Critical test methods for evaluating structural repair materials

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ny repair work requires appropriate selection of the repair aterials. The successful performance of a repair material pends on its dimensional behaviour and its compatibility ith the substrate concrete. It is therefore essential to conduct alistic critical performance testing of the materials by andard and non-standard methods. In this paper, the author esents a review of such test methods.

einforced concrete is the most versatile material of nstruction and is used for constructing all strategic uctures such as bridges, off-shore platforms, decks, bours, etc. Durability can be achieved by proper material lection, design, supervision and workmanship during nstruction[1]. The required degree of high standard is not ways achieved and as a result of this the structure is affected hich in turn requires early repair and renovation work. fter the investigation process is completed, the repair work rts with the selection of suitable repair materials. The lection of repair materials requires thorough understanding material behaviour in the anticipated exposure conditions. e successful performance of repair material is based on its ensional behaviour and its compatibility with the bstrate concrete. The relative dimensional changes cause rnal stresses within the repair material, substrate and at interface when subjected to loads, temperature and isture loss[2,3].

Although broad categories of repair materials are ilable having a broad range of property variations. The ufacturer's data on repair materials are often inadequate tructural properties such as tensile strength, elastic dulus shrinkage and bonding properties, etc[4]. In addition, hould possess resistance to diffusion of aggressive ions h as chlorides, sulphates, carbon dioxide, etc. The data sheet of the repair material supplied by the manufacturer or the supplier normally contains brief description of the material, mix proportions and compressive stress. These characteristics properties alone are not sufficient to adopt the repair materials for repair works since realistic critical performance testing by standard and non-standard test methods are essential requirements. In this paper, test methods which are essentially required to evaluate structural properties of the repair materials are discussed.

Selection of repair materials

The foremost parameter to select any repair material is, it should have relative dimensional stability with substrate concrete[3]. The relative dimensional changes cause internal stresses within the repair material, substrate and at the interface. The importance of dimensional compatibility has been discussed by several researchers[5,6,7,8]. The dimensional compatibility of cementitious materials deals with four types of deformations such as shrinkage, creep, temperature strain and instantaneous elastic deformations. The resin-based materials have good adhesion with the substrate concrete, their coefficient of thermal expansion is many times more than substrate concrete. However, it fails predominantly at the interface[5]. Due to its exothermic reactions, it contracts and fails at the interface if proper bonding or adhesion is not ensured. The elastic modulus is another important parameter for dimensional compatibility. Normally resin-based repair materials offer slightly less elastic modulus when compared to cement-based materials. Mismatch in the modulus of elasticity (stiffness) becomes a great concern in load sharing capacity[9]. The material with lower modulus deforms more and it causes redistribution of stresses within the member[5,10,11]. It is reported that the repair material should have 30 percent more elastic modulus than the substrate

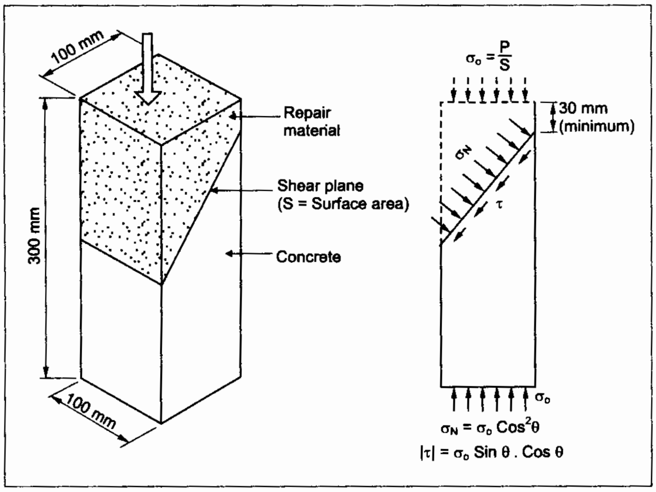


Fig 1 Slant shear test

concrete[10]. Following are some characteristic requirements of repair materials to be viewed before selecting repair materials. It should have:

- *(i)* dimensional stability with respect to substrate concrete; it depends on shrinkage, thermal movement due to wetting and drying conditions.
- *(ii)* ability to bond adequately with the substrate to act as a single composite system for efficient load sharing without causing any interfacial bond fracture.
- *(iii)* characteristic compressive, tensile, flexural and shear strengths compatible to that of substrate concrete.
- *(iv)* ability to offer chemical passivation to the embedded steel reinforcements.
- *(v)* reduced permeability towards aggressive ions.
- *(vi)* ability for easy application.
- *(vii)* durability against chemical and weathering.
- *(viii)* maximum resistance to cracking, tensile strength, shear strength should be as high as possible and creep, drying shrinkage, coefficient of thermal expansion should be as low as possible.

In the repair of corroded concrete structures, the following three types of repair materials are generally adopted based on their durability, strength and service requirements.

- *(i)* Hydraulic cement-based materials
  - Portland cement-sand mortar
  - Portland cement concrete
  - Portland cement mortar or concrete with fibres.
- *(ii)* Resin-based materials

  (Epoxy, acrylic, latex and polyester resins are normally used as resin for the structural repairs with appropriate curing agents and other admixtures)
  - Resin –sand mortar (polymer mortar)
  - Resin concrete
  - Resin mortar or concrete with fibres.
- *(iii)* Polymer-modified cement materials
  - Resin- cement –sand mortar
  - Polymer added cement concrete
  - Polymer added cement concrete or mortar w fibres

The admixture normally added to the repair materi are superplasticiser, fillers and shrinkage-reduci admixtures. Fibres may be steel or polypropelene to increa the tensile strength of the material.

Critical performance tests

Tests on bonding layer

Shear-bond tests

A wide range of repair materials is available in the mar today. A complete critical evaluation for efficient repair required for key properties such as shrinkage, shear streng and bonding before using it.

Good adhesion of repair material on substrate concrete very important for any structural repair work. The streng and integrity of the repair joint is only dependent on materi property, roughness and soundness of the prepared surfa In practical situations, the interface may be subjected compression, tension or a multi-stress state. There are thr types of bond tests namely compression-shear, tension-she and pure shear to test the adhesion of bonding layer in all t loading conditions.

Compression shear test

Slant shear test in compression mode puts the bond interfa in a combined state of shear and compression. This test w formulated in 1976 and it was known as Arizona slant she test and later this was modified by Tabor[12,13]. It was adopt in BS 6319 and it is also found in ASTM C882-91[14,15]. Thou the angle of inclination is specified as 30° to the vertical pla and this was analysed and discussed by the vario authors[16-20]. It was reported that the mode of failure crucial depends on the inclination, surface roughness and mic cracks present at the inclined plane[16,17]. This test is sensitive differences in elastic modulus of the repair material whi may cause stress concentration and edge failure[17]. Bo failure occurs if the inclined surface is smooth to rough, t mode of failure will be compression and if micro cracks a present, the mode of failure will be tension[17]. The effect surface roughness depends on the critical angle of the she plane. The critical angles for smooth, medium rough a rough surfaces are 27°, 23° and 19° respectively[17]. One deg variation causes 10 percent, 5 percent and 1 percent chang in failure load with rough, medium rough and smooth surfa respectively[17]. It is also reported that the elastic modu differences between the two materials of a combined syst cause eccentricity of loading during slant-shear test[10]. modulus of repair material is less than that of substr

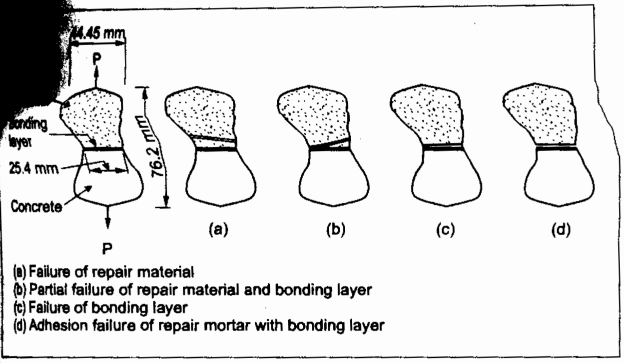


Fig 2 Testing of repair material in direct tension[26]

material, the stress at the ends of the interface is maximum which is normal to the interface and shear stresses occurring at the sides of repair material[17].

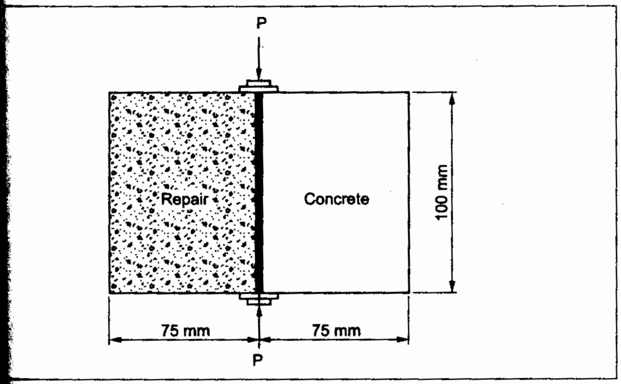
From the above it is inferred that the slant-shear test is affected by the following factors:

- The shear failure along bond interface varies with the inclination of bond plane and surface roughness.
- Modulus mismatch causes local stress concentration along the edges of the shear plane if repair material has lower elastic modulus.

Following are other tests to evaluate the adhesion of bonding layer under different loading conditions.

(i) ***Direct tension test:*** Briquette specimen of standard size, as shown in *Fig* 2, should be used. The actual structural concrete is placed and compacted in one half and the remaining half is cast with the repair material after ordinary concrete has been cured for 28 days. Before casting with the repair material the concrete surface must be dry sand blasted and bonding agent must be applied. These briquettes are subjected to direct tensile test in tensometer and the type of failure that occurs must be observed. The higher the stress value, higher will be the adhesion of bonding layer.

(ii) ***Direct split-tension test***: Prisms of size 75 mm x 75 mm x 100 mm should be cast with representative concrete and with proposed material as shown in *Fig* 3 with necessary bonding agent. This composite section is subjected to direct split tension test in compression mode. From the load at failure the stress can be calculated. In this test the adhesion of bonding layer has been tested in tension shear mode. The best bonding layer is the layer which has higher stress.



3 Direct split tension test[26]

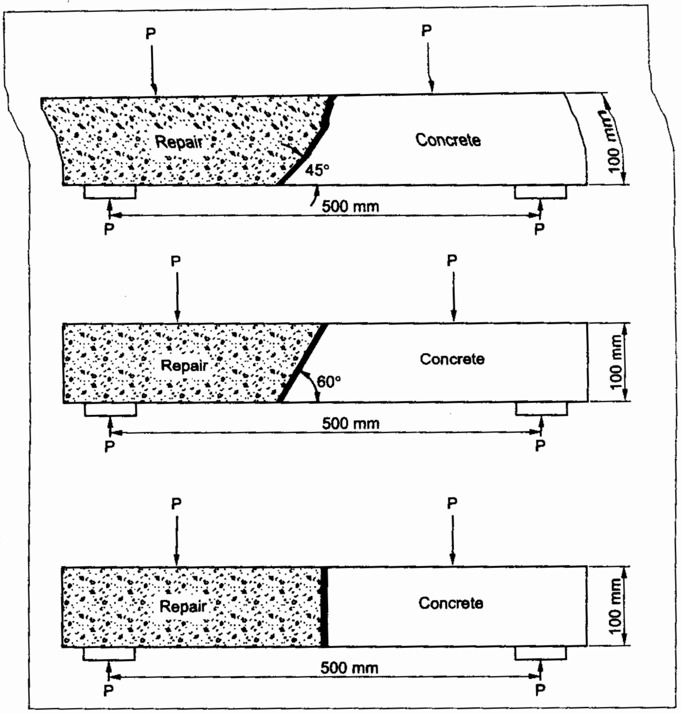


Fig 4 Flexural bond tests[26]

(iii) ***Flexural bond test:*** Flexural beams of size 100 mm x 100 mm x 500 mm should be cast as shown in *Fig* 4 illustrating the three types of flexural planes such as vertical, inclined at 45° and 60° to the horizontal. The substrate concrete as well as repair concrete is cast with bonding layer. These specimens are tested with flexural testing machine to assess the bond strength in flexural-shear. The maximum load at failure is the criteria for selecting the best bonding agent.

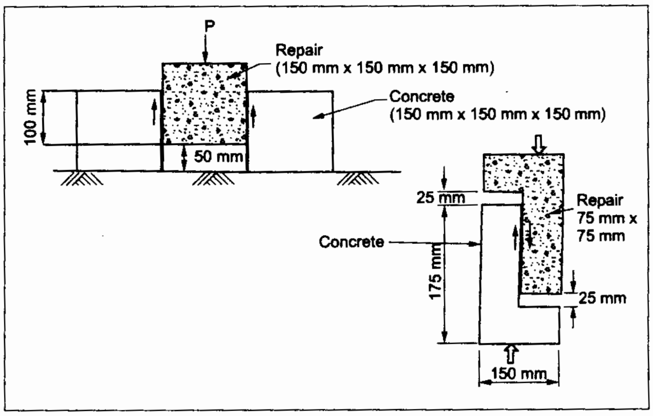


Fig 5 Bond strength in pure shear[26]

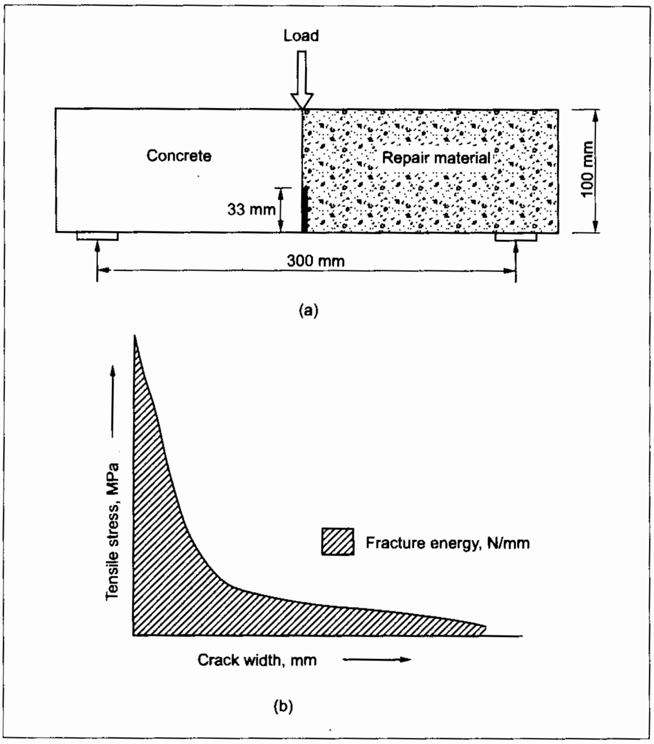


Fig 6 ***(a)*****Tension softening test** ***(b)*** **Tension softening diagram**[21]

- *(iv)* ***Direct shear-bond test:*** There are two types of tests which are conducted: the first one is with the cube specimens bonded as shown in *Fig* 5 *(a);* the second one is with "L" prisms cast as shown in *Fig* 5*(b)*. The load at failure divided by the bonded area with concrete gives the shear stress at failure. The repair material which has higher shear stress is selected for the repair work .
- *(v)* ***Tension-softening test:*** The delamination behaviour of the repair material can be assessed by the tension-softening test . In this test, the fracture energy is computed from tension-softening diagram obtained by flexural test[21]. A composite beam of size 100 mm x 100 mm x 300 mm is cast and subjected to flexure test. The load versus crack width curve is plotted as shown in *Fig* 6. The hatch area under the tension-softening curve gives the fracture energy required to cause disbondment. The more the fracture energy, the more will be the resilience of the material.

Shrinkage tests

There are two types of shrinkages normally encountered in substrate-repair composite section — restrained shrinkage and drying shrinkage. Cement-based materials have low tensile strength compared to resin-based material and hence induce restrained shrinkages in the material[6]. Location of patch repair is also important, for example, if the repair is at a corner, it induces restrained shrinkage. Drying shrinkage is due to moisture loss and used to study the dimensional stability of the repair system[22]. This is mainly influenced by the composition of the material and environmental conditions such as temperature, wind velocity, etc. The time taken for developing shrinkage depends on geometry of the repair. If the volume of the repair is high then it takes more time to develop shrinkage cracks. In the case of cement-based materials, the shrinkage cracks are developed by evaporation of surface water and in resin-based materials by exothermic reaction during curing as the fresh repair or concrete tends to shrink, the substrate concrete restrains it[5]. This causes differential movement which in turn produces tensile stresses in the repair material and which is balanced by th compressive stress within the concrete. If the tensile capacity of the repair material is low or if the adhesive strength at th interface is low, then fracture or disbondment occurs. This leads to cracking and delamination of the repair materia These shrinkage incompatibilities are more associated wit cement-based material than resin-based materials.

To overcome these shrinkage problems, the repair materia should have more tensile strength and lower coefficient c thermal expansion than the substrate concrete. Sometime shrinkage-reducing admixtures such as alkoxylated alcoho and alkoxylated alcohol-based oligomers are used with dosage range of 1 to 4 percent by weight of cement but th compressive strength of the material significantly reduced Another way of eliminating delamination and disbondmen by drying shrinkage is removing weak boundary layer the interface by roughening. This improves the bonding ar with good mechanical anchorages.

To evaluate the shrinkage properties, the following no standard tests are conducted.

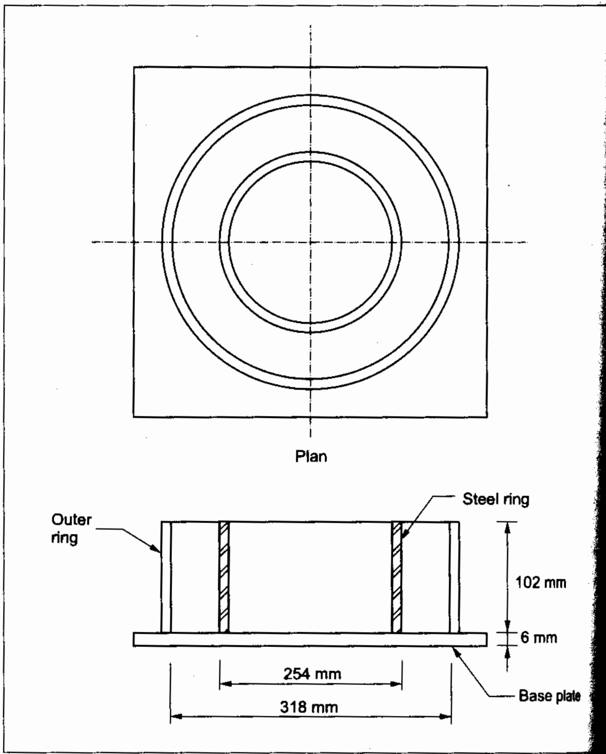


Fig 7 Restrained shrinkage (Ring) test[3]

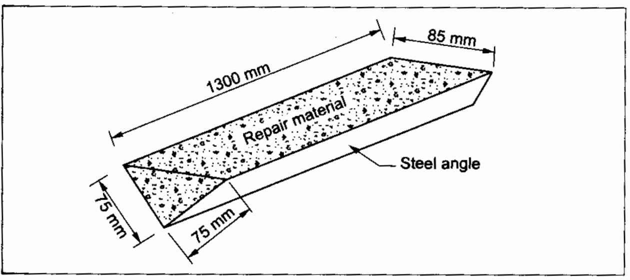


Fig 8 Linear restrained shrinkage test (German angle test)[6]

Restrained shrinkage test (Ring test)

In this test ring specimens have been in use for testing the repair mortar/concrete since 1939. In this test a 25-mm thick repair mortar ring should be cast around a steel ring as shown in *Fig* 7. The top and bottom surfaces of the repair material are sealed with epoxy resin so that the drying is allowed to occur from the outer circumferential surface. The configuration of this ring specimens does not impose stress concentrations and it allows volume changes, stress development including creep and creep relaxation. Different researchers use different thickness and heights for the ring as there is no standard dimension.

The cast specimens should be exposed to the environment and observed for any crack development with time. The lengths and widths of the cracks are recorded over a period. The shrinkage strain is computed by dividing the average crack width by ring circumference[3].

Linear restrained shrinkage test (German angle test)

A steel angle of size 75 mm x 75 mm x 8 mm thick and 1.03 m long should be used for this test. This method was developed by the Technical Academy Aachen, Germany and adopted as The Technical Test Regulations (TP BE-PCC) by Highway Construction Department of the Federal ministry for Transport[25].

The repair material is cast in the angle as shown in *Fig* 8 and exposed to the atmosphere without covering. The material in the trough is to be observed for the number of cracks, the average length, width, etc and recorded for a period of about 18 months. There shall not be any disbondment of material from the angle surface and cracks wider than 0.1 mm are not accepted.

Restrained volume change test (SPS plate test)

A thin mild steel (flexible) plate of size 100 mm wide and 1.3 m long is used in this test. The repair material which is usually polymer modified or resin mortar is tested by this method. The repair mortar is spread over the plate exactly to the dimensions of the flexible plate to a thickness of 50 mm. After the material is set, one end is fixed as shown in *Fig* 9. with clamp and the other end is left free to deflect upward. If any curl or upward deflection at free end will be monitored by the deflectometer due to shrinkage effects. The material of high shrinkage properties will show maximum curl and the minimum upward curl for the low shrinkage materials. The SPS-plate test can be used for comparative evaluation studies of repair mortars.

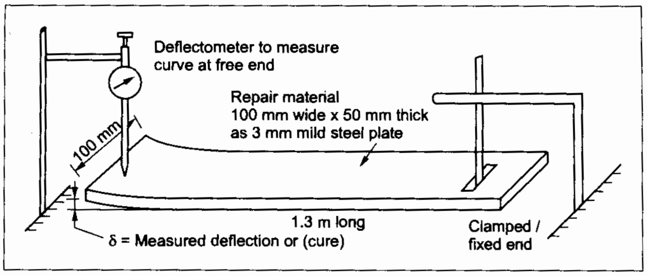


Fig 9 Restrained volume test (SPS test)[7]

Apart from these critical evaluation properties, *Table* 1 suggests other important tests normally conducted for performance evaluation of repair materials.

Concluding remarks

Based on the above discussion, following conclusions are drawn.

(i) Compressive strength of the repair material is not as important as tensile strength. Many structural damages and cracks often occur at tension zone. Therefore, due importance must be given to material with improved tensile strength of repairs.

Table 1: Test methods for performance evaluation[29-49]

	Performance requirement	*Test standards*
1	Density	ISO 6276; BS 1881: Part- 114; ASTM C 905
2	Workability	ISO 4109; Vebe ISO 4110; Flow table ISO 9812;
3	Compressive strength	ISO 4012 concrete; BS 6319 Part 2 PC Mortar; ASTM C579-91; ASTM C39; ASTM C109; DIN 1164
4	Elastic modulus	ASTM C78-94; ISO 6789; RILEM NDT 2
5	Direct tensile strength	ASTM C307-94; ASTM E 149-76; RILEM 13 MR
6	Flexural strength	ASTM C78-94; ASTM C190; DIN 1164; BS 6319: Part-4
7	Splitting tensile strength	ASTM C496- 90; BS 1881
8	Water absorption	ASTM C413-94; BS 1881: Part-122
9	Initial surface absorption	BS 1881: Part-208
10	Permeability	DIN 1048;
11	Stiffening and service life	BS 4557 and BS 5075
12	Abrasion resistance	ASTM C418-90; DIN 53754
13	Direct shear	ACI SP-89
14	Slant shear test	ASTM C882-91;ASTM C1042-91; BS 6319: Part-IV
15	Thermal compatibility	ASTM C884-89
16	Effective shrinkage test for resins	ASTM C 883-89
17	Dimensional stability tests	ASTM C 596, C827; PC mortars BS 6319 Part 12 German- trough test, Ring test (restrained), SPS- Test
18	Pull-off test	Dutch CUR 20 Derived from RILEM TC 52 RAC 1
19	Gas permeability	Test derived from Nord test- by UKTG
20	Durability/compatibility	RILEM TC 52- RAC No. 6
21	Resistance to carbonation	RILEM CPC-18,
22	Chloride ion diffusion	ASTM C 1202- 1995
23	Linear co-efficient of shrinkage	ASTM D 2566

(ii) Adhesive strength or bonding of repair material with the structural concrete is a crucial parameter. This has to be evaluated with utmost care under all types of loading condition explained above for effective composite action.

(iii) The inclination of slant-shear test and the surface roughness is another important aspect. The specified inclination of 30° with the vertical axis and smooth surface alone gives exact slant-shear value. Any increase in surface roughness or reduction in shear plane angle results in material failure. Therefore, mild sand blasting to remove the laitance is sufficient.

(iv) The repair material and the substrate concrete should have almost equal elastic modulus. Any modulus mismatch results in redistribution of stresses at the interface as a result of stress concentrations along the edges.

(v) The coefficient of thermal expansion of repair material and the substrate concrete must be equal to avoid relative movements due to temperature effects.

(vi) In practice, no free shrinkage is caused in the structural repair. Therefore, the value of restrained shrinkage is of much importance and the repair material should be subjected to all types of restrained shrinkage tests. The materials of lower restrained shrinkage are to be adopted for repair works.

(vii) Resin-based repair materials are to be selected where thin sections are to be repaired. For larger size repair works cement-based repair materials are suitable and economical.

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