RECLAMATION

Managing Water in the West

Concrete Repair Engineering Experimental Program (CREEP)

Development of Test Methods to Evaluate Cracking Tendency of Repair Materials—Field Study Phase II

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Development of Test Methods to Evaluate Cracking Tendency of Repair Materials—Field Study Phase II

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1 Introduction

Significant progress has been made in the ability to select durable cement-based repair materials. The menu of materials available for a particular repair application is extensive. The main task in the selection of repair materials is to be able to identify the product that will be the most resistant to the formation of cracks for a given application.

Under conditions of restraint typical for most concrete repairs, the drying shrinkage of a repair material and the resulting cracking is a critical factor for the repair durability.

Shrinkage of a hardened material, when restrained, produces tensile stresses. Since the tensile strength of cementitious repair materials is low, they may crack. Cracking generally is not serious enough to jeopardize the structural integrity of the repaired structure, but it is harmful for durability. External cracks, interlinking with microcracks, which are always present in cement-based materials, make it easy for water and aggressive chemicals and gasses to permeate into the interior—to the embedded reinforcement. Also, cracks look bad and are the most frequent subject of complaints about repairs, particularly to architectural concrete.

A signifiacnt problem in concrete and repair material is not the lack of strength or stiffness, but rather lack of resistance to initiation and propagation of cracks. One can allow for lack of strength and stiffness in design, but it is much more difficult to allow for cracks which are "life-threatening wounds on concrete bodies" (Vaysburd and Emmons 2006).

1.1 Background

The overall objective of the research undertaken by the Concrete Repair Engineering Experimental Program (CREEP) is development of test methods to evaluate the cracking tendency of repair materials. The cracking tendency can be defined as the susceptibility of restrained material to cracking under effects from its natural volume changes and from environmental factors. A material that resists cracking is termed a material with a low cracking tendency. Conversely, a material that cracks easily can be termed a material with a high cracking tendency.

Cracking tendency cannot easily be related to the tensile strength since the tensile stress it must resist depends on shrinkage, thermal stresses, elastic modulus, and creep and stress relaxation.

The main objective of the Phase I Report published by the Bureau of Reclamation (Reclamation) in March 2005 (Morency et al. 2005) was to evaluate the performance of cementitious repair materials in experimental repairs placed in geometrically different cavities of prefabricated reinforced concrete slabs and select the optimum cavity geometry and slab configuration for further studies of sensitivity to cracking of repair materials. As a result of the Phase I study, the "Baenziger block" was judged as the optimal specimen configuration and was recommended for further studies in Phase II of the project.

Near the end of 2004, ASTM International (ASTM) adopted ASTM C1581-04, *Standard Test Method for Determining Age of Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage*. This test method covers the laboratory determination of the age at which cracking first occurs and the induced tensile stress characteristics of mortar or concrete specimens under restrained shrinkage. In the test, a material ring is cast around a steel ring instrumented with strain gauges. The strain accumulation and the length of time before cracking occurs indicate the cracking tendency of the material. Materials that create less strain on the steel ring and take longer to crack have a lower cracking tendency.

The age at first cracking for the tested materials can be compared and used as the basis for material selection. For materials that have not cracked during the test, the rate of stress development at the end of the test can be compared and used as the basis for material selection.

The major advantage of this relatively easy laboratory test is that it accounts for all of the material factors that influence shrinkage cracking from the time of casting. It does not require complex calculation or assumptions of early material behaviour. It simultaneously considers stress development, dimensional changes and creep at early ages. Prior to adoption of ASTM C1581, ASTM C157, *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*, was widely used to measure deformability of cementitious repair materials. The method is adequate for measuring the free shrinkage of cementitious repair materials; however, it is not reliable for measuring materials' shrinkage in repair situations because it does not take into account the complexity of stress development under restrained conditions. The other shortcomings of the method include:

- The initial measurement neglects the volume changes that occur before demolding.
- The ratio of the specimen's longitudinal to lateral dimensions is far greater than normally encountered in most repair installations.

Therefore, the results obtained using this laboratory test method may deviate from actual in-situ behaviour up to 20 percent (Temper and Spellman 1963).

The ASTM C1581 test method covers the determination of the cracking tendency of restrained specimens. The procedure is comparative and not intended to determine the time of initial cracking of repair material cast in a specific type of repair, where cracking may depend on many variables including construction methods, curing, degree of restraint, hydration effects, and environmental factors. The method is useful for determining the relative likelihood of cracking thereby aiding in the selection of materials that are less likely to crack. This test method can be used to evaluate relative effects of material variation on cracking potential. These variations may include, but are not limited to, cement type, cement content, supplementary cementing materials, water content, aggregate type, aggregate gradation, and chemical admixtures. The cracking potential of the repair material can be classified on the basis of either how long it takes the material to crack or the rate of stress development in the material.

History of the "ring" test method for sensitivity to cracking of cementitious materials has about 70 years of history. Following is a brief background on research into the cracking tendency of materials used with the ring method.

In the years from 1939 to 1942, Carlson and Reading (1988) conducted restrained shrinkage tests using a ring specimen. In these tests, a very thin concrete ring was cast around a steel ring. The 34-mm (1.5-in) high steel ring had an internal diameter of 125 mm (5 in) and an external diameter of 175 mm (7 in). The concrete ring was 25 mm (1 in) in radial thickness and matched the height of the steel ring. The top and bottom surfaces of the concrete were sealed so that drying only occurred from the outer circumferential surface. Concrete rings were dried at 25, 50, and 75 percent relative humidity after an initial moist curing period. Coutinho, in 1959, reported on his studies employing the ring test (Couthino 1959). Coutinho studied the rupture strengths of pastes and mortars to resist the restrained shrinkage using unrestrained and restrained ring specimens. The influence of the type of cement on its cracking tendency was researched. His research considered the cracking tendency of natural cement, standard portland cement, high-early-strength portland cement, and aluminous cement.

The test specimens of pastes and mortars had cross-sectional dimensions of 25 by 25 mm (1 by 1 in). Coutinho developed the concept of the quotient of maximum stress for specimens that were uncracked after 90 days. The quotient is calculated by dividing the stress in the restrained concrete ring after a drying period of 90 days by the shrinkage of the free ring after 90 days. If cracking occurred at an earlier period, the stress and shrinkage strains at cracking are used instead of the values at 90 days. As a rule, cements with low cracking tendency present quotients lower than those more liable to crack.

$$\text{Quotient of maximum stress} = \frac{\sigma_{90}}{\delta_{90}}$$

where,

σ_{90} = stress in restrained concreete ring at 90 days
δ_{90} = shrinkage strain in unrestrained ring at 90 days

The quotient of maximum stress indicates how much relaxation occurred in the material due to creep. Large values indicate that small amounts of relaxation had occurred in the specimen whereas small values of the quotient indicate that substantial creep relaxation had occurred.

Almeida (1990) investigated the cracking resistance of high strength concretes with compressive strengths between 60 and 100 MPa (8,700 and 14,500 lb/in^2).

Ring specimens with an external diameter of 810 mm (31.9 in) were used. The concrete cross section was 80 by 80 mm (3.1 by 3.1 in). One set of rings in each series was cast around a restraining aluminum ring. Dimensions were chosen so that theoretical variation of stresses within the concrete rings could be disregarded.

The strains induced by shrinkage in the aluminum rings were measured during drying. At some time after initial drying, the concrete ring would crack. From the strain data, the rupture stress of the concrete at cracking could be determined. The compressive strength, flexural strength, weight loss, and creep were also measured on companion specimens.

Almeida used the methods proposed by Coutinho for determining the quotient of maximum stress. No simple relationships were found between cracking and the major parameters typically used such as strength or shrinkage.

In 2001, Attiogbe et al. (2001) reported on studies on cracking potential of concrete and mortar using ring specimens.

Attiogbe's research unquestionably contributed to the development of the presently adopted ASTM test method. However, no reported experimental studies correlate test results using ring test and in-situ performance of repair materials. In other words, how reliable is this method for predicting cracking behaviour of repair materials in real life repairs?

In 1996, the Transportation Research Council issued a report (1996) in which studies on cracking in bridge decks and concrete behaviour in ring tests were analyzed. Soon after publication of this report, the American Association of State Highway and Transportation Officials (AASHTO) implemented a provisional standard (AASHTO 1999) that used the ring test to help quantify a materials propensity for cracking.

However, the actual cracking in service depends on many variables such as type of structure, geometry, degree of restraint, construction and curing methods, and environmental factors, and, of course, there are significant differences between concrete volume changes and stresses in bridge decks and repair material in composite repair systems.

No one has yet published results about whether the ASTM ring test is a reliable test method for evaluating the cracking behavior of repair materials in repair situations.

2 Research Objectives, Approach, and Scope

2.1 Objective

The overall objective of the CREEP research project is to provide the industry with reliable methods and means to evaluate the performance of repair materials. The specific objectives are to:

- Develop laboratory/field reliable test methods to evaluate the long-term performance of repair materials and, particularly, their sensitivity to cracking
- Assess the reliability of some of the existing test methods for evaluating the cracking tendency of repair materials under "real-life" conditions
- Establish performance criteria for selecting crack-resistant repair materials

The objectives of the Phase II study of the CREEP project is to correlate results from selected test methods from Phase I and the ASTM ring test to experimental repairs. The scope of the work of the Phase II study is to establish the correlation, if any, between:

- Ring test (ASTM C1581) material evaluations and its in-situ performance
- Baenziger block test and experimental repairs
- Free shrinkage (ASTM C157) and experimental repairs

2.2 Research approach

Three locations were selected to conduct field and laboratory testing for the second phase of this project. Reclamation (Denver, Colorado), the U.S. Navy facilities (Port Hueneme, California), and Laval University (Quebec, Canada) were selected. At both the Reclamation and U.S. Navy facilities, experimental field repairs were performed, and laboratory tests were conducted at Laval University.

The experimental repairs were represented by eight 15-ft by 15-in by 3-in thick overlay slabs over existing concrete pavement slabs. Four cement-based materials were selected for eight experimental repairs at each designated site. Four of the repairs were performed with repair mortars and four with the same mortars extended with aggregate. The repairs were monitored for cracking behavior for 9 months at Reclamation and for 12 months at the Navy facilities The results of the ring, Baenziger, and free shrinkage tests were analyzed and compared to material behavior in the experimental repairs. Figure 1 shows the two sites for the repair slabs and the assembled formwork for repairs.

Table 1 summarizes the tests performed at each location.

Figure 1.—Reclamation (left) and U.S. Navy (right) experimental sites.

Table 1 .—Tests carried out at each location

Test performed	Reclamation	U.S. Navy	Laval University
Experimental repairs	✓	✓	
Ring test (ASTM C1581)			✓
Baenziger block test	✓		
Free drying shrinkage (ASTM C157)	✓		✓
Compressive strength (ASTM C39)	✓	✓	✓
Tensile splitting test (ASTM C496)	✓		✓
Modulus of elasticity (ASTM C469)	✓		✓
Flexural creep test (Laval U. method)	✓		✓

3 Field Testing

Four proprietary cementitious repair materials (numbered 1 to 4) from three manufacturers were used as mortars (M) and as extended mortars (C). To extend the mortars, ⅜-inch gravel provided by each manufacturer was added to the mixture. Each manufacturer specified the amount of aggregate addition. The repair materials used were premixed and bagged at the respective manufacturers' plants and sent to each location.

Since materials used were proprietary materials, their composition was unknown. After testing started, it was found that materials 1M and 1C were magnesium-phosphate-cement-based fast-setting materials. Materials 2M, 2C, 3M, and 3C were portland-cement-based materials and had typical setting times. Materials 4M and 4C exhibited shorter setting times than is usual for portland-cement-based materials. A problem occurred at the U.S. Navy location for material 4C, and the results for this material at the U.S. Navy location were not used, nor was the experimental repair monitored.

The mortars were mixed in a mortar mixer (paddle type), and the extended mortars were mixed in a concrete mixer (rotating drum mixer) as shown in Figure 2.

3.1 Experimental repairs

The field testing program included experimental repairs at both Reclamation and U.S. Navy facilities. For each material, one experimental repair was done. The experimental repair consisted of a 15- by 180-in, 3-in thick overlay. Figure 3 presents a schematic view of the experimental repair.

Figure 2.—Paddle type mixer (left) and rotating drum mixer (right).

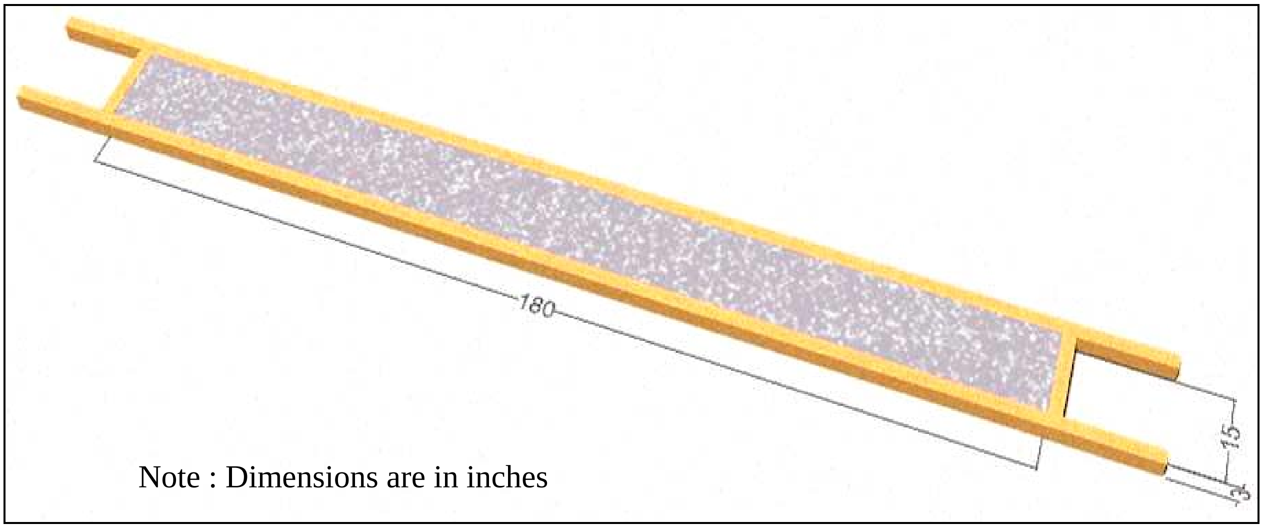

Figure 3.—Geometry of experimental repair.

The surface preparation for repairs at Reclamation was accomplished using shotblasting. It allowed removing the thin layer of paste at the existing concrete surface, lightly exposing the coarse aggregate (Figure 4).

At the U.S. Navy Facilities at Port Hueneme, hydrojetting was used, which exposed the aggregate to a larger extent than at the Reclamation facility (Figure 5).

After the surface preparation was completed, inspection of the concrete surface revealed the presence of pre-existing cracks on both experimental sites. To diminish the possibility of crack reflection into the repair and avoid nonuniform moisture absorbtion from the repair mixture into the substrate, an expoxy bonding

Figure 4.—Surface preparation at Reclamation.

compound was applied to the substrate concrete 20 minutes prior to repair material placement. For this purpose, SikaDur HiMod 32 was used.

The material mixtures were placed in one single layer to avoid cold joints, and each was cured according to manufacturers' instructions. For materials 1M and 1C, the curing method consisted of placing a plastic sheet on the repair material for 24 hours. For all other materials, curing consisted of covering the slabs for 72 hours with wet burlap and plastic sheeting.

The monitoring for cracking was conducted every day for the first week and once a week for the first month. After a month, readings were taken every 2 months.

Figure 5.—Surface preparation at the U.S. Navy.

Figure 6.—Placement of the repair material at Reclamation (left) and U.S. Navy (right).

The same curing methods were used for the Baenziger block tests. The specimens for the mechanical properties (3- by 6-in cylinders) and for the free drying shrinkage tests were covered with wet burlap and plastic sheeting for 24 hours and then stored in a fog room (100% R.H) until testing began. For the ring test, wet burlap and plastic sheeting were applied over the ring for 72 hours.

3.2 Baenziger block test

The Sika Corporation developed the Baenziger block test in Switzerland. It is used to evaluate cracking sensitivity of repair materials. This test consists of a cavity repair in the 350- by 1,050-mm prefabricated concrete slab and monitoring the repair for cracking. The concrete mixture used to manufacture the Baenziger blocks (Table 2) had a design strength of 35 MPa (5,000 lb/in^2).

Table 2.—Concrete mixture for Baenziger blocks

Constituents	kg (m^3)
Cement	422
Sand	670
Coarse aggregate (5-14 mm)	1026
Water	180
Water reducer (ml/kg of cement)	2.38
Air-entraining admixture (ml/kg of cement)	0.25

A schematic diagram of the Baenziger block both prior to and after placement of a repair material is shown in Figure 7. The repair thickness is constant (30 mm) over the first 500 mm from the left and varies from 30 to 60 mm from the center to the right. On the opposite side (the left side) and part of the inner side, there is a border that increases the level of restraint.

After manufacture of the Baenziger blocks, they were aged until drying shrinkage deformations were completed. The cavity surface preparation consisted of light sandblasting. After the repair materials were placed in the Baenziger blocks, they were exposed to field conditions along with the experimental repair slabs. The blocks were monitored for cracking over a period of 9 months.

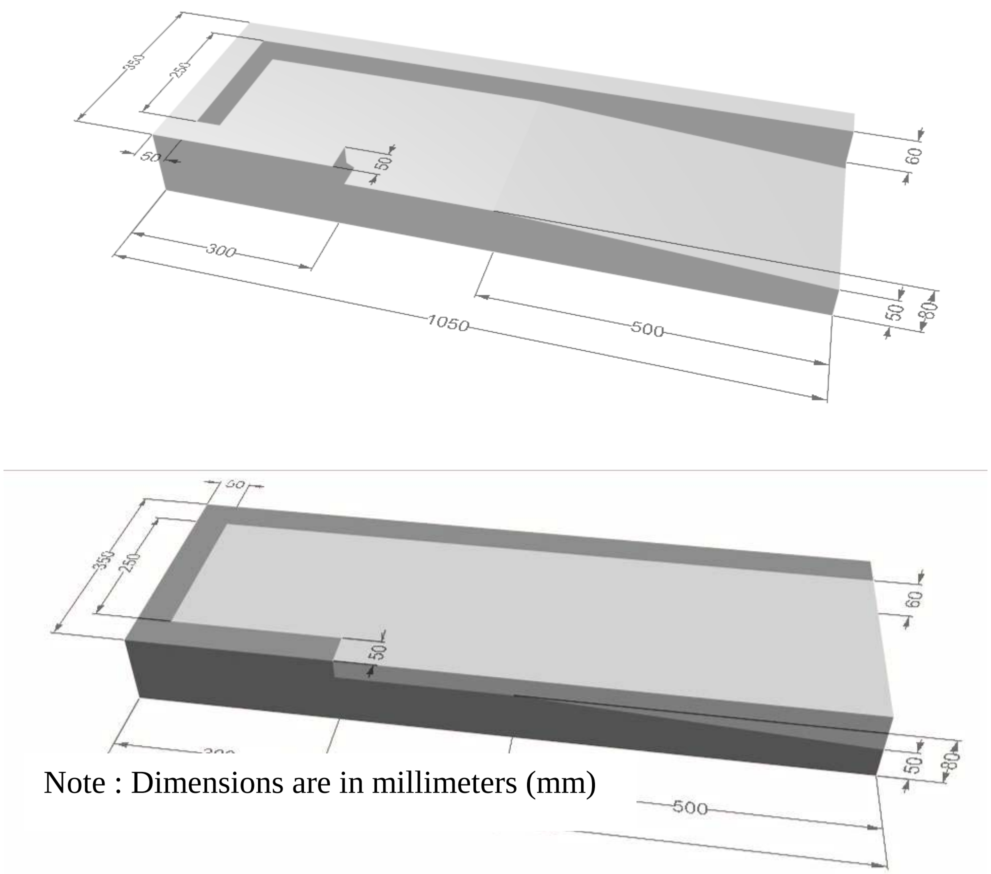

Figure 7.—Baenziger block prior to (top) and after (bottom) "repair."

3.3 Bond test

Bond of each repair material to the substate was tested using hammer blows to sound for delaminations. In addition, pull-off bond tests were conducted after 9 months of field exposure. The pull-off tests were performed on three materials (2C, 3C, and 4C) at both locations (Reclamation and U.S. Navy). The materials selected were the extended mortars that showed the best resistance to cracking, in order to verify if the good resistance to cracking was not the result of a poor bond between the repair material and the substrate.

The pull-off tests were carried out using German Instrument apparatus (Figure 8). The 3-in diameter cores were drilled 30 mm down into the substrate. For each material, three pull-off tests were performed.

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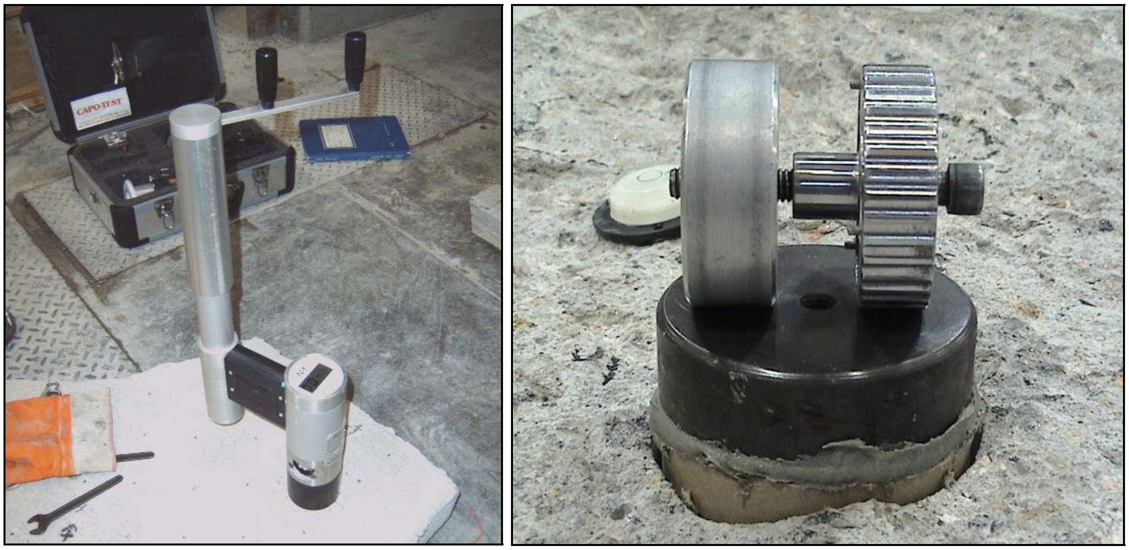


Figure 8.—German Instrument pull-off test apparatus.

4 Laboratory Testing

4.1 Mechanical properties

The following tests were performed during the Phase II study:

- Compressive strength.—ASTM C39, *Standard test method for compressive strength of cylindrical concrete specimens*
- Splitting tensile strength.—ASTM C496, *Standard test method for splitting tensile strength of cylindrical concrete specimen*
- Modulus of elasticity.—ASTM C469, *Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression*

Three 75- by 150-mm (3- by 6-in) cylindrical specimens were used for each test.

4.2 Free drying shrinkage

The free shrinkage tests were carried out at Reclamation and Laval University in accordance with ASTM C157, *Standard test method for length change of hardened hydraulic-cement mortar or concrete* (modified). The test procedure was modified in accordance with the REMR Report (USACE March 1999). For all repair mixtures, 75- by 75- by 285-mm (3- by 3- by 11¼-in) specimens were used. Two types of comparator were used to obtain the readings. The first is described by ASTM C157 (Figure 9) and was used at Laval University. The

Figure 9.—Standard comparator for measuring free drying shrinkage

strain (Laval University).

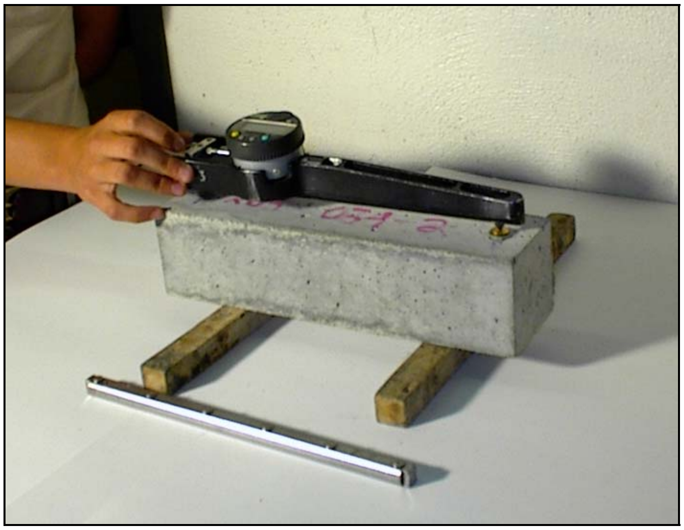


Figure 10.—Mobile plate comparator for measuring free drying shrinkage strain (Reclamation).

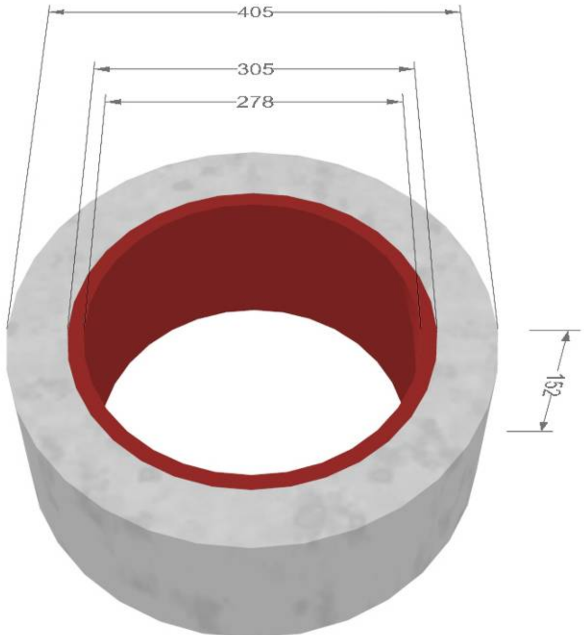
comparator used at Reclamation utilized a fixed seating pin and a pin mounted on a mobile plate (Figure 10).

4.3 Ring test

The restrained shrinkage test was carried out in accordance with ASTM C1581, *Standard test method for determining age at cracking and induced tensile stress characteristics of mortar and concrete under restrained shrinkage*. The test method consists of a steel ring that acts as the restraining support, around which material mixture is poured. The ring test material specimen is shown in Figure 11.

The steel rings are equipped with four strain gages linked to a data acquisition system that records the strain in the steel at a rate of one reading every 15 minutes. Data acquisition started right after specimen casting. This allows for pinpointing the exact moment of crack occurrence and documenting the stress at the time of cracking.

The rings were cured in the mold under wet burlap and plastic sheeting for 72 hours. After the curing period, the molds were removed.



Note: Dimensions are in millimeters

Figure 11.—ASTM C1581 test specimen.

The calculations to determine the average stress in a repair material were made as follows:

$$\sigma_{avg}(t) = \frac{E_s \; r_{ic} \; h_s}{r_{is} \; h_c} * \left(\varepsilon_s(t)\right) * 10^6$$

where,

$\sigma_{avg}(t)$ = average tensile stress in concrete as a function of time (MPa)
E_s = steel modulus of elasticity (MPa)
r_{ic} = internal radius of concrete (mm)
r_{is} = internal radius of steel (mm)
h_c = concrete wall thickness (mm)
h_s = steel wall thickness (mm)
$\varepsilon_s(t)$ = steel strain as a function of time (µm/m)

5 Test Results

5.1 Mechanical properties

Mechanical properties test results are presented below and are the average of test results for three specimens.

5.1.1 Compressive strength

Compressive strength test results are presented in Table 3.

Table 3.—Compressive strength test results (ASTM C39)

Material	Age (days)	Reclamation lb/in² (MPa)	U.S. Navy lb/in² (MPa)	Laval University lb/in² (MPa)
1M	3	4077 (28.1)	-	3130 (21.6)
	28	5273 (36.4)	-	4220 (29.1)
	56	-	4701 (32.4)	-
1C	3	5017 (34.6)	-	3393 (23.4)
	28	6447 (44.5)	-	4205 (29.0)
	56	-	6178 (42.6)	-
2M	3	3550 (24.5)	-	3364 (23.2)
	28	4843 (33.4)	-	4886 (33.7)
	56	-	6637 (45.8)	-
2C	3	3740 (25.8)	-	2958 (20.4)
	28	5043 (34.8)	-	3900 (26.9)
	56	-	5353 (36.9)	-
3M	3	2680 (18.5)	-	2856 (19.7)
	28	4067 (28.0)	-	4524 (31.2)
	56	-	5846 (40.3)	-
3C	3	2960 (20.4)	-	2480 (17.1)
	28	5043 (34.8)	-	3378 (23.3)
	56	-	5933 (40.9)	-
4M	3	4847 (33.4)	-	5031 (34.7)
	28	5870 (40.5)	-	6264 (43.2)
	56	-	4410 (30.4)	-
4C	3	4033 (27.8)	-	5365 (37.0)
	28	4870 (33.6)	-	6870 (47.4)
	56	-	1773 (12.2)*	-

* Inadequate mixing affected the strength.

5.1.2 Modulus of elasticity

Table 4 presents results of modulus of elasticity tests performed at Reclamation and Laval University.

Table 4.—Modulus of elasticity test results (ASTM C469)

Material	Age (days)	Reclamation $x10^6$ lb/in^2 (GPa)	Laval University $x10^6$ lb/in^2 (GPa)
1M	3	3.84 (26.5)	4.04 (27.8)
	28	4.09 (28.2)	4.28 (29.6)
1C	3	5.36 (36.9)	5.16 (35.6)
	28	6.05 (41.7)	5.86 (40.4)
2M	3	2.93 (20.2)	3.33 (23.0)
	28	3.57 (24.6)	3.88 (26.8)
2C	3	3.27 (22.5)	2.94 (20.2)
	28	3.39 (23.4)	3.35 (23.1)
3M	3	2.40 (16.6)	2.64 (18.2)
	28	2.84 (19.6)	3.39 (23.4)
3C	3	2.67 (18.4)	2.75 (18.9)
	28	2.97 (20.5)	3.41 (23.5)
4M	3	3.39 (23.4)	4.07 (28.1)
	28	3.49 (24.0)	4.47 (30.8)
4C	3	3.41 (23.5)	3.83 (26.4)
	28	N/A	4.61 (31.8)

5.1.3 Splitting tensile strength

Splitting tensile strength tests results performed at Reclamation and Laval University are presented in Table 5.

Table 5.—Splitting tensile strength test results (ASTM C496)

Material	Age (days)	Reclamation lb/in^2 (MPa)	Laval University lb/in^2 (MPa)
1M	3	457 (3.1)	218 (1.5)
	28	560 (3.9)	323 (2.2)
1C	3	540 (3.7)	267 (1.8)
	28	640 (4.4)	348 (2.4)
2M	3	450 (3.1)	371 (2.6)
	28	500 (3.4)	463 (3.2)
2C	3	423 (2.9)	312 (2.2)
	28	590 (4.1)	374 (2.6)
3M	3	283 (2.0)	384 (2.6)
	28	413 (2.9)	490 (3.4)
3C	3	363 (2.5)	241 (1.7)
	28	550 (3.8)	332 (2.3)
4M	3	540 (3.7)	441 (3.0)
	28	657 (4.5)	473 (3.26)
4C	3	468 (3.2)	405 (2.79)
	28	570 (3.9)	523 (3.61)

5.2 Field experiments

5.2.1 Experimental repairs

The crack patterns at the end of the monitoring periods are presented in Figure 12 and Figure 13 for Reclamation and the U.S. Navy, respectively. In these figures, the localized debonding of the repairs are shown by the shaded areas. Debonding occurred only for materials 1M and 4M at the Reclamation site. Table 6 presents the number of cracks for each experimental repair.

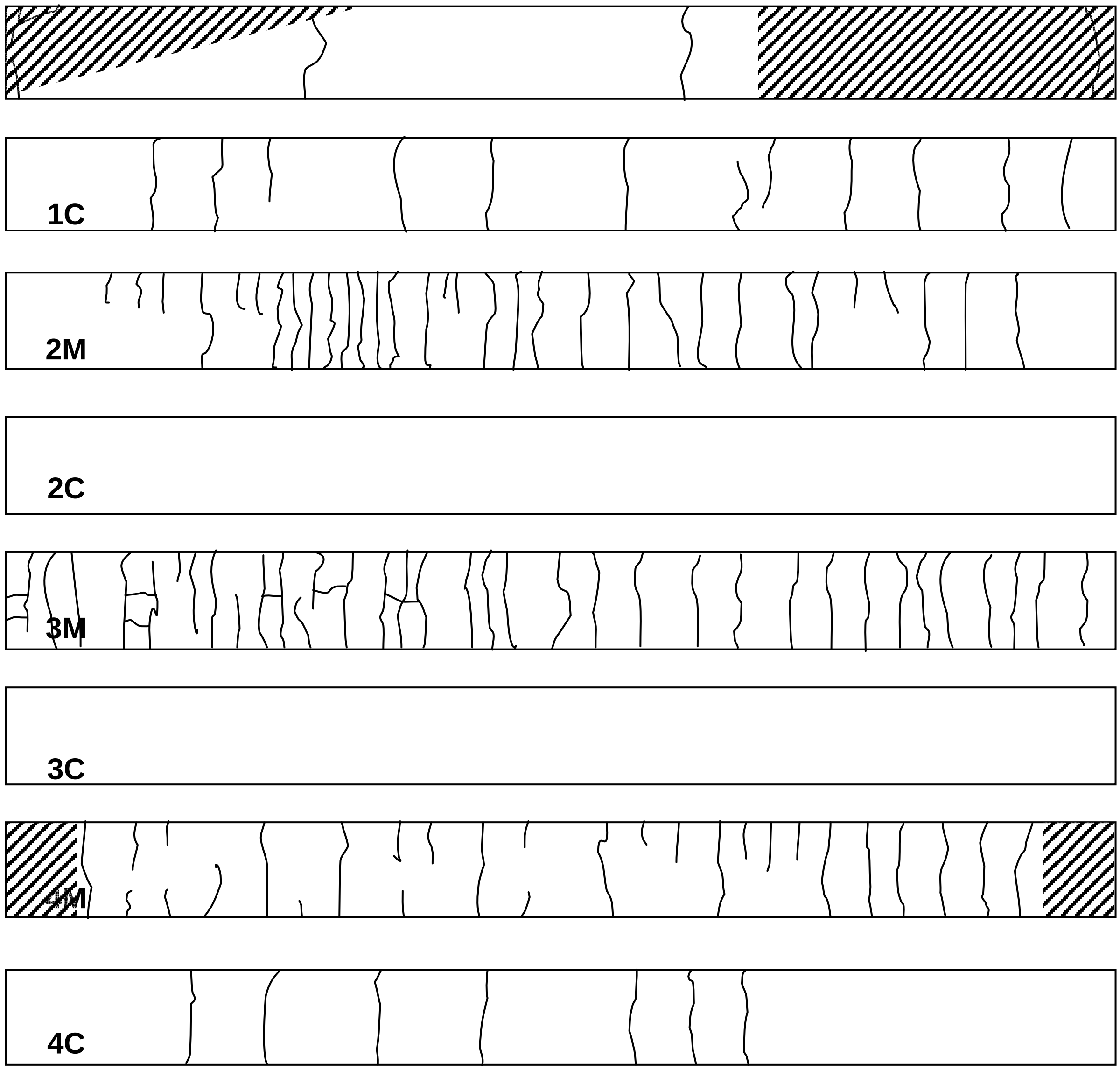


Figure 12.—Cracking in experimental repairs at Reclamation (9 months after placement).

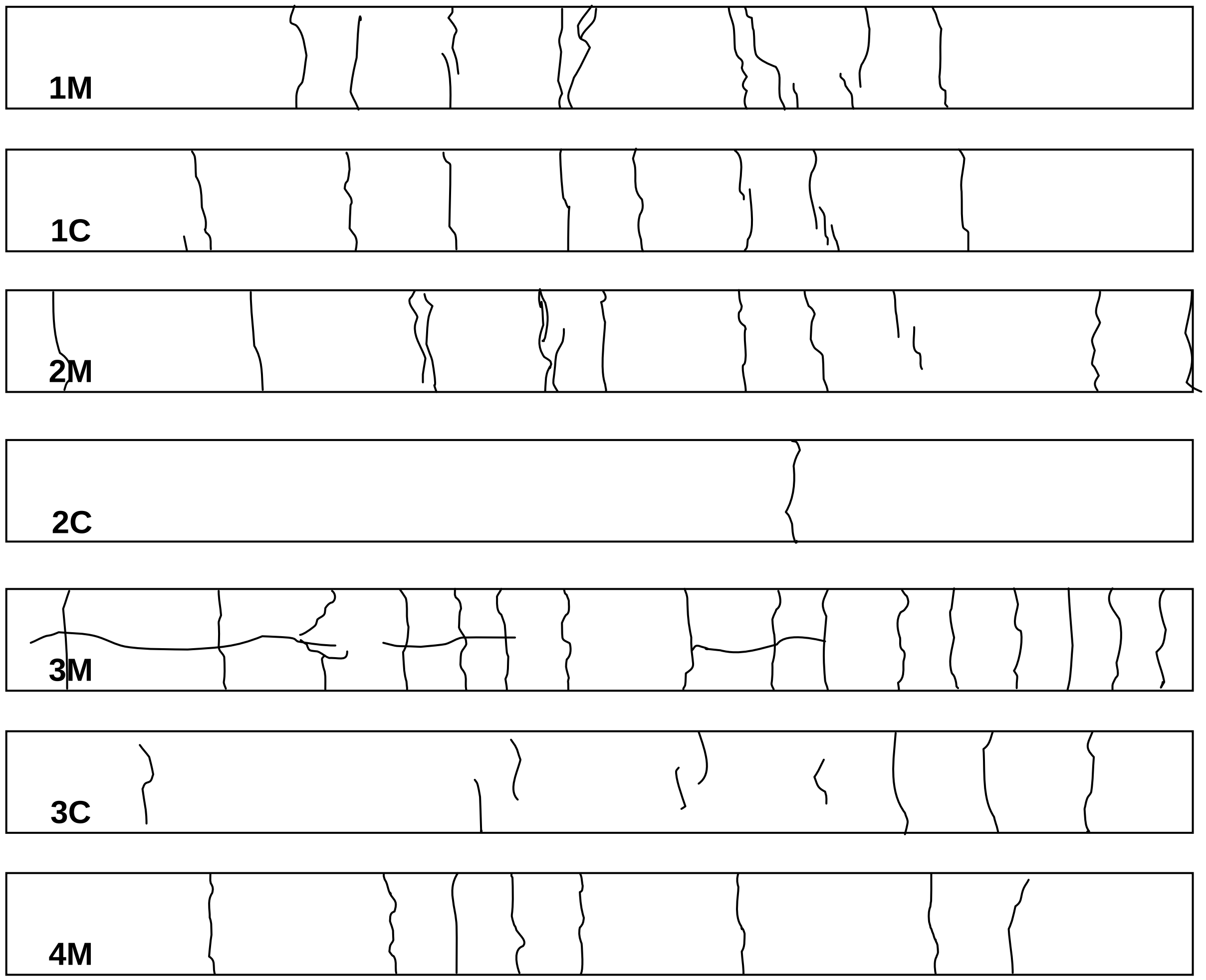


Figure 13.—Cracking in experimental repairs at U.S. Navy (9 months after placement).

Table 6.—Summary of cracking in experimental repairs

Material	Reclamation–number of cracks	U.S. Navy–number of cracks
1M	4	9
1C	12	8
2M	31	12
2C	0	1
3M	45	16
3C	0	4
4M	22	8
4C	8	-

5.2.2 Baenziger block test

The results of the Baenziger block test are presented in Figure 14 and Table 7. Only materials 2M and 3M experienced cracking in the Baenziger block test.

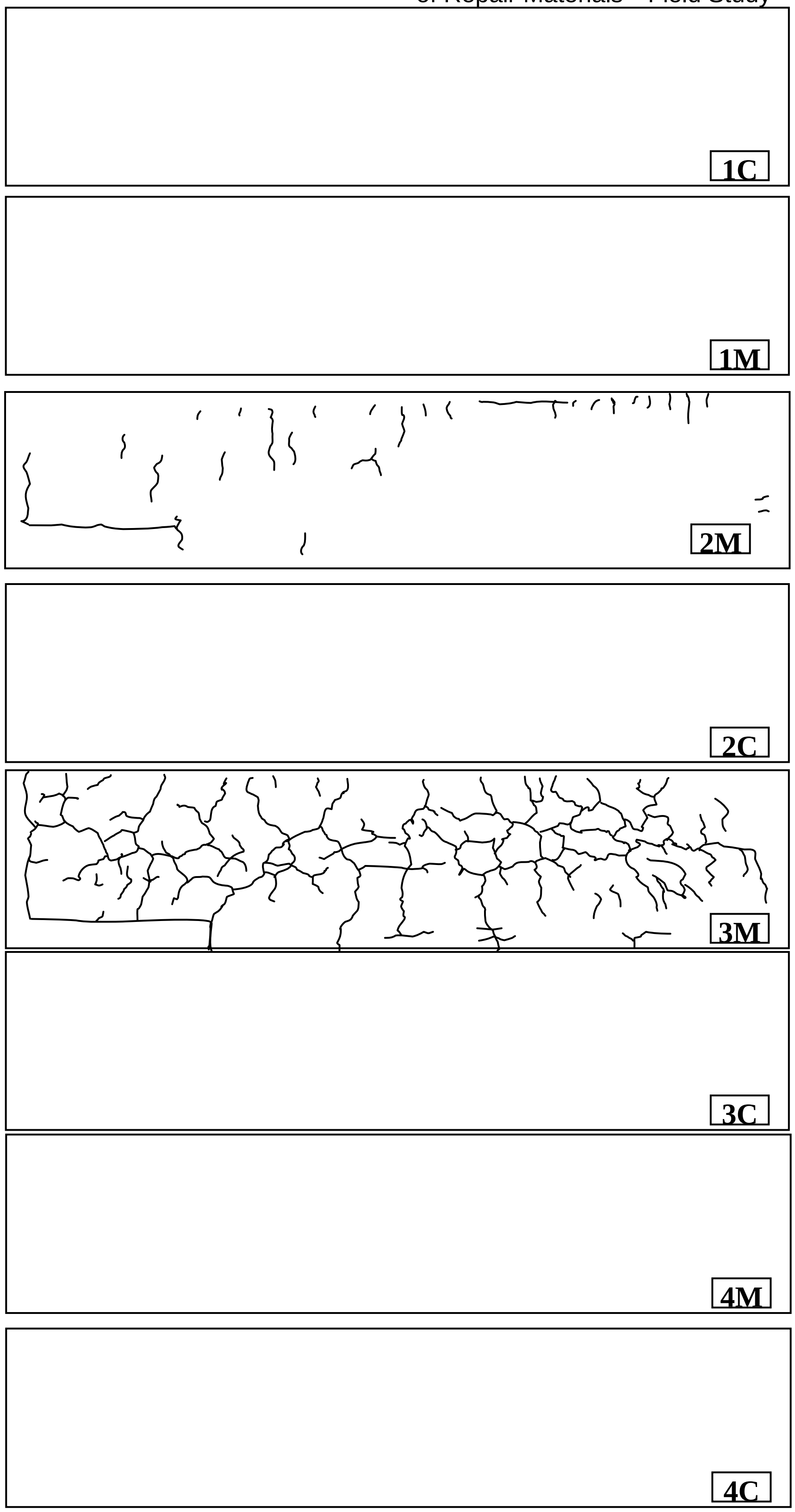


Figure 14.—Cracking of Baenziger blocks exposed to field conditions at Reclamation (9 months after placement).

Table 7.—Summary of cracking in Baenziger blocks

Material	Number of crack
1M	0
1C	0
2M	15
2C	0
3M	50+
3C	0
4M	0
4C	0

5.2.3 Bond test

The pull-off test results are presented in Figure 15 and Table 8.

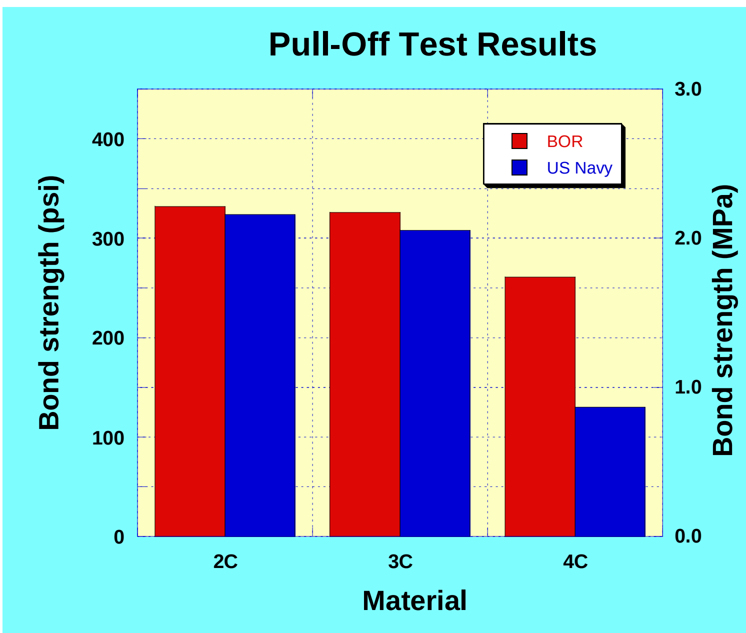


Figure 15.—Bond test results.

Table 8.—Bond strength results

	Reclamation		U.S. Navy	
Material	Bond strength (lb/in^2)	Failure	Bond strength (lb/in^2)	Failure
2C	325	Substrate	340	Substrate
	328	Interface	306	Substrate
	341	Substrate	325	Substrate
Average	331		324	
3C	341	Substrate	290	Sub/repair
	318	Substrate	306	Substrate
	318	Substrate	329	Substrate
Average	326		308	
4C	318	Interface	120	Repair
	276	Interface	132	Repair
	177	Interface	139	Repair
Average	257		130	

5.3 Laboratory testing

5.3.1 Free drying shrinkage test (ASTM C157 Modified)

The results of the free drying shrinkage test conducted at Reclamation and Laval University are presented in Figure 16 and Figure 17.

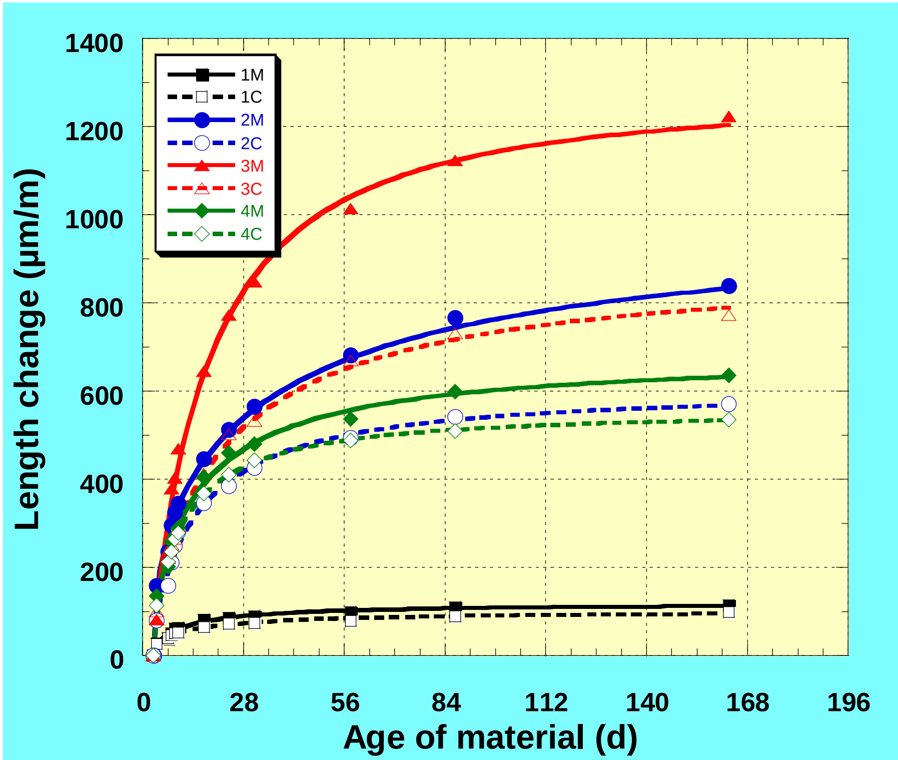


Figure 16.—Drying shrinkage test results (ASTM C157 modified) from Reclamation.

Table 9.—Summary of length change test results for tests conducted at Reclamation location

	Length change (ASTM C157 mod.)—Reclamation	
Material	28 days (µm/m)	150 days (µm/m)
1M	90	120
1C	75	90
2M	540	825
2C	415	565
3M	825	1200
3C	515	785
4M	475	630
4C	440	530

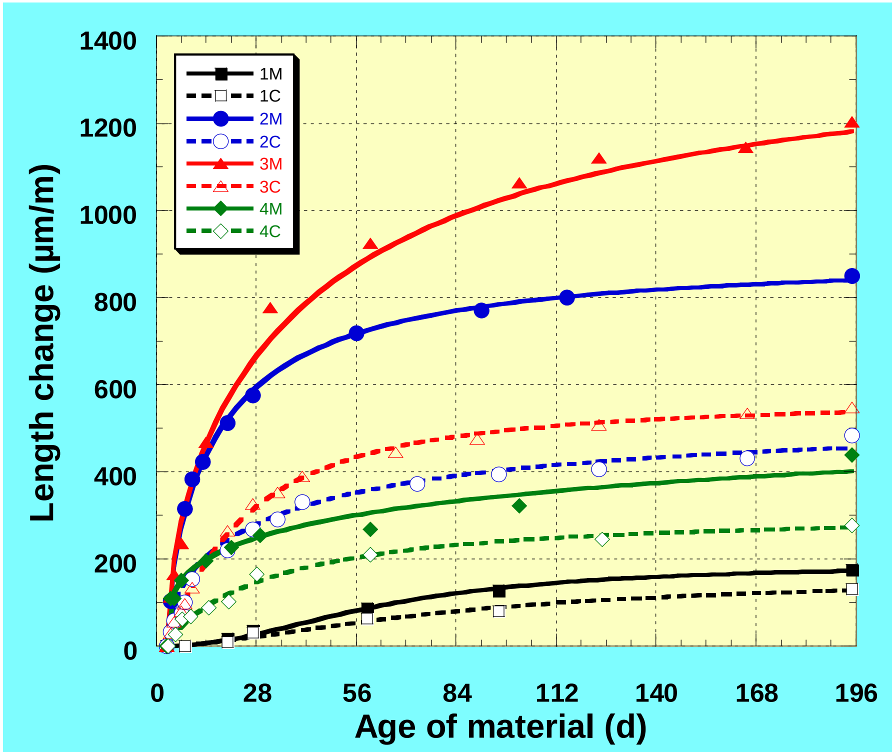


Figure 17.—Drying shrinkage test results (ASTM C157 modified) from Laval University.

Table 10.—Summary of length change test results for tests conducted at Laval University

Material	Length change (ASTM C157 mod.)—Laval University 28 days (µm/m)	150 days (µm/m)
1M	25	160
1C	20	110
2M	590	825
2C	280	440
3M	725	1130
3C	425	525
4M	245	380
4C	145	265

5.3.2 Ring test (ASTM C1581)

Ring test results are presented in Figure 18 through Figure 29. The sign (-) indicates tensile stress. The summary of the ring test results is presented in Table 11 and Table 12.

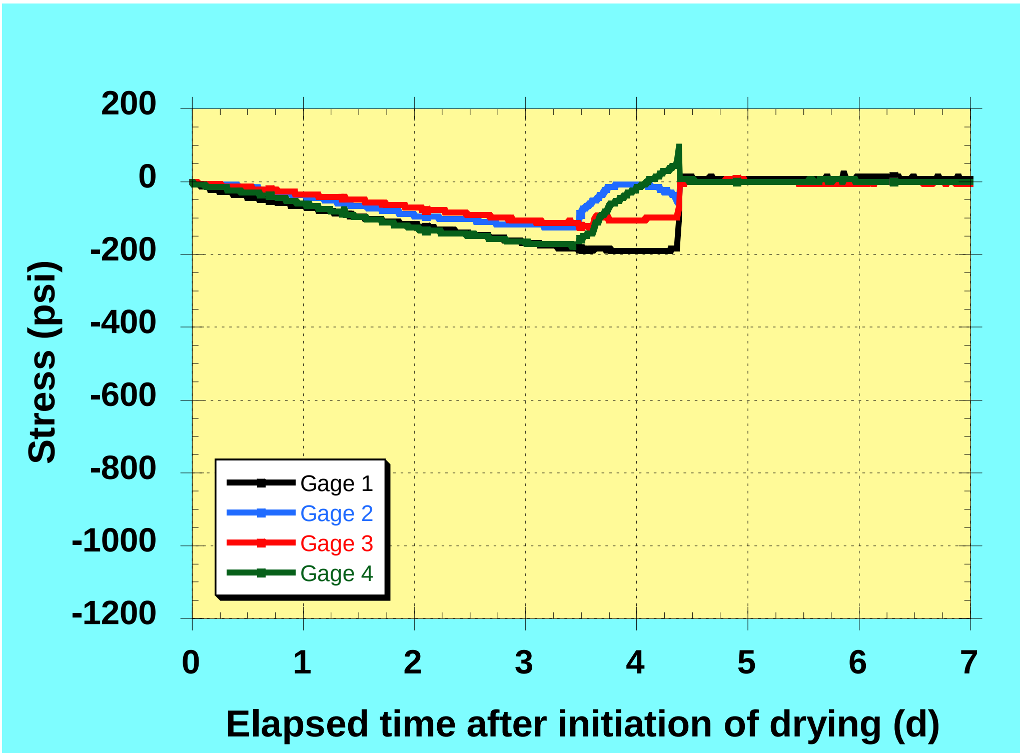


Figure 18.—ASTM C1581 ring test results for material 2M, specimen 1.

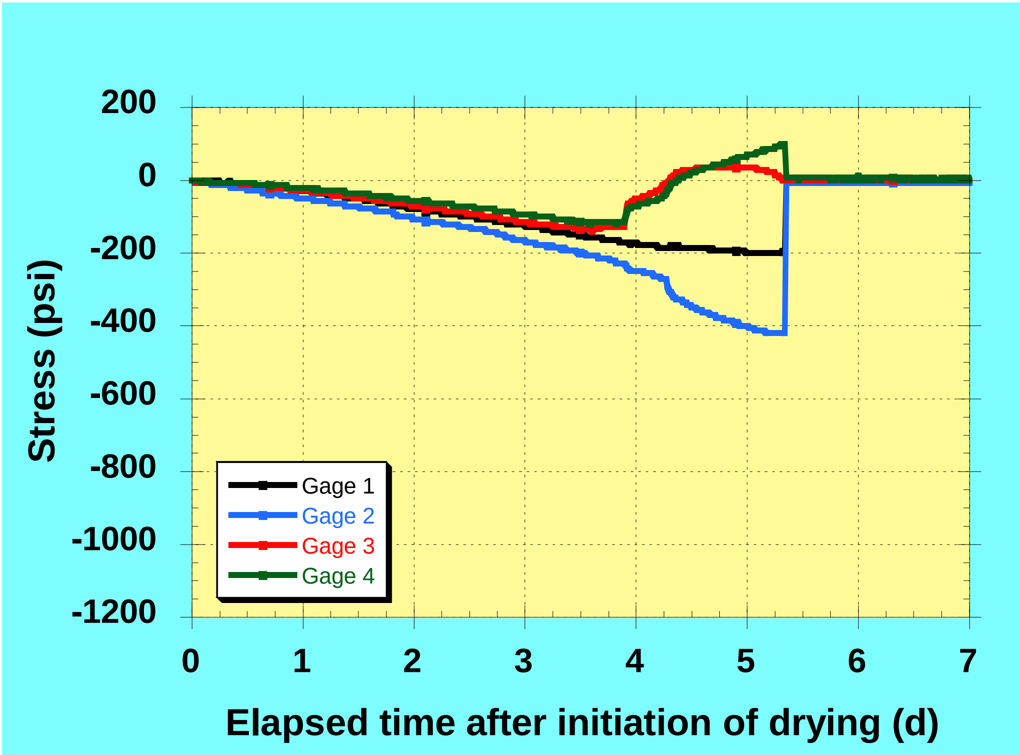


Figure 19.—ASTM C1581 ring test results for material 2M, specimen 2.

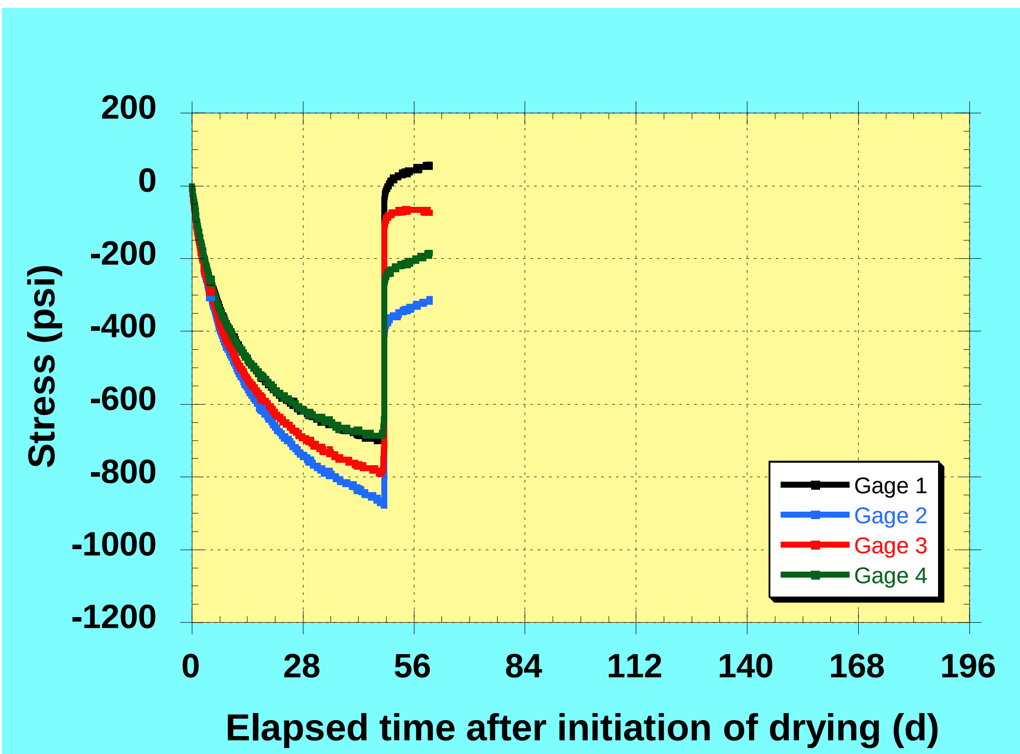


Figure 20.—ASTM C1581 ring test results for material 2C, specimen 1.

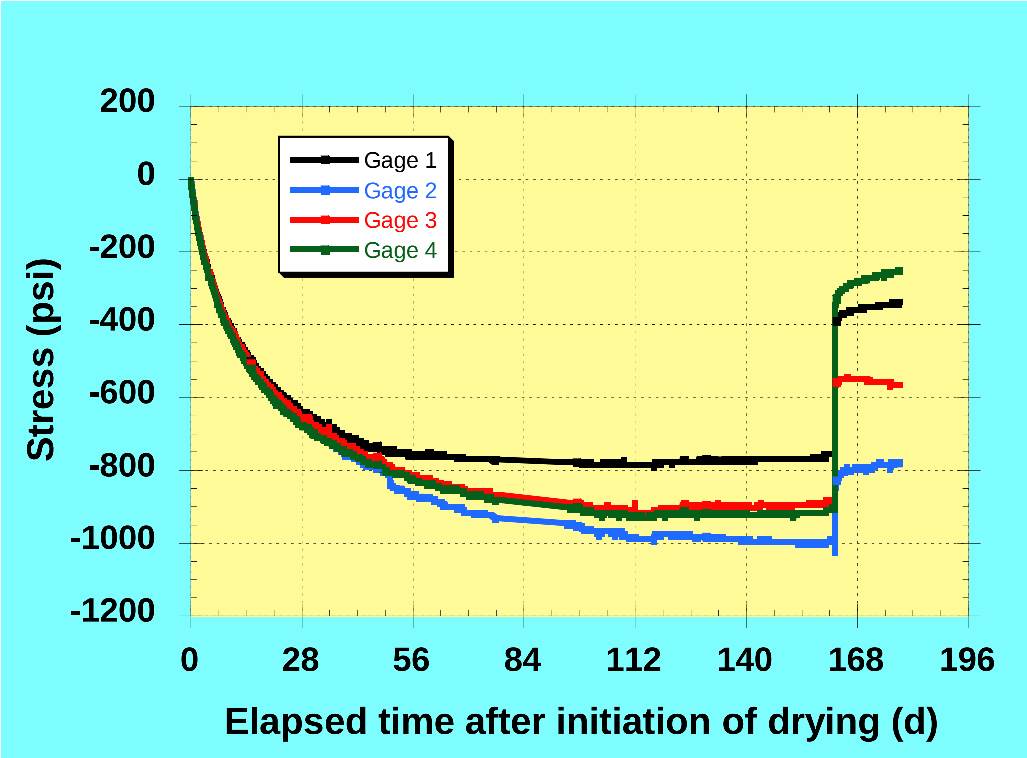


Figure 21.—ASTM C1581 ring test results for material 2C, specimen 2.

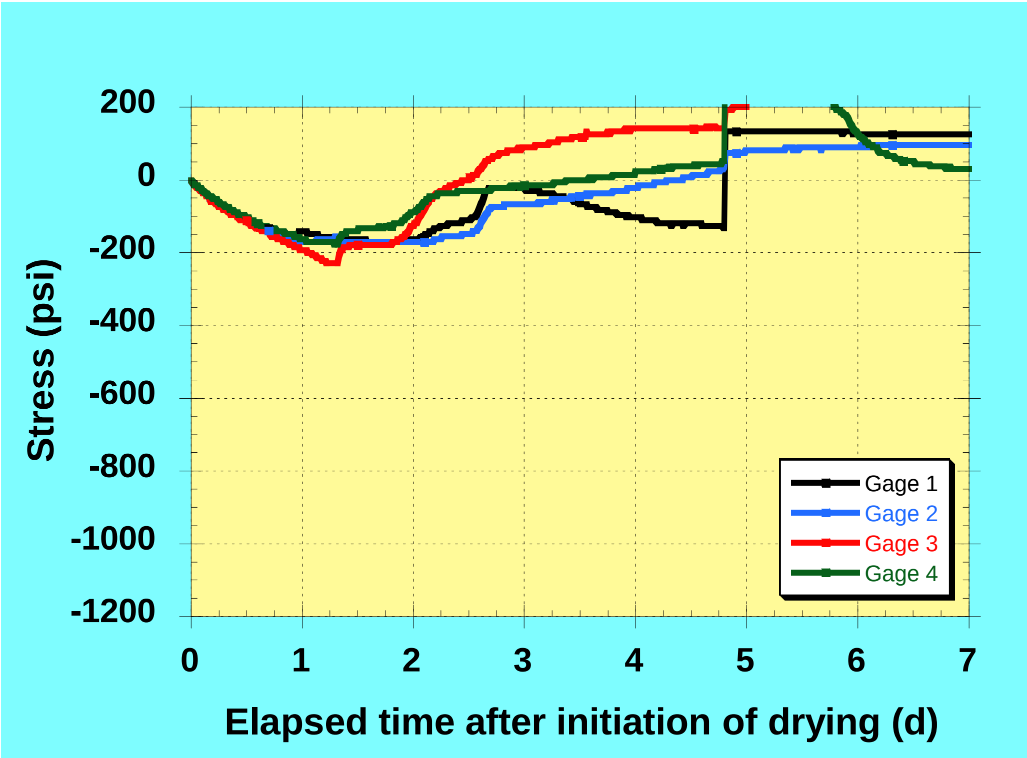


Figure 22.—ASTM C1581 ring test results for material 3M, specimen 1.

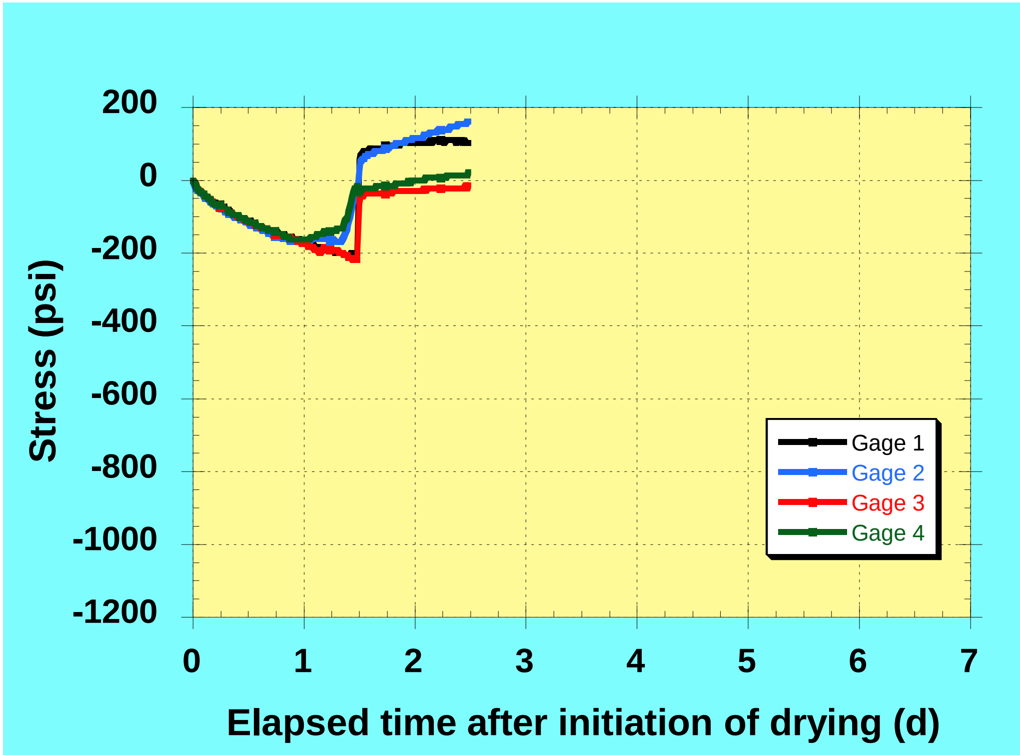


Figure 23.—ASTM C1581 ring test results for material 3M, specimen 2.

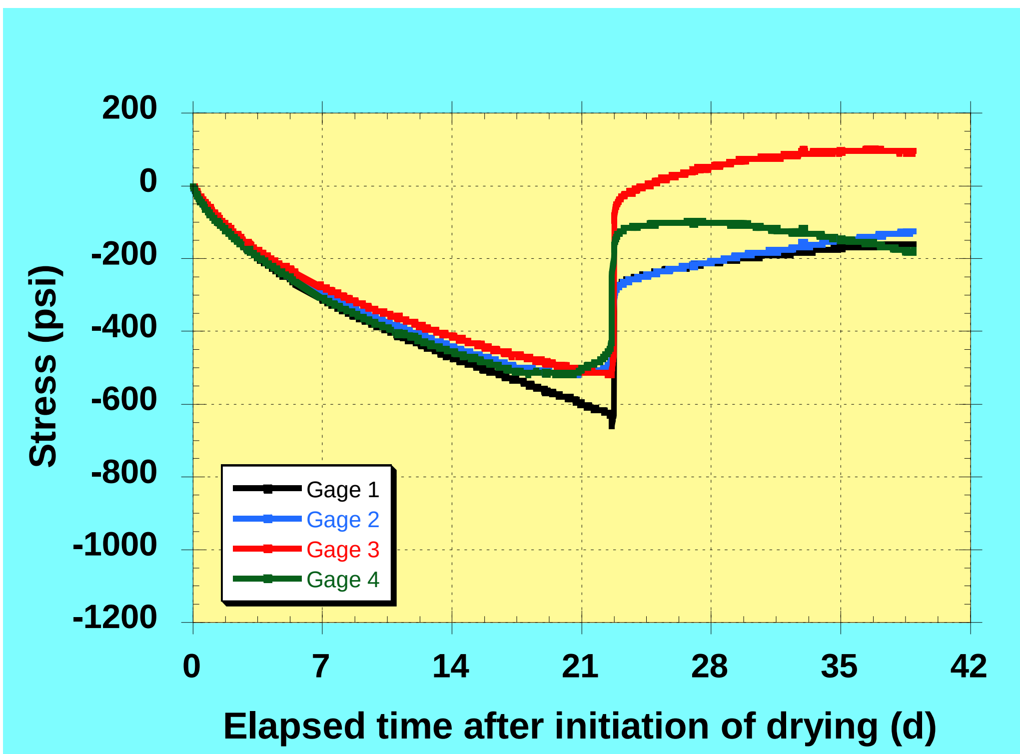


Figure 24.—ASTM C1581 ring test results for material 3C, specimen 1.

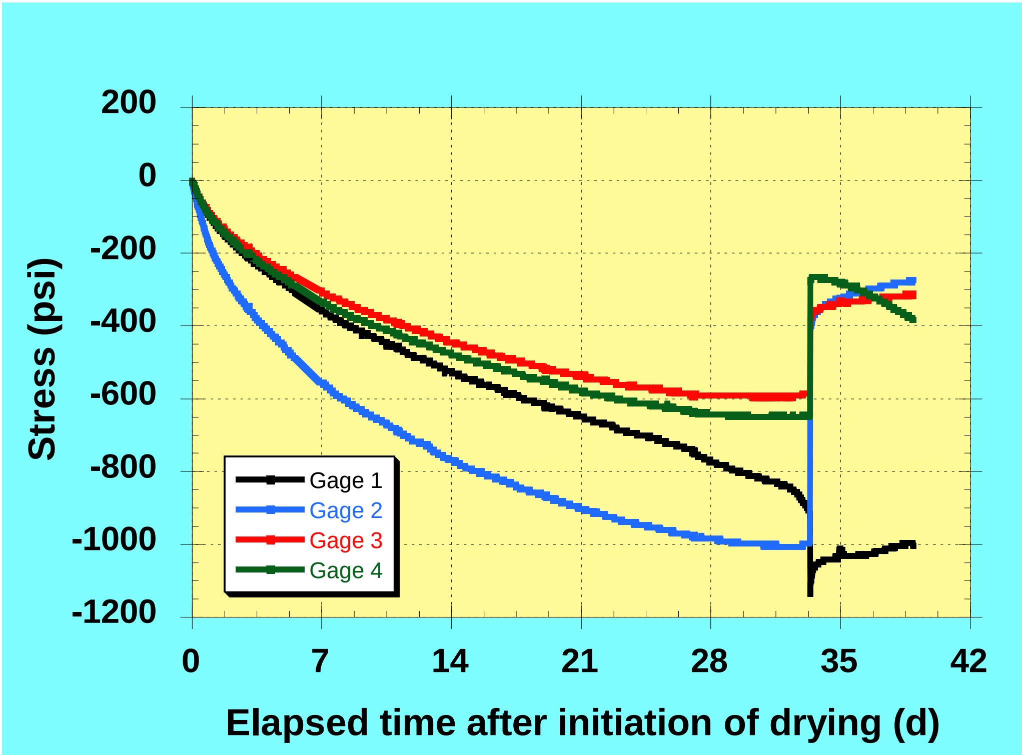


Figure 25.—ASTM C1581 ring test results for material 3C, specimen 2.

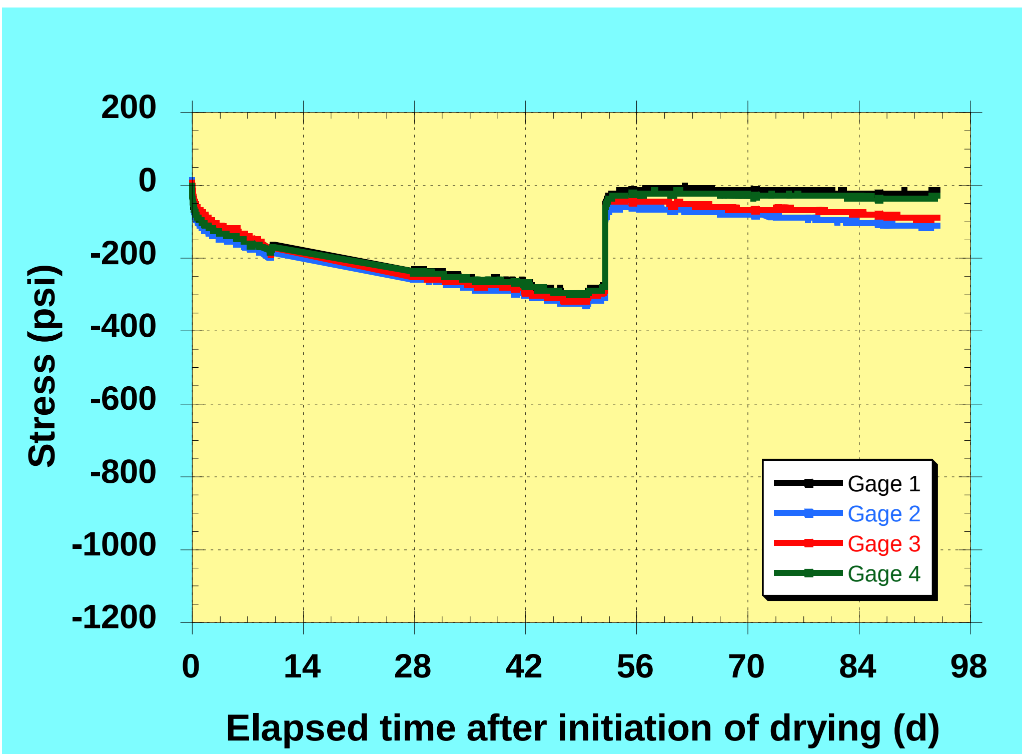


Figure 26.—ASTM C1581 ring test results for material 4M, specimen 1.

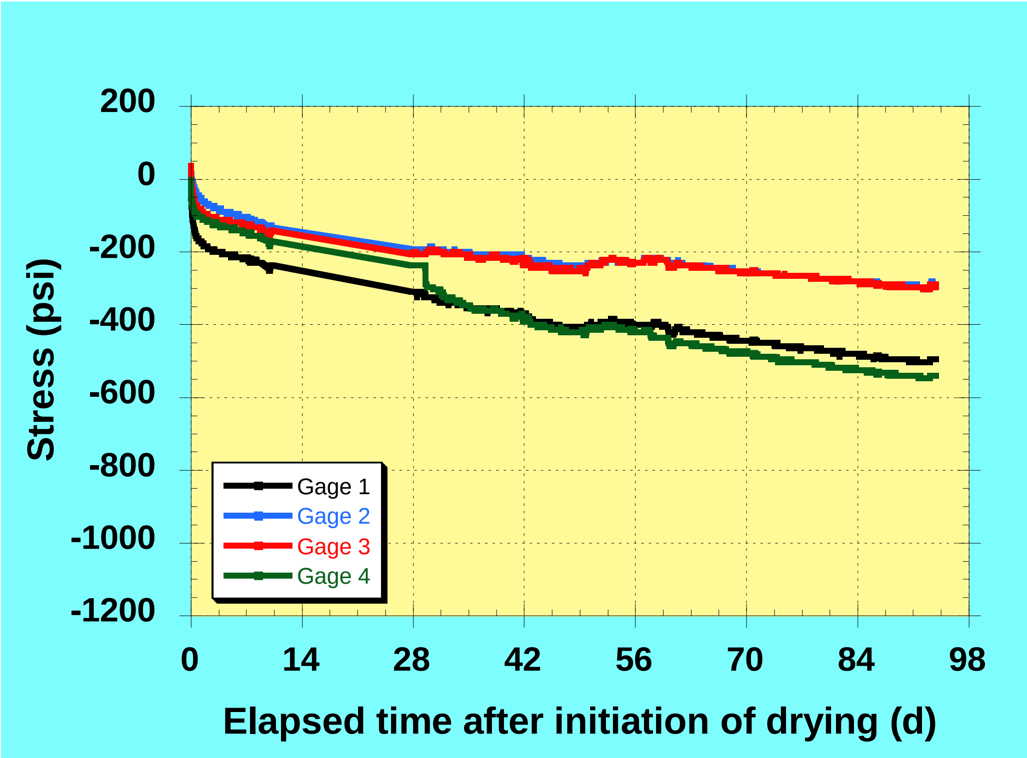


Figure 27.—ASTM C1581 ring test results for material 4M, specimen 2.

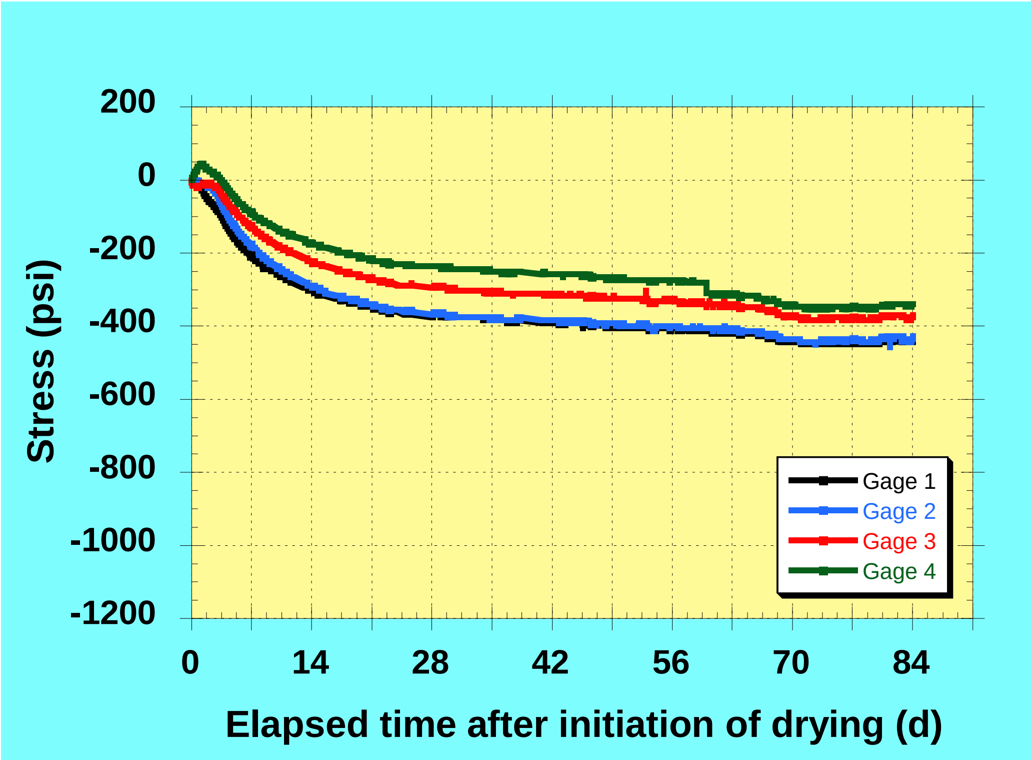


Figure 28.—ASTM C1581 ring test results for material 4C, specimen 1.

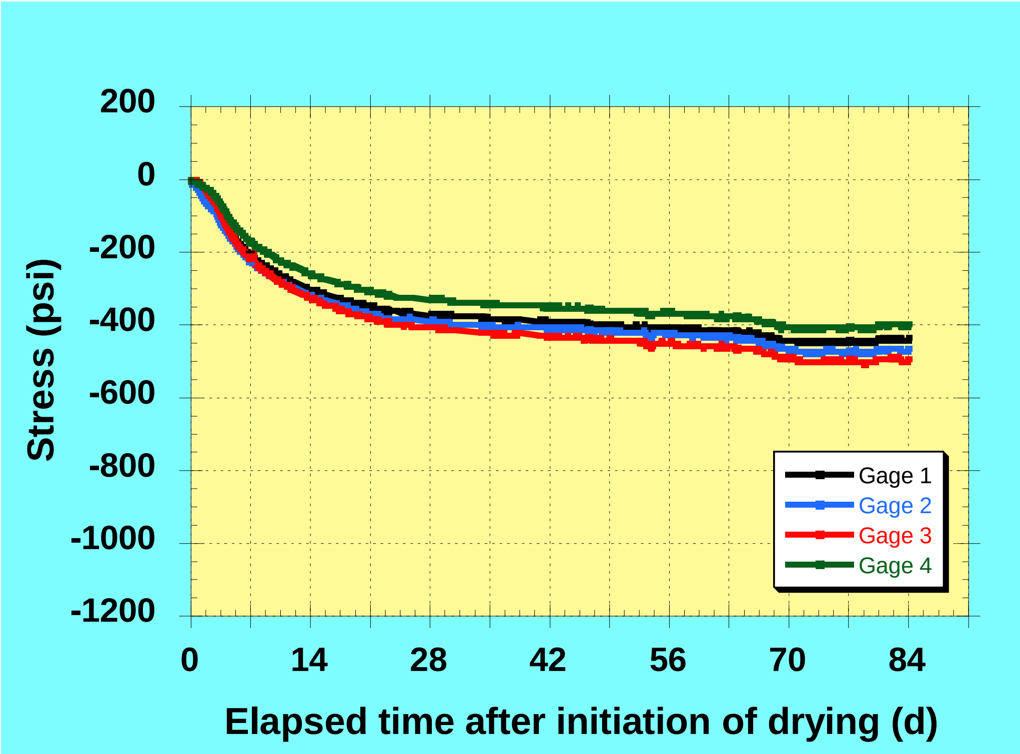


Figure 29.—ASTM C1581 ring test results for material 4C, specimen 2.

Table 11.—Summary of ring test results

Material	Specimen	Time of first crack (d)	Number of crack(s)	Crack opening (mm)		
				A	B	C
2M	2M-1	7	1	2.0	-	-
	2M-2	8	1	2.1	-	-
2C	2C-1	44	0	0.2	-	-
	2C-2	164	1	0.1	-	-
3M	3M-1	5	1	1.7	-	-
	3M-2	5	2	1.5	0.75	-
3C	3C-1	26	1	1.5	-	-
	3C-2	36	1	1.1	-	-
4M	4M-1	56	1	0.05	-	-
	4M-2	94	1	0.05	-	-
4C	4C-1	No crack	0	-	-	-
	4C-2	No crack	0	-	-	-

Table 12.—Summary of the maximum stresses at age of cracking and corresponding length change on ASTM C157 free shrinkage test

		Ring test (ASTM C1581)		Length change (ASTM C157 mod.)
Material	Specimen	Age at cracking (days)	Maximum stress (lb/in^2)	Strain at age of cracking (με)
2M	2M-1	7	180	280
	2M-2	8	200	280
2C	2C-1	44	800	340
	2C-2	164	900	440
3M	3M-1	5	190	180
	3M-2	5	200	180
3C	3C-1	26	550	300
	3C-2	36	800	350
4M	4M-1	56	300	300
	4M-2	94	390	340
4C	4C-1	No crack	400	275
	4C-2	No crack	460	275

6 Discussion

This section presents analysis and discussion of the experimental results of the second phase of the CREEP Project. The aim of the discussion is to establish correlations, if any, between laboratory tests and experimental field repairs.

6.1 Field repair behavior

As expected, mortars 2M, 3M, and 4M exhibited more severe cracking than their extended counterpart. The only exception was found with mortar 1M at the Reclamation experimental site. This can be attributed to large areas of debonding of the 1M repair, which significantly reduced the restraining tensile stresses responsible for cracking.

Under otherwise equal conditions, all extended mortars—1C, 2C, 3C, and 4C exhibited substantially improved characteristics with regards to cracking sensitivity.

Materials 2C and 3C were found to be the most crack-resistant: no cracking occurred at the Reclamation testing site, and only one crack was recorded in material 2C at the U.S. Navy location. Materials 1M and 1C exhibited very early age cracking with several cracks recorded after 4 days at both locations. This can be explained by the high temperature of hydration generated in this rapid-setting material. Discrepancies between the observed test results for material 4C at the Reclamation and U.S. Navy test sites were most likely caused by variations in material compositions. In fact, the 4C material at the Reclamation site had very different workability characteristics, as well as different mechanical properties from the 4C material at the Navy site.

6.2 Bond test

In order to verify whether the absence of cracks in some of the experimental repairs was due to bond failure, pull-off tests were carried out on materials 2C, 3C, and 4C. Test results show that tensile bond was more than satisfactory (> 300 lb/in^2) for all tested materials at the Reclamation site. At the U.S. Navy site, materials 2C and 3C still exhibited adequate bond strength (> 300 lb/in^2), but material 4C developed a relatively low bond to the substrate (about 130 lb/in^2).

In addition to the bond tests performed on selected materials, each experimental repair was sounded with a hammer in order to check for any bond failure between the repair material and the substrate. At the Reclamation site, material 1M exhibited significant debonding, as idendtified by shaded areas in Figure 12.

Material 4M also exhibited small zones of debonding at both ends of the repair (Figure 13). All other experimental repairs were free of debonding areas.

6.3 Baenziger block test

The Baenziger Block tests were only conducted at the Reclamation site, where they were exposed to the environment next to the experimental repairs. Cracks were not observed for material 1M and 1C at the end of the 9-month monitoring period. After the same period, the experimental repairs with materials 1M and 1C exhibited substantial cracking. For materials 2M and 3M, 15 and 50 cracks were recorded, respectively, for the Baenziger blocks. The experimental repairs with these materials accounted for 31 and 45 cracks. Baenziger block tests and experimental repairs with materials 2C and 3C remained crack-free. Materials 4M and 4C did not crack in Baenziger block tests but cracked moderately in the experimental repairs.

The analysis of Baenziger block test results shows strong correlation with field behavior for repair materials 2M, 2C, 3M, and 3C. On the contrary, no correlation was found between this test and actual repair behavior for materials 1M, 1C, 4M, and 4C.

6.4 Free-drying shrinkage test

Free shrinkage tests were conducted at Reclamation and Laval University. The results were similar for most materials, but slight differences were found in the case of materials 3C, 4M, and 4C.

The ultimate free-drying shrinkage values range from 100 to 1,200 µm/m. Materials 1M and 1C exhibited particularly low magnitude shrinkage compared to other materials tested. Since materials 1M and 1C are magnesium-phosphate-cement-based materials, most of the deformation occurs within the first day, which is not covered by the free shrinkage test method used in this study. It is therefore normal to see a low magnitude of shrinkage.

For materials 2M, 3M, and 4M and 4C, there is a relationship between the length change and number of cracks in the repair (Figure 30). However, this relationship becomes less obvious for rapid set materials 1M and 1C.

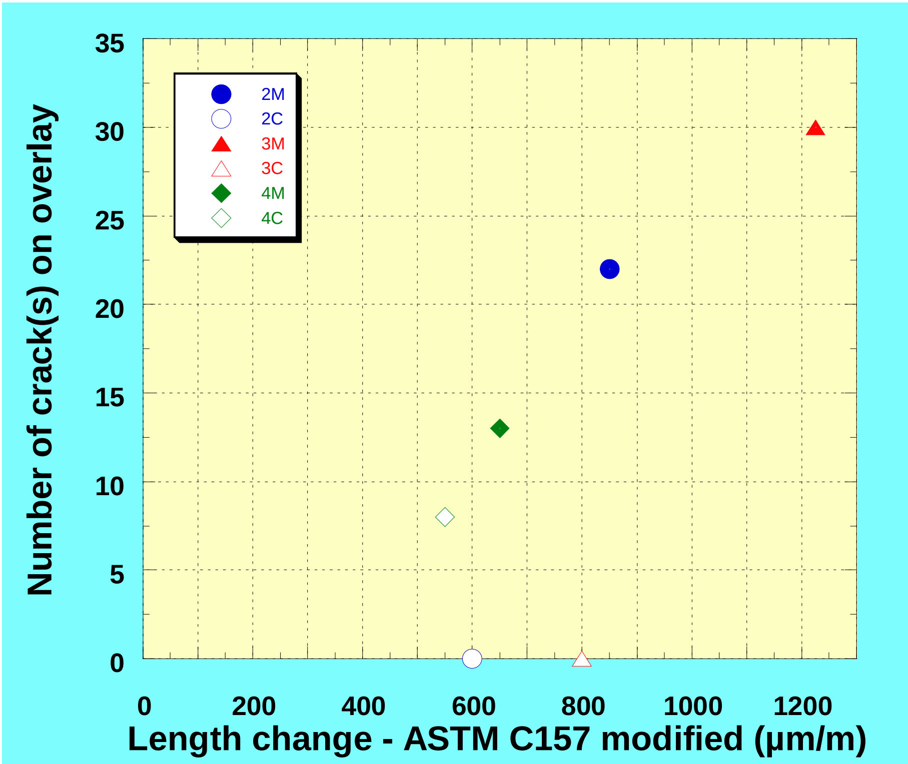
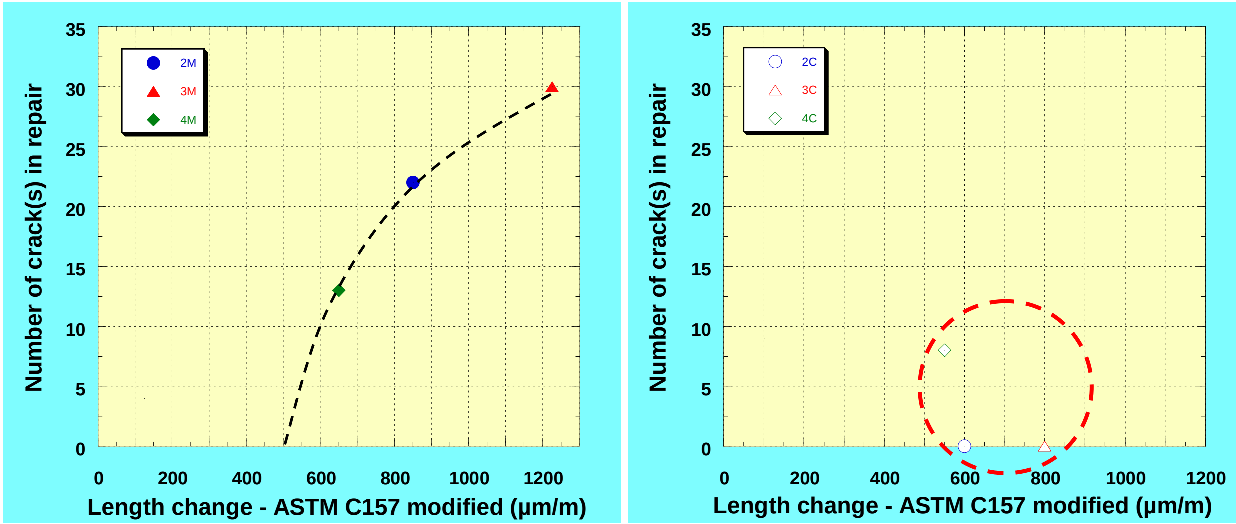


Figure 30.—Relationship between length change and number of cracks in repair—Reclamation.

The correlation between the length change (free-drying shringage) test results and the number of cracks in repair is much stronger for mortar materials than for extended mortars (see Figure 31).

The test results and analysis lead to the conclusion that the free-drying shrinkage test, ASTM C157 modified, can be used to predict cracking behavior of mortar type cementitious materials, but it is not reliable for predicting the performance of extended mortars and concretes.

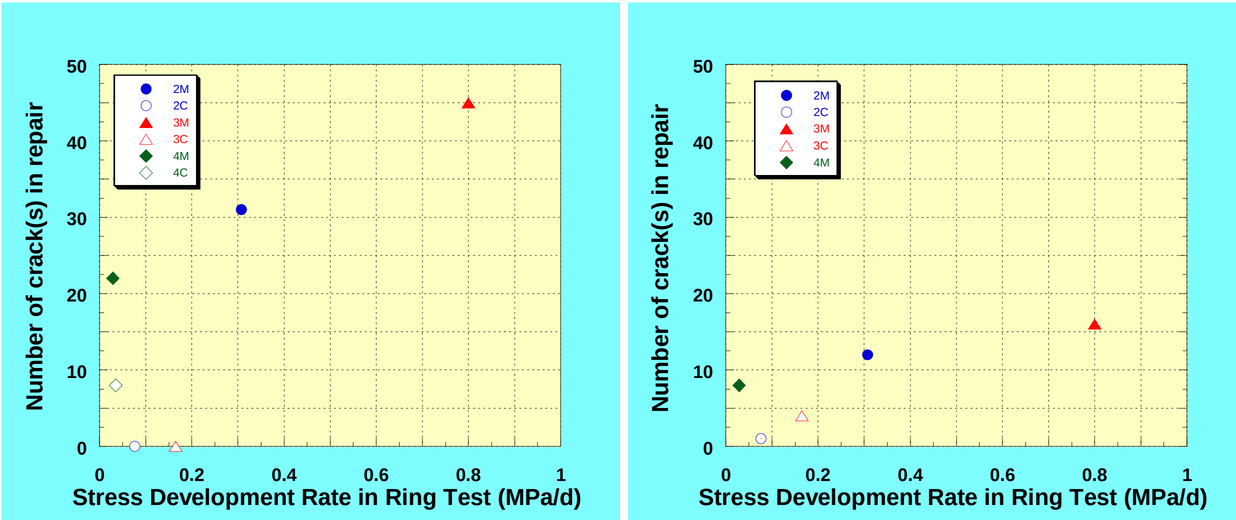


(a) Mortars (Reclamation) (b) Extended mortars (Reclamation)

Figure 31.—Relationship between free shrinkage and cracking in experimental repairs (after 9 months).

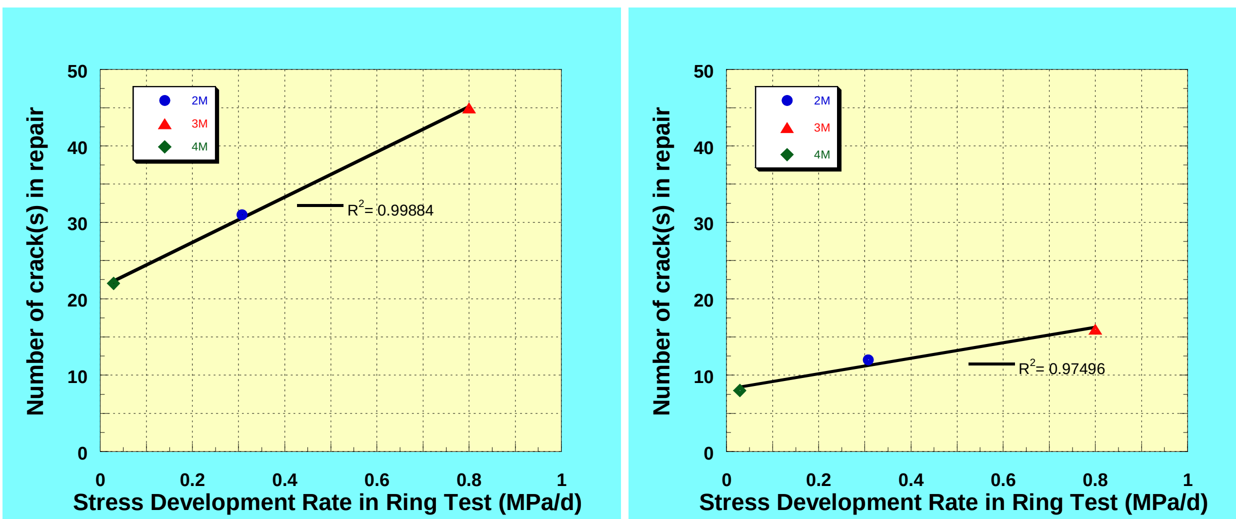
6.5 Ring test

Figure 32 shows the relationship between the number of cracks in the experimental repair and the stress development rate in the ASTM C1581 ring test for Reclamation and the U.S. Navy location, respectively. A strong correlation was found between the cracking behavior of repair mortars 2M, 3M, and 4M and the stress development rate in the ring test. However, the age at cracking in the ring test did not correlate well with the number of cracks in the repair slabs for extended mortar repair materials 2C, 3C, and 4C. Materials 2C and 3C did not show crack in the repair slabs but cracked in the ring test. Material 4C did not crack in the ring test but exhibited cracking in the repair slab.



(a) Reclamation (b) U.S. Navy

Figure 32.—Relationship between stress development rate in the ring test and the number of cracks in the experimental repairs (after 9 months).



(a) Reclamation (b) U.S. Navy

Figure 33.—Relationship between ASTM C1581 ring test and cracking of experimental repairs for mortars.

The correlation between the mortar materials test results in the ring test and cracking in experimental repair slabs is consistent with the relationship found between the ASTM C157 modified free shrinkage test and the cracking behavior in repair slabs. This means that for mortar type materials, there is a good relationship between the ring test results and the ASTM C157 modified test results (see Figure 34).

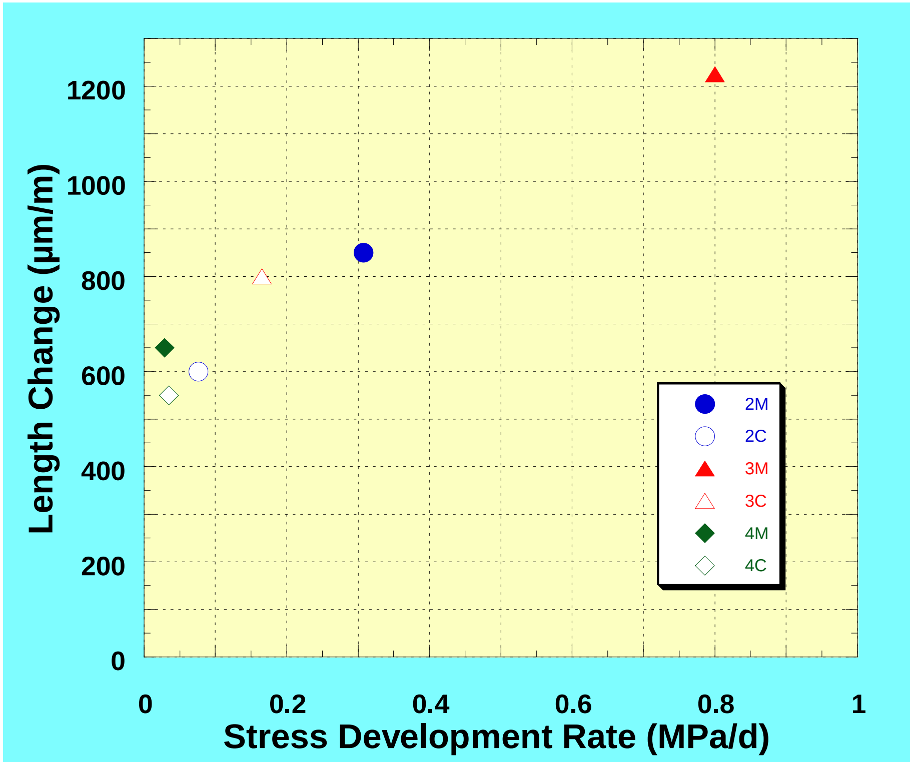


Figure 34.—Relationship between age at cracking in the ring test (ASTM C1581) and the length change test (ASTM C157 modified).

7 Conclusions

Based on results of the testing program performed during Phase II of this study, the following conclusions can be drawn:

- A good correlation was found between the ring test and cracking behavior of experimental repairs performed utilizing repair mortars. A good correlation was found between ASTM C1581 ring test results and ASTM C157 (modified) test results for repair mortars and mortars extended with coarse aggregate. No such correlation was found for ASTM C1581 or ASTM C157 (modified) and experimental repair for mortars extended with coarse aggregate.

- For the ASTM C1581 ring test, the stress development rate was found to be the most reliable indicator of experimental repair cracking and should be used instead of time to first crack.

- For the proprietary repair materials, geometry of experimental repairs, and exposure conditions utilized in this program, no reliable correlation was found between ASTM C1581 ring test results and cracking behavior of experimental repairs performed with mortars extended with coarse aggregate.

Further studies are recommended to verify the applicability of the ASTM C1581 ring test for predicting the cracking behavior of concretes and mortars extended with coarse aggregate in repair projects.

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