APPRAISAL OF THE BOND STRENGTH OF FERROCEMENT SKIN AND CORE MATERIAL OF FERROCEMENT

BY

AMEH, Juliet Eyum

MTech/SET/2018/8278

DEPARTMENT OF BUILDING

FEDERAL UNIVERSITY OF TECHNOLOGY

MINNA

NOVEMBER, 2023

APPRAISAL OF THE BOND STRENGTH OF FERROCEMENT SKIN AND CORE MATERIAL OF FERROCEMENT

BY

AMEH, Juliet Eyum

MTech/SET/2018/8278

A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF TECHNOLOGY IN CONSTRUCTION TECHNOLOGY.

NOVEMBER, 2023

DECLARATION

I hereby declare that this thesis titled: "**Appraisal of the Bond Strength of Ferrocement Skin and Core Material of Ferrocement**" is a collection of my original research work and it has not been presented for any other qualification anywhere. Information from other source (published or unpublished) has been duly acknowledged.

AMEH, Julie Eyum
MTECH/SET/2018/8278
FEDERAL UNIVERSITY OF TECHNOLOGY
MINNA, NIGERIA

SIGNATURE/DATE

CERTIFICATION

This thesis titled: "**Appraisal of the Bond Strength of Ferrocement Skin and Core Material of Ferrocement**" by Ameh, Juliet Eyum (MTech/SET/2018/8278) meets the regulations governing the award of the degree of Masters of Technology (MTech) of the Federal University of Technology, Minna and it is approved for its contribution to the scientific knowledge and literary presentation.

Dr. T. O. Alao ______________________________

SUPERVISOR **Signature & Date**

Dr. J. A. Apeh ______________________________

HEAD OF DEPARTMENT **Signature & Date**

Prof. O. A. Kemiki ______________________________

DEAN OF SCHOOL OF ENVIRONMENTAL TECHNOLOGY **Signature & Date**

Engr. (Prof.) O. K. Abubakre ______________________________

DEAN OF POSTGRADUATE SCHOOL **Signature & Date**

DEDICATION

This work is dedicated to THE GOD ALMIGHTY, who made Heaven and the Earth, the one who was, who is and who is to come. He gave me the grace to be among the living. May His name be praised forever.

ACKNOWLEDGEMENTS

My appreciation goes to God Almighty for the grace to successfully complete this study. Indeed, what God cannot do, does not exist. I want to thank my supervisor Dr. T. O. Alao for his effort from the inception to the completion of my study. I would like to appreciate the former Postgraduate Coordinator of Building Department, Dr. R. B. Isa for always making sure I am making progress.

I want to specially thank our able and ever supporting Head of department, Dr. J. A. Apeh, for his contribution and advice towards the completion of my study. I also wish to acknowledge the following lecturers; Dr. E. B. Ogunbode, Dr. B. J. Olawuyi, Dr. E. A. Agbo, Prof. R. A. Jimoh, Dr. C. U. Ayegba, Miss H.G Nmadu, and Mr Y.Y. Garba for their contribution and encouragement.

A big thanks you to Mal. Mohammed Dan-Azumi for his support throughout my experimental works in the laboratory. Thanks also, to Alh. Babako, Mr. Sunday Olawale and Mal. Saka for always checking up on me. I cannot forget my ever-caring parent, especially my late dad, Chief Nobel Stephen Adah Ameh KSJ, JP, who stood by me financially, morally and other wise to ensure the success of my academic pursuit. A special thanks to my darling husband Lieutenant U.T. Younge, for his care and support and to my beautiful daughter Favour Abahi for her understanding.

Lastly, I want to appreciate my lovely siblings Dr. Linus Ameh, Moses Ameh, Simonpeter Ameh, Martha, Mary, Jossy and Cecillia God bless you all. I cannot also forget my daughter Helen, thank you for standing by me.

ABSTRACT

Ferrocement permanent forms supporting structural beam is subjected to flexural forces due to the beam's self-weight. The bond between the ferrocement form skin and the core material results in the mobilization of the tensile bond strength at the interface which is a plane bond. The study attempted to improve the bond strength by proposing an interlock bond at the interface. This was achieved by characterizing the bond strength according to the material strength used as the ferrocement skin and that of the core material. Experimentation was conducted in the laboratory using normal mortar, Granite mortar and self-compacting concrete-mortar interfaces as replicas to ferrocement forms with in-filled/core materials. Cubes were cast from the mixes of these materials and their compressive strength determined. Similarly, cylinders were cast from the mixes of these materials with tensile and bond strengths determined by a direct tensile method for both the plane bond (control) and the proposed interlock bond. Results indicate that bond strength values for both the plane and interlock bond depends on the compressive strength of the interface materials. It also shows that for the plane bond, bond strength values ranged from 1.57 N/mm^2-1.97 N/mm^2 at 28 days curing and for the interlock bond, its bond strength values ranged from 1.70 N/mm^2-2.17 N/mm^2 at 28 days curing age. The granite mortar used at the interface of the ferrocement skin and core material with an interlock bond has a bond strength value of 2.17 N/mm^2 compared with similar interface material but with a plane bond, value of 1.97 N/mm^2. The interlock bond strength improved by 9.22 % over that for the plane bond and granite mortar as interface material for permanent ferrocement form is a promising material.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

Ferrocement otherwise known as ferrocrete, being a relatively new material consist of cement mortar and wire meshes. It is a building technique that produces a very flexible concrete structure or structural member. It was first developed by P.L. Nervi, an Italian Architect and Engineer in 1940. The first ferrocement structure developed was the boat. In terms of construction, it consists of forming the shape of the required structure with a mesh of fine reinforcement, such as chicken mesh or expanded metal (Abdel, 2012; Fahmy *et al*., 2005; Fahmy *et al*., 2013; Korany, 1996). Multiple layers can be used to achieve the required density of steel and the whole can be stiffened with a few standard reinforcing bars. A stiff mortar is then applied to both sides of the layer of reinforcement known as the amarture and finished to the required thickness

Ferrocement has been used for casting domestic over-head tanks, grain silos used to preserve the grain from moisture and rodents. It is also used in wider applications. There is a growing awareness about the advantages of this technique worldwide. For example, conventional reinforced concrete members are too heavy, brittle and develop cracks which cannot be repaired satisfactorily if damaged. This implies that ferrocement structures or structural elements can performed better in terms of stiffness and flexure compared with conventional reinforced concrete (Fahmy, 2013; Naaman, 2000; Mays & Barnes, 1995).

The basis of construction material research lies on the optimal use of its properties as well as the reduction or total elimination of the behaviour that is undesirable. This approach provides more application and economic use of the materials. In order to increase the effectiveness of most construction materials, it is imperative that their merits are combined. Composite materials readily find applications and has such advantages especially composite members of concrete-to-concrete type. This type of composites is made by connecting two materials of the same or similar type. In previous years, main attention of researchers has been drawn to connecting normal concretes but now, a new type of concrete, such as high performance and self-compacting concrete is increasingly substituting regular concrete. When composite structures or structural elements are constructed with normal concrete and any other type of concrete, it enjoys the advantages of both materials. When compared with using HPC, the entire construction cost reduction is greatly achieved. Furthermore, the works of Tayeh *et al*. (2013) shows that HPC is also used to prepare construction elements for increased loading and for the repair of damaged sites in existing elements. The use of self- compacting concrete (SCC) to mitigate cracks and vibration problem in elements with high volume of rebars has also been highlighted.

In composite members, best bond transfer is ensured when concrete-to-concrete type is used. Composite strength between concrete layers or skins depends largely on the degree of adhesion between them. It is commonly used both in existing concrete elements and in the realization phases where the fresh concrete has not attained its matured strength. A lot of studies have also been conducted on composites and ferrocement but not much attention has been given to the bond strength between interfaces in ferrocement form.

1.2 Statement of the Research Problem

When two or more materials are in contact, the physico-chemical phenomena which occurs at the interface of the two or more materials which leads to the initial bonding of the materials is called adhesion. It is the forces of attraction acting between molecules of the materials in contact. The force required to separate such two materials is a measure of adhesion or the bond strength in composite structures such as ferrocement, where three main factors can be attributed. The work of

Halicka (2007) shows that there are natural adhesion and friction between concrete layers or skin. Natural adhesion results from the physico-chemical phenomena occurring at the interface of the two materials, which is further classified into mechanical and specific adhesion. Mechanical adhesion occurs when for example, glue penetrate into the irregularities of the surface which creates a bond (Tayeh *et al*., 2013). For a concrete surface with a glue applied on it, the glue is taken by the cement paste of the overlay. For the specific adhesion, examples are adsorption phenomena (chemical bonding, hydrogen bonds, Vander waal forces), electrostatics and diffusions. For the friction adhesion, it is the force acting on any two surfaces in contact that opposes motion of one surface over the other. Friction adhesion abounds naturally. It enables one to walk on a surface. On an extremely smooth surface where friction is almost zero, it is absolutely impossible to walk on such surface hence the two surfaces cannot be bond together and one easily slips over the other (Tayeh *et al*., 2013). For two concrete layers, mechanical adhesion plays a vital role as the cement paste of the overlay penetrates the substrate as well as adsorption to form a bond. The chemical content of both the connected elements is either the same or very similar. Inter-particulate forces act from the moment the fresh mixture comes in contact with the existing concrete element. This facilitates the penetration of the cement paste of the overlay. A key factor to be considered is the use of appropriate technology that will enhance the production of a more efficient precast ferrocement form. The bond between the ferrocement form skin and the core material is an adhesive bond which is of interest. There is usually, no perfect bond between any interface. For the ferrocement form, the interface between the concrete substrate and the overlay where the bond is formed is in a vertical plane and it is vertically oriented in the direction of the applied load or forces. The plane is common and exist through the entire strata of the ferrocement form, from top to bottom. This presents a weak link in the ferrocement form. A good bond is critical to the performance of the ferrocement form. Also, ferrocement, being a thin reinforced concrete product and as a laminate cement-based composite, has two main challenges; cracking and compaction which has to be addressed. In the study, normal vibrating concrete was replaced with SCC that solved the problem of cracking and compaction issues in ferrocement laminate Form.

The work of Tawab *et al.* (2012) on precast permanent ferrocement forms showed that, even though there was no application of any bonding agent or mechanical shear connection between the form and the core material. Test results indicated considerable serviceability and ultimate loading conditions, crack resistance control and good energy absorption capacity in these areas but was silent on the bond strength of the ferrocement form. The work of Fahmy *et al*. (2013) on ferrocement beams introduced bonding agent and mechanical shear connectors in between the inner skin of the ferrocement form and the core material but the bond strength and its effect(s) on the form has not been studied. Moreover, volume fraction and specific area of the reinforcement meshes used in the study does not meet prescribed specifications, thus the precast forms are more of reinforced mortars rather than ferrocement forms. In order to produce a more efficient precast ferrocement form, an improved technology which entails the use of SCC in place of normal vibrated concrete, an application of an interlocking bond at the ferrocement skin and core material interface was introduced (Tayeh *et al*., 2013; Harris *et al*., 2011). Previous studies have not addressed bond strength between ferrocement skin and core material which was addressed in the study. This study also intends to also develop properties of SCC incorporating ferrocement form with an interlocking bond between ferrocement skin and core material in precast ferrocement form.

1.3 Aim and Objectives of the Study

1.3.1 Aim

The aim of the study is to evaluate the bond strength at the interface between ferrocement skin and core material with a view to improving interlocking bond strength of the ferrocement form.

1.3.2 Objectives

To achieve the aim, the following objectives were to:

i) Determine the physico-chemical properties of constituent materials

ii) Determine the compressive strength properties of the core in-fill materials and ferrocement materials including Normal Cement Mortar (NC), ferrocement Self-Compacting Concrete (SCC) and Granite Powder Mortar (GPM).

iii) Evaluate the interfacial bond strength properties between ferrocement skin and core materials

1.4 Scope of the Study

The study was conducted at the macro level which entailed an experimental determination of the Plane and interlocking bond strength of SCC, normal Mortar, granite Mortar, Ferro -cement Form Skin and its core material and the effects of varying Core Materials on the interlocking bond strength of the Ferrocement Form.

1.5 Significance of the Study

The study is significant because it investigated the feasibility and efficacy of incorporating ferrocemnt laminate as permanent form for reinforced concrete beam for construction. It is innovative to combine ferrocement form with core material and with effective bond between them and construct or fabricate it as a structural element. The bond strength of the interlocking interface between core material and ferrocement skin was evaluated as an improvement over that of existing ferrocement form in the work of Fahmy *et al*. (2013). The volume fraction and specific surface area of the reinforcing meshes used for the study met requirements for ferrocement form. This study is an effort to improve material production processes used in structural concrete in ferrocement. This will lead to increase in strength, strength-to-weight ratio and other structural response of the form. The innovative technology that was applied in the construction of the form improved bond strength and mechanical efficiency thus lowering material consumption and production cost. The study is an added technical information that will enhance the design, construction and development of ferrocement concrete form and will serve as a veritable tool for modeling of ferrocement concrete forms.

CHAPTER TWO

2.0 LITERATURE REVIEW

In a bid to overcome structural challenges, there is a shift towards the use of economic structures through improved methods of design and use of higher strength materials which are vital in the field of reinforced concrete. The development of ferrocement apparently surpassed the limiting features of ordinary reinforced concrete. It is a type of reinforced concrete section usually constructed with hydraulic cement mortar, reinforced with closely spaced layers of continuous and relatively small size weld mesh. It has found applications in new structures, in repair and rehabilitation of existing structures because of its ability to act as a thin reinforced concrete product as well as a laminated cement based composite material.

The works of Naaman (1979) and Korany (1996) have reported values for its physical and mechanical properties and also numerical test data that evaluated the performance of Ferrocement in service. The work of Al-Rifaei and Hassan (1994) on ferrocement channels has shown that the structural element can undergo large deflections before failure and thus suitable for construction of transverse spanning units subjected to one-way loadings. The work of Rosenthal and Bijuger (1985) showed that ferrocement has been used as precast permanent forms for concrete beams. Furthermore, Sandowicz and Grabowski (1985) used ferrocement permanent formwork for construction of houses in Poland. Mays and Barnes (1995) reported that an increase in strength of 15% over conventional reinforced concrete beam was obtained when permanent ferrocement served as part of the concrete beam used to resist load over openings. About 18% of steel content and 80% of labour hours was saved when the same technology was used by Roa and Roa (1987). However, the beams were reinforced with steel meshes whose draw -back is mainly corrosion. This led to the application of non-metallic reinforcements and fibers such as Kevlar, Aragrid, carbon and PVA in ferrocement. Though non-corrosive, its major draw- back is cost and availability locally. This brings to focus the dire need to either identify more suitable non-metallic meshes for use in ferrocement or devise another construction approach or innovation so as to achieve not only higher performance, but also help eliminate the susceptibility of corrosion of conventional reinforcement such as steel meshes in ferrocement forms.

Shaaban (2018) and Saini & Singh (2022) investigated the feasibility of ferrocement as a permanent formwork and to improve structural behaviour of flexural reinforced concrete beams. He concluded that using expanded wire fabric as a permanent formwork and adding wings tailored by the same fabric resulted in increased load carrying capacity of the beams by 20% and reduced crack width by 15%. In addition, Shaaban (2018) studied ferrocement as permanent formwork for reinforced concrete beams. They incorporated mechanical shear connectors between the ferrocement form skin and the core materials. The results showed that ferrocement formwork contributed about 16-75% to the flexural strength of the composite beams. The concrete beams which were incorporated with shear connectors exhibited a 10% increase in strength and a reduced overall deflection when compared with those without shear connectors. Tawab *et al*. (2012) investigated the viability of precast permanent U-shaped ferrocement laminates of different types of mesh reinforcement. They reported high serviceability and ultimate loads, good crack resistance and good impact resistance from the use of the Ferrocement formwork. The study was further continued by Fahmy *et al*. (2013) and applied the ferrocement concept in the development of reinforced concrete beams made of precast permanent U-shaped reinforced mortar forms which used different core materials as viable alternative to traditional reinforced concrete beam. They used different types and amount of mesh reinforcement layers for the U-shaped ferrocement forms. The different core materials used was to achieve extra light weight elements. Adhesive bonding layer and mechanical connectors were used as shear connectors between the core material and the precast permanent reinforced mortar form. The results from the experimental work validated proposed system as having better crack behaviour, high serviceability and high failure loads with good energy absorptions.

2.1 Composite Structural Element

Ferrocement form is a structural composite element or member. The purpose of using composite members of either concrete-to-concrete type or concrete-to-mortar type is to ensure the best transfer of load. The adhesion between concrete or mortar layers is the principal factor that determines the strength of the composite since adhesion is the principal factor responsible for the strength of the composite ferrocement form, it is imperative that it is studied in details. Ferrocement form is made of the mesh, mortar and core materials. Mortar is used to bind the mesh together which can be in single or multiple layers as laminates.

2.1.1 Ferrocement meshes

Ferrocement meshes could be of steel or other materials usually in net-form. The net form could be in square, rectangular, oval or in any other shapes. In ferrocement permanent formwork, the mesh essentially provides the tensile resistance and because of its configuration proffer solution for the high resistance to shear stress thus preventing crack formation in the ferrocement form.

2.1.2 Ferrocement mortar matrix

Ferrocement consists basically of the mesh and the cement mortar matrix. The mesh which provides the tensile capacity for the ferrocement form is made up of a single layer or more embedded in the cement mortar matrix. The strength of the mortar matrix is designed so as to attain maximum density, impermeability, required workability to minimize voids and cracks. This is achieved with the use of appropriate grade of fine aggregate (sand) and portland cement. The work of Varma and Hajare (2015) shows that the mortar matrix in the ferrocement acts as an insulator and the reinforcing mesh reduce surface spalling better than in plain concrete. Ferrocement mortar consists of fine aggregates and occupy at least 95 % of volume of the ferrocement form. The sand-cement ratio is between 1.5 to 2.5, richer than conventional mortar used for block or brick bonding whose cement- sand ratio is between 1:3 and 1:6 respectively, (ACI 549, 2006). The water-cement ratio should be between 0.35 to 0.45 so as to achieve sufficient plasticity and facilitates laying with ease. The mix should be stiff enough but not to prevent full penetration into the mesh.

The work of Naaman (2000) has shown that the compressive strength of a mortar matrix suitable for a ferrocement form should be 37N/mm^2 for 28 days curing age. For ferrocement structures like water tanks, it is desirable that the mortar strength should be as high as 70N/mm^2 with high resistance to porosity, improved impermeability and water tightness (Batra *et al*., 2017). Depending on the type of ferrocement structures, admixtures and additives can be added to improve the performance of the cement mortar.

2.1.3 Placement of ferrocement mortar

The penetration of mortar into the ferrocement mesh during its construction plays a vital role during the construction of the ferrocement form. The impregnation of the mortar in the ferrocement mesh is achieved either by plastering or by shotcreting so as to obtain a homogenous mixture of ingredients whose end results is a fabric of mesh coated and well packed with mortar. Another approach of laying mortar on a ferrocement mesh is by laminating process developed by forms of California (Fahmy *et al*., 2005). It involves placing the mesh in the mortar rather than the mortar in the mesh. Then successive layers of meshes are placed in layers of freshly sprayed or manually placed mortar. To prevent mesh layers from poping out unto another layer, a thin mortar cover layer is placed first, allowed to set before the application of another/second mortar on the first layer. This is ensuring good bonding between the first and second layers. If the first layer is allowed to dry completely before the application of the second layer, this will result to poor bonding between the layers. The mortar layer for each mesh should be at least 3 mm thick so as to enhance the visual full placement contact and any gap in the mortar is corrected immediately (Naaman, 2000). Edges of ferrocement laid are property shuttered by the mechanical vibration ensuring proper cover so as avoid leakage, initiating water penetration and less durability (Fahmy *et al*., 2013). In laminated construction of ferrocement forms, delamination may occur due to splitting between layers or springing back or bridging of the mesh during construction. Furthermore, mechanized and precast methods of application of cement mortar on ferrocement mesh is adopted in many developing countries. When ordinary R. C. is compared to ferrocement, apparently, composites action between the matrix and the ferrocement is more pronounced in ferrocement form than in RC (ACI committee 549, 2006). When carrying out laying of mortar in ferrocement construction, correct material specification and proper workmanship should be strictly adhered so as to avoid failure of ferrocemnet structures (Fahmy *et al*., 2013).

2.1.4 Bond between ferrocement skin and core material

The ferrocement form consisting of ferrocement skin and the core material can be made by using normal concrete, self- compacting concrete and mortar while the core material could also be mortar, recycled concrete, wastes such as broken bricks or any other low-cost materials. The bond formed at the interface between cement skin and the core material is called, adhesion. This is due to the physico-chemical interplay of the ferrocemeent skin and the core material. Their physical and chemical properties inter-play to form the bond.

2.2 Bond between Concrete Layers

Considering the bond between concrete or mortar layers, the physical-chemical phenomena which occur at the interface of the two materials which culminates to the mutual bonding of the materials is referred to as adhesion. A measure of this adhesion will require an amount of a force that can separate such two materials.

The work of Halicka (2007) shows that three basic factors that can contribute to the bond strength of composite structures are the natural adhesion, friction between concrete layers and the use of reinforcements. Material adhesion is concerned with the physico-chemical phenomena which occurs at the interface of two materials. Natural adhesion can be grouped into mechanical and specific adhesion.

2.2.1 Mechanical adhesion

Mechanical adhesion which is a type of natural adhesion which occurs when for example, glue penetrates into the irregularities of the surface of an interface which creates a bond. Considering concretes, the cement pastes act like a glue on the overlay.

2.2.2 Specific adhesion

This type of adhesion is readily found in phenomena such as adsorption which includes chemical bonding, hydrogen bonds, Vander Waals forces, electrostatics and diffusions (Dybel, 2017).

2.3 Bond Strength

Bond strength in composites can be assessed in different ways in order to determine the strength of the bond. In assessing the bond strength of a ferro cement form, a suitable bond strength approach should be adopted. This is because in composite materials, there are many approaches for the evaluation of the bond strength. Different approaches for evaluating bond strengths are possible depending on the direction of load application. The work of Korani (1996) has shown that a proper method should be chosen, depending on the requirements concerning the repair conducted. In the same vein, a proper method should be adopted, in the assessment of bond strength of ferrocement form. An approach is the pull-off method, in which adhesion is assessed by measuring the strength of pulling off of the overlay from the substrate which is widely used (Dybel & Walach, 2017). Though widely used in practice, this is not suitable for ferrocement form because, the core material is not on top of the ferrocement, they lay side by side as an integral component of the ferrocement form. Secondly, direction of line of action of force or load is vertically downwards on the joint which forms the bond and not in the opposite direction as in the case of the pull-off test method. Thirdly, a considerable amount of force is required to displace the potential energy of the overlay before reaching the bond which is the point of interest. All these points render pull-off test method not suitable.

The second test method is the direct shear method. This method is based on applying a force horizontally that will shear the overlay from the substrate. This method is not suitable, since in practice, the load acting on the ferrocement form is vertically in a downward direction. The third method which is the compression slant shear test approach is also not suitable because, it requires an amount of force to overcome the potential energy of a portion of the overlay before the joint is reached and overcome. The overlay lies side by side with the substrate and not on top of the substrate. The fourth approach, the splitting tensile strength approach is based on applying a longitudinal compressive load on the interface of the concrete substrate and the overlay. This method is quite appropriate since the substrate and the overlay lie side by side and the longitudinal compression load acts on the interface of the concrete substrate and the overlay. This is in accordance with the provisions of ASTM C 496 (1996). Control of interfacial bond strength is a key factor influencing the overall mechanical properties of composites. In order to obtain desired mechanical properties for the composites, the interfacial bond strength should be carefully controlled, which can be achieved using different techniques. The work of Tayeh *et al*. (2016) on evaluation of bond strength between normal concrete substrate and ultra- high performance fiber concrete as a repair substance revealed that a pretty good to excellent bond is attained within the interface of the materials using the split cylinder tensile strength test.

2.4 Ferrocement and its Uniqueness

Ferrocement is a thin construction element with thickness in the order of 10-25 mm and uses rich cement mortars; no coarse aggregate is used and the reinforcement consists of one or more layers of continuous/small diameter steel wire/weld mesh netting. It is requiring no skilled labour for casting and employs only little or no formwork (Batra *et al*., 2001). In ferrocement, cement matrix does not crack since cracking forces are taken over by wire mesh reinforcement immediately below the surface.

The use of ferrocement is a promising technology for increasing the flexural strength of deficient reinforced concrete members. Its behavior in performance differs from conventional R.C. in terms of flexure, stiffness and resistance to cracks. Considering the fact that Shelter is one of man’s basic need in the world, developing countries more than any world experience deficit in housing need which is as a result of population growth, internal migration, War, and natural disaster, just to mention but a few. As a building material, ferrocement is being employed in place of stone, brick, prestressed concrete and timber and also as structural components in terms of walls, floors, roofs, beams, columns and slabs, water and soil retaining structures. The main advantage of ferrocement over conventional RC is that it can be fabricated into any desired shape or structural configuration that is generally impossible with standard masonry, RC.

2.4.1 Ferrocement in tension

One of the good properties of ferrocement over RC is its high tensile strength which accounts for very minute tensile cracks that occurs when it is in service. When ferrocement is under load, its tensile resistance gradually increases so as to resist loading. The work of El-Sayyed *et al*. (2013) showed that tensile strength of ferrocement is directly proportional to its specific surface which in turn is dependent on the type of reinforcement or wire mesh.

The surface area of a composite is the total surface area of reinforcement per unit volume of the composite. The tensile strength of ferrocement depends chiefly on the volume of reinforcement and the tensile strength of the mesh. Types of sand, normal weight, light weight and ratio of sand and water has little effect on the tensile strength of ferrocement. The tensile strength of ferrocement is related to the tensile strength of the reinforcement in the direction of the loading and also depends on the orientation of the wire mesh and whether the applied load is uniaxial or biaxial. A tensile strength test can then be used to assess the tensile bond strength between the core material and the ferrocement skin of the ferrocement form.

2.4.2 Ferrocement in cracking

One of the main features of ferrocement is cracking. When compared to conventional concrete, the work of Fahmy *et al*. (2005) shows that its cracks are narrower numerically. Ferrocement has a higher ability to resist overloading or structural settlement (Fahmy *et al*., 2005). Under the aforementioned condition, delamination may occur at or near the neutral axis. Hair line cracks that occur on the surfaces of ferrocement due to temperature changes and or drying shrinkages (provided they are not visible) may be left unattended but cracks due to occasional impact or overload and are visible need to be repaired (ACI committee 349, 2006). This is imperative so as not to allow hair-line cracks expand to become major cracks which ultimately leads to failure of ferrocement structural element. Incorporation of fibers in ferrocement panels can significantly improve cracking behaviour under flexure.

2.4.3 Repair techniques using ferrocement

For a structure to perform efficiently and increase in strength and stiffness, it must be repaired and regularly maintained. For ferrocement structures to perform well, its surfaces must be water tight at all times which prevents ingress of aggressive substances to the steel surface which decreases its durability (Jumaat *et al*., 2006). Ferrocement can be used for the repair of structural elements such as columns, beams and slabs up to 30% in terms of stiffness, energy absorption or toughness as well as towards the prevention of cracking. Such repair methodology can be in form of ferrocement patch in columns, bottom and middle portions of beams, soffit of slabs, ferrocement confinement is conducted around defective circular, square or rectangular columns so as to enhance strength, ductility and energy absorption capacity of existing concrete columns. For example, a jacketing layer of 30mm can be created around the column with ferrocement so as to increase its load carrying capacity and water tightness thus increasing its durability. When such a repair or retrofit is conducted on a structural element using ferrocement, it increases its performance and also enhances its finishing.

2.4.4 Ferrocement in shear

Ferrocement form or panels used in construction while in services is often subjected to shear depending on functions such as walling panels. In-plane forces act on the panels and subjected them to shear and ultimately to cracking if not mitigated. Also, when they form part of composite elements. Semi-precast floor slab (called half-slab in Malaysia has been used widely in different parts of the world. It consists of a reinforced concrete precast layer that acts initially as a formwork using shear connectors, steel reinforcement in form of shear link, studs and/steel truss, used to transfer the horizontal shear between the two composite layers. Longitudinal shear failure is common in such composite slabs. The work of Frith *et al*. (2013) used an interlocking concept to transfer the horizontal shear between the interfaces of the pre- cast and the cast-in-situ layers of the concrete slab. This concept supersedes the use of steel truss, studs to resists the horizontal shear and also to help bond the composite slab together.

2.4.5 Interlocking mechanism for shear transfer in composite materials

Composite floor slabs used in the erection of buildings are often subjected to horizontal shear in between the two composite layers held together by shear link or studs; leading to horizontal shear failure. To mitigate this short coming, an interlocking concept is introduced between the composite layers which is more effective than the shear link studs (Frith *et al*., 2013). This completely eliminates the use of shear link studs. The effectiveness of the interlocking mechanism in transferring the stresses developed due to the applied load was very high. This approach can also be used to replace the system where trusses are used to resist the stresses developed due to the application of load. This approach reduces costs by eliminating the steel trusses used between the composite layers of the floor or wall as the case may be.

2.4.6 Core materials in ferrocement form

Ferrocement produced with cementitious composites are considered as construction materials because of its high potential for meeting the increasing demand for high performing, economical sustainable and complex structures Its production and application as cement-based composites are environmentally friendly for its less energy consumption, thus, a sustainable construction alternative. As an alternative to the conventional steel and wooden formwork, ferrocement laminates have also been utilized as permanent forms which eventually remain as part of structural elements such as beams and slabs as it is more cost- effective (Matalkah *et al*., 2017). Ferrocement formwork has the great potential for speedy construction and material maximization at minimal cost, especially in curved structures. When compared with beams and slabs, it has less tensile reinforcement because of the steel mesh at its tensile zone which contributes to the tensile capacity for the ferrocement form. The works of Fahmy *et al*. (2013) shows that the physical and mechanical properties of ferrocement are excellent in terms of strength, crack control, impact resistance and toughness compared to other laminate construction materials. Fahmy *et al*. (2013) worked on the effect of steel mesh type and the number of steel mesh layers on the performance of the beams of U-shaped ferrocement formwork. Test results showed that the beams have better performance in terms of high ultimate and serviceability loads, enhanced crack control, high ductility and improved energy absorption capacity. Similar results were reported by Shaaban *et al*. (2018), in their work on the effectiveness of U- shaped ferrocement forms reinforced with different types reinforcement for the construction of reinforced concrete Slabs.

The work of Memon *et al*. (2006) showed that the use of lightweight aerated concrete as a core material in ferrocement matrix for lightweight structural applications. Ferrocement encased lightweight aerated concrete sandwich walls were used to study its flexural strength, failure mode, load-deflection behaviour and load-strain behaviour. Test results showed potential application of ferrocement encased lightweight structural elements. From the test results, failure mode of ferrocement elements is a reflection of the transformation of pure brittle characteristics of aerated concrete into ductile behaviour due to the ferrocement encasement. The work of Shaaban *et al*. (2018) on flexural characteristics of lightweight ferrocement beams used various types of core materials such as autoclaved aerated brick (AAB), extruded foam core (EFC), lightweight concrete core (LWC), and normal concrete as control. Test results showed that ferrocement beams exhibited higher ductility indices than that of the control, normal and lightweight test beams to different degrees. Ferrocement beams of EFC core material generally has the lowest ductility index while beams with AAB and LWC cores showed highest ductility. The study, however did not evaluate bond strength between theses core materials and the ferrocement skin, nor did it address the effect (s) of these core materials on the bond strength between the core materials and the ferrocement skin.

2.5 Application of ferrocement

Ferrocement products are used for other applications in the field of transportation and storage facilities. In addition, they are mostly used, particularly for low-income housing purposes.

2.5.1 Application of ferrocement in transportation

Ferrocement can be used as substitute for materials used in construction for varying means of transportation; especially in the construction of traditionally shaped means of transportation such as boats. This, requires the establishment of technical feasibility and field trials or demonstration, so as to overcome local resistance to innovation in boat building. Institutions like the Food and Agricultural Organization of the United Nations (FAO) and the United Nations Industrial Development Organization (UNIDO) have taken the initiative in introducing ferrocement in developing countries so as to achieve its use in the construction of boats and other sea vessels aimed at fishing in order to improve the economic base of the people. Because of its characteristics, low cost, strength, ease of maintenance and repair, it has found easy application.

2.5.2 Ferrocement for food storage facilities.

Because of the unique characteristic of ferrocement, it can be used as food storage facility. In developing countries where there are no durable means of storage of food items after harvesting, ferrocement wall find easy application. The dire need to preserve grains and other food crops to be safe from insect attacks in developing countries cannot be over emphasized. They can be used as silos and bins for grain storage. The existence of successful prototypes of water tanks in Bangkok, Thailand is an indication that it is feasible. What is required is for Government to make an initiative. This is imperative, considering the effect(s) of high temperature and humidity which promotes the growth of mold and rot on foodstuffs, destroy moisture-sensitive materials such as bagged cement or fertilizer and encourage thermal or ultraviolet degradation of many products. Insects, rodents and birds take an enormous toll, perhaps about 25% of each years' food crop in the developing world is rendered unfit or unavailable for consumption because of improper handling, storage methods and facilities. Hence the need for the use of ferrocement as food storage facility is imperative. Furthermore, ferrocement can be used to replace steel in some units of basic manufacturing equipment. Many foods, highly perishable foods affected by temperature changes and biological and chemical contaminants are lost to mankind because there are no rural processing plants to preserve, convey or process food products soon after harvest. In many developing areas, because of costs there are no even simple manufacturing equipment. This is because of the use of stainless steel which is usually imported is costly. Such costs can be drastically reduced if ferrocement-food-processing equipment is developed. With the development of ferrocement processing equipment, there are advantages such as fabrication using local materials, structural strength and reliability, ease of maintenance and repair and others.

2.5.3 Ferrocement in low-cost roofing

Ferrocement, being a thin-shelled material can be used as a roofing component, though laboratory trials are yet to commence, it is imperative to consider effort in this direction as it will go a long way in solving shortage of shelter especially in developing countries. Housing or shelter in developing countries is a major issue, hence roofs made with ferrocement materials can go a long way in mitigating housing deficits in developing countries. This is because ferrocement materials are cheap, affordable and durable especially in developing countries within the tropics. Use of ferrocement is a potential solution to roofing problems because of its comparative low-costs, durability, weather resistance and particularly its versatility. Unlike other materials, ferrocement can easily be shaped into surface or free-form areas. Because of its ease in fabrication, even in rural areas by supervised local labour using mainly local materials. It is an excellent medium for on-the-site manufacture of small or large tiles (shingles) or other roofing elements.

Another vital application of ferrocement is in the area of disaster relief materials. After fire, floods, droughts and earthquakes, the need of food, shelter and public health facilities are imperative. Transportation is often disrupted by destruction of roads, bridges, boats and airstrips. Supplies of bulky conventional building materials may be stranded outside the disaster area, whereas the basic ingredients of ferrocement may be available on site or easily transported.

Because of ferrocement versatility, it reduces logistical supply problems. Wire mesh, cement, sand and water can be substituted for the metal used for roofing, woods or plastic for shelters and clinics, steel for bridges, and so on. Moreover, most ferrocement structures though built for an emergency, will last long after the emergency is over.

As the development of light-weight, cost-effective and sustainable housing is increasingly being demanded and research into ferrocement as an alternative construction material to meet this demand is gaining significance as seen in the work of El-Sayed *et al*. (2023), there is a need to add or increase the scope of existing research literature on bond strength of ferrocement forms. This is the focus of the study.

CHAPTER THREE

3.0 MATERIALS AND METHOD

3.1 Materials

Portland cement (PC) CEM 1 42.5 N which conforms to BS EN 196-6 (1992) and BS EN 197-1 (2016) was used to make concrete mixes. Fine aggregates of natural siliceous sand and granite powder particles were used as shown in Figures 3.1 and 3.2. Granite crushed aggregates of 10 mm, 5 mm and 2.5 mm nominal sizes was blended and used for the study. Steel mesh was used for the formation of the ferrocement forms for the determination of the optimum properties of the ferrocement concrete form. Four (4nos) core materials namely: Normal concrete (NC), Normal cement Mortar, Self-Compacting Concrete, (SCC), Granite powder mortar, (GPM) was used for the study. Normal Cement Mortar, (NCM) and SCC mortar were used for the ferrocement skin. Preliminary tests were conducted on the materials to determine their suitability.

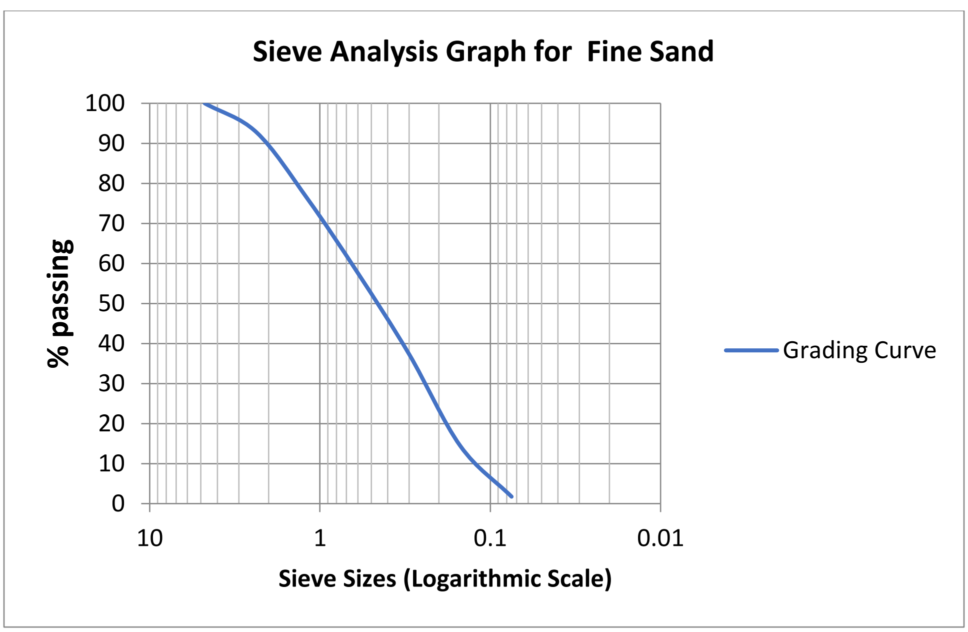

Figure 3.1: Sieve Analysis Graph for Fine Sand

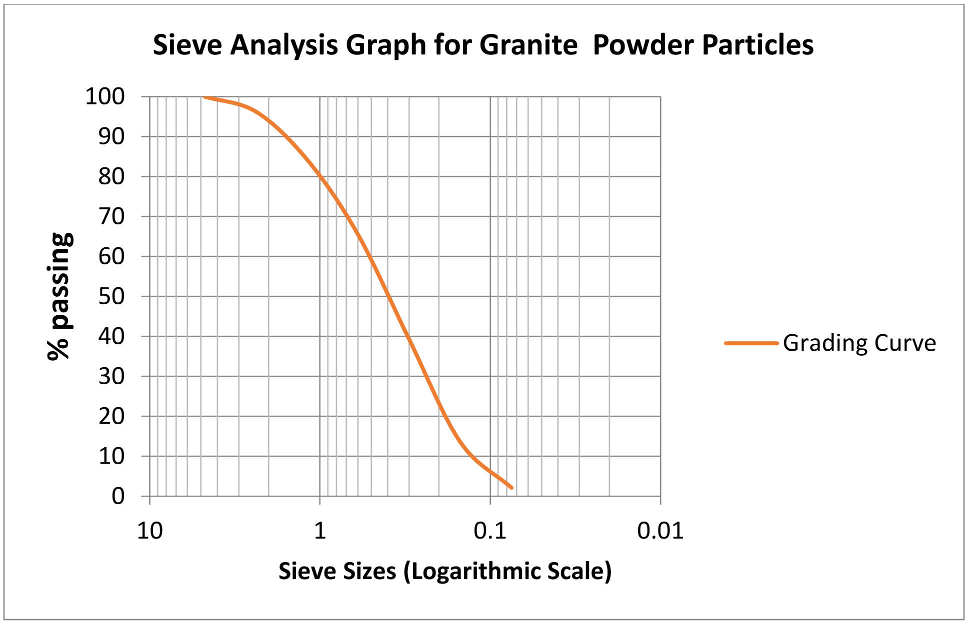

Figure 3.2: Sieve Analysis Graph for Granite Particle Sand

3.2 Mix proportion

For proportioning of SCC constituents, it was based on the guidelines of the European Project group, 2005. Mix design (Okamura & Ouchi, 2003) was adopted for the study. The method is rational with aggregate quantities being fixed, with W/B ratio of 0.4 and Super-plasticizer (SP) dosage being adjusted so as to achieve optimum passing, Filling ability and segregation which conformed to EFNARC (2005) specifications. The mix proportions of constituent materials in the work of Apeh & Ameh (2020) was adopted. For the mortar, a mixed ratio 1:3 was adopted.

Table 3.1: Designed mix Proportions for cube and cylinder tests for core and Ferrocement

Mix ID Composition (Kg/m^3)	NC	SCC	MORTAR	GPM
PC	375	400	250	250
Water	160	170	125	150
Sand (FA)	848	848	750	
Coarse Aggregates (10mm)	741	501		
Coarse Aggregates (5mm)		741		
Granite Powder				750
Super Plasticizer (%)		2.20		2.42
W/B Ratio	0.43	0.43	0.50	0.60

*NC – Normal concrete, SCC – Self compacting concrete, GPM- Granite Powder Mortar

3.3 Method

The methodology adopted here is to improve the bond strength by proposing an interlock bonding mechanism at the interface and comparing with the plane bonding. This enabled characterization of the bond strength according to the material strength with the ferrocement skin and that of the core material.

3.3.1 Experimental program and test procedure

All mixes (Table 3.1) were prepared accordingly. Slump flow tests for each mix was conducted in accordance with EFNARC (2005). Ninety (90) test specimen cubes and (90) cylinders were cast and cured for 3,7,14, 21and 28 days for the cubes and the cylinders and tested for bond and compressive strength of the control, Ferrocement skin and core material test specimens.

3.3.2 Preparation of test specimens

These consists of U-shaped ferrocement laminates and the direction of bonding in Figures 3.3, 3.4 and 3.5 incorporated a permanent form (150 x 300 x 1200 mm) in practice. Here, the specimen was used as cylinders (10 mm Φ X 200 mm). The SCC permanent ferrocement forms (cylinders) and the three different core infill materials were cast with Mortar, SCC and Granite Powder Mortar. The interfaces are shown in Figures 3.3, 3.4 and 3.5. Three (3) cylinders were cast using normal interface joint to serve as control specimens while another three (3nos) ferrocement forms with inter-lock joints were also cast as aforementioned using normal Mortar, SCC and Granite Mortar for the ferrocement skin and as core materials. The composite samples were produced at two stages. The mix representing the ferrocement skin was cast first, which occupied 50 % volume of the cylinder mould, then, allowed to set for about 20 minutes and the core material was cast too (Plates 3.1, 3.2 and 3.3). This was repeated for all the mixes for all the core materials and the ferrocement skin used for the study.

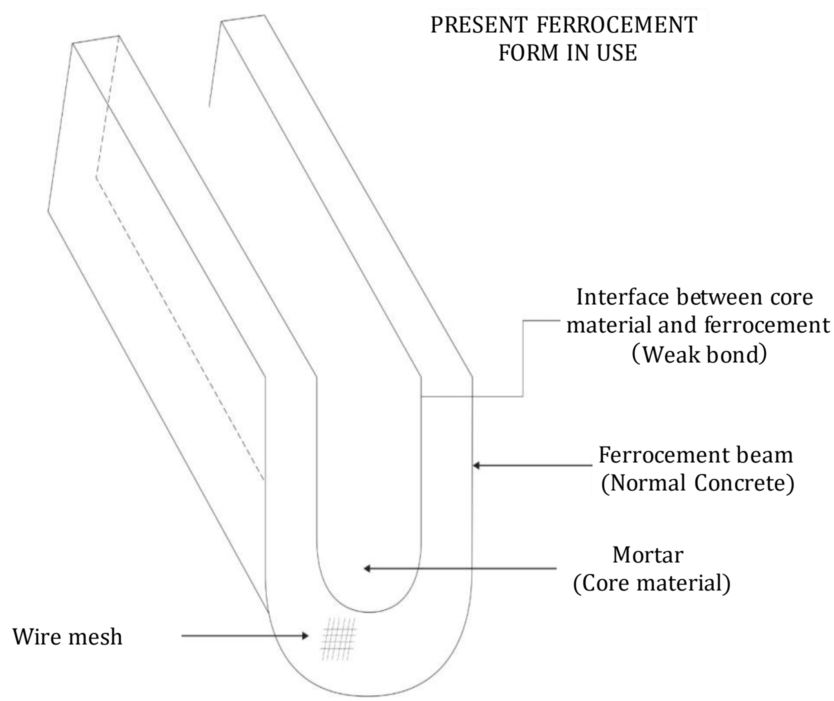

Figure 3.3: Existing Ferrocement Form (Plane bond)

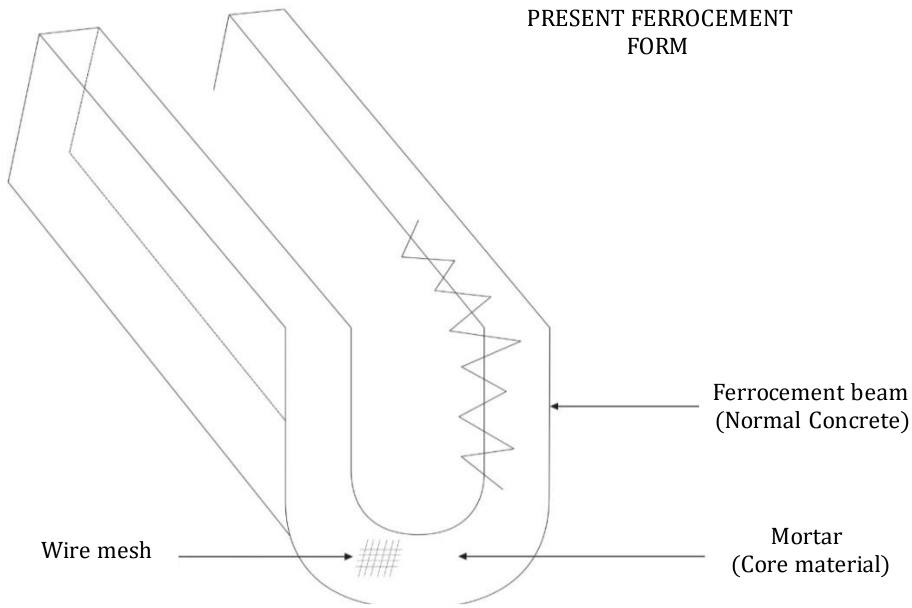

Figure 3.4: Experimental Ferrocement Form (Interlock bond)

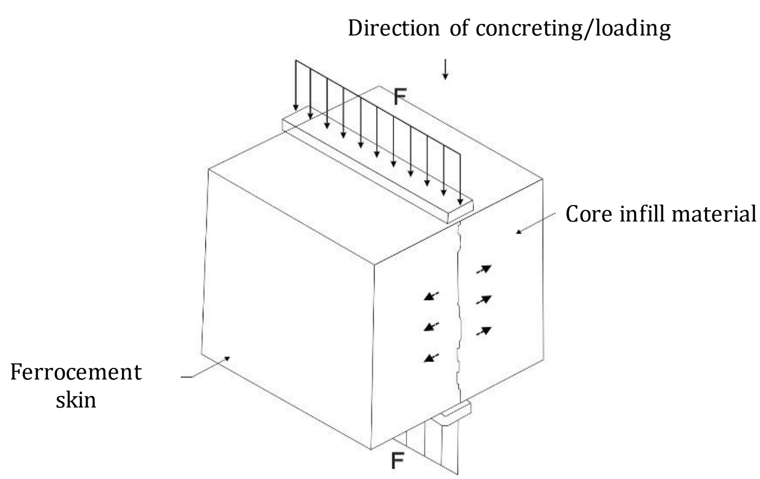

Figure 3.5: 2-D representation of specimen for plane bond testing

Plate 3.1: Material used to form Interlock Bond

Plate 3.2: Layout of interlock test specimen preparation

Plate 3.3: Cast Interlock bond Specimens

3.3.3 Test Method

The study was achieved experimentally by characterizing the bond strength of the ferrocement form. Experiments was conducted in the Building Department Laboratory. The cubes were crushed using a Universal Testing Machine, after each curing duration with the simulated cylinders as replicas of the ferrocement form. The specimens were tested using an indirect tensile test method and the bond strength determined using equation 3.1. The bond strength of the tested samples was characterized based on values in Table 2, in accordance with Springkel & Ozyilidirim (2000) and ASTM C496 (1996). The effect of test parameters (types of core materials) on the bond strength of the form were evaluated in Equation 3.1.

$$f_{ct} = \frac{2 . P}{\pi \, . \, l.d} \qquad (3.1)$$

Where:

f_{ct} is the splitting tensile bond strength (N/mm^2)

P - Maximum Load (N),

L – Length of contact line (mm)

d = cross-section size (mm)

Table 3.2: Bond strength quality

Bond quality	Bond strength (N/mm^2)
Excellent	> 2.10
Very good	1.70 - 2.10
Good	1.40 - 1.70
Fair	0.70 - 1.40
Poor	0 - 0.70

Source: Sprigkel & Ozyilidirim, (2000)

Bond strength test specimen sample is shown in Plate 3.4. Bond Strength analysis was performed using simple statistics of mean, standard deviation and Coefficient of Variation (COV) on the sample specimens tested and the results related to compressive strength values of the mixes. The bond strength values were also related to the type of bond (Plane and interlocking) and the optimum result values obtained.

Plate 3.4: Test Specimens ready for testing

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Test Results

Bond strength test results for the study show that the basic phenomenon which attract bond strength is the adhesion between concrete and mortar layers which develops with curing age of the parent concrete (ferrocement skin). Bond strength development could be linked to the development of the compressive strength of the ferrocement skin which is the parent concrete. Test result values of control specimens of ferrocement forms in terms of bond strength, relative bond strength development with plane and interlock bond interface were compared. Similarly, the effects of test parameters (types of core materials) on the bond strength of the forms were also compared.

. It should be noted that effect of mesh types and number of layers on the bond strength were not considered as these has no effect on the bond strength because ferrocement form and core material both have covers. Table 4.1 shows the test results for all the component specimens. A total of eighteen specimens were tested. An average value of three tests is reported. Three each, has its interface subjected to plane and interlocking bonding. For all the test specimens, bond strength increased with curing age. From the results of the test specimens, GM_1-GM_1 which is made of Granite Mortar as both the ferrocement skin and the core material and subjected to interlock bond has the highest tensile bond strength of $2.17N/mm^2$ at 28 days of curing. This is an increase of 9.20 % over that of same specimen subjected to plane bond. When SCC_1-M_1 (with interlock bond) is compared with SCC_2-M_2 (with plane bond), the Bond strength for the former has an improvement of 15.74% over that of the latter. This implies that the interlocking bond strength has an improvement over the plane bond method. This also show that the materials used as ferrocement skin and core materials play a vital role in the improvement of the bonding. The materials for the specimen SCC_1-M_1, is a self-compacting concrete and mortar. The bond strength for the interlock bond was 15% better than that with a plane bond.

Table 4.1: Test results of the strength of specimens

Compressive strength of composites at curing Ages (Composite Specimens)						
Specimen ID	Curing Age (Days)	Ferrocement Skin f_{cm}(N/mm^2)	Core Material f_{cm}(N/mm^2)	Bond Strength T_b(N/mm^2)	Type of Bond	Relative Bond Strength
M-M	3	10.90	10.90	1.27	Plane	0.76
	7	11.85	11.85	1.34		0.80
	14	13.85	13.85	1.41		0.84
	21	14.28	14.28	1.47		0.88
	28	16.63	16.63	1.67		1.00
SCC_1-M_1	3	14.20	11.00	1.40	Interlock	0.76
	7	16.80	12.20	1.50		0.81
	14	19.20	13.40	1.57		0.85
	21	25.30	15.30	1.61		0.87
	28	30.50	16.15	1.85		1.00
GM_1-GM_1	3	13.85	13.85	1.91	Interlock	0.88
	7	14.89	14.89	1.97		0.91
	14	15.75	15.75	2.04		0.94
	21	16.82	16.82	2.08		0.96
	28	18.25	18.25	2.17		1.00
M_1-M_1	3	10.90	10.90	1.37	Interlock	0.81
	7	11.85	11.85	1.43		0.84
	14	13.85	13.85	1.47		0.86
	21	14.28	14.28	1.53		0.90
	28	14.63	14.63	1.70		1.00
GM_2-GM_2	3	13.85	13.85	1.75	Plane	0.89
	7	14.89	14.89	1.79		0.91
	14	15.75	15.75	1.85		0.94
	21	16.82	16.82	1.91		0.97
	28	18.25	18.25	1.97		1.00
SCC_2-M_2	3	14.20	11.00	1.35	Plane	0.86
	7	16.80	12.20	1.46		0.93
	14	19.20	13.40	1.50		0.96
	21	25.30	15.30	1.53		0.98
	28	30.50	16.25	1.57		1.00

*M-M (Control specimen)

Results from the Table 4.2 show that the specimen (GM_1-GM_1) has an excellent bond strength with a bond strength value of 2.17N/mm^2 while specimen SCC_2-M_2 has a good bond with a bond strength value of 1.97N/mm^2. This results further show that the bonding strength between specimens tested ranged between good and excellent bonding performances.

For Specimen M_1-M_1 (with interlock bond), the bond strength improved in value over same specimen (with plane bond by a value of 2%. In summary, specimens with interlock bond compared with same specimens with plane bond improved in bond values of 9.20%, 15.14% and 2.0% respectively over values for specimens with plane bonds. This implies that the interlock bond strength has an improvement over that for Plane bonding. When the bond strength values for specimens with plane bond are compared with control value, GM_2-GM_2 has an improved bond value of 15.23%, SCC_2-M_2 has a decreased value of 6.37%. This shows that granite dust material when used as both ferrocement skin and core material has better bond strength values hence it is a promising material. Figures 4.1 and 4.2 show the bond strength development for both plane and interlock bond types. This increased with increase in curing age irrespective of bond type.

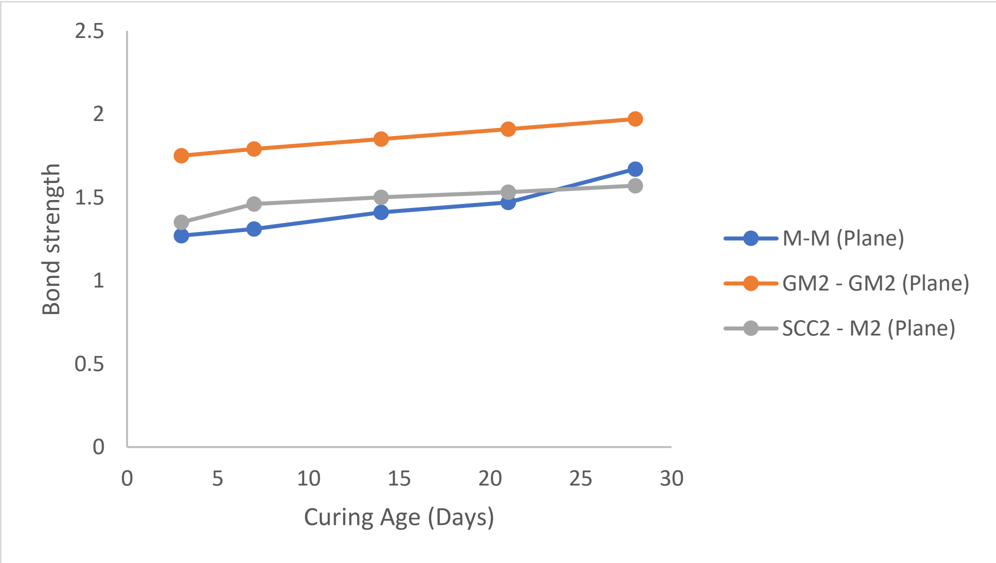

Figure 4.1: Bond strength versus curing Age for Plane bond specimens

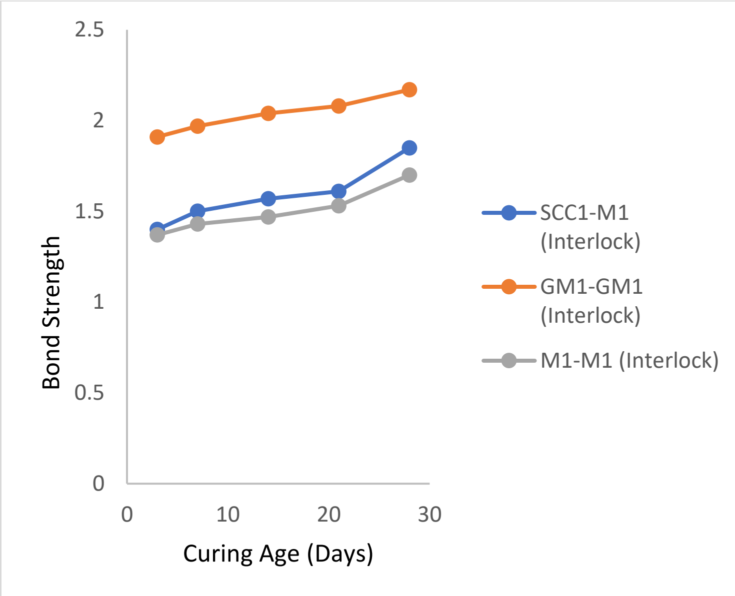

Figure 4.2: Bond strength versus curing Age for Interlock bond specimens

4.2 Relative Increase of Bond Strength

Figures 4.3 and 4.4 show the relative development of tensile bond strength for all tested specimens with both plane and interlock bonds. The relative development of a bond strength for a test specimen is the ratio of the bond strength at a particular age to that of the bond strength at 28 days of curing age. For both plane and interlock bonds, the relative bond strength for each specimen increased with curing age. The relative increase of bond strength for specimen GM_2- GM_2 is similar to that for SCC_2-M_2 specimen. This is because of the presence of mortar as both the ferrocement skin and the core material for the specimen while for SCC_1-M_1 specimen, Mortar was used as core material while SCC was used as ferrocement skin. Because of over-presence of mortar, it controlled the relative strength development and secluded the effect of SCC as the ferrocement skin on the bond strength for the composite. The relative increase in bond strength for specimen GM_1-GM_1 (Figure 4.4), with interlock bond is higher than that for any of the specimens containing Mortar. This is because the granite dust is pozzolanic and enhance strength development through its pozzolanic reaction in addition to the PC hydration unlike in mortar that has only PC hydration and the inert sand particles not aiding additional hydration. The relative increase in bond strength development for specimens containing SCC has a slight edge over that containing solely mortar (Figure 4.1). Again, this is because SCC often contain additives which are pozzolanic and hence with its pozzolanic reaction, will improve relative bond strength development in addition to the PC hydration in the Mortar Mix.

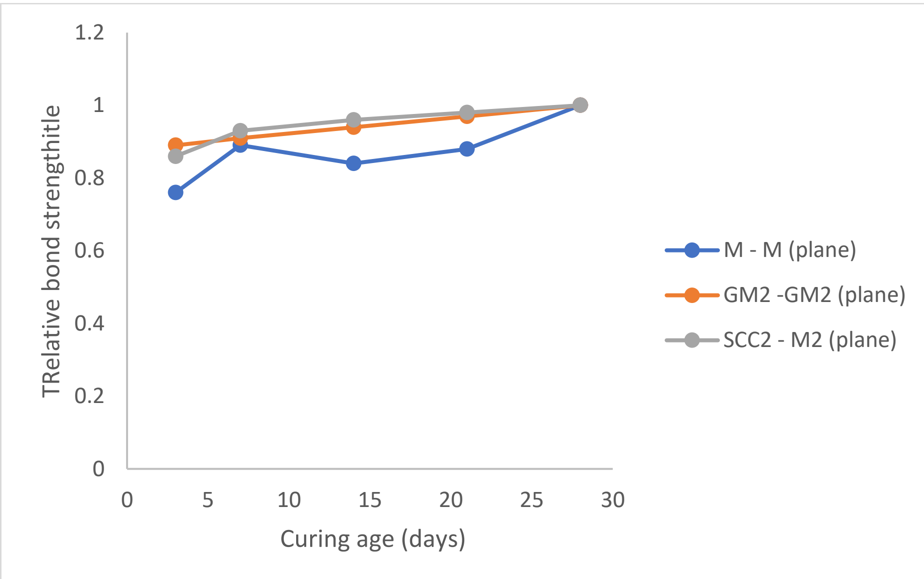

Figure 4.3: Relative bond strength versus curing Age for Plane bond specimens

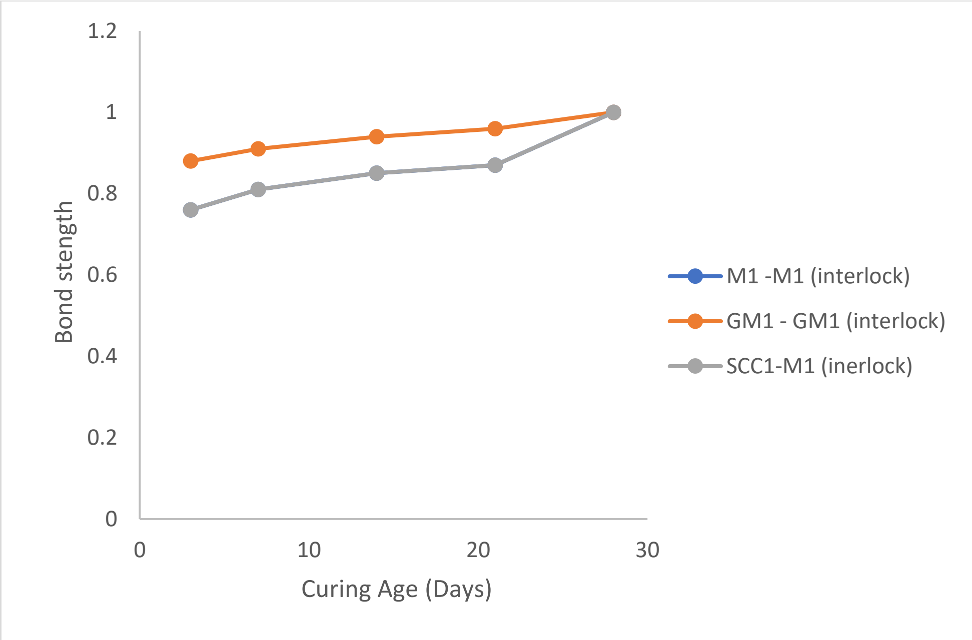

Figure 4.4: Relative bond strength versus curing Age for Interlock bond Specimens

4.2.1 Failure pattern of specimens

The failure of specimen samples occurred through interface failure. Most of the common interface failure mode occurred within the Core Material Transition Zone (CTZ). This type of interface failure mode was characterized by a thin layer of the core material added to the ferrocement skin. Therefore, failure occurred principally in the micro-concrete materials for the SCC_1-M_1 and GM_1-GM_1 specimens, the interface failure mode was observed both in the core material transition zone and in ferrocement skin. This indicates a strong adhesion of the matrix SCC in the ferrocement skin and the mortar matrix which served as the core material.

4.2.2 Quality of Tensile Bond Strength

The work of Springkel and Ozyilidirim (2000) shows that the interfacial bond strength test results of composite materials can be classified as shown in Table 4.2. Based on this classification, in the test specimen (QM_1-GM_1), the bond strength value of 2.17N/mm^2 at 28 days curing age is an excellent bond. The summary test results are shown in Table 4.2.

Table 4.2: Quality of Tensile bond strength of tested specimens

S/No	Specimen 1D	Curing age (days)	Bond Strength (N/mm2)	Remarks
1	M-M (Control)	28	1.67	Good
2	SCC_1-M_1	28	1.85	Very good
3	GM_1-GM_1	28	2.17	Excellent
4	M_1-M_1	28	1.7	Very good
5	GM_2-GM_2	28	1.97	Very good
6	SCC_2-M_2	28	1.57	Good

Results from the Table 4.2 show that the specimen (GM_1-GM_1) has an excellent bond strength with a bond strength value of 2.17N/mm^2 while specimen SCC_2-M_2 has a good bond with a bond strength value of 1.97N/mm^2. This results further show that the bonding strength between tested specimens tested ranged between good and excellent bonding performances

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATION

5.1 Summary of Findings

The study sought to determine the bond strength between ferrocement skin and core material of ferrocement form with a view towards its improvement. This was achieved by subjecting plane and interlocking bonds of composites specimens simulated as cylinders of varying materials such as Mortar, SCC and Granite dust Mortar. Mixes of these materials were prepared; cubes were cast and compressive strength determined. Cylinders from the same mixes were also cast, cured and the tensile bond strength determined using the aforementioned materials as ferrocement skin and core materials. The test results were analyzed and discussed making reference to relevant literature. The summary of findings are as follows:

i) The bond strength of tested specimens for the study ranged from 1.57N/mm^2 to 1.97N/mm^2 for plane bonds and 1.70N/mm^2 to 2.17N/mm^2 for interlock bonds.

ii) All failures occurred in the core material close to the bond interface suggesting that the ferrocement skin is stronger for the composite specimens.

iii) The bond strength and the relative bond strength development increase with curing age confirming the fact that bond strength is related to compressive strength of the composite specimens tested.

iv) The bond strength of tested specimens with interlock bond improved in value ranging from 9% to 15% over same specimens but subjected to plane bonding.

v) Among the materials used as the ferrocement skin and core material, Granite Mortar (GM_1-GM_1) test specimen has the highest bond strength of 2.17N/mm^2 (interlock bond) and Self compacting Mortar (SCC_2-M_2) has the lowest bond strength with a value of 1.57N/mm^2 (plane bond). The bond strength quality ranged from good to excellent bond.

5.2 Conclusion

The study sets out to evaluate the bond strength between ferrocement skin and the ferrocement form. Experimental tests were conducted and based on the results, analysis, discussions and findings, it is concluded that: The bond strength of ferrocement form when inter locked, improved over that with plane bound by 9 to 15%. The bond strength quality of ferrocement form ranged from good to excellent.

Among materials used as ferrocement skin and Core Material, Granite-Mortar Mix (GM_1-GM_1) is the most suitable with a bond strength of 2.17N/mm^2. The bond strength between ferrocement skin and core material irrespective of type of materials used for either the ferrocement skin or for the core material, increased with duration in curing age.

5.3 Recommendation

From the summary of findings and conclusions drawn herein, it is recommended that:

i) Interlock bond be adopted between ferrocement skin and the core material for optimal bond strength.

ii) For the ferrocement form, granite dust mortar mix be used as the ferrocement skin and the core material as well for optimal bond strength.

5.4 Contribution to knowledge

The following are the knowledge contributions from the experimental work:

i) Bond strengths for interlock faces have been experimented and the improvements have been highlighted

ii) Bond strengths for a variety of a variety of infill material interfacing permanent ferrocement forms have been investigated and values of the bond strengths obtained

iii) Failure patterns corresponding to the different core infill materials have been investigate and found out that permanent ferrocement ferrocement forms are strong since failure occured only in the core infill materials

REFERENCES

Abdel, T. A. (2012). Development of permanent formwork for Beams using ferrocement Laminates, Ph.D.Thesis submitted to Menoufia University, Egypt.

ACI Committee 549 – IR- 88 (2006). Guide for the design, Construction and repair of Ferrocement. Manual of concrete Practice 30(1). Farmington Hill; American concrete Institute. American Concrete Institute.

Al- Rifaei, W. N. & Hassan, A. H. (1994). Structural behavior of thin ferrocement one-way bending elements. *Journal of ferrocement*, 24 (2), 115 – 126.

Apeh, J. A. & Ameh, J. E. (2020). Properties of steel fiber self- compacting concrete in-corporating Quarry dust fine powder. *Challenge Journal of Concrete research Letters*,11(1), 1-10.

ASTM C496 (1996). Standard Test Method for Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. American Society for Testing and Materials

Batra, A., Ghangas, S., Kumar, L. & Saxena, H. (2017). A review study of Application of Ferro-cement. *International Research Journal of Engineering and Technology (IRJET)*. 04(06). 1592-1597.

BS EN 196-6 (1992). Methods of Testing Cement: Determination of Fineness. The British Standard Institute, London

BS EN 197-1: (2016). Specifications for common cements. British Standard Institute London

Dybeł, P. & Wałach, D. (2017). Evaluation of the development of bond strength between two concrete layers. In IOP Conference Series: Materials Science and Engineering 245(3). doi:10.1088/1757-899X/245/3/032056

EFNARC, (2005). The European project Group (2005). The European Guidelines for Self-Compacting concrete. SCC European Project Group.

El-Sayed, T. A., Shaheen, Y. B., Mohamed, F. H. & Abdelnaby, R. M. (2023). Performance of Ferrocement Composites Circular Tanks as a New Approach for RC Tanks. *Case Studies in Construction Materials*, ResearchGate. 19(2). doi:10.1016/j.cscm.2023.e02228

Fahmy, E. H., Shaheen, Y. B. I., Abouzeid, M. N. and Gaafar, H. M., (2013). Ferrocement Sandwich and Hollow core Panels for Floor construction. *Canadian Journal of Civil Engineering*, 39(12), 1297-1310.

Fahmy, E. H., Abou Zeid, M. N., Shaheen, Y. B. & Abdelnaby, A. A. (2005). Permanent Ferrocement Forms: A viable alternative for construction of concrete beams. 30th Conference on Our world in Concrete and Structures. August 23-24, Singapore. doi:10.1617/s11527-012-9834-1

Frith, Y., Vidal, T., Turatsinze, A. & Pons, G. (2013). Flexural and Shear Behaviour of Steel Fiber Reinforced SCC Beams: *KSCE Journal of Civil Engineering*. 17(6), 1383-1393. doi:10.1007/s12205-013-1115-1

Halicka, A. (2007). Parameters of interface between shrinkable and expansive concrete resulting from their adhesion. *Electronic Journal of Polish Agricultural Universities*. Series Civil Engineering, 10(4).

Harris, D. K., Sarkar, J. & Aliborn, T. M. (2011). Interface bond characterization of Ultra-high Performance concrete Overlays. Paper presented at the transportation research Board. 90th annual Meeting.

Jumaat, M. Z., Kabir, M. H., & Obaydullah, M. (2006). A review of the repair of reinforced concrete beams. *Journal of Applied Science Research*, *2*(6), 317-326.

Korany, Y. S. (1996). Repairing reinforced concrete columns using ferrocement laminates. M.Sc. Thesis submitted to the American University in Cairo, Egypt, 151-250.

Matalkah, F., Bharadwaj, H., Soroushian, P., Wu, W., Almalkawi, A., Balachandra, A. M., & Peyvandi, A. (2017). Development of sandwich composites for building construction with locally available materials. *Construction and Building materials*, *147*, 380-387. doi:10.1016/j.conbuildmat.2017.04.113

Mays, G. C. & Barnes, R. A., (1995). Ferrocement permanent Formwork as protection to Reinforced concrete. *Journal of Ferrocement*, 25(4), 331-345.

Memon, N. A., Sumadi, S. R., & Ramli, M. (2006). Strength and Behaviour of Lightweight Ferrocement aerated Concrete Sandwich Blocks. *Malaysian Journal of Civil Engineering*. 18(2), 99-108.

Naaman, A.E. (1979). Performance criteria for ferrocement; Journal of ferrocement, 9(2), 75-91.

Naaman, A.E. (2000). Ferrocement and laminated cementitious composites; MI Techno Press.

Okamura, H., & Ouchi, M. (2003). Self-compacting concrete. *Journal of Advanced Concrete Technology,* 1(1), 5-15. doi:10.3151/jact.1.5

Roa, P. K. & Rooa, V, J. (1987). Development and application of composite precast Ferrocement and concrete roofing/flooring system. Proceedings of the First International Conference on Structural Science and Engineering, India.

Rosenthal, I. & Bijuger, F. (1985). Bending behavior of ferrocement-Reinforced concrete Composite. *Journal of ferrocement*, 15, (1), 15-24.

Saini, B. S. & Singh, S. P. (2022). Flexural fatigue strength and failure Probability of Self-Compacting Concrete made with RCA and blended cements. Science Direct. 45, 299-314. doi.org/10.1016/j.istruc.2022.09.031

Sandowicz, M. & Grabowski, J. (1985). Application of ferrocement channel elements to Housing. Proceedings of the Second International symposium on ferrocement, International Ferrocement Center, Bangkok. 493-505.

Shaaban, I. G., Shaheen, Y. B., Elsayed, E. L., Kamal, O. A., & Adesina, P. A. (2018). Flexural characteristics of lightweight ferrocement beams with various types of core materials and mesh reinforcement. *Construction and Building materials*, *171*, 802-816. doi:10.1016/j.conbuildmat.2018.03.167

Springkel, M. M. and Ozyilidirim, C., (2000). Final Report on Evaluation of High-performance concrete Overlays placed on Route 60, Over Lynnhaven Inlet. Virginia Transportation Research Council. U.S. Department of Transportation Federal Highway Administration, Charlottesville, Virginia

Tawab, A. A., Fahmy, E. H., & Shaheen, Y. B. (2012). Use of permanent ferrocement forms for concrete beam construction. *Materials and Structures*, *45*, 1319-1329. doi:10.1617/s11527-012-9834-1

Tayeh, B. A., Bakar, B. A., Johari, M. M., & Voo, Y. L. (2013). Evaluation of bond strength between normal concrete substrate and ultra high-performance fiber concrete as a repair material. *Procedia Engineering*, 54(21), 554-563. doi:10.1016/j.proeng.2013.03.050

Varma, M. B. & Hajare, M. B. (2015). Ferro-Cement: Composite Material and its Applications.

International Journal of Pure and Applied Research in Engineering and Technology. 3(8). 296-307**.**