Physical Properties and Characteristics Affecting the Sensitivity to Cracking of Cementitious Repair Materials

Keywords: coefficient of thermal expansion; cracking; creep; dimensional compatibility; drying shrinkage; durability; elastic modulus; physical properties; repair material; tensile strength.

Question:

What properties and characteristics of cement-based repair materials influence cracking in repairs?

Discussion

One of the main factors assuring the durability and long-term performance of concrete repairs is its resistance to cracking. Cracks are open pathways providing aggressive agents easy access into the repair, promoting the development of reinforcement corrosion and deterioration of the repaired structure (Vaysburd 1995; ACI 224.1R). Repair materials typically crack as a result of restrained volume changes. To achieve dimensional compatibility and minimize cracking in repairs, the relevant physical properties and characteristics of the repair material should be appraised during the selection process, notably in the case of cement-based repair materials. The cracking sensitivity of concrete repairs is also influenced by factors such as surface preparation; patch geometry; and presence of reinforcing steel, placement conditions (notably the temperature and relative humidity of both the existing concrete and ambient air, which may result in significant gradients within the repair), curing, and expansive forces in the existing concrete, which are addressed elsewhere and not discussed herein.

Structural and nonstructural repairs are considered in this discussion. Structural repairs are intended to increase the load-carrying capacity of a structural component beyond its current capacity or to restore a damaged structural component to its original design load-carrying capacity. For example, repairs to structural elements such as columns subjected to applied loads should accommodate these loads. Conversely, protective repairs performed to reestablish the original configuration without altering the structural capacity of a member are generally defined as nonstructural. Nevertheless, in ACI 562, the definition of a structural repair has been widened to include any repair that creates an unsafe condition in the event it fails, irrespective of the structural capacity consideration.

Cracking caused by restrained contraction occurs when the induced tensile stress exceeds the tensile strength of the repair material. External and internal restraint conditions that induce tensile stresses that can lead to cracking are discussed in ACI 207.2R and ACI 224.1R. Restrained contractions that can induce cracking are primarily caused by shrinkage and thermal volume changes. In the case of cementitious repair materials, these volume changes may occur individually or in combination, while the material is in either a plastic or hardened state.

The magnitude of shrinkage is generally the dominant factor, but not the only factor affecting the cracking sensitivity of a repair material. The other important factors and characteristics interplaying in the overall cracking behavior of the material are (Vaysburd et al. 1999, 2000, 2014; McDonald et al. 2002; Bissonnette et al. 2015; Courard et al. 2015):

a) Degree of restraint
b) Tensile strength
c) Modulus of elasticity
d) Creep
e) Coefficient of thermal expansion

The combination of properties that are most desirable to reduce the advent of cracking in cement-based materials can be lumped into the single notion of extensibility (Mehta and Monteiro 1993), which corresponds the sum of their short-term (elastic) and long-term (creep) tensile strain capacity. Cement-based materials with a high degree of extensibility can resist volume changes (deformations) without cracking. Therefore, to limit the potential for cracking, cement-based repair materials should have low shrinkage, and should also exhibit as much extensibility as possible, through a combination of low elastic modulus, high creep, high tensile strength, or all these.

Overall, the requirement for long-lasting monolithic behavior is that the repair materials have properties and dimensional behavior that will make them compatible with the existing concrete substrate for the application considered. Dimensional compatibility is defined as a balance of strains between a repair material and the existing substrate, such that the composite repair system withstands all stresses induced by the various volume changes without distress and deterioration over a designed period of time.

A comprehensive investigation conducted by the U.S. Army Corps of Engineers (Vaysburd et al. 1999; McDonald et al. 2002) evaluated the relationship between these properties, characteristics, and the repair material's field performance with respect to crack resistance. While the results did not reveal conclusive trends when considering the properties and characteristics individually, a correlation with the cracking sensitivity was found when considering them together. The in-depth analysis of the data generated in both laboratory and field experiments led to the identification of preliminary performance criteria for the most influential repair material properties and characteristics. The relative importance of the latter varies depending on application and service conditions; therefore, the requirements should be modified as necessary to achieve compatibility with the existing substrate.

Tensile strength—Intuitively, the easiest way to improve the resistance of cementitious materials to cracking would be to achieve substantially high tensile strength. In reality, because the tensile capacity of cement-based materials cannot be increased substantially, the primary goal should be to reduce tensile stresses to minimize cracking. Nonetheless, it was concluded in the study by the U.S. Army Corps of Engineers (Vaysburd et al. 1999; McDonald et al. 2002) that the tensile strength of the repair material should be a minimum of 400 psi (2.8 MPa). Such a value would be expected for conventional concrete with a compressive strength of approximately 4000 psi (28 MPa).

The term "tensile strength" has no absolute meaning for cement-based materials and needs to be expressed in terms of the specific test procedure used. Three types of tests are primarily used for cementitious materials tension testing: the direct tension test, the flexural test, and the splitting tensile test. The direct tension test is challenging to perform because of the inherent difficulty of ensuring that the load is truly axial. In a ductile material, some eccentricity will not have much effect on tensile strength, but in brittle cementitious materials, there is relatively little stress redistribution and, consequently, the test gives an underestimate of true tensile strength. Still, when properly conducted, a direct tension test such as the one described in the USACoE CRD-C 164 procedure yields a more representative measure than indirect methods. The results from the flexural strength or beam test (modulus of rupture) and the splitting-strength test are both known to overestimate the tensile strength of the material. Data by Price (1951) demonstrate that flexural strength testing tends to overestimate the tensile strength of concrete by 50 to 100 percent. Despite their simplicity, the indirect tests fail to reproduce the state of stress developed within a centrically tensioned specimen and, consequently, the values of the corresponding strengths differ from the pure tensile strength values.

The compressive strength of a repair material intended for structural repair should ideally be similar to that of the existing concrete. Generally, it is not desirable to have repair materials with compressive strengths in excess of 4000 psi (28 MPa) for nonstructural repairs. Rather, it is generally agreed that high-strength repair materials are more prone to cracking because of high stresses developed from restrained shrinkage, as a result of typically high elastic modulus and lower creep. In addition, the use of rapid-setting materials to achieve high early strength often leads to increased cracking because of higher early-age volume changes, increased stiffness, and less creep.

Modulus of elasticity—In a repair, the modulus of elasticity controls, to some extent, the load sharing between the repaired area and the rest of the element, as well as the level of tensile stress generated due to volume changes such as shrinkage and thermal deformations. For structural repair, the modulus of elasticity of the repair material should be compatible with that of the existing concrete. Conversely, it was concluded in the USACoE CRD-C 164 investigation that the modulus of elasticity of materials for nonstructural repairs, determined in accordance with ASTM C469/C469M, should be specified not to exceed 3.5×10^6 psi (24 GPa).