Structural Crack Repair

[Excerpts from Dr. Fixit Guide to Healthy Construction – 1, Cracks & Crack Repair (Unpublished)]

1.0 Methods of Structural Crack Repair

1.1 Epoxy Injection

When hardened concrete is cracked in depth or when hollow plane delaminations or open joints exist in hardened concrete and when structural integrity or watertightness must be restored for the structure to be serviceable, resin injection shall be used for repair, as directed. However, since not all cracked, delaminated, or jointed concrete can be restored to serviceable condition by resin injection, resin injection repairs shall be made only as directed by the structural consultant. Epoxy resins are used to rebond cracked concrete and to restore structural soundness. Epoxy resins may also be used to eliminate water leakage from concrete cracks or joints, provided that cracks to be injected with epoxy resin are stationary. Cracks that are actively leaking water and that cannot be protected from uncontrolled water inflow shall not be injected with epoxy resin. Cracks to be injected with epoxy resin shall be between 0.1 mm and 6 mm in width.

Epoxy resins are injected for repair of hair line cracks and fissures as narrow as 0.05 mm due to their unique property of super low viscosity. The appropriate viscosity of the epoxy will depend on the crack size, thickness of the concrete section, and injection access. For crack width of 0.3 mm or smaller a low viscosity epoxy injection can be used. For wider cracks, or where injection access is limited to one side, a medium to gel viscosity material may be suitable.

Injection can be made of low pressure or high pressure system depending on the nature of cracks. It is advisable to use two-component pumps with a static mix head to prevent premature reaction.

Epoxy grouts are widely used because:

- They adhere strongly to both fresh and hardened concrete
- Formulations are available which will adhere to most surfaces and harden even under wet conditions
- They have good mechanical strength and low shrinkage
- They are resistant to a wide range of chemicals, including alkalis
- They are almost totally UV resistant

Generally epoxy resins will have either good chemical resistance or good heat resistance, but not both. Another characteristic of this type of product in its cured state is the lack of flexibility, and the system might be prone to failure if movement occurs due to seismic activity, and or expansion/contraction. The two-component epoxy resins have good expansive properties.

The step by step approach of epoxy injection (Fig. 1 and Fig. 2 a to e) are shown to restore structural soundness of buildings, bridges, and dams where cracks are dormant or can be prevented from moving further. Except for certain specialized epoxies, the method cannot be used if the cracks are actively leaking. The detailed description is given as follows:

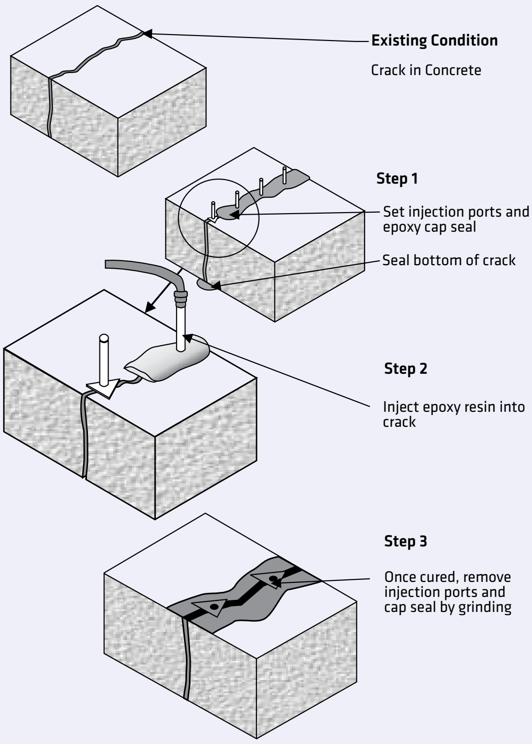

Fig. 1: Schematic diagram of epoxy Injection

- Clean the cracks : Cut and open the cracks. Remove any contamination by flushing with water or some especially effective solvent. Then blow out the solvent with compressed air, or allow adequate time for air drying.
- Seal the surfaces : This keeps the epoxy from leaking out before it gelled. A surface can be sealed by brushing an epoxy over the surface of the crack and allowing it to harden. If extremely high injection pressures are needed, cut out the crack in a V-shape, fill with an epoxy, and strike off flush with the surface.

Install the entry ports : There are three ways to do this:

- Fitting of nozzles inserted in drilled holes Drill a hole into the crack for 8 mm dia injection packers @ 200 to 300 mm c/c, (Fig 2 a) penetrating below the bottom of the V-grooved section. Insert a fitting such as a pipe nipple or tire valve stem into the hole and bond with an epoxy adhesive. A vacuum chuck and bit will help keep the cracks from being plugged with drilling dust.
- Bonded flush fitting when the cracks are not V-grooved, a common method of providing an entry port is to bond a fitting flush with the concrete face over the crack.

Fig. 2 a: Packer and Injection hand pump

Fig. 2 b: High pressure Injection pump

Fig. 2 c: Fixing the hose into the packer and start pumping

Fig. 2 d: Injection in progress

Fig. 2 e: Injection in underside

- Interruption in sealing is another way to allow entry is to omit the seal from part of the crack. This method uses special gasket devices that cover the unsealed portion of the crack and allow injection of the adhesive directly into the crack.
- Mixing: Mix the two components epoxy injection grout of base and hardener in a suitable container with heavy duty slow speed drilling machine with paddle attachment.
- Mix it for 2 to 3 minutes to obtain a uniform colour.
- Inject the epoxy: Hydraulic pumps (Fig 2 b), paint pressure pots, or air-actuated caulking guns can be used. Select the pressure carefully, because too much pressure can extend the existing cracks and cause more damage.
- If cracks are clearly visible, injection ports can be installed at appropriate interval by drilling directly into the crack surface. The surface of the crack between ports is allowed to cure. For vertical cracks, start by pumping epoxy into the entry port at the lowest elevation until the epoxy level reaches the entry port above. Then the lower injection port is caped and the process is repeated at successively higher ports until the crack has been completely filled in. For horizontal cracks, injection starts from one end of the crack to the other in the same way (Fig 2 c). When the pressure is maintained, the crack is filled completely (Fig 2 d). For injection from underside of ceiling of flat roof a lot of pressure is being exerted (Fig 2 e). Hence care should be taken while injecting from underside (Fig 2 e).
- Removal of the surface seal : After the injected epoxy has cured, the surface seal is being removed by grinding or some other appropriate means. Fittings and holes at entry ports should be covered with epoxy fairing putty prior to repainting.

1.2 Stitching

This method involves drilling holes on both sides of the crack and grouting in stitching dogs (U-shaped metal units with short legs) that span the crack. Stitching may be used when tensile strength must be reestablished across major cracks. Stitching a crack tends to stiffen the structure, and the stiffening may accentuate the overall structural restraint, causing the concrete to crack elsewhere. Therefore, it may be necessary to strengthen the adjacent section with external reinforcement embedded in a suitable overlay.

The stitching (Fig. 3) procedure consists of drilling holes on both sides of the crack, cleaning the holes, and anchoring the legs of the dogs in the holes, with either a nonshrink grout or an epoxy-resin-based bonding system. The stitching dogs should be variable in length and orientation or both, and they should be located so that the tension transmitted across the crack is not applied to a single plane within the section but is spread over an area.

Spacing of the stitching dogs should be reduced at the end of cracks. In addition, consideration should be given to drilling a hole at each end of the crack to blunt it and relieve the concentration of stress. Where possible, both sides of the concrete section should be stitched so that further movement of the structure will not pry or bend the dogs. In bending members, it is possible to stitch one side of the crack only. Stitching should be done on the tension face, where movement is occurring. If the member is in a state of axial tension, then the dogs must be placed symmetrically, even if excavation or demolition is required to gain access to opposite sides of the section.

Stitching will not close a crack but can prevent it from propagating further. Where there is a water problem, the crack should be made watertight as well as stitched to protect the dogs from corrosion. This repair should be completed before stitching begins. In the case of active cracks, the flexible sealing method may be used in conjunction with the stitching techniques.

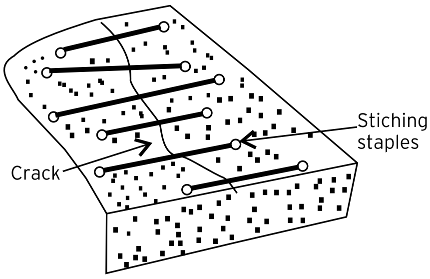

Fig. 3 : Stiching of cracks

2.0 Materials for Crack Repair of Water Retaining Structures

2.1 Polyurethane grouts

Polyurethane grouts are usually used to repair cracks that are 0.12 mm and greater in width, both wet and active, and leaking a significant amount of water through joints or cracks. These grouts are semi flexible; thus, they may tolerate some change in crack width. The reaction time to form the foam may be controlled from 30 to 45 seconds up to several minutes using different catalyst additives.

Polyurethane grouts generally are not suitable for structural repairs. Additionally, a highly skilled work crew is required along with special injection equipment. Finally, these materials typically are not stable when exposed to UV light. This is usually not a major concern because the material is injected into a narrow crack where exposure to UV light is minimal.

Because of the immediate crack arresting nature they are well suited for tanks for the storage of liquids, dams, tunnels, sewers, and other water-containment structures.

Polyurethane chemical grouts are usually injected under pressure as a liquid resin into or in the vicinity of the leak. Once the resin contacts water, a chemical reaction occurs. Depending on the material formulation, the grout/water combination forms either expansive closed cell foam or a gel (Fig. 4). The foam created can be flexible and resilient (hydrophilic) or ridged, meaning the cell structure of the foam crushes when compressed (hydrophobic).

Fig. 4: Injected material

2.2 Cementitious Crystalline

It is a cementitious chemically-reactive system which forms millions needle like crystals (Fig. 5) in presence of water and fill the pores, spaces and cracks between the concrete particles. Crystalline chemicals are adsorbed into the concrete by capillary action and diffusion. Once the cracks are filled in, they lie in a dormant stage until the new cracks develop through which water enters and reactivate the chemicals which form and grow to new crystals and fill the pores and arrest the cracks. This becomes a self-sealing process which permanently repairs the cracks and stops leaking.

Fig. 5: Growth of crystals

3.0 Methods for Crack Repair of Water Retaining Structures

3.1 Polyurethane (PU) injection

These materials are injected at high pressures. The grout prepolymer is usually mixed with water at ratios of 6:1, 8:1, and up to 12:1 (water to polymer ratio) to obtain a gel ranging from firm to weak. Hydrophilic expansive foam grouts are typically single component products requiring small delivery systems for the injection process. Pumping systems for hydrophilic foam grouts tend to be high pressure and low volume, while the gels utilize high volume and lower pressure systems.

The initial cure is the time it takes for the polyurethane grout to foam up, and the final cure is the time it takes for the grout to fully expand. This final cure time, which may take up to 12 hours, is critical to the success of the grouting process. The expansion rate of hydrophilic foam grouts can be up to 5 to 8 times its original volume and hydrophilic gels typically do not gain volume upon curing rather they shrink after cure in the absence of water.

These types of grouts are used in below grade structures, basements, and other areas that are often wet, such as subways and interior portions of a concrete dam as they will shrink in a dry environment.

Hydrophilic expansive foam grouts stick to concrete and stretch in a moving crack. Hydrophilic gel grouts will not stick to concrete and are not recommended for moving cracks. They are used for sealing sewer joints and manholes, and other underground applications. Due to their relatively short gel times and high viscosities compared to the acrylics, they are usually not used in sealing lateral sewers with remote lateral packers. They are generally much faster reacting systems and can reach up to 25 times expansion in as little as 7 to 10 seconds. With the high expansion rates and extremely fast reaction times, they can have the potential to move structures and require extreme care when using.

Hydrophobic foams can also be used to fill voids or abandoned underground pipes, vaults, tanks, etc. A major advantage to sealing active leaking cracks/joints is that material is water activated as opposed to most materials that require the water intrusion to be eliminated before the repairs can be done. The cured resin is designed to accept movement, allowing the materials to be successful in applications subject to movement due to seismic activity, contraction/expansion or movement designed into the structure where a rigid material like epoxy is prone to failure. Typical applications of hydrophobic PU include sealing cracks/joints, creating a water impenetrable barrier between the backside of a structure and the soil matrix from the negative side.

Most polyurethane grouts are considered to be "non toxic" although safe handling procedures should be closely followed with these and all other chemicals. Some hydrophilic foam grouts are certified to be used with potable drinking water systems.

3.2 Integral Crystalline System

The cracks are chiseled out along the length of the crack. Then they are cleaned and surface is pre-wetted. A cementitious highly concentrated crystalline dry pack is prepared and packed thoroughly through the cracks.

A cementitious coating is applied on the surfaces. This is a permanent self-sealing crack repair system mostly applied on positive side (Fig. 6) and also can be applied even on negative sides. It is suitable for basement, foundations, walls, tunnels, bridges, and dams, water retaining structures, sewage treatment tanks and pools. For using in water tanks the safety of the product has to be checked from the manufacturer.

3.3 Strip-and-seal System

Strip-and-seal systems may be used to treat cracks of any width, but are most commonly used to treat cracks that are 6 mm or greater in width. Strip-and-seal systems consist of a flexible sheet, such as synthetic rubber, that spans over a crack and is adhered to the structure on each side of the crack using a suitable adhesive.

These systems are designed to span over the crack and prevent leakage of liquids; the crack itself is not actually filled or repaired. Some systems have a high resistance to aggressive chemicals. These systems have virtually no limitation to the crack width. Moisture-insensitive epoxies may be used as an adhesive on damp surfaces. The elongation properties of these systems are excellent,

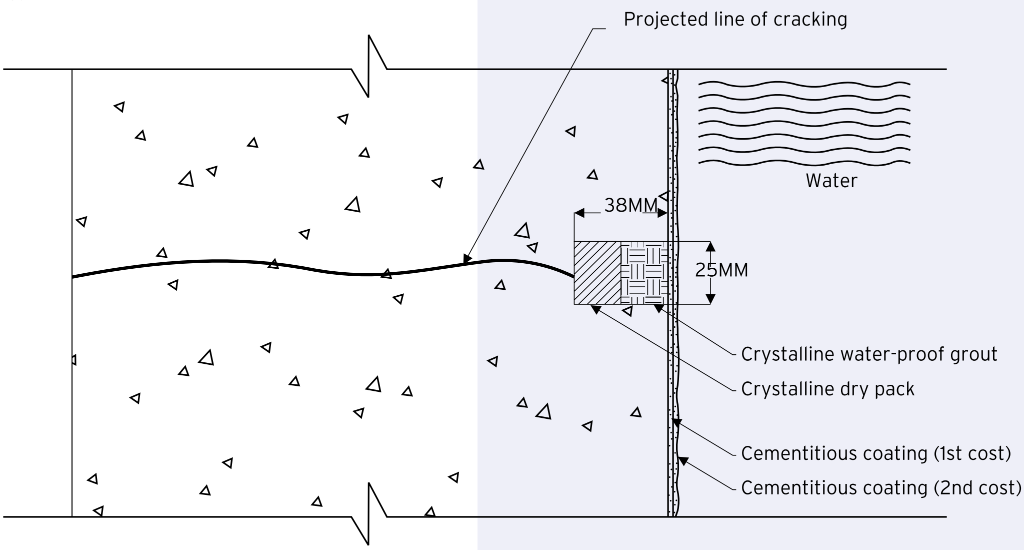

Fig. 6: Crystalline coating system

making them appropriate for use on active joints. Some strip-and-seal systems are highly resistant to UV light; thus, they do not chalk or weather. Generally, these systems do not require any special worker skills or equipment to install.

4.0 Quality Assurance

4.1 Causes of Repair Failures

There are many causes of failure of repair system. The various causes are

- Wrong diagnosis of crack formation.
- Material: Incorrect specifications, bad quality, properties like incompatibility.
  - Contraction of repair materials may cause cracking.
  - If tensile strength of repair material is too high compared to the bond strength on the substrate, a ring shape crack may occur at the boundary of crack repair.
  - If bond strength is higher than tensile strength, cracks may develop on surface of repair.

Method of application: In correct surface preparation, wrong way of application, unskilled workmanship.

For any repair failure the blame goes to the quality of the material. But material failure accounts for 1% of total failure. Hardly any material fails but it is the wrong diagnosis and incorrect surface preparation which cause maximum failure of the repair.

4.2 Tests for Effectiveness of Crack Repair

Performance of a concrete repair needs to be measured in physical terms and quantification of physical parameters for comparison is also necessary. Other parameters such as environmental effects, safety and whole-life costs should be taken into consideration. Hence, after the repair of crack it is essential to test the effectiveness of the repair system. The most of polymeric repair materials fail due to improper surface preparation, wrong application methods, incompatibility of the repair material with the original concrete etc.

To check the effectiveness of crack repair by injection method, core samples of 50 mm dia should be extracted from the locations (Fig. 7) where there is no reinforcement. Cores should be taken after the final setting of injected materials. Extracted cores can be visually inspected and further tested for compressive as well as split tensile strength. The cores should be filled in with an expansive cementitious or epoxy grout with proper surface preparation.

The following NDT (Non destructive tests) such as Ultrasonic pulse velocity, pull-off test, impact echo, can be performed to find out the effectiveness of the concrete repair system.

Ultrasonic pulse Velocity test : To determine the cracks and honeycombs.

Impact Echo : To detect flaw and evaluate thickness and integrity

Slab Impulse Response : To detect voids, delamination and structural integrity

Pull off Test : To determine Adhesive force of repair material (Fig. 8).

Fig. 7: Core sample taken from crack area

Fig. 8: Pull off test on concrete repaired surface

Half-cell potential surveys: To highlight areas of ongoing corrosion, before, immediately after and sometime after electrochemical treatment.

Acid soluble chloride profile analysis: To determine total chloride content at depths before and after treatment.

Pore water analysis: To determine the chloride ion (free chloride) and hydroxide ion concentrations before and after treatment.

Petrographic analysis: To examine the structure and quality of the concrete and to examine for alkali-silica reaction (post treatment).

The most of the failure takes place at the interface of the bonding for which bond strength is very important. Bond strength increases between 28 days to 1 year after which failure may occur. Hence bond strength should satisfy after 1 year of repair. A more stiff material than parent concrete is suitable for crack repair. All corrosion related cracks should be tested by corrosion analyzer etc. All water retaining structures should be tested for water tightness of the structures. Structural crack repairs should be tested for an in-situ non destructive load testing to demonstrate satisfactory performance under an overload above the design working value after 28 days.

4.3 Performance requirements of repair materials and systems

New repair materials and methods are developing day by day which is not followed with enough experience on their performance. The selection of the best repair option should be based on technical and economical (apart from social) considerations and, therefore, it seems that a life cycle cost analysis, (LCCA) is the most suitable methodology for making an inter comparison between them. This can be calculated by repair index method (RIM) which is based on defining a set of requirements: safety, serviceability, environmental impact, durability and economy that are quantified through certain weightage given to them based on level of importance for determining repair performance indicators (RPI). All indicators can be ranged in four categories such as slight (4), moderate (3), severe (2) and very severe (1).The performance requirements for calculating repair index is given below.

- Safety

It is related to the structural safety during and after repair.

  - Structural consequences of the failure
  - Failure type
  - The quality control of the repair execution
  - The feasibility of post repair monitoring
  - Safety of workers
  - Safety of users

- Serviceability, functionality, aesthetics

They are related to the limit state on serviceability during and after the repair.

  - Fitness for use
  - The disturbance of the aesthetical appearance of the structure due to the repair or to its dimensions or function.

- Environmental impact
  - Emission of pollutants to the environment during and after application
  - The sustainability of the materials and techniques used in the repair.
- Durability
  - The expected service life

The repair itself has been identified as one of the RPI of this requirement. The four categories have been classified based on repair duration of 15, 30, 50 or more than 50 years.

  - Number of attack types
  - The aggressivity of exposure

- Economy
  - Direct cost by m^2 of structure,
  - Extension of the damage (m^2)
  - Period of disturbance or stopping of the functional use of the structure
  - Maintenance cost of the structure after being repaired
  - Need of preparation of the substrate.

The repair index is calculated by assigning some percentage to all those five factors and taking their weighted arithmetic mean. The economy is given as 50%, Durability is given as 20%, and other 30% equally divided among safety, serviceability and environment. Sometimes safety is given more importance. Higher the repair index value of the system more suitable for a cost economy durable repair and considering all other factors. Lesser the repair index value may not have a cost economy and durable repair system. This analysis will help to find out an economy and a durable repair system.

5.0 Safety, Health & Environment

5.1 Material safety

Some of the Crack repair materials are hazardous and some are non-hazardous. However Material Safety Data Sheets (MSDS) should be read and understood before the application. Many of the materials are corrosive or flammable for which care should be taken for transportation, storage, application and disposal of such material. The chemicals can change or decompose under storage conditions. Generally all such polymeric materials should be kept in cool areas. Proper label has to be given during storage.

Education of Personnel: All the people should be informed of the characteristics and hazardous of those materials that they are going to handle.

5.2 Personal Safety

- Wearing protective clothing and protective eyewear where required
- Wearing rubber gloves or barrier creams for hand protection
- Having eye wash facilities available
- Wearing respirators where needed
- Providing ventilation of closed spaces
- Secured storage of hazardous materials
- Having necessary cleaning materials on hand
- Notifying occupants of pending repair procedures

5.3 Health issues

Typical health problems which may be encountered when carelessly handled are:

- Skin irritation such as burns, rashes and itches old skin sensitization due to allergic reactions. This can occur if the materials come in direct contact with the body then shower immediately with soap and water of the materials come in contact with the eyes then flush out with large amounts of water for at least 15 minutes followed by immediate medical check-up.

- Most solvents have some degree of volatility and the vapors can be toxic when inhaled.

5.4 Environmental issues

- Emission of pollutants to the environment during and after application : The materials used should be of low VOC or no VOC contents.
- The sustainability of the materials and techniques used in the repair. It should be considered in terms of materials and energy consumed. Systems which consume higher amount of energy are not eco-friendly. Materials which release chemical contaminants should be avoided.
- Disposal of solvents: Disposal of excess materials, disposable protective gear and empty containers should be taken care. Some materials can be incinerated.

6.0 Bill of Quantities (BOQ) of Structural Repair

A standard bill of quantities of concrete structural repair and strengthening is given in table below for a reference.

Sr.	Description	Unit
1.	**Injection Grouting**	
1.1	**Nozzle Fixing:** Drilling 12-16 mm dia holes at honeycomb portions / voids / construction joints cracks etc spaced at specified spacing and placing 8-12 mm dia. Nozzle of length 75 mm suitable for grounting into a 150 mm deep hole using polymer mortar including cutting of nozzle after the grounting and finishing with polymer mortar etc. complete	Nos
1.2	Drilling 16 mm dia holes at honeycomb portions / voids / construction joints etc. at spacing specified and placing 12 mm PVC flexible tubes for grouting and sealing the gaps with quick setting repair mortor (spacing as per detailed specifications).	Nos
1.3	Drilling 13 mm dia holes and providing & fixing special injection nozzles in cracks and joints in columns, Beams, silo shells and other concrete members where major honeycombing is found by drilling 12 mm dia. Holes at a grid specified for Epoxy grouting and sealing. (spacing as per detailed specifications).	Nos
1.4	Providing and applying injection grouting through the nozzles provided into the cracks / homeycombed areas by suitable grouting pump under pressure till the refusal including all labour, supervision, tools and tackles and transportation etc., complete as per specification and as directed.	Nos
a.	Cement slurry mixed with non-shrink polymer grouts	Kg
b.	a. Using low viscous two components epoxy resin based grouts of Dr.Fixit Epoxy Injection Grouts to meet the requirement of ASTM C-881 as per direction of Engineer-in-charge.	Kg
c.	Super low viscous (100-150 CPS) epoxy resin injection grouts.	Kg
d	Using cementitious injection grouts mixed with OPC cement, dry sand upto 2mm admixed with Dr. Fixit Pidicrete AM to meet the requirement of ASTM C 109: 99 and ASTM C 307 as per direction of Engineer-in-charge.	Kg
e	Using low viscous two components epoxy resin based grouts of Dr.Fixit Epoxy Injection Grouts to meet the requirement of ASTM C-881 as per direction of Engineer-in-charge	Kg
2.0 Structural strengthening by Fibre warpping		
	Fibre Wrapping : Strengthening structural elements with specified Fibre wrapping and compatible saturate, by dry/wet layup system including the following and as per direction of Engineer-in-charge:-	
	Surface preparation: Grinding / moulding concrete substrate, cleaning it with wire brush removing oil, laitance if present, rounding sharp edges to min 25mm radius etc. complete. Profilling: Applying compatible primer of approved make and brand on prepared substrate, filling the holes and uneven surface with thixotropic putty etc.complete.	
	Wrapping: Wrapping the fibre sheet with approved / recommended overlapping to structural element at desired orientation using tamping roller to avoid any air voids etc. repet the same procedure for multiple layer with the interval of 8 hrs.	
	Sand Pasting: Applying second coat of saturate after min 12 hrs. rectify air voids if any, paste the coarse sand on it to make surface rough to take any further finishes. (Mode of measurment: Per Sqm surface area of application per layer).	Sqm
2.1	Glass Fibre:With non metallic composite fibre sheet (900 GSM).	Sqm
2.2	Carbon Fibre:With non metallic composite fibre wrapping system comprise of uni-directional high strength carbon fibre sheet (200 GSM).	Sqm
3.0 Structural strengthening by Steel plate bonding.		
	Providing & strengthening of structural steel members at their locations by providing splice plates, additional plates to the flanges or web of the members providing stiffeners etc as per the requirment and as directed including cutting fixing in position by bolting and welding.	Kg

7.0 Conclusion

The concrete repair requires breaking by mechanical means where the dust, noise and vibration are generated. Personal safety needs to be ensured by PPE, and standard safety procedures need to be strictly adhered during the repair work.

The demolition work creates large pieces of concrete and aggregate, which can be cleaned, graded and used as recycled aggregates in new concrete.

The environmental issues in concrete repair and strengthening system should be considered such as use of green material, VOC content, recyclability, energy efficiency, embodied energy, life cycle cost analysis and sustainability.