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**Concrete Repair Engineering Experimental Program (C.R.E.E.P)**

# Development of a Test Method to Evaluate Cracking Tendency of Repair Materials, Phase I Report

**Research Report 2004-1**

**U.S. Department of the Interior**
**Bureau of Reclamation**
**Denver, Colorado**

**March 2005**

# Acronyms

| | |
|---|---|
| ACI | American Concrete Institute |
| ASTM | American Society of Testing and Materials |
| COE | U.S. Army Corps of Engineers |
| GPa | giga Pascal(s) |
| ICRI | International Concrete Repair Institute |
| mL/kg | milliliters/kilogram |
| mm | millimeter(s) |
| MPa | mega Pascal(s) |
| µm/m | micrometers/meter |
| Reclamation | Bureau of Reclamation |
| SPS Plate | Structural Preservation System Plate |

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# Development of a Test Method to Evaluate Cracking Tendency of Repair Materials, Phase I Report

## Research Report 2004-1

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# Contents

## Tables



## Figures

## **Figures** (continued)

Figure Page

# A. Introduction

## 1. Problem Background

Carrying out concrete repairs is a labor-intensive operation. The major costs come from gaining access to the site and preparing for the repairs, such as removing unsound concrete and preparing the existing concrete and reinforcement substrate to receive the repair material. The final treatment of the substrate and the choice of the right material have a disproportionate effect on the durability and, therefore, the success or failure of the repair project. At present, there is little information on the durability of repair systems. The choice of material is made largely by using the manufacturer's data sheets, contacts with sales representatives, guesswork, and by experience with what has worked adequately in the past. This present process is not conducive to bringing about improvements for the future. Few repair systems have demonstrated reliability for periods in excess of 8 to 10 years.

Research on reliable methods of testing for durability of repair materials and systems will build confidence in the choice of materials to be used and, in otherwise equal conditions, will result in a more effective performance of repaired concrete structures. It will also allow improvement in repair materials and systems as knowledge is gained of their performance in repaired structures.

There are few standard tests for performance of repair materials, although there are positive moves to address testing standards within the American Concrete Institute (ACI), International Concrete Repair Institute (ICRI), and others. However, the present situation with repair durability demands more rigorous tests.

The premature deterioration and failure of concrete repairs in service is a result of a variety of physicochemical and electrochemical processes occurring in composite repair systems. Among the most serious causes of repair failures is cracking in the repair. Cracking may result in the reduction in the effective cross-sectional area of the repaired structure and always substantially increases permeability, which leads to premature corrosion and deterioration. Figure 1 shows an idealized model of repair failure.

Many material properties affect the susceptibility of concrete repair to cracking. Drying shrinkage of repair materials is one of the major mechanisms leading to cracking. The tensile strains and stresses generated by the restrained shrinkage (figure 2) can easily exceed the tensile strength of the repair material and, thus, cause cracking and/or debonding. Tensile stresses caused by restrained shrinkage can be, to a certain degree, relaxed by creep, and it is quite probable, according to some researchers, that the satisfactory performance of some superficial repairs is due to this phenomenon.

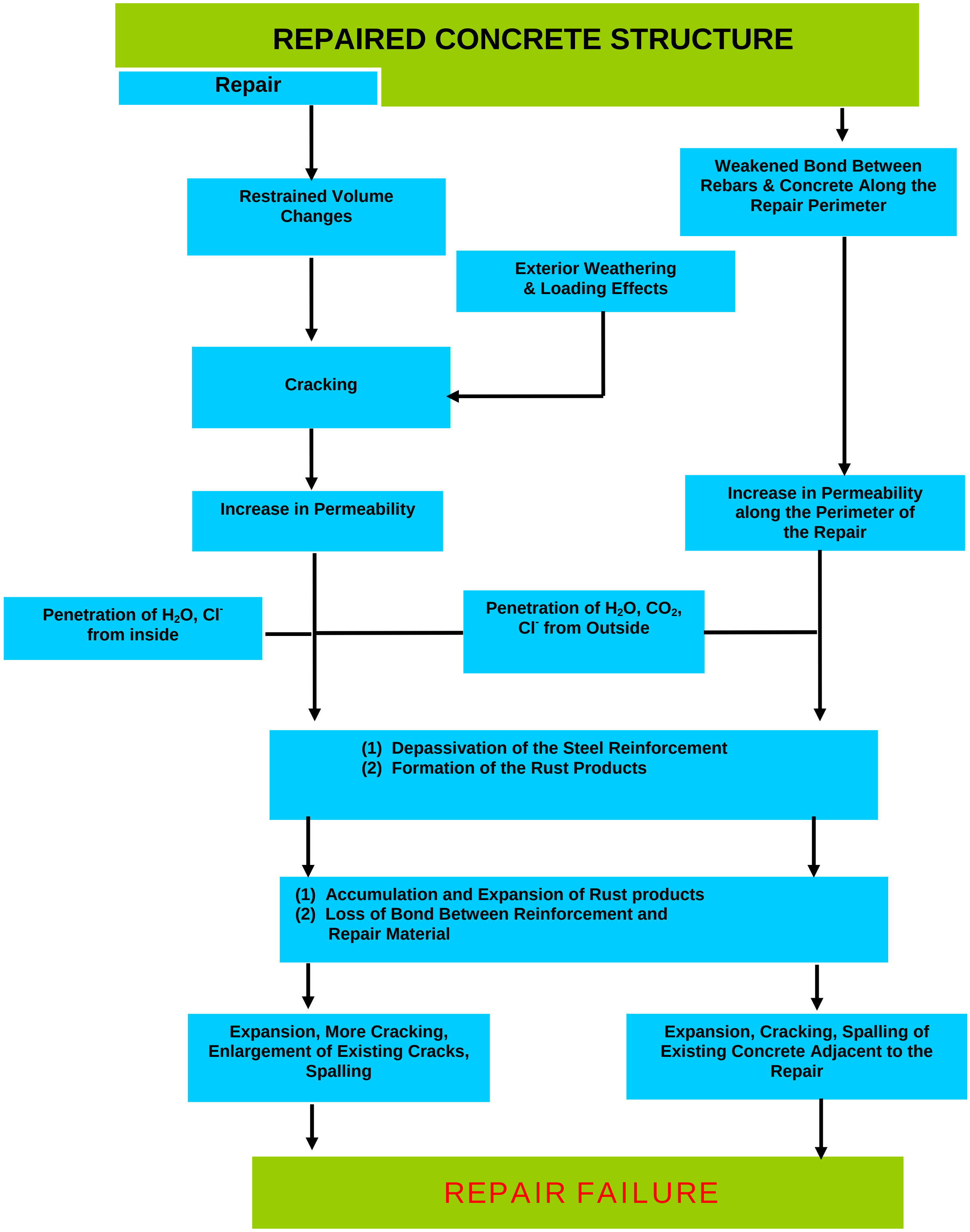



Figure 1.—Idealized model of concrete repair failure.

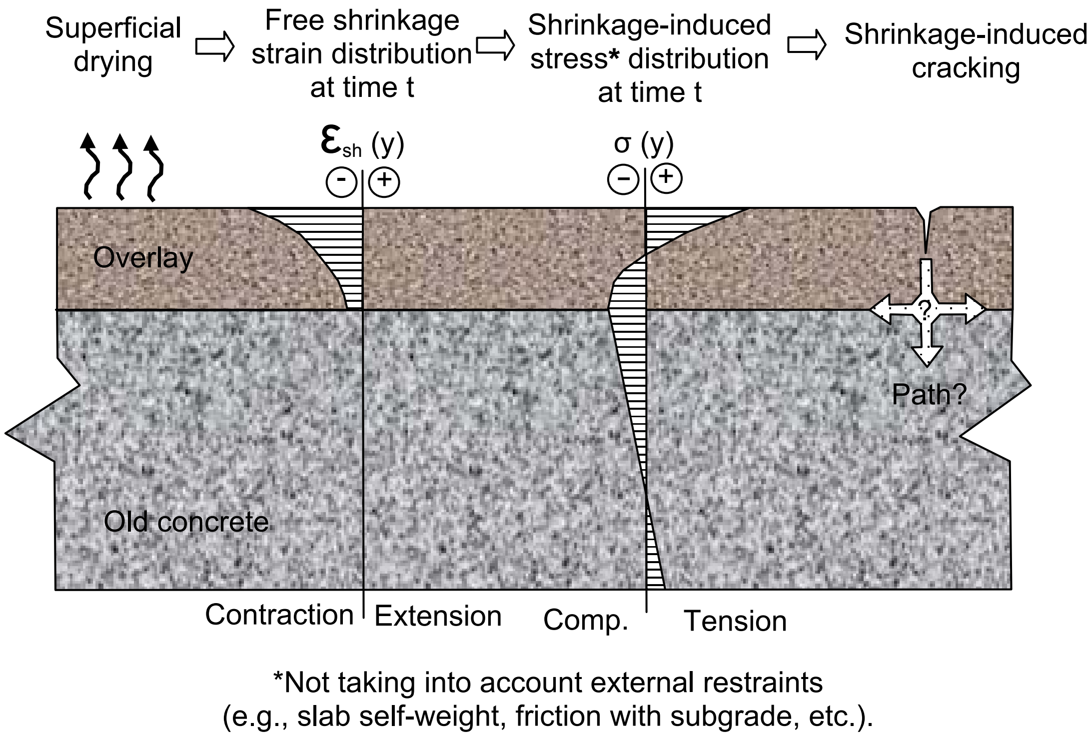



Figure 2.—Simplified representation of shrinkage-induced stresses and cracks in a concrete overlay (tension: positive; compression: negative) (Pigeon and Bissonnette, 1999).

Also, there are other factors which, to a large degree, affect the cracking tendency of the repair. Among them are important material properties, such as modulus of elasticity, creep, and the composite repair system's characteristics, such as degree and uniformity of restraint. However, there is currently no agreement on the relative influence of each of these properties and factors on the susceptibility of repair to cracking. Some of the properties are found so interrelated that it is practically impossible to affect one of them without affecting another. Results of a U.S. Army Corps of Engineers (COE) study (COE, March 1999) indicate that the higher stresses induced by increased drying shrinkage more than offset any additional stress relaxation caused by increased creep.

These difficulties may be resolved when the approach of the total strain in a drying repair is adopted. This approach is adopted in such testing methods as the Ring Test (COE, April 1998), German Angle Test (COE, April 1998), Structural Preservation System Plate (SPS Plate) Test , Laval University Beam Deflection Test (Vaysburd et al., March 2001), and others.

Though some progress has been achieved lately, it is still difficult to reliably correlate the results of these tests to actual field performance and predict with reasonable confidence the cracking behavior of the repair material in-situ.

# B. Research Objectives, Approach, and Scope

## 1. Objective

This project focuses on the performance of cementitious repair materials in concrete surface repairs with the main goal of minimizing cracking. The specific objectives of the project are to:

- Develop a laboratory/field reliable test method 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

- Contribute to the development of performance criteria for selecting crack-resistant repair materials

The objectives of the Phase I study were to evaluate performance of materials in experimental repairs placed in different geometry cavities of the prefabricated reinforced concrete slabs (Box Test) and selection of the optimal box geometry for further studies in Phase II.

## 2. Research Approach

There are many papers on shrinkage and creep of cementitious materials and their effect on cracking sensitivity. Usually, the problem has been approached from two opposite directions. Some authors tried to formulate the deformation on the basis of shrinkage and creep measurements carried out on material specimens. This approach is not sufficient to clearly understand the complex processes involved in shrinkage and creep deformations under restrained conditions, such as the conditions created by concrete surface repair. Some physically meaningful mechanisms of creep and, especially, shrinkage can be described. However, the actual deformational behavior depends, to a large extent, on so-called “apparent” mechanisms occurring in repair situations. Some of these mechanisms are affected by the volume-to-surface ratio of repair, contact surface characteristics, microcracking in the repair material, and other factors. All of these lead to internally created states of stress that substantially modify time-dependent deformations in repairs, such as creep and shrinkage, which are studied on specimens that are not restrained.

The opposite approach is based on a “macrostructural”/engineering concept that the net deformation is governing sensitivity to cracking in repair systems such as concrete repair. The attempts to subdivide total deformation of a drying repair material into shrinkage and creep components or, vice versa, to add both components to determine total deformation have not worked.

Net deformation is the only well-defined quantity. Net deformation is adopted in the present study, and the resulting tests are an attempt to create with engineering models. By using the results of the study, it will be possible to reliably determine the deformational behavior and sensitivity to cracking of repair materials.

### 3. Scope

Any test method(s) to be developed should cover the determination of the cracking tendency of a repair material under real-life repair conditions. The procedure is comparative and not intended to determine possible cracking in a specific type of structure and specific location of the repair in a structure. Actual cracking in service depends on several variables including design details, repair methods, degree of restraint, substrate surface preparation, construction practices, and environmental factors. The method(s) should be applicable for evaluating the sensitivity of repair materials to cracking and for selecting crack-resistant repair materials.

The scope of Phase I of the project was as follows:

- To select the optimum geometry of the experimental repair configuration. The size of the specimen and the cavity in it has to be sufficiently small and light to allow for easy handling in the laboratory yet be representative of an in-situ repair.

- To perform characterization tests of repair materials used in testing the experimental repair configuration. The basic properties, such as strength, shrinkage, flexural creep, and modulus of elasticity, were determined.

- To perform several standard and nonstandard, shrinkage, and tendency-to-crack tests on repair materials.

- To evaluate the possible correlation between various shrinkage tests and the experimental repair test (Box Test and/or Baenziger Block Test).

The results of the evaluation program performed in Phase I of this study and the recommendations of Phase II are presented in this report.

## C. Evaluation

### 1. Box Test Geometry

Three different box geometries were selected for evaluation in this task (figures 3 and 4). In addition to the “Box Test,” the Baenziger Block Test was also used in this task (figures 5 and 6) (Gillespie, March 1999). They are described below:

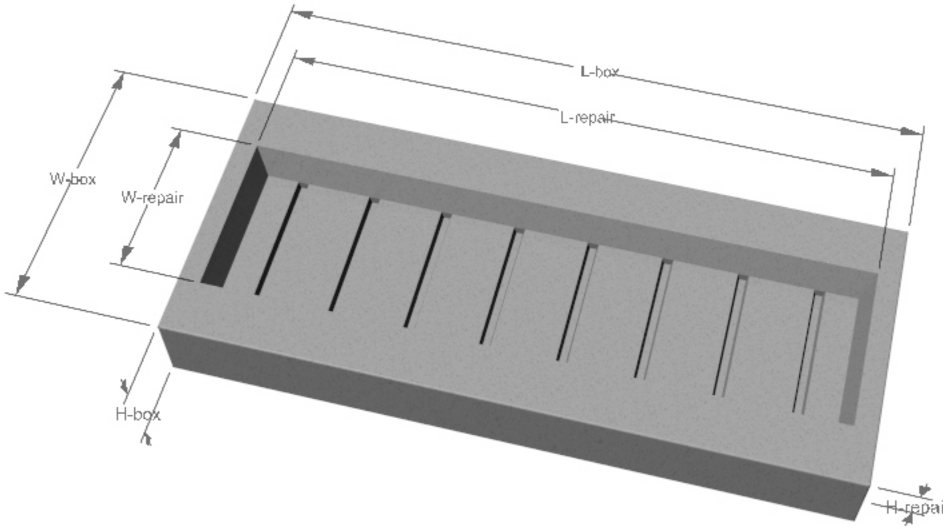



Figure 3.—“Box” geometry.

Figure 4.—View of the experimental “box.”

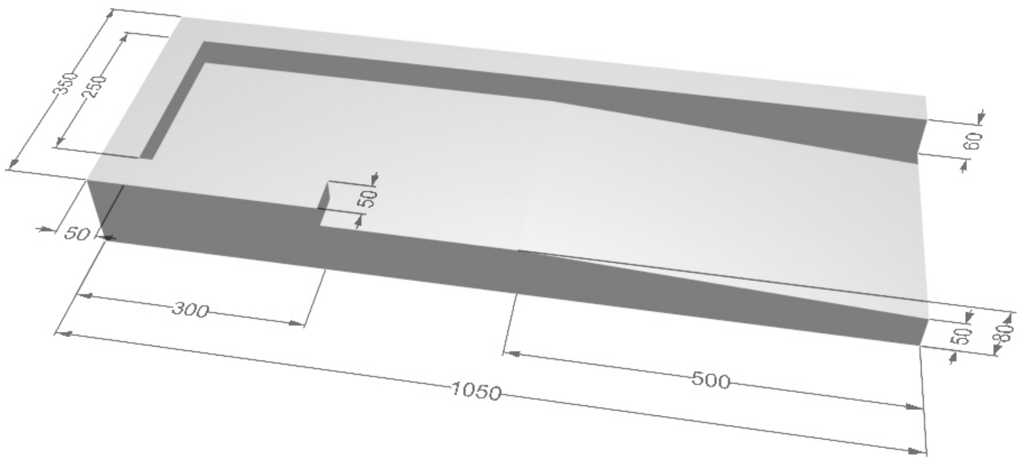



Figure 5.—Baenziger Block.

Figure 6.—Baenziger Block containing test material.

Table 1 presents the dimensions of the experimental "boxes."

Table 1.—Geometry of the experimental "boxes"

| Dimensions | Box size | | |
|---|---|---|---|
| | Small | Medium | Large |
| $L_{box}$ (millimeters) | 1,000 | 1,500 | 2,000 |
| $W_{box}$ (millimeters) | 500 | 625 | 750 |
| $H_{box}$ (millimeters) | 175 | 175 | 175 |
| $L_{repair}$ (millimeters) | 900 | 1,400 | 1,900 |
| $W_{repair}$ (millimeters) | 300 | 375 | 450 |
| $h_{repair}$ (millimeters) | 75 | 75 | 75 |
| Volume of repair (liters) | 20.3 | 39.4 | 64.1 |

- A "large" precast concrete box with a cavity of 450 by 1,900 by 75 millimeters (mm) (18 by 76 by 3 inches) was used that corresponds to that used in the COE study (COE, September 1998). The overall geometry of the box was revised based on its rigidity analysis. All boxes were required to be sufficiently rigid to eliminate any deformations caused by handling and/or by stresses generated by the restrained shrinkage of the repair material.

- A "medium" precast concrete box with a cavity of 375 by 1,400 by 75 mm (15 by 56 by 3 inches) was used.

- A "small" precast concrete box with a cavity of 300 by 900 by 75 mm (12 by 36 by 3 inches) was used.

The Baenziger Block is a prefabricated, nonreinforced concrete slab with a cavity in it. The thickness of the repair is a constant 30 mm (1.25 inches) for 500 mm (20 inches) of the length and then varies from 30 to 60 mm (1.25 to 2.5 inches) for the rest of 650 mm (25.5-inch) cavity length (figures 5 and 6).

The concrete used in manufacturing the experimental boxes had a design compressive strength of 35 mega Pascals (MPa) (5,000 pounds per square inch). The concrete mixture for the precast boxes and Baenziger Block is presented in table 2.

Table 2.—Concrete mixture for the experimental boxes and Baenziger Block

| Constituents | Quantity (kg/m3) |
|---|---|
| Cement | 422 |
| Sand | 670 |
| Coarse aggregate (5 –14 mm) | 1,026 |
| Water | 180 |
| Water reducer (mL/kg)[1] | 2.38 |
| Air entraining admixture (mL/kg of cement) | 0.25 |

[1] Milliliters per kilogram.

For each box geometry and Baenziger Block, nine specimens were fabricated at Laval University during the summer of 2000. The test specimens were stored and cured in a warehouse for about 10 months. During this time, the surfaces of the cavity were lightly sandblasted. Also, all the exposed surfaces of the test specimens were sealed by penetrating Siloxane sealer (40-percent solids) to avoid moisture absorption by the "substrate" concrete.

## 2. Repair Materials

The three repair material mixtures employed in this study are shown in table 3.

Table 3.—Repair material mixtures

| | kg/m$^3$ | | |
|---|---|---|---|
| Constituents | Concrete | Mortar | Polymer-modified Mortar (P-mortar) |
| Cement | 441 | 675 | — |
| Sand | 837 | 1,340 | — |
| Coarse aggregate (5 – 14 mm) | 900 | — | — |
| Water | 191 | 270 | — |
| Superplasticizer (mL/kg of cement) | 14.5 | 18.9 | — |
| Air entraining admixture (mL/kg of cement) | 0.26 | 0.07 | — |

## 3. Experimental Repairs

Each repair material was used to repair the cavities in the three test boxes and the Baenziger Blocks. This testing program was performed at Laval University and included material mixing, placing the repair material in the boxes, and curing and monitoring for cracking for a minimum of 18 months. Immediately before placing the repair material, the surfaces of the box cavity were coated with an epoxy resin, SikaDur Hi-Mod 32 (figure 7), to prevent moisture loss from the repair material mixture into the concrete substrate. The repair material was placed in two relatively equal layers and consolidated by using an interior vibrator with 18 mm (3/4-inch) diameter needle. The surface of the repair was leveled with a wooden straightedge and trowel finished.

Figure 7.—Applying epoxy resin to cavity surfaces.

Wet curing under burlap was performed for 72 hours. After curing, the experimental repairs were exposed to the exterior environment and were systematically monitored for crack occurrence.

## 4. Material Characterization Tests

The following basic material characterization tests were performed at Laval University and the Bureau of Reclamation (Reclamation).

### *a. Mechanical Properties*

- *Compressive Strength* – American Society of Testing and Materials ASTM C39, "Standard test method for compressive strength of cylindrical concrete specimens."

- *Compressive Strength* – American Society of Testing and Materials ASTM C109, "Standard test method for compressive strength hydraulic cement mortars (using 2-inch or 50-mm cube specimens)."

- *Modulus of Elasticity* – ASTM C 469, "Standard test method for static modulus of elasticity and Poisson's Ratio of concrete in compression."

- *Splitting Tensile Strength* – ASTM C 496, "Standard test method for splitting tensile strength of cylindrical concrete specimens."

The tests were performed at 3, 28, and 56 days. Three cylindrical specimens were used for each test: 75 by 150 mm (3 by 6 inches) for concrete and 25 by 50 mm (1 by 2 inches) for mortars.

### *b. Free Drying Shrinkage*

ASTM C157, "Standard test method for length change of hardened hydraulic-cement mortar and concrete" (modified).

The modification was done in accordance with the REMR Report (COE, March 1999).

For the concrete mixture, 75- by 7- by 275-mm (3- by 3- by 11-inch) specimens were cast. For the mortar mixtures, 25- by 25- by 275-mm (1- by 1- by 11¼-inch) specimens were cast. Two types of measuring comparators were used to obtain the readings. The first is described by ASTM C157 (figure 8), and the second is a comparator using a mobile plate (figure 9).

The length-change readings started after 72 hours of wet curing, then the readings were taken every day for the first week and once a week for the first month. After a month, readings were taken monthly. The length change was monitored for a minimum of 180 days.

Figure 8.—Standard comparator for measuring drying shrinkage strain.

Figure 9.—Comparator with mobile plate for measuring drying shrinkage strain.

## 5. Restrained Shrinkage Tests

Four different tests (one standard and three nonstandard) were performed to evaluate the restrained shrinkage or cracking tendency of the repair materials used in the experimental repairs.

### *a. Ring Test*

This test was performed using the REMR Ring Test configuration as described in the Repair Material Data Sheet Protocol (COE, March 1999, figures 10 and 11). In this test, the time at which the first crack appears is monitored and documented. Also, the evolution of the crack's width is monitored over time.

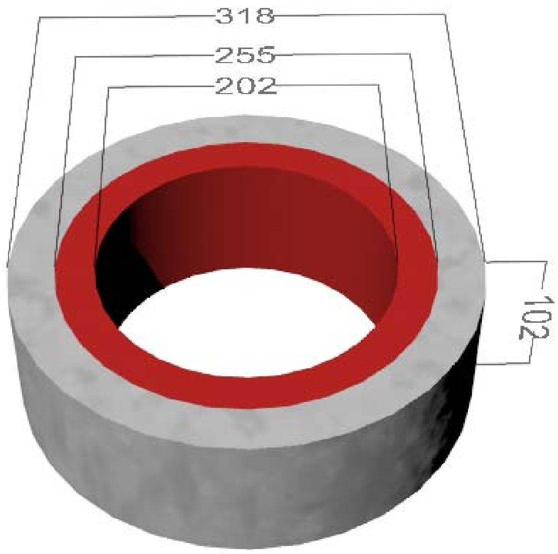



Figure 10.—REMR Ring Test configuration.

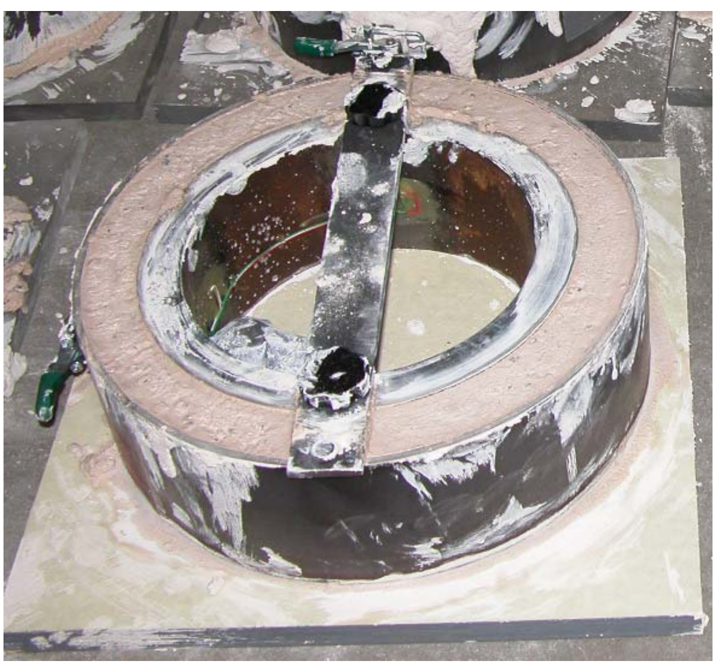


Figure 11.—REMR Ring Test containing repair material.

### *b. German Angle Test*

This test consists of filling a steel angle (figures 12 and 13) with the repair material. The angle was initially thoroughly cleaned by light sandblasting. An epoxy bonding compound was applied to the interior angle surfaces immediately before casting the specimen. Three angle specimens were cast for each type of material. The specimens were wet cured for 72 hours and then kept under laboratory conditions (Reclamation) and field conditions (Laval University). They were monitored for cracking for at least 180 days.

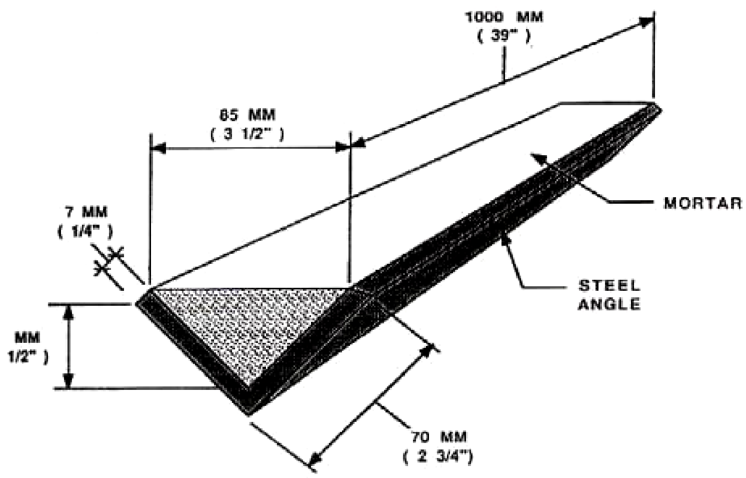



Figure 12.—Schematic of the German Angle Test.

Figure 13.—German Angle Test – Placing material.

### *c. SPS Plate Test*

The SPS Plate Test (COE, September 1998) was used to evaluate the net deformation due to restrained shrinkage. It consisted of a 50- by 100- by 1,320-mm (2- by 4- by 52-inch) repair-material beam cast over a 1.5-mm (1/16-inch) thick steel plate. To allow for a good bond, the steel plates were lightly sandblasted and epoxy resin was applied before placing the material. The beam was clamped over 150 mm (6 inches) from one end, which gave a free cantilever of 1,170 mm (46 inches) long. The test is presented in figures 14 and 15.

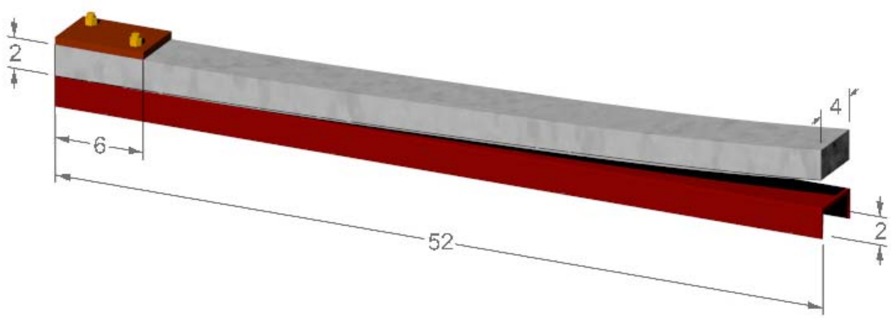



Figure 14.—Schematic view of SPS Plate Test.


Figure 15.—SPS Plate Test.

The test consists of monitoring the beam tip curling with a precision caliper. The test started after 72 hours of moist curing. After that time, the specimen was clamped to the steel channel using the two threaded rods embedded in the material and a steel plate on the top. The readings were made every day over he first week and then weekly during the first month and once a month after that.

### *d. Laval Beam Deflection Test*

The Laval Beam Deflection Test (Bissonnette at al., March 2001) consisted of a 50- by 100- by 1,000-mm (2- by 4- by 40-inch) repair material beam cast over a 1.5-mm-thick epoxy coated steel plate (figures 16 and 17). All surfaces of the beam, except the top one, were paraffin-wax sealed.

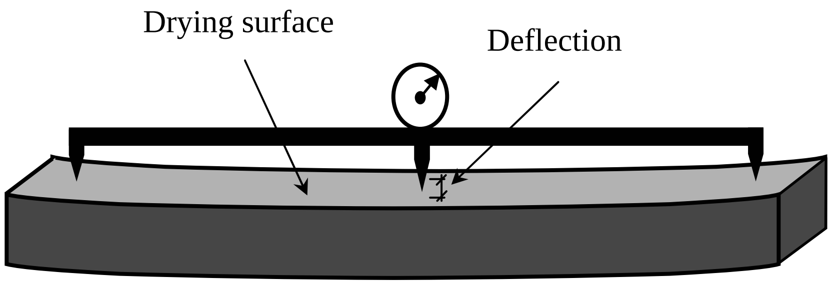



Figure 16.—Schematic of the Laval Beam Deflection Test and measuring device.

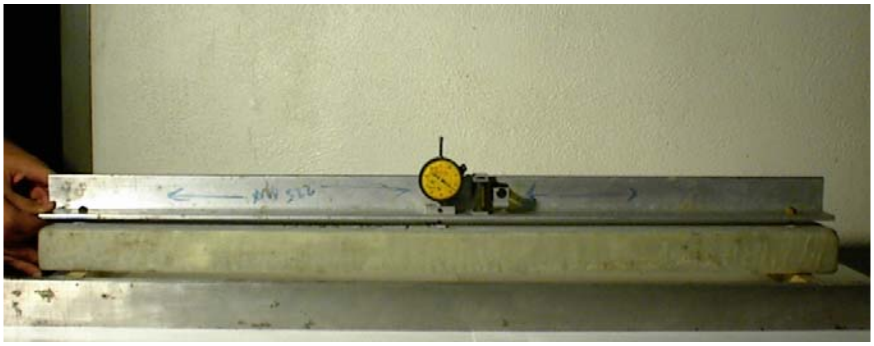


Figure 17.—Laval Beam Deflection Test with measuring device.

The test procedure consisted of monitoring the mid-span deflection. The test started after 72 hours of moist curing, and the reading schedule was identical to the SPS Plate Test.

To find the relationship (if any) between the Laval Beam Deflection and the SPS Plate Test, the Laval Beam Test results were expressed in terms of an SPS Plate Test cantilever beam of identical geometry. The calculations were made as follow:

From basic formulas:

$$\Delta_{CL} = \frac{L^2}{8R} \quad \text{and} \quad \Delta_{END} = \frac{L^2}{2R}$$

Where:

$\Delta$CL = Mid-span deflection
$\Delta$END = Beam tip curling
L = Length of span or cantilever arm
R = Radius of curvature

From these two equations, $\Delta_{END-BD} = 4\Delta_{CL-BD}$, and, thus, the beam tip curling of the Laval BD Test specimen is four times it's mid-span deflection.

To compare the SPS Plate Test and the Laval BD Test, corrections were made for the different length of the cantilever arm (assuming a beam of a longer span but same curvature).

$$\frac{\Delta_{END-SPS}}{\Delta_{END-BD}} = \frac{\left(L^2_{END-SPS}/2R\right)}{\left(L^2_{END-BD}/2R\right)} = \frac{L^2_{END-SPS}}{L^2_{END-BD}}$$

$$\Delta_{END-SPS} = 4\Delta_{CL-BD}\left(\frac{L^2_{SPS}}{L^2_{BD}}\right)$$

Where:

$\Delta$END-BD = Beam tip curling for the Laval Beam Deflection Test geometry specimen
$\Delta$END-SPS = Beam tip curling for the SPS Plate Test geometry specimen
$\Delta$CL-BD = Mid-span deflection of the Laval Beam Deflection specimen
LSPS = Length of the cantilever arm in the SPS Plate Test specimen
LBD = Span of the Beam Deflection specimen
R = Radius of curvature

# D. Test Results

The results of the testing program are summarized as follows:

## 1. Material Mixture Properties

Material mixture properties used for experimental repairs and specimens are shown in table 4.

Table 4.—Material mixtures properties

| Property | Concrete | Mortar | P-mortar |
|---|---|---|---|
| Slump (mm/inch) | 200/8 | 235/9 | 235/9 |
| Air content (percent) | 10.5 | 9.0 | 6.5 |
| Temperature (ºC) | 18.5 | 21.5 | 20.5 |

## 2. Material Characterization Tests

The results of the mechanical properties tests at 72 hours and 28 days are summarized in tables 5 and 6, respectively.

Table 5.—Seventy-two-hour mechanical properties

| Test | Batch | Concrete | Mortar | P-mortar |
|---|---|---|---|---|
| Compressive strength (MPa) | Field 1 | 28.9 | 29.8 | 21.7 |
| | U.L[1]. batch 1 | 30.2 | 30.9 | 19.0 |
| | U.L. batch 2 | 30.2 | 21.0 | 14.6 |
| | U.L. batch 3 | 23.3 | 33.5 | 23.7 |
| | Lab Reclamation | 29.5 | 33.2 | 23.2 |
| Splitting Tension Strength Test (MPa) | Field 1 | 3.2 | 3.1 | 2.4 |
| | U.L. batch 1 | 3.2 | 3.2 | 2.3 |
| | U.L. batch 2 | 3.3 | 3.5 | 1.8 |
| | U.L. batch 3 | 2.3 | 3.0 | 2.1 |
| | Lab Reclamation | 2.9 | 2.8 | 2.2 |
| Elastic Modulus (GPa)[2] | Field 1 | 31.8 | 31.2 | 16.5 |
| | U.L. batch 1 | 33.5 | 29.6 | 16.2 |
| | U.L. batch 2 | 25.0 | 25.9 | 12.4 |
| | U.L. batch 3 | — | — | — |
| | Lab Reclamation | 21.2 | 23.5 | 11.4 |

[1] University Laval.
[2] Giga Pascal.

Table 6.—Twenty-eight-day mechanical properties

| Test | Batch | Concrete | Mortar | P-mortar |
|---|---|---|---|---|
| Compressive strength (MPa) | Field 1 | 37.6 | 44.4 | 36.0 |
| | U.L. batch 1 | 41.1 | 38.6 | 32.1 |
| | U.L. batch 2 | 37.2 | 34.9 | 23.7 |
| | U.L. batch 3 | 33.3 | 43.9 | 33.4 |
| | Lab Reclamation | 41.4 | 44.9 | 43.0 |
| Splitting Tension Strength Test (MPa) | Field 1 | 4.1 | 3.8 | 2.5 |
| | U.L. batch 1 | 3.8 | 3.5 | 2.1 |
| | U.L. batch 2 | 3.7 | 4.1 | 2.7 |
| | U.L. batch 3 | 3.0 | 3.1 | 3.6 |
| | Lab Reclamation | 4.0 | — | — |
| Elastic modulus (GPa) | Field 1 | 39.9 | 44.5 | 18.2 |
| | U.L. batch 1 | 43.9 | 41.0 | 18.0 |
| | U.L. batch 2 | 29.2 | 26.0 | 17.4 |
| | U.L. batch 3 | 30.1 | 40.5 | 18.8 |
| | Lab Reclamation | 24.7 | 29.9 | 16.6 |

The results of the length change (drying shrinkage) ASTM C157 Modified Test are shown in figures 18 and 19. This test was performed at Laval University and Reclamation.

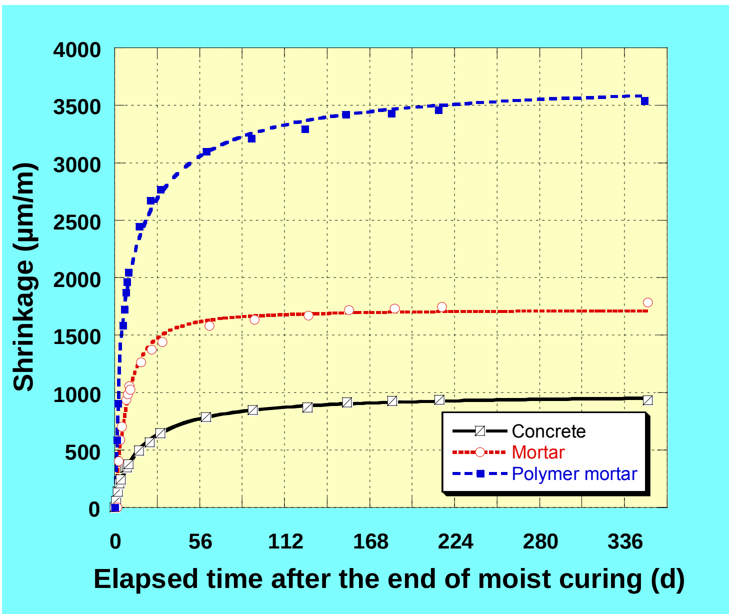



Figure 18.—ASTM C157, "Standard test method for length change of hardened hydraulic-cement mortar and concrete," modified (Reclamation).

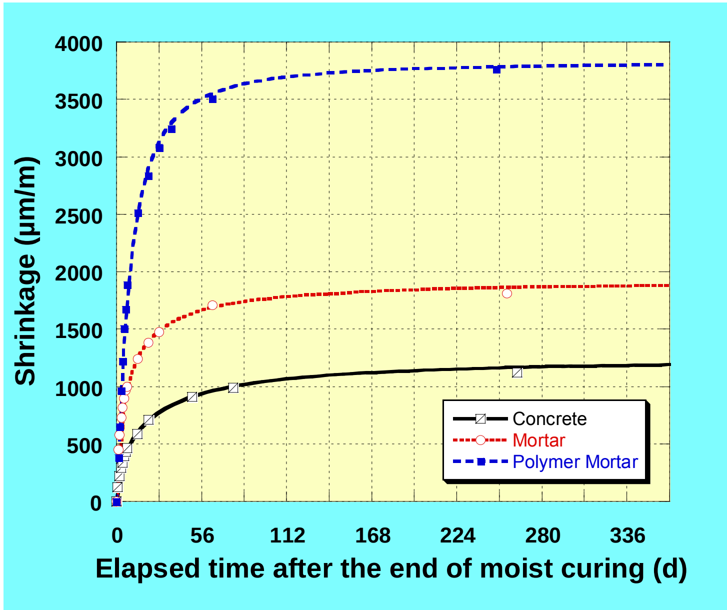



Figure 19.—ASTM C157, "Standard test method for length change of hardened hydraulic-cement mortar and concrete," modified (Laval University).

The same test was performed under the nonstandard outside conditions at Laval University (same environment as for the Box and Baenziger Tests). The results are presented in figure 20.

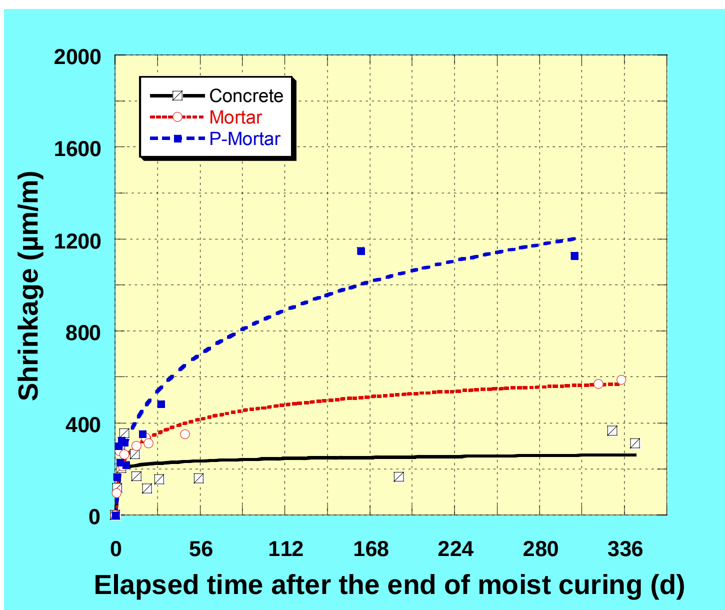



Figure 20.—ASTM C157, "Standard test method for length change of hardened hydraulic-cement mortar and concrete," modified (Laval University, outside).

The ASTM C157 Modified Test was also conducted using a different device to monitor the deformation (see figure 9). The results are presented in figure 21.

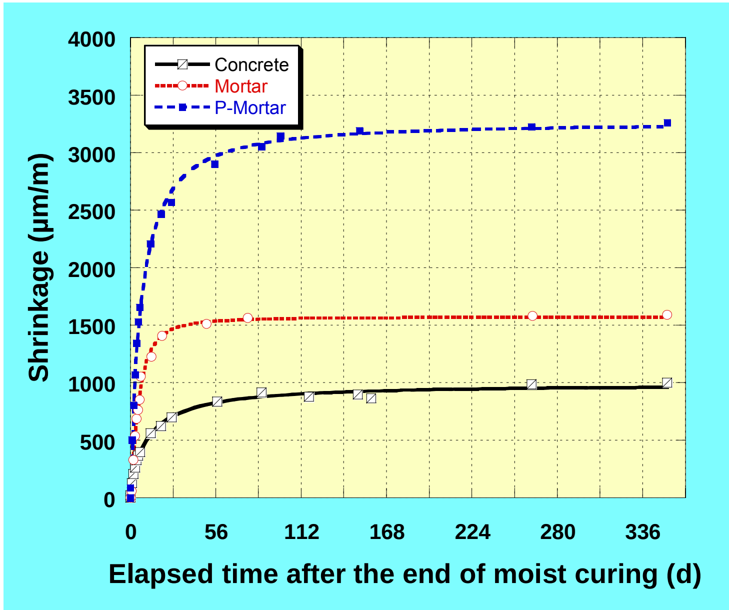



Figure 21.—ASTM C157, "Standard test method for length change of hardened hydraulic-cement mortar and concrete," modified using the comparator with mobile plate (Laval University).

Following are the crack mapping sketches for all box geometries and materials (figures 22 to 33). A crack map is a digital picture of the repair through the transparency film. The colors are removed using imaging software. The results presented are based on the final monitoring performed in fall 2003 (at age of 2 years). A summary of cracking manifestation is presented in table 7.

Table 7.—Summary of cracking manifestation

| Material | C.R.E.E.P Box | | | Baenziger Block | German Angle | |
|---|---|---|---|---|---|---|
| | Small | Medium | Large | | Field | Lab |
| Concrete | No cracks | Small cracks on one specimen | No cracks | No cracks | Fine cracks | Cracks |
| Mortar | Few cracks on every specimen | Cracks on every specimen | Extensive cracking on every specimen | Every specimen had cracks | Crack every 100 mm | Crack every 60 mm |
| Polymer Mortar | Important surface crazing | Extensive surface crazing | Extensive surface crazing | Extensive surface crazing | Lots of cracks; fine cracks | Many cracks; average crack spacing is 50 mm |

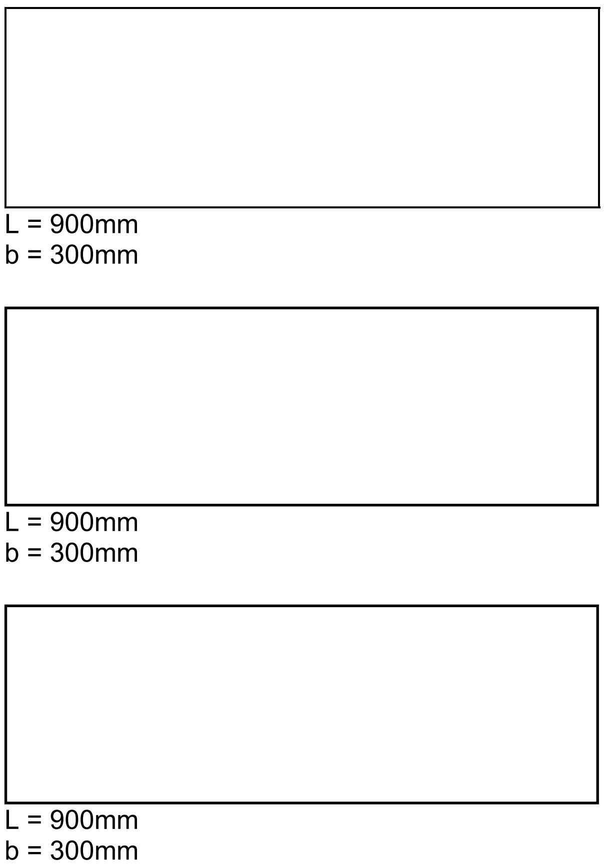
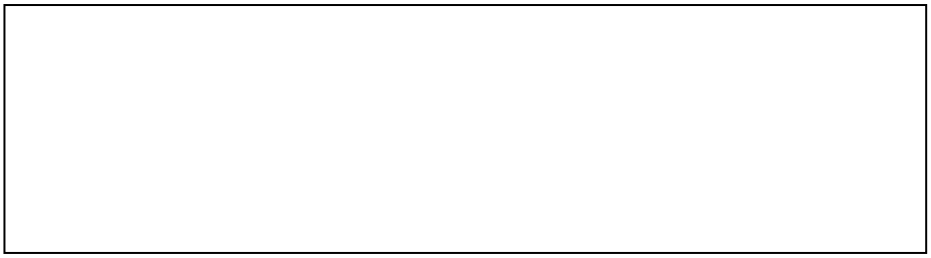
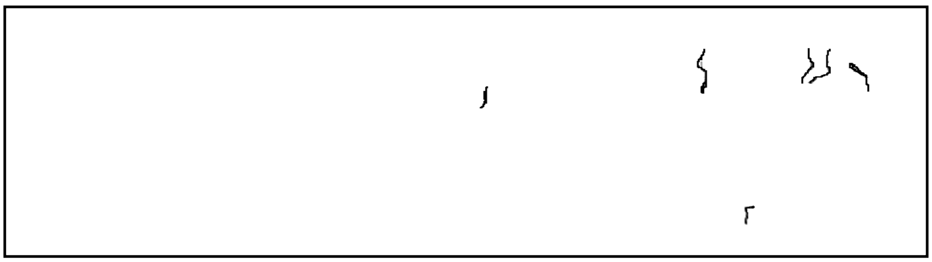



Figure 22.—Crack maps of concrete in small boxes (no cracks).

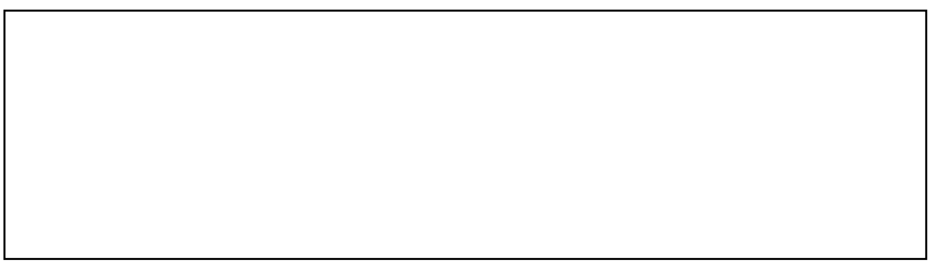
**Medium boxes – Concrete**



L = 1,400mm
b = 375mm



L = 1,400mm
b = 375mm



L = 1,400mm
b = 375mm

Figure 23.—Crack maps of concrete in medium boxes.

**Large boxes – Concrete**

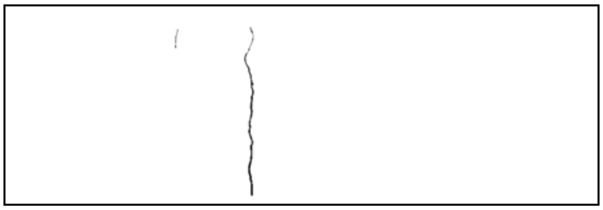
L = 1,900mm
b = 450mm

L = 1,900mm
b = 450mm

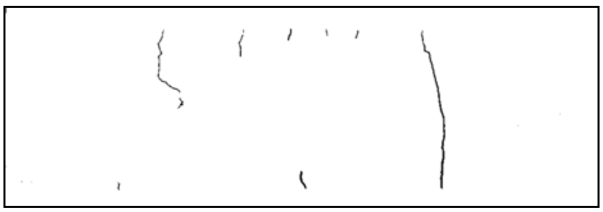
L = 1,900mm
b = 450mm

Figure 24.—Crack maps of concrete in large boxes.

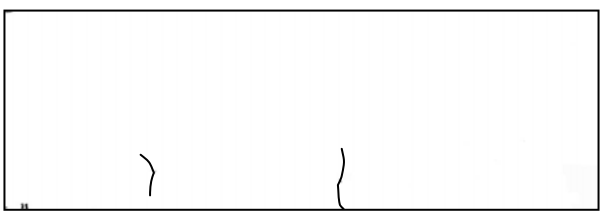
**Small boxes – Mortar**



L = 900mm
b = 300mm



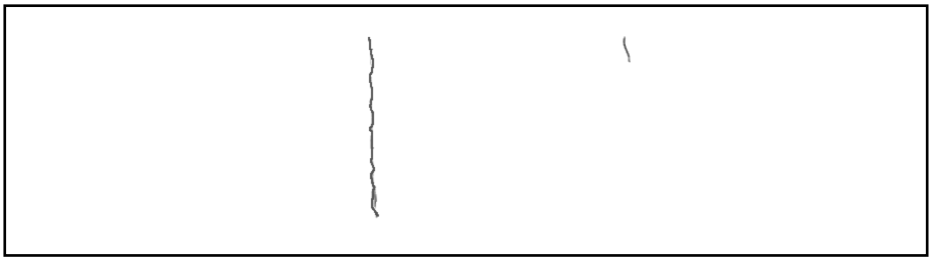
L = 900mm
b = 300mm



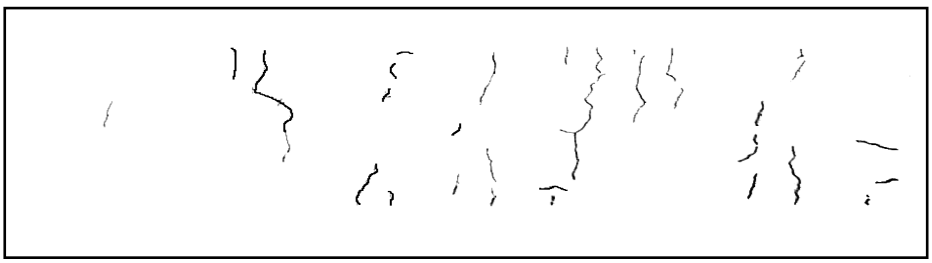
L = 900mm
b = 300mm

Figure 25.—Crack maps of mortar in small boxes.

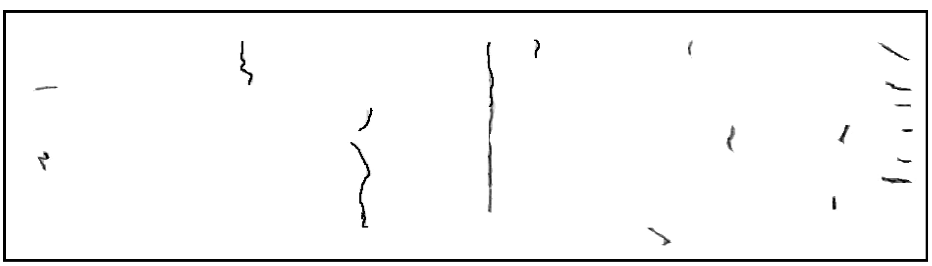
**Medium boxes – Mortar**



L = 1,400mm
b = 375mm



L = 1,400mm
b = 375mm

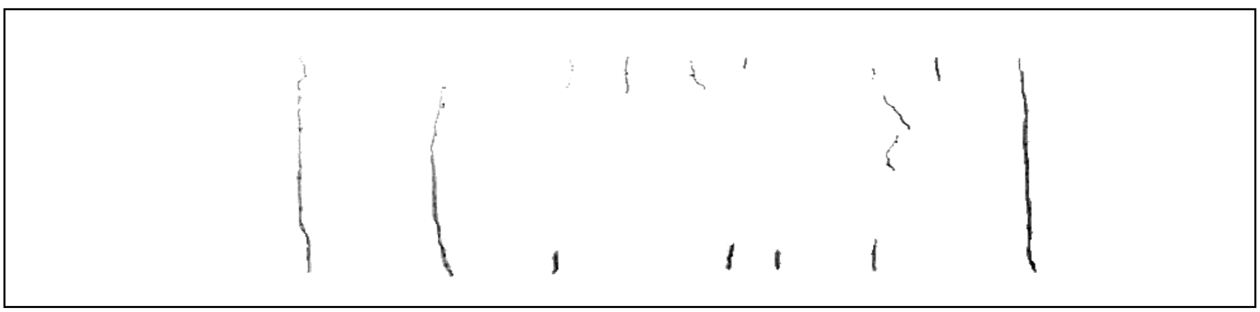


L = 1,400mm
b = 375mm

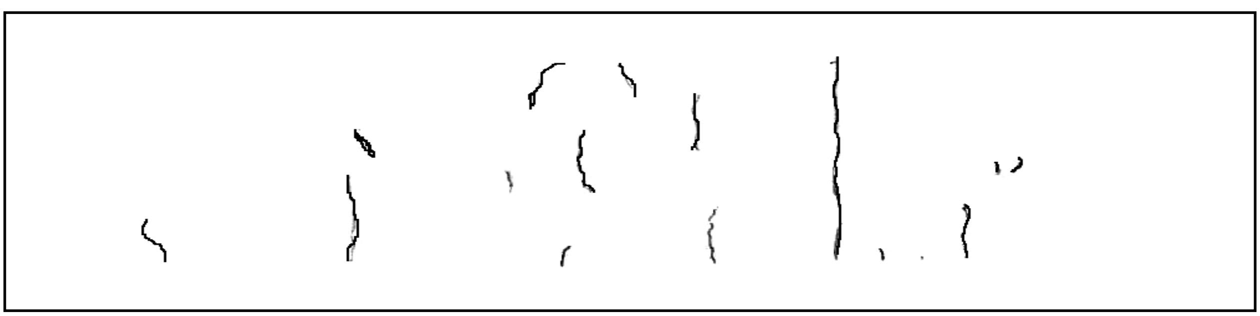
Figure 26.—Crack maps of mortar in medium boxes.

**Large boxes – Mortar**

L = 1,900mm
b = 450mm



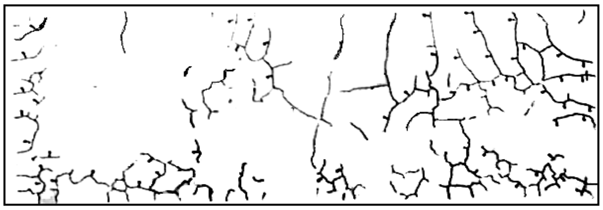
L = 1,900mm
b = 450mm



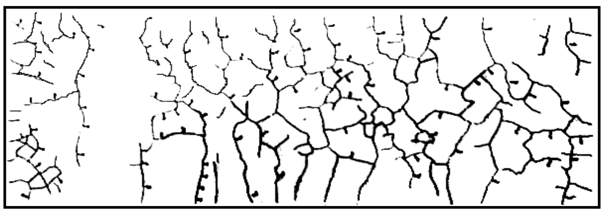
L = 1,900mm
b = 450mm

Figure 27.—Crack maps of mortar in large boxes.

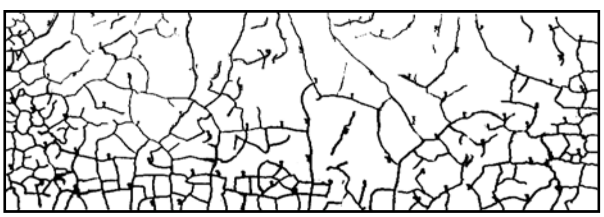
**Small boxes – P-mortar**



L = 900mm
b = 300mm



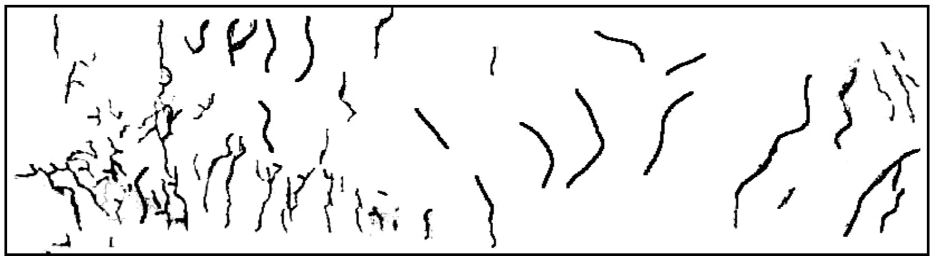
L = 900mm
b = 300mm



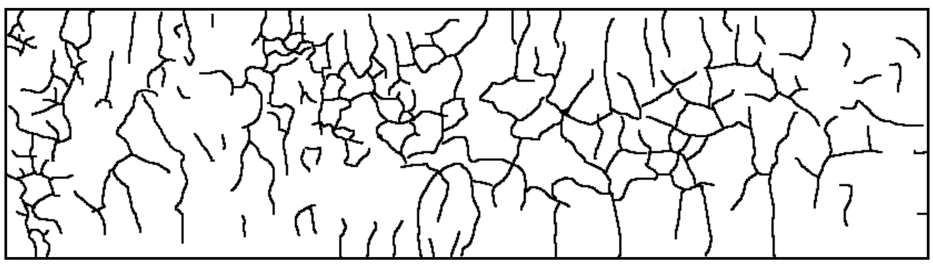
L = 900mm
b = 300mm

Figure 28.—Crack maps of P-mortar in small boxes.

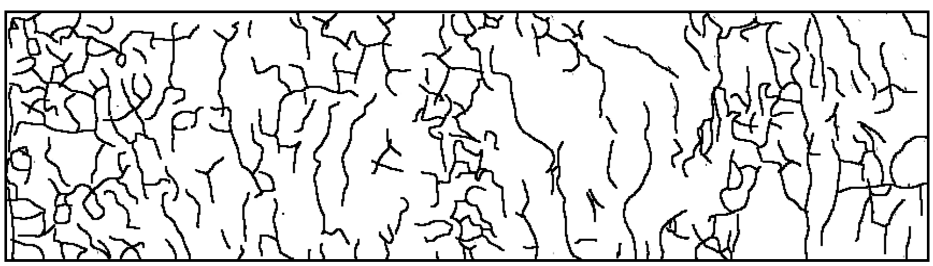
**Medium boxes – P-mortar**



L = 1,400mm
b = 375mm



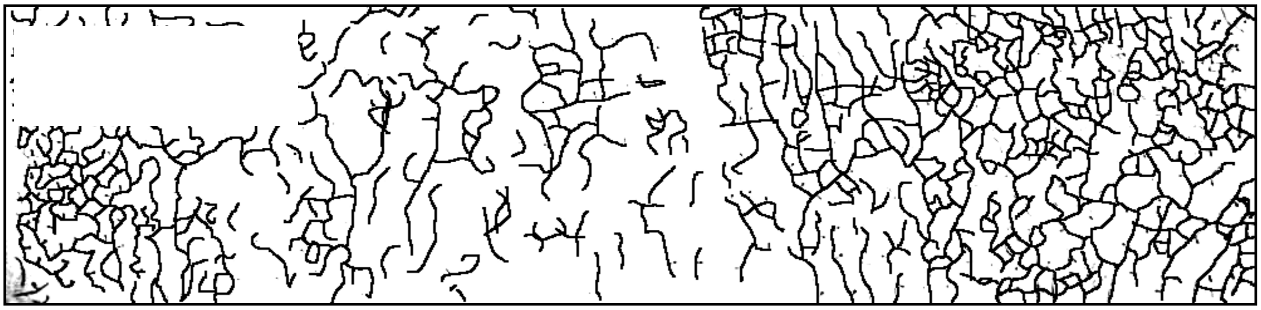
L = 1,400mm
b = 375mm



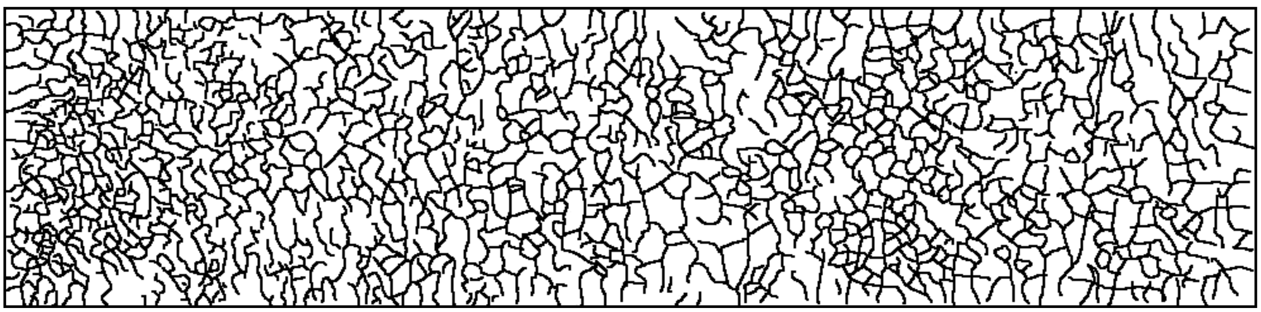
L = 1,400mm
b = 375mm

Figure 29.—Crack maps of P-mortar in medium boxes.

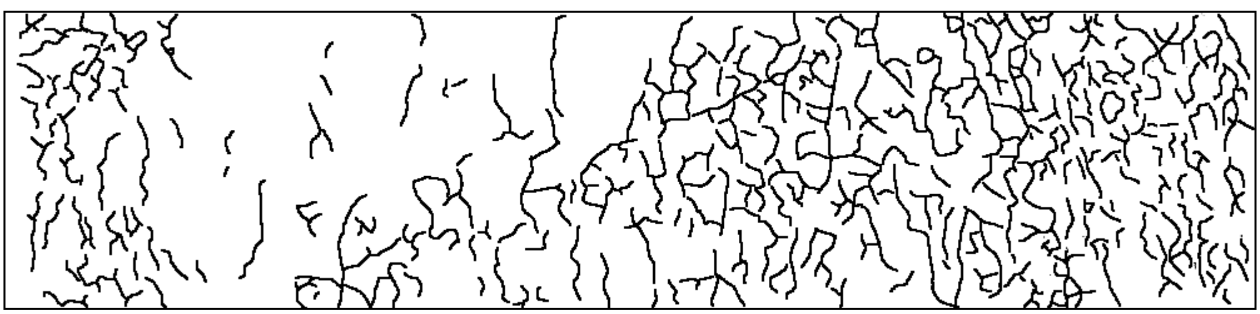
**Large boxes – P-mortar**



L = 1,900mm
b = 450mm



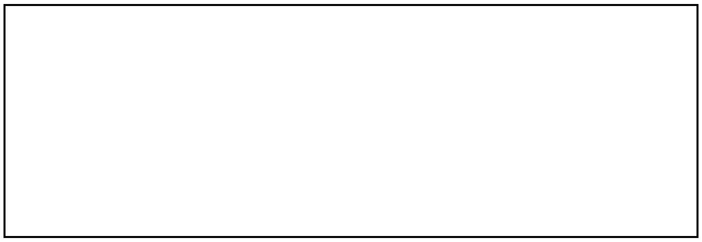
L = 1,900mm
b = 450mm



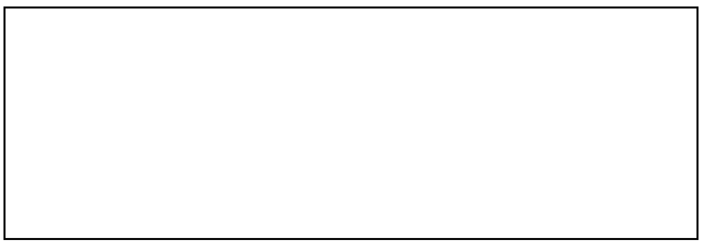
L = 1,900mm
b = 450mm

Figure 30.—Crack maps of P-mortar in large boxes.

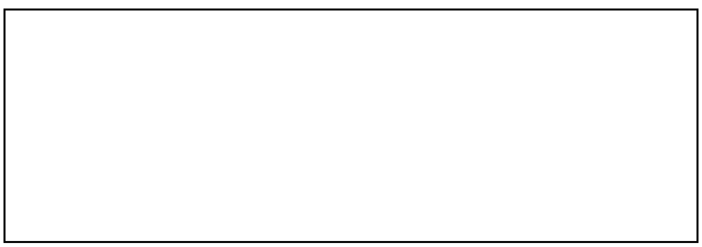
**Baenziger Blocks – Concrete**



L = 1,050mm
b = 300mm



L = 1,050mm
b = 300mm

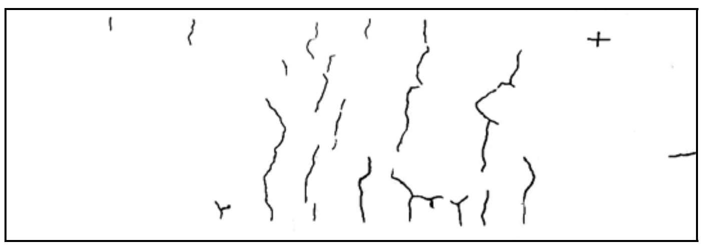


L = 1,050mm
b = 300mm

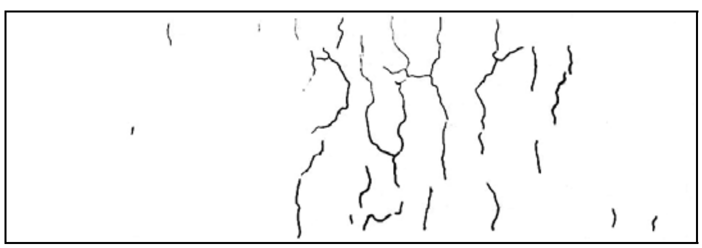
Figure 31.—Crack maps of concrete in Baenziger Blocks.

### Baenziger Blocks – Mortar

L = 1,050mm
b = 300mm



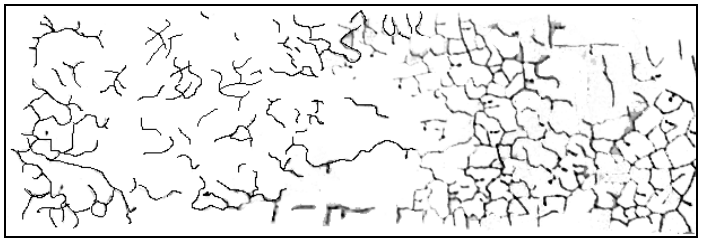
L = 1,050mm
b = 300mm



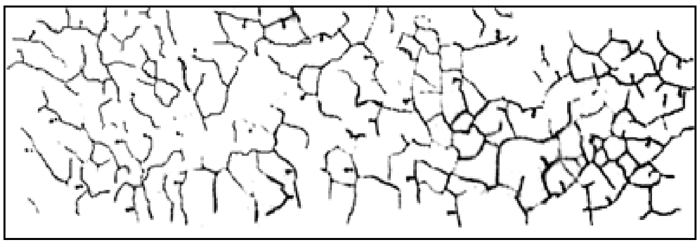
L = 1,050mm
b = 300mm

Figure 32.—Crack maps of mortar in Baenziger Blocks.

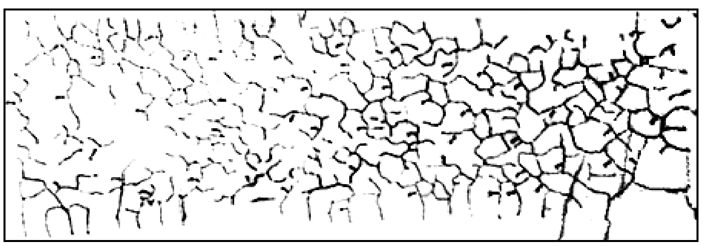
**Baenziger Blocks – P-mortar**



L = 1,050mm
b = 300mm



L = 1,050mm
b = 300mm



L = 1,050mm
b = 300mm

Figure 33.—Crack maps of P-mortar in Baenziger Blocks.

Cracking shown in figures 30 through 32 and figure 35 representing Polymer Mortar is not considered drying shrinkage cracking. It is a surface phenomenon called “crazing.”

Crack intensity analysis was performed for each material tested in each box geometry, Baenziger Block and German Angle (tables 8 and 9). The “crack density” approach was selected to characterize the cracking behavior. Three options were used for defining the crack density.

Table 8.—Analysis of cracking behavior

| Material tests | Specimen | Crack density | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Cracking area[1] (mm²/m²) | | | Crack length[2] (mm/m²) | | | Number of cracks density[3] (cracks/m²) | | |
| | | Concrete | Mortar | P-mortar | Concrete | Mortar | P-mortar | Concrete | Mortar | P-mortar |
| Small Box (Field cond.) | 1 | 0 | 133 | 744 | 0 | 2,570 | 17,678 | 0 | 33.3 | 103.7 |
| | 2 | 0 | 108 | 1,354 | 0 | 1,493 | 34,400 | 0 | 7.4 | 207.4 |
| | 3 | 0 | 3 | 1,373 | 0 | 63 | 37,000 | 0 | 7.4 | 218.5 |
| | **Average** | **0** | **81** | **1,157** | **0** | **1,375** | **29,693** | **0** | **16.0** | **176.5** |
| Medium Box (Field cond.) | 1 | 9 | 56 | 1,238 | 367 | 808 | 31,656 | 15.2 | 3.8 | 118.1 |
| | 2 | 0 | 209 | 1,477 | 0 | 4,733 | 35,544 | 0 | 66.7 | 135.2 |
| | 3 | 0 | 91 | 1,500 | 0 | 1,898 | 59,178 | 0 | 32.4 | 217.1 |
| | **Average** | **3** | **118** | **1,405** | **122** | **2,480** | **42,126** | **5.1** | **34.3** | **156.8** |
| Large Box (Field cond.) | 1 | 0 | 212 | 1,660 | 0 | 2,882 | 43,933 | 0 | 32.7 | 86.5 |
| | 2 | 0 | 154 | 1,263 | 0 | 2,717 | 33,700 | 0 | 25.7 | 73.7 |
| | 3 | 0 | 121 | 1,743 | 0 | 2,343 | 61,111 | 0 | 25.7 | 152.0 |
| | **Average** | **0** | **162** | **1,556** | **0** | **2,647** | **46,248** | **0** | **28.0** | **312.2** |
| Baenziger Block (Field cond.) | 1 | 0 | 163 | 1,394 | 0 | 4,217 | 43,067 | 0 | 48.6 | 260.4 |
| | 2 | 0 | 203 | 1,187 | 0 | 5,500 | 37,056 | 0 | 79.9 | 187.5 |
| | 3 | 0 | 198 | 1,536 | 0 | 6,970 | 49,111 | 0 | 97.8 | 305.6 |
| | **Average** | **0** | **188** | **1,372** | **0** | **5,562** | **43,078** | **0** | **75.4** | **251.2** |
| German Angle U.L. (Field cond.) | 1 | 100 | 450 | 852 | 2,000 | 8,000 | 15,000 | 23.5 | 94.1 | 176.5 |
| | 2 | 50 | 375 | 1,196 | 1,000 | 8,000 | 18,000 | 11.8 | 94.1 | 211.8 |
| | 3 | 0 | 613 | 792 | 0 | 9,000 | 12,000 | 0 | 105.9 | 141.2 |
| | **Average** | **50** | **479** | **946** | **1,000** | **8,333** | **15,000** | **11.8** | **98.0** | **176.5** |
| German Angle Reclamation (Lab cond.) | 1 | 1 | 10 | 24 | 1,292 | 7,000 | 16,000 | 129.4 | 105.9 | 188.2 |
| | 2 | 3 | 12 | 24 | 3792 | 11,000 | 16,000 | 188.2 | 129.4 | 188.2 |
| | 3 | 1 | 14 | 23 | 1,050 | 13,000 | 17,000 | 82.4 | 152.9 | 200.0 |
| | **Average** | **2** | **12** | **24** | **2,045** | **10,333** | **16,333** | **133.3** | **129.4** | **192.1** |

[1] Cracking area density is the total crack opening multiplied by total crack length per square meter of surface.
[2] Crack length density is the total crack length per square meter of surface.
[3] Number of cracks density represents the number of cracks per square meter of surface.

Table 9.—Summary of cracking behavior analysis

| Material tests | Exposure | Crack density | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Cracking density (mm²/m²) | | | Crack length (mm/m²) | | | Number of crack density (cracks/m²) | | |
| | | Concrete | Mortar | P-mortar | Concrete | Mortar | P-mortar | Concrete | Mortar | P-mortar |
| Small Box | Field (L.U.) | 0 | 81 | 1,157 | 0 | 1,375 | 29,693 | 0 | 16.0 | 176.5 |
| Medium Box | Field (L.U.) | 3 | 118 | 1,405 | 122 | 2,480 | 42,126 | 5.1 | 34.3 | 156.8 |
| Large Box | Field (L.U.) | 0 | 162 | 1,556 | 0 | 2,647 | 46,248 | 0 | 28.0 | 312.2 |
| Baenziger Block | Field (L.U.) | 0 | 188 | 1,372 | 0 | 5, 562 | 43,078 | 0 | 75.4 | 251.2 |
| German Angle | Field (L.U.) | 50 | 479 | 946 | 1,000 | 8,333 | 15,000 | 11.8 | 98.0 | 176.5 |
| | Lab. (Reclamation) | 166 | 1,131 | 2,045 | 2,045 | 10,333 | 16,333 | 133.3 | 129.4 | 192.1 |

Results of the Restrained Shrinkage Tests are presented below. The Ring Test results are summarized in table 10.

Table 10.—Summary of the Ring Test results

| Location | Characteristics | Concrete | | | Mortar | | | P-mortar | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Laval University | Time of first crack (d) | 6 | 10 | — | 3 | 5 | — | —[1] | 2 | 3 |
| | Average crack width (mm) | 0.9 | 0.080 | — | 0.21 | 1.5 | — | 2 | –[1] | 3.5 |
| | Number of cracks | 1 | 5 | — | 5 | 1 | — | 1 | 2 | 1 |
| Bureau of Reclamation | Time of first crack (d) | 6 | 6 | 9 | 2 | 2 | 5 | 4 | 2 | 2 |
| | Average crack width (mm) | 0.40 | 0.27 | 0.04 | 1.00 | 1.15 | 0.32 | | 3.68 | 3.71 |
| | Number of cracks | 2 | 4 | 5 | 2 | 2 | 4 | 2 | [2]4 | [2]9 |

[1] The concrete ring fell off.
[2] Only one major crack, and the others were hairline cracks.

SPS Plate Test results are presented in figure 34.

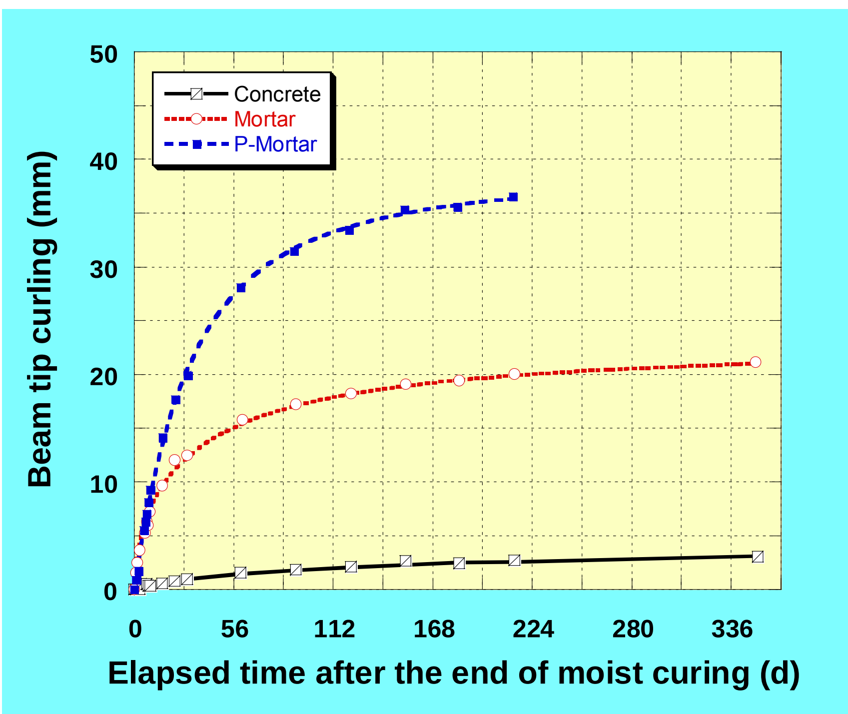



Figure 34.—SPS Plate Test under laboratory conditions (Reclamation).

Laval Beam Deflection Test results are presented in figures 35 through 37.

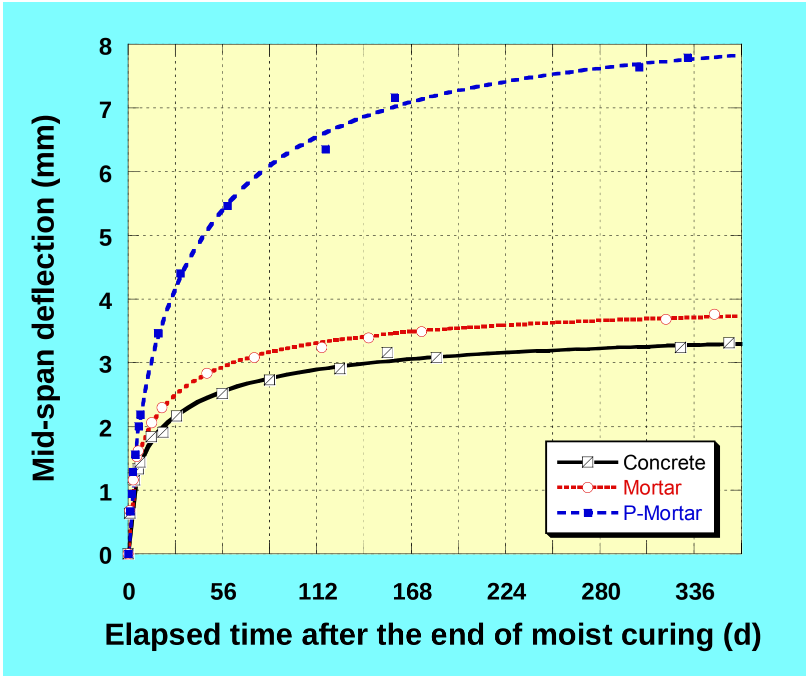



Figure 35.—Laval Beam Deflection Test under laboratory conditions (Laval University).

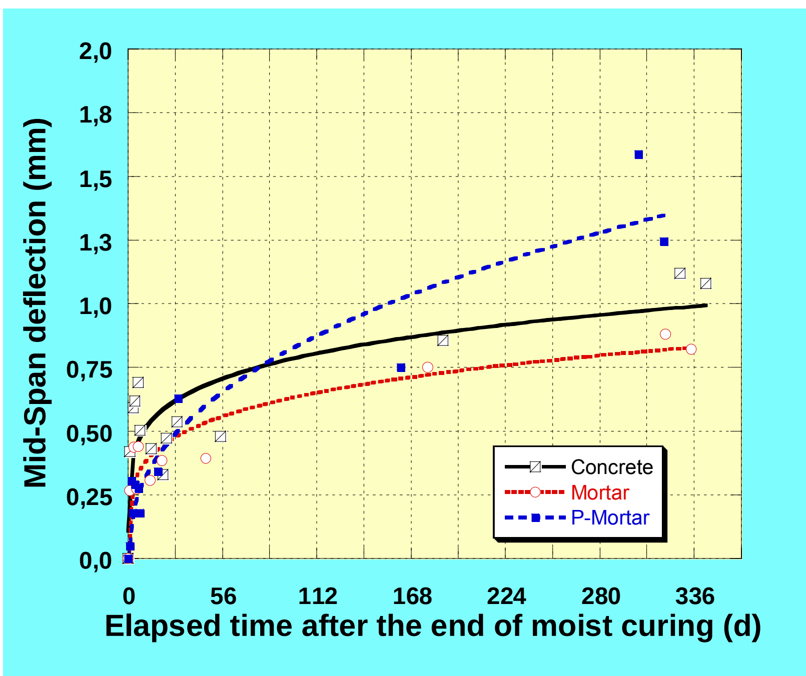



Figure 36.—Laval Beam Deflection Test under field conditions (Laval University).

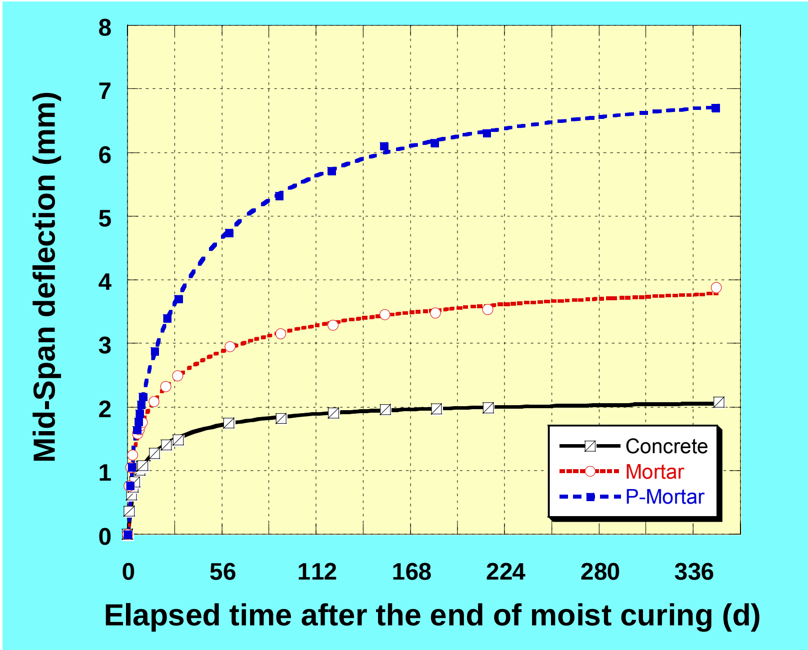



Figure 37.—Laval Beam Deflection Test under laboratory conditions (Reclamation).

The relationship between the Laval Beam Deflection Test and the SPS Plate Test is shown in figures 38 and 39. The results of the above Laval Beam Deflection Test are expressed in the terms of SPS Plate Test (beam tip curling), described above.

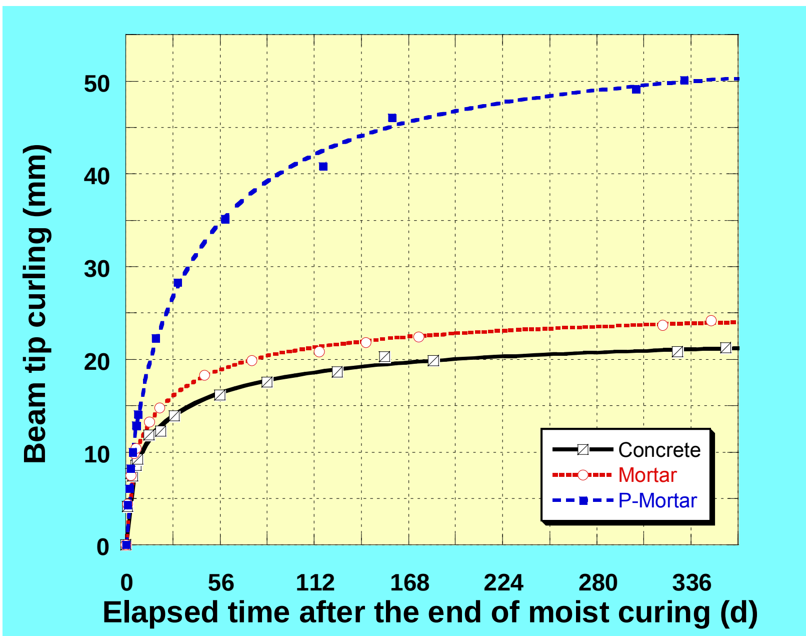



Figure 38.—Laval Beam Deflection Test under laboratory conditions (Laval University) expressed in terms of tip curling (SPS Plate Test).

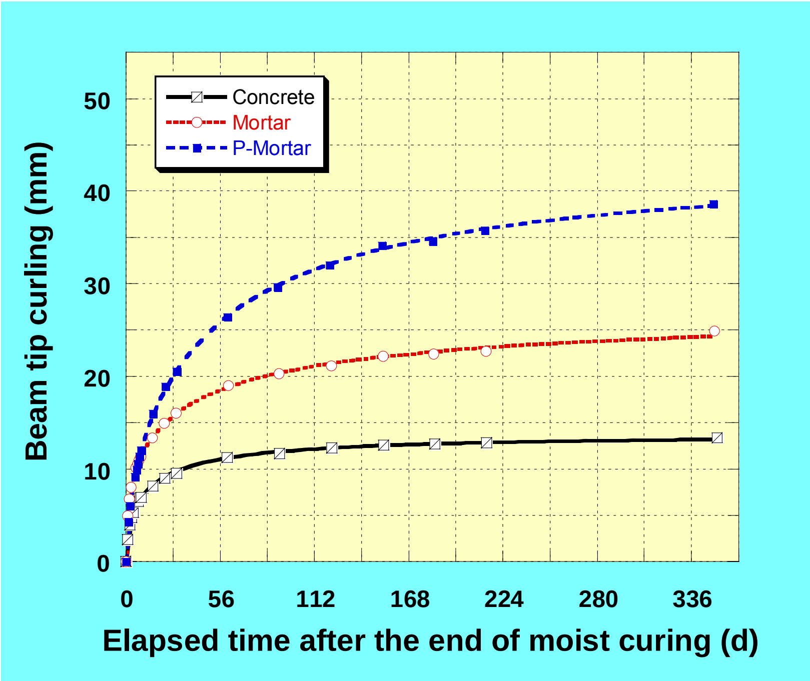



Figure 39.—Laval Beam Deflection Test under laboratory conditions (Reclamation) expressed in terms of tip curling (SPS Plate Test).

A comparison of the results of SPS Plate and Laval Beam Tests is presented in figures 40 and 41.

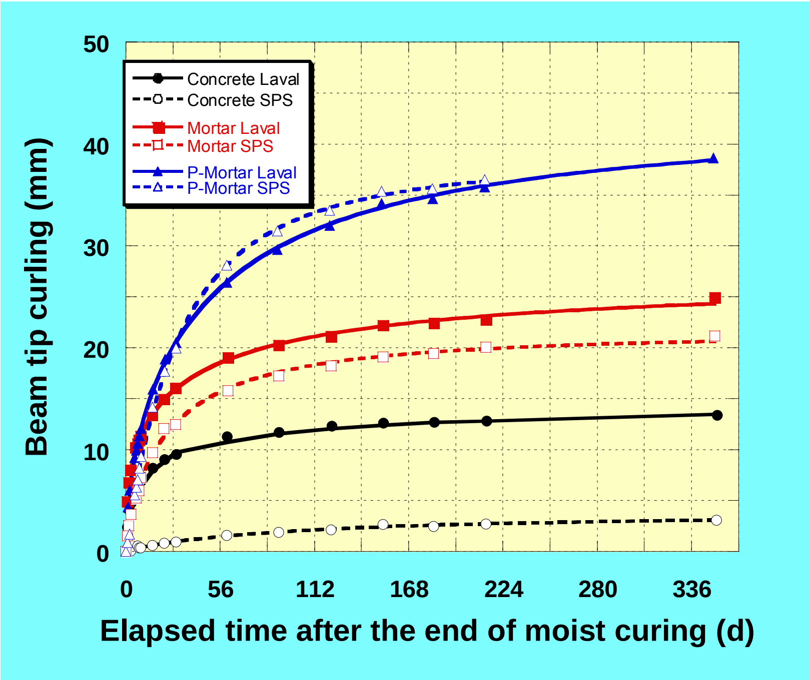



Figure 40.—Comparison of the SPS Plate and Laval Beam Test results.

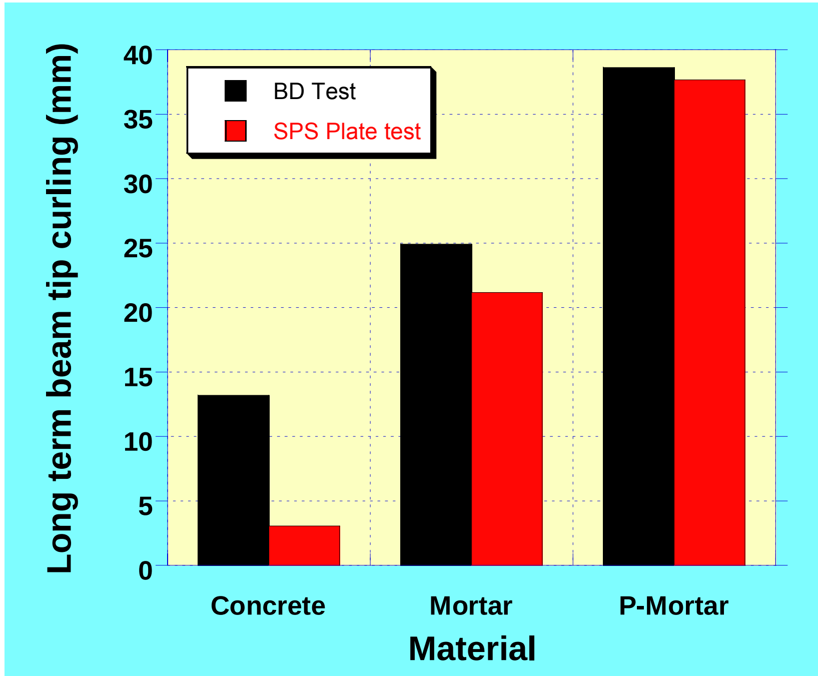



Figure 41.—Comparison of the SPS Plate and Laval Beam Ultimate Test results.

# E. Discussion

## 1. General

This section summarizes the results of the tests conducted in Phase I of this study. These results are discussed in the context of selecting an optimal geometry of an experimental specimen to evaluate the repair material's sensitivity to cracking. In addition, any correlation between materials cracking in experimental repair and various shrinkage tests was analyzed.

## 2. Box Test

The repair mortar exhibited various degrees of cracking in each of the box geometries (figure 42).

The concrete mixture used for repair of cavities did not exhibit cracking in any of the four different specimen geometries. Several factors could explain an absence of cracking. To verify whether the debonding of the material was the cause, Pull-Off Tests were performed on the experimental repairs. The results are presented in figures 43 and 44. The results show that there was an adequate bond between all materials and substrate.

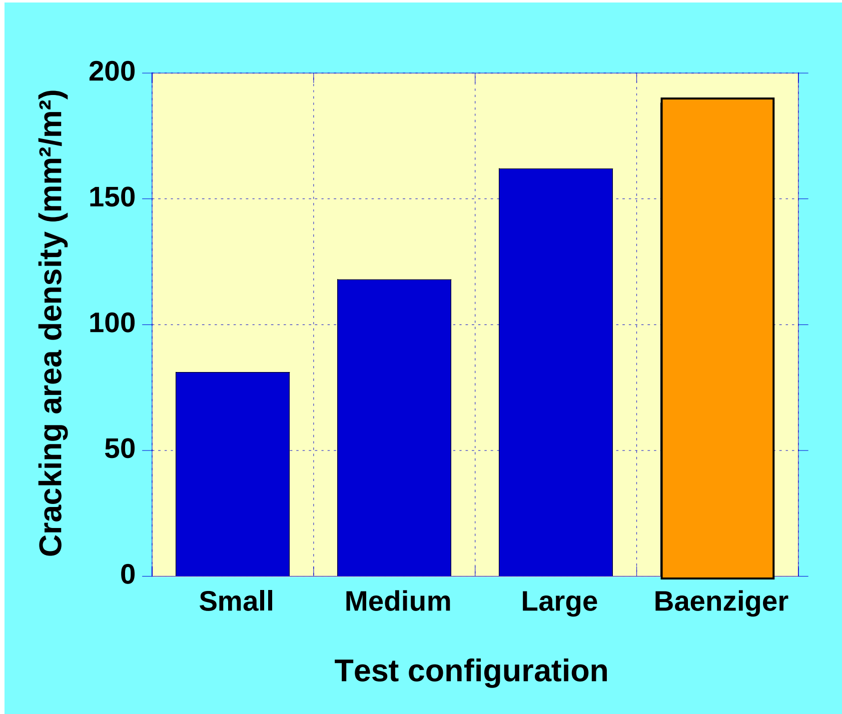



Figure 42.—Cracking density for mortar in the various test configurations.

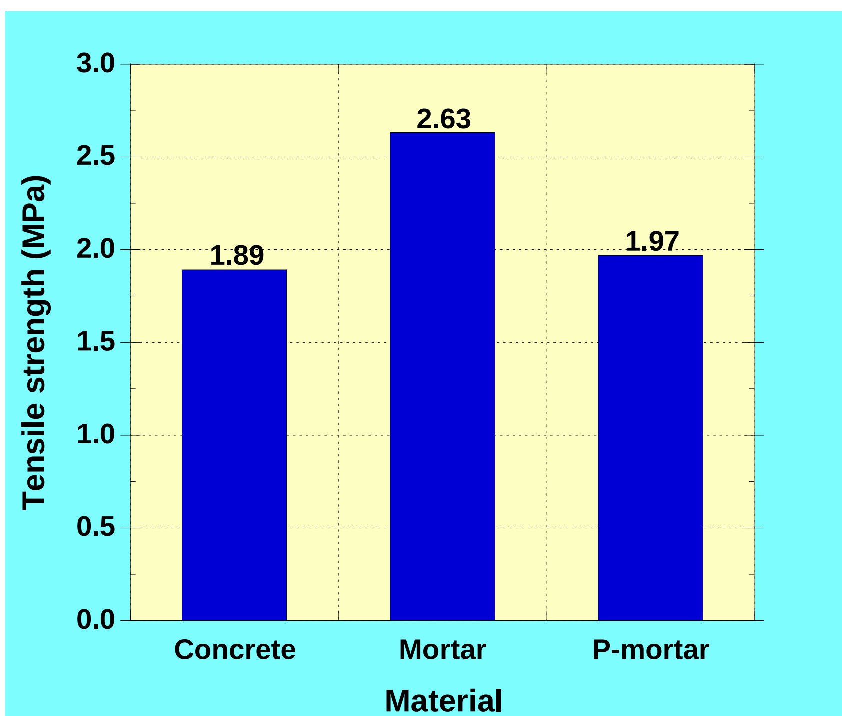



Figure 43.—Summary of the Pull-Off Test results.

Figure 44.—Pull-Off Tests carried on experimental repairs.

The polymer-modified repair material exhibited very severe surface crazing in all specimens' geometries, and, therefore, it was difficult to determine, with a reasonable degree of certainty, whether shrinkage cracks existed. Figure 45 is a longitudinal saw-cut of a Baenziger Block showing that most of the cracks are not going deeper than few centimeters from the surface.


Figure 45.—Longitudinal saw-cut of a Baenziger Block showing that the cracks are a surface phenomenon.

Based on the cracking density analysis, which is probably the most reliable indicator of materials sensitivity to cracking, the large box and Baenziger Block are the optimal experimental repair specimen geometries among those tested. However, the Baenziger Block is recommended for use in Phase II studies because of its ease of handling, smaller size, and lower weight.

## 3. Free Shrinkage Test

There is a correlation between the free drying shrinkage test (ASTM C157) and cracking observed on experimental repairs. After 2 years of field exposure and monitoring, the concrete did not show any cracks, but mortar showed extensive cracking. The ultimate drying shrinkage is 1,000 micrometers per meter (μm/m) for concrete and 1,800 μm/m for the mortar. A higher ultimate drying shrinkage strain leads to a greater cracking density. However, it is not possible to establish a direct relationship because the cracking density of the mortar is not 1.8 times the cracking density of the concrete regardless of the experimental repair configuration (table 9).

The two apparatuses used to measure shrinkage of materials produced very similar results (figures 19 and 21).

The ASTM C157 is recommended for use in Phase II.

## 4. Restrained Shrinkage Tests

### *a. German Angle Test*

Cracking was observed in the concrete specimens. This indicates that no correlation exists between German Angle and Baenziger Block Test results.

The cracking density in the German Angle Test using repair mortar was 479 $mm^2/m^2$, which is 2.5 times higher than in the Baenziger Block Test.

The results of the German Angle Test also contradicted the results of similar tests performed by COE (COE, September 1998).

The German Angle Test in not recommended for use in Phase II.

### *b. Ring Test*

All materials tested exhibited very early first crack occurrence (less than 10 days). These test results for concrete do not correlate with Baenziger Block and Large Box Tests. Ring Tests employing ASTM C1581-04, “Standard test method for determining age of cracking and induced tensile stress characteristics of mortar and concrete under restrained shrinkage,” are recommended for Phase II of this study. However, mortar that exhibited cracking in boxes and Baenziger Blocks cracked at an earlier age than the concrete in the Ring Test.

### *c. PS Plate and Laval BD Tests*

For Mortar and P-mortar, there was a good correlation between the two test methods. No correlation was found for the concrete mixture tested; therefore, further studies are recommended in Phase II of the project.

# F. Objectives, Conclusions, and Recommendations

The objectives of the Concrete Repair Engineering Experiment Program are:

- Develop laboratory/field reliable test method(s) to evaluate the long-term performance of repair materials and, in particular, their sensitivity to cracking.
- Assess the applicability of some of the existing test methods for evaluating cracking tendency of repair materials.
- Contribute to the development of performance criteria for selection of crack-resistant repair materials.

The objectives of Phase I of the above project were as follow:

- Evaluate the performance of materials used in experimental repairs placed in geometrically different cavities of the prefabricated reinforced concrete slabs.
- Select the optimal geometry for further studies in Phase II.

The following conclusions and recommendations are based on the results of Phase I of this study:

- The Baenziger Block is the optimal specimen configuration for evaluating the sensitivity to cracking of repair materials, and, therefore, it is recommended for further studies in Phase II of the project.
- The results of the Ring Test configuration (COE, March 1999) that was employed in this program did not allow for adequate direct correlation with experimental repairs. Therefore, it is recommended that studies in Phase II use the ASTM Ring Test configuration (ASTM C1581-04, "Standard test method for determining age of cracking and induced tensile stress characteristics of mortar and concrete under restrained shrinkage").
- The Free Shrinkage Test should be carried out in Phase II. Further tests are necessary to establish whether or not there is an ultimate shrinkage threshold limit.
- Since correlation between the SPS Plate Test and Laval Beam Deflection Test has been found for only two materials out of three, further studies are recommended during Phase II.

- The studies during the Repair Material Test Program for Phase II should incorporate field placements of repair materials to provide for correlating field and lab test results.

## G. Bibliography

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