EVALUATION OF REPAIR MATERIALS: ISSUES AND METHODS

S.R. Karade, R. Lakhani and K.K. Asthana

Organic Building Materials Division,

Central Building Research Institute, Roorkee –247667 (India)

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ABSTRACT

A variety of repair materials is available in the market. It is often difficult to select a suitable repair material for a given condition. Various researchers use different evaluation methods, but the required specifications are not established. Recently research has been carried out throughout the world to address this problem. This paper attempts to review these methods adopted so far to evaluate the repair materials and the suggested criteria for the selection of repair materials. The key issues involved and methodology are discussed and finally recommendations are made for selection of repair materials.

1. INTRODUCTION

Large numbers of ageing concrete structures are deteriorating due to various in-service and the environmental conditions they are exposed to. To restore their functioning and to enhance their lifespan these structures need suitable repairs. There are number of approaches adopted for repair and retrofitting of the deteriorated structures, such as: stitching, strengthening with panels, patch repair, structural repair, coating and so on. However, the repairs can be broadly classified in two major categories: structural and cosmetic. Structural repair is required to improve the load bearing capacity of structure or to bring it to at least its original load carrying capacity. Cosmetic repair, also called surface or patch repair, is necessary to protect the structure from detrimental elements and to improve aesthetics. For different types of repairs the selection of a suitable repair material is vital and needs a through understanding of the behaviour of the repair material under the service conditions.

The requirement of properties of materials for repair and retrofitting of concrete structures varies according to the properties of the base concrete and form of the repair i.e. structural or cosmetic. To achieve the desired properties in the repair material polymers are often used for most of the repair works. Polymers not only bring in many desirable properties like low shrinkage and good adhesion with the substrate, but they also increase the thermal expansion of the repair material. However, polymers are relatively costly material and therefore, optimum dose of the polymers is very important. By varying types of polymer or additives and their dose in a cement/polymer mortar a wide range of properties can be achieved. Evaluating the properties of various compositions of the polymer modified repair materials from the end use point of view optimisation of the different formulation is essential. For this purpose various researchers carry different types of tests often following dissimilar test methods. Presently, there is no standard code available specifically for repair materials because of diverse nature of the materials and varying requirements. However, professional societies or institutes like American Concrete Institute (ACI) provide some guidelines, which are quite useful [1]. Recently, in Europe standards are being prepared for this purpose [2].

The success of a concrete repair depends on several factors. Traditionally, high compressive strength and low permeability were considered for selection of repair material, but now shrinkage, creep, elastic modulus and tensile strength properties are also taken into account [3-9]. Efforts have been made to relate not only compressive strength but also properties like elastic modulus, shrinkage, thermal expansion and permeability with the performance of a concrete repair [3,4]. Despite all these efforts, there are several issues unresolved. For example, it is still not established what properties should be evaluated and what should be the minimum acceptable values to achieve an effective repair for different situations. What are the materials that meet these requirements? Do they perform in the same way in all weathering conditions, such as hot and dry or cold and wet, saline and industrial environment?

This article reviews the various test methods and requirements for the repair materials suggested by the researchers. The main issues involved in the selection of repair material and methodology are discussed. Finally, few suggestions are given in the form of recommendations.

2. REQUISITE PERFORMANCE

Various researchers have addressed the issue of the required performance of the repair material with respect to the substrate concrete [3, 10-13]. There seems to be an agreement that the repair material must have the dimensional, structural, permeability, chemical and thermal compatibilities with the substrate and therefore expected to meet the requirements given in Table 1. However, the methods for assessment of these compatibilities and the specification for repair materials are not yet established. Engineering materials are being tested for several tests, but all may not be relevant to the repair materials at different situations.

During the past two decades several researchers have attempted to evaluate different repair materials. They conducted different tests and followed different methods. Some of them are summarised in Table 2. The test methods followed by the researchers vary, particularly those followed in America and in Europe.

2.1 Dimensional compatibility

The dimensional compatibility is probably the most important compatibility parameter in selecting a suitable repair material. It refers to the capacity of the repair system to withstand the stresses generated due to the different volume changes in the applied repair material and the substrate. If there is no dimensional compatibility between the repair material and the substrate concrete, debonding between these two components may occur, which will cause delamination at the interface. The main elements that cause the dimensional problems are shrinkage (plastic, drying and autogenous) in the repair material, excessive expansion in shrinkage compensating materials and high thermal expansion due to change in temperature. The other parameters are the size, the shape & thickness, modulus of elasticity, strain capacity and creep of repair materials.

To ascertain dimensional compatibility different properties, such as shrinkage, thermal expansion and creep are measured and matched with those of the substrate concrete. The methods adopted to measure these properties are discussed in the following paragraphs.

Table 1 General requirement of patch repair materials [3, 13].

Property	Relationship of repair material (R) to concrete substrate (C)
Strength (Compression, Tensile and Flexural)	R>C
Modulus of Elasticity (Compression, Tensile and Flexural)	R≈C
Creep coefficient (for repair in compression)	R<C
Creep coefficient (for repair in tension)	R>C
Strain capacity	R>C
Adhesion	R>C
Thermal expansion coefficient	R≈C
Shrinkage strain	R<C
Porosity and receptivity	R=C
Fatigue performance	R>C
Chemical reactivity	R<C

2.1.1 Drying shrinkage

Shrinkage refers to the decrease in length or volume of a material due to drying and chemical changes. Very high shrinkage of a repair mortar causes cracking and most of the failures. Cementitious mortars considerably shrink due to loss of moisture. This problem is being increasingly recognised worldwide.

Very low shrinkage cementitious mortars for concrete repair have been developed for this reason. Specifications that deal with shrinkage and compatibility factors have now appeared in several countries.

For measurement of drying shrinkage prismatic specimens are moulded and the change in length is monitored under the predetermined test conditions. A method is given in ASTM C 157-93 for determination of length change in hardened cement mortar and concrete. Nevertheless, researchers often use their own methods also. Mirza *et al*. [9] used six prismatic specimens made of the repair material of size 25 x 25 x 285 mm under dry (three specimens at 23 ºC and RH 100% for two days and then at 23 ºC and relative humidity (RH) 50% for next 26 days) and wet curing conditions (three specimens at 23 ºC and RH 100% for 28 days). The length measurements were taken at 1, 3, 7, 21 and 28 days. Postan *et al.* [8] determined the drying shrinkage under different RH– 20, 50 and 90% on 76 x 76 x 286 mm sized specimens following ASTM C 157-93. Besides these, various other sizes and shapes are also used. For example, Mangat and Limbachiya [5] tested beams of 100 x 100 x 500 mm size, while Hassan *et al.* [14] used 75 mm diameter and 265 mm high cylindrical specimen. The prescribed limit for shrinkage or expansion according to ASTM C928-92a is ±0.15% of the original length and the shrinkage and expansion should be less than 0.20%.

Table 2 Test conducted by researchers to evaluate repair materials

Property	Emberson and Mays [3]	Plum [4]	Mangat & Limbachiya [5]	Hasan *et al*. [7]	Postan *et al*. [8]	Mirza *et al*. [9]
Compressive strength	√	√	√	√	√	√
Flexural strength	√	√	√	—	√	—
Tensile strength	√	—	—	√	√	—
Modulus of Elasticity	√	√	√	√	√	—
Poisson’s ratio	√	—	—	—	√	—
Shrinkage	√		√	√	√	√
Creep in compression	√	√	√	—	√	—
Creep in tension	—	—	—	—	√	—
Thermal expansion	√	—	—	—	√	√
Adhesion or Bond strength	√	√	—	—	—	√
Permeability	—	—	√	√	—	√
Abrasion resistance	—	—	—	—	—	√
Resistance to freeze and thaw	—	—	—	—	—	√

2.1.2 Restrained shrinkage

For measurement of restrained shrinkage there is no standard method available so far. Postan *et al*. [8] evaluated the restrained shrinkage by conducting three different types of non-standard tests – ring test, German angle test and SPS test. The details of these tests and further references are given in Postan *et al.* [8]. These authors did not find the German angle test a reliable method for determination of restrained shrinkage.

2.1.3 Thermal expansion

Coefficient of thermal expansion is a parameter representing the change in length of a material due to change in temperature. Different materials have different values of the coefficient of thermal expansion. If two materials of different coefficient of thermal expansion are bonded and exposed to varying temperature environment there will be development of tensile or compressive stresses, which ultimately leads to delamination at the interface.

Mirza *et al.* [9] measured thermal expansion of repair materials using the method given in ASTM C884-92. For this purpose concrete slabs of 75x150x300 mm capable of sustaining 300 freezing and thawing cycles were used as concrete substrate. These slabs were subjected to sand blasting, cleaning and brought to the surface saturated dry condition. Thereafter a 10 to 12 mm thick layer of the repair mortar was applied and cured at a temperature of 23 ºC and RH 100% for 28 days. Then the specimens were undergone five 48 h freezing and thawing cycles. Afterwards observations were made to check any debonding, cracking, or scaling. Postan *et al.* [8] used specimens of 76 x 76 x 286 mm size and followed the method described in ASTM C531-85 for determination of coefficient of thermal expansion. Emberson and Mays [3] used prisms of size 25 x 25 x 530 mm in the temperature range -60 to 60ºC.

2.2 Structural compatibility

The mismatch of structural properties of the repair material with the concrete substrate can lead to serious consequences. For structural repair the compressive, flexural and tensile strength of the repair material must be more than that of the substrate concrete. Second requirement is that the repair material should have approximately the same elastic modulus. To find out the structural compatibility few researchers test compressive strength and bond strength only, but others test tensile as well flexural strength also, as can be seen in Table 2. Recently, considerable importance has been given to creep also.

2.2.1 Compressive strength

For a long time compressive strength is being considered as an indication of the quality of cementitious materials and therefore many specification rely upon this property of the repair material. For determination of the compressive strength of the repair material different sizes of the samples are used. Furthermore, these specimens are cured under varying curing regimes. Generally, cube or cylinders of the repair material are tested at the age of 28 days. Few researchers test the specimen at an early age also.

Walters [15] and Mirza *et al.* [9] used 50 mm size cubes following ASTM C109-92 while Postan *et al*. (2001) used 76 x 152 mm cylinders following ASTM C39-93a. Emberson and Mays (1990a) and Plum (1990) followed BS6319: Part2: 1983 and used 40 mm cubes for resinous material, but for cementitious materials Emberson and Mays [3] tested 70 mm cubes (BS4550: Part 3:1978). Hassan *et al.* [7] used 50 mm size cube, but in other study [8] they used 150 mm diameter cylindrical specimen. Mangat and Limbachiya [5] tested 100 mm size cubes for concrete as well as for polymeric repair materials instead of the smaller size mentioned in BS 6319 for polymeric materials. The main reason for using the same shape and size for both the materials was their desire to compare the properties of the polymeric mortars with concrete that contained coarse aggregate.

From these studies, it appears that for resinous material small sized specimens are used, but for cementitious materials containing coarse aggregate bigger size specimens are used. The results obtained on different size and curing conditions cannot be directly compared. To overcome this problem some studies in this direction should be carried out by the researchers.

2.2.2 Flexural strength

Flexural strength is an indirect measure for assessing the tensile strength of cementitious materials, which are brittle and difficult to test in tension. Beams of the repair materials are tested either in three-point or four-point bending test. The four-point bending test yields lower values of flexural strength because in this test method a greater portion of the specimen comes under stress which causes more probability of failure. It has also been found that the effect of curing condition is more pronounced in flexural than in compression [16].

Postan *et al*. [8] used 152 x 152 x 533 mm sized beams for determination of 3, 7, and 28 days flexural strength of the repair material following ASTM C78-94a. Using the same standard (ASTM C78-84) Walters [15] used beams of 25 x 25 x 127 mm size. Emberson and Mays [3] used three different sized specimens: 40 x 40 x 160 mm (three-point loading) and 25 x 12.5 x 200 and 25 x 25 x 320 mm (four-point loading). Plum [4] followed BS6319: Part 3: 1983. Mangat and Limbachiya [5] tested beams of 100 x 100 x 500 mm size under four-point load at 28 days.

This survey of methods adopted by the researchers for flexural test of repair material indicates great variation in the specimen size and method of testing. Clearly the results obtain from these tests cannot be compared for selecting a material. Therefore, while selecting repair material using flexural properties, these aspects should be considered.

2.2.3 Tensile strength

Most of the concrete structures fail in the tensile zone and need repair. During shrinkage the restrain provided by the substrate causes tensile stresses in the repair. Therefore, it is important to assess the tensile property of the repair material. Although testing of cementitious material is difficult due to problem in holding them in grips of the testing machine, researchers made attempts to test by various means. The reliability of such tests is yet to be established. The resinous mortars are comparatively easy to test in tensile.

Postan *et al*. [8] measured direct tensile strength on 76 x 76 x 305 mm sized samples notched at mid height making a cross section of 51 x 76 mm for 3, 7 and 28 days tensile strength. Emberson and Mays [3] used briquettes following BS6319: Part7: 1985 for resinous repair material and briquettes based on BS12:1971 Part 2 for cementitious materials. Hassan *et al.* [14] used bobbin shaped specimens (75 mm diameter and 325 mm height) and measured at 28 days.

Keeping in view the importance of the tensile strength of repair materials in long-term durability of the repair, specifications are appearing which specify a minimum required value for tensile strength of the repair mortar [17].

2.2.4 Modulus of Elasticity

In selection of repair material modulus of elasticity (MOE) is an important criteria because it indicates how much the material will deform under loads. A low modulus material used in structural repairs will deform excessively and may not contribute in load carrying capacity of the structure. This will make the repair inefficient and will not serve any purpose. A significant difference in values of MOE of the repair material and the base concrete can cause stress concentration. Therefore, MOE of the repair material and concrete substrate is tested, mostly in compression but few researchers have tested in flexural and tension also. Like compression test, several types of specimens are used for determination of MOE, but usually measured at the age of 28 days. Postan *et al*. [8] used 76 x 152 mm cylinders for measurement of MOE at the age of 28 days following ASTM C469-94. Hassan *et al.* [14] used

150 mm diameter cylindrical specimen and tested at the age of 28 days in the stress control mode. The deformations were measured using strain gauges (20 mm length). Mangat and Limbachiya [5] tested prisms of size 100 x 100 x 500 mm at 28 days, while others [3, 4] used smaller specimens (size 40 x 40 x 160 mm) following the method given in BS 6319: Part 6: 1984. It is important to note that ASTM C469-94 is applicable for cement concrete, while BS 6319 is for resinous compositions. Thus, there exists a confusion which standard to follow for testing concrete and for repair material. For a real comparison similar test method for both the materials should be followed.

2.2.5 Bond strength

For a durable repair it is important that there is a good bond between repair material and the substrate. The quality of the bond determines the performance of the repair. The bond strength of the repair material is influenced by several factors such as surface preparation method, shrinkage and thermal expansion. The main purpose to conduct this test is to ascertain a sufficient bonding between repair and the substrate concrete.

Several types of bond tests are being carried out. Although BS and ASTM (BS6319: Part4; ASTM C 882-91) suggest the shear slant test, many researchers [3, 4] are of the view that in this test the material is being tested under combination of shear and compressive stresses. Therefore, they use tests based on pullout methods, which impose more severe stress condition.

For assessing the bond strength of the repair mortars Mirza *et al*. [9] followed ASTM C 882-91 and used base concrete cylinders of 75 mm diameter and 150 mm height cured in wet conditions (at 23 ºC and RH 100% for 28 days). The cylinders were then cut to an angle of 30º to the vertical axis and the roughness of the diagonal area was enhanced by sandblasting. The samples were then kept in water for next 24-hour and wire brushed. After applying the repair mortar on the rough surfaces the cylinders were cured either in dry condition (at 23 ºC and RH 100% for two days and then at 23 ºC and RH 50% for next 26 days) or wet condition (at 23 ºC and RH 100% for 28 days).

Kuhlmann [18] developed a test method for measuring the bond strength of repair mortar with concrete. In this method a 38 mm thick and 76 mm diameter of repair mortar is overlaid on a similar diameter concrete cylinder and pulled in tension after a specified curing period. The concrete and mortar are contained in steel pipe nipples. More recently, Austin *et al.* [19]) reviewed the different bond test methods. Based on their results they suggested that the performance of the bond could be better understand by making a bond failure envelope considering all normal/shear stress combinations in slant-shear tests. Although it needs a number of plane orientations from 0 to 45º, it can help in predicting the bond performance in different geometrical patterns.

In view of the various test methods adopted for bond/adhesion test, care must be taken while comparing the values of the different materials tested by different methods.

2.2.6 Creep

Most of the materials, particularly polymers, deform with time under constant loads. For a durable repair it is important to have knowledge of this property of the repair material. Since concrete is mainly loaded under compression, creep of the repair material is mostly tested in compression. However, few researchers tested creep in tensile and flexural also to study the effect of changing ambient conditions. In a given environmental condition a low creep is desired for structural repairs, while higher creep is beneficial for patch repairs [4]. The higher creep helps in redistribution of stresses, thus stress relaxation in the high stressed areas. It helps in prevention of premature failure in the highly stressed parts of the repairs.

2.2.6.1 Compressive creep

In this test prismatic or cylindrical specimens are kept under a constant load using mechanical or hydraulic jacks and the deformation is recorded over a period of time. Postan *et al*. [8] used six cylinders of 76 x 152 mm size. Two cylinders kept without any loading to record the drying shrinkage. For the measurement of the deformation mechanical gauges were fixed to 'diametric opposite sides' of the specimens. Two cylinders were placed in the creep frames and loaded to a stress equivalent to 20% of the 28 days compressive strength of the concrete being tested. Two other specimens were loaded to 40% of the 28 days compressive strength value. The test method given in ASTM C512-94 was followed. Emberson and Mays [3] adopted the method given in BS 6319: Part 11: 1989 and used 40 x 40 x 160 mm size prisms. Plum (1990) used 17.5 mm and 15 mm diameter by 100 mm long specimens cured for 7 days in ambient conditions. Mangat and Limbachiya [5] tested prisms of 100 x 100 x 500 mm size after 28 days curing at stress of 30% and 45% of 28-days strength. It is clear that different configurations are used for compressive creep testing of the repair materials.

2.2.6.2 Tensile creep

The test method is similar to that used for creep in compression except that the specimens are loaded in tension and the increase in length is recorded. Postan *et al*. [8] used specimens of size 76 x 76 x 152 mm for determination of tensile creep. The specimens were loaded to 40% of the 3, 7 and 28 days tensile strength. It means that the load on specimen was varied with the gain in strength of the specimen up to 7 and 28 days and afterwards the load was kept constant. The elongation was measured upto a period of 8 months with a mechanical strain gauge having a gauge length of 250 mm.

2.3 Chemical compatibility

The repair material should not have any harmful effect on the repaired structure. The detrimental elements could be chloride ion, which may cause corrosion of reinforcing steel, or sodium/ potassium ions may increase the alkali aggregate reaction rate. Surface repair material with low pH value may not provide sufficient protection against corrosion. Further, the acidic components may degrade the base concrete. Therefore, the repair material should be analysed for these detrimental elements. However, the permissible limits for maximum content of these chemicals are not yet established.

2.4 Electrochemical compatibility

The repair material should not corrode the reinforcing steel in the base concrete, but the repair material being different from the base concrete can cause galvanic corrosion in the unrepaired area. Few researchers found that cement mortar causes corrosion due to the differential shrinkage of the substrate; therefore, they used polymer-modified mortar, but others of the view that the repair material should have similar composition as of the substrate concrete. It appears that there is no agreement on acceptability of criteria for electrochemical compatibility. To overcome this situation work has been in progress in Canada to develop some accelerated tests to assess the compatibility with the substrate [12].

2.5 Permeability compatibility

Permeability of the repair material is determined to understand if the material can resist the ingress of water in the concrete. The penetration of moisture not only promotes the chemical reaction in the concrete but also brings in detrimental elements in dissolved form that can react with steel, lime and other components of concrete. However, in some cases complete stoppage of water transport is not desired and the choice of the material depends upon the situation in which the material is proposed to apply. For example, it is suggested that low permeability material should be avoided in hydraulic structure because the complete blockage of water can saturate the underlying concrete, which may be dangerous in frost condition. Nevertheless, the permeability properties of the repair are often related to the durability of the system.

Permeability is measured by using various penetrants and techniques. For example, water permeability and nitrogen gas permeability. Some other methods including capillary water absorption, chloride ion penetration, resistance to carbonation and resistance to seawater & sulphates can be found in literature.

2.6 Durability

2.6.1 Resistance to freeze and thaw

In cold countries concrete structures are exposed to very low temperature. As a result the free water present in the concrete freezes and the resultant volume increase induces tensile stresses in the material, which ultimately leads to cracking. An assessment of the repair material under freeze-thaw cycles can reveal important information about its behaviour at low temperatures.

Mirza *et al*. [9] examined the effects of freezing and thawing by conducting 300 cycles at the rate of six cycles per day on 75 x 150 mm size cylinders. After 300 cycles the cylinders were weighed to check any weight loss or weight gain, cracking, spalling or other defects. Walter [15] assessed the effects of 25 cycles of freeze and thaw on flexural strength of 25 x 25 x 127 mm sized beams.

2.6.2 Acid resistance

In service condition, the repair material may come in contact with acidic solutions. Particularly, in industrial sector use of acid resistant material is important. Walters [15] immersed beams of size 25 x 25 x127 mm in an aqueous solution of sulphuric acid (2%) and nitric acid (1%) and observed the change in flexural strength. After 28 days curing the specimens were immersed in the solution for 14 days then immersed in distilled water for two days and then dried in lab for additional two days before testing.

2.6.3 Weathering resistance

The concrete structures are exposed to various weathering conditions. Several accelerated tests are available to assess the weather resistance of repair materials. Walters [15] tested weather resistance of latex modified cement mortar. The flexural test specimens were subjected to 336 accelerated weathering cycles. Each cycle exposed the specimens to ultraviolet (UV) light at 60 ºC for 4 h then at 50 ºC and 100% RH for 4 h. These specimens were compared with the controlled specimens kept in the laboratory for 140 days after preparation.

2.6.4 Resistance to abrasion

In many situations the repaired area directly comes under abrasive environment and therefore the knowledge of abrasive resistance of the repair material is important. Mirza *et al*. [9] used a mortar sample of 50 x 50 x 12.5 mm size. The specimen was placed in the sample holder of the abrasion testing equipment and was subjected to rotation and a water jet with a velocity of 40 m/s.

Table 3 Some recommended performance criteria for repair materials

Property	Dector and Keeley [20]	Postan *et al.* [8]	McDonald *et al.* [17]
Compressive strength, minimum			
3 days	Similar to substrate	17.2 MPa	–
28 days		27.6 MPa	–
Tensile strength, minimum 28 days	Similar to substrate	10% of the compressive strength	2.8 MPa
Modulus of elasticity,	Similar to substrate	–	24 GPa (Max.)
Bond strength	> 0.8 MPa	–	–
Coefficient of Thermal expansion	Similar to substrate	–	12 millionths/ºC (Max.)
Drying shrinkage, maximum			
7 days	<300 microstrain	–	–
28 days	<500 microstrain	400 millionths	400 millionths
1 year		–	1000 millionths
Restrained shrinkage		Tip curling from the SPS plate should be less than 0.25 mm at 28 days.	No cracks within 14 days, 1000 millionths (1 year)

3. DISCUSSION

Various test methods for the repair materials are available to choose from. However, it is not known which test method is better or whether all tests are required for a repair material and what should be the acceptable values. Nevertheless, recently some recommendations have been made regarding acceptable values for the repair materials. Some of these values are presented in Table 3.

The number of tests to be carried out can be reduced if correlations can be developed between various properties. In this direction some efforts have been made, but no significant correlation was found between compressive strength and dimensional stability of the repair materials [17]. Depending upon the severity of the tests Mirza *et al.* [9] recommended the following order of the lab tests: thermal compatibility with base concrete, freeze and thaw test, drying shrinkage, bond strength, permeability, abrasion-erosion resistance. Prior to selection of a repair material the purpose and location of the repair should be clearly known, so that the relevant material properties could be identified and matched with the requirements.

4. KEY ISSUES

Concrete is vulnerable to change, not only in volume but also in shape due to the effects caused by moisture, temperature, load, chemical attack and other factors. The change in concrete can either be irreversible or reversible in nature and can result in the development of cracks in the structure, if the stress developed exceeds the strength of concrete. Any structure deformity due to any reason should be dealt separately. Due to the large variety of structural defects, their origins and consequences, repair activities differ in nature. Until now there is no systemisation in this field, hence it is vital for the restorer to be fully aware of the key issues involved in the repair/strengthening of the structures. It is difficult to meet all the required properties from a repair material. It is quite possible that a material have an excellent individual property, but the other properties may cause problems. For example, polymer based materials have excellent resistance to water ingress, but they have high thermal expansion. It has been suggested that while selecting a repair material the whole repair system must be examined using the so-called *'System concept'* or a "*‘holistic approach’* [12, 21].

Presently, there is no standard design code available for repairs. It is therefore necessary to develop design methods, which can use the test results. Currently, in the absence any standard design code the use of the results depends upon the design engineer’s judgement and experience. For designing the repair system, care must be taken while using the short-term properties because in long term these properties may change and need further repair. For example, Shambira and Nounu [22] found that due to comparatively higher time-dependent properties of the repair material the load bearing function of the repair material was lost in few weeks. However, for achieving the long-term properties the moulding or liquid state properties should not be compromised.

5. METHODOLOGY

Before taking up any restoration activity, it is essential to know the present status of the materials/structures. Present status can be depicted by the alteration in the appearance, strength, coherence, dimension or chemical behaviour of the materials, either individual element or part of structure. The factor includes chemical attack, mechanical disruption, disfigurement, exfoliation, disintegration etc. On the basis of these diagnostic tools, one can assess the present status of the materials/ structures. In diagnosing the real problem, it is essential to analyse the phenomenon of decay and surrounding environment. A diagnosis of the deterioration is the first step. Incomplete and inaccurate diagnosis can result inaction or inappropriate restoration measures. A survey of environmental condition can provide additional clues to the restorer for identifying the deterioration process.

The first problem we should analyse before taking the restoration activities is the choice of the repair material. The materials to be used for restoration work should perform effectively under the end use conditions. It means that the restored structure should perform safely and should preserve all required properties for many years. Two main properties are repair material, which should satisfy the durability requirement are compatibility with the materials being repaired and adhesion guarantying durable jointing effects i.e. bond strength with the jointing surface, mechanical and thermal deformability, chemical and rheological features.

Although a great number of research has been done on evaluation and design of repair systems, several issues are yet to be addressed such as do we need different safety factors for repair? For example, studies using finite element method (FEM) indicate that in adhesion test of patch repairs there are localised areas of high stress concentrations [10]. While using the test results this type of aspects are important.

6. WORK CARRIED OUT AT CBRI

In CBRI, we have undertaken a project **"**Development of Suitable Repair Materials for the Restoration of Heritage Buildings". In this project, numbers of repair materials have been developed viz., patching materials, reinforcement coatings and grouting materials. Diffrent tests have been devised for assessing the suitability of these materials from the end use application point of view. A detailed project completion report, one review and two research papers are published [23-26]. Apart from this, work has also been carried out for the development of repair materials for the restoration of repositories for the disposal of nuclear wastes. In this project, tests have been devised for assessing the suitability of repair materials using parameters like chemical resistance, modulus of elasticity, bond strength, compatibility and durability [27]. Few test set-ups are shown in Figs. 1 - 4. More recently we have developed a few self-curing repair materials for the restoration of buildings. It has been found that repair of the huge structures by using cementitious repair materials causes problems, because of the requirement of water for curing. To address this problem, we have developed self-curing repair materials for applications in buildings [28]. Detailed studies for assessing their suitability from different application point of view is in progress.

7. CONCLUSIONS & RECOMMENDATIONS

There are number of tests being conducted to assess the compatibility between concrete substrate and the repair material. Conducting all these tests for each repair material is not viable. Furthermore, the test methods also vary, which make it difficult to choose a suitable material. Therefore, there is a need to identify the critical properties and test methods, and to develop correlation between various properties of the repair material. This will help in reducing the number of tests required and the criteria to be met.

The first problem that should be analysed before a structural restoration work is the choice of material. The selected material should guarantee durability of restoration effects. It means that the restored structure should perform safely and should preserve all the required properties for many years. Long-term performance of repair materials under the service conditions is of prime importance. Upto now experience guides us in identifying the major influencing factors that determine the service life of the structure. Experience gained in case studies must be carefully analysed and negative and positive elements must be taken into account. Concerted efforts of scientists, engineers, contractors and manufacturers are required to identify the critical tests and acceptance criteria for repair materials for different situations.

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Fig.1: Test set-up for bond strength (in perpendicular direction)

Fig.2: Test set up for bond strength (shear)

Fig.3:- Test set up filled with water / solution

Fig.4:-Test set up for bond strength in flexure