 (2.63)	516 (3.56)	662 (4.56)
Splitting tensile strength, psi (MPa)	ASTM C496/C496M	182 (1.25)	299 (2.06)	463 (3.19)
Direct tensile strength, psi (MPa)	CRD-C164	—	293 (2.02)	420 (2.90)
Short-term bond strength, psi (MPa)	ICRI No. 210.3 (formerly 03739)	110 (0.76)	232 (1.60)	399 (2.75)
Volume change properties and behavior:				
Modulus of elasticity, $\times 10^6$ psi (GPa)	ASTM C469/C469M	1.96 (13.5)	2.64 (18.2)	3.07 (21.2)
Compressive creep (28 days), $\times 10^{-6}$/psi (MPa)	ASTM C512/C512M	0.329 (47.7)		
Coefficient of thermal expansion, $\times 10^{-6}$/°F (°C)	CRD-C39	5.70 (10.3)		
Length change (28 days), $\times 10^{-6}$	ASTM C157/C157M	470		
Cracking resistance (time to cracking), days	ASTM C1581/C1581M	> 32		
Durability:				
Freezing-and-thawing resistance	ASTM C666/C666M,	**Cycles**	**DF, %**	**Exp., %**
	Procedure A	125	< 60	0.21
Scaling resistance, lb/ft^2 (kg/m^2)	ASTM C672/C672M	0.0091 (0.044), visual rating: 0 to 1		
Rapid chloride permeability, coulomb	ASTM C1202	1218		
Chloride ponding (3 months), % weight	ASTM C1543	**Depth, in. (mm)**	**Cl$^-$, %**	
		0.4 to 0.8 (10 to 20)	0.056	
		1.0 to 1.4 (25 to 35)	0.020	
		1.6 to 2.0 (40 to 50)	0.012	
		2.2 to 2.6 (55 to 65)	0.012	
Sulfate resistance (6-month expansion), %	ASTM C1012/C1012M	0.048		

that of the parent concrete, and the flexibility to use a single product in both manually applied, small patches (Fig. 8) and larger form-and-place applications. Once repairs were completed and cured, the structure was painted with an elastomeric coating. In both the vertical patches and formed elements, the material was applied successfully and performed quite satisfactorily, without reported cracking to this day.

Hence, the field performance of the material is quite promising, especially considering the severe exposure conditions experienced in both case studies. Many other projects are in the planning stage.

Fig. 7: A parking garage deck in Utica, NY, USA, repaired with the rubber-modified repair material, after 4 years in service

Fig. 8: Restoration of a 40-story reinforced concrete building in Philadelphia, PA, USA, in 2016. Spalled areas were repaired with a rubber-modified repair material. Repairs were to be subsequently covered with a polymer coating

Summary

Failures observed on repaired concrete structures often correspond to either one of the following two modes: cracking in the repair material layer and/or delaminating at the interface due to stresses induced by differential shrinkage between repair and concrete substrate, followed in many instances by corrosion of reinforcing steel, more extensive cracking and delamination, and spalling.

Numerous measures have been taken over the years to improve durability and service life of concrete repairs, but very few have targeted one of the root causes of the problem—the inherent brittleness and low deformability of cementitious materials. The approach taken in the development and practical application of the repair material described in this article deviates from the current emphasis on high-strength, high-density, low-bulk permeability materials, being instead directed toward balancing strength, ductility, and compatibility with the existing concrete substrate. Such an approach is desirable in the development of cementitious materials for repair applications with minimum maintenance and extended serviceability between repair cycles.

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Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**. CRD-C39, "Test Method for Coefficient of Linear Thermal Expansion of Concrete," and CRD-C164, "Standard Test Method for Direct Tensile Strength of Cylindrical Concrete of Mortar Specimens," are available at **www.wbdg.org/ffc/army-coe/standards**. ICRI Technical Guideline No. 210.3 (formerly 03739), "Guideline for Using In-Situ Tensile Pull-Off Tests to Evaluate Bond of Concrete Surface Materials," is available at **www.icri.org**.

Selected for reader interest by the editors.

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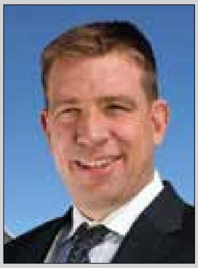

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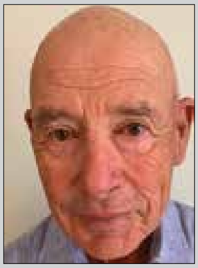

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