

WALLAGA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

AN EXPERIMENTAL STUDY ON STRENGTHENING OF RECTANGULAR REINFORCEMENT CONCRETE BEAM BY FERROCEMENT REINFORCEMENT LAMINATES

By Gurmessa Namomsa



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ABBREVIATIONS AND ACRONYMS

A	:	Cross sectional area of the specimen
At	:	Tension span length
b_{eff}	:	Effective width
b	:	Breadth of the beam
BP	:	Control beams
BRC	:	Cast in-situ loading beam
BRP	:	Plate loading beam
CFRP	:	Carbon fiber reinforced polymer
Db	:	Depth of the beam
Di	:	Diameter of the cylindrical specimen
DyF	:	Ductility factor
De	:	Effective depth
Fc	:	Compressive strength
Fdir	:	Direct tensile test
fr	:	Flexural tensile test
FMC	:	Ferrocement model code
FRP	:	Fiber Reinforced polymer
fsp	:	Splitting tensile test
Fl	:	Maximum load at fracture
Ft	:	Tensile strength of concrete
Ff	:	Load applied to the middle of the prism at fracture
GFRP	:	Glass fiber reinforced polymer
Lc	:	Length of the cylindrical specimen
Lb	:	Effective span of the beam
L	:	Distance between the supports

Lw	:	Member width span
Ps	:	Longitudinal steel ratio
Pmax	:	Maximum load applied to the specimen
Pf	:	Load at failure
Pt	:	Transversal steel ratio
Pu	:	Ultimate failure load
RC	:	Reinforced Concrete
RCC	:	Reinforcement Concrete
R_f	:	Flexural strength
Rc	:	Compressive strength
бu	:	Deflection at ultimate load
бy	:	Deflection at yield load

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ABSTRACT

Deterioration in reinforced concrete structures may result from inherent material deficiencies (steel and concrete), unfavorable local conditions, or adverse environmental effects. Structural damage caused by overloading is a significant concern, as it leads to excessive deflection and flexural cracking. This research investigates the behavior and rehabilitation of reinforced concrete beams damaged by overloading. A total of fourteen beams were cast and tested. Two beams (BP1 and BP2) served as control specimens. Six beams (BRP1–BRP6) were retrofitted using ferrocement laminates through the plate loading technique, while another six beams (BRC1–BRC6) were retrofitted using the cast-in-situ technique, with each set incorporating three different reinforcement volume fractions. In this study, the beams were preloaded to 67% of their ultimate load-carrying capacity (Pu) to simulate overloading damage. The damaged beams were then rehabilitated using ferrocement laminates with three different reinforcement volume fractions: - 2.192%, 4.384%, and 6.576%. Two rehabilitation techniques were adopted: the plate loading technique and the cast-in-situ technique. The study compares maximum deflection, ductility, energy absorption capacity, and cracking patterns between beams retrofitted using the two techniques. The results provide insights into the effectiveness of each method and suggest suitable retrofitting strategies based on the observed cracking behavior.

Keywords: Ferrocement reinforcement laminate, plate loading technique, cast-in-situ technique, structural behavior, retrofitting

CHAPTER ONE

INTRODUCTION

1.1 Background

The factors affecting the deterioration of reinforced concrete structures, pre-stressed concrete structures and the mechanisms of deterioration are well understood by everyone. The major factors responsible for the deterioration of structures are a faulty design, unsuitable materials, improper workmanship, overloading and exposure to an abnormally aggressive environment. The main causes of deterioration of concrete structures are:

- Cracking and spalling of concrete
- Environmental conditions such as corrosion and
- Extremely heavy loads

Once a structure is built in concrete, it is more or less considered permanent and does not need much attention for maintenance. However, over the years several structures have manifested deterioration thereby exploding this myth. The concept of durability and serviceability of a structure has been considered by the Ethiopian engineers during design and construction. New materials, methodologies and construction techniques have been developed and used to ensure the durability of structures.

Damage can be defined as the change in structural performance which can be identified in terms of discrete cracks or a weak zone formation and a consequent stiffness reduction. Damage can be of any physical form and its growth under a particular type of loading differs based on various factors like the type of material, location and intensity of loading. The investigation of reasons for damaged structures is largely a matter of gathering information by observation, studying earlier records, doing preliminary testing and then interpreting the information thus obtained. A systematic study on concrete structures is highly important and essential to find the cause of damage, to assess the condition of the structures in their damaged state and to formulate recommendations for repair and restoration. A wide range of approaches is available, for estimating the strength of concrete. A conventional destructive test method enables the strength of concrete to be measured using cores or cubes cut from the structure. However, this is not possible in all

cases and especially for slender members. In non-destructive testing, the strength properties are not measured directly but the other related properties are analysed and the strength can be estimated by calibration. Naturally, in these methods, the great advantage is that the concrete is not damaged. In partially destructive tests, the concrete is tested to failure but the destructive resulting in much localized and the member under the tests is not weakened to any significant extent.

The excess of load above the design loads on structural members is called overloading and it causes basic symptoms of cracking. Subsequently, it leads to spalling and disintegration. Deterioration of reinforced concrete structures is frequently caused by a combination of various factors. It may result from physical damage, chemical attack and material degradation on exposure to a severe environment. Physical damage to reinforced concrete can arise from several causes like fire damage, explosive damage, impact damage and damage from natural calamities such as floods, cyclones and earthquakes. The chemical causes of concrete deterioration are alkali-silica reaction, alkali-carbonate reaction, carbonation, sulphate attack and steel corrosion. The other factors contributing to concrete degradation include high structural stress, thermal stress, shrinkage and poor quality of materials.

1.2. REQUIREMENTS FOR REHABILITATION

Repair is the technical aspect of rehabilitation which refers to the identification of a structure partly or wholly which is damaged in appearance and serviceability. Rehabilitation consists of restoring the structure to the service level, it once had and that too at a low cost. The rehabilitation envisages restoration of the structural system as close to the original configurations as possible. The structures in distress are to be brought in line and require strength so that they could be put back in service without endangering their safety and utility.

The basic aims of rehabilitation work would be as under:

- To prevent harmful development to restore the integrity of the structure and to provide effective protection.
- To improve functional utility and service life.
- To reduce distress and remove defects that involves hazards to life and affects the durability of a structure.

- To improve the aesthetic appearance.

The repair of structural damage and rehabilitation is possible by several methods. These methods include:

- Use of steel plates or FRP in the damaged regions to increase the load-carrying capacity of the structure.
- Removal of the corroded steel bars and damaged concrete and their substitution by fresh materials of the same type.
- Using of epoxy mortar alone or in combination with the above-mentioned two methods.
- Using of ferrocement in the damaged portion to restore the performance of the structure.

1.3. CRITERIA FOR SELECTION OF REPAIR MATERIALS

The selection of repair material is one of the most important tasks for ensuring durable and trustworthy repair. Though the pre-requisite for a sound repair system is the detailed investigation and determining the exact cause of distress, an understanding of the process of the deterioration of the repair materials such as concrete and other auxiliary materials like plastics, resins under service conditions is vital. Of course, the availability of materials by relevance, equipment and skilled labour has to be explored before deciding upon the repair material. Also, the selection of the repair material has a chemical angle and the manufacturer's literature normally highlights the composition of the material rather than the performance characteristics. Since cementitious products have a tendency to shrink and hardening with age, the repair material for repairing concrete or plaster should be non-shrink type and compatible with parent material.

Therefore, a careful selection of repair material is necessary for the following reasons:

- Almost every repair job has unique conditions and special requirements
- The composition and properties of repair materials have a profound effect on the performance and durability of repair work.
- The repair materials perform adequately only if they are prepared, applied and cured as per the specified procedures, which may necessitate the use of appropriate tools and considerable skill.

The major objective of repair or renovation work for the concrete structure is to restore the structure to a satisfactory level of performance at a reasonable cost. For any repair and renovation programs of Civil Engineering structures, Humayun and Robels (1991) proposed the suitability of ferrocement as a renovation material because of:

- Better cracking behavior
- Low shrinkage properties
- The capability of improving some of the desired mechanical properties of the treated Structures
- Requisite setting and hardening properties
- Further modification or repair of ferrocement treatment is not difficult
- The imposition of little additional dead load requiring no adjustment of the supporting structures
- Ability to withstand thermal changes very efficiently
- Ability to achieve waterproofing property without providing any surface treatment
- Readily available constituent materials
- No need for special equipment
- Ability to be used in the repair program with no distortion or downgrading the architectural concept of the structures

The ACI committee 549 (1993) defines ferrocement as a "type of thin-wall reinforced concrete construction where usually hydraulic cement is reinforced with layers of continuous and relatively small diameter mesh throughout the matrix, the material under stress acts approximately as a homogenous material". An important aspect of ferrocement which gives it a distinct advantage over reinforced concrete in certain situations is its enhanced resistance to cracking which is due to the closely spaced small diameter reinforcements. Enhanced crack resistance combined with high toughness, the ability cast into any shape, its rapid constructions with no heavy machinery involved, small additional self-weight it imposes and considering the economic aspects of rehabilitation, thin materials prove to be a cost-effective solution for rehabilitation and applications.

Ferrocement is a form of reinforced concrete that differs from conventional reinforced or prestressed concrete primarily by a manner in which the reinforcing elements are dispersed and arranged. It consists of closely spaced multiple layers of mesh or fine rods completely embedded in cement mortar. A composite material is formed that behaves differently from conventional reinforced concrete in strength, deformation and potential applications and thus is classified as a separate and distinct material. It can be formed into thin bands or sections generally 15 mm to 25 mm thick, with only a thin mortar cover over the outermost layers of reinforcement. Unlike conventional concrete, ferrocement reinforcement can be assembled into its final desired shape and the mortar can be plastered directly in place without the use of a form. Ferrocement has a very high tensile strength to weight ratio and superior cracking behaviour in comparison to conventional reinforced concrete. This means that thin ferrocement structures can be made relatively light and water-tight. Hence ferrocement can be used with confidence on suitable rehabilitation and restrengthening material for a wide range of applications such as:

- Tanks, containers and silos
- Floors and Roofs
- Heavy-duty floor tiles
- Waterproofing
- Decorative panels and tiles
- Cooling towers
- Telephone and electric power poles
- Wall paneling, Strengthening of RCC structures

1.4. NEED FOR STUDY

This study will consider ferrocement as a rehabilitation material in plate bonding technique to bond in the tension face of the RC beam. The main constituents of ferrocement are mortar and reinforcement in the form of steel wire mesh. The cementing mix will made of cement and sand mortar while the reinforcement steel wire mesh will be openings large enough for adequate bonding. The closer distribution and uniform dispersion of reinforcement, transform the otherwise brittle mortar into a high-performance material distinctly different from reinforced concrete. The present study aims to study the effect of ferrocement laminates attached to reinforced concrete beams by plate bonding technique and cast situ technique. This study also examines the effects of

different volume fractions of ferrocement laminate reinforcement in both plate bonding technique and cast in situ bonding technique. A comparative study on the performance of laminated and rehabilitated beams will be made on both plate bonding technique and cast in situ bonding technique. This will be planned to be achieved by conducting extensive experimental studies and analytical studies on reinforced concrete beams under the undamaged and pre-damaged rehabilitated status.

1.5. STATEMENT OF THE PROBLEM

Most of the investigation reports on strengthening of damaged RC structures are based on patch repairing and using FRP sheets for flexural, shear and compressive strengthening of members. The external bonding of FRP in RC beams for strengthening and retrofitting cannot be achieved adequately, because of the formation of localized flexural and shear cracks which affects the bonding between the interface of concrete and FRP, as a result the improvement in load carrying capacity cannot be obtained effectively. FRP sheet also more expensive. Therefore, incorporating ferrocement into the concrete is an effectual system to control the formation of micro cracks and propagation of macro cracks and this may avoid or delay the debonding of FRP composites. This research work is mainly focused on retrofitting of RC beams using ferrocement laminating sheets. It aims at studying the effect of ferrocement laminating sheets used as strengthening materials by adopting plate bonding technique and cast in situ technique on RC beams made of various grades of concrete.

1.6. SCOPE AND OBJECTIVES

SCOPE

The reinforced concrete structures may be subjected to many types of damage and distress. But, the scope of this study is limited to damages of reinforced concrete beams due to overloading alone. The damaged structures could be repaired and rehabilitated to a satisfactory level of performance at a reasonable cost by different methods. This study proposes two methods of repairing, rehabilitating, and strengthening reinforced concrete beams by plate loading technique and also by cast-in-situ loading technique at a reasonable cost.

OBJECTIVES

Reinforced concrete structures study proposes two methods of repairing, rehabilitating, and strengthening reinforced concrete beams by plate loading technique and also by cast-in-situ loading technique. A comparative study was made on the two techniques based on the performance of reinforced concrete beams. This objective was planned to be achieved by an experimental study on reinforced concrete beam elements. After rehabilitation, the depth of cracks will be reduced and the deflections were arrested with restoring the load-carrying capacity of the damaged beams because ferrocement laminate was a highly ductile material with a better crack arresting mechanism.

1.6.1. General objective:

To study Strengthening of Rectangular Beam by Ferrocement Reinforcement Laminates.

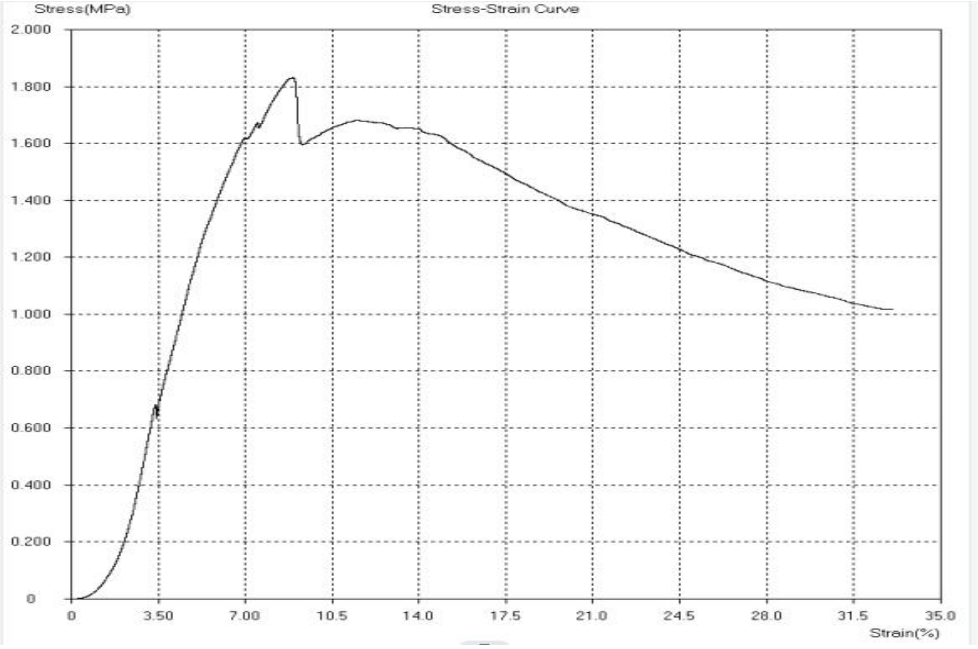
S. No	Beam code	Damage level % Pu	Vr %	Technique adopted	Performance evaluation
1	BP1&BP2	control beam	----	----	Strength and deflection under static test
2	BRP1&BRP2	Ferrocement laminate beam	2.192	Plate loading technique	Effect of strengthened by ferrocement laminates
	BRP3&BRP4		4.384		
	BRP5&BRP6		6.576		
3	BRC1&BRC2	Ferrocement laminate beam	2.192	Cast in-situ loading technique	Effect of strengthened by ferrocement laminates
	BRC3&BRC4		4.384		
	BRC5&BRC6		6.576		

1.6.2. Specific objectives:

- To state the static behaviour of reinforced concrete beams as ferrocement control beam and ferrocement laminated beams experimentally by plate loading technique.

- To describe the static behaviour of reinforced concrete beams as ferrocement control beam and ferrocement laminates beams experimentally by cast-in-situ loading technique.
- To compare performance and behaviour of laminated beams by plate loading technique and cast-in-situ loading technique.

The specific conclusions on the static behaviour of the control beam and ferrocement laminates beams were drawn based on the analytical investigation.



1.7. SIGNIFICANCE OF THE RESEARCH

Accurate estimation of the ultimate deformation and ductility of deteriorated reinforced concrete elements has long been a significant challenge and the aim of researchers. A new approach was developed to estimate both the ultimate deformation and load capacity of reinforced concrete structures subjected to corrosion. The proposed method was used as an effective analytical tool for displacement and performance-based design.

This was considered as a starting point for future researches and development of design codes in the tension design of RC structures subjected to different loading conditions.

Forty-two beams were cast for flexural test, and into three series. The first series of two beams as control beams (BP1 and BP2) and was tested for ultimate failure load (Pu) and was observed as 44kN. The second series of beams as BRP1, BRP2, BRP3, BRP4, BRP5 and BRP6 and third series BRC1, BRC2, BRC3, BRC4, BRC5 and BRC6 respectively.

CHAPTER TWO

LITERATURE REVIEW

2.1 GENERAL

Many scientists and researchers have studied the aspects of causes of damages in structures and the required remedial measures to bring it into the satisfied level. The assessments of damages due to various causes and the novel rehabilitation techniques can be made in many ways. A brief review of the works done by various authors is presented in this chapter.

2.2 STUDIES ON EPOXY BONDED STEEL PLATES

MacDonald and Calder (1982), studied the behaviour of concrete beams externally reinforced with steel plates bonded to their tension flanges. They tested a series of beams under four-point loading. Results showed that full composite action was provided by the adhesive and that significant improvements in performance could be achieved in terms of load, crack control, and stiffness. Exposure tests were carried out on unreinforced concrete beams with steel plate bonded to one face. Results showed that significant amounts of corrosion of the steel plate may take place due to natural exposure. Also, loss in bond strength at the steel-epoxy interface was observed resulting from the corrosion of the steel plate. The reduction in the overall strength of the exposed beams was attributed to the corrosion.

Gehlers and Moran (1990), studied the effect of flexural peeling stresses on the serviceability and ultimate strength of upgraded concrete beams with bonded plates. The failure of beams caused by large cracks in the concrete region between the plates and the longitudinal steel re-bars was categorized in terms of forces that were present near the end of plates. That paper focused mainly on the problem of flexural peeling and the effect of shear forces which had no flexural peeling to the formation of diagonal shear cracks. Equations were developed to predict the ultimate peeling moment that caused the initial formation of peeling cracks. It was concluded that the peeling strength depended on the flexural rigidity of the cracked plated section, the tensile strength of the concrete, and the thickness of the plate.

Hamoush and Ahmad (1990), investigated the behaviour of damaged concrete beams strengthened by external bonded steel plates, using linear-elastic fracture mechanics and the finite element method. The study investigated the failure by interface de-bonding of the steel plate and the adhesive layer as a result of interfacial shear stresses. Simply supported concrete beams under monotonically increasing symmetric loads were considered in the study. They reached the conclusion that the strain energy release rate for an interface crack between steel plate and adhesive layer was negligibly small and the steel plate-strengthened beams had high interface bonding load and the strain energy 9 release rate initially reached a maximum value when the length of the interface crack was approximately equal to the length of the flexural cracks.

2.3 STUDIES ON EPOXY BONDED FRP PLATES

Hamid Saadatmanesh and Ehsani (1996), experimentally investigated the static strength of reinforced concrete beams strengthened by gluing glass fiber reinforced polymer (GFRP) plates to their tension face of the beams. The measured load versus strain in GFRP plates, steel rebar, extreme compression fiber of concrete, and the load versus deflection for the section at mid span of the beams were plotted and compared to the predicted values. The results indicated that the flexural strength of RC beams could be significantly increased by gluing GFRP plates to the tension face. In addition, the epoxy bonded plates had improved the cracking behaviour of the beams by delaying the formation of visible cracks and reducing crack widths at higher load levels.

Garden and Hollaway (1998), studied and reported that carbon fiber reinforced polymer (CFRP) materials were all suited to the rehabilitation of civil engineering structures due to their corrosion resistance, high strength to the weight ratio, and high stiffness to weight ratio. The anchorage system for the plate had more structural benefit under low shear span/ depth ratio.

Arockiasamy et al. (2001), presented some studies on the long-term behaviour of the beams reinforced with carbon- epoxy FRP under uniform sustained loading. An analytical method was developed to predict the long- term behaviour of CFRP internally reinforced concrete beams. The calculated deflections, strains, and curvatures agreed reasonably with the experimental values. A simplified equation for calculating the long- term deflection was proposed for CFRP reinforced concrete beams.

2.4 STUDIES ON EPOXY BONDED FERROCEMENT COMPOSITES

Suryakumar and Sharma (1976), presented a comparison of the results of tests of thirty-five specimens with the theoretical values of ultimate strength, predicted by the conventional reinforced concrete theory. They concluded from the study that; conventional reinforced concrete theory could be adopted for predicting the ultimate flexural strength of ferrocement. The ultimate strength and first crack strength of ferrocement was found to increase linearly with increase in the percentage area of reinforcement.

Perumalsamy et.al (1979) carried out experiments on ferrocement beams reinforced with volume fraction varying from 2% to 6% with variety of square steel meshes which were subjected to fatigue flexure with three levels of loading corresponding to approximately 40%, 50% and 60% of static yield load. Based on the observed experimental results linear regression equations were proposed by them to predict fatigue life of ferrocement as a function of the stress range in the outermost layer of steel mesh. Also, an exponential relation with two parameters was built to predict the increase in deflection, average and maximum crack widths as a function of applied load and number of loading cycles. The proceeding relations established by them are carefully adaptable to reinforced concrete subjected to fatigue flexure.

Ahmed et.al (1991), presented the rehabilitation technique for reinforced concrete structural beam elements using ferrocement. This technique involved strengthening of the reinforced concrete beams by application of hexagonal chicken mesh and skeletal steel combined by ordinary plastering. The basic parameters involved were the amount of wire mesh applied, its geometrical configuration and the degree of distress in the beams. The test results found were in good compliance with the original design capacity of the beam. A number of rehabilitation methods had been developed. The use of ferrocement as a rehabilitation material was comparatively a new approach and was relatively a better method due to the various inherent properties of this method. They concluded that ferrocement laminates was used as an alternative material in rehabilitation of distressed structural elements. It could also effectively control the cracks and mid-span deflections. The dead weight of the rehabilitation material was almost negligible and hence it did not require any catering for the additional dead weight as in most of the other rehabilitation materials.

Prakash Desayi and Nanda Kumar (1992), presented the behaviour and strength of ferrocement in shear. An experimental investigation on the shear strength of ferrocement was described. Tests were conducted on 155 simply supported rectangular ferrocement specimens under four-point loading. The variables of the study were the number of layers of wire mesh, two mesh layouts strength of the mortar and shear span to depth ratio. Two types of shear cracking and failure, namely those due to flexure-shear and web shear were noticed. The test results indicate that for both of the mesh layouts considered, the shear strength was increased as the shear span to depth ratio decreased. The shear stress at which the flexure shear crack formed for the uniformly disturbed mesh layout was higher than the shear stress at which the same kind of crack formed for the lumped mesh. This could be due to the fact that the meshes when distributed uniformly in the depth of specimen offered greater resistance to crack formation than when lumped at the two edges. They have concluded that two types of shear cracking and failure, namely those due to flexure-shear and web shear were observed. The strength of ferrocement in flexural shear cracking and web shear cracking increases as the (a/h) ratio was decreased and the volume fraction of mesh wire was increased for all mortar mixes and the two-mesh layout were studied.

Hughes and Evbuomwan (1993), investigated that the strength of reinforcement concrete beams enhanced due to polymer modified ferrocement. This paper reported some of the results of on-going research in the development of the reinforced repair mortar to be used in enhancing the strength of downgraded reinforced concrete beams. One of the main problems faced by the buildings and construction industries was the deterioration of concrete structures. The high level of spending within the industries for concrete repairs showed that the degree of concerns that had arisen due to the number of structures in need of repair. The common techniques employed in the repair of concrete structures were resin injection, shortcreting and patch repairs. They concluded that there was an increase in ultimate and cracking loads and ductility of the enhanced beam in comparison with the controlled beam. They also concluded that the beams enhanced with reinforced materials exhibited a much higher ultimate flexural strength than the controlled beams. The beams enhanced by the material were absorbed to exhibit both higher cracking and ultimate loads compared with the enhanced beam. The use of the material also led to increased stiffness and ductility.

Gurdev and Guang (1995), had given their findings of flexural fatigue characteristics of ferrocement for reliable design, as for designing ferrocement against fatigue by using the probability-stress-life (P-S-N) plot. Ferrocement specimens of size 350 mm×125 mm×30 mm was used. Six layers of weld mesh were used as reinforcement to give a nominal percentage of reinforcement of 1.2%. The use of S-N relationships for predicting fatigue behaviour leads to an unreliable design, however the proposed method for producing P-SN relationships, incorporating the probability aspects was more appropriate. Finally, they concluded that rectangular stress distribution was relatively more reliable and economical for predicting steel stress when designing ferrocement against fatigue by using the P-S-N relationship of wire tested in the air.

Ezzat Fahmy et.al (1997), presented a proposed method for repairing concrete beams using ferrocement laminates as a viable alternative to steel plates which were directly glued to the cracked tension face of the beam by epoxy resins. The results of both experimental and analytical investigations to examine the effectiveness of this method were reported and discussed including strength, deflection, and cracking characteristics of the repaired specimens. Twenty-seven reinforced concrete beams were tested over simply supported one meter span. Each specimen was first loaded with a central line load till collapse or upto 85% of the ultimate load of the control specimen. After unloading, the damaged beam specimens were repaired by either one layer at the tension face, two layers at the tension face or u-shaped layer around the beam cross section. The finite element technique was used to analytically investigate the effectiveness of the proposed repair method. Based on the results and observations of both the experimental and analytical investigations presented, they concluded that under short term loading conditions, reinforced concrete beams failed due to overloading could be restored with enhanced strength and performance using ferrocement laminates. After repairing, all the repaired tested specimens showed large deflections at ultimate load and significant increase in the ductility ratio. Repairing reinforced concrete beams with a u-shaped layer around the beam cross section, increased the gain in the ultimate moment about three times. This was obtained only when one laminate was attached to the tension face.

Masood et.al (2005), investigated experimentally the rehabilitation of RC and FRC beams by ferrocement. The experimental investigation consisted of casting and testing of 21 beams of size 115 ×170 × 3350 mm. The beams were tested by two- point loading. After

testing the beams, the parent beams were rehabilitated by applying Epoxy resin on the 26 four faces exposed to form a good bond between old and new concrete before fixing square welded mesh to the main reinforcement in the tension zone. It had been observed that the rehabilitated beams were able to attain the same level of strength and stiffness as the virgin beams. The average load deflection values for parent/virgin and rehabilitated beams were reasonably close. The rehabilitated beams were able to attain the same level of strength and stiffness as the virgin beams with the restrengthened beams showing appreciable improvement in the load deflection behaviour apart from successfully sustaining the same ultimate load as the virgin beams. Thus, the suggested repair and re strengthening method adopted for the damaged beams could be safely carried out.

Mohd. Zamin Jumaat et.al (2006) in their study discussed the causes of deterioration of concrete as well as repairing by cement grout, mortar, concrete, shortcrete, epoxy, ferrocement with mortar, fibre reinforced polymer and spray gel fibre reinforced polymer. The techniques of applying those materials and also some resin-based materials for bonding agent between interface of old concrete and new concrete were also reported by them. The advantages and disadvantages of those materials, causes of debonding between concrete substrate and new concrete applied on substrate and preventive measures were discussed and suggested by them that the cement-based materials were more suitable. They established a fact that the effectiveness of a repair work depends upon the quality of the material, implementation techniques, and effective supervision.

2.5 STUDIES ON CAST INSITU BONDED FERROCEMENT COMPOSITES

Paramasivam et.al (1994), investigated the flexural behaviour of reinforced concrete Tee beams strengthened with thin ferrocement laminates attached to the tension face. Twelve simply supported beams were tested under concentrated loads at mid span. The ferrocement laminates were attached using L-shaped mild steel round bars as shear connectors. The parameters that were varied include the spacing of the shear connectors, method of surface preparation and volume fraction of reinforcement was the ferrocement laminates. Performance was generated in terms of cracking characteristics, mid span deflection, stiffness, and ultimate load capacity. The shear connector used comprised 8 mm diameter smooth mild steel bars. They were inserted and anchored into pre-drilled holes at the soffit of the beams using epoxy resin adhesive. The free ends were then bent and secured to reinforcement in the ferrocement laminates. A total of twelve simply

supported T-beams were tested under concentrated loads applied at mid-span. A 30 mm thick strengthening ferrocement laminates consist of two smooth mild steel bars of diameter 6 mm sandwiched between two layers of galvanized welded wire mesh. They concluded that the addition of the ferrocement laminate to the tension face of reinforced concrete beams using L-shaped bar connectors could substantially improve the performance of the beams. The appearance of the first crack was delayed by the presence 34 of the ferrocement laminate. The flexural rigidity of the strengthened beams was higher than the unstrengthened beams. The increase in flexural capacity was dependent on the amount of additional reinforcement and preservation of full composite action until failure.

SUMMARY

Based on the review of the available literature, the following points had been taken note of:

· Most of the rehabilitation and retrofitting works had been done on FRP as a rehabilitation material.

· Most of the works had been carried out on the rehabilitation of structures undergone short term failure.

· Many researchers had used steel plates or fibre laminates for retrofitting purpose.

· The study of ferrocement as a rehabilitation material was few in number and some of the ferrocement rehabilitation study had dealt with number of layers of ferrocement reinforcement and few of them in terms of volume fraction of ferrocement reinforcement upto 3.53% with single type of mesh.

· There were very limited studies on plate bonding technique for rehabilitation and retrofitting of structures and very limited studies on cast insitu bonding technique for rehabilitation and retrofitting of concrete structures.

· Only limited studies have dealt with the prediction of ultimate load carrying capacity

CHAPTER THREE

MATERIALS AND METHODS

3.1 INTRODUCTION

In general, cracking in reinforced concrete structural elements is not damage, but an expected natural phenomenon due to inherent low tensile strength. At the same time, cracks that are caused due to overloading, poor quality of concrete, poor workmanship were parameters that could lead to unacceptable cracking which further leads to an increased level of damage. In this study damages caused due to overloading of reinforced concrete elements were considered. In recent years, there was a growing need for rehabilitation of structures. Many methods of rehabilitation of structures were developed by researchers and adopted over the years. In present study Plate loading technique of ferrocement laminates has to be introduced as normal repair and strengthening method. Another method for repair and strengthening of reinforced concrete elements were cast in-situ loading technique of ferrocement laminates. A detail experimental programme has to be finalized after assessing the percentage of overloading and type of rehabilitation procedures.

3.2 EXPERIMENTAL PROGRAMME

A total of forty-four beams of size 100 mm width, 150 mm depth and 500 mm overall length has to cast and test. All the beams have to be tested in two points loading over an effective span of 450 mm. Out of 44 beams two beams (BP1 and BP2) has to be used as control beams, another six beams (BRP1 to BRP6) have to be strengthened with ferrocement laminates with three different volume fractions (Vr) of ferrocement reinforcement in virgin condition by plate loading technique. Another six beams (BRC1 to BRC6) have to be strengthened with ferrocement laminates with three different volume fractions of ferrocement reinforcement in virgin condition by cast in-situ loading technique. The variables considered in this study include different levels of damages, different volume fraction of reinforcement in ferrocement laminates as rehabilitation material and different methods of laminating the ferrocement laminates. A comparative study has to be made between the control beams and ferrocement laminated beams by both plate loading technique and cast in-situ loading technique.

3.3 DETAILS OF TEST PROGRAMME

Total 44 numbers of beams has to be cast and tested in the laboratory under 14 categories and three series. Series 1 consists of two numbers of beams BP1 and BP2 and these beams have to be tested up to ultimate load carrying capacity Pu. They have to be tested under static monotonic loading. Series 2 and Series 3 consist of six beams under each category. Under each series (BRP1 to BRP6 and BRC1 to BRC6) they have to be strengthened by ferrocement laminates having three different volume fractions of ferrocement reinforcements, the principal type of wire meshes used in the ferrocement Laminates Arrangements of mesh reinforcements with volume fraction (Vr = 2.192%) contributes with one layer of weld mesh and one layer of woven mesh. Arrangements of mesh reinforcements with volume fraction (Vr = 4.384%) contributes two layers of weld mesh and two layer of woven mesh. Arrangements of mesh reinforcements with volume fraction (Vr = 6.576%) contributes three layers of weld mesh and three layer of woven mesh. Respectively for two beams in each volume fraction Vr in virgin condition by plate loading technique and cast in-situ loading technique. The expectance damaged by overloading by subjecting the beams to a preloading which corresponds to 67% of the ultimate load carrying capacity (Pu) of the control beams (BP1 and BP2) and rehabilitated with ferrocement laminates with three different volume fractions (Vr) of ferrocement reinforcement, two beams in each category has to be determined by both plate loading technique and cast in situ loading technique. The summary of the test plan is presented in Table 3.1.

Table 3.1 Summary of Test Plan

S. No	Beam code	Damage level % Pu	Vr %	Technique adopted	Performance evaluation
1	BP1&BP2	control beam	----	----	Strength and deflection under static test
2	BRP1&BRP2	Ferrocement laminate beam	2.192	Plate loading technique	Effect of strengthened by ferrocement laminates
	BRP3&BRP4		4.384		
	BRP5&BRP6		6.576		

3	BRC1&BRC2	Ferrocement laminate beam	2.192	Cast in-situ loading technique	Effect of strengthened by ferrocement laminates
	BRC3&BRC4		4.384		
	BRC5&BRC6		6.576		

3.4 MATERIALS USED

The mean strength of concrete used for the beams will be 20 N/mm^2. The concrete mix used for the beam will be 1:1.5:3 with water cement ratio of 0.50. The concrete mix proportions will be designed by Indian Standard (IS) method to achieve the mean strength of 20 N/mm^2. Ordinary Portland Cement of 42.5 R, fine aggregate of locally available river sand passing through 4.75mm sieve and retained on 600 microns conforming to zone II of EBCS 2 (1995) with specific gravity 2.48, coarse aggregate of crushed granite type passing through 20 mm sieve and retaining on 10 mm sieve conforming to EBCS 2 (1995) with specific gravity 2.91, were used as the concrete ingredients. Ordinary portable water free from impurities was used for preparing and curing of concrete.

For the beams, 2 numbers of 8 mm diameter HYSD bars has to be used as main reinforcement and 2 numbers of 8 mm diameter HYSD bars have to be used as hanger bars and 6 mm diameter mild steel bars have to be used for shear stirrups at 120 mm c/c throughout the span of the beam. The yield strength of steel reinforcements has to be used in this experimental program was determined by performing the standard tensile test on the one specimens of each bar. The average yield stresses of steel bars obtained were 240 N/mm^2 for 12 mm, 8 mm and 6 mm diameter respectively.

For ferrocement laminates the cement mortar in the ratio 1:2 having mean strength of 43.67 N/mm^2 with water cement ratio 0.42 has to be used. The workability expressed in terms of slump, not exceeding 50 mm as specified in Ferrocement Model Code (FMC) for the fabrication of laminates. The materials have to be used Ordinary Portland Cement of 42.5, natural river sand conforming to zone II of EBCS 2 (1995) and also satisfying the requirements of Ferrocement Model Code (FMC). The modulus of mortar has to be used for ferrocement laminates was 30697 N/mm^2 and Poisson's ratio was 0.28. Two types of meshes namely, have to be welded wire mesh of 15 mm x 15 mm, 2 mm diameter wire and woven mesh of thickness 0.8 mm and gauge 20 have to be used as shown in Figure 3.1 and Figure 3.2. We have to be tied together and used as one layer of ferrocement

reinforcement having volume fraction Vr=2.192% in casting of ferrocement laminates. Similarly, two layers of ferrocement reinforcement with volume fraction Vr=4.384% and three layer of ferrocement reinforcement with volume fraction Vr=6.576% have to be taken for fabrication the ferrocement laminates both by plate bonding technique and cast insitu bonding technique.

Volume fraction (Vr) may be expressed as,

$$V_r = N\pi dw_2/2hD$$

For any other type of meshes,

$$V_r = Nw_r/h\alpha r$$

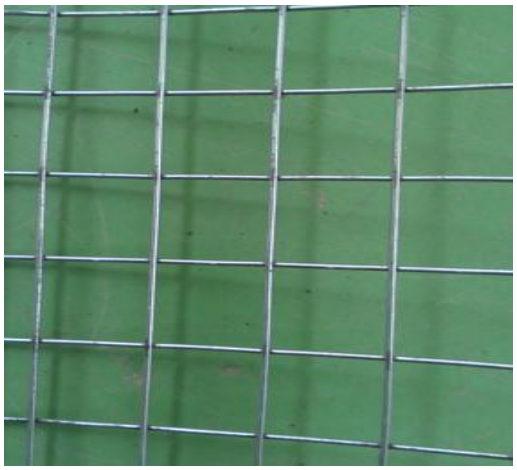


Figure 3.1 Welded wire mesh



Figure 3.2 Wove mesh

3.5 FABRICATION OF BEAMS

The beam reinforcement along with Tension reinforcements of cross section of the beam and longitudinal section of the beam are shown in Figure 3.3 and Figure 3.4. The form work of size 100 mm width, 150 mm depth and 500 mm length for the beam to be made up of teak wooden blanks. A thin layer of waste oil to be applying to facilitate easy removal of form work after 24 hours of casting. Required quantities of fine aggregate, coarse aggregates and cement are mixed thoroughly and the measured quantity of water to be poured on the dry mix and mixed thoroughly to get uniform colour and the required consistency. The steel reinforcement is to be kept inside the mold. The thoroughly mixed to be poured inside the mold and vibrated using a high frequency needle vibrator. Control

specimens in the forms of cubes and cylinders have to be also cast under the identical condition as that of the beam. The beam mold to be removing after 24 hours from the time of casting and the specimens are cured using wet gunny bags for 28 days.

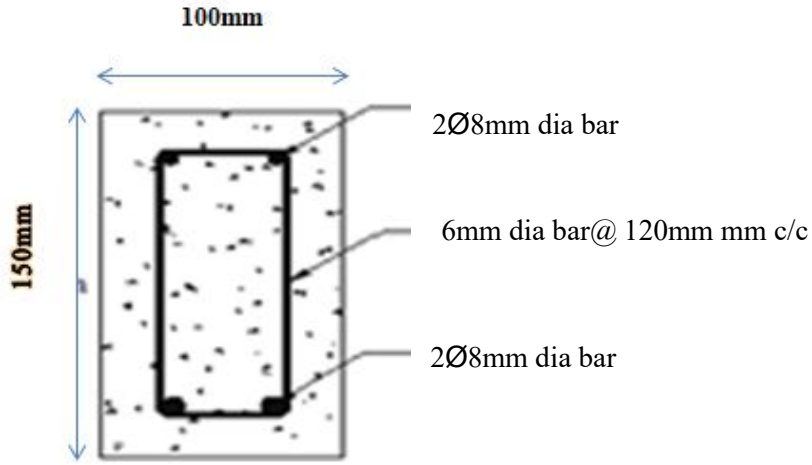


Figure 3.3 Cross section of the beam

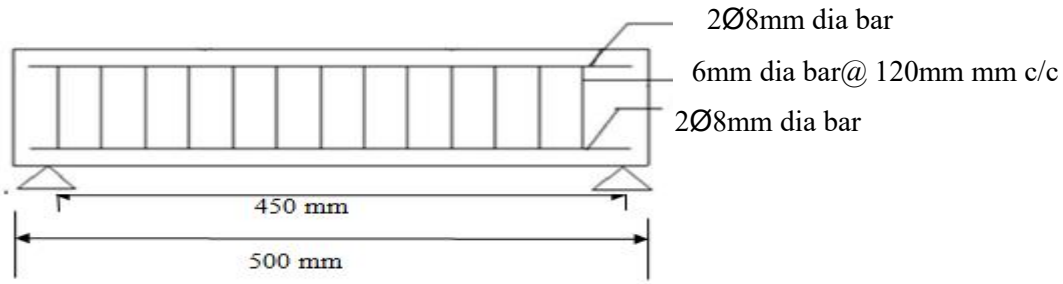


Figure 3.4 Longitudinal section of the beam

3.5.1 EXPERIMENTAL SET UP

All the beams have to be tested under flexure in a loading frame of capacity and all the beams have to be tested for a simply supported condition. The beam of size 100 mm width, 150 mm depth and 500 mm overall length to be simply supported over an effective span of 450 mm. Three points loading have to be applied on all beam's capacity.

3.6 FABRICATION OF FERROCEMENT LAMINATES FOR PLATE LOADING

Cement and sand have to be mixed in 1:2 ratios, with water cement ratio 0.42. The wooden mold of 450 mm length, 100 mm width and 25 mm thick have to be arranging as per requirement. A thin mortar layer to be applying for requires thickness.

The arrangements of ferrocement reinforcement conforming to volume fractions Vr=2.192%, Vr=4.384`% and Vr=6.576%

3.6.1 Bonding Procedure for Plate Loading

Technique before bonding the ferrocement laminate on the tension face of the beam, the tension face of the beam surface have to be made rough using a sand blower and cleaned with an air blower to remove all dirt and debris. The newly fabricate ferrocement laminate to be place within a maximum of 2 hours to the applied surface. According to the supplier's manual, one kilogram of mixed material to cover approximately 2 to 2.5 square meters of the surface. The actual coverage to depend on the texture and porosity of the surface and be applied for bonding old and new cementitious surfaces like old concrete to new concrete. The low viscosity of the epoxy resins to enable easy penetration into hair line cracks and apply on the soffit of the require beams. The high bonding strength to ensure good adhesion to concrete substrate.

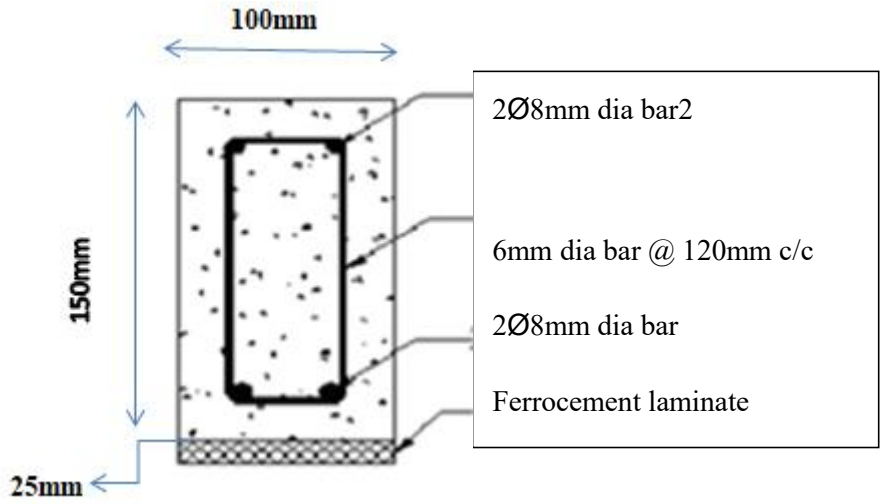


Figure 3.5 Schematic cross section of beam with ferrocement laminate

3.7 FABRICATION AND LOADING PROCEDURE FOR CAST INSITU LOADING TECHNIQUE

Before fabricating the ferrocement laminate onto the beam surface, the bottom of the beam surface is made rough using a sand blower and cleaned with an air blower to remove all dirt and debris. Cement and sand were mixed in 1:2 ratios, with specified water cement ratio. The wooden planks are arranging as per requirement. A thin mortar layer is apply of require thickness. One layer of woven mesh and one layer of weld mesh are tied together having volume fraction Vr=2.192% to be place over it. Again, a thin mortar layer is apply.

Finally shear connector is flattening. The top surface is finishing properly. The molds are removed after the specified time and the sides are finish. The above said procedure is adopted for strengthening of pre-damaged beams by cast insitu bonding technique. Same procedure was repeated for ferrocement laminates having volume fraction Vr=4.384% and Vr=6.576%

3.8 TESTING OF BEAMS

All the beams are placed over the loading plate form according to the specifications. According Addis Ababa Science and Technology to the test programme the first two beams is tested up to failure and the failure load is Pu. The other sets of beams, series 2 and series 3 are loading to different determine damage level of 67% Pu. These damaged beams are strengthen by ferrocement laminates having three different volume fractions (Vr=2.192%, Vr=4.384% and Vr=6.576%) of ferrocement reinforcements both by plate loading technique and cast in situ loading technique. The series 2 and series 3 is ferrocement control beam and the strength by ferrocement laminates having three different volume fractions of reinforcements both by plate loading technique and cast insitu loading technique.

3.9 TESTING OF FERROCEMENT LAMINATED BEAMS

All the Ferrocement laminated beams are grouped in series 2 and series 3. The second series of beams BRP1-BRP6 were ferrocement laminated by plate loading technique with three different volume fractions of ferrocement reinforcements with two beams under each volume fraction Vr. The three series of beams BRC1-BRC6 are ferrocement laminated by cast insitu loading technique with three different volume fractions of ferrocement reinforcements with two beams under each volume fraction Vr. All the ferrocement laminated beams was tested as per the procedure explained earlier for the Control beam BP1 and BP2.

3.10 EXPERIMENTAL CAST

In general, cracking in reinforced concrete structural elements is not damage, but an expected natural phenomenon due to inherent low tensile strength. At the same time, cracks that were caused due to overloading, poor quality of concrete, poor workmanship were parameters that could lead to unacceptable cracking which further leads to an increased level of damage. In this study damages caused due to overloading of reinforced

concrete elements were considered. In recent years, there was a growing need for rehabilitation of structures. Many methods of rehabilitation of structures were developed by researchers and adopted over the years. Plate bonding technique of ferrocement laminates had been introduced as normal repair and strengthening method. Another method for repair and strengthening of reinforced concrete elements was cast insitu bonding technique of ferrocement laminates. A detailed experimental programme was finalized after assessing the percentage of overloading and type of rehabilitation procedures.

3.11 EXPERIMENTAL PROGRAMME

A total forty-four beams of size 100 mm width, 150 mm depth and 500 mm overall length were cast and tested. All the beams were tested in two points loading over an effective span of 450 mm. Out of 42 beams two beams (BP1 and BP2) were used as perfect beams, another six beams (BRP1 to BRP6) were strengthened with ferrocement laminates with three different volume fractions (Vr) of ferrocement reinforcement in virgin condition by plate bonding technique. Another six beams (BRC1 to BRC6) were strengthened with ferrocement laminates with three different volume fractions of ferrocement reinforcement in virgin condition by cast insitu bonding technique.

The variables considered in this study include different levels of damages, different volume fraction of reinforcement in ferrocement laminates as rehabilitation material and different methods of laminating the ferrocement laminates. A comparative study was made between the Control beams, ferrocement laminate beams rehabilitated beams by both plate bonding technique and cast insitu bonding technique.

3.12 DETAILS OF TEST PROGRAMME

A total of forty-four beams were categorized into three series and tested in the laboratory. Series1 consists of 2 beams BP1 and BP2 and these beams were tested up to ultimate load carrying capacity Pu. They were tested under static monotonic loading. Series2 and Series3 consist of six beams under each category. Under each series (BRP1 to BRP6 and BRC1 to BRC6) they were strengthened by ferrocement laminates having three different volume fractions of ferrocement reinforcements viz Vr=2.192%, Vr=4.384%, and Vr=6.576% respectively for two beams in each volume fraction Vr in virgin condition by plate bonding technique and cast insitu bonding technique. The summary of the test plan is I am used presenting in Table 3.1 page 17.

3.13 EXPERIMENTAL AND MATERIALS USED

CEMENT: In this investigation Dangote cement which is of the Ordinary Portland cement of 42.5N grade was used throughout the work.



Figure 3.6: Ordinary Portland cement

FINE AGGREGATE: The fine aggregate used in this investigation was clean river sand, whose max size is 4.75mm the sand was first air-dried in order to reduce considerably its moisture content.



Figure 3.7: Fine aggregate

COARSE AGGREGATE: Machine crushed blue granite stone angular in shape and rough surface was used as coarse aggregate of size 20mm passing through 16mm retained as per IS:2386-1963 recommendation.



Figure 3.8: Course aggregate

WATER: Water is an important ingredient of concrete and mortar as it is actively participating in the chemical reaction with cement. Since it helps to form strength, giving cement gel, the quantity and quality of water is to be looked very carefully.

3.13.1. METHEDOLOGY

In this project various test are conducting on cement, fine aggregate and coarse aggregate as well as workability measurement are conducting by using different methods. The observation is tabulated and the results are calculated. Graphs are plotted if it necessary by using suitable readings.

The various parameters of the strength characteristic studied are

1. Compressive strength

2. Tensile strength

3. Flexural strength

1. COMPRESSIVE STRENGTH TEST

Specimens of dimensions 150x150x150mm were prepared. They are tested on 2000KN capacity compression testing machine.

Procedure for Compressive strength of concrete or Cube test: -

1. Place the prepared concrete mix in the steel cube mould for casting.
2. Once it sets, after 24 hours remove the concrete cube from the mould.
3. Keep the test specimens submerged underwater for stipulated time.

4. As mentioned, the specimen must be kept in water for 7 or 28 days

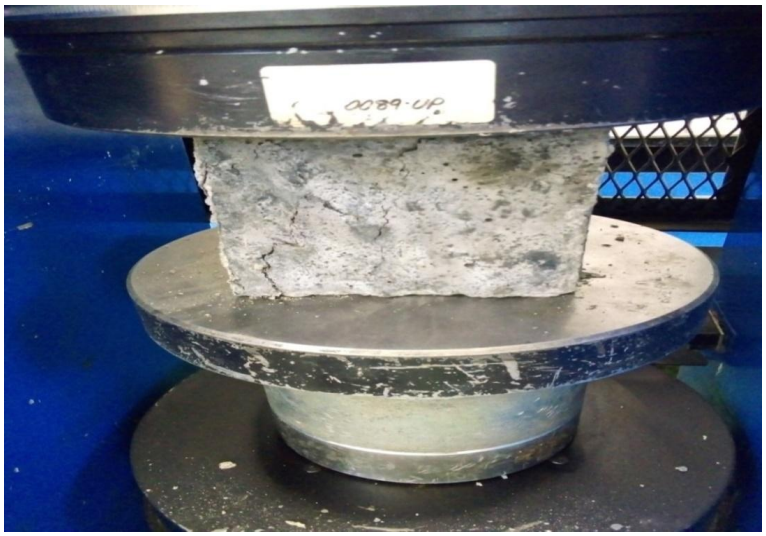


Figure 3.9: Compressive strength test

The compressive strength is calculated by using the equation,

$$Compressive\ Strength\ of\ Concrete = \frac{Maximum\ Load\ Carried\ by\ Specimen}{Top\ Surface\ area\ of\ Specimen}$$

F=P/A ----------1

Where, F= Compressive strength of the specimen (MPa).

P= Maximum load applied to the specimen (N).

A= Cross sectional area of the specimen (mm^2) = 22500 mm^2

Compressive strength of Concrete Formula:

The Compressive strength of specimen can be calculated by dividing maximum load carried by the specimen by cross-sectional area of the specimen cubes.

The surface area of specimen: = 150x150x150 = 3,375,000 mm^2 = 3,375cm^2




Figure 3.10: Compressive Strength of concrete

2. TENSILE STRENGTH TEST

Cylindrical specimens of diameter 150mm and length 300mm were prepared. Tension test was carried out on 2000 KN capacity compression testing machine.

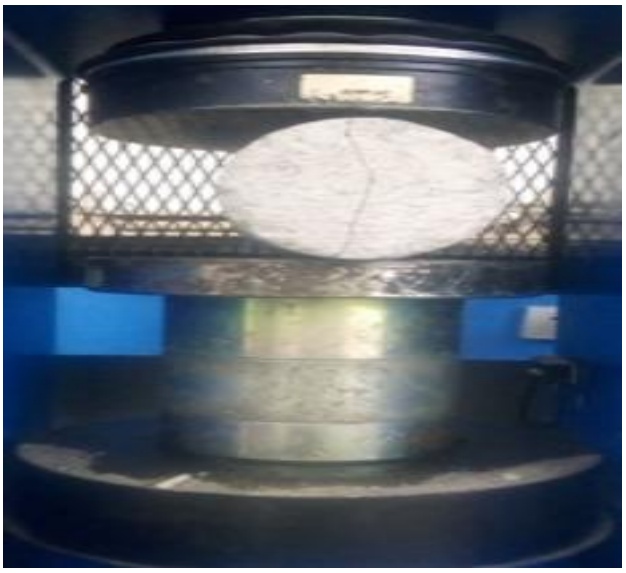


Figure 3.11: Tensile strength test

The tensile strength is calculated using the equation,

$F=2P/(\pi DL)$ ----------2

Where, F = Tensile strength of concrete (MPa).

P = Load at failure (N).

L = Length of the cylindrical specimen (mm).

D = Diameter of the cylindrical specimen (mm).

3. FLEXURAL STRENGTH TEST

Beam specimens of dimensions 100x100x500mm were prepared. During testing two points loading was adopted on an effective span of 400mm.

Flexural strength can be determined at laboratory on a concrete beam sample of size 500mm x 100mm x 100mm using flexural strength testing equipment.

Flexure results in compressive and tensile stresses in a beam. The minimum compressive strength of M20 concrete shall be 20N/mm^2. There can be major variation in the strength of M20 concrete depending on how you chose the mix, how water is controlled, what is the water cement ratio, how the concrete is placed, compacted and cured their proportions and properties, of course the properties of the main constituents like coarse and fine aggregates, and cement.

Tensile Stress or Strength

The Tensile strength of concrete ranges from of the compressive strength of concrete beam 7- and 28-days strength. However, it can be theoretically calculated using following equations depending upon the nature of test you are interested in.

1-Direct tensile test

$f_{dir} = 0.25 \sim 0.4 \sqrt{fcu}$----------3

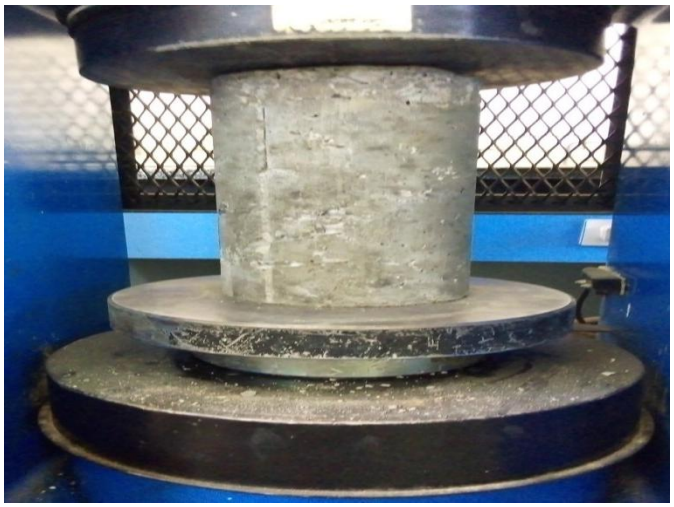


Figure 3.12: Tensile test

2-Splitting tensile test

f_{sp} =0.5~0.7 $\sqrt{fcu}$----------4



Figure 3.13: Splitting tensile test

3-Flexural tensile test

f_r =0.65~1.00 $\sqrt{fcu}$----------5

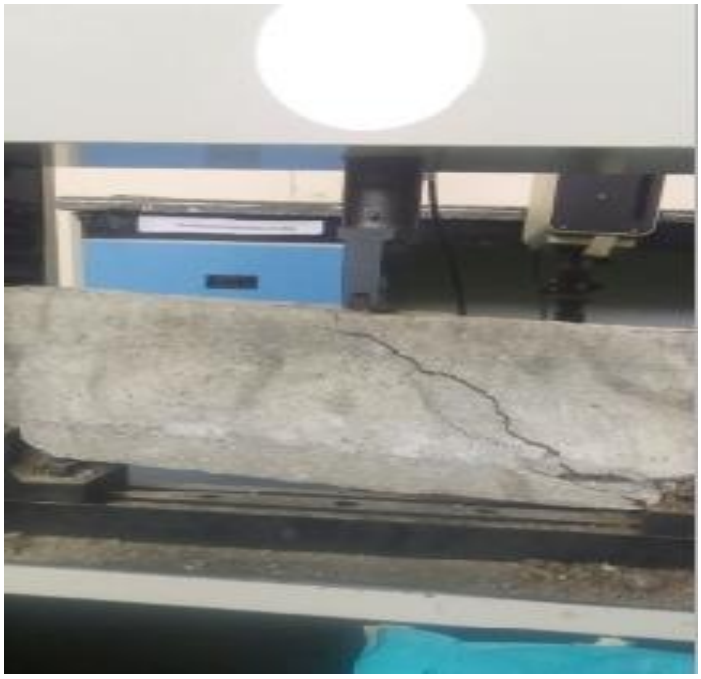


Figure 3.14: Flexural tensile test

In most of the countries, these equations are provided in the practice code for engineers.



Figure 3.15: Flexural strength test

Flexural strength is calculated using the equation:

$$F=PL/(bd^2) \text{ ----------6}$$

Where, F= Flexural strength of concrete (MPa).

P= Failure load (N).

L= Effective span of the beam (400mm).

b= Breadth of the beam (100mm).

d= Depth of the beam (150mm).

Mortar Strength constituents

Sand

General EBCS Standard sands, which are produced in various countries, shall be used to determine the strength of cement in accordance with this standard. The conformity shall be attested by the national standardization organization within whose area of jurisdiction.

Cement

When the cement to be tested is kept for more than 24 h between sampling and testing, it shall be stored in completely filled and airtight containers made from a material which does not react with cement.

Water

Distilled water shall be used for reference testing. For other tests, drinking water may be used.

Size of specimens

The test specimens shall be 40 mm × 40 mm × 160 mm prisms.

Testing the specimens

Testing procedures

Use the centre-point loading method to determine the flexural strength by means of the equipment specified.

Test the half prisms obtained in the flexural test in compression on the moulded side faces over an area of 40 mm × 40 mm.

When the flexural strength value is not required, this test may be omitted. The compressive strength tests shall then be carried out on the two halves of the prism broken by suitable means which do not subject the prism halves to harmful stresses.

Flexural strength

Place the prism in the testing machine with one side face on the supporting rollers and with its longitudinal axis normal to the supports. Apply the load vertically by means of the loading roller to the opposite side face of the prism and increase it smoothly at the rate of (50 ± 10) N/s until fracture.



Figure 3.16: Flexural test

Calculate the flexural strength Rf in N/mm2 from:

$R_f=1.5FfxL/b^3$ ----------7

Where:

R_f- is the flexural strength, in Newtons per square millimetre;

b- Is the side of the square section of the prism, in millimeters;

Ff- is the load applied to the middle of the prism at fracture, in Newtons;

l- Is the distance between the supports, in millimeters.

Compressive strength

Test the prism halves in compression on the side faces by means of the equipment specified. Centre the prism halves laterally to the platens of the machine within ± 0,5 mm, and longitudinally such that the end face of the prism overhangs the platens or auxiliary plates by about 10 mm. Increase the load smoothly at the rate of (2 400 ± 200) N/s over the entire load application until fracture. Where the load increase is regulated by hand, make adjustment for the decrease of the loading rate near the fracture load.

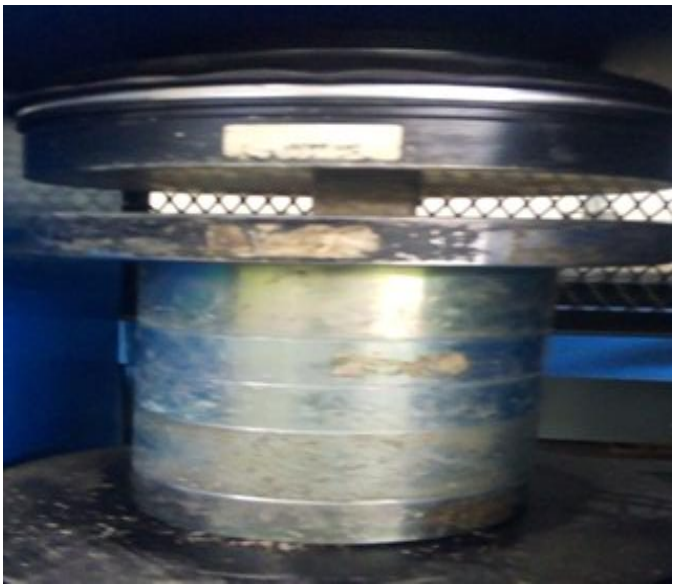


Figure 3.17: Compressive test

Calculate the compressive strength Rc in N/mm2 from:

Rc= Fc/1600----------8

Where: - RC- is the compressive strength, in Newtons per square millimetre;

Fc- is the maximum load at fracture, in Newtons;

1600 = 40 mm × 40 mm is the area of the platens or auxiliary plates, in square millimeters.

3.14 BONDING PROCEDURE FOR PLATE BONDING TECHNIQUE

Before bonding the ferrocement laminate on the tension face of the beam, the tension face of the beam surface was made rough using a sand blower and cleaned with an air blower to remove all dirt and debris. The epoxy resin COROCRETIN IHL-18, a product of dorite Anticorrosive.

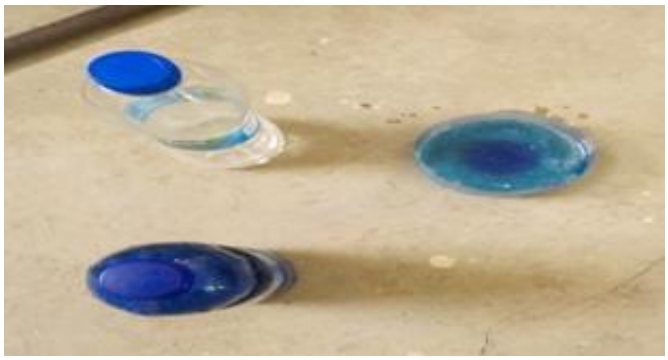


Figure 3.18: Epoxy resin with hardener

The components were thoroughly mixed in their individual packs before they were mixed together in the recommended ratio. Component A was taken in a vessel and to this required quantity of component B was added and stirred thoroughly so that a uniform mix is obtained. This mix should be applied by brush to the prepared surface, and when used as a seal coat, it is recommended to apply two coats. The newly fabricated ferrocement laminate should be placed within a maximum of 2 hours to the applied surface. According to the supplier's manual, one kilogram of mixed material will cover approximately 2 to 2.5 square meters of the surface. The actual coverage may depend on the texture and porosity of the surface and be applied for bonding old and new cementitious surfaces like old concrete to new concrete. The low viscosity of the epoxy resin enables easy penetration into hair line cracks and was applied on the soffit of the required beams. The high bonding strength ensures good adhesion to concrete substrate.

The epoxy resin was applied bottom on laminate and beam surface and bonded properly without any air gap as show in figure



Figure 3.19: Beam bottom applied with epoxy resin



Figure 3.20: Beam and laminate bonded together

3.15 FABRICATION AND BONDING PROCEDURE FOR CAST INSITU BONDING TECHNIQUE

Before fabricating the ferrocement laminate onto the beam surface, the bottom of the beam surface was made rough using a sand blower and cleaned with an air blower to remove all dirt and debris. The surface was prepared to the required standard locations to fix the shear connectors. Epoxy resin COROCRETIN IHL-18 was mixed in accordance with the manufacturer instruction and resin.

Cement and sand were mixed in 1:2 ratios, with specified water cement ratio. The wooden planks were arranged as per requirement. A thin mortar layer was applied of required thickness. One layer of woven mesh and one layer of weld mesh tied together having volume fraction Vr=2.192% was placed over it. Again, a thin mortar layer was applied. Finally shear connector was flattened. The top surface was finished properly. The moulds were removed after the specified time and the sides were finished. The above said procedure adopted for strengthening of predamaged beams by cast insitu bonding technique is shown in the Figure 4.14 and Figure 4.15. Same procedure was repeated for ferrocement laminates having volume fraction Vr=4.384% and Vr=6.576%.

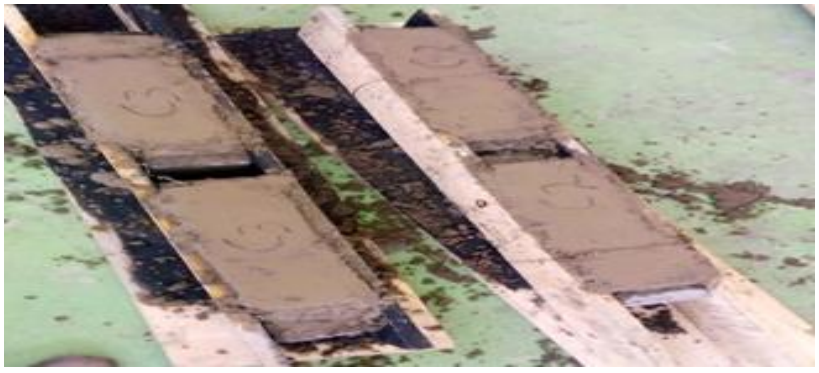


Figure 3.21: Beam with Form work

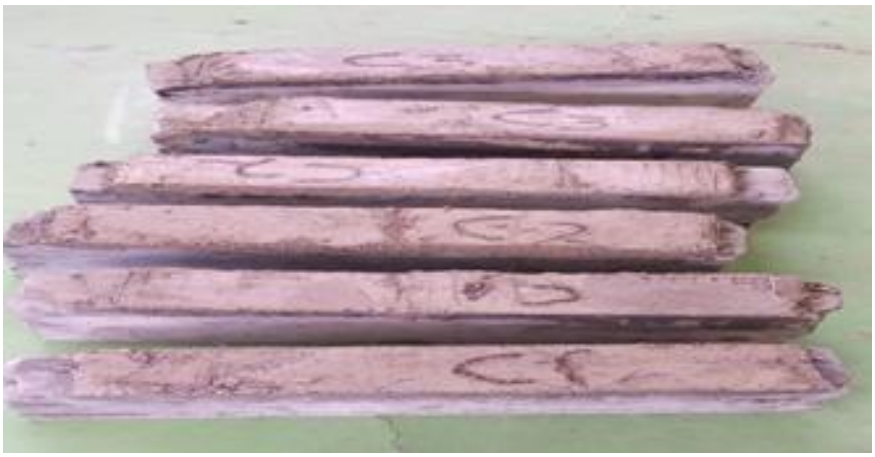


Figure 3.22: Finished form of beams

CHAPTER FOUR

RESULTS AND DISCUSSION

The compressive strength of the concrete cube test provides an idea about all the characteristics of concrete. By this single test one judge that whether Concreting has been done properly or not. Concrete compressive strength for general construction varies from 27 MPa and higher in commercial and industrial structures.

Compressive strength of concrete depends on many factors such as water-cement ratio, cement strength, quality of concrete material, quality control during the production of concrete.

Compressive strength is the ability of concrete to resist crushing or compression under a load. It is one of the most important mechanical properties of concrete, as it helps determine the load-carrying capacity of structures such as columns, beams, slabs, and foundations. The strength is measured in terms of the maximum stress the concrete specimen can withstand before failure. Concrete with higher compressive strength is more durable and suitable for heavy structures like bridges, dams, and multi-story buildings.

Test for compressive strength is carried out either on a cube or cylinder. Various standard codes recommend a concrete cylinder or concrete cube as the standard specimen for the test.

Compressive strength is the ability of material or structure to carry the loads on its surface without any crack or deflection. A material under compression tends to reduce the size, while in tension, size elongates.

4.1 CONCRETE STRENGTH TEST

The compressive strength of concrete is measured by its ability to withstand compressive loads without failing. It indicates how well the material can resist pressure and maintain its integrity under stress.

4.1.1 COMPRESSIVE STRENGTH RE RESULT

Compressive strength is a widely accepted measure to access the performance of a given concrete mixture. Considering this aspect of concrete is important because it is the primary measure determining how well concrete can withstand loads that affect its size. It

accurately tells you whether or not a particular mix is suitable to meet the requirements of a specific project.

Concrete can excellently resist compressive loading. This it is suitable for constructing arches, columns, dams, foundations, and tunnel linings.

The Compressive strength of concrete ranges from of the concrete beam 7 days and 28 days strength. To accurately test the compressive strength of concrete, standardized specimens are required. The shape and size of these specimens affect the result, as different geometries distribute stress differently during testing Cubic and Cylinder. Compressive strength depends on several interrelated factors. Conducting a compressive strength test requires careful attention to the preparation and handling of the concrete specimen. Even minor errors like air voids, improper curing, or misalignment in the testing machine can significantly affect the results. Even small changes in water content, curing time, or material properties can influence the result. For consistent quality and durability, all these factors must be well-controlled during construction.

Table 4:1 Compressive strength of concrete

Maximum Compression Strength of concrete	7 Days	28 Days
F1	7.276 Mpa	9.773 Mpa
F2	6.204 Mpa	9.99 Mpa
F3	7.072 Mpa	10.049 Mpa

4.1.2 TENSILE STRENGTH OF CONCRETE

The tensile strength of concrete is its capacity to resist cracking or breaking under tension I used Indian Standard. Although concrete is rarely loaded under pure pressure in a structure, determining the tensile strength is necessary to understand the extent of the possible damage. Breaking and cracking arise when tensile forces surpass the tensile strength.

The Tensile strength of concrete ranges from of the concrete beam 7 days and 28 days strength. The tensile strength of concrete is most commonly measured by the indirect split-

cylinder test. The new test method had undergone preliminary experimental study to determine the testing procedure that would yield the most reliable and consistent results.

Table 4.2 Tensile strength of concrete

Tensile strength of concrete	7 days	28 days
F1	1.159 Mpa	1.370 Mpa
F2	1.119 Mpa	1.257 Mpa
F3	1.120 Mpa	1.200 Mpa

4.1.3 FLEXURAL STRENGTH OF CONCRETE

Flexural strength establishes the ability of concrete to withstand bending. It is an indirect measure of tensile strength them Indian Standard.

Let us understand flexure strength with this classic example – several structures, including pavements, slabs, and beams, and its components are subject to bending or flexure. Talking of a beam, it may be loaded at the center and be supported at the ends. Its bottom fibers are in tension, whereas upper ones are in compression. If this beam is constructed with concrete, it will experience a tensile failure in the lower fibers because concrete has a weaker tension. However, including a few steel bars in the lower region will sustain a more significant load as the reinforcing steel has high tensile strength. In fact, if the reinforcing steel is pre-stressed in concrete, the beam will still be strong.

The Flexural strength of concrete ranges from the concrete beam 7 days and 28 days strength, the flexural strength of concrete is usually determined by testing a simple beam where the concentrated load is applied at each of the third points.

Table 4.3 Flexural strength of concrete

Flexural strength of concrete	7 days	28 days
F1	1.83 Mpa	2.70 Mpa

F2	1.58 Mpa	2.72 Mpa
F3	1.63 Mpa	2.75 Mpa

4.2 MORTAR STRENGTH TEST

The cement cube test is used to determine the compressive strength of hydraulic cement and other mortars. This quality is very important for almost all cement and mortar applications, especially when relating to infrastructure. Because compressive strength plays such a large role in cement mortar functionality and success. Cube testing is one of the most simple and common ways to determine the compressive strength of cement and mortar mixes. To ultimately calculate the resulting compressive strength, the load at the failure is divided by the area of the specimen.

4.2.1 FLEXURAL STRENGTH OF MORTAR

Flexural strength is a measure of tensile strength under bending, while direct tensile strength tests are also performed to determine the material's resistance to pulling forces. Flexural strength of mortar is a measure of its ability to resist bending or breaking under stress. It's essentially a measure of the mortar's tensile strength when subjected to bending forces. Different mortar types and mix designs are exhibit varying flexural strengths.

The Flexural strength of mortar from ranges the mortar 7 days and 28 days strength.

Table 4.4 Flexural strength of mortar

Flexural strength of mortar	7 days	28 days
R_{f1}	46.125 N/mm2	58.5 N/mm2
R_{f2}	38.0625 N/mm2	58.125 N/mm2
R_{f3}	40.125 N/mm2	65.625 N/mm2

4.2.2 COMPRESSIVE STRENGTH OF MORTAR

Mortar is a mixture of cement and sand in a specified ratio on which the strength of the mortar depends. If the mortar is weak then also its compressive strength is very low but if

the mortar is a strong one then its compressive strength is also very high. The mixture of sand and cement in water is generally weak intension and is strong in compression that is why when the concrete is subjected to tensile forces then it is provided with steel rods in area of tension that is why it is then called as reinforced concrete. Therefore, it is obvious the mortar will be strong in compression as compared to tension. Mortar is generally used for brick masonry and plastering. In first case the mortar is subjected to very high compressive loads such as the load of the wall above it, therefore it is very much necessary to test the mortar for its compressive strength.

While flexural strength is a measure of tensile strength under bending, it is often correlated with compressive strength. Mix designs often target a minimum flexural strength, which is then correlated with a compressive strength that is easier to measure in the field**.**

The Compressive strength of mortar from ranges the mortar 7 days and 28 days strength.

Table 4.5 Compressive strength of mortar

Compressive strength of mortar	7 days	28 days
Rc_1	23.187 N/mm^2	41.812 N/mm^2
Rc_2	17.750 N/mm^2	38.000 N/mm^2
Rc_3	23.687 N/mm^2	39.312 N/mm^2

4.3 TESTING OF BEAMS

All the beams are placed over the loading platform according to the specifications. The load is applied observed under the loading point and also at the Centre for every 2.0 kN load increment and recorded. According to the test program the first two beams are tested up to failure and the failure load is Pu. The other sets of beams, series 2 and series 3 were loaded to different Ferrocement laminated beam level of 65%Pu. These Ferrocement laminate beams were strengthened by ferrocement laminates having three different volume fractions (Vr=2.192%, Vr=4.384% and Vr=6.576%) of ferrocement reinforcements both by plate bonding technique and cast in situ bonding technique.

4.3.1 STATIC BEHAVIOUR OF CONTROL BEAMS

The static behaviour of beams includes studying the structural behaviour aspects such as deflection, crack propagation and ultimate load carrying capacity of the beam under monotonic conditions. Hence, the first series of beams namely perfect beams (BP1 and BP2) are tested monotonically with simply supported boundary conditions. These 42 beams are loaded up to failure and the deflections were measured for a load increment of 2.0KN and these load deflection values are used as base values for other beams. The ultimate load of the Control beam was noted and Pu. The load-deflection curves obtained for the beams BP1 and BP2 from the monotonic test is shown in Figure 4.1. The crack patterns obtained for the beams are shown in Figure 4.2.

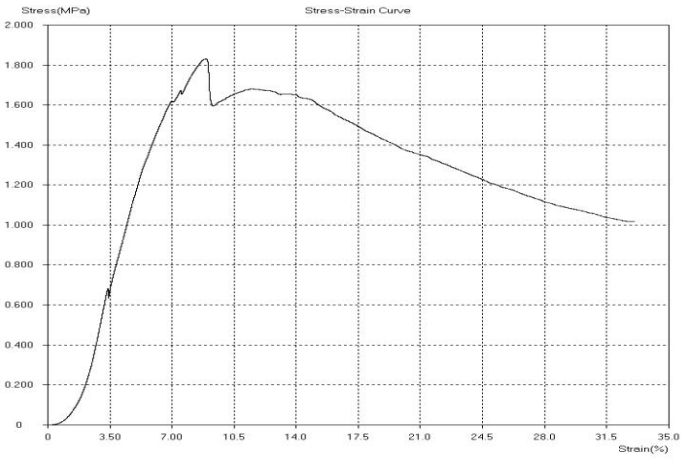


Figure 4.1: Load Stress-Strain behaviour of perfect beam (series 1)

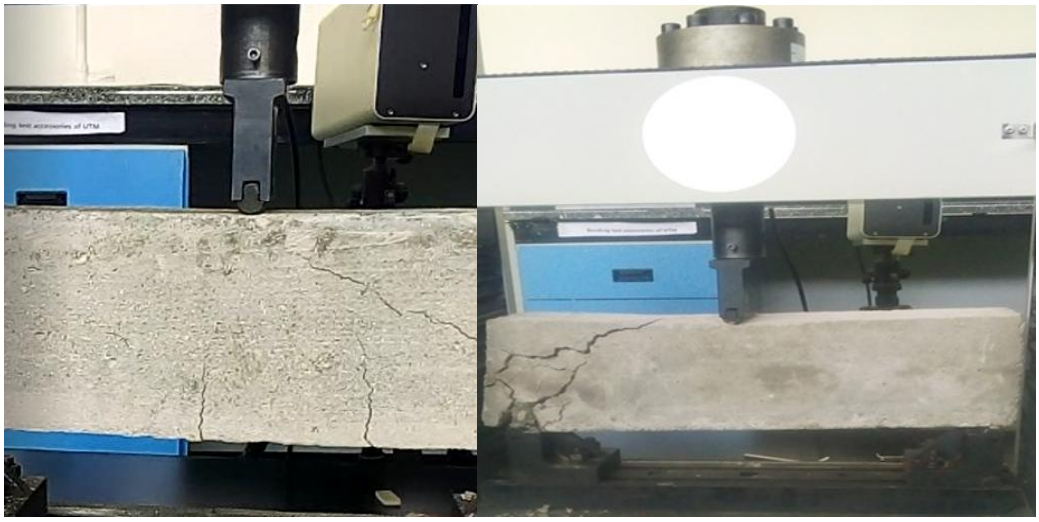


Figure 4.2: Crack patterns of perfect beams

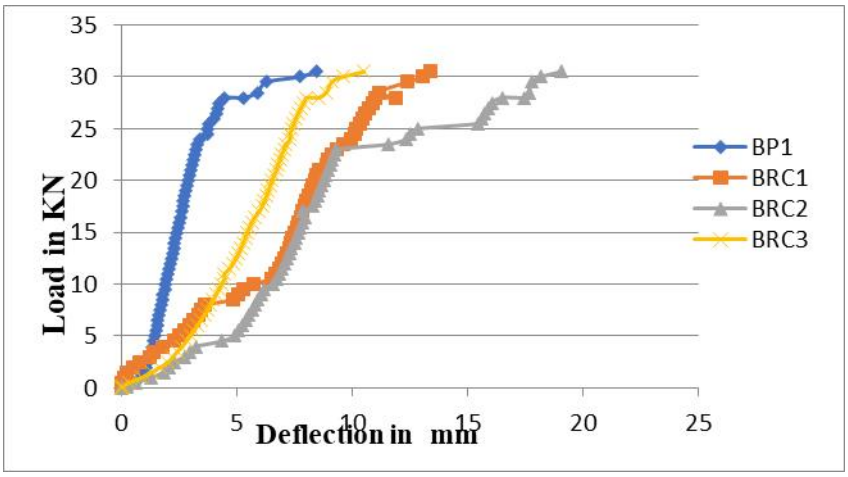


Figure 4.3: Load Deflection behaviour of Ferrocement laminated beams Cast in situ load

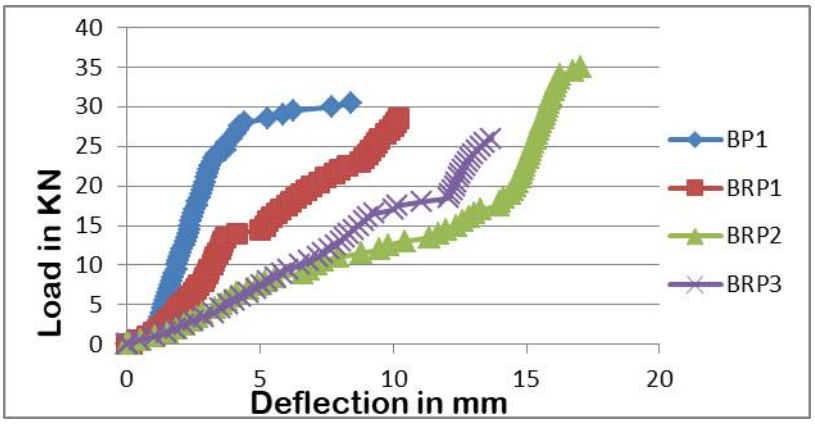


Figure 4.4: Load Deflection behaviour of Ferrocement laminated beams Plate load

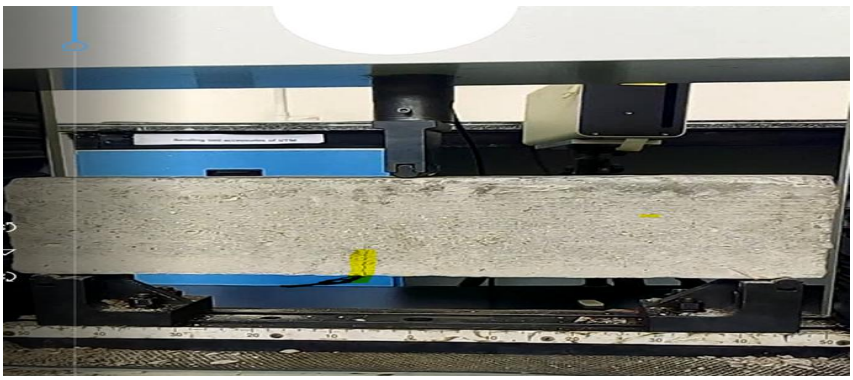


Figure 4.5: Load Deflection behaviour of Ferrocement laminated beams

4.4 FABRICATION OF FERROCEMENT LAMINATES FOR PLATE BONDING

Cement and sand are mixed in 1:2 ratios, with water cement ratio 0.42. The wooden mould of 3000 mm length, 125 mm width and 25 mm thick is arranging as per requirement. A thin mortar layer is applying for required thickness. One layer of welded 48 wire mesh and one layer of woven mesh tied together having volume fraction Vr=2.192% is placed over it. Again, a thin mortar layer is applying. The top surface is finished properly and the moulds are removing after the specified time and the sides are finish, as shown in Figure 4.8 and Figure 4.9.

The arrangements of ferrocement reinforcement conforming to volume fractions Vr=2.192%, Vr=4.384% and Vr=6.576% are shown in Figure 4.10. The arrangement of ferrocement reinforcement with volume fraction (Vr=2.192%) contribute with,

1 layer of weld mesh - 1.676%

1 layer of woven mesh - 0.516%

The arrangement of ferrocement reinforcement with volume fraction (Vr=4.384%) contribute with,

2 layer of weld mesh - 3.352%

2 layer of woven mesh - 1.032%

The arrangement of ferrocement reinforcement with volume fraction (Vr=6.576%) contribute with,

3 layer of weld mesh - 5.028%

3 layer of woven mesh - 1.548%

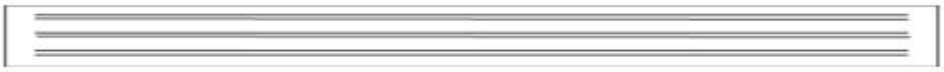


Figure 4.6: Finished bottom surface of the laminate

Vr=2.192%



Vr=4.384%



Vr=6.576%

Figure 4.7: Arrangement of meshes in ferrocement laminates

4.5 TESTING OF FERROCEMENT LAMINATE BEAMS

All the rehabilitated beams were grouped according to the amount of preloading given. Series 2 were given 67%Pu preloading, were rehabilitated with ferrocement laminates by using plate bonding technique having three different volume fractions under two beams in each volume fraction. The beams in series 3 rehabilitated with ferrocement laminates by using cast insitu bonding technique having three different volume fractions under two beams in each volume fraction.

4.5.1 Behaviour of Ferrocement Laminate Beams

The experimental load-deflection curves for beams BRP1-BRP6 and BRC1-BRC6 along with those of control beam BP1the bonding of ferrocement laminate to the tension face of the beams by cast insitu bonding technique have given good improvement in load carrying capacity than that of the beams by plate bonding technique. There was a good reduction in deflection of beams bonded by cast insitu bonding technique than plate bonding technique, particularly for beams strengthened with ferrocement laminate having volume fraction Vr=2.192%. This response may be attributed in an increase in lever arm due to bonding of ferrocement laminates and the increase in the composite moment of inertia of the section. The crack patterns obtained for the Ferrocement laminated beams by plate bonding (series 2) and the Ferrocement laminated beams by cast insitu bonding (series 3).

The crack propagation was restricted at the constant bending moment zone for the series 2 and series 3 of laminated beams BRP1 and BRP2, BRC1and BRC2 strengthened with ferrocement laminates having volume fraction Vr=2.192%. The second set of laminated beams BRP3 and BRP4, BRC3 and BRC4 strengthened with ferrocement laminates

having volume fraction Vr=4.384%, the performance was better than that of the perfect beams BP1, BP2. But, for the third set of beams BRP5 and BRP6 strengthened with ferrocement laminates having volume fraction Vr=6.576%, bonded by plate bonding technique, performance was better than the perfect beams but the performance was lower compared with that of beams laminated with volume fraction Vr=2.192% and Vr=4.384%. This was due to more volume fraction of ferrocement reinforcement and less bonding strength between the beam surface and laminate surface. In the case of beams BRC5 and BRC6 strengthened with ferrocement laminates having volume fraction Vr=6.576% bonded by cast insitu bonding, the performance is better than the perfect beams and also better than beams laminated by plate bonding having volume fraction Vr=6.576%.

4.5.2 Effect of Bonding of Ferrocement Laminates on Load Carrying Capacity

From the load-deflection curve the initial crack load is obtained by visual examination and also from the initial stage of load-deflection behaviour. The experimental yield loads were obtained by inspection corresponding to a stage of loading, beyond which the load deflection response is not linear. The experimental ultimate loads are obtained corresponding to a stage of loading, beyond which the beam would not sustain additional deformation at the same load intensity. The load carrying capacity obtained experimentally for undamaged ferrocement laminated beams by both plate bonding technique and cast insitu bonding technique are compared with those of the perfect beams BP1 and BP2 and tabulated in Table 4.6.

Table 4.6 Load carrying capacity at various stages of undamaged laminated beams

Series No	Beam code	Vr %	Load at different stages in KN		
			Initial crack	Yield	Ultimate
1	BP1, BP2	-----	18.0	20.0	44.0
2	BRP1, BRP2	2.192	19.5	23.0	50.0
	BRP3, BRP4	4.384	19.5	23.0	48.0
	BRP5, BRP6	6.576	19.0	21.5	48.0
3	BRC1, BRC2	2.192	21.0	26.0	56.0
	BRC3, BRC4	4.384	21.0	24.0	54.0
	BRC5, BRC6	6.576	19.0	22.0	48.0

From the test results, it is seen that the undamaged ferrocement laminated beams strengthened by cast insitu bonding technique (BRC1 to BRC4) show a good increase of

16.7% of load carrying capacity with respect to that of the perfect beams in the initial cracking stage. But the undamaged ferrocement laminated beams strengthened by plate bonding technique (BRP1 to BRP4) exhibit an increase of 8.3% of load carrying capacity with respect to that of the perfect beams in the initial cracking stage. This increase in percentage in undamaged laminated beams by cast insitu bonding technique was due to the anchorage of laminates with the base beams by the provision of shear connectors. The shear connector plays a major role in increasing the load carrying capacity of beams 58 bonded by cast insitu bonding technique than that of the beams bonded by plate bonding technique. In the yield stage, the sixth series of undamaged laminated beams BRC1, BRC3, BRC5 having three different volume fractions of ferrocement reinforcements by cast insitu bonding technique exhibit an increase of 30%, 20% and 10% respectively in load carrying capacity with respect to perfect beams BP1and BP2. whereas the second series of undamaged laminated beams BPR1, BRP3, BRP5 bonded by plate bonding technique with three different volume fractions exhibit an increase of 15%, 15% and 7.5% with respect to perfect beams BP1 and BP2. In the ultimate stage, the sixth series of undamaged laminated beams BRC1, BRC3, BRC5 bonded by cast insitu bonding technique having three different volume fractions of ferrocement reinforcements exhibit an increase of 27.3%, 22.7% and 9.1% respectively in load carrying capacity with respect to perfect beams BP1 and BP2. The second series of undamaged beams BPR1, BRP3, BRP5 bonded with plate bonding having three different volume fractions of ferrocement reinforcements exhibit an increase of 13.6%, 9.1% and 9.1% with respect to that of perfect beams BP1 and BP2. The cast insitu bonding technique behaves in an excellent way for strengthening of the undamaged beams in comparison with that of plate bonding technique. The experimental results clearly indicate that bonding of ferrocement laminates on the tension face of the reinforced concrete beams have given an enhancement in load carrying capacity and especially 2.192% volume fraction of ferrocement reinforcement laminates behaves in an excellent way in both cast insitu bonding technique and plate bonding technique.

4.5.3 Effect of Bonding of Ferrocement Laminates on Deflection

Deflection of a beam primarily depends on the span, moment of inertia of the section, type of loading, modulus of concrete and volume fraction (Vr) of ferrocement reinforcements in laminates. Bonding of ferrocement laminates to the tension face of the reinforced concrete beams results in the increase in moment of inertia and consequently, stiffness.

This increase in section influences the reduction of deflection of the strengthened beams during different load increments. The deflections of undamaged laminated beams at initial cracking stage, yield stage and at the ultimate stage with perfect beams are tabulated in Table.

Table 4.7 Deflection at various stages of damaged laminated beams

Series No	Beam code	Vr%	Deflection at different loading stages in mm		
			Cracking stage	Yield stage	Ultimate stage
1	BP1&BP2	---	1.12	6.45	34.86
2	BRP1&BRP2	2.192	0.98	5.36	30.58
	BRP3&BRP4	4.384	1.02	5.65	29.40
	BRP5&BRP6	6.576	1.08	5.85	31.25
3	BRC1&BRC2	2.192	0.88	4.98	30.68
	BRC3&BRC4	4.384	0.92	5.22	29.65
	BRC5&BRC6	6.576	0.98	5.35	30.48

At the initial cracking stage, the sixth series of beams BRC1, BRC3 and BRC5 strengthened by cast insitu bonding technique, with three different volume fractions of ferrocement reinforcements exhibit a decrease in deflection of 21.4%, 17.9% and 12.5% respectively with respect to perfect beams, while the second series of beams BRP1, BRP3 and BRP5 strengthened by plate bonding technique, with three different volume fractions of ferrocement reinforcements exhibit a decrease in deflection of 12.5%, 8.9%, 3.6% respectively with respect to perfect beams. At the yield stage, the sixth series of beams BRC1, BRC3 and BRC5 strengthened by cast insitu bonding with three different volume fractions of ferrocement reinforcements exhibit a decrease of 22.8%, 19.1% and 17.1% respectively with respect to perfect beams while the second series of beams BRP1, BRP3 and BRP5 strengthened by plate bonding with three different volume fractions of ferrocement reinforcements exhibits an decrease of 16.9%, 12.4% and 9.3% respectively with respect to perfect beams. At the ultimate stage, the sixth series of beams BRC1, BRC3 and BRC5 strengthened by cast insitu bonding with three different volume fractions of ferrocement reinforcements exhibit a reduction of 12.0%, 14.9%, and 12.6% respectively, while the second series of beams BRP1, BRP3 and BRP5 strengthened by plate bonding using three different layers of ferrocement reinforcements showed a reduction in deflection by 12.3%, 15.7%, and 10.4% respectively with respect to perfect

beams. 60 From the test results, it is found that the beams strengthened by cast insitu bonding technique and plate bonding technique showed good reduction in deflection when compared to perfect beams.

4.5.4 Different cracking pattern will be observed due to Ferrocement Laminate

The crack pattern at yield as obtained experimentally for Ferrocement laminated beams are compared with perfect beams is shown in Table.

Table 4.8 Crack width and Crack spacing of undamaged laminated beams

Series No	Beam code	Vr%	Crack width (mm)			Average crack spacing
			Cracking Stage	Yield Stage	Ultimate stage	
1	BP1&BP2	---	0.095	0.457	0.743	89
2	BRP1&BRP2	2.192	0.047	0.280	0.570	61
	BRP3&BRP4	4.384	0.057	0.342	0.576	62
	BRP5&BRP6	6.576	0.061	0.369	0.654	73
3	BRC1&BRC2	2.192	0.039	0.263	0.546	55
	BRC3&BRC4	4.384	0.046	0.326	0.559	59
	BRC5&BRC6	6.576	0.048	0.347	0.618	64

The crack pattern and flexural failure modes for undamaged ferrocement laminated beams by cast insitu bonding technique enhances in its performance compared with undamaged ferrocement laminated beams by plate bonding technique. The beams experienced considerable flexural cracking and enormous vertical deflection and compression failure at ultimate stage. The sixth series of undamaged laminated beams by cast insitu bonding technique with three different volume fractions of ferrocement reinforcement exhibit a decrease of 59%,52% and 49% crack width in the initial stage, 42%,29% and 24% in the yield stage and 27%, 25% and 17% in the ultimate stage when compared with perfect beams. The decrease in average crack spacing at yield stage is found to be 38% with respect to perfect beams. The second series of undamaged laminated beams by plate bonding technique with three different volume fractions of ferrocement reinforcement exhibit a decrease of 51%, 40% and 36% crack width in the initial cracking stage, 39%, 25% and 19% in the yielding stage and 23%, 22% and 15% in the ultimate stage as compared to perfect beams. The decrease in average crack spacing at yield stage was found to be 31% with respect to perfect beams

4.6 TESTING OF REHABILITATED BEAMS

All the rehabilitated beams were grouped according to the amount of loading given. Series 2 and series 3 were given 67% Pu loading. The beams in series 2 rehabilitated with ferrocement laminates by using plate bonding technique having three different volume fractions under two beams in each volume fraction. The predamaged beams in series 3 rehabilitated with ferrocement laminates by using cast insitu bonding technique having three different volume fractions under two beams in each volume fraction.

4.6.1 Behaviour of Rehabilitated Beams

The load-deflection response of the rehabilitated beams was very similar in pattern with respect to perfect beams. The load and deflection of the beams for various stages namely the initial cracking stage, yielding stage and ultimate stage were obtained from experimental data. The crack patterns obtained for the beams rehabilitated by plate bonding technique (series 2) and the beams rehabilitated by cast insitu bonding technique (series 3) Figure 4.8.

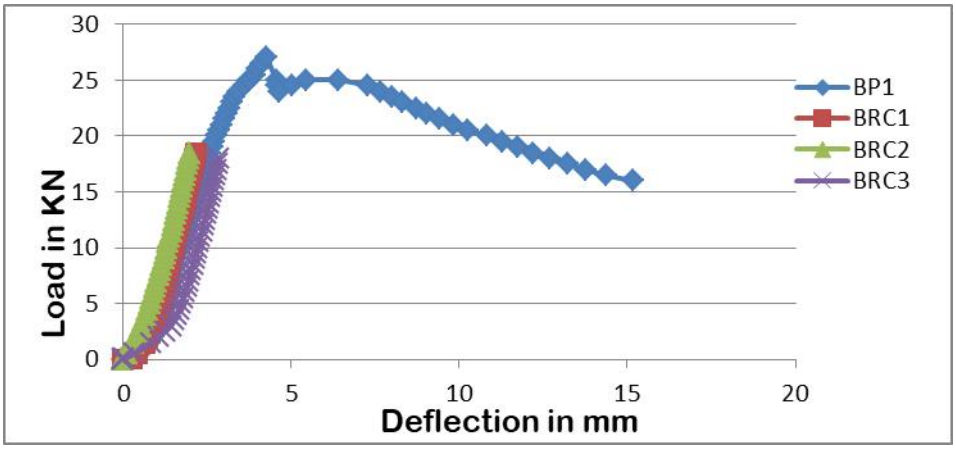


Figure 4.8: Load-Deflection behaviour of Ferrocement Laminates Cast in situ load rehabilitated beam

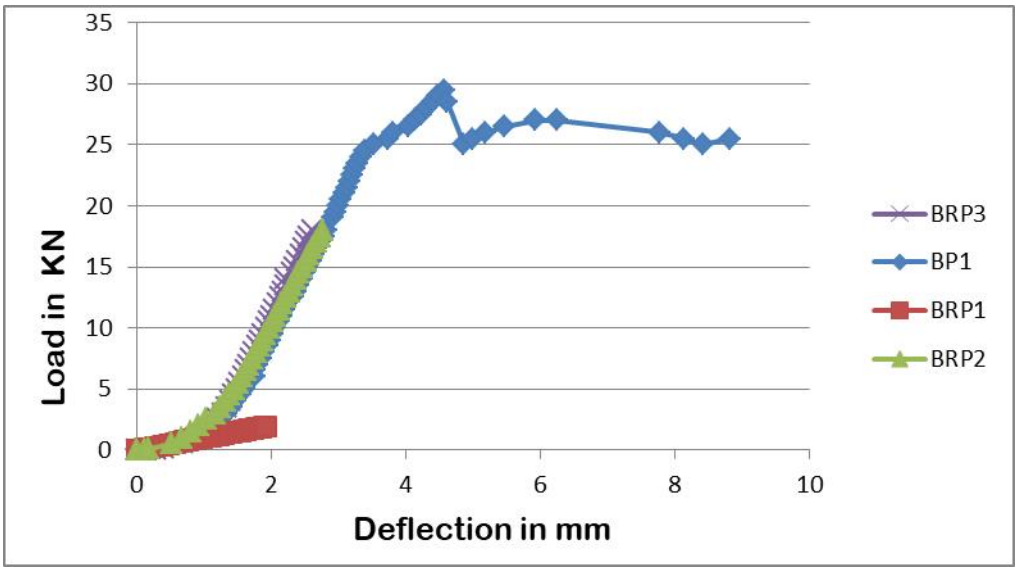


Figure 4.9: Load-Deflection behaviour of Ferrocement Laminates Plate load rehabilitated beams

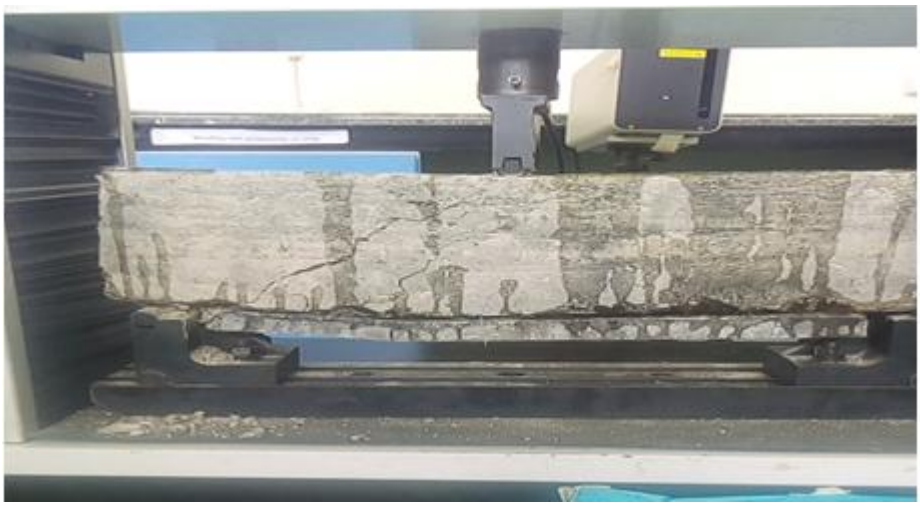


Figure 4.10: Crack patterns of Ferrocement Laminates rehabilitated beams in plate load

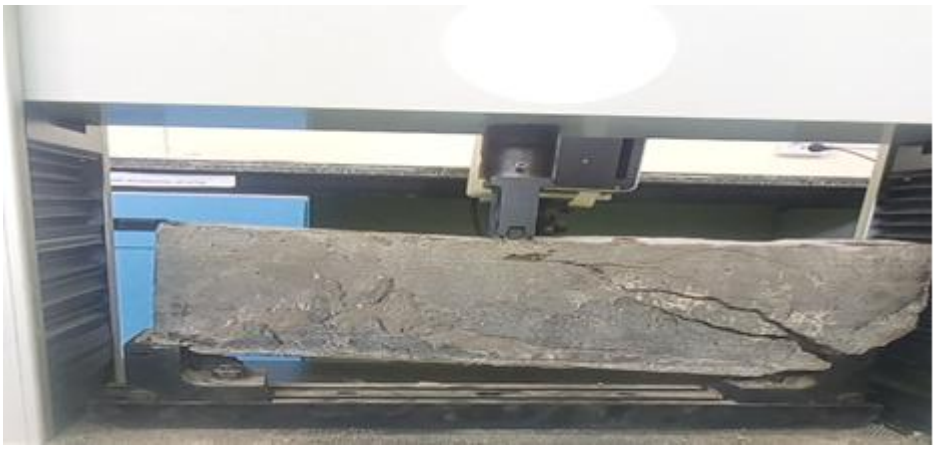


Figure 4.11: Crack patterns of Ferrocement Laminates rehabilitated beams in cast in situ load

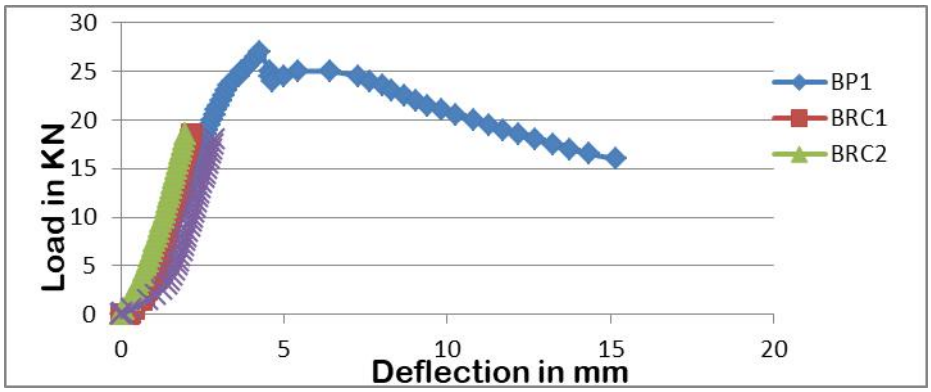


Figure 4.12: Load-Deflection behaviour of Ferrocement Laminates Cast in situ load rehabilitated beam

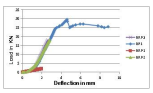


Figure 4.13: Load-Deflection behaviour of Ferrocement Laminates Plate load rehabilitated beams

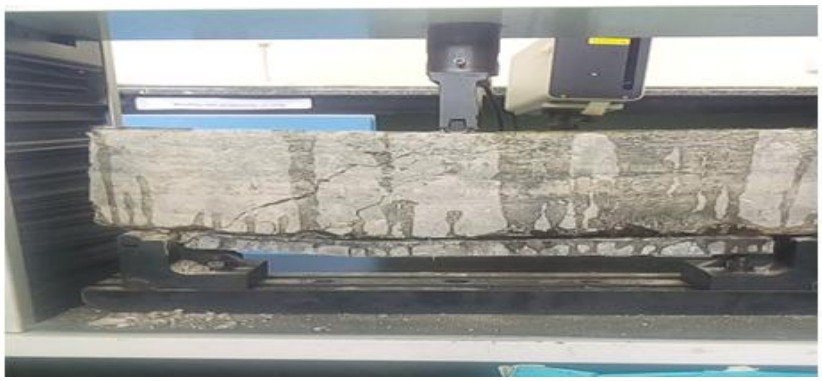


Figure 4.14: Crack patterns of Ferrocement Laminates rehabilitated beams in plate load



Figure 4.15: Crack patterns of Ferrocement Laminates rehabilitated beams in cast in situ load

4.7 PREDICTION OF DUCTILITY FACTOR

Ductility factor (DyF) was an important parameter considered in the design of structure subjected to deformation. Generally, it was defined in the case of member subjected to flexure, as the ratio of deflection at ultimate load to the deflection at yield load ($\delta u/\delta y$).

4.7.1 Prediction of Ductility Factor Plate bonding and Cast in Situ Bonding

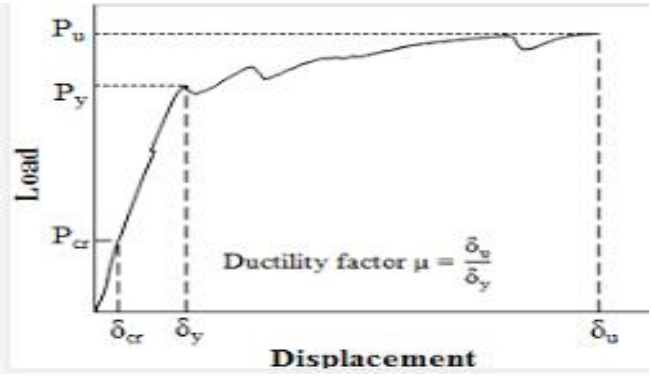
Using the experimented results, the ductility was calculated for Ferrocement laminated beams and Ferrocement rehabilitated beams by plate bonding technique and Cast in Situ technique are shown in Table 4.9

Table 4.9 Ductility Factor Plate bonding and Cast in Situ Bonding

S. No	Beam code	Damage level % Pu	Vr %	Ductility factor (DyF)	Load technique

1	BP1&BP2	control beam	----	1	
2	BRP1&BRP2	Ferrocement laminate beam	2.192	1.572	Plate loading technique
	BRP3&BRP4		4.384	1.674	
	BRP5&BRP6		6.576	1.462	
3	BRC1&BRC2	Ferrocement laminate beam	2.192	1.672	Cast in-situ loading technique
	BRC3&BRC4		4.384	1.874	
	BRC5&BRC6		6.576	1.562	

The relationship between ductility factor (Dy F) and the properties of ferrocement reinforcement (VrSr) for undamaged laminated beams by plate bonding have been established. Similarly, the relationship between the ductility factor (Dy F) and the properties of ferrocement reinforcement (VrSr) combined with degree of distress (Dd) for the rehabilitated beams by plate bonding and cast insitu bonding.



SUMMARY

Out of a total forty-two beams, first series of two beams were perfect beams tested under static monotonic loading. The series 2 consists of six Ferrocement laminated beams by ferrocement laminates with three different volume fractions of ferrocement reinforcements by plate bonding technique and series 3 consists of six Ferrocement laminated beams by ferrocement laminates with three different volume fractions of ferrocement reinforcements by cast insitu bonding technique were by loading the beams which corresponds to 67% of the ultimate loads of perfect beams and then rehabilitated by bonding of ferrocement laminates with three different Vr of ferrocement reinforcement using plate bonding technique. Another Ferrocement by loading the beams which corresponds to 67% of the ultimate loads of perfect beams and then rehabilitated by bonding of ferrocement laminates with three different Vr of ferrocement reinforcement using cast insitu bonding technique. All the above of beams were tested for determining the load deflection relationship and ultimate load carrying capacity. The overall performances of the perfect beams, Ferrocement laminated beams, Ferrocement rehabilitated beams were evaluated by means of effectiveness factors based on deflection and energy approaches.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSIONS

The regression-based predictive models developed in this study provide practical guidelines for engineers to estimate the strength enhancement and performance improvements achieved through ferrocement rehabilitation. These models enable evaluation of strengthened beams not only in terms of ultimate load-carrying capacity but also under serviceability limit states, which are essential for ensuring long-term structural safety, durability, and functional performance.

The proposed repair system is designed to achieve quantitative enhancement in structural capacity while extending the service life of deteriorated reinforced concrete members. This research establishes a systematic methodology for rehabilitating reinforced concrete beams using ferrocement laminates and demonstrates the improvement in structural behavior compared to control beams. The rehabilitation process involved bonding ferrocement laminates to the tension face of beams using plate bonding and cast-in-situ bonding techniques.

Experimental results confirm that ferrocement laminates, when properly bonded to the tension zone of reinforced concrete beams, significantly enhance flexural strength capacity. Among the configurations investigated, ferrocement laminates with a 2.192% volume fraction (Vr) of reinforcement exhibited superior performance compared to laminates with 4.384% and 6.576% volume fractions. The improved performance may be attributed to better stress distribution, effective bonding characteristics, and reduced brittleness at the optimal reinforcement ratio.

Overall, the study clearly demonstrates that ferrocement laminates constitute an effective and efficient strengthening technique for reinforced concrete beams. Properly designed and implemented ferrocement rehabilitation systems result in:

- Significant enhancement in flexural strength
- Improved crack control behavior
- Reduction in mid-span deflection

- Increased ductility and energy absorption capacity

The integrated experimental, analytical, and numerical approaches adopted in this research provide a comprehensive framework for the assessment and design of ferrocement rehabilitation systems. This methodology can be effectively implemented in practical engineering applications, offering a cost-effective, durable, and sustainable solution for extending the service life of existing concrete infrastructure.

5.2 RECOMMENDATION

The ferrocement layer has given adequate confinement for the reinforced concrete beams. Hence during testing of beams, splitting of concrete did not occur for the beams rehabilitated by plate bonding and cast insitu boding. The addition of ferrocement laminate in damaged beams increases the stiffness of the beam and hence increases in load carrying capacity and reduction in deflection. For the ferrocement laminate beams rehabilitation by cast insitu bonding is more than plate bonding technique of strengthening.

This thesis may be an input for further research. Future works can be performed in the following area.

1. Strength Enhancement of Rectangular RC Beams Using Ferrocement Laminates: An Experimental Study.
2. Investigate the long-term behavior of ferrocement-strengthened RC beams under sustained loading, creep, shrinkage effects, and environmental exposure conditions such as chloride attack, sulphate attack, and freeze–thaw cycles. Effectiveness of ferrocement laminates in improving shear capacity, torsional resistance, and combined flexure–shear performance of beams.
3. Examine the effectiveness of ferrocement laminates in improving shear capacity, torsional resistance, and combined flexure–shear performance of beams.
4. Detailed investigation on bond characteristics between the ferrocement laminate and concrete substrate can be carried out to understand failure mechanisms and debonding behavior.

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