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Performance Criteria for Dimensionally Compatible Repair Materials

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Aging of the country's infrastructure has resulted in significant growth of the concrete repair industry in the United States. However, in all too many cases, we find ourselves “repairing repairs.”

A major problem faced by the U.S. Army Corps of Engineers and the repair industry is the unacceptably high failure rate for concrete repairs. It is generally acknowledged that the primary problem is cracking of repair materials—typically the result of dimensional incompatibility between the repair material and the concrete substrate.

To achieve durable repairs, it is necessary to consider the factors affecting the design and selection of repair systems as parts of a composite system. Compatibility between repair material and existing substrate is one of the most critical components in the repair system. Unfortunately, information on the material properties that affect dimensional compatibility, how the various properties interrelate, and values that should be specified as performance criteria for individual properties is very limited.

To address this need, the Corps of Engineers initiated a two-phase program of research in 1994 to develop performance criteria for dimensionally compatible cement-based repair materials that will provide durable crack-free repairs.

Phase I of the study involved a literature review to identify pertinent material properties, appropriate test methods, and factors affecting field performance of concrete repairs (Emmons and Vaysburd 1995). The preliminary performance criteria were then evaluated in parallel field and laboratory investigations during Phase II (Emmons and others 1998, Poston and others 1998). Results of all the investigations were correlated to develop the proposed performance criteria (Vaysburd and others 1998). These criteria include a minimum value for tensile strength; maximum values for modulus of elasticity, coefficient of thermal expansion, and drying shrinkage; and a requirement for resistance to cracking in restrained shrinkage tests.

Field evaluation

The field evaluation (Emmons and others 1998) entailed repair of simulated spalls in precast concrete slabs and monitoring of material performance. The preformed repair cavities were 0.5 m wide, 1.8 m long, and 76 mm deep. Each of the 12 selected materials was used to repair three cavities (Figure 1) at each of the three test sites.

Figure 1. Repair of simulated spalls in precast concrete slabs

The commercially available repair materials were chosen to represent a wide range in composition and properties, particularly drying shrinkage. The exposure sites were chosen to represent a wide range of environmental conditions (freezing and thawing, high temperature and low humidity, high temperature and high humidity). In addition to the simulated repairs, the field performance of each material was evaluated with two restrained drying shrinkage test methods. The performance of all specimens was monitored for a minimum of 18 months. Results of the field evaluation are summarized in Table 1.

Table 1
Overall Summary of Field Test Results

Material No.	SPS Plate Test Max. Deflection, mm (in.)	German Angle Observations	Repair Monitoring Observations	Conclusions
1	6.60 (0.26)	No cracks.	No cracks.	Good crack resistance.
2	6.60 (0.26)	No cracks.	Cracked in Arizona.	Early-age cracking when exposed to low humidity and high temperature.
3	10.92 (0.43)	Cracked in Arizona.	Minor cracking in Arizona.	Susceptible to cracking when exposed to low humidity and high temperature.
4	5.33 (0.21)	No cracks.	No cracks.	Good crack resistance.
5	3.30 (0.13)	Cracked in Florida; debonded in Illinois.	Cracked.	Prone to cracking, particularly when not extended with aggregate.

(Continued)

Table 1 (Concluded)				
Material No.	**SPS Plate Test Max. Deflection, mm (in.)**	**German Angle Observations**	**Repair Monitoring Observations**	**Conclusions**
6	16.50 (0.65)	Cracked.	Cracked.	Prone to cracking.
7	13.72(0.54)	Cracked severely in Arizona.	Surface crazing in Florida and Illinois. Cracked in Arizona.	Prone to surface crazing. Cracked when exposed to low humidity and high temperature.
8	5.08 (0.20)	Cracked in Arizona.	Fine surface crazing in Florida.	Good crack resistance. Surface crazing attributed to finishing.
9	8.64 (0.34)	Cracked in Arizona.	Minor surface crazing in one Florida repair.	Good crack resistance.
10	9.91 (0.39)	Cracked in Arizona.	Surface and edge cracking.	Prone to surface crazing and cracking.
11	6.10 (0.24)	Cracked in Arizona.	No cracks.	Good crack resistance.
12	8.13 (0.32)	No cracks.	Surface deterioration in one Illinois repair.	Good crack resistance.

Simulated repairs

Overall, the 12 repair materials exhibited more resistance to cracking than was originally anticipated. Fine surface crazing of Material 8 in Florida, minor surface crazing of Material 9 in one repair in Florida, and minor surface deterioration of Material 12 in one repair in Illinois appeared unrelated to dimensional compatibility properties. Therefore, results of these tests indicate that one half of the materials (Nos. 1, 4, 8, 9, 11, and 12) demonstrated satisfactory dimensional compatibility and resistance to cracking under the range of service conditions studied. Two materials (Nos. 2 and 3) were susceptible to cracking only when subjected to high-temperature and low-humidity conditions, and their performance was rated as marginal. The remaining materials (Nos. 5, 6, 7, and 10) exhibited cracking in each exposure condition, and their performance was rated as unsatisfactory.

Restrained shrinkage tests

Two types of tests were conducted under field-exposure conditions to evaluate restrained volume changes and cracking potential of the repair materials. The Structural Preservation System (SPS) plate test specimen was a nominal 51- by 102- by 1,321-mm beam (Figure 2). As the material expanded or contracted in response to moisture and temperature changes, deflection of the unrestrained end of the specimen was measured. The German angle test consisted of filling 70- by 70-mm steel angles that were 1.0 m long (Figure 3) with a repair material. Following casting, the test specimens were monitored for cracking under field-exposure conditions. Field test results indicate that both the SPS plate and German angle tests can be used for a general assessment of a material's dimensional compatibility, or resistance to cracking.

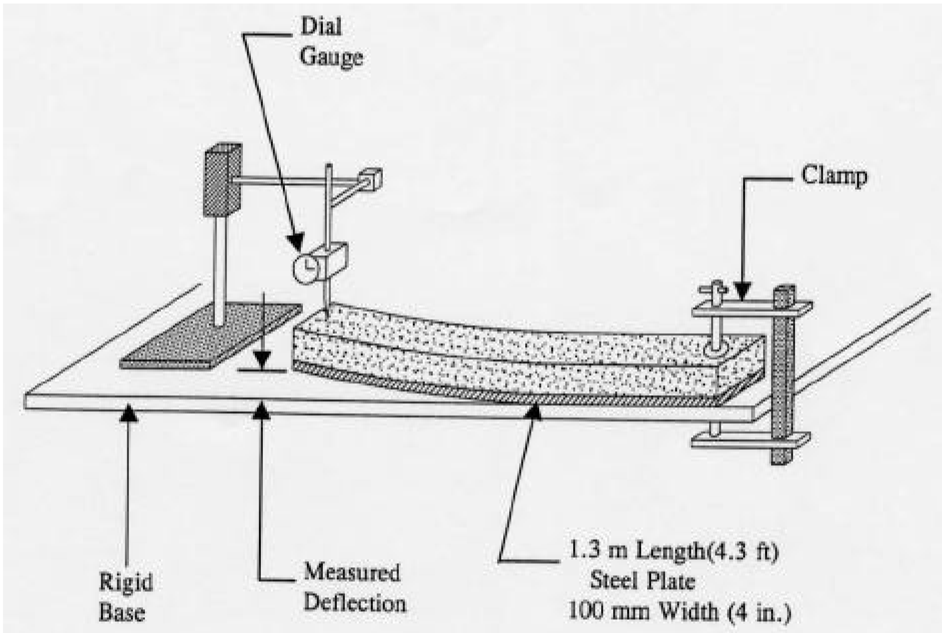

Figure 2. SPS plate test

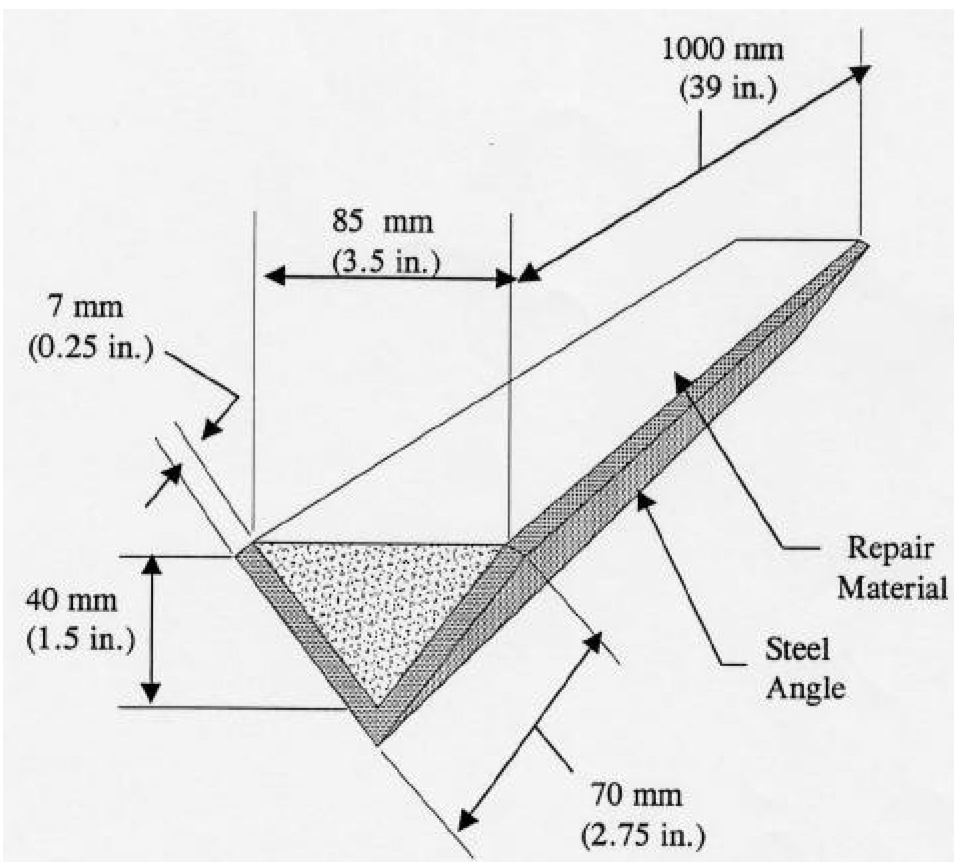

Figure 3. German angle test

Laboratory evaluation

The laboratory component of the study was conducted to determine pertinent properties of the concrete repair materials, particularly those properties affecting dimensional compatibility. This evaluation (Poston and others 1998) included selected standard tests and some nonstandard tests developed specifically to provide a basic understanding of restrained shrinkage in repair applications.

Three restrained shrinkage tests were conducted for comparison with the results of unrestrained drying shrinkage measurements in accordance with American Society for Testing and Materials “Standard Test Method for Length change of Hardened Hydraulic-Cement Mortar and Concrete” (ASTM C 157, Modified) (ASTM 1994a). A restrained-ring test was conducted in addition to the previously described SPS plate and German angle tests. In the ring test, material was cast around a section of 254-mm-diam steel pipe. Following demolding and curing, the specimens were monitored daily under standard laboratory conditions for evidence of cracking. Ten of the twelve materials exhibited cracking in the ring test. Measured crack widths were divided by the circumference of the ring to compute implied strains. There was a significant correlation between these restrained shrinkage strains and unrestrained shrinkage strains (28-day and peak values) and results of SPS plate tests. None of the materials cracked in the German angle test.

Creep test results did not provide definitive information on the effects of compressive or tensile creep on restrained shrinkage cracking. Results indicate that increased creep alone is insufficient to offset cracking of materials that are also prone to high shrinkage. Additional testing is needed to better understand the effect of creep on restrained cracking of repair materials.

Correlation of results

Results of the laboratory and field investigations were correlated to evaluate how individual material properties, or combinations of properties, affect the potential for cracking of field repairs.

Strength

It is generally agreed that the potential for cracking of cement-based repair materials increases with high compressive strengths, despite inherently higher tensile strengths. Increased cracking is usually attributed to the typically higher modulus of elasticity, lower creep, and possibly higher shrinkage of high-strength materials. However, the results of this study indicate that, for the range of materials tested (Table 2), there was no significant correlation between compressive strength and dimensional stability of the field repairs. Therefore, a requirement for compressive strength was not included in the performance criteria for nonstructural or protective repairs, which are the primary focus of this study. Overall, there was no significant correlation between direct tensile strength and field performance of repair materials, although the trend was for improved field performance with increased tensile strength. However, there was a significant correlation between tensile strength and field performance for those materials that exhibited marginal and unsatisfactory performance (Figure 4).

The proposed performance criteria (Table 3) require a minimum direct tensile strength of 2.8 MPa. The results of this study indicate that there was no correlation between flexural strength and field performance. In fact, there was no apparent trend between flexural strength and field performance.

Modulus of elasticity

It is generally agreed that the potential for cracking of cement-based repair materials decreases with decreases in modulus of elasticity because of its effect on the magnitude of stresses induced by drying shrinkage and stress relaxation through creep. However, the results of this study indicated that, for the range of materials tested, there was no significant correlation between modulus of elasticity and field

Table 2
Correlation Between Field Performance and Laboratory Test Results

	Field Test Results			Laboratory Test Results												
									Drying Shrinkage Millionths		Ring Test				Specific Creep @ 1 year Millionths/psi	
Mat'l No.	Field Perf. Rank	German Angle	SPS Plate Defl., in.	Compressive Strength, psi	Tensile Strength, psi	Flexural. Strength, psi	Modulus of Elasticity psi x 10^6	Coeff. of Thermal Expansion, Millionths per °F	28-days	Peak	Age at 1st Crack days	Implied Strain Millionths	German Angle	SPS Plate Defl., in.	Compressive	Tensile
Group 1 - Satisfactory Field Performance																
1	1-3	No crack	0.26	6,610	451	289	2.8	5.8	178	366	6	667	No crack	0.06	0.451	0.420
4	1-3	No crack	0.21	11,530	348	779	3.8	8.3	201	703	140	560	No crack	0.08	0.260	0.609
11	1-3	Crack in AZ	0.24	9,620	390	503	5.9	7.6	339	641	15	810	No crack	0.24	0.483	0.555
12	4	No crack	0.32	6,940	742	805	3.0	9.3	293	634	None	0	No crack	0.16	1.157	0
8	5-6	Crack in AZ	0.20	4,060	215	139	2.7	9.2	305	1,109	8	1,222	No crack	0.43	1.894	3.587
9	5-6	Crack in AZ	0.34	4,780	323	415	2.7	6.9	429	877	23	955	No crack	0.32	1.301	1.163
Average			**0.26**	**7,260**	**412**	**488**	**3.5**	**7.8**	**291**	**722**		**701**		**0.22**	**0.924**	**1.267**
Group 2 - Marginal Field Performance																
3	7	Crack in AZ	0.43	6,360	513	421	3.7	7.1	479	1,116	17	685	No crack	0.37	1.913	1.449
2	8	No crack	0.26	7,180	399	445	3.2	7.8	391	1,032	22	364	No crack	0.33	0.603	0.831
Average			**0.35**	**6,770**	**456**	**433**	**3.4**	**7.4**	**435**	**1,074**		**525**		**0.35**	**1.258**	**1.140**
Group 3 - Unsatisfactory Field Performance																
10	9	Crack in AZ	0.39	5,230	402	495	4.2	9.9	16	678	None	0	No crack	0.21	2.037	0.072
7	10	Crack in AZ	0.54	4,330	467	365	2.7	8.5	1,779	2,682	4	3,414	No crack	1.49	3.485	2.835
6	11	Cracked	0.65	9,760	323	493	5.3	9.3	301	878	7	1,808	No crack	0.06	0.872	0.608
5	12	Cracked	0.13	6,940	93	758	4.5	7.8	258	690	10	840	No crack	0	0.562	27.73
Average			**0.43**	**6,560**	**321**	**528**	**4.2**	**8.9**	**59**	**1,232**		**1,516**		**0.44**	**1.739**	**7.81**

Note: Divide psi by 145 to obtain MPa; Multiply inches by 25.4 to obtain millimetres.

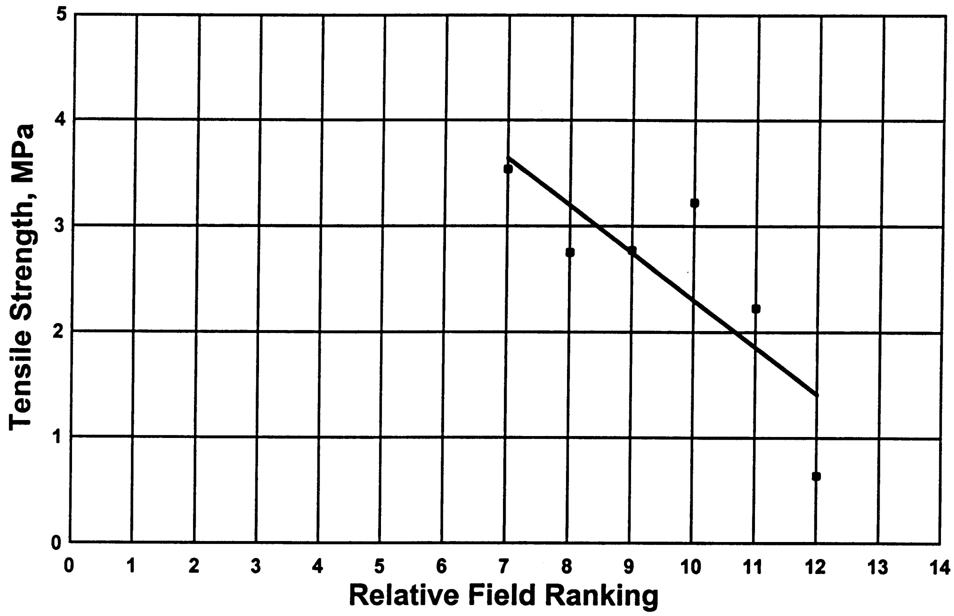

Figure 4. Correlation between tensile strength and field performance

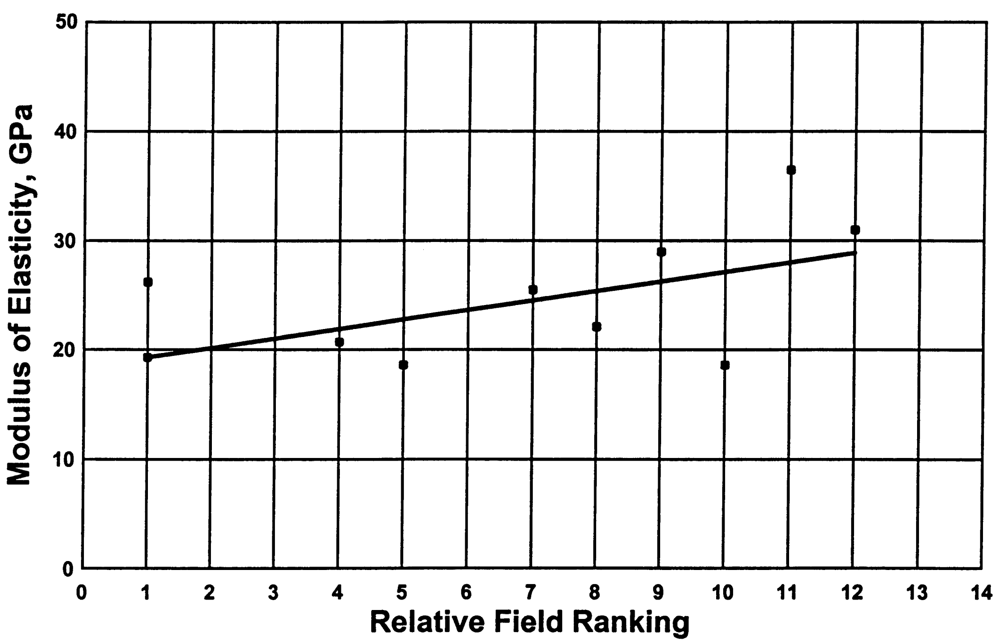

Figure 5. Correlation between modulus of elasticity and field performance

Table 3
Performance Criteria for Repair Materials

Property	Test Method	Requirement
Tensile strength, minimum 28 days	CRD-C 164 (*Handbook for Concrete and Cement*)	2.8 MPa (400 psi)
Modulus of elasticity, maximum	ASTM C 469 (ASTM 1994b)	24 GPa (3.5 x 10^6 psi)
Coefficient of thermal expansion, maximum	CRD-C 39 (*Handbook for Concrete and Cement*)	12 millionths/deg C (6.7 millionths/deg F)
Drying shrinkage, maximum 28 days 1 year	ASTM C 157 (Modified) (ASTM 1994a)	400 millionths 1,000 millionths
Restrained shrinkage-cracking - implied strain at 1-year age, maximum	Ring method (Poston and others 1998)	No cracks within 14 days 1,000 millionths

performance. It should be noted that 10 of the 12 materials exhibited moduli within a relatively narrow range of approximately 19 to 31 GPa. Excluding Material 11, which exhibited a significantly higher modulus of elasticity compared with the other materials with acceptable field performance, there was a modest correlation between modulus of elasticity and field performance (Figure 5). The proposed performance criteria limit modulus of elasticity to a maximum value of 24 GPa.

Thermal expansion

Overall, there was no significant correlation between coefficient of thermal expansion and field performance. However, the trend was for improvement in field performance with decreasing coefficients of thermal expansion (Figure 6).

Coefficients of thermal expansion, determined in accordance with ASTM C 531 (ASTM 1994c), were higher than anticipated and generally higher than that normally associated with concrete. The proposed performance criteria limit coefficient of thermal expansion to a maximum of 12 millionths/deg C (determined in accordance with CRD-C 39, *Handbook for Concrete and Cement*).

Unrestrained shrinkage

Overall, there was no significant correlation between unrestrained drying shrinkage at 28-days age and field performance, although the trend was for improved field performance with decreasing shrinkage. Attempts to correlate peak drying shrinkage with field performance yielded similar results. However, excluding the materials that demonstrated unsatisfactory field performance, there was a significant correlation between both 28-day and peak drying shrinkage and field performance (Figure 7). The proposed performance criteria limit drying shrinkage at 28-days age to a maximum of 400 millionths. In addition, the criteria limit the peak (ultimate) drying shrinkage to a maximum of 1,000 millionths at 1 year.

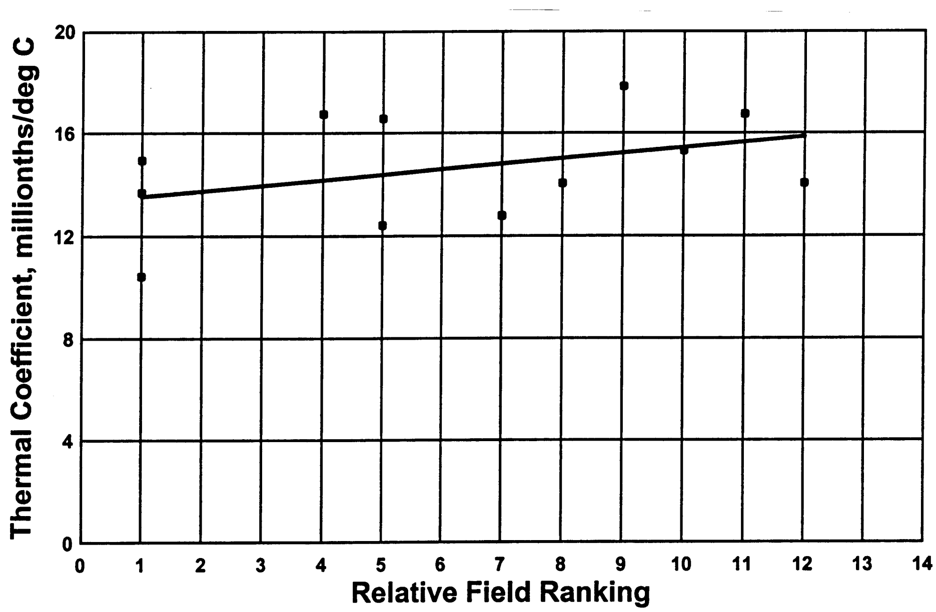

Figure 6. Correlation between coefficient of expansion and field performance

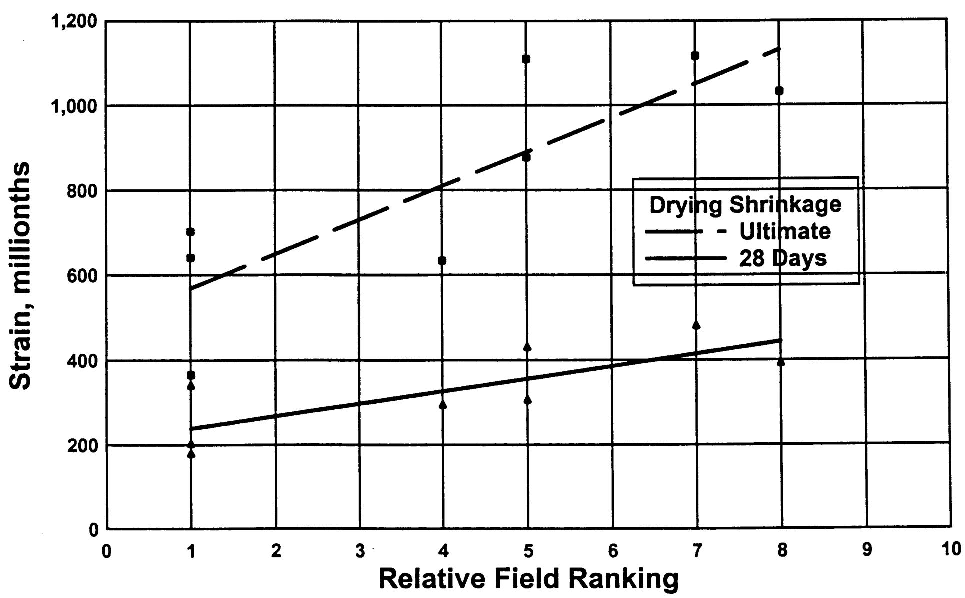

Figure 7. Correlation between drying shrinkage and field performance

Creep

The study results appeared to contradict the generally accepted theory that higher creep aids in relaxation of stresses and strains induced by restrained shrinkage in concrete repairs, thus reducing the potential for cracking. Although there was no significant correlation between either compressive or tensile creep and field performance, the trend in each case was for improved field performance with decreased creep. These unexpected results are attributed in part to the generally higher drying shrinkage associated with materials that exhibited high creep characteristics. Apparently, the higher strains induced by increased drying shrinkage more than offset any additional strain relaxation because of increased creep. Additional research is necessary to quantify the effect of creep on cracking resistance of repair materials.

Restrained shrinkage

Three restrained shrinkage tests were conducted as previously described. All materials except Nos. 10 and 12 exhibited cracking in the ring test because shrinkage strains induced during drying exceeded the tensile strain capacity at the time. In contrast to its good performance in the laboratory, Material 10 exhibited unsatisfactory crack resistance in the field tests. This poor performance is attributed in part to the highest coefficient of thermal expansion of all materials, a property that would be much more significant under widely varying field temperatures compared with controlled laboratory conditions. Material 12 exhibited good crack resistance in field tests.

The remaining materials exhibited first cracks in the ring test at ages ranging from 4 to 140 days. The average age at first crack of materials with acceptable field performance was 33 days. However, excluding Material No. 4, the ages at first crack ranged from 8 to 23 days with an average age of 15 days. In comparison, the average age at first crack of materials with unsatisfactory field performance was only 7 days.

The proposed performance criteria require that repair materials exhibit no cracking after 14 days of restrained shrinkage. Crack widths were measured periodically, and implied shrinkage strains were computed by dividing the sum of the crack widths by the circumference of the ring. Overall, there was a significant correlation between restrained shrinkage strains and both 28-day and peak values of unrestrained drying shrinkage. Also, there was a modest correlation between calculated strains and field performance (Figure 8). Implied strains for those materials with acceptable field performance ranged from 364 to 1,222 millionths, with an average of 752 millionths. In contrast, implied strains for those materials with unsatisfactory field performance ranged from 840 to 3,414 millionths with an average of 2,021 millionths. The proposed performance criteria limit implied strain to a maximum of 1,000 millionths at 1-year age.

In the German angle test, restrained shrinkage specimens were monitored for crack formation under laboratory and field-exposure conditions. Field test results indicate that the German angle test can provide a general assessment of a material's resistance to cracking when the test specimens are exposed to varying exposure conditions. Eight of the twelve materials exhibited cracks in field tests with this method.

In contrast to the field tests, none of the materials cracked when German angle test specimens were exposed in a controlled laboratory environment. Consequently, this test appears to offer minimal potential for prediction of field performance based on laboratory tests unless the anticipated service conditions can be simulated in the laboratory. Overall, there was no significant correlation between SPS plate test deflections measured in controlled laboratory conditions and field performance, although the trend was for improved field performance with decreasing deflection. However, excluding the materials that exhibited unsatisfactory performance in field repairs, there was a significant correlation between laboratory test results and field performance (Figure 9).

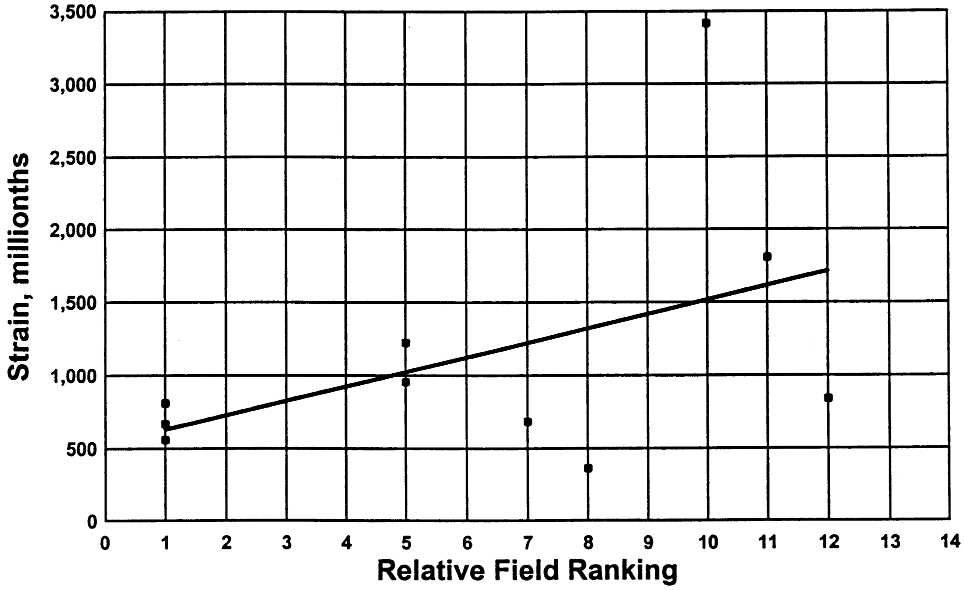

Figure 8. Correlation between restrained drying shrinkage and field performance

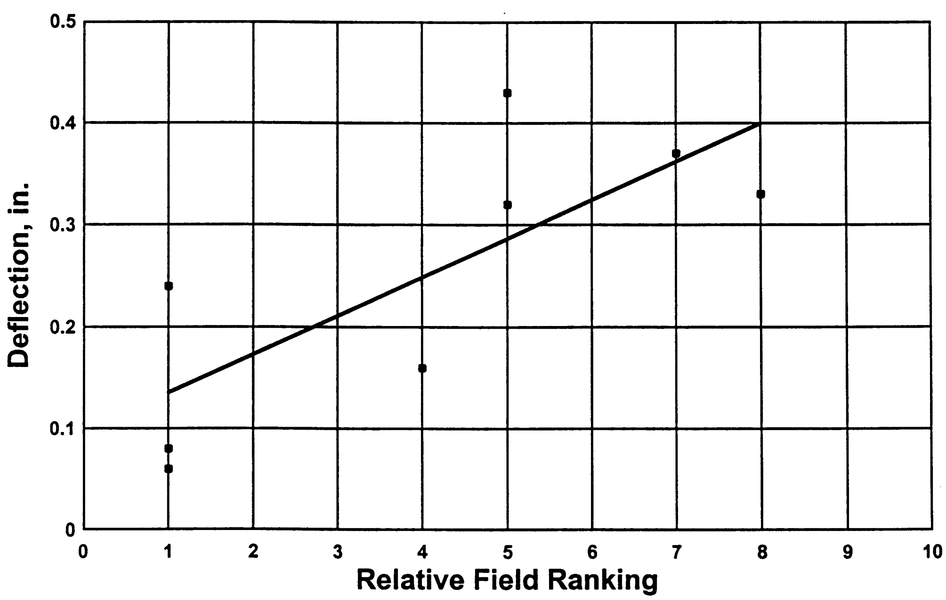

Figure 9. Correlation between SPS plate test results

There was a modest correlation between the results of plate tests conducted in the field and performance of field repairs. Excluding Material 5, which exhibited some cracking attributed to plastic shrinkage and thermal gradients, there was a significant correlation between field test results and performance of field repairs. Test results indicate that the plate test can be used for a general assessment of a material's dimensional compatibility, or resistance to cracking; however, modifications to specimen details and instrumentation are necessary to make this promising test more precise.

Conclusions

The results of laboratory and field-exposure tests were correlated to help develop performance criteria for the selection and specification of dimensionally compatible cement-based repair materials. These studies indicate that it is possible to predict the field performance of repair materials based on a combination of material properties determined in laboratory tests. The proposed performance criteria should be considered as a general profile of desired material properties. The relative importance of individual properties will vary, depending on the anticipated application and service conditions for a given repair. Therefore, the requirements should be modified as appropriate for a specific repair.

The general lack of significant correlation between individual material properties and field performance emphasizes the need for a comprehensive analytical model to predict the cracking resistance of repair materials. Also, there is a need for new or improved test methods whereby time-dependent strains induced by drying shrinkage and potential for cracking can be accurately quantified. Any such model or test method must consider the interrelationship of pertinent material properties and the relative importance of individual properties.

Ongoing research

The research needs identified in this study are being addressed by the Corps of Engineers' High-Performance Materials and Systems (HPM&S) Research Program. News about the Program is available online at ***http://www.wes.army.mil/SL/HPMS/hpms.htm***.

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