Static and Cyclic Performance of Repaired Reinforced Concrete Beams Using a Range of Underlays

Abid Abu Tair and Mohamed Nabil Omar
Faculty of Engineering & IT, British University in Dubai, Dubai, U.A.E
Email: abid.abu-tair@buid.ac.ae, eng_m_nabil@yahoo.com

***Abstract*—The repair and strengthening of concrete structures has become a significant area of specialization in the construction industry, in many countries the cost of repair and strengthening is accounting for nearly 50% of the overall expenditure within the construction industry. Generally, concrete properly made and compacted has a high resistance against deterioration and possible damage. However, structures may suffer damage or deterioration from a variety of internal and external causes. Repair may carried out to protect the reinforcement, to restore the structure to its original strength, or merely to restore the original appearance. Whatever the reason, an essential requirement is that the repair achieves a satisfactory bond with the substrate concrete and maintains good adhesion and protection over the service life of the structure. A range of repair of repair materials and techniques are available to the maintenance engineer, the selection of the best suitable materials and most effective technique are essential in a durable and effective technique. In this investigation, three types of materials used representing the full range of repair materials available, namely, a basic cementitious, a polymer modified cementious and an epoxy render. Twelve reinforced concrete beams, with preformed faults, were repaired and tested under three loading systems, a static loading, a service level cyclic loading and a near ultimate fatigue loading, the results from these beams were compared to control beams with similar reinforcement and made from similar concrete, but with no faults.**

***Index Terms*—repair, strengthening overlays/underlays, reinforced concrete, static & cyclic loading**

I. Introduction

The repair and strengthening of concrete structures has become a significant area of specialization in the construction industry, in many countries the cost of repair and strengthening is accounting for nearly 50% of the overall expenditure within the construction industry [1]. Generally, concrete properly made and compacted has a high resistance against deterioration and possible damage. However, structures may suffer damage or deterioration from a variety of internal and external causes. The internal causes being unsoundness of cement, poor quality aggregates corrosion of the reinforcing steel or an adverse chemical reaction between cement and aggregate. External causes are overloading, mechanical damage, chemical attack, freezing and thawing. It is therefore vital that, before any attempt is made to repair damage, the causes should be clearly established.

Repair may carried out to protect the reinforcement, to restore the structure to its original strength, or merely to restore the original appearance. Whatever the reason, an essential requirement is that the repair achieves a satisfactory bond with the substrate concrete and maintains good adhesion and protection over the service life of the structure.

A range of repair of repair materials and techniques are available to the maintenance engineer, the selection of the best suitable materials and most effective technique are essential in a durable and effective technique, limited number of studies looked at the cyclic behavior of patch repaired systems and materials [2,3]. In this investigation, three types of materials were used representing the full range of repair materials available, namely, a basic cementitious, a polymer modified cementitious and an epoxy render. The main properties of the three materials including bond strengths were reported by Abu -Tair et al [4-8], Abu -Tair el al [9] also reported on the effectiveness of resin injection of cracked reinforced concrete beams similar to those in this investigation and using similar loading systems. The cost of the repair materials is a major factor in deciding on a repair system, the cost of typical cementitious: polymer modified: epoxy mortars vary in the ratio 1:6.5:20 respectively [10].

Twelve reinforced concrete beams, with preformed faults, were repaired and tested under three loading systems, a static loading, a service level cyclic loading and a near ultimate fatigue loading, the results from these beams were compared to control beams with similar reinforcement and made from similar concrete, but with no faults. In other work by the author, different types of faults were investigated under the same loading systems, another test series looked at resin injection of beams with and without faults and tested statically and subjected to the three loading systems after injection, resin injection was shown to work very effective. [6, 7].

II. Experimental Programme

Twelve reinforced concrete beams 2500mm long, 190mm deep and 140mm wide cast and repaired. Apart

Manuscript received August 8, 2019; revised March 15, 2020.

doi: 10.18178/ijscer.9.2.138-143

from the controls, the beams were all cast with one preformed fault requiring a patch repair. The type of fault was chosen to test the ability of the repair material to transmit the various stresses initiated in the tension zone through the substrate and into the upper section of the beam. The recent trend towards strengthening or improving the durability of a concrete element gave rise to the need for the repair systems to transmit shear and tensile stresses. This factor also affects the choice of the fault types. The stresses include shear stresses, it was therefore decided not to use any links in the beam and to rely on the repair material for transmitting all the stresses to the concrete section. Details of the types of beams, repair materials and loading system are shown in Table I below.

TABLE I. DETAILS OF THE TESTED BEAMS INDICATING BEAM TYPE, REPAIR MATERIAL AND LOADING SYSTEM USED.

Beam No.	Beam Type	Repair Material	Loading system	Figures
RCONl	Repaired	Concrete	Service and Near Ultimate	9
RCON2	Repaired	Concrete	Service and Near Ultimate	10
RCON3	Repaired	Concrete	Service and Static	3+6
RCEM4	Repaired	SBR	Service and Near Ultimate	11
RCEM5	Repaired	SBR	Service and Near Ultimate	12
RCEM6	Repaired	SBR	Service and Static	4+7
REPX7	Repaired	Epoxy	Service and Near Ultimate	15
REPX8	Repaired	Epoxy	Service and Near Ultimate	16
REPX9	Repaired	Epoxy	Service and Static	17
RCTLlO	Control		Service and Near Ultimate	13
RCTLll	Control		Service and Near Ultimate	14
RCTL12	Control		Service and Static	5+8

The types of repair materials used for patch repairs range from the basic cementitious to a wide range of modified cementitious to another range of epoxy-based materials. To cover the very wide range of repair materials, it was decided to choose three representative repair materials. The first was an epoxy type material, the second was a cementitious modified material and the third was a basic Portland cement concrete repair material.

The epoxy repair material was a lightweight epoxy render; this will be referred to thereafter as EPX . The cementitious modified repair material was an SBR (styrene butadiene rubber, commercially known as Ronafix). A major concrete repair firm in London used the concrete repair material. For both the SBR and epoxy mortars, two coats of primer were applied to the reinforcement. The manufacturer's instructions were strictly adhered to, for both the mixing and curing stages. fu order to assess the effect of cyclic loading on the repaired / strengthened concrete beams, they were subjected to three loading systems, one static and two cyclic. fu the cyclic systems, two load ranges were applied. The first load range was from 30 to 60% of the average ultimate static strength. This load system will be referred to a 'service loading'. The second cyclic load range was from 40 to 90% of the average ultimate static strength; this will be referred to as 'near ultimate loading'. The beams were tested in four point bending. The load was applied using a hydraulic -servo controlled jack at a frequency of two cycles per second and the results recorded electronically.

All twelve beams were cycled at service loading to one million cycles. For practical reasons, thetests were terminated at this point and they were then tested to failure by either statically loading them to failure or increasing the cycling range up to 40-90% of the ultimate static failure load. The static failure loads for the various types of beams were obtained from previous tests. Four beams were tested statically applying the load in 5kN increments, the other eight beams were cycled between 40 - 90% of the ultimate load.

All beams were cast from the same mix of concrete having nominal proportions 1: 1.1: 2.54: cement: sand: aggregate and a water-cement ratio of 0.42. The mix was designed in accordance with the BRE design to give a characteristic strength of 40 N/mm^2. After casting, the beams were cured for seven days in water, then removed and left to cure at room temperature. The beams were designed as under-reinforced beams with flexural failure expected. The beams were only reinforced in the tension zone with two 12mm diameter high yield steel. The theoretical ultimate failure load was calculated in accordance with BS8110 [11]. The testing of over forty 100mm cubes in compression gave a characteristic strength of 60 N/mm^2.

The various types of faults were performed before casting, for all the faults excess concrete was left so that it had to be later cut. Twenty-eight days after casting, the surface of the preformed fault was cut with a Kango hammer to create a roughened surface over the substrate. Finally, the whole surface was pressure washed to remove any remaining concrete particles and dust. The steel was usually cleaned by wire brushing. The beam was then ready for repair.

III. STATIC AND CYCLIC LOADING

The repaired reinforced concrete beams together with the control beams were tested in four a point bending as shown in Fig. 1. The load was applied using a hydraulic servo controlled jack and the results recorded electronically.

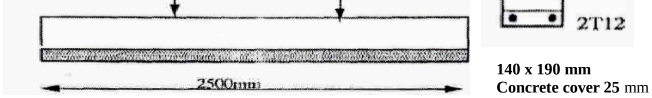

Figure 1. Beam and fault dimensions, shear force & bending moment diagrams.

IV. RESULTS AND OBSERVATION

The purpose of cyclic loading is to investigate the effectiveness of the repair and strengthening techniques employed in this investigation. Such type of repeated loading may arise when the structure is subjected to earthquake excitation and when the ratio of live and dead loads is very high. Apart from the epoxy repaired beams (which were tested after 7 days); the other beams were tested not less than 28 days after repairing.

A. Crack Patterns

The crack patterns for the various types of beams are given in Fig. 2. During the loading of the beams, a series of hairline cracks developed and they occurred in the zone of maximum moment with no sign of shear cracking. The range of loads at which cracks first appeared in the repaired. Material being typically between 40 to 50% of the ultimate load for the SBR compared with 20 to 30% for the concrete repair. The control beams generally first exhibited cracks at the same range as the SBR repaired beams.

It was observed that where the cracks that developed in the shear zone were more closely spaced than those were occurring in the middle third, a shear/bond failure occurred. When the cracks were closely spaced in the middle third and those occurring in the shear zone were more widely spaced, a bending (or flexural) failure occurred.

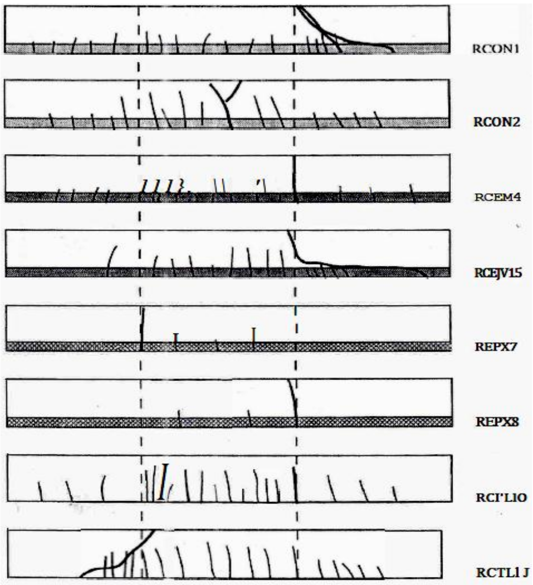

Figure 2. Crack pattern of tested beams.

From the figures it can seen that in the case of the SBR repair, the number of cracks were slightly less than those that occurred in the control or the concrete repaired beams. This to be expected as the SBR repair is more of a homogenous material and is much stronger in tension. A crack microscope was used to measure the crack widths at various depths of the beam. The cracks ranged in width from 0.1-2.0mm and they narrowed down to 0.03mm or less nearer to the compression zone. A branching of the micro-cracks from the main crack was observed especially around the large pieces of aggregate.

During the loading of the epoxy repaired beams, a series; of crackles could be heard before any main cracks were observed. This is likely to be due to the de-bonding either at the interface between the substrate and the epoxy repair or at the surface of the reinforcement. The number of cracks was noticeably less than those occurred in other beams. This is to be expected of the epoxy being more of a homogenous material.

B. Beams Cycled At 'Service Loading'

The service loaded beams were cycled at two cycles per second, with the maximum and minimum loads and deflections being logged every two hours or where a maximum deflection changed by more than 0.05mm. Figs. 3-8 show the deflection behavior of the three beams cycled at service, before being tested statistically, with the first graph in each pair showing deflection against number of cycles and the latter showing the load against deflection. The increase in deflection was rapid in the early stages with an average 50% of the change taking place in the first 10,000 cycles. Thereafter, the changes in deflection were in the order of 0.15mm/100,000 cycles although in the case ofRCEM6 there was a sudden increase of 0.42mm at approximately 0.6M cycles as shown in Fig. 4. The cause of this occurrence could not be ascertained, but an instrument malfunction caused by fluctuation in the power supply cannot be discounted. The service loading was limited to one million cycles that took more than five days to complete.

C. Static Test Results

The beams were loaded up to 40 kN in increments of 5 kN and thereafter in increments of l kN until failure occurred. The mid span deflection was recorded for each load increment. The three beams tested .failed in flexure with the cementitious failing at 47.SkN and the control at 53kN.The stiffness of the repaired/strengthened beams was seen to be very similar to that exhibited under the original loading. The crack patterns were also similar to the other statically tested beams, and cyclic loading did not seem to alter the beams many way.

RCON3 showed unique results when compared to other beams, as it failed statically at 62kN which is considered to be fairly high. This was due to the movement of the reinforcement during the vibrating of the concrete thus increasing the effective depth which further increases the ultimate static load by about 20% (see Figs. 6-8.).

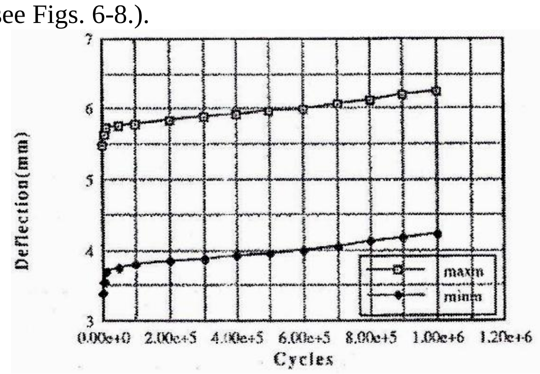

Figure 3. Beam RCON3 First Cycled at Service Loading to 1M cycles, before being Tested Statically.

D. Beams Tested at 'Near Ultimate' Loading

1) RCON1 and RCON2.

These beams showed similar behavior in the early stages of cycling as other tested beams. A significant part of the change in deflection was again observed to be occurring in the early stages, that is, in the first 10,000 cycles where crack initiation and propagation occurred. Thereafter, the deflection continued to increase at a much greater rate than the service loading and accelerated rapidly in the last cycles prior to failure.

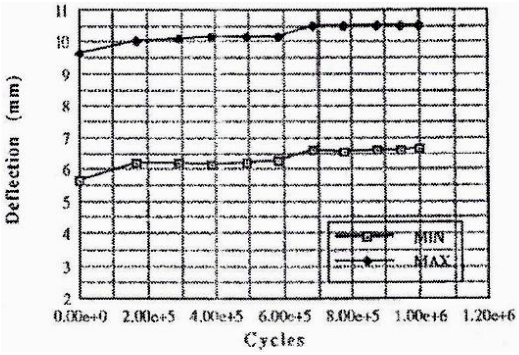

Figure 4. Beam RCEM6 first cycled at service loading to 1M cycles, before being tested statically.

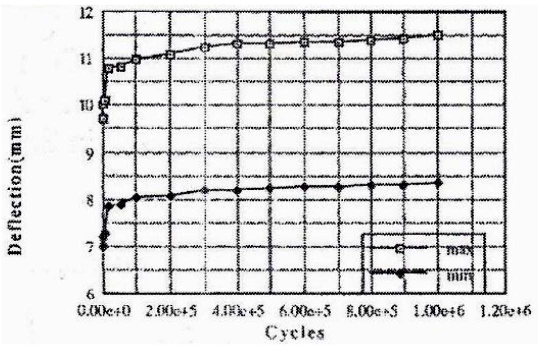

Figure 5. Beam RCONT12, first cycled at service loading to 1M cycles, before being tested statically.

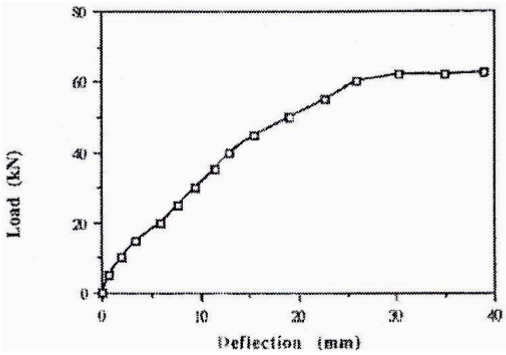

Figure 6. Beam RCON3 showing load against deflection.

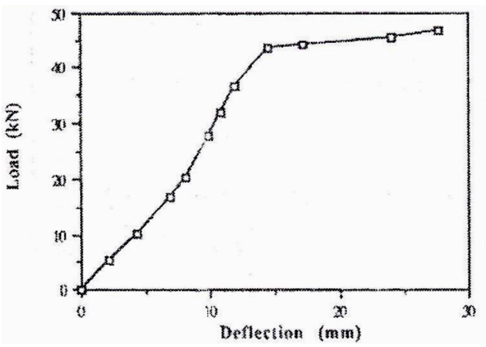

Figure 7. Beam RCEM6 showing load against deflection.

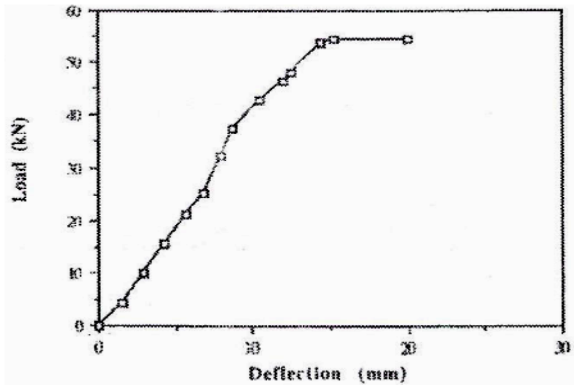

Figure 8. Beam RCONT12 showing load against deflection.

Due to the nature of the concrete as a repair material, the beams exhibited a different behavior when loaded at 'near ultimate'. This is seen in the difference in the average number of cycles endured before failure .This was in the order of 118,000 cycles, which is more than 50% less than beams repaired with SBR cementitious modified mortar. One of the tension bars was actually broken which could again be attributed to fatigue failure in the reinforcement. (Figs. 9-12).

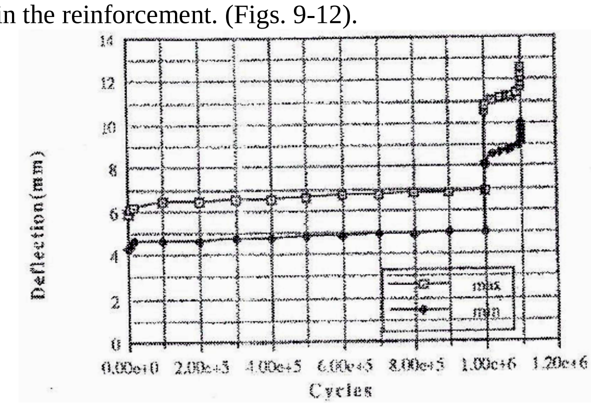

Figure 9. Beam RCON1 first cycled at service loading to 1M cycles, then to failure at near ultimate.

2) RCEM4, RCEM5, RCTL10 and RCTL11.

These beams were cycled at both service and near ultimate loading. The frequency of loading was again two cycles per second and the maximum and minimum deflections were logged every hour or where a change of more than 0.05mm occurred. In the early stages of cycling, the behavior was similar to the service loaded beams with a significant part of the change in deflection happening in the early stages. However, the deflection continued to increase at a much greater rate than the broken that could be attributed to fatigue failure in the reinforcement (Figs. 11-14).

3) REPX7, REPX8 and REPX9.

All three beams failed at the loading stage prior to cycling. The failure loads were 27, 34 and 36kN respectively. This 'unexpected' premature failure leads to further tests to determine the cause of such behavior. The test rig was first thoroughly checked to ensure that a malfunction had not occurred. This gave us good background to question the suitability of the repair material. (Figs. 15-17).

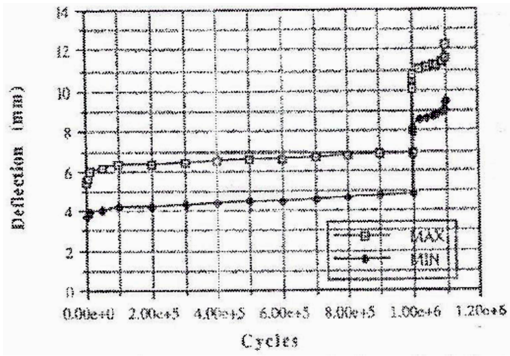

Figure 10. Beam RCON2 First Cycled at Service Loading to 1M cycles, then to failure at Near Ultimate.

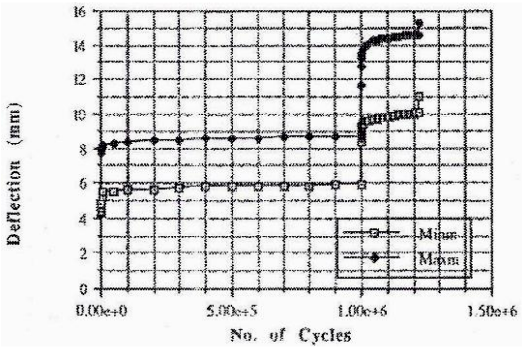

Figure 11. Beam RCEM4 First Cycled at Service Loading to 1M cycles, then to failure at Near Ultimate.

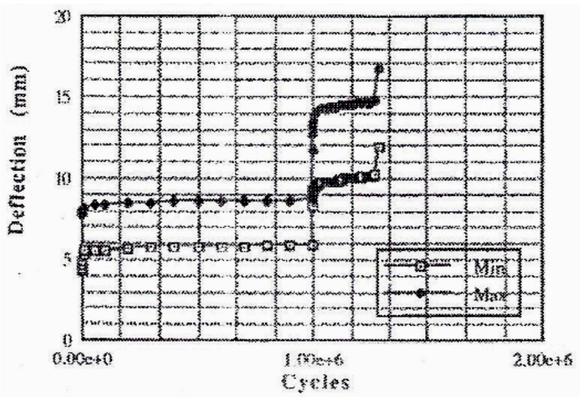

Figure 12. Beam RCEM5 first cycled at service loading to 1M cycles, then to failure at near ultimate.

It was clear from visual inspection of the beams that slippage of the reinforcement may have occurred. To verify this hypothesis, pull off tests were carried out, a total of 15 cores were cut, the results obtained indicate that the epoxy repair showed a range of failure modes from full bond failure of 1.5 N/mm2 to full material failure, be it in the concrete or in the epoxy of 1.13 N/mm2 The epoxy repair was found to be the lowest in strength when compared to other materials.

The flexural test results showed that epoxy bas the lowest flexural strength when compared with concrete, SBR and the control prisms. The compressive strength of the material was very low ran in between 5 and 15 N/mm2. In addition, different sections along the beams were cut and analyzed to verify that slippage of the reinforcement bas occurred.

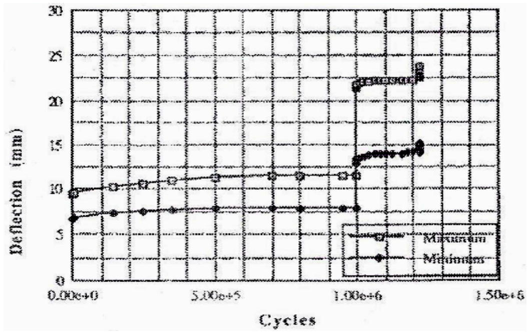

Figure 13. Beam RCONT10, first cycled at service loading to 1M cycles, then to failure at near ultimate.

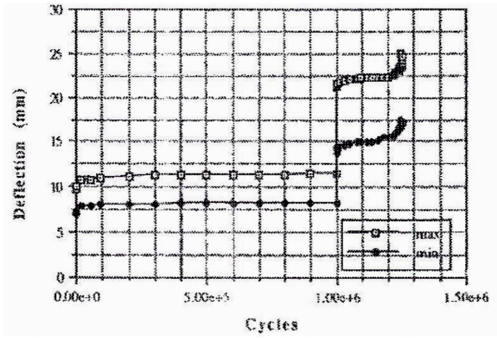

Figure 14. Beam RCONT11, first cycled at service loading to 1M cycles, then to failure at near ultimate.

It was found that the reinforcement has moved in all three beams - the slippage ranging between 25 to 32mm.This lead us to conclude that the material at hand (and not epoxy resins in general) was inappropriate for use in that particular application employed in this investigation.

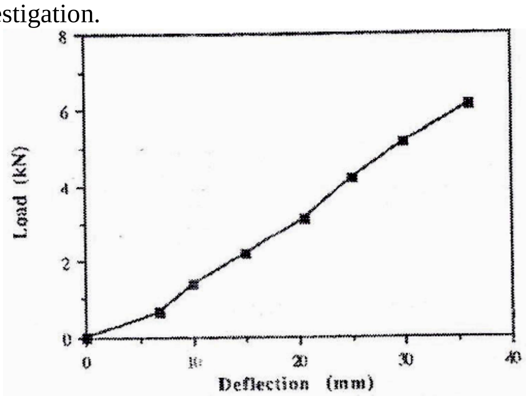

Figure 15. REFX7, showing load against deflection.

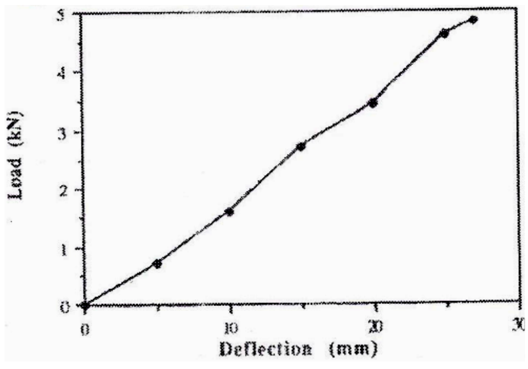

Figure 16. REFX8, showing load against deflection.

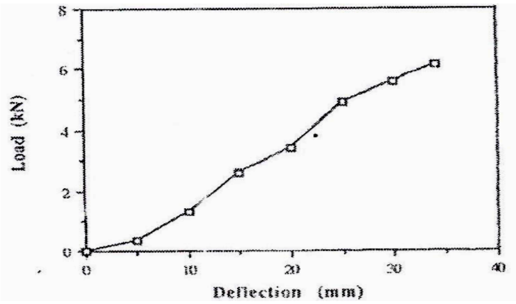

Figure 17. REFX9, showing load against deflection.

V. DISSCUSION

The aim of this investigation was to determine the behavior of repaired/ strengthened concrete. In addition, the effectiveness of different repair materials under different surface preparation and loading conditions bas been assessed and studied. These tests provide valuable information to enable the repair of damaged or deteriorated concrete to be more appropriately and accurately specified.

The results obtained give us a good indication of the reliability of the strengthening technique employed in the course of this investigation. All tests performed tend to confirm that SBR was the strongest material being able to restore the beams' original performance.

Analysis of the results of the repaired beams has shown that the epoxy repair material used and not epoxy resins in general was inappropriate or unsuitable for use in this particular application. The above fact was established in view of the test results of the various experiments conducted.

The pull-off tests carried out and the flexural strength tests confirmed the unsuitability of the material. The very low compressive strength also tends to direct us in that path. As for the concrete repaired beams, they showed a distinctive feature that becomes clear when comparing them to the SBR repaired beams. This is seen in the number of cycles endured before failure at ultimate, being at an average of 118,000 cycles for concrete compared to 250,000 cycles for SBR.

Comparing the results of the SBR repaired beams with the control beams shows considerable similarity in their behavior. The number of cycles endured by both types of beams was approximately the same. The flexural test results however indicate that the SBR is by far a stronger material having 10.72N/mm2 compared to 4.72N/mm2 for the controls. This may suggest that the technique can actually enhance the loading capacity of the beams. This could be said 'cautiously ' as results of static testing after service loading indicate a failure load of 47kN for the SBR repaired beam compared with 53kN for the controls. However, what could be said with considerable confidence is that the technique has restored the original performance and original capacity of the beam.

VI. CONCLUSIONS

The results obtained from the various tests conducted in the course of the investigation, lead to the following conclusions:

- The average number of cycles endured at near ultimate loading for the control beams repaired with polymer modified and concrete were 220,000, 250,000 and 118,000 cycles respectively.
- The ultimate static failure loads for the control beams, polymer modified and concrete were 53, 47.5 and 62kN.
- The epoxy material used in this investigation was unsuitable.
- The strengthening technique has restored the original performance and original capacity of the beam, for the concrete and the cementitious modified beams.

CONFLICT OF INTEREST

There is no conflict of interest in this research work.

AUTHOR CONTRIBUTIONS

The testing work and result analysis were carried out by the first author, the second author, worked on the drafting and editing of the manuscript.

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