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High-Performance Materials and Systems Research Program

# Performance Criteria for Polymer-Modified Repair Materials

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**Synopsis:**

This paper describes research initiated by the U.S. Army Corps of Engineers to develop performance criteria for cement-based repair materials. In Phase I of the study, preliminary performance criteria for dimensionally compatible repair materials were identified based on a review of the literature. This review concentrated on identifying pertinent material properties, appropriate test methods, and demonstrated field performance. Laboratory and field exposure tests to evaluate the preliminary performance criteria were conducted in Phase II of the project. Of the 12 cement-based materials selected for this study, one-half contained polymer-modified cement. Results of laboratory and field tests were correlated to provide a basis for development of proposed performance criteria for the selection and specification of dimensionally compatible repair materials. Proposed performance criteria include a minimum value for tensile strength and maximum values for modulus of elasticity, coefficient of thermal expansion, and drying shrinkage. Also, resistance to cracking in restrained shrinkage tests is a requirement.

## INTRODUCTION

The unacceptably high failure rate for concrete repairs is a major problem in the repair industry. In many cases, failures are 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 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. Consequently, a comprehensive, multi-phase research program was initiated to develop performance criteria for the selection and specification of dimensionally compatible cement-based repair materials that will provide durable crack-free repairs.

The objective of Phase I of this study was to identify preliminary performance criteria for dimensionally compatible repair materials based on a review of the literature on cement-based repair materials. This review (Emmons and Vaysburd 1995) concentrated on identifying pertinent material properties, appropriate test methods, and factors affecting field performance of concrete repairs. Concurrent field and laboratory investigations to evaluate the preliminary performance criteria were conducted in Phase II of the project. Attempts were made to select 12 commercially available repair materials representing a wide range in composition and properties, particularly drying shrinkage, for laboratory and field tests. One-half of the materials contained polymer-modified cement. Results of all tests were correlated in a summary report (Vaysburd et al. 1999) to form a basis for development of performance criteria for cement-based materials. The objective of this paper is to evaluate the relative performance of cement-based repair materials with and without polymer modification.

## FIELD EVALUATION

The field evaluation study (Emmons et al. 1998) included repair of simulated spalls in precast concrete slabs and monitoring of material performance. The preformed repair cavities were 0.5 m (1.5 ft) wide by 1.8 m (6 ft) long and 76 mm (3 in.) deep. Each of the 12 selected materials was used to repair three cavities at each of three test sites. 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.

Overall, the 12 repair materials exhibited more resistance to cracking than was originally anticipated. Fine surface crazing of Material No. 8 in Florida, minor surface crazing of Material No. 9 in one repair in Florida, and minor surface deterioration of Material No. 12 in one repair in Illinois appear to be 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 of these six materials contained polymer-modified cement. One material of each type (Nos. 2 and 3) was 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. Three of these four materials contained polymer-modified cement.

## LABORATORY EVALUATION

Laboratory tests were conducted to determine pertinent properties of the concrete repair materials, particularly those properties affecting dimensional compatibility. The evaluation (Poston et al. 1998) included selected standard tests and nonstandard tests developed specifically to provide a basic understanding of restrained shrinkage in repair applications. Results of selected laboratory tests are summarized in Tables 2 and 3.

A restrained shrinkage test was conducted for comparison with the results of unrestrained drying shrinkage measurements in accordance with ASTM C 157 (Modified) (ASTM 1994). In the restrained-ring test, material was cast around a section of 254-mm (10-in.)-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. The two materials that did not crack contained polymer-modified cement. Implied strains were computed by dividing measured crack widths by the circumference of the ring.

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 drying 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 in an attempt to evaluate how individual material properties, or combinations of properties, affect the potential for cracking of field repairs.

Compressive strengths of the polymer-modified materials ranged from 28 to 67 MPa (4,060 to 9,760 psi) with an average strength of 42 MPa (6,110 psi). Compressive strengths of the materials without polymer modification ranged from 33 to 80 MPa (4,780 to 11,530 psi) with an average strength of 54 MPa (7,780 psi). 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, there was no significant correlation between compressive strength and dimensional stability of the field repairs (Figure 1). 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.

Direct tensile strengths of the polymer-modified materials ranged from 1.5 to 5.1 MPa (215 to 742 psi) with an average strength of 3.1 MPa (444 psi). Tensile strengths of the materials without polymer modification ranged from 0.6 to 3.1 MPa (93 to 451 psi) with an average strength of 2.3 MPa (334 psi). Overall, the trend was for improved field performance with increased tensile strength (Figure 2). However, there was a significant correlation between tensile strength and field performance for those polymer-modified materials that exhibited marginal and unsatisfactory performance (Figure 3). The proposed performance criteria (Table 4) require a minimum direct tensile strength of 2.8 MPa (400 psi).

Flexural strengths of the polymer-modified materials ranged from 1.0 to 5.6 MPa (139 to 805 psi) with an average strength of 3.1 MPa (453 psi). Flexural strengths of the materials without polymer modification ranged from 2.0 to 5.4 MPa (289 to 779 psi) with an average strength of 3.7 MPa (532 psi). The results of this study indicate that there was no correlation between flexural strength and field performance.

The modulus of elasticity of the polymer-modified materials ranged from 19 to 37 GPa (2.7 to $5.3 \times 10^6$ psi) with an average value of 25 GPa ($3.6 \times 10^6$ psi). Values for modulus of elasticity of the materials without polymer modification ranged from 19 to 41 GPa (2.7 to $5.9 \times 10^6$ psi) with an average value of 26 GPa ($3.8 \times 10^6$ psi). 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. Excluding Material No. 11, which exhibited a significantly higher modulus of elasticity compared with the other materials, there was a general correlation between modulus of elasticity and field performance for both types of materials (Figure 4). The proposed performance criteria limit modulus of elasticity to a maximum value of 24 GPa ($3.5 \times 10^6$ psi).

The coefficient of expansion of the polymer-modified materials ranged from 12.8 to 17.8 millionths/deg C (7.1 to 9.9 millionths/deg F) with an average value of 16.0 millionths/deg C (8.9 millionths/deg F). The coefficient of expansion of the materials without polymer modification ranged from 10.4 to 14.9 millionths/deg C (5.8 to 8.3 millionths/deg F) with an average value of 13.3 millionths/deg C (7.4 millionths/deg F). There was no correlation between coefficient of thermal expansion and field performance of the polymer-modified materials. Materials without polymer modification exhibited a slight trend toward improved field performance with decreasing coefficients of thermal expansion (Figure 5). Coefficients of thermal expansion, determined in accordance with ASTM C 531(ASTM 1994), were higher than anticipated and generally higher than those normally associated with concrete. The proposed performance requires that a repair material be thermally compatible with the existing concrete substrate. This criterion will generally limit coefficient of thermal expansion, determined in accordance with CRD-C 39 (USAEWES 1949), to a maximum of about 14 millionths/deg C (8 millionths/deg F).

The unrestrained drying shrinkage of polymer-modified materials ranged from 16 to 1,779 millionths with an average value of 529 millionths at 28-days age. In comparison, the unrestrained drying shrinkage of materials without polymer modification was significantly less, ranging from 178 to 429 millionths with an average value of 299 millionths. The peak drying shrinkage of polymer-modified materials ranged from 634 to 2,682 millionths with an average value of 1,183 millionths. The peak shrinkage of materials without polymer modification ranged from 366 to 1,032 millionths with an average value of 718 millionths. Overall, the trend was for improved field performance with decreasing values of both 28-day and peak drying shrinkage. Excluding the materials that demonstrated unsatisfactory field performance, there was a significant correlation between both 28-day and peak drying shrinkage and field performance (Figures 6 and 7). The proposed performance criteria limit drying shrinkage at 28-days age to a maximum of 500 millionths. In addition, the criteria limit the peak (ultimate) drying shrinkage to a maximum of 1,200 millionths at 1 year.

A restrained shrinkage test was conducted as previously described. All materials except Nos. 10 and 12 (both polymer-modified) 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 No. 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 to controlled laboratory conditions. Material No. 12 exhibited good crack resistance in field tests.

The remaining polymer-modified materials exhibited first cracks in the ring test at ages ranging from 4 to 17 days. The average age at first crack of materials with acceptable field performance was 12 days. In comparison, the average age at first crack of materials with unsatisfactory field performance was 6 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. There was a modest correlation between calculated strains and field performance (Figure 8). The proposed performance criteria limit implied strain to a maximum of 1,500 millionths at 1-year age.

Results of this study appear 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 general trend was for slightly improved field performance with decreased creep. These unexpected results are attributed in part to the generally higher drying shrinkage associated with the materials that exhibited high creep characteristics (Figure 9). 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.

## CONCLUSIONS

Laboratory and field exposure tests were conducted and the results were correlated to provide a basis for development of 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.

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c. ASTM C 531, "Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts and Monolithic Surfacings."

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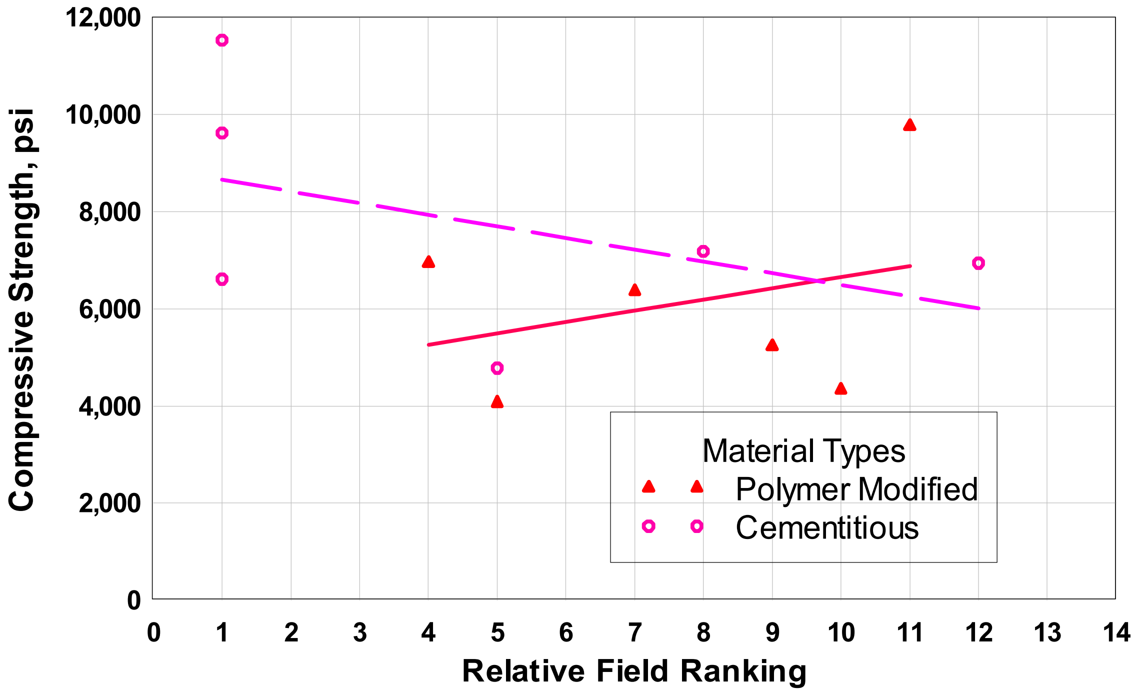


**Figure 1. Correlation between compressive strength and field performance**

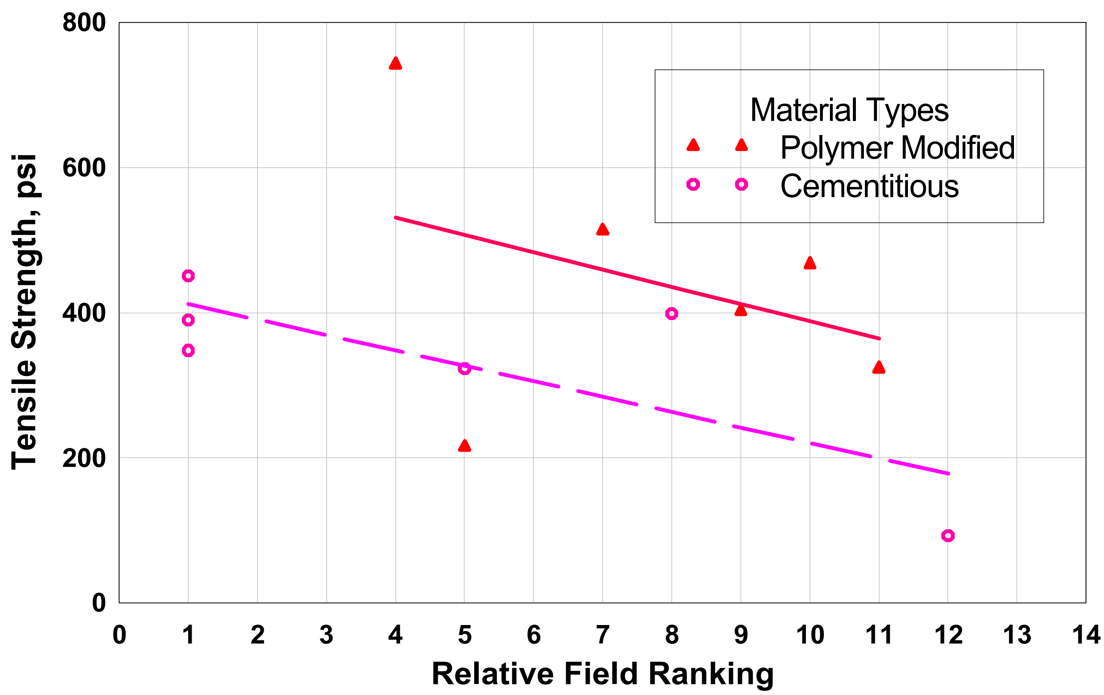


**Figure 2. Correlation between tensile strength and field performance**

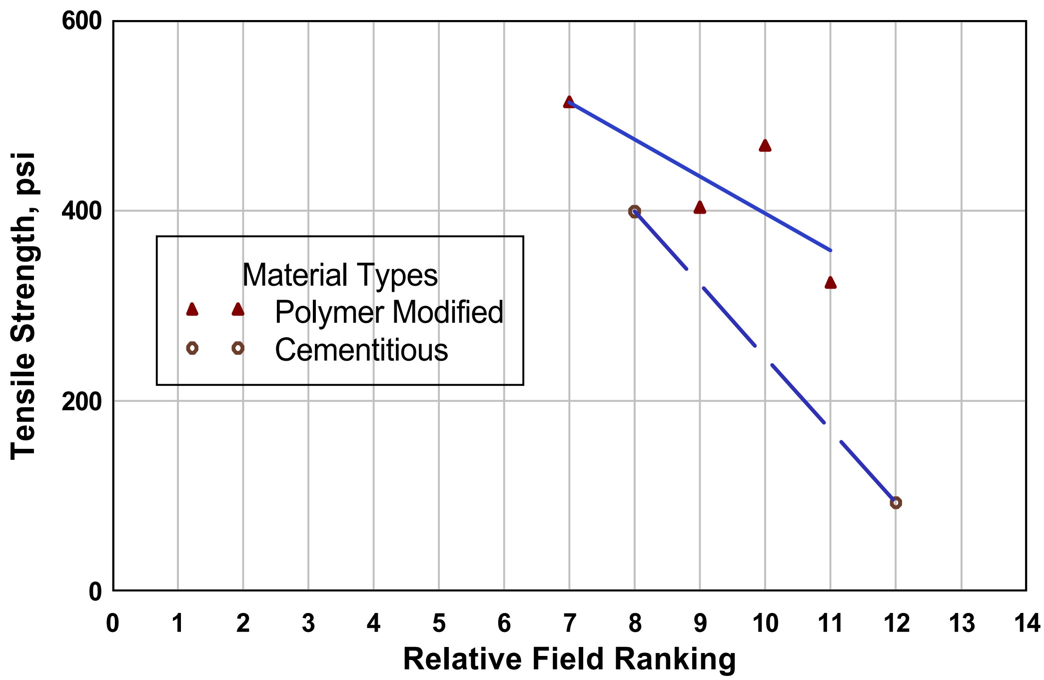


**Figure 3. Correlation between tensile strength and field performance of marginal and unsatisfactory materials**

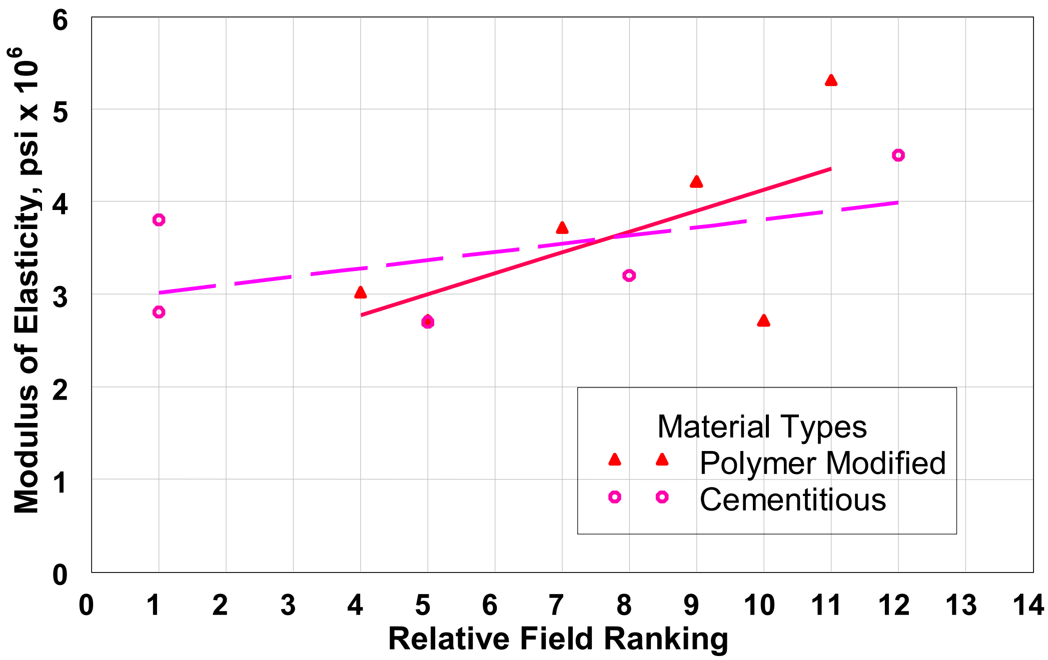


**Figure 4. Correlation between modulus of elasticity and field performance excluding Material No. 11**

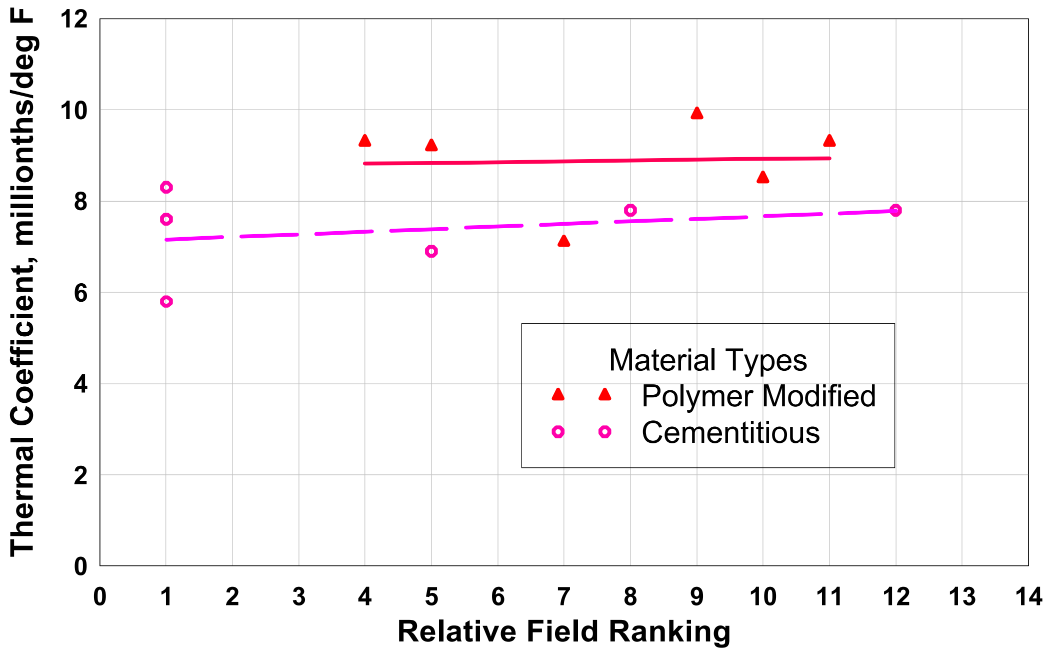


**Figure 5. Correlation between coefficient of thermal expansion and field performance**

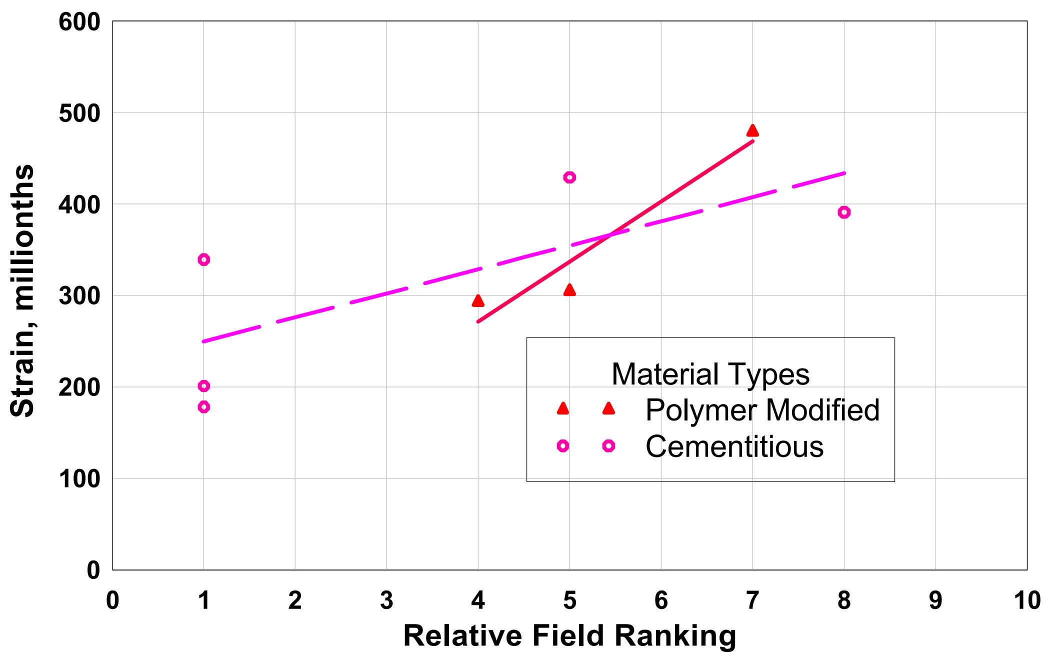


**Figure 6. Correlation between 28-day drying shrinkage and field performance of acceptable materials**

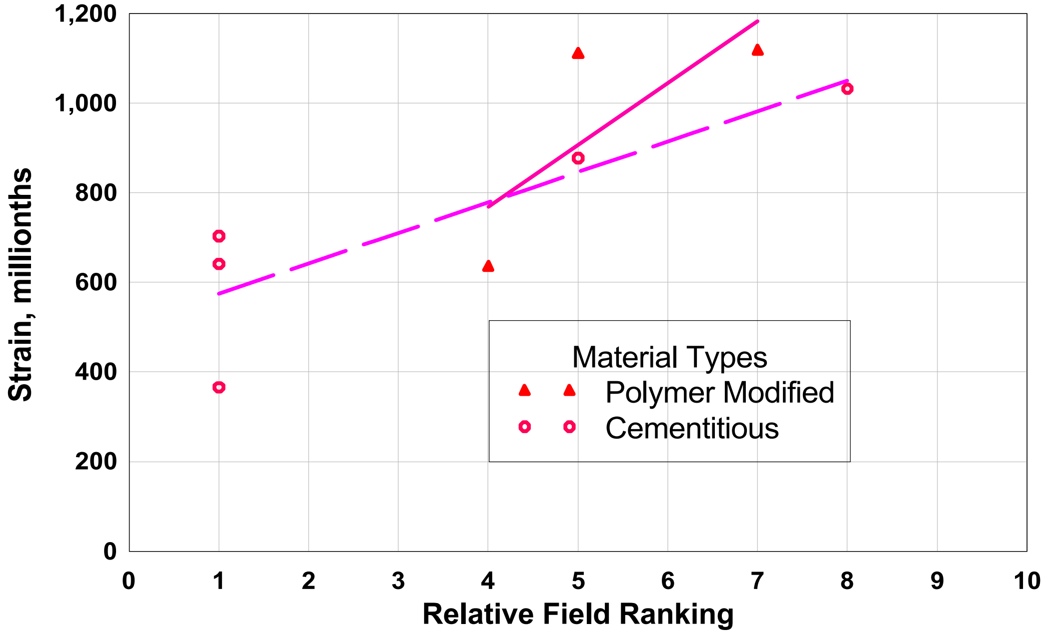


**Figure 7. Correlation between peak drying shrinkage and field performance of acceptable materials**

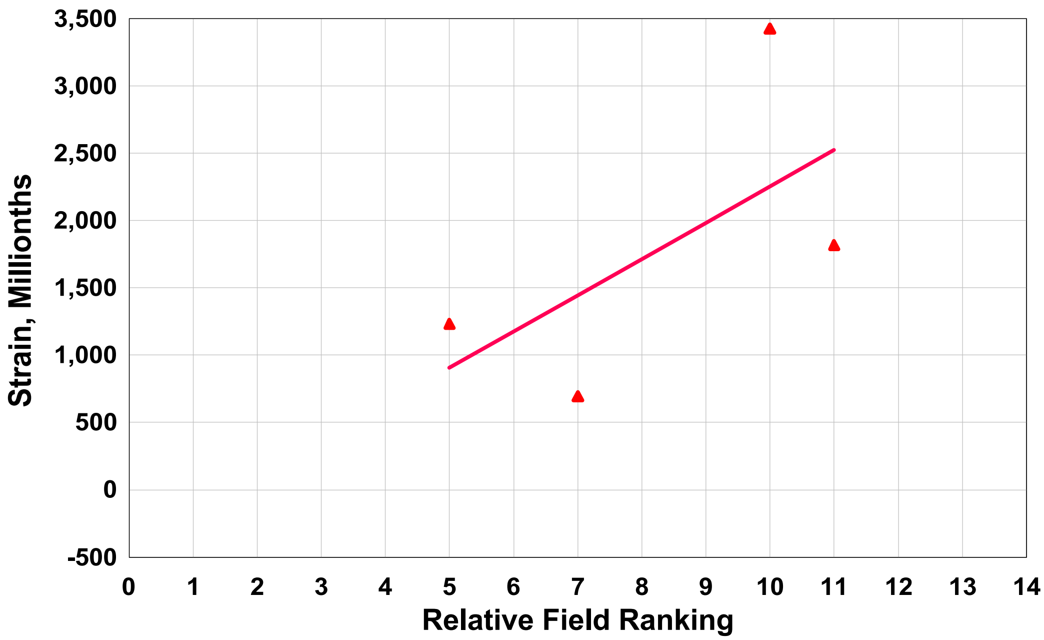


**Figure 8. Correlation between implied strain and field performance of polymer-modified materials**

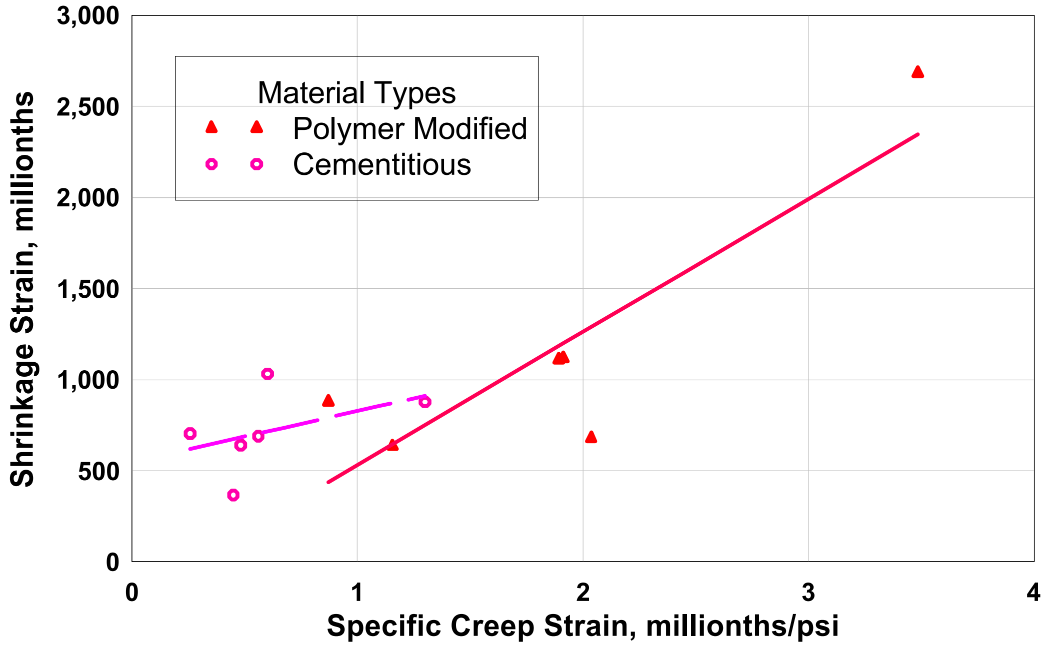


**Figure 9. Correlation between peak drying shrinkage and compressive creep**