Compatibility Considerations for Durable Concrete Repairs

P. H. EMMONS AND A. M. VAYSBURD

Concrete repair and rehabilitation will have an even more vital role in the future than it does now. Major reconstruction of our aging infrastructures can no longer be delayed. Critical to achieving long service life of repaired structures is the correct choice and use of materials. Evaluation of materials by research and testing falls far behind the development of new products. Regrettably, design professionals still do not fully understand such aspects of their medium as (a) the importance and meaning of compatibility between repair materials and existing substrate and (b) the considerable differences between the properties measured by existing standard methods and the properties of the same materials in situ. The designer and prospective user of materials are not equipped with performance criteria that provide a rational analytical tool for selecting the appropriate materials for a particular repair in a specific environment. Without such criteria, durable concrete repair is more of an art than a science. Compatibility, the most important factor determining the durability and structural effectiveness of concrete repairs, is defined and discussed; drying shrinkage, one of the decisive components of compatibility, is discussed in detail. A ranking system that would help in the selection of repair materials with a lower risk of shrinkage stresses, cracking, and debonding is proposed. In conclusion, there is an urgent need for development of performance criteria for the selection of compatible repair materials, along with the selection or development of a reliable industrywide shrinkage test method.

Many papers and reports during the past few years have described the condition of our nation's infrastructure. The rapid growth in construction of highways, bridges, and airports during the 1950s and 1960s has significantly slowed, and the rehabilitation, reconstruction, and repair of existing structures will consume a growing share of our efforts.

Concrete repair and restoration is considered the growth sector of the construction industry of the 1990s. It was recently estimated that nearly $50 billion will be needed to repair or restore currently deficient bridges in the United States. Repair of buildings, parking structures, and other concrete structures will substantially increase this figure.

Even though concrete repair is a growth industry, there is no great increase in the number of durable concrete repairs being performed. However, more people are devoted to concrete repair research and more contractors are dedicated to repair, rehabilitation, and reconstruction.

The quality and maintenance of our 21st-century infrastructure will depend on our ability to properly design, specify materials, and construct to ensure the long-term performance of repaired concrete structures. Most people concerned with long service life of concrete repairs simply use the rule of trying to determine what materials and proportions and construction practices had previously been used successfully in a comparable exposure. There is an attempt to duplicate—or at least simulate—those materials, without understanding in particular detail why these materials and methods yielded a durable repair.

Structural Preservation Systems, Inc., 3761 Commerce Drive, Suite 414, Baltimore, Md. 21227.

Indeed, we do have successful repair projects where, to paraphrase the late Robert Philleo (*1*), reliance was placed on assumption, and assumption was based on intuition, available properties, and test results. Painful experience, however, has proved that knowledge is preferable to assumption.

The theories of durable repair have been derived, probably for as long as we have used concrete, from observations and through trial and error, with both good and bad results. Theoretically, we can predict the probability that a repair will withstand the complex forces and elements acting on it. Practically, we do not have enough reliable information to select correctly a repair system required to oppose the destructive stresses from volume changes and environment. Today, the field of concrete repair cannot give the complete answer to the engineer's problem and satisfy the main requirement of the task: to design a durable repair.

The phenomenal explosion of proprietary repair materials and systems has increased the complexity of material selection and the risk of failures. Evaluation by research and testing falls far short of the development of new products. Regrettably, design professionals still do not fully understand their medium. There is a lack of understanding of (a) the importance and meaning of compatibility between repair materials and existing substrate and (b) the considerable differences between the properties measured by current standard tests and the properties of the same materials in situ.

The designer and prospective user of materials are not equipped with a rational analytical tool for selecting the appropriate materials for a particular repair in a specified environment. This tool can be achieved by developing performance criteria for selection of repair materials. Without such criteria, durable concrete repair is more of an art than a science.

In any examination of the durability of concrete repairs, it is important to distinguish between two elements of durability: the selection of repair material and the production of a durable repair.

The topic of durability of concrete repair is too broad to be presented in a single paper. This paper, therefore, will be limited to reviewing one problem aspect of repair: compatibility. This paper is an attempt to characterize compatibility between repair materials and existing concrete and its relative contribution to durability.

COMPATIBILITY OF REPAIR MATERIALS AND EXISTING CONCRETE

The term "compatibility" has become very popular in the field of concrete repairs. Then why do we not normally specify compatibility as the primary factor of concrete repair durability, other than because it is not traditional to do so? There are probably four reasons:

1. Lack of clear definition of compatibility;
2. Absence of performance criteria for selecting materials on the basis of compatibility;
3. Lack of reliable industrywide, easy-to-use test methods for evaluating different components of compatibility; and
4. Lack of correlation between laboratory test results and expected in situ performance.

Compatibility is always associated with the repair durability in general and with the load-carrying capacity of structural repairs. Durability and compatibility are defined in this paper as they relate to concrete repairs. Durability is the capability of a repaired structure or its components to maintain serviceability over a designed period of time in a specified environment. Compatibility may, in general, be defined as the balance of physical, chemical, and electrochemical properties and dimensions between repair material and existing substrate that ensures that the repair withstands all anticipated stresses induced by volume changes, chemical and electrochemical effects without distress, and deterioration over a designed period of time (Figure 1).

The compatibility of materials and sections is a complex subject with many facets. However, dimensional compatibility (the phenomenon of volume instability) is a major problem of concrete repair. Dimensional incompatibility impairs the durability and load-carrying capacity of structural repairs. In structural repairs, dimensional incompatibility may lead to an inability to carry the expected proportion of the load and would not necessarily affect durability.

Chemical compatibility properties include alkali content, C_3A content, and chloride content; electrochemical compatibility properties include electrical resistivity and pH. Failure to take into account each of these items may harm the durability of repairs.

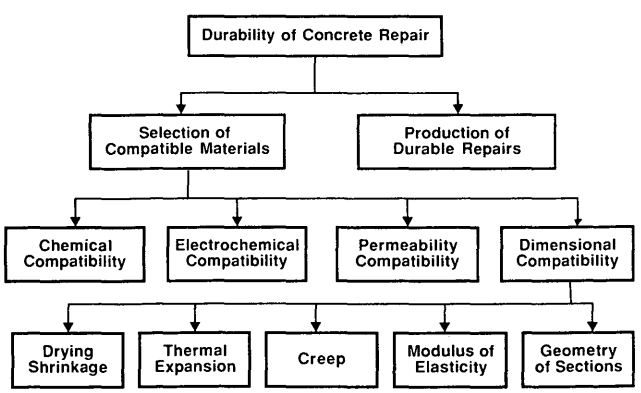

FIGURE 1 Factors affecting durability of concrete repair.

All aspects of chemical compatibility must be considered when selecting materials. For instance, when concrete being repaired includes potentially reactive aggregates, a repair material with low alkalinity must be specified.

For each reinforced concrete repair case, electrochemical compatibility must be considered and the electrochemical behavior of local (substrate) and potential (repair material) macrocell must be evaluated. For instance, in some cases, the repair material must be able, as in concrete, to passivate the steel at pH values of about 12.5 and to bind small amounts of chloride ions in the C_3A. Unfortunately, ignorance of electrochemical compatibility during attempts to repair deteriorated structures and prevent further corrosion has actually caused disastrous failures. For example, applying a surface repair to a portion of a potentially anodic area can increase the cathode/anode area ratio, accelerating the corrosion process. Protecting the cathodic area, where moisture and oxygen should be restricted, would be the proper solution. In another example, macrocells can be introduced inadvertently during the repair of a spalled area. The deteriorated concrete is removed from the spall or delamination and replaced with non-chloride-contaminated concrete. In many instances, the surrounding concrete is contaminated with chlorides. The result is a macrocell in which the rebar around the perimeter of the repair is the anode and the rebar in the repaired area provides a large cathode. A delamination occurs either adjacent to the repair or completely around it (*2*).

It is thought that extremely low permeability is very desirable for repair material, which is not true for all cases. This generally accepted concept can, in some cases, lead to a false sense of security and unsuitable materials incapable of providing lasting performance. Following is an example of unsuccessful use of a low-permeability repair material. The problem occurred where latex-modified shotcrete was used around the pier cap to repair initial damage from deicing salts; however, the top of the cap was not protected and the source of the salt and moisture penetration not eliminated. In this case, an even more severe attack on the reinforcement with subsequent steel corrosion and spalling can develop. Water with deicing salts on the bridge deck drips onto the pier cap, penetrates it, and is unable to escape. Without such a repair, continued deterioration could have been expected, but with the repair it was accelerated and intensified (*3*). The lesson from this example is that in some cases, the selection of low-permeability repair materials not compatible with existing concrete may lead to failure. It is important to note that a few through cracks in the repair, or its debonding, will drastically offset the benefit of having a repair material with very low permeability. In the cases discussed, repair materials with permeability compatible with the existing concrete should have been specified and used.

As was indicated earlier, compatibility is a prime factor related to durability of concrete repairs. Dimensional compatibility, as can be seen from the chart in Figure 1, is an element of fundamental importance.

DIMENSIONAL COMPATIBILITY

Material properties that influence dimensional compatibility include drying shrinkage, thermal expansion, modulus of elas-

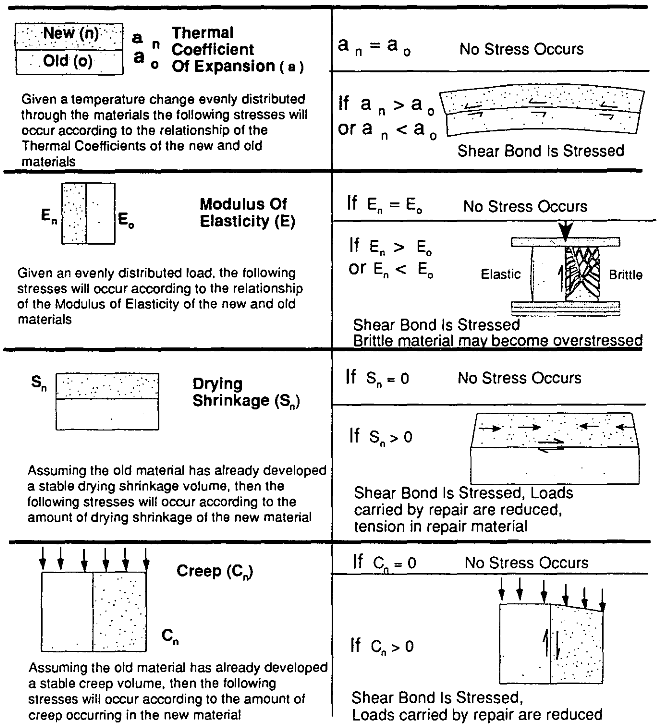

FIGURE 2 Volume change effects on repair.

ticity, and creep. Many materials change volume as they initially set, and practically all of them change volume with moisture and temperature changes. Tensile stresses are induced in one material, compressive stresses in the other; as a result, a substantial shear will occur at the interface. Identical stresses will result from the differential thermal shrinkage and moduli of elasticity (Figure 2) (*4*).

When polymer concretes are used for thick concrete repairs, often the result is distress caused by significant differences in the shrinkage and mechanical and physical properties of the two materials. For example, the flexural modulus of elasticity of an epoxy mortar is about 6.9×10^6 KPa (10^6 psi), and that of the base concrete is 3.1×10^7 KPa (4.5×10^6 psi). (*5*). If a repair with such an epoxy mortar is thick and continuous, tensile stresses induced by cycling of temperature will cause cracking. The volume change from the wetting and drying of the concrete can increase the stress.

Restrained contraction of repair materials—the restraint being provided through the bond to the existing concrete substrate—significantly increases the complexity of repair projects as compared with new construction. Volume changes cause contractions that often result in cracking and debonding of the repair section. Therefore, the specified repair materials must be dimensionally compatible with the existing concrete substrate to minimize the potential for cracking and delamination as a result of restrained contraction.

The stress states that develop at the subsequent bonds vary considerably depending on the type and use of the structure. For example, the bond on a bridge deck overlay may be subject to shear stress in conjunction with tensile or compressive stresses induced by shrinkage or thermal effects, in addition to compression and shear from service loads.

Table 1 indicates typical differences in some of the important short-term properties of repair materials (*6*). Differences in properties will always exist between the repair material and the substrate concrete, regardless of the material. Even by using concrete as a repair material, it is impossible to match all properties because at the time of the repair a large percentage of the ultimate shrinkage has already taken place. And do we need to match the properties of two materials in a composite structure? The temptation to seek parity of properties of the repair materials and base concrete is strong, but attempts to avoid mismatches founder on the definition of compatibility (*7*). The real requirements for durable and structurally adequate repairs are clearly spelled out in the definition of compatibility.

TABLE 1 Typical Short-Term Properties of Repair Materials

Property	Resin Mortar	Polymer modified cementitious mortar	Plain cementitious mortar
Compressive strength (MPa)[a]	50-100	30-60	20-50
Tensile strength (MPa)	10-15	5-10	2-5
Modulus of elasticity in compression (MPa)	$(10\text{-}20) \times 10^3$	$(15\text{-}25) \times 10^3$	$(20\text{-}30) \times 10^3$
Coefficient of thermal expansion (mm/mm/ °C)[b]	$25\text{-}30 \times 10^{-6}$	$10\text{-}20 \times 10^{-6}$	10×10^{-6}
Water absorption (% by weight)	1-2	0.1 - 0.5	5-15
Maximum service temperature (°C)[c]	40-80	100-300	>300

[a] 1 MPa = 145.0326 psi
[b] mm/mm/°C = 0.56 in./in./°F
[c] °C = (°F-32)/1.8

Selecting repair materials on the basis of compatible thermal coefficients and moduli of elasticity is relatively simple because they are known quantities. Shrinkage, however, is not easy to deal with. Selecting repair materials on the basis of minimal shrinkage requires an understanding of the shrinkage processes. Volume changes accompany the loss of moisture from either fresh or hardened cementitious materials. The term "drying shrinkage" is generally used for hardened material. The term "plastic shrinkage" is used for fresh material since its response to loss of moisture is quite different. "Carbonation shrinkage," which occurs when hydrated cement reacts with carbon dioxide from the atmosphere, can be regarded as a special case of drying shrinkage. Shrinkage is only a cement paste property: any aggregates and reinforcing components in the material have a restraining effect on the volume changes.

Loss of water from fresh repairs, if not prevented, can cause cracking. The most common situation is surface cracking due to the evaporation of water from the surface. Suction of water from the repair by the substrate can also cause cracking or add to the effects of surface evaporation. When the water is removed from the cementitious paste by evaporation, a complex series of menisci is formed. These, in turn, generate negative capillary pressures, causing the volume of the paste to contract. The effects of plastic shrinkage are not uniform throughout the material and are restrained at the interface. Differential volume changes can also cause cracking under induced tensile stresses.

Plastic shrinkage cracking is most common on horizontal surfaces of repair, where rapid evaporation occurs. Its occurrence affects the integrity of the repair and reduces its durability. Plastic shrinkage may be aggravated by special environmental conditions such as a combination of high wind velocity, low relative humidity, high air temperature, and a high temperature of the repair material. The most effective way to control plastic shrinkage is to ensure that the surface of the repair is kept moist until it has been finished and curing has begun.

In our view, perhaps the most significant property with regard to dimensional compatibility is drying shrinkage. Shrinkage, as related to the cementitious and polymer-modified cementitious repair materials, is discussed not only because of its importance for compatibility, but also because it is the most ignored property in published research literature on repair materials.

Drying shrinkage of hardened material is a much more important and critical phenomenon than plastic shrinkage. It should be emphasized, however, that the fundamental processes underlying drying shrinkage are yet to be fully understood. About 70 percent of the ultimate drying shrinkage occurs in the first 30 days.

Tensile stresses begin to accumulate in the repair material when shrinkage begins. As shrinkage stresses accumulate, the repair material resists cracking until the stress exceeds the tensile capacity of the repair material (Figure 3). The phenomenon of repair distress is triggered by the stress concentrations at the interface—a region in which the probability of failure is higher than in the material itself.

The load-carrying capacity of the new repair material does not come into play when the repair material fails to fill the cavity as designed because of the effects of drying shrinkage.

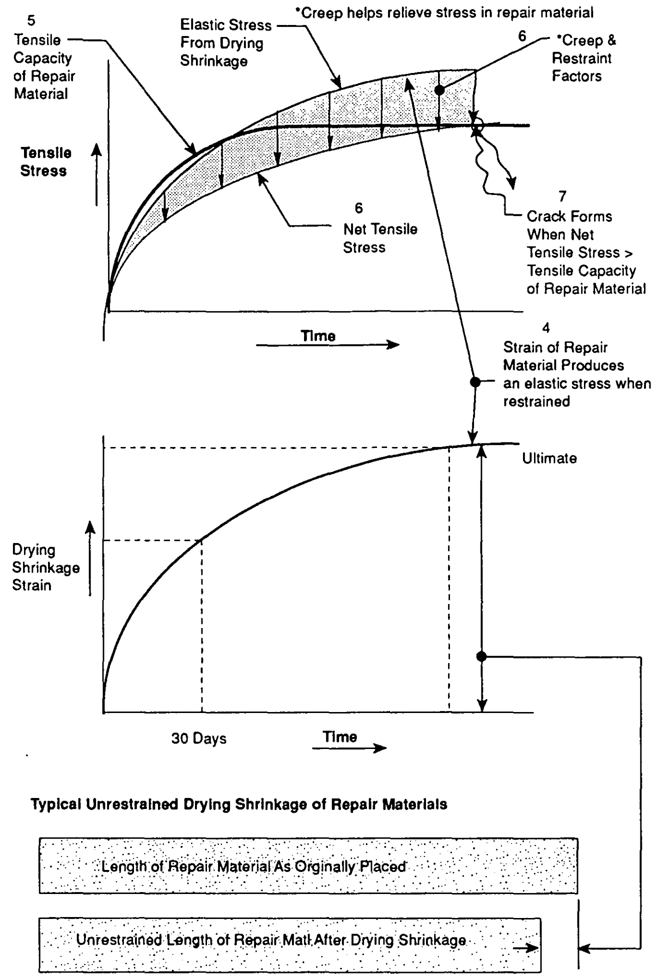

FIGURE 3 Drying shrinkage effects on repair.

Figure 4 shows the stress distribution around a new repair that does not carry its part of the load.

The effect of a repair under load is very important. The behavior of small surface repairs introduced to restore durability to the member is likely to be influenced considerably by the deformation of the surrounding steel and concrete. Here, the strain capacity of the repair material rather than its ability to carry stress is of prime importance. With larger structural repairs where a contribution to member stiffness is required, the repair material must possess properties that ensure not only that it stays in place to protect the steel but also that it is able to resist stress for the subsequent design life of the structure. In both contexts, the effect of repair under load is important (*6*).

The desirable shrinkage of repair material for satisfactory performance should be 0.00 percent. But what is the acceptable value of low shrinkage, and how do you select repair materials with low shrinkage? Parameters must be established to define shrinkage for repair materials.

In 1987 Alberta Transportation and Utilities conducted an evaluation program for concrete patching materials (*8*). In this study, 46 repair materials were evaluated for various properties, one of which was drying shrinkage. The ASTM C157 shrinkage test was used to determine individual values,

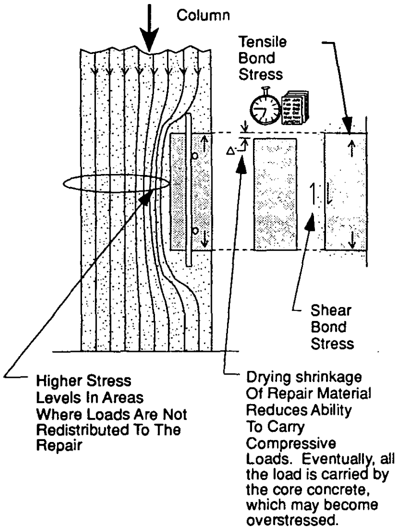

FIGURE 4 Stress distribution around the repair not participating in load sharing.

and all the tests were performed by one independent laboratory. Figure 5 presents a diagram of the results of the shrinkage testing sorted from the lowest shrinkage on the left to the highest shrinkage on the right.

By sorting the test results from low to high shrinkage, a cross section of the industry's repair materials was available for comparison. The study yielded a surprising result: the shrinkage of most of the repair materials far exceeded the shrinkage value of normal concrete: 0.05 percent at 30 days (*9*,p.2). The percentages of shrinkage do not sound large, but their effects are dramatic. Restrained shrinkage induces tensile stress. Most repair materials have a tensile capacity of 1.4 to 6.9 MPa (200 to 1,000 psi), depending on age and design. Shrinkage of 0.025 percent translates into 6.9 MPa (1,000 psi) tensile stress assuming an elastic modulus of 27 480 MPa (4,000,000 psi).

Today the industry cannot require the manufacturers of repair materials to meet a certain maximum shrinkage value because the basis for acceptable shrinkage value has not been established. ASTM C928-91 provides physical requirements for packaged cementitious concrete repair materials. This standard calls for shrinkage not to exceed 0.15 percent. According to the classification outlined in Figure 6, shrinkage of 0.15 percent is in the high range, being three times the shrinkage of normal concrete that is established as a benchmark in the classification. It is our opinion that repairs with such materials will be highly susceptible to excessive drying shrinkage stress, cracking, delamination, and failure.

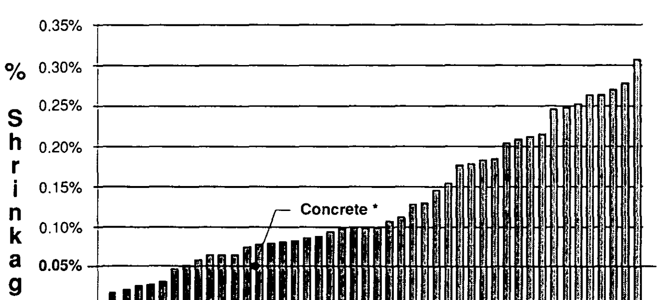

FIGURE 5 Repair material shrinkage test rests: ASTM C157 30- and 60-day results.

For purposes of this discussion, the presented classification materials are grouped into three basic categories of shrinkage:

- Low: less than 0.05 percent.
- Moderate: 0.05 through 0.10 percent
- High: more than 0.10 percent.

It is interesting that according to the classification, only 7 of the 46 repair materials tested (15 percent) can be labeled as low-shrinkage materials. It appears that many manufacturers of repair products are not designing for minimized shrinkage despite claiming that the materials are expansive, nonshrinking, or shrinkage-compensating.

A review of product data sheets indicates that compressive strengths of repair materials are unnecessarily high (Table 2). The excessive compressive strengths for some products may indicate excessive cement content. Although some products have a low water-cement ratio, they have significant shrinkage because shrinkage is proportional to both the cement content

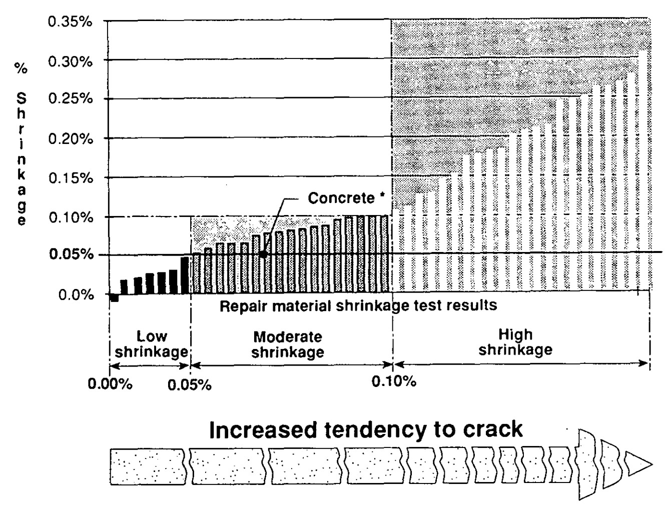

FIGURE 6 Classification of repair materials.

TABLE 2 Compressive Strength of Representative Surface Repair Materials

PRODUCT TYPE	COMPRESSIVE STRENGTH (28-DAY) MPa[a]
cast-in-place	48
trowel	41
cast-in-place	48
cast-in-place	76
trowel	47.9
cast-in-place	42
rapid set	58.6
shotcrete	76

and the total water content. Shrinkage is not eliminated or reduced by simply achieving a low water-cement ratio. Because of this, the typically high cement factors of repair materials are a disadvantage.

And what is the advantage of repairing the existing 24 MPa (3,500 psi) concrete of a deteriorated bridge pier with 48 MPa (7,000 psi) repair material? So that as the pier disintegrates with time, the patch will stay as a monument of the specifiers' incompetence?

METHODS OF TESTING

It was found that only limited properties are available from manufacturers' data sheets. Information about shrinkage is not even listed on some of them. To select materials for a particular application by comparing properties, and shrinkage in particular, the necessary data must be available.

Given a particular application, the relative merits of the materials available can be assessed objectively only if one standard method is used for testing. Manufacturers tend to use different tests and standards to evaluate the performance of their products. Many tests are modified; some are found to be deficient or to provide unrealistic results. It has become clear that test results must be examined critically to ensure their validity.

As a result of the arbitrary application of test methods, predicting the performance of many materials is uncertain. Our survey of material data sheets revealed that manufacturers used eight shrinkage test methods:

- CRD-C 621-82A
- ASTM C596
- ASTM C490
- ASTM C157
- ASTM C157 Dry
- ASTM C157 Modified
- Ring Modified
- DIN 52450

Variations in the techniques and conditions in each of these test methods—including restraint conditions, specimen dimensions, curing, temperature, time of initial readings, and test duration—make it impossible to interpret the comparative test results.

A study of the available test methods for properties that influence dimensional compatibility must be conducted to evaluate the existing repair methods, to identify their limitations, and, if necessary, to develop new test methods that will ensure that test results are reliable for predicting field performance of repair materials.

More research is needed on the long-term performance of repair materials in actual field conditions. The ultimate test of material durability is how it performs in the environment in which it has been placed. Laboratory tests should be used with extreme caution for predicting field performance of repair materials, because different scales of application and different environmental conditions may lead to damage by different mechanisms. Currently, no acceptable method exists for comparing the severity of different environments when different mechanisms may be responsible for damage. More research is needed to clarify compatibility of materials in various environments so that better comparisons can be made between the laboratory tests and expected field performance. This is especially important with the development of new materials that are significantly different from cementitious materials that have been used in the past to develop the current body of knowledge concerning the resistance of concrete to natural weathering. Finally, performance criteria and guide specifications for dimensionally compatible repair materials must be developed. There is a demonstrable need for such criteria to ensure dimensional compatibility and to provide durability for repair jobs.

CONCLUSIONS

1. As a prerequisite for concrete repair durability, clear understanding of compatibility between repair materials and the existing concrete is essential.
2. Drying shrinkage is one of the most important factors influencing dimensional compatibility. An investigation into the desirable shrinkage properties of various repair materials for satisfactory performance was undertaken. Materials are grouped into three basic classifications and shrinkage of concrete is taken as a benchmark.
3. Existing test methods and practices do not produce comparative shrinkage measurements due to variations in techniques and test conditions. The industry must choose or develop a test method that will ensure reliable test results for predicting the field performance of materials.
4. There is a need to integrate our knowledge and understanding of the compatibility of repair materials with existing concrete and to develop performance criteria to provide an engineer with the methodology of modeling for repair durability under various conditions of repair-environment interaction.
5. If the service life span expected on repaired structures is to be achieved, the construction of durable repairs is essential and it is vital for the engineer to apply engineering principles to the design and specification of repair materials just as it is done in designing structures and structural elements.

ACKNOWLEDGMENTS

The shrinkage classification presented is based on test results from an evaluation program carried out at the Research and Development Branch of Alberta Transportation and Utilities, Canada. The authors are grateful to Paul Carter for allowing them to use the results of the report.

REFERENCES

1. R. E. Philleo. A Need for In Situ Testing of Concrete. *Concrete International*, No. 9, Sept. 1979, pp. 43–44.
2. A. M. Vaysburd. Some Durability Considerations for Evaluation and Repair of Concrete Structures. *Proc., 2nd National Concrete Engineering Conference*, Chicago, Ill., 1992.
3. E. Schrader and R. Kaden. Durability of Shotcrete. *ACI SP-100: Katharine and Bryant Mather International Conference on Durability of Concrete*, Vol. 2, pp. 1071–1101.

4. P. H. Emmons. Selecting Concrete Repair Materials For Long-Term Durability Based on Available Test Data. *Proc., 2nd National Concrete Engineering Conference*, Chicago, Ill., 1992.
5. M. Schupack. Divorces and Ruptured Relations Between Epoxies and Concrete. *Concrete Construction*, No. 10, Oct. 1980, pp. 735–738.
6. G. Mays and W. Wilkenson. Polymer Repairs to Concrete: Their Influence on Structural Performance. *ACI SP-100: Katharine and Bryant Mather International Conference on Durability of Concrete*, Vol. 1, pp. 351–375.
7. D. R. Plum. The Behavior of Polymer Materials in Concrete Repair, and Factors Influencing Selection. *The Structural Engineer*, Sept. 1990, pp. 337–345.
8. *Alberta Concrete Patch Evaluation Program Report*. Report ABTR/RD/RR-87/05. Edmonton, Alberta, Canada, 1987.
9. Volume Change of Concrete. *Concrete Information*. Portland Cement Association, Skokie, Ill., Chapter 12 (revised).

Publication of this paper sponsored by Committee on Performance of Concrete.