Forensic Investigation and evaluation of the structural and durability performance of the polymer based repair material

Poonam I. Modi*, Chaitanya J. Patel**
*(Assistant Professor, Applied Mechanics Department, L.D. College of Engineering, Ahmedabad)
** (Ex-Professor, Applied Mechanics Department, L.D. College of Engineering, Ahmedabad)

ABSTRACT
Forensic investigation of the polymer based repair material was carried out. The material was tested for its various mechanical properties like Compressive strength, Flexural strength, Bond strength and Modulus of Elasticity. The effectiveness of the material thus investigated was later evaluated for its structural and short term environmental durability performance by repairing a set of reinforced concrete beams using the same material. This paper reports an experimental programme to this effect. Reinforced concrete beams were cast and wet cured under laboratory conditions. The repair material was injected into the partially cracked beams which were then subjected to accelerated deterioration by spraying salt water for duration of 3 months under alternate wetting and drying cycles to induce the ingression of chloride ions. The grouted beams were then tested in compression & flexure. It was interesting to observe the load carrying capacity of the test as well as the control specimens were in close agreement. The modulus of elasticity of the repair material as determined from the tests was found to be very low. In spite of the large strains in the repair material there was no adverse effect on the load carrying capacity of the grouted beams.

***Keywords* – Accelerated deterioration, Compatibility, Bond strength, 2-Pack Epoxy Resin system, Flexural capacity**

1. INTRODUCTION
Cast in-situ concrete structures are hardly ever built under ideal conditions so, for a variety of reasons, defects may occur as the concrete is being cast or very soon afterwards. It goes without saying that cracking in a concrete structure, whether it be reinforced or not, is undesirable. It certainly mars appearance, and in the course of time it will also affect its serviceability. Whilst the specific causes of cracking in concrete are manifold, it must be appreciated that some type of cracks can directly arise from construction practices unless precautions are taken. The majority of faults and problems are caused by lack of attention to design details, specifications and poor-in-situ workmanship. Material, although important is less of an evil. Material does not perform, but the end product made from a material- the repaired structure performs. The concern here should not be solely with repair material themselves, but with the gray area of overlap between material properties and the end Engineering product- the repaired structure. A weakened structure may need to be repaired or strengthened to bring it back to its original intended capacity. Similarly, a sound structure may need to be upgraded or retrofitted to bring about an enhancement of its capacity to carry additional load. The erstwhile concept of "repair and maintenance" of structures by frequently re-plastering and re-painting is a thing of the past and "repair, strengthen, protect" using newer yet proven methods and materials is the new maxim.

While carrying out a repair we attempt to create a bond between the old structure and new repair material. A good repair material should have lowest shrinkage, low modulus of elasticity and low coefficient of thermal expansion. The normal cement based repair systems are not good enough because of low tensile and flexural strength, poor bonding with set concrete, porosity and poor flexibility. Introducing polymers into cement systems can solve these problems. Polymer improves the physical and chemical properties of pure cement systems. However, for many typical situations, even the polymer modified cementitious systems do not meet the requirement. The latest generation repair products are based on reactive resins, accelerators, fillers, etc., where cement has been totally eliminated. The most popular reactive resin for this purpose is Epoxy. Use of Epoxy Resin as a repair material has been rising steadily all over the world since their commercial introduction in the early 1950s.One of the primary factors assuring the durability of concrete repairs is the resistance to cracking. Concrete repair is an intricate, complex and composite system. A Durable Repair can be defined as "the capability of a repaired structure and its components to maintain the serviceability over the designed period of time in a specified environment".

In order to have a durable concrete repair, it is very essential to have compatibility between the repair material and existing concrete substrate, and for that it is necessary to consider repair material as a "part of the whole, a component of the composite". The compatibility is crucial, as the repaired member must behave monolithically and carry all stresses in the region of the repair without distress and deterioration. The lack of widely agreed upon methods of testing leaves repair materials subject to a limited evaluation that is driven more by manufacturers than by the users. All too frequently only the isolated properties of repair materials are emphasized, whereas the more important properties of the composite are neglected. Hence the testing of the composite repair under stimulated field conditions is more appropriate.

An attempt has been made in this paper to conduct tests to determine the various mechanical properties of the repair material. Just as before using concrete, the concrete mixes are designed and tested, similarly the repair material must also be tested for its properties. The tested material was then checked for its efficacy in restoring the strength and exhibiting compatibility with the substrate by subjecting the grouted beams to accelerated deterioration.

2. EXPERIMENTAL PROGRAMME

The experimental programme was divided into two stages. In the stage one various tests were conducted to determine the mechanical properties of the repair material whose effectiveness was to be studied later.

2.1 Testing of Repair Material

Tests like compressive, flexure, and bond strength and Modulus of elasticity were carried out to evaluate the performance criteria of selected commercially available repair material. Mechanical properties of Epoxy resin – a two pack grouting material was determined in accordance to the test methods in BS 6319 parts 1-12, initially drafted by FeRFA. The nit material used for the testing consisted of a two part epoxy resin system. It was a liquid system consisting of a base and a hardener. The individual components were sampled by mixing the proportion as specified by the manufacturer in the proportion of Base: Hardener as 3.359:1Method: All the constituents were hand mixed in a porcelain bowl. The mixing was then continued until the material was homogeneous in appearance. The mixed material was then immediately transferred to the moulds. Moulds used were as per the requirements stipulated in BS:6319:1983 and were of the size to produce cuboids, rectangular prisms, plaques for compression, flexure, modulus of elasticity & bond strength respectively.
Since the nit material formed a free flowing compound, the moulds were kept level during filling. As the formation of the meniscus was making it difficult to produce a casting with an upper face flush with the top of the mould, a loosely fitting glass plate coated with the releasing agent was used. The upper surface of the specimen was finished so that it was smooth and flush with the mould surface. The filled moulds were then cured at a temperature of 24±1°C. Demoulding was done after 24 h and care was taken not to damage the specimen whilst taking it out from the mould. Specimens were then cured for a period of 7 days.

Specimens used were cubes of size 40 mm x 40 mm x 40 mm for compressive strength. Flexural and Modulus of elasticity were determined for rectangular prisms of size 25mm x 25mm x 320 mm. The properties as determined from the tests are mentioned below in the Table 1

Table 1 : Properties of tested repair material

Mechanical Property	Mean strength
1. Compressive strength	83.54 MPa
2. Flexural strength	38.93 MPa
3. Modulus of Elasticity	3150.30 MPa

Bond Strength (Slant shear Method): Most uses of resin compositions involve their application to hydraulic cement concrete and require the development of a strong adhesive bond between these two materials. The purpose of this test was to investigate the strength of that bond. Bond strength was performed on the composite test specimens that were right true prisms having dimensions 55 mm x 55 mm x 150 mm sawn from composite plaques having dimensions of 55 mm x 150 mm x 150 mm. Bond strength was found on the specimens in both dry and wet conditions.

The hydraulic cement concrete plaques were prepared and sawn as mentioned in BS:6319. The individual components of resin composition were sampled by mixing the proportion of Base:Hardener 3.359:1.

The resin composition was then applied on the half plaques by means of a brush. The two halves were then brought together and were kept in plane by means of a stout rubber – band as shown in Fig: 1. The bonded plane was then left undisturbed until the resin had hardened.

Fig 1 Preparation of plaques for Bond strength

After the resin had cured, the composite plaque was again sawn into three sections, so that in the middle section the repair interface bisects the prism at a nominal angle of 30° and runs out of the prism on two opposite long sides, as shown in the Fig 2 below.

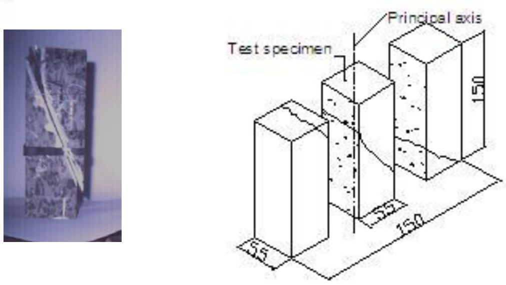

Fig 2 Specimen under Slant shear

The slant shear bond strength for the specimens in dry condition as determined from the test was 43.75 Mpa and the slant shear bond strength for the specimens in wet condition was 61.157 Mpa.

2.2 Effectiveness of the repair material

The selected repair material which was evaluated for its performance criteria exhibited excellent properties such as high strength and strong adhesion with concrete. However the laboratory studies were not terminated there; experiments were performed to study the effect of the accelerated environmental deterioration on this composite system formed by the repair material and the existing concrete substrate for its load carrying capacity, and ability to retard the ingression of penetration of aggressive elements in to concrete.The experimental programme consisted of 3 main steps:

2.2.1 Preparation of the reinforced concrete (RC) beams:

The details of the concrete mix, cube strength and the reinforcement strength details of the beams are described in the Table 2,3 & 4. Two sets of reinforcement cages were prepared for the beams. The beam size and the other details were fixed based on the availability of the formworks, testing platforms. RC beams were wet cured for 28 days. Total 12 numbers of beams were cast.

Table 2 : Mixed Proportions per cubic meter of concrete

Mix	Cement (kg)	C.A(kg)	F.A (kg)	Water
M20	391	540.58	1186.5	191.6

Table: 3 Steel Reinforcement Details

Bar dia	Yield stress	Ultimate stress
8 mm	395.9 MPa	524.3 MPa
10 mm	484.3 MPa	561.67 MPa

Table: 4 Concrete Properties (MPa)

Specimen casted	Age (days)	Avg. cube strength in MPa	Avg, cylinder strength in MPa
Day 1	28	30	19
Day 2	28	33.33	20
Day 3	28	30	21.65
Day 4	28	32	20

2.2.2 Preparation of the Test specimens:

Out of the 12 beam specimens, 10 of them were prepared as the test specimens. 7 out of 10 were the specimens which were cracked and grouted with the epoxy resin and the remaining 3 were the fully monolithic sections i.e. un-cracked and un-grouted. The beam specimens were loaded under two point loading to simulate the artificial cracks. The loading set up is as shown in the Fig 3.The width of the cracks for the study were selected keeping in view the normal size of the cracks, 1 mm to 3 mm encountered in various structures for epoxy grouting. The cracked specimens were then repaired. The cracks were grouted under pressure with a low viscosity epoxy system. The characteristics & the mechanical properties of the selected repair material is described in the Table 5

Table: 5 Properties of repair material (low viscosity epoxy system)

Ratio of Base: Hardener		3.359:1
Mix viscosity	Centipoise	360
Pot life at 30°C	Minutes	30
Compressive strength	MPa	83.54
Flexural strength	MPa	38.93
Modulus of elasticity in	MPa	3150.3
Bond strength	MPa	43.75

The epoxy grouting of the cracks was done through surface nipples i.e surface entry ports. The selected two pack resinous system was then injected into cracks by means of pump at a pressure of 4 kg/cm2. The process was carried out until the whole length of the crack was treated. The system was then allowed to be cured. .Pulse velocity readings were taken to provide quick and effective quality assurance for determining the penetration of the repair material into the cracks.

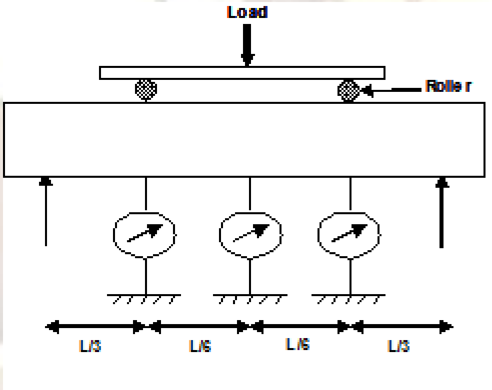

Fig 3 Loading Set-up

2.2.3 Exposure of the test specimens to accelerated deterioration:

In order to evaluate the short term durability performance of the repair material the test specimens were subjected to salt water spray. Accelerated deterioration of the specimens was simulated by extensive salt water spray accompanied by alternate wetting and drying for duration of 3 months. The purpose of inducing the ingression of chloride ions by salt water spray was to give way to corrosion of reinforcement. It is only as a consequence of this corrosion that the surrounding concrete gets damaged and is one of the major causes of deterioration of concrete. The drying periods were kept longer supporting the fact that wetting of concrete occurs very rapidly and drying is much slower. Moreover the diffusion of ions during the wet periods is fairly low.

3. Test Results and Observations

The test specimens thus prepared and subjected to accelerated deterioration were then tested to failure under two point loading. Constant observations were carried out for the crack pattern with the help of magnifying glass and the new cracks were marked in black. Since the controlled and test specimens were to be tested together, the beam specimens were re-numbered from 1 to 12 for identification. Beams with nos 1,2 & 4 were the ones that were uncracked & ungrouted but subjected to accelerated deterioration. Beams 5 & 6 were the controlled specimens and rest all the beams were cracked, grouted and subjected to salt water spray.
General observations concerning the failure of the beams and comparisons of the specimens are discussed below.

Performance attributes of interest were (i) The location of crack relative to the initially repaired crack, (ii) The load carrying capacity of the test as well as the controlled specimens.

Most significantly the failure mode of the test specimens was that the new crack propagated through the parent concrete and not through the repaired crack indicating that both the Bond strength and the material strength of the repair material exceeded the strength of the concrete adjacent to the repaired crack in spite of being subjected to accelerated deterioration. The comparison of the flexural test data of both the test as well as the control specimens is summarized below in Table 6.

The effectiveness of the repair material in not allowing the ingression of the water and chloride ions was also checked. In order to study the same, the chloride profile was prepared for both the control and test specimens. The profile was determined by the chemical analysis of dust samples obtained by incremental drilling to depths of 25 mm, 50 mm and 75 mm from the surface.

The extent of the carbonation was also determined in the specimens. This was done by treating freshly broken surface of concrete with a solution of phenolphthalein in diluted alcohol. An intense red (pink) color was exhibited by the surface indicating that accelerated deterioration did not show any extra carbonation in the test specimens.

Table 6 Summary of the Flexural Test Data

Beam No	**Flexural capacity, kN**		**Shear capacity, kN**		**Failure Mode**
	Theo [1]	Exp [2]	Theo [1]	Exp [2]	
4	64.72	80.50	20.38	40.25	Shear, new crack in concrete
5	64.72	88.98	20.38	44.49	Flexure, new crack in concrete
9	64.72	97.46	20.38	48.73	Flexure, new crack in concrete
10	64.72	101.70	20.38	50.85	Flexure, new crack in concrete
11	64.72	114.20	20.38	57.10	Flexure, new crack in concrete
12	64.72	110.00	20.38	55.00	Shear, new crack in concrete
1	82.13	118.30	22.07	59.19	Failed in shear
2	82.13	151.70	22.07	75.85	Failed in shear
3	82.13	80.50	22.07	40.25	Shear, new crack transverse to repaired crack
7	82.13	101.70	22.07	50.85	Shear, new crack transverse to repaired crack
8	82.13	97.50	22.07	48.75	Shear, new crack transverse to repaired crack
6	82.13	130.80	22.07	65.40	Failed in shear crack running diagonally
1 – Theoritical ; 2 – Experimental					

4. Conclusion

The following conclusions were drawn based on the experimental studies that were carried out:

1. The mechanical properties of the repair material selected for study, after testing was found to be as per the required standards.
2. The flexural test data indicates that the load carrying capacity of the test as well as the control specimens are in close agreement. This proves the utility of the epoxy resins for grouting of cracks in concrete for restoration of strength.
3. The Modulus of elasticity of epoxy resins as determined from the test was found to be very low, in spite of the larger strains in epoxy there was no adverse effect on the load carrying capacity of the grouted beams.

4. The chloride profile of the dust samples of control and test specimens did not vary much, which proves the effectiveness of the repair material in restraining the ingression of water and chloride ions.
5. The new cracks propagated through the parent concrete indicating that in spite of being subjected to accelerated deterioration, bond strength and the material strength of epoxy resins exceeded the strength of substrate.

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