DEVELOPMENT OF LIGHTWEIGHT FERROCEMENT SANDWICH PANELS FOR MODULAR HOUSING AND INDUSTRALIZED BUILDING SYSTEM

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ABSTRACT

(Keywords: Lightweight, pre-fabricated, aerated concrete sandwich ferrocement)

The development and construction of lightweight pre-fabricated sandwich structural elements in building construction is a growing trend in construction industry all over the world due to its high strength-to-weight ratio, reduced weight, and good thermal insulation characteristics. Sandwich construction element consists of thin face sheets or encasement of high performance material and a thick, lightweight and low strength material as core. Ferrocement is regarded as highly versatile thin material possessing superior properties which cannot be matched by other conventional thin materials. Aerated concrete is a cellular lightweight material which exhibits relatively higher strength than the conventional core materials such as foam. Additionally, sandwich construction deals with the problem of delamination of face sheets leading to their premature failure. This can be avoided by providing encasement over the core. This study was focused on the development of ferrocement encased aerated concrete sandwich wall elements, where ferrocement thin box encases a thick core of lightweight aerated concrete. The study was conducted in two phases. First phase involved the development of high workability and high performance slag-cement based mortar mix to cast proposed ferrocement encasement. The developed mortar was aimed to replace the traditional manual method of plastering the wire mesh by a mechanized casting method. The performance of mortar was investigated in terms of compressive strength, strength development, unit weight, effect of curing regime, and partial replacement of cement by weight with 50% and 60% of slag. The second phase of the study embarked on the development and investigation of the characteristics of ferrocement encased lightweight aerated concrete sandwich wall elements. To achieve the objective, about 600 specimens including large size wall elements were cast and tested. Ferrocement encasement was maintained at 12mm throughout the study. The parameters studied were compressive strength, flexural strength, failure mode, load-deflection behaviour, load-deformation behaviour, load-strain behaviour, unit weight, water absorption, initial surface absorption uniformity, and role of type and layers of the wire meshes. The results revealed the potential application of ferrocement encasement of lightweight aerated concrete to produce lightweight structural elements which leads towards the industrialization of building system. Finally, two mathematical models were developed to predict compressive strength of high workability slag-cement based mortars and the ultimate load of ferrocement encased aerated concrete sandwich wall elements. The values predicted from the mathematical models were 95%-100% accurate to the experimental results.

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ABSTRAK

Pembangunan serta penghasilan anggota struktur apit pasang siap ringan untuk binaan adalah merupakan suatu tren yang mengembang dalam industri pembinaan seluruh dunia disebabkan oleh nisbah kekuatan-berat yang tinggi, berat yang berkurangan, dan ciri-ciri penebatan haba yang baik. Anggota pembinaan apit terdiri dari lapisan muka nipis atau bahan salut berprestasi tinggi yang menyaluti bahagian anggota teras yang tebal, ringan tetapi berkekuatan rendah. Simenfero dikenali sebagai bahan serba guna nipis yang mempunyai ciri-ciri kelebihan yang tidak dimiliki oleh bahan-bahan konvensional yang lain. Manakala konkrit ringan berudara adalah merupakan bahan ringan selular yang mempamirkan kekuatan lebih tinggi secara perbandingan dengan teras konvensional seperti bahan berbusa. Seterusnya pembinaan melibatkan penggunaan bahan apit biasanya berhadapan dengan permasalahan pemisahan atau pengupasan lapisan muka yang menjurus kepada kegagalan sebelum waktunya (premature). Fenomena ini boleh dielakkan dengan penyediaan salut menyelaputi teras. Maka kajian ini tertumpu kepada pembangunan anggota dinding apit konkrit ringan diselaputi kekotak simenfero. Kajian ini telah dijalankan dalam dua fasa. Fasa pertama melibatkan pembangunan bancuhan mortar berasaskan sangga-simen berkebolehkerjaan serta perprestasi tinggi untuk dijadikan bahan salut simenfero yang dicadangkan untuk anggota tersebut. Mortar berkenaan yang dituang secara mekanikal adalah untuk menggantikan bahan mortar konvensional yang digunakan dalam proses melepa secara tradisional dalam pembikinan simenfero. Prestasi mortar telah dikaji dari sudut kekuatan mampatan, perkembangan kekuatan, berat unit, kesan regim pengawetan, serta kesan penggunaan gantian separa simen oleh sangga. Pasa kedua pula melibatkan pembangunan serta penyiasatan ciri-ciri anggota dinding apit konkrit berudara ringan bersalut simenfero. Untuk tujuan ini sejumlah spesimen termasuk anggota dinding bersaiz besar telah disediakan dan diuji. Salut simenfero ditetapkan dengan ketebalan 12mm dalam keseluruhan kajian. Parameter yang telah dikaji adalah kekuatan mampatan, kekuatan lenturan, mod kegagalan, kelakuan bebanan-pesongan, kelakuan bebanan-ubahbentuk, kelakuan bebanan-keterikan, berat unit, penyerapan air, ujian serapan permukaan awal, keseragaman, dan peranan serta kesan jenis serta jumlah lapisan jejaring yang digunakan untuk simenfero. Kajian ini mendapati bahawa kaedah penggunaan konkrit apit seperti dalam kajian ini amat berpotensi dalam pembikinan anggota struktur ringan yang seterusnya selangkah ke hadapan dalam perlaksanaan sistem binaan berindustri. Akhirnya dua model matematik telah dibangunkan bagi mentaksir kekuatan mampatan motar berkebolehkerjaan serta perprestasi tinggi yang berasaskan sangga-simen, serta kekuatan muktamad anggota apit tersebut. Di mana nilai taksiran diperolehi dari model sangat hampir dengan keputusan ujikaji.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 General Appraisal

The concept of industrialization of the construction technology has emerged as well accepted and preferred option in the field of building construction now a days, in order to reduce insitu construction up to maximum extent. This could be achieved by employing a number of strategies including the application of newly developed cement based composites for structural applications. Cement based composites perform better than conventional plain concrete. The development of new construction materials and technology can partly relieve pressures on the existing building material supply and help to arrest the spiraling rise in cost of these materials and also may reduce insitu construction activities (Abang, 1995).

Ferrocement is one of the relatively new cementitious composite considered as a construction material. It is a type of thin walled reinforced concrete commonly consists of cement mortar reinforced with closely spaced layers of continuous and relatively small wire mesh (ACI 549R, 1997; ACI 549 2R, 2004). The closely-spaced and uniformly-distributed reinforcement in ferrocement, transforms the otherwise brittle material into a superior ductile composite. Thus, ferrocement has been regarded as highly versatile construction material possessing unique properties of strength and serviceability. Its advantageous properties such as strength, toughness, water tightness, lightness, durability, fire resistance, and environmental stability cannot be matched by any other thin construction material (Naaman, 2000). Ferrocement is the promising composite material for prefabrication and industrialization of the building industry (Suresh, 2004; Austriaco, 2006). However, as an alternative construction material, ferrocement has not gained widespread acceptance in both; developed countries in general and developing countries in particular. Its acceptance is hindered mainly due to its small thickness and labor intensive method of production (Abang, 1995; Naaman, 2001). In order to cope with the problem of thickness, one of the options currently suggested is to develop ferrocement sandwich elements. This technique provides not only the thickness but makes the sandwich element lightweight and good heat insulating.

Sandwich panel is a three-layer element comprising of two thin, flat facing plates of relatively higher strength material and between which a thick core of relatively lower strength and density is encased or it could consists of thin skin box of relatively higher strength material in-filled with relatively weaker and lower density material known as core. These have been used in the aerospace industry for many years and more recently they are being used as load bearing members in naval structures (Mahfuz *et al.*, 2004). Presently, it has gained attention to be used as an effective structural form in the building and construction industries. Sandwich construction form has distinct advantages over conventional structural sections, because it promises high stiffness and high strength to weight ratios (Tat and Qian, 2000; Arafa and Balaguru, 2006). Hence, it is only natural that currently almost every field of industry resorts to the use of sandwich material in building and construction. The introduction of new materials such as laminated composites; ferrocement, for the face sheets/skin box and low density materials like aerated concrete, for the core presents new possibilities in the design of sandwich construction.

Aerated concrete is either cement or lime mortar, classified as lightweight concrete, in which air-voids are entrapped in the mortar matrix by means of suitable aerating agent (Arreshvhina, 2002; Narayanan and Ramamurthy, 2000a). Aerated concrete refers to concrete having excessive amounts of air voids. These air bubbles are created to reduce the density of the concrete and to make it lightweight, which provides good thermo-acoustic insulation too. However, aerated concrete, which is a porous material and classified as cellular construction material exhibits low compressive strength and high rate of water absorption (Arreshvhina 2002; Arreshvhina and Zakaria, 2002). It can be used as a potential material for core in sandwich composite because of its relatively more compressive strength compared to the traditional lightweight core materials like foam. Attention has not been paid in order to investigate its suitability as core material in sandwich construction. Most recently, its application as core material in FRP-AAC sandwich panels has been reported so far (Nasim *et al.*, 2006; Juan *et al.*, 2007). However, the literature is silent about its application as core in cement-based sandwich composite structural panels.

It is therefore, this study is aimed to develop a cement based ferrocement-aerated sandwich wall elements by encasing the aerated concrete with ferrocement.

1.2 Background and Rationale

In Malaysia the pace of development and construction activity achieved since last three decades was even beyond the expectations rather dreams three decades ago. It has spurred the demand for fast, cost-effective and quality residential buildings (Zakaria, 1999). The supply of houses by both the public and private sectors is still far from meeting the demand (Waleed *et al.*, 2004). In this age of rising cost of building materials and labor is another problem which makes it imperative to study the economic and systematic application of new construction materials and systems.

Industrialization of the building system by developing efficient prefabricated composite cellular structural elements may deal with the problem amicably where the fabrication of the elements takes place in factory and the elements are installed with minimum time period and labor at the site. This may also lead to the reduction in the foreign labor engaged in the construction industry of the country causing economical and social problems.

1.3 Statement of the Problem

The development of lightweight, industrialized and sustainable housing system in Malaysia as per modular coordination system is a need of the day. The present modular coordination system usually focus on the use of cement or concrete blocks for the infill or to certain extent as load bearing walls which are heavy in weight. Ferrocement structural elements are widespread as lightweight, high performance composite material which can replace its counterpart conventional materials. However, these could not gain popular acceptance here due to its thin section causing noise and heat transfer and also the perceived corrosion problem particularly in the tropical environment of Malaysia. Moreover, the psychological factor coined with buildings constructed with such thin sections would be perceived as unsafe to live, is also another factor which hinders the application of ferrocement.

Thus, sandwich composite construction system, presents one of the potential solution, where, ferrocement is applied as face sheets/encasement and lightweight aerated concrete is adopted as core. The problem of the labor intensive production of ferrocement may be addressed by developing mechanized system of casting identical to that of the ordinary RC sections. The structural sandwich elements should be as per the standard size leading towards the industrialization of building system, in order to reduce the insitu construction which is associated with social and economy problems.

1.4 Aim and Objectives of the Study

The main **aim** of this research investigation is to manufacture and study the behaviour and properties of ferrocement encased aerated concrete sandwich wall elements.

Towards achieving the above mentioned aim, the related objectives associated were identified as follows:

1. To investigate the minimum flow value (flow table) of cement mortar capable to be poured during the casting of thin ferrocement encasement.
2. To establish the optimum high workability and high performance mortar with slag and superplasticizer.

   This pertained to the compressive strength, strength development, unit weight, curing regime, water absorption and ISAT (permeability) as parameters of study
3. To study the behaviour of ferrocement encased aerated concrete sandwich specimens.

   This part of study was focused on, to optimize the various variables; in compression as principal testing and in flexure as additional testing.. The variables investigated were, type and number of wire mesh layers, overall unit weight, core dimensions (core-encasement volumetric ratio) to achieve lightweight sandwich, and the encasement direction (parallel or perpendicular to the loading direction) effective in terms of compressive strength. Water absorption and ISAT tests were also included in this part of study. A variety of specimens of standard size; cubes, blocks and prism beams were cast and tested.
4. To investigate the behaviour of ferrocement encased lightweight aerated concrete wall elements of relatively large size particularly in compression with additional flexural and ultrasonic pulse velocity (UPV) tests.
5. To develop mathematical models.

   This was final step towards this research study during which two mathematical models were developed to predict:

(a) Compressive strength of high workability slag cement based mortar for ferrocement.

(b) Ultimate load of ferrocement encased aerated concrete sandwich wall elements in compression.

1.5 Scope and Limitations of the Study

The study is almost experimental in nature. The study consists of two-phase study scheme. First phase of the present research focuses on development of optimum, high workability and high performance mortar, which should be capable to be poured during the casting of ferrocement skin boxes over aerated concrete, in single operation. The performance of the mortar was investigated in terms of compressive strength, strength development, water absorption, and unit weight. The specimens were cured in three curing regimes namely water, air, and natural weather in order to determine the appropriate curing regimes to be adopted for sandwich specimens. The effect of slag as cement replacement in mortar to make it low cost is also included.

During the second phase of the experimental programme, behaviour of sandwich specimens; cubes, blocks prism beams and wall elements of relatively large size, were investigated under compression as major parameter and under bending as additional parameter. To achieve the main aim, a stepwise strategy was adopted by addressing a number of variables. Two types of wire mesh namely square welded wire mesh, and chicken wire mesh were incorporated in ferrocement box by varying the number of layers; 0, 1, 2, 3 and 4. The performance of the sandwich specimens were studied in terms of ultimate compressive strength and flexural strength (modulus of rupture), unit weight load-axial deformation, and load-lateral deformation under compression along with load-deflection and load-strain relationship under bending. The failure mode and composite action of sandwich elements under both the loading conditions were also studied. In addition, efforts were made that it should be low cost, lightweight, and water resistant. To investigate the material uniformity of sandwich wall elements applying UPV test was also included in the scope of this study. Aerated concrete previously developed in UTM (Arreshvhina, 2002) and subsequently improvised were used as core during this study. Finally mathematical models were developed which were related to both the phases of this study. The mathematical models developed were applicable to predict compressive strength of high workability slag-cement based mortar and ferrocement encased lightweight aerated concrete sandwich wall elements.

1.6 Significance of Research

The research and its findings will encourage the use of the new approach to produce lightweight composite wall elements for industrialized building system and hence promoting better quality construction and innovative system in our construction industry. The study surely is a step forward in the right direction to achieve quality products.

This current project is able:

1. To produce a new potential structural composite, that is an integration of ferrocement and aerated concrete for modern industries of modular housing and building system.
2. To develop a novel method of prefabrication ferrocement sandwich wall element for use in modular housing and building system which can be developed and marketed nationally and internationally.
3. To help solve the problem of low and middle income earners to own houses.

CHAPTER 2

LITERATURE REVIEW

2.1 General Appraisal

The world is witnessing a revolution in construction practices along with a new phase of development fuelled by the rapid economic growth and the high rate of urbanization. Construction provides the direct means for the development, expansion, improvement and maintenance of urban settlements (Suresh, 2004). The construction industry is entering in an era of globalization where the utilization of the latest technology and material shall no longer recognize national borders (Abang, 1999). Thus, the construction industry must keep up with the advanced technology and systems to cope with the modern trends and demands. The growing need for affordable houses is a much discussed subject because due to spiraling construction cost, housing today is not an affordable proposition for the common people even on the international scene. Malaysia also is not spared from the problem of inadequate housing. There is still a very high demand for affordable houses in the country (Mahyuddin and Wahab, 1994; Abang, 1995; Waleed *et al*., 2004). Especially in the case of developing countries, the gap between demand and supply of adequate housing is continuously increasing (Shaikh, 1999; Arif *et al.*, 2001; Waleed *et al*., 2004). The duration of construction is vital in this regard. In order to minimize the time span of the construction, prefabrication is generally preferred.

Prefabricated structures are also preferred for rapid construction of tourism facilities such as, transportation utilities, communication units, hotels etc. In order to satisfy the ascending demand for rapid construction of the structures mentioned, the method of prefabrication is remarkably employed now days (Korkmaz and Tankut, 2005). Precast concrete members offer various advantages in service and quality over their cast-in-place correspondents; such as their higher allowance for quality control (Seckin and Fu, 1990; Soubra *et al*., 1991; Soubra *et al.*, 1993), the ready supply of good quality aggregates, much higher strength due to better batching and quality control of the concrete achieved through the use of a specialized labour force under factory conditions and results in the reduced construction activities at the site (Korkmaz and

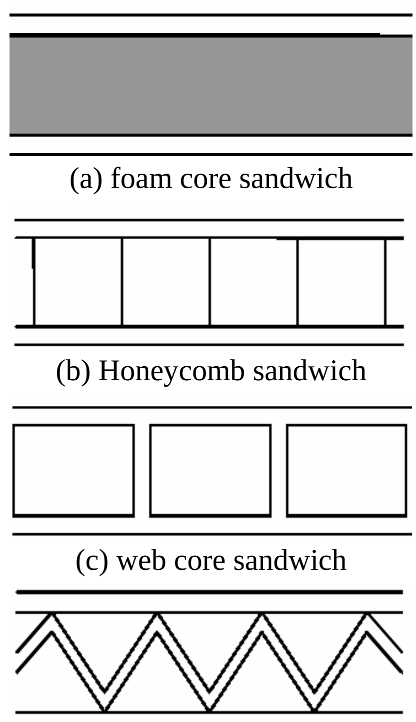
Tankut, 2005). In this context, there is need for the adoption of cost-effective and environmentally appropriate technology and materials.

Recent years has seen a renewed interest in the development of precast composite structural elements by adopting the technique of sandwich. Precast sandwich elements present a series of possibilities for the solution of housing problems.

2.2 Sandwich Structural Elements/Members

2.2.1 Introduction

A sandwich panel is a three-layer element, comprising two thin, flat facing plates of high-strength material and between which a thick lightweight core of low average strength is attached. Figure 2.1 presents a few types of sandwich panel elements. Such sandwich structures have gained widespread acceptance within the aerospace, naval/marine, automotive and general transportation industries as an excellent way to obtain extremely lightweight components and structures with very high bending stiffness, high strength and high buckling resistance (Mahfuz *et al.*, 2004; Liang and Chen, 2006).



(d) Truss core sandwich

Figure 2.1: Types of sandwich elements (An, 2004)

2.2.2 Advantages of Sandwich

Sandwich construction form has distinct advantages over conventional structural sections because it promises high stiffness and high strength-to-weight ratio (Tat and Qian, 2000; Araffa and Balaguru, 2006) as compared with a solid member. Sandwich composite structure possesses excellent flexural and shear properties. Their inherent lightweight characteristics make them ideal structural components where weight reduction is desirable (Serrano *et al.*, 2007). Thus structural sandwich panels are becoming important elements in modern lightweight construction.

In concrete construction, self-weight of structure itself represents a very large proportion of the total load on the structures (Mouli and Khelafi, 2006) thus, reduction in the self-weight of the structures by adopting an appropriate approach results in the reduction of element cross-section, size of foundation and supporting elements thereby reduced overall cost of the project. The lightweight structural elements can be applied for construction of the buildings on soils with lower load-bearing capacity (Carmichael, 1986).

Reduced self weight of the structures using lightweight concrete reduces the risk of earthquake damages to the structures because the earth quake forces that will influence the civil engineering structures and buildings are proportional to the mass of the structures and building. Thus reducing the mass of the structure or building is of utmost importance to reduce their risk due to earthquake acceleration (Ergul *et al.*, 2004).

Among the other advantages, its good thermal insulation due to the cellular thick core makes it an ideal external construction component (Bottcher and Lange, 2006). Some recent investigations suggest their excellent energy-absorbing characteristics under high-velocity impact loading conditions (Villanueva and Cantwell, 2004). Sandwich structures have been considered as potential candidate to mitigate impulsive (short duration) loads (Nemat-Nasser *et al.*, 2007).

2.2.6 Precast Concrete Sandwich Panels

PCSP consists of two layers of concrete called wythes separated by a thick, lightweight and very low strength core layer. The concrete wythes are connected to each other by concrete webs, steel connectors or the combination of the two, called as shear connectors. PCSP with shear truss connectors is typically fabricated of two concrete wythes tied together with truss-shaped shear connectors equally spaced along the length of the panel as depicted in Figure 2.2, while Figure 2.3 shows the PCSP, where the wythes are connected by webs.

It is generally accepted that this type of panels has been in use for more than 40 years in North America. Their application, however, has been restricted as cladding panels. Now a days, many sandwich panels in use in the North America and Europe are proprietary but very limited is available, because the producers are reluctant to share information with their competitors (PCI, 1997; Bush and Zhigi, 1999).

The first prefabricated panels were of non-composite type and consisted of a structural wythe (layer) and a non-structural wythe separated by a layer of insulation, whereas composite type panels were manufactured later (Benayoune *et al*., 2007a).

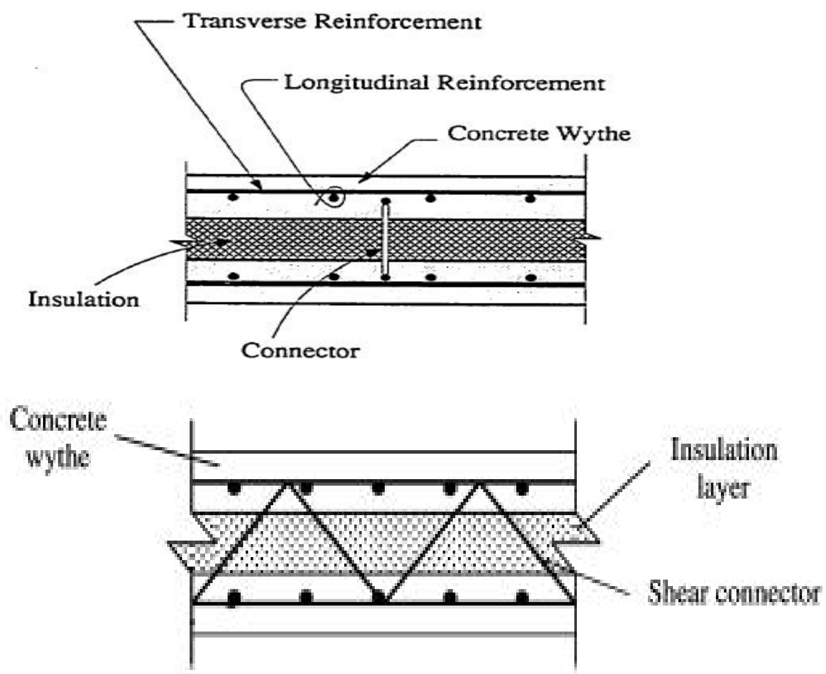


Figure 2.2: Sections of PCSP with shear connectors (Lindsay, 2003)

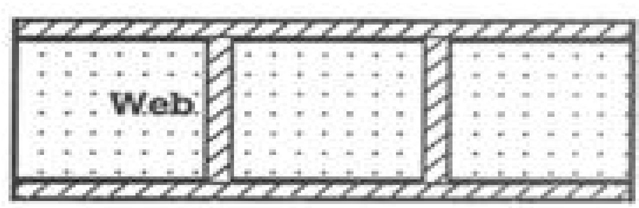
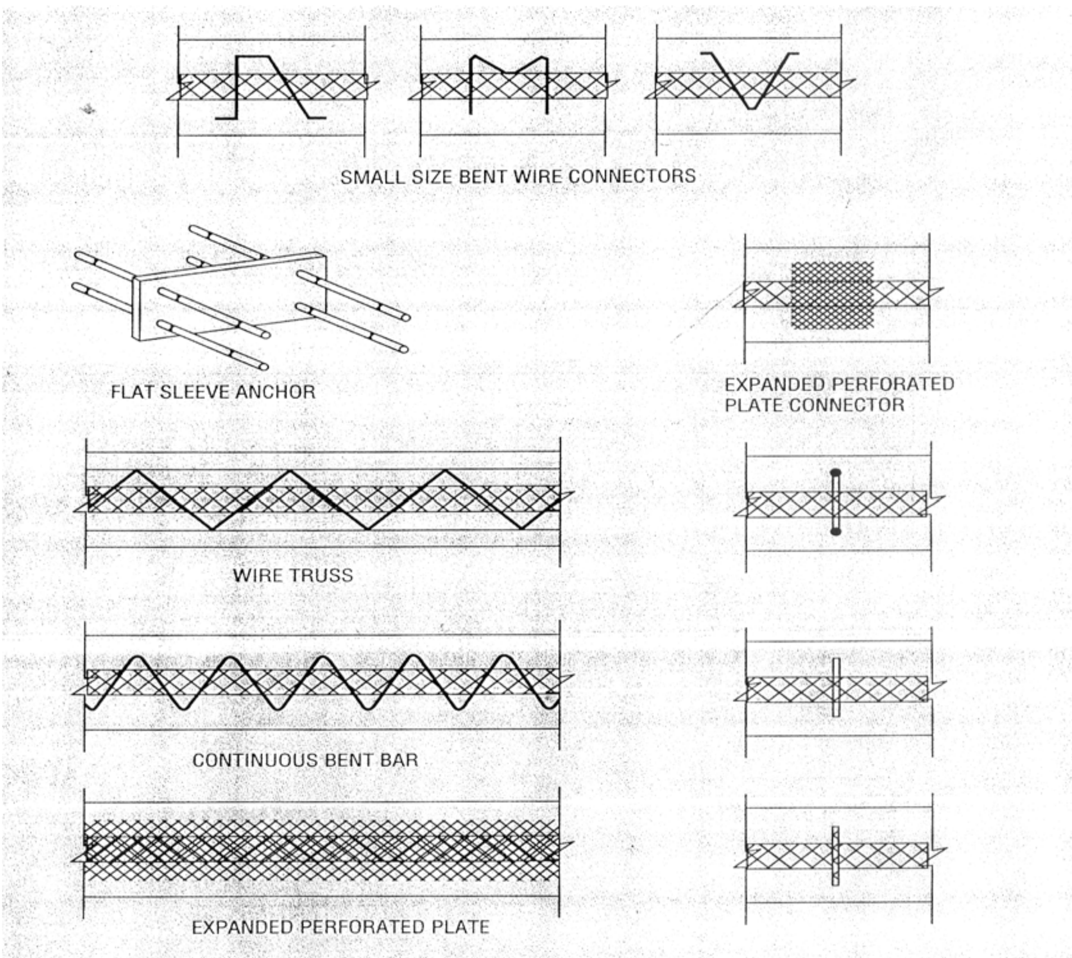


Figure 2.3: Sandwich elements with webs

Although PCI (1985; 1989) propose the wythe thickness ranging between 15mm to 75 mm, however it is mentioned that the appropriate thickness of the wythes be decided as per the requirement of the structure. The structural behaviour of the panel depends greatly on the strength and stiffness of the connectors, while the thermal resistance of the insulation layer governs the insulation value of the pane. The arrangement and spacing of shear connectors in PCSP vary depending on several factors, such as desired composite action, applied load, span of the panel and type of shear connectors used. Various types of connectors used are shown in Figure 2.4.



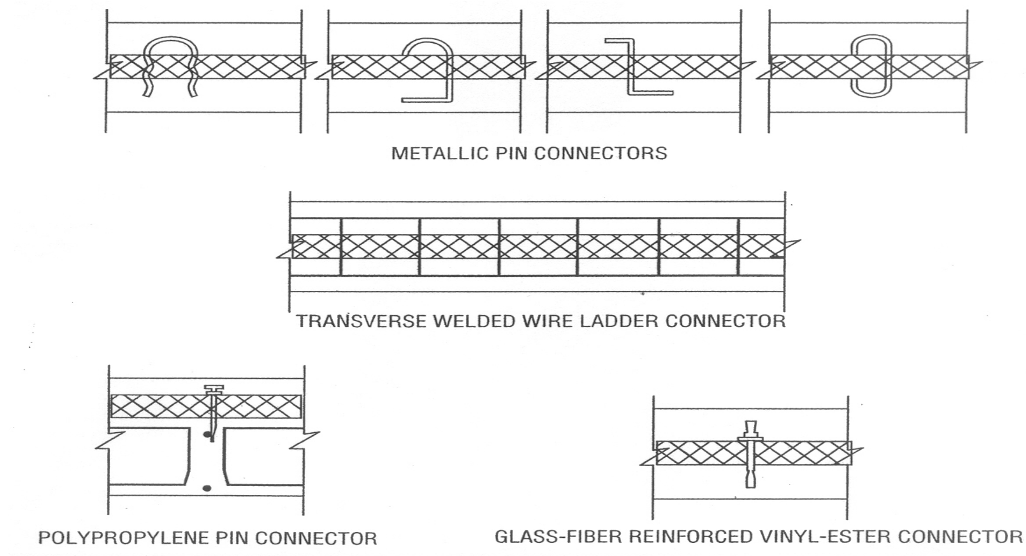


Figure 2.4: Types of shear connectors (PCI, 1997)

The insulation between the wythes may in some cases provide a shear resistance between the wythes. Rough faced dense insulation provides more shear transfer than slick faced insulation. Shear resistance that may be available from bonded insulation is considered temporary. In semi-composite panels, the assumption is made that the insulation provides sufficient shear transfer to create composite action during stripping, handling and erection, but the shear transfer is not relied on to provide composite action for resisting service loads.

The structural integrity of any sandwich construction, to enjoy the full advantage of the strength of two wythes and to prevent individual wythe buckling, depends on the strength of connection/bonding of the connectors/core with wythes (Frostig and Thomson, 2005; Grove *et al*., 2006; Benayoune *et al*., 2006). Commonly, the connection between the connectors and the two facing plates is achieved by the one-side spot welding, or self-taping screws/rivets. The fabrication of conventional sandwich panels necessitates adequate contact area between the core and facing plates ensure proper connection between these elements (Tat and Qian, 2000). In case of honeycomb, and steel connectors, the cell walls provide a very small area for connection/bonding; inadequate to hold the two wythes connected until failure thereby causing the separation of two wythes and also may cause buckling of the diagonals (Benayoune *et al*., 2006). Also it is laborious and may face difficulties during production (Al-Kubaisy and Jumaat, 2002). Thus, difficulty in the production of such panels affects the reliability of the connection between the elements resulting in uncertain role of connectors and interaction between various components. This is why, it continues to be a problem for investigators and fabricators alike (Tat and Qian, 2000; Benayoune *et al.,* 2006).

Moreover, the connectors pass from one concrete wythe to the other concrete wythe through the insulation layer. Thus, the placement of the connectors interrupts the continuous insulation layer. These interruptions are known as thermal bridges. Depending upon the material used to make the connectors in a panel, the thermal performance of panel may be decreased; in some cases as much as 40% by the large quantities of heat conducted through the shear connectors passing through the insulation (Lee and Pessiki, 2006).

On the other hand, the foam cores are bonded with the wythes by means of various types of bonding agents. Although the foam cores provide a large area in contact with the wythes, however it entirely depend upon the type, quality, an efficiency of bonding material along with the skills adopted during the bonding process. Flaws in the form of debond between the wythes and the core are likely to prevail, and if the flaws propagate they may impart effect on the load-bearing capacity of the structure because of the loss of load transfer between the facings (Prasad, 1993).

In addition, it has been demonstrated time and again that during flexural loading be static or cyclic, core (foam cores) basically controls the failure of the sandwich structures. Interfacial delaminating in a sandwich panel represents a severe defect that affects the overall integrity and safety of the structure. It typically begins as a delamination crack at the core–skin interface near the loading point, advances towards the support along the sub-interface (Mahfuz *et al*., 2004; Frostig and Thomson 2005; Russo and Zuccarello, 2006) kinks into the core. Figure 2.5 shows the interfacial delamination between core and wythes. Thus, in any event, it is clear that the delamination at the sub-interface region and the shear strength of the core in essence dictate the performance of the sandwich composites under flexure.

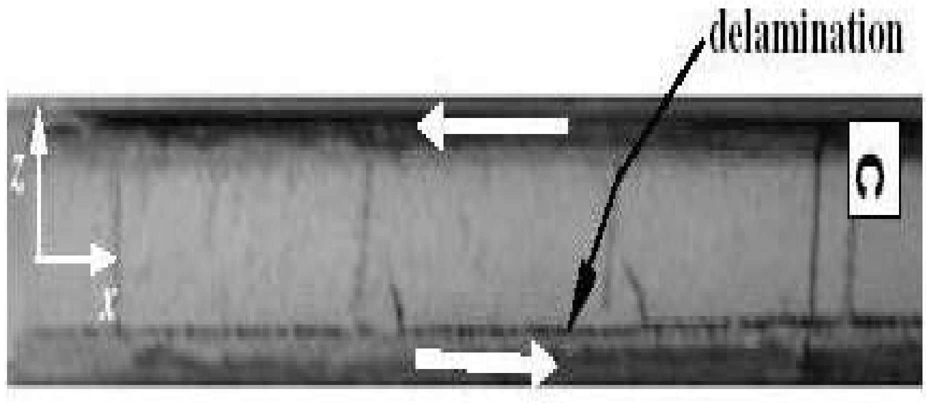


Figure 2.5: Pictorial view of delamination of core (Russo and Zuccarello, 2006)

Sandwich structures with compliant/soft core materials (foam etc) are notoriously sensitive to failure by the application of concentrated loads, at points or lines of support, and due to localized bending effects induced in the vicinity of points of geometric and material discontinuities. The reason for this is that, although sandwich structures are well suited for the transfer of overall bending and shearing loads, localized shearing and bending effects, as mentioned above, induce severe transverse (vertical) normal and interfacial shear stresses. These stress components can be of significant magnitude, and may in many cases approach or even exceed the allowable stresses in the core material as well as in the interfaces between the core and the face sheets (Frostig and Thomson, 2005).

The evolution of new high performance and lightweight cement based composites and laminates are emerging as an alternative of the traditional construction materials in modern techniques of the construction of structural elements. According to (Allen, 1996) "any structural material which is available in the form of thin sheet may be used to form the faces of a sandwich panel."

Ferrocement is a thin laminated structural composite and its advantageous properties such as its versatility of application, strength, toughness, lightness, water tightness, durability, fire resistance and environmental stability can not be matched by another thin construction material (Naaman, 2000; 2001)

2.2 Ferrocement

2.3.1 Introduction

"Ferrocement is a type of thin wall reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small diameter wire mesh; the mesh may be made of metallic or other suitable materials" (ACI 549R, 1997; ACI-549 2R, 2004).

2.3.3 Constituents of Ferrocement

Ferrocement is defined as being made of cement-based mortar mix and steel wire mesh reinforcement. However, a broader definition of ferrocement includes the use of skeletal steel in addition to the mesh system.

2.3.3.1 Mortar Mix

The hydraulic cement mortar mix consists of Portland cement, fine aggregate (sand), water and various admixtures as per the requirement. The materials should satisfy standards similar to those used for quality reinforced concrete construction, with particular attention paid to the type of application (IFS-10, 2001). Naaman (2000) proposed that the actual mix design should be optimized, whenever possible, with respect to the available local materials and environmental conditions.

2.3.3.2 Wire Mesh Reinforcement

Steel wire meshes are considered the primary mesh reinforcement. This include the various types of the shape; square woven or welded meshes, chicken (hexagonal/aviary) wire mesh, expanded metal mesh lath etc. Except for expanded metal mesh, generally all the meshes are used galvanized. Figure 2.6 depicts the typical steel wire meshes used in ferrocement applications.

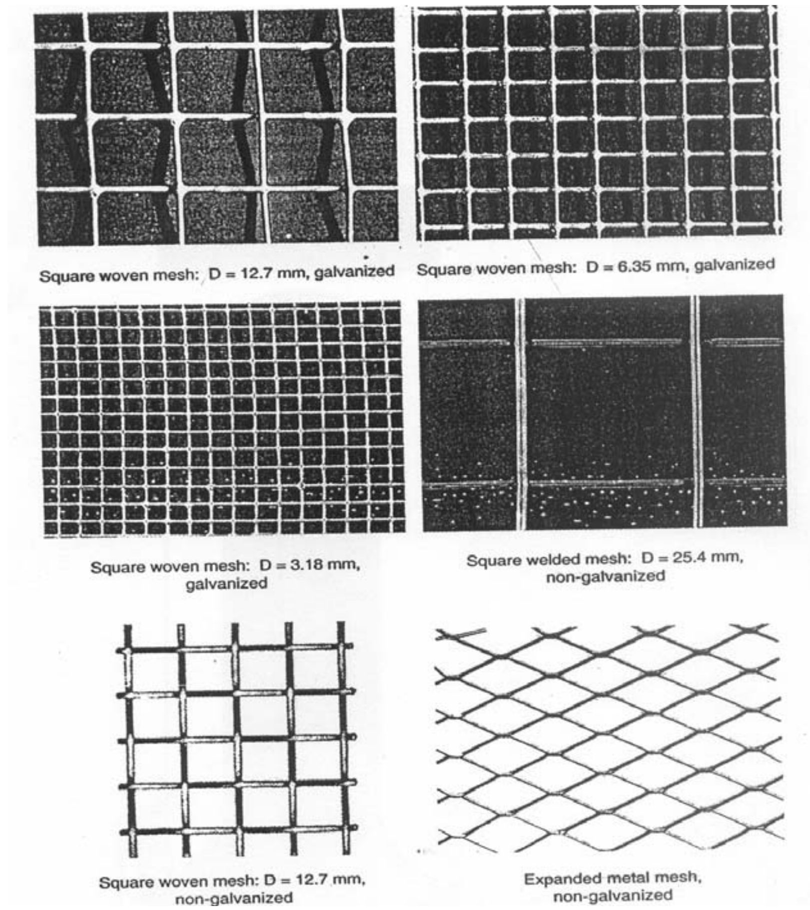


Figure 2.6: Typical steel meshes used in ferrocement (IFS-10, 2001)

2.3.3.3 Skeletal Steel

Skeletal steel used in ferrocement is in form of welded fabric as a grid of steel rods, strands of small diameters. Skeletal reinforcement is needed to form the shape of the structure to be built; around mesh layers are attached. Skeletal steel is only used when the thickness of the ferrocement element allows.

2.3 4 Ferrocement versus Reinforced Concrete (Distinct Characteristics)

As stated in the definition, ferrocement is a type of reinforced concrete construction. While, such a definition implies many similarities between ferrocement and reinforced concrete, there is a number of differentiating factors sufficiently important to explain the differences in their behaviour.

Compared to reinforced concrete, ferrocement (Figure 2.7):

- Is a thinner material.
- Has distributed reinforcement.
- Is reinforced in two directions (transverse and longitudinal).
- Has matrix made of fine mortar or paste instead of concrete which contains larger size aggregates (the maximum size of the particles in ferrocement is controlled by the average opening of the stack of mesh system to be encapsulated).

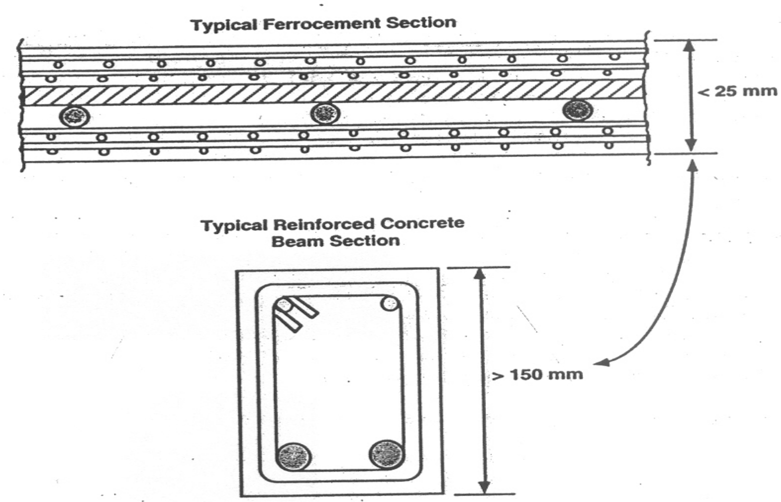


Figure 2.7: Typical cross section of ferrocement versus reinforced concrete (Naaman, 2000)

2.3.5 Ferrocement: A Composite and a Member of the Structural Concrete Family

Cement-based composites are generally viewed as two-component materials: the cement-based matrix and the reinforcement. In fact, the matrix alone (which generally comprises cement, sand, water, and other additives) may be considered a composite by itself; while steel reinforcement is not a composite material. A composite is a material made of at least two different components, resulting in a synergism where the composite property of interest for a particular application is better than either of components taken separately.

Although ferrocement was the first type of reinforced concrete, today it is considered a member of the general family of structural concrete materials, or, using different terminology, of cement-based composites. The family includes conventional reinforced concrete, prestressed concrete, partially prestressed concrete, fiber reinforced concrete, and several of their combinations. The flow chart in Figure 2.8 attempts to place ferrocement in this family and shows that each member can stand alone or in combination with other members. Applications where a combination of materials or concepts is used include, for instance, where ferrocement is applied as a jacket to confine reinforced concrete columns, or where discontinuous fibers are added to ferrocement to provide a hybrid composite with improved properties.

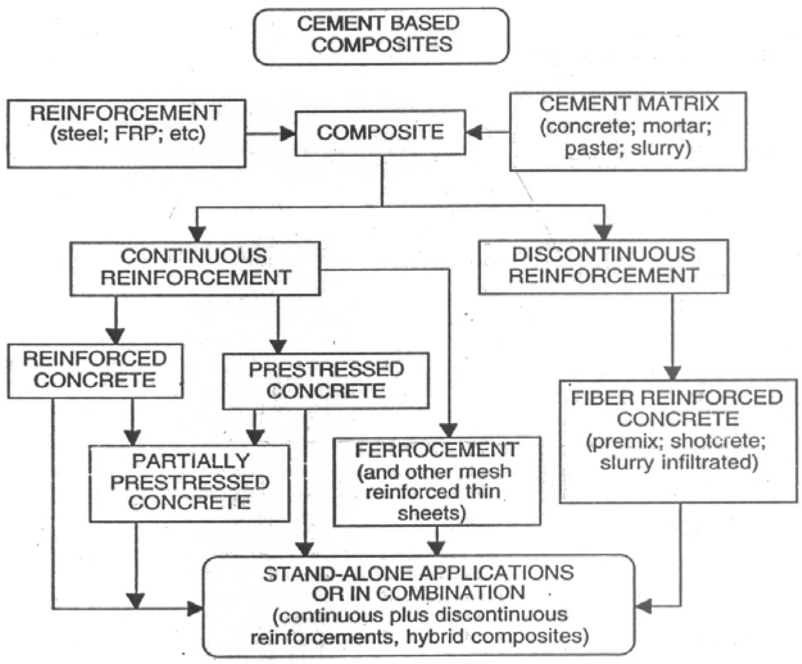


Figure 2.8: Ferrocement as a member of structural concrete family (Naaman, 2000)

2.3.7 Mechanical Properties

Many of the properties unique to ferrocement derive from the relatively large amount of two-way reinforcement made up of relatively small elements with much higher surface area than conventional reinforcement.

In the words of Nervi (ACI 549R, 1997), who first used the term ferrocement, its most notable characteristics are "greater elasticity and resistance to cracking given to the cement mortar by the extreme subdivision and distribution of the reinforcement. Where, volume fraction and the specific surface area are the two factors that recognize the definition of extreme subdivision and distribution of reinforcement in ferrocement.

2.3.7.1 Tensile Strength

Ferrocement is often described in the professional literature as a wonder material that does not crack and that has a variety of marvelous properties. In fact, ferrocement can be considered a small-scale model of a super reinforced concrete; it does indeed crack, but cracking in ferrocement under service loads can be so fine that it is not visible to the naked eye. Ferrocement possesses a distinct behaviour in tension compared to that of reinforced concrete.

The behaviour of ferrocement in tension is extremely interesting since ferrocement seems to adapt slowly to increasing load by increasing its extensibility. When cracks keep forming, crack width does not increase proportionately to the applied load, and thus crack widths tend to remain smaller than otherwise in reinforced concrete. The stress, at which no more new cracks formed, is called the stabilization stress. Beyond the stabilization stress (at crack saturation), the width of the existing cracks increases with loading and the behaviour of the composite is controlled. However, crack widths in ferrocement can be one or two orders of magnitude smaller than in reinforced concrete by that of the reinforcement (Arif *et al.*, 1999; Naaman, 2000).

In tension, the load carrying capacity is essentially independent of specimen thickness because the matrix cracks before failure and does not contribute directly to composite strength (ACI 549R, 1997). Typically the tensile strength of ferrocement is directly proportional to the number of layers (volume fraction) of the wire mesh layers. However, what is the counter intuitive is that the elongation at failure also increases when the volume fraction of reinforcement (layers of reinforcing mesh) increases. Figure 2.9 shows typical load elongation curve of ferrocement containing various number of mesh layers.

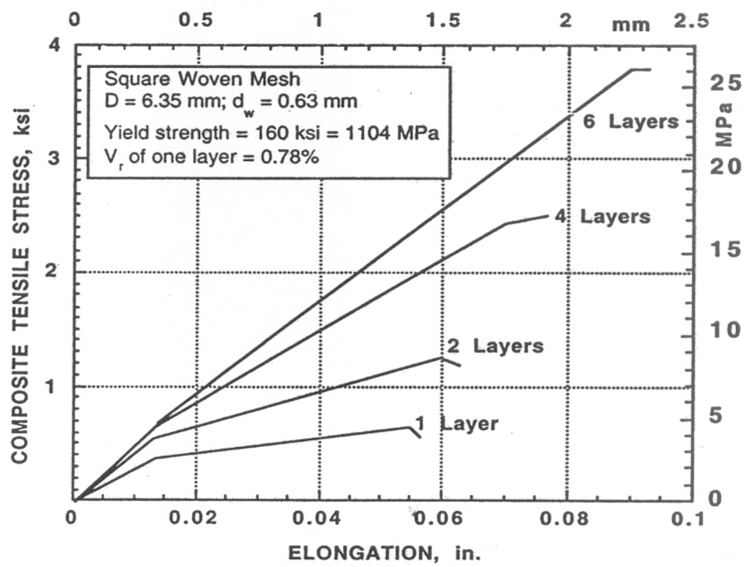


Figure 2.9: Typical load-elongation curve of ferrocement.(Naaman, 2000)

One of the key characteristics of ferrocement when compared to reinforced concrete is its substantially higher (one to two orders of magnitude) specific surface of reinforcement for a volume fraction of reinforcement of about the same order. This leads to a number of features particular to ferrocement behaviour, as observed in numerous experimental investigations. The studies have observed that, everything else being equal, the tensile strength at first cracking in ferrocement is directly proportional to the specific surface of reinforcement (Swamy and Shaheen, 1990; Somayaji and Naaman 1985; Arif *et al*., 1999; Naaman, 2000). This can also be observed in Figure 2.10 which illustrates qualitatively the influence of the specific surface of reinforcement on the stress at first cracking, the stress at crack stabilization (or saturation), the ultimate elongation of the composite, and the average crack spacing and width. The tensile strength of ferrocement depends on the mesh orientation and whether the applied loading is uniaxial or biaxial because of the change in volume fraction in the loading direction (Arif *et al*., 1999; Abdullah and Mansur, 2001).

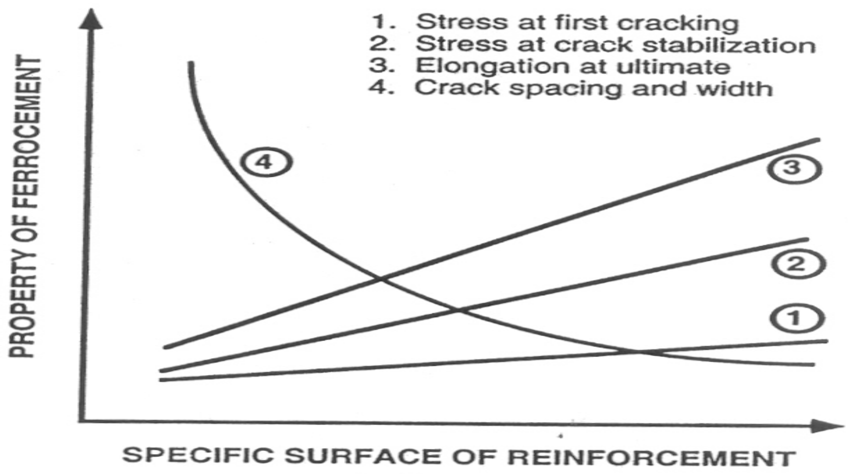


Figure 2.10: Typical qualitative influence of specific surface of reinforcement on properties of ferrocement (Naaman, 2000)

Figure 2.11 defines orientation and loading directions for typical meshes. While, Figure 2.12 shows the effect of orientation on the load carrying capacity due to change in orientation. The mesh orientation at 45^0 results in the lowest volume fraction of the wire mesh in the loading direction, thus, exhibiting poorest performance (Arif *et al*., 1999; Hossain and Inoue, 2000)

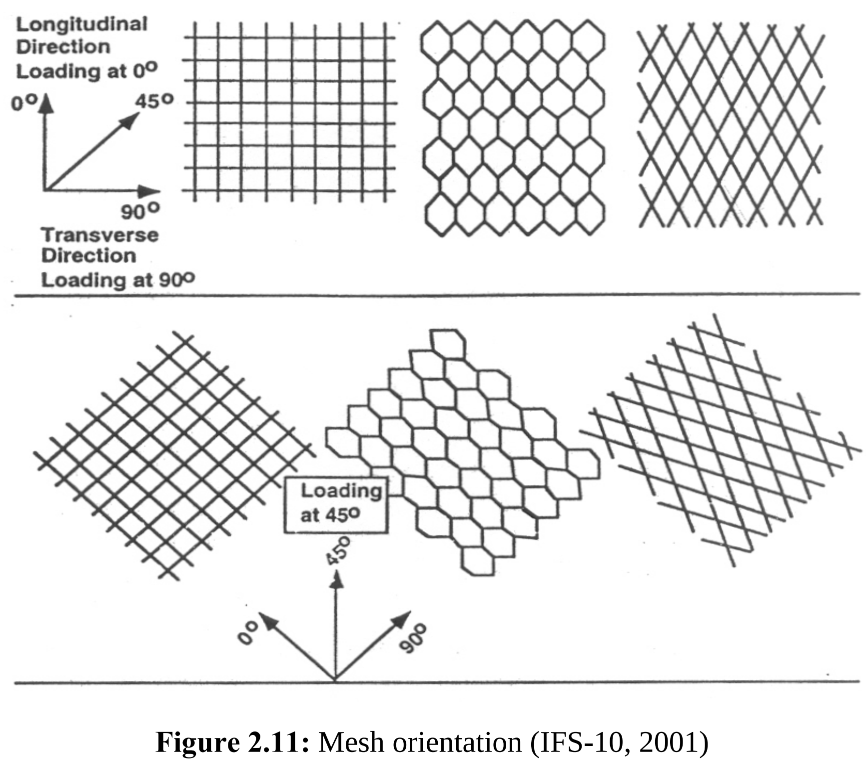


Figure 2.11: Mesh orientation (IFS-10, 2001)

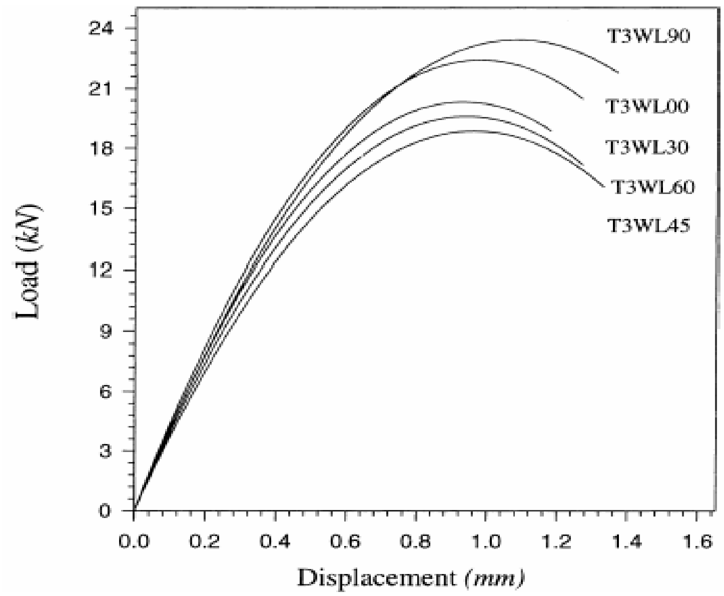


Figure2.12: Effect of mesh orientation on load carrying capacity of ferrocement in tension. (Arif *et al*., 1999)

The tensile strength of ferrocement can be of the same order as its compressive strength by increasing the tensile strength of the mesh reinforcement which leads to a direct increase in composite tensile strength. Whereas, the meshes with smaller openings lead to smaller crack widths and allow a more efficient use of high strength reinforcements (Naaman, 2000).

2.3.7.2 Compressive Strength

The compressive strength and the related properties of ferrocement are generally controlled to a great extent by the properties of the cementitious mortar mix. Typical compression test results of ferrocement prisms suggest that the compressive strength of ferrocement is smaller than that of the matrix alone, where, the delamination (due to splitting transverse tensile stresses) and buckling of the mesh reinforcement in compression account for the reduction in strength (Al-Noury and Haq, 1988; ACI 549R, 1997; Mansur and Abdullah, 1999; Naaman, 2000). In general, the compressive strength of ferrocement is considered as that of the mortar mix (ACI 549R, 1997; IFS-10, 2001). On the contrary, solid and hollow columns prophetically reinforced with wire mesh exhibited enhanced strength significantly. This is attributed to the lateral wires in the mesh acting in a manner similar to conventional helical reinforcement by restraining the enclosed matrix (ACI 549R, 1997).

Everything else being equal, the mesh type (expanded or hexagonal versus square) and its orientation (such as 45 versus 0 or 90 degrees) also influence the compressive strength The hexagonal and expanded metal meshes oriented in the direction of loading are less effective than similarly oriented welded square wire meshes. Meshes oriented at 45 degrees are also less effective than meshes aligned along the loading direction (ACI 549R, 1997; Hossain and Inoue, 2000).

There is initial and final non-linearity of strain-stress plots of ferrocement with non-linearity in between. Generally 50-60% of the ultimate strength, ferrocement exhibits the linearity (Rao and Rao, 1986; Rao, 1992; Hossain and Inoue, 2000).

2.3.7.3 Bending (Flexure)

Bending reflects the combined influence of parameters controlling both tensile and compression properties, such as mortar compressive strength, mesh type, mesh properties and mesh orientation. Moreover, it is believed that the two-way nature of the mesh reinforcement generally imparts some additional strength and safety when bending is considered in one direction only (one-way bending). Similar to the case of tension, ferrocement exhibits typical behaviour in bending also.

The ferrocement with the mesh layers even bundled at the centre of the cross-section behaves similar to that of the plane mortar under bending. Thus, in ferrocement bending elements, as in reinforced concrete, the most efficient layer of mesh is that closest to the extreme fiber or face of the element (Paramasivam and Ravindarajah, 1988). The specific surface of reinforcement does not have as strong an influence on the cracking behaviour in bending as in tension. The average crack width in ferrocement bending elements is primarily a function of the tensile strain in the extreme layer of mesh and the transverse wire spacing (Naaman, 2000)

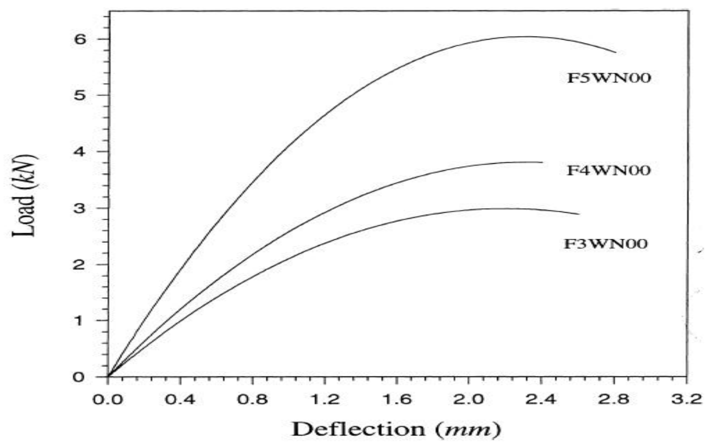


Figure 2.13: Load versus various mesh layers of ferrocement in flexure. (Arif *et al.*, 1999)

Everything else being equal, square welded wire meshes perform better in bending than the other meshes. This is due to the transverse wires in welded meshes provide a better anchorage for bond zone, thereby strengthening the matrix through biaxial confinement. Hexagonal mesh has the poorest performance among the wire meshes. Likewise in tension, the orientation of meshes at 45 degrees is the weakest configuration in bending also (ACI 549R, 1997; Naaman, 2000; Arif *et al.*, 2001). Figure 2.14 depicts the effect of mesh orientation on load carrying capacity of ferrocement under bending.

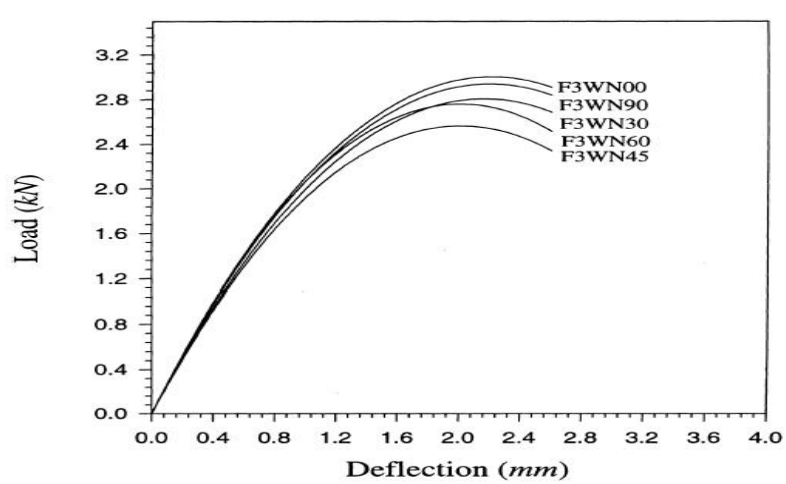


Figure 2.14: Effect of wire mesh orientation in bending (Arif *et al.*, 1999)

In ferrocement crack width at working load remain very small compared to that of reinforced concrete, thereby leading towards to good impermeability, stiffness, and durability (Onet *et al*., 1992; Suksawang *et a*l., 2006) However, the compressive strength of mortar does not seem to have much influence on the bending resistance of ferrocement beams. Everything else being equal, an 80 percent increase in mortar compressive strength led to an average increase of only 11% in bending strength (Montesinos and Naaman, 2004; Suksawang *et al.*, 2006).

2.3.7.4 Shear

The shear strength of ferrocement is reported to be approximately equal to 32 percent of its equivalent bending strength regardless the type and content of mesh or mortar strength used (Mansur and Ong, 1987). However, in general, shear failure is preceded by the attainment of flexural capacity of ferrocement (Mansur and Ong, 1991). Whereas, cracking shear strength of ferrocement is reported to increase with the decrease in span-to-depth ratio and increase in mesh layers and mortar strength (Al-Kubaisy and Nedwell, 1999).

Ferrocement beams behave in a manner similar to conventional concrete beam, except for demonstrating excellent crack control characteristics in shear. Furthermore, unlike the beams failing in flexure, the beams failing in shear exhibits little sign of impending failure besides the formation of a large number of diagonal cracks and a negligible plastic behaviour after the multiple cracking (Alsulaimani and Basunbal,1991; Mansur and Kiritharan, 2001)

2.3.7.5 Impact Resistance

Resistance to impact is often measured by the amount of energy absorbed during the impact loading. Reports attesting to the favourable characteristics of ferrocement in collisions between boats or with the rocks are numerous (ACI 549R, 1997). Ferrocement is very adequate to resist the impact, due to its higher ability of absorbing impact energy as compared with the conventional reinforced concrete, and the damage is localized at the impact zone (Al-Rifai, 2006). While, the impact energy to cause the failure of ferrocement due to repeated impact loading is 60% more than the concrete compared and 25% larger cracking resistance (Eswaramoorthi and Subramanian, 2006). Ferrocement wall panels could resist blast load effectively, and posses high deformability. Ferrocement walls of 20 mm thickness exhibited higher blast resistance capabilities then the 100 mm thick conventional plastered brick and block masonry walls (Pheerphan *et al*., 2006).

The impact strength of ferrocement increases with the volume fraction and the specific surface of reinforcement. The thickness of the ferrocement is a vital factor affecting impact resistance, which also depends on the type of mesh system used. Impact results in the fracture of the mortar on the back face of resulting from the reflected tensile wave. This is accompanied by spalling of the inside mortar, and possible delamination of the mesh layers (Naaman, 2000).

An increase in fracture energy and reduction in total crack width and maximum displacement of slabs were observed with the increase in wire mesh layers when the slabs were subjected projectile load by dropping hemispherical hammer from a height of 4m (Khan *et al*., 1999)

2.3.8 Durability

Durability can be defined as the resistance to deterioration of properties when the ferrocement composite is subjected to various loading and environmental exposures. Although the measures required to ensure durability in conventionally reinforced concrete also apply to ferrocement, two other factors which affect durability are unique to ferrocement,

(a) The cover of mortar to the mesh reinforcement is small and consequently it is relatively easy for corrosive liquids to reach the reinforcement. (Mansur *et al*., 1996; Nedwell, 2000).

(ii) The surface area of the reinforcement is unusually high; so that area of contact over which corrosion can take place, and the resulting rate of corrosion are potentially high (Naaman, 2000).

However, these factors assume varying degrees of importance, depending on exposure conditions. An adequate cover should essentially be provided during the construction of ferrocement elements. The armature cover in compressed regions could be as much as 6mm, however in case of medium aggressive environments this value must be at least 10mm. (Mansur *et al*., 1996; Liborio and Hanai, 1992). An OPC mortar cover of 5mm is reported to provide sufficient protection for the galvanized weldmesh against corrosion for a simulated load-marine corrosion environment (Xiong, 1997)

Ferrocement subjected to180 drying and wet cycles in fresh water showed unaffected strength of ferrocement elements in flexure, rather, the continued hydration of cement and resulting increase in the maturity of the mortar contributed to an improvement in the first crack strength in flexure (Al-Rifai and Al-Shukur, 2001).

Deterioration of wire mesh fabric in ferrocement showed deterioration due to sustained exposure in saline water casting and curing conditions. However, the strength of panels under saline casting and saline curing condition is more as compared to panels under normal casting and saline curing condition because of better pore structure minimizing the ingress of water, due to the presence of fly ash and the saline water during casting (Masood *et al.*, 2003). Ferrocement subjected to180 drying and wet cycles in fresh water showed unaffected strength of ferrocement elements in flexure, rather, the continued hydration of cement and resulting increase in the maturity of the mortar contributed to an improvement in the first crack strength in flexure (Al-Rifai and Al-Shukur, 2001).

2.3.9 Thermal/Sound Conductivity

Thermal conductivity in ferrocement increases with the increase in volume fraction of reinforcement. However, it is significant when mesh layers are placed along the direction of heat flow. This rarely exists in ferrocement structures because in the conventional form of ferrocement construction, the mesh layers are arranged normal to the anticipated direction of heat flow (Hawaldar, 1990). Ferrocement elements were found to be thermally acceptable and behaved better in natural calamities of Bangladesh (Salimullah, 1994)

However, it is believed that, the ferrocement has high thermal and sound conducting properties due to its small thickness of section. This could be addressed by providing a cavity insulation or infilling the cavity with low conductivity materials, when ferrocement elements are produced in hollow sections (Methews *et al.*, 1992; Kandaswamy and Ramachandraiah, 2002).

2.3.10 Applications of Ferrocement

In its role as a thin reinforced concrete product and as a laminated cement-based composite, ferrocement can be used in numerous applications. These applications can be classified in three major categories; marine applications, terrestrial applications, and repair and strengthening applications.

2.3.11 Strengthening /Confinement

Ferrocement is useful for repair of concrete structures. It can restore the durability of structures which may undergo distress due to aggressive environments causing the corrosion of embedded reinforcement (Rajamane *et al*., 2003). Its application as overlays on masonry walls can increase its total load capacity, tension and shear strength. It also provides the ductility, and. cracking control. The application of ferrocement overlays is potential option in the situations where high performance of the walls is required (Fabiana and De Hanai, 2002).

A significant enhancement in stiffness, strength, and durability can be achieved under compression when concrete is confined with various degree of ferrocement confinement. Compressive strength enhancement of the order of 20 to 30% was achieved by ferrocement confinement (Abdullah and Takiguchi, 2002a).

Ferrocement jacketing of RC columns is a feasible technique to prevent their shear failure and to provide the ductility when loaded in compression. It enhances the stiffness, strength, energy dissipation, and ductility significantly, where, the mode of failure changed from brittle shear failure to ductile flexural failure (Takiguchi and Abdullah, 2000; Takiguchi and Abdullah, 2004). Ferrocement jackets were produced by wrapping the required number of wire mesh layers over R/C columns and injecting the mortar slurry in meshes.

Confinement of high strength concrete in ferrocement shell in addition to rectangular ties under axial compression indicated that the additional confinement in the form of ferrocement shell improved ultimate strength, strain, strain at ultimate strength and the ductility of high strength concrete. It also improved the dimensional stability (Rajesh, 2001).

Encasement of brick masonry columns by ferrocement considerably increased the load carrying capacity of column in compression. It changes the brittle behaviour of the masonry columns in ductile. The mortar strength strongly affected the overall load carrying capacity of the columns (Al-Rifai and Mohammad, 2000)

Provision of ferrocement shell improves the flexural behaviour of reinforced concrete beams. It improved peak stress, the corresponding strain and the ductility of concrete. The improvement in curvatures was also obtained in RC beams irrespective of type of beam and these curvatures at ultimate were improved with ferrocement shell confinement (Seshu, 2000).

2.3.12 Ferrocement in Sandwich Construction

A very little information is available regarding the application of ferrocement in sandwich elements especially members under compression. Ferrocement when used as middle plate in a sandwich panel prevented cracking and disintegration of the middle plate when subjected to a hard lateral impact (Paramasivam and Santosh, 2006).

The behaviour of sandwich panels under low velocity impacts (Santosh *et al*., 2003) showed large permanent deformations in the steel cover plates but no fracture. Middle plates of normal and high strength concrete cracked into pieces under this kind of impact but the introduction of a ferrocement layer to the middle plate reduced the steel strains and also prevented disintegration of the middle plate.

Ferrocement skins of a bolted sandwich panels tested exhibited a significant increase in the punching shear strength when compared with a corresponding single skin. The increase in upper skin strength was greater than that of the lower skin which was of the order of 221% and 119% for the upper and lower skins respectively under punching (Al-Kubaisy and Jumaat, 2002).

Ferrocement sandwich panels made of two outer ferrocement skins separated by a polystyrene core with two typical cross sections; with and without web connections showed a high ductility under bending when those compared to that of asbestos sheets as skins of sandwich. The load carrying capacity of the sandwich elements with webs was almost twice of that of the panels without web where as the ultimate load was proportional to the thickness of the elements (Naaman, 2000).

One of the main factors that have so far hindered the full development and acceptance of high performance ferrocement is its cost. The relatively high cost of ferrocement, in comparison to reinforced concrete, is mainly due to the labour intensive nature of its fabrication (Nedwell, 2000; Naaman, 2001), Since the ferrocement elements are thin in section ranging between 10mm to 30mm and contains the wire mesh layers closely spaced inside, this often results in reinforcement congestion and poor concrete quality in the end product if the elements are produced by the method of the pouring. This is why; the common method of the construction of ferrocement elements is by plastering the wire mesh with cement mortar manually in three stages. This method is not only the labour intensive and time consuming but the quality of the product too becomes non uniform thus exhibiting poor performance (Naaman, 2000; 2001).

The major problem associated with the casting of thin ferrocement elements by the method of pouring the cement mortar in form work pertains to the workability/flow of mortar mix. A few researchers adopted the method of pouring by enhancing the w/c ratio randomly, to ensure the adequate workability of mortar mix (Waliuddin and Rafeeqi, 1994; Abdullah and Takiguchi, 2002b) resulting the increase in porosity of the mortar mix thereby increasing the water absorption and decrease in compressive strength. The porosity of mortar can be controlled by adjusting the water cement ratio with the corresponding addition of a superplasticizer to maintain the workability. In fact, the matrix in ferrocement has 95% or more pronounced influence on the behavior of final product (ACI 549R, 1997; Kumar *et al*., 2002a; 2002b) which entirely depends on the composition of the mortar mix. Thus the properties of mortar mix like compressive strength, water absorption are very important to consider during the design of ferrocement structural elements. However to the best knowledge of the authors, the literature is silent about any systematic study to investigate the minimum flow (workability) required to cast such thin sections with the method of pouring.

As cited before, ferrocement has been used as the face sheets to the sandwich elements and exhibited better performance. Since, Precast Concrete Sandwich Panels (PCSP) generally span vertically between foundations and floors or roofs to provide an insulated outer shell to buildings carrying mostly axial loads (Einea, 1995; PCI, 1997). In fact, it is also mentioned that the compressive strength of ferrocement is smaller than that of the matrix alone due to delamination (due to splitting transverse tensile stresses) and buckling of the mesh reinforcement in compression (Al-Noury and Haq, 1988; Mansur and Abdullah, 1998). This is because of, generally the mesh reinforcement is arranged parallel to the applied load in one plane only and it is common to consider that the compressive strength of ferrocement is the same as that of the mortar mix (Naaman, 2000; IFS-10, 2001).

However, on the contrary solid and hollow columns prophetically reinforced with wire mesh exhibited enhanced strength significantly (ACI 549R, 1997; Lim *et al*., 2000). This is attributed to the lateral wires in the mesh acting as confining reinforcement and literature review reveals the ferrocement as efficient and preferred option adopted for the confinement of normal and high strength concrete even in compression. El Debs *et al.* (2000) reported the sandwich wall panel produced by polystyrene foam core encased in ferrocement box, which exhibited better compressive strength and to some extent composite behaviour also. Figure 2.15 shows one of the panels developed and tested.

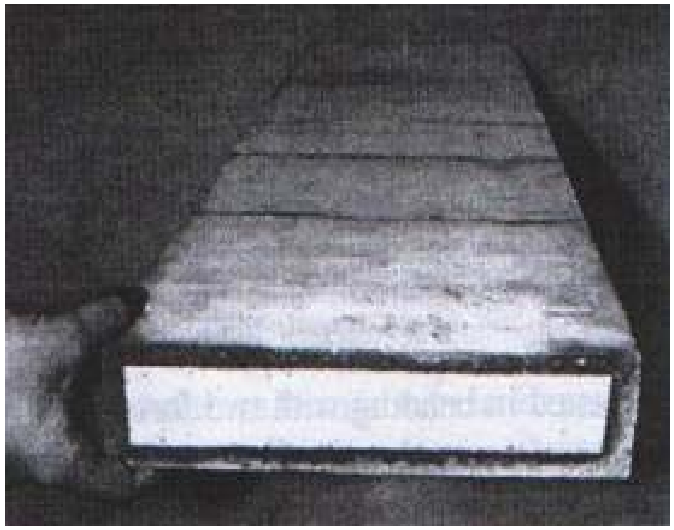


Figure 2.15: Sandwich panel tested (El Debs *et al.*,2000)

Moreover, high interfacial bond against slip (shear) along the surfaces of contact between ferrocement and the concrete is reported without any bonding agent like resin, and shear connectors (Thandavamoorthy, 2000; Lim *et al.*, 2002).

The possible uses of composite materials in infrastructure related applications is an area of active research now a days and autoclaved aerated concrete is a proven building material that will become much more widely used for both residential and commercial construction. It is also important that the building material be cost effective, energy efficient, and available throughout the world (Nasim *et al.*, 2006). Aerated concrete is significantly lighter than regular concrete, has similar properties to commercially available foam materials rather imparts better strength, and is significantly cheaper than commercial polymeric foams (Juan *et al.*, 2007).

2.4 Aerated Concrete

2.4.1 Introduction

Aerated concrete refers to concrete having excessive amounts of air voids. These air bubbles are created to reduce the density of the concrete and provide good thermal insulation. Aerated concrete was first produced in Sweden in 1930s and can also be referred to as cellular, foamed or gas concrete (Neville, 2003).

In fact the name ‘concrete’ is inappropriate since the material contains no coarse aggregate. According to Narayanan and Ramamurthy (2000a), aerated concrete is either a cement or lime mortar, classified as lightweight concrete, in which air-voids are entrapped in the mortar matrix by means of suitable aerating agent; the air entraining agents may be chemical (metallic powders like Al, Zn, H_2O_2) or mechanical (foaming agents) (Narayanan and Ramamurthy, 2000b). Thus, the manufacturing process of aerated concrete consists in the creation of macro-porosity (called as induced porosity). Between 60 to 90% of volume of hardened aerated concrete consists of pores, which are classified as micro and macro capillaries and artificial air voids (Roels *et al.*; 2002; Kus and Carlson, 2003). The aerating agents; among these aluminum powder is most commonly used, reacts with the water and the lime liberated by the hydration of the binder (Witman, 1983). Equation 2.1 (Mostafa, 2005) shows the chemical process of creating the air bubbles within aerated concrete mass

$$2AH + 3C_a(OH)_2 + 6H_2O \rightarrow 3C_aO \cdot Al_2O_3 \cdot 6H_2O + 3H_2 \uparrow \qquad 2.1$$

Thus the gaseous release generated by this chemical reaction causes the fresh mortar to expand and leads to the development of pores, which give aerated concrete its well known characteristics; low weight and high thermal performances (Narrayanan and Ramamurthy, 2000b). The foaming method (foamed concrete) has no chemical reactions involved. Introduction of pores is achieved through mechanical means either by pre-foaming (foaming agent mixed with a part of mixing water) or mix foaming (foaming agent mixed with the mortar). The various foaming agents used are detergents, resin soap, glue resins, hydrolyzed proteins such as keratin. Manufacturing of aerated concrete is very efficient, simple and economical, as it takes little manpower to produce (RILEM, 1993).

2.4.2 Classification of Aerated Concrete based on Curing Method.

Aerated concrete can be non-autoclaved (NAAC) or autoclaved (AAC) based on the method of curing. The compressive strength, drying shrinkage, absorption properties directly depend on the method and duration of curing. The strength development is rather slow for moist cured products (Narayanan and Ramamurthy, 2000a). NAAC has larger volume of these fine pores due to presence of excessive pore water (Tada and Nakano, 1983). High porosity of aerated concrete is essential to its main function, that is its thermal insulation but it leads to poor mechanical strengths. Hence the most usual technique to make up for this lack of strength is the autoclave treatment performed under high pressure and temperature, but this one is economically and environmentally costly (Cabrillac *et al*., 2006).

2.4.3 Density of Aerated Concrete

Aerated concrete of wide range of densities (300-1800 kg/m^3) can be produced depending upon method of production, thereby offering flexibility in manufacturing products for specific applications; insulation, partition, and structural grades (Narayanan and Ramamurthy, 2000a).

The density of aerated concrete is influenced by the water-cement ratio which controls the aeration process thus, the density. For a given density, water-cement ratio increases with proportion of sand. Therefore, when pozzolans are used, water-solids ratio is more important than the water-cement ratio (Arreshvhina, 2002).

For gas concrete, a lesser water-solids ratio leads to insufficient aeration while a higher one results in rupture of voids, increase in density being consequence in both the cases (Narayanan and Ramamurthy, 2000a). In fact, the density of aerated concrete is also greatly dependent on the dosage of the aerating agent; the prime responsible to induce artificial voids in the mass. The increase in the dosage of aerating agent (Al powder) decreases the density (Arreshvhina, 2002).

Everything else being equal, the curing method also influences the density of aerated concrete. The material as delivered from autoclave may be 15-25% heavier than oven-dry material. This value can be as high as 45% for very low density aerated concrete (RILEM, 1993).

2.4.4 Porosity

As stated in preceding section, aerated concrete with wide range of densities for specific applications can be manufactured by varying the method of production; composition of constituents and type of curing. Cabrillc *et al*., (2006) reported that an increase in the cement dosage increases the introduced porosity where as increase of the sand or lime dosage decreases the introduced porosity.

Whereas, the influence of the water dosage depends on the presence or absence of lime in the composition; with lime the increase of water dosage increases the introduced porosity, while it does not influence the introduced porosity in the absence of lime.

Furthermore, the additional autoclaved treatment greatly affected the mechanical strength rather than the introduced porosity. The high porosity of aerated concrete allows the penetration by liquids and gases, which may lead to the damage of the matrix (RILEM, 1993).

2.4.5 Compressive Strength

Generally it is believed that the compressive strength is linearly proportional to the density of the concrete. However, in case of aerated concrete, the specimen size and shape, method of pore formation, direction of loading, age, water content, characteristics of raw material used and method of curing are reported to influence its compressive strength (Isue *et al*., 1995; Hanecka *et al*., 1997; Narayanan and Ranmamurthy, 2000a). The strength of NAAC increases 30%-80% between 28 days and 6 months, and marginally beyond this period. A portion of this increase is attributed to the process of carbonation (Hanecka *et al*., 1997). Houst *et al*. (1983) reported the inverse proportion between compressive strength and moisture content of aerated concrete. This could be attributed to the pore water which may act as lubricant in the microstructure of the material.

2.4.6 Drying Shrinkage

Drying shrinkage occurs due to the loss of adsorbed water from the material and it is significant in aerated concrete because of its high porosity and specific surface of pores thereby accelerating the drying water within the mass. The decrease in pore size combined with a higher percentage of smaller size pores is also reported to be responsible to shrinkage in aerated concrete (Narayanan and Ramamurthy, 2000a). While, the capillary tension theory of drying shrinkage of porous building materials states that the water in the pores exit in tension which produces an attractive forces between the pores of walls, thereby causing shrinkage (Tada and Nakano,1983).

Aerated concrete with only cement as binder is reported to cause higher value of drying shrinkage than the aerated concrete produced with lime or lime-cement. Whereas, the duration and method of curing, pressure of autoclaving (in case of AAC), fineness and chemical composition of mineral admixtures, the size and shape of specimen affects the drying shrinkage (Schubert, 1983; Narayanan and Ramamurthy, 2000a). Due to high level of moisture loss, dry curing influences significantly the drying shrinkage of aerated concrete than the water curing (Mirza *et al.*, 2002).

ASTM C426-06 (2006) specifies the drying shrinkage or expansion of a specimen limiting between ±0.15 percent of their initial dimension in consideration. Drying shrinkage values ranging from 0.06 to over 3% are reported in literature (Narayanan and Ramamurthy, 2000a).

A higher shrinkage in NAAC is reported due to its larger volume of finer pores (Tada and Nakano, 1983). However, when the same product is autoclaved, fundamental changes take place in the mineral constitution, which may reduce shrinkage to one quarter or even one-fifth of that air-cured product. Nevertheless, Arreshvhina (2002) found the drying shrinkage of the order of 0.03% of slag-cement based NAAC which is substantially smaller than those the extreme specifications of ASTM C426-06 (2006).

2.4.7 Water Absorption and Permeability

Aerated concrete is porous material, consists of a substantial portion of its volume by pores. Therefore, it has strong interaction between water, water vapor and the porous system. In dry state, pores are empty and the water vapors diffusion dominates, while some pores are filled in higher humidity regions (if any).

2.4.8 Thermal Conductivity

Thermal conductivity is largely a function of density. In aerated concrete it does not really matter whether the product is moist cured or autoclaved (Narayanan and Ramamurthy, 2000a). However, the amount of pores and their distribution are also critical for thermal insulation; finer the pores better the insulation (Bave, 1980). Other factors, which could affect the thermal conductivity to some extent, include moisture content, temperature level, raw materials and pore structures (Loudun, 1983).

2.4.9 Fire Resistance

One of the most remarkable properties of aerated concrete is its fire resistance capability due to its cellular structure (Nasim *et al.*, 2006). Since the aerated concrete is relatively homogeneous in nature and independent of coarse aggregates unlike normal concrete, thereby avoiding the differential rated of expansion, cracking and disintegration caused by these aggregates (Narayanan and Ramamurthy, 2000a). It also neither spalls due to fire and nor requires the plastering to achieve good fire resistance

(Buekett and Jennings, 1996). The good fire resisting property of aerated concrete is where its closed pore structure pays rich dividends, as heat transfer through radiation is an inverse function of the number of air-solid interfaces traversed. Adding this to their low thermal conductivity and diffusitivity, gives an indication that aerated concrete possess good fire resisting properties

Most recently autoclaved aerated concrete (AAC) is used as core material in FRP-AAC sandwich panels and have proven to be structurally efficient combination for lightweight structural components. AAC-CFRP composites have great excellent absorbing capabilities under impact force. While the resin infiltrates into the concrete micro-pores of the AAC panel, additional strengthening is provided. The potential advantages of panelized construction using AAC core as building material are lightweight, energy efficient, easy to use, fire resistant, environmental friendly, weather resistant, pest resistant, durable, acoustically efficient (Juan *et al.*, 2007; Lim and Kang, 2006). Furthermore, if the strength is not the major criteria, then non-autoclaved aerated concrete is more cost effective and easy to produce possessing almost all other properties nearest similar to those of AAC as discussed in previous section.

Mouli and Khelafi (2006) reported that the interfacial bond strength of composite sections is significantly affected by the type of concrete. LWC exhibits higher results push-loads and thus better composite action than the normal concrete. Therefore, it is believed that if aerated concrete is used as core with cement based composite as face sheets to produce sandwich element, a superior interfacial bond can be achieved between the two without use of any bonding agent. This led to the idea to use non-autoclaved aerated concrete (NAAC) as core material during this study. This also will lead to the basic concept of the affordable housing that, the building material be cost effective, energy efficient, easily available.

2.5 Cost Effectiveness

To reduce the overall construction cost of the building has been the much focused area of the current period for developed countries in general and for developing countries in particular. This could be achieved by reducing the material cost by replacing traditional materials with cheaper materials and also adopting mechanized construction techniques. Averagely 10-20% of the material cost can be saved compared to normal dense concrete when lightweight aerated concrete is used. Table 2.1 shows an outline of costing for a project in United States. The project was to build 36-story luxury condominium. The cost savings have been calculated in the Malaysian currency (RM) also. It is evident that about 10% of the total cost has been saved with the use of aerated concrete and in addition the ongoing saving of US$40,000 per year is accomplished in terms of reduction of electricity cost due to lower air-conditioning requirements caused by the insulation behavior of aerated concrete.

The reduction in the cost can also be achieved by the application of the industrial by-products to replace costly conventional materials is major technique in this regard. The utilization of industrial by products offer triple benefits namely: conservation of fast declined natural resources, planned gainful exploration of waste materials and release of valuable land for more profitable use (Swamy, 1989). Using by-products, such as silica fume, fly ash and blast furnace slag, in concrete products has been done for many years because of ecological, economical and diversified product quality reasons. Their use also improves the concrete properties.

Table 2.1: Cost saving details of a project using aerated concrete in United States (Pan Pacific, 2000)

Description	Cost (US$)	Cost (RM)
Foundation/Structural cost	1,600,000.00	6,080,000.00
Concrete 3500m^3	70,000.00	266,000.00
Transportation/crane	30,000.00	114,000.00
Air-Conditioning Installation	500,000.00	1,900,000.00
Total saving	2,200,000.00	8,360,000.00

Fly ash mortar also has been used for ferrocement (Kausik *et al.*, 2002). However, workability of the fly ash mortar continues to be a problem. The mortar becomes harsh and poses considerable problems in preparation, flow, placing and compaction. This results in improper encapsulation of wire meshes in matrix thereby leading to poor performance. However, GGBFS commonly known as slag does not affect the workability significantly. It is therefore, investigations on the properties of concrete and mortar with slag as partial replacement of cement is remained active area of research.

The effectiveness of slag in terms of compressive strength of concrete, mortar and aerated concrete, especially at 28 days and later is reported in literature (Swamy and Ammar, 1990; Arreshvhina *et al.*, 2005; Agarwal and Deepali, 2006; Barnett *et al.*, 2006). In most cases, GGBFS slag has been used in proportions of 25 to 70 percent by mass of total cementitious material but 50% appears to be an optimum blend of GGBFS slag that produces the greatest strength at 28 days (ACI 226, 1987; Swamy, 1990; Arreshvhina, 2002). Since each slag, behaves differently with different cements, it is important to prepare trial mixes with the cement and ground slag to be used, to determine the correct mix proportions and insure adequate performance of the concrete (Mantei, 1994).

The overall construction cost of ferrocement elements can further be reduced by casting the thin ferrocement encasement with a mechanized approach replacing the cost intensive traditional method of construction, where, wire meshes are plastered in three stages manually.

2.6 Concluding Remarks

The modern and innovative techniques, approaches and systems are being adopted by the construction industry to industrialize the building system in order to coup with the problem. Precast and prefabrication of the lightweight structural members/elements in factory provides the quality construction, rapid progress of structure erecting, minimized construction activities at site and the reduced construction duration of the project. Sandwich form of construction serves the purpose efficiently.

Based on the application of sandwich, it is produced with a wide variety of alternative core materials, including wood, honeycomb, polymer foams and steel connectors. Each material has its own advantages and disadvantages, but for buildings steel connectors and foams are preferred. Whereas, many high performance materials are in common use to produce face sheets, but the concrete wythes are commonly used in sandwich elements for the buildings along with the recent attention paid to the ferrocement due to its high performance compared to the other thin materials.

However, sandwich faces the severe problems pertained to the small area of connection where shear connectors are connected to the wythes. While, in case of foam cores bonded with the wythes, the performance of sandwich is governed by the type, quality and efficiency of the bonding resins which are expensive too. Thus, it was deemed to adopt a novel technique to produce sandwich composite by encasing lightweight aerated concrete with high performance ferrocement eliminating the shear connectors and the bonding materials with a mechanized simultaneous casting of core and encasement.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 General Appraisal

This chapter describes the methodology adopted to achieve the aim and objectives of the study, details of the materials used, and the experimental procedures applied to investigate various parameters.

3.2 Experimental Programme of Study

The main aim of the study was to investigate the characteristics of ferrocement encased aerated concrete sandwich wall element. In order to achieve the aim and the related objectives mentioned in chapter one, a two-phase experimental study; each comprised of stepwise strategy was adopted. Following are the details of the two phases, stepwise research methodology adopted.

3.2.1 Phase-I: To Investigate Optimum High Workability and High Performance Mortar Mix for encasement

The phase-I was completed in four steps detailed as follows.

3.2.1.1 Minimum Mortar Flow Value

Initially thin ferrocement plates of 6mm, 8mm, 10mm and 12 mm thick thickness were cast on trial and error method (by adjusting water-binder ratio and adding superplasticizer). Minimum flow of mortar required to cast the proposed ferrocement encasing box for sandwich wall elements was determined using flow table test.

3.2.1.2 Maximum Dosage of Superplasticizer

The maximum dosage of superplasticizer reducing the water-binder ratio by maintaining the minimum flow determined was also examined. In all three mixes were selected at random were used. These mixes were of different mix proportion with and without GGBFS. In each mix superplasticizer dosage was utilized with an increment 0.1% of total binder by weight until its further increase did not render desired results. Throughout this step, mortar flow was maintained at the value determined from previous step.

3.2.1.3 Flow versus Mix Proportions (A Comprehensive Flow Test Programme)

On the basis of the results of previous two steps a comprehensive test programme was conducted to establish the criteria between mix proportions, water-binder ratio, dosage of superplasticizer and partial replacement of cement with GGBFS at constant mortar flow determined previously. The details of the mix proportion, level of partial replacement of cement with GGBFS to achieve the economy and the dosage of the superplasticizer applied to reduce the water-binder ratio at specific flow, are as follows:

(a)	Mix proportion:	binder : sand 1: 2, 1: 2.5, 1: 3
(b)	GGBFS:	0%, 50% and 60% by weight of the total binder as partial replacement of cement
(c)	Superplasticizer:	Used from 0.1%; of total binder by weight up to maximum dosage determined during previous step. It was applied in an increment of 0.1% each time

All in all 54 mixes were developed, tested and analyzed during this step, the details of which are given in chapter 4.

3.2.1.4 Characteristics of High Workability Slag Cement Based Mortar

Initially cube specimens of size 70.6mm x 70.6mm x 70.6mm for all the 54 mixes developed from previous step were cast and tested with following variables

(a)	Curing regime	Water
(b)	Age of Mortar:	28 days.
(c)	Tests:	Cube crushing strength and Density of mortar

As a step further, based on the strength and density results obtained, seven high strength (compressive strength > 45MPa) and economical mixes (with GGBFS) including one control mix were selected and were tested with following variables.

(a)	Curing regime	:	Water (at 27 ^{0}C room temperature in water tank)
(b)	Strength development	:	3, 7, 28, 90, and 180 days
(c)	Water absorption	:	at 28 days
(d)	ISAT (permeability)	:	at 28 days

As the concluding step, two mixes were selected based on the results from previous testing, and were tested for effect of curing regime by curing with following variables

(a)	Curing regime:	Water (in water tank at 27 ^{0}C room temperature temperature. Air (inside room at 27 ^{0}C room temperature) Natural whether (ambient environment; outside the laboratory under open sky at temperature from 25 ^{0}C to 35 ^{0}C)
(b)	Tests :	Compressive strength
(c)	Specimens Age:	3, 7, 28, 90, and 180 days

Finally on the bases of the entire results and the discussions made, an optimum high workability and high performance mortar was selected to cast ferrocement encasing box to produce ferrocement-aerated sandwich.

3.2.2 PHASE-II: To Investigate Characteristics of Ferrocement Encased Aerated Concrete Sandwich Wall Elements

This phase of the experimental study was accomplished in two parts. As the wall elements considered in the final step of this study were of relatively large size, hence it was deemed necessary to carry an intensive experimental programme with large number of variables but with small size specimens as per the specifications of various standards. Throughout the study it was decided to adopt 12mm thick ferrocement encasement to produce sandwich. The encasement was achieved by producing ferrocement box around four sides of the entire specimens. The details of the study are as follows:

3.2.2.1 Sandwich Cubes, Blocks and Prism Beams

(a) Shape and size of specimens

Cubes A	:	70.6mm x 70.6mm x 70.6mm (Figure 3.1)
Cubes B	:	100mm x 100mm x 100mm (Figure 3.2)
Blocks	:	400mm x 200mm x 100mm (Figure 3.3)
Prism beams	:	500mm x 100mm x 100mm (Figure 3.4)

(b) Variables

Type of mesh:	Chicken and square weld wire meshes
Number of mesh layers:	1 to 4 layers in chicken wire mesh and 1 to 3 layers in square weld wire mesh (Since square weld mesh was of greater diameter thus the maximum number was limited to 3 in this case)
Curing regime:	Water
Age of specimen:	28 days,
Core Volume:	Varying with size of specimens
Encasement effectiveness	Method of testing the specimen for compression comprised of (i) Holding encasement parallel to loading direction (Figure 3.5a) (ii) Holding encasement perpendicular to loading direction (Figure 3.5b)

(c) Tests

Ultimate compressive strength

Flexural strength (Modulus of rupture)

Ductility (Load deflection curves)

Weight comparison

Failure mode (both; under compression and flexure)

Water absorption

ISAT (Permeability)

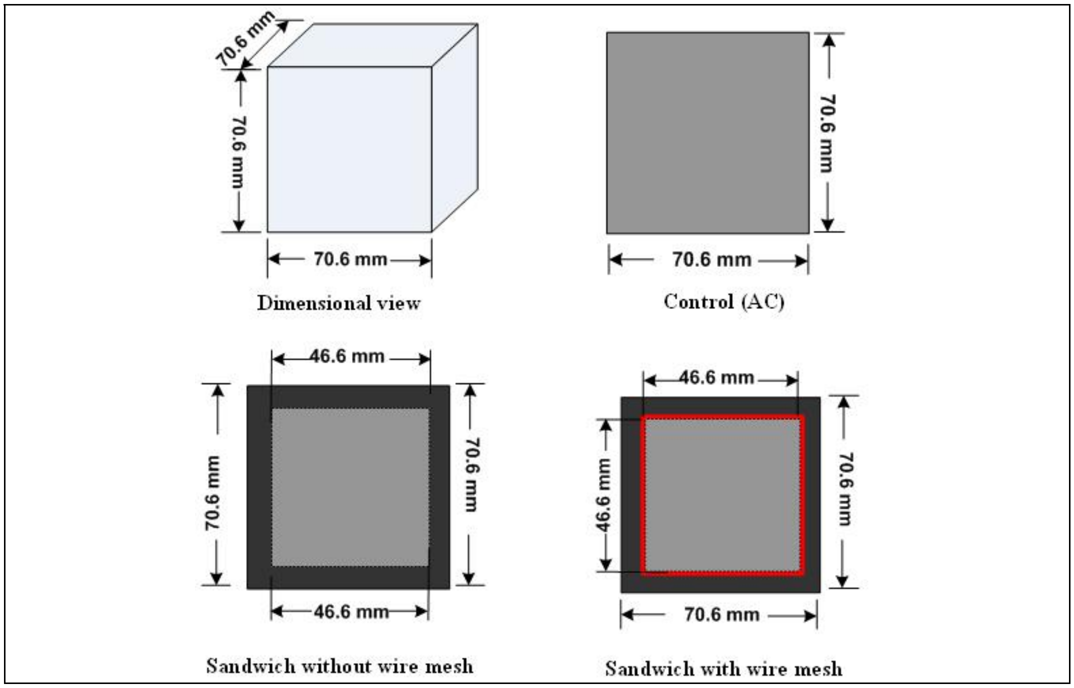


Figure 3.1: Dimensions and cross sections of cubes A

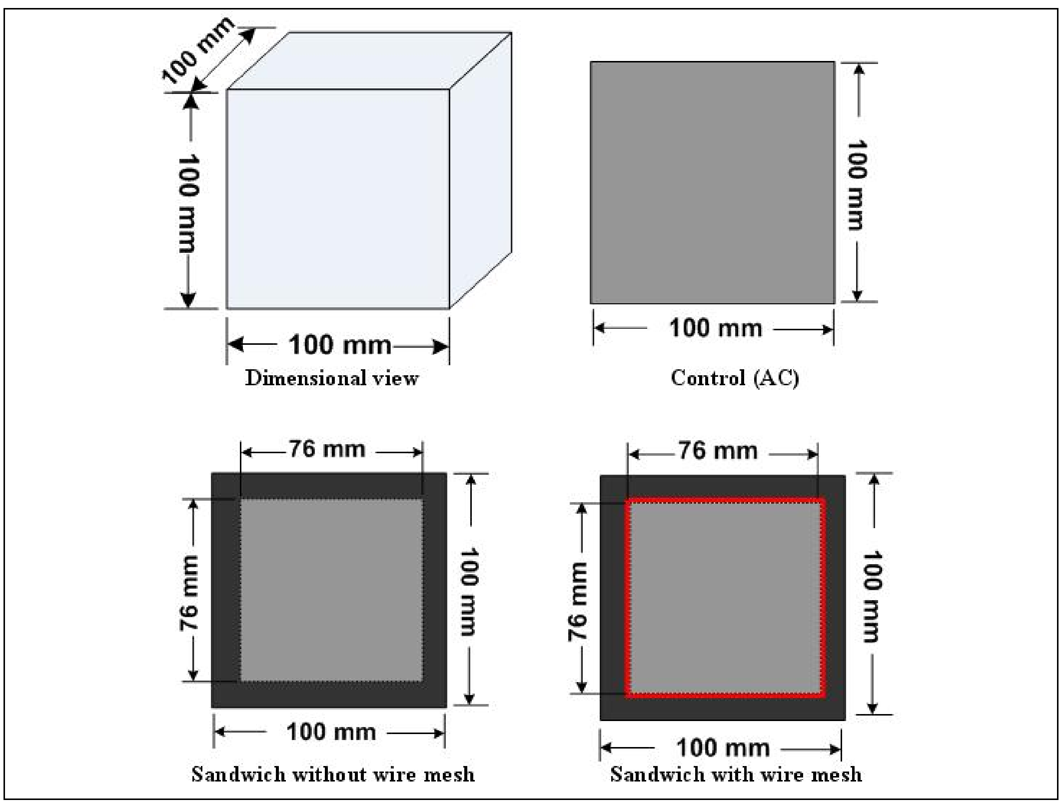


Figure 3.2:.Dimensions and cross sections of cubes B

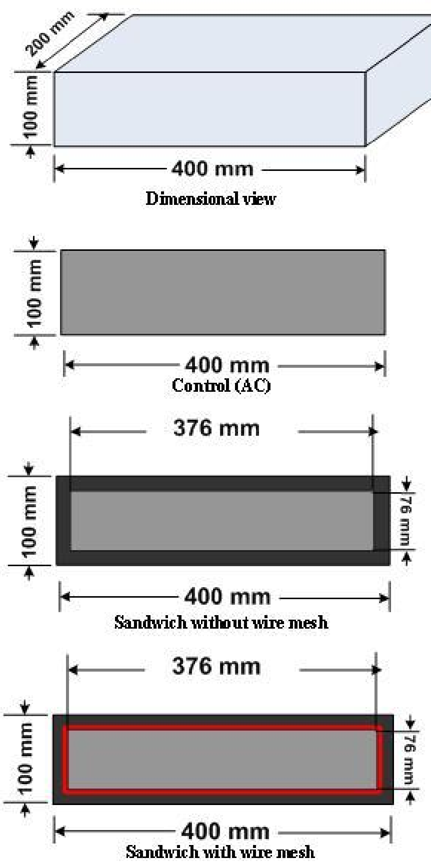


Figure 3.3: Dimensions and cross sections of blocks

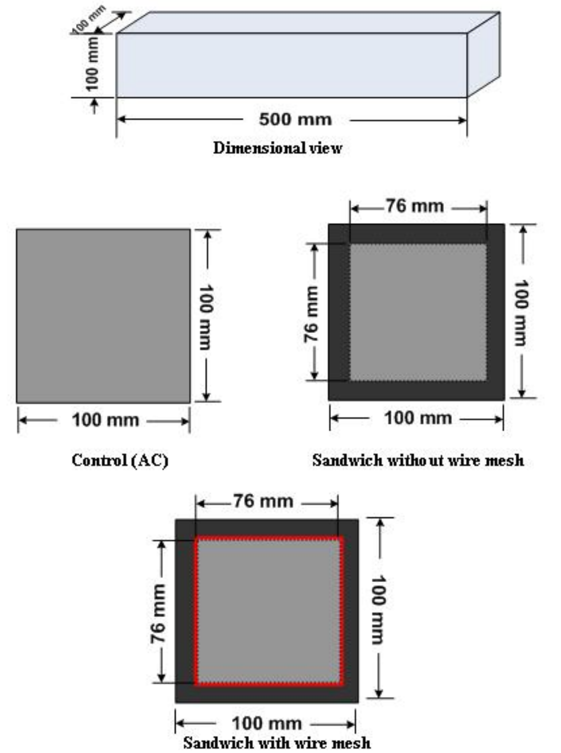


Figure 3.4: Dimensions and cross sections of prism beam

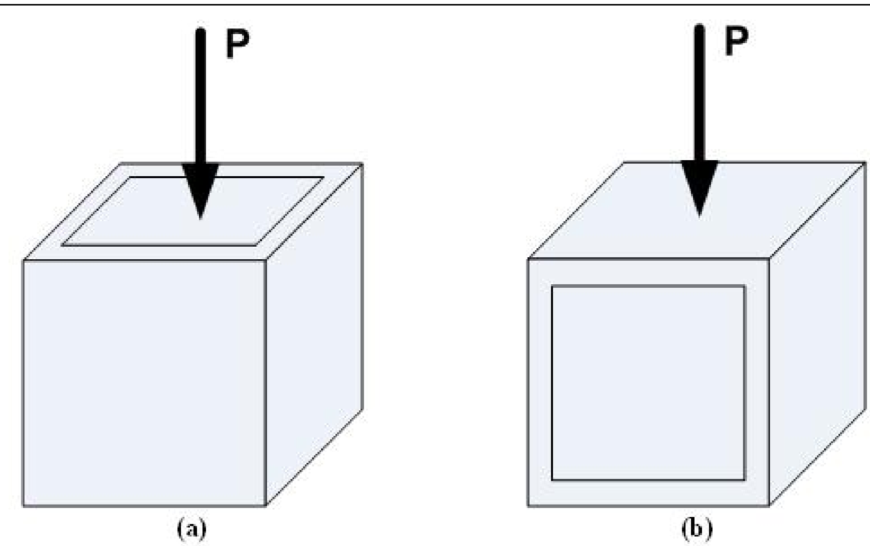


Figure 3.5: Encasement direction in compression

3.2.2.2 Sandwich Wall Elements

Finally ferrocement encased aerated concrete sandwich wall elements of relatively large size were tested. The details are as follows:

(a) Dimensions of wall elements

Wall elements	700 x 300 x 100 mm (Figure 3.6)
Wall elements	700 x 400 x 100 mm (Figure 3.7)
Wall elements	1400 x 400 x 100 mm (Figure 3.8)

(b) Variables

Mesh layers:	Optimum number of wire mesh obtained from previous step (section 3.12.1)
Curing regime:	Water moist
Age of Wall element:	28 days.

(c) Tests

(i) Compression

Ultimate load

Load-lateral deformation behaviour

Load-axial deformation behaviour

Failure mode

Composite action of sandwich wall elements

(ii) Flexure (bending)

Ultimate load

Load deflection behaviour (ductility)

Failure mode

Load-strain behaviour

Composite action of sandwich wall elements

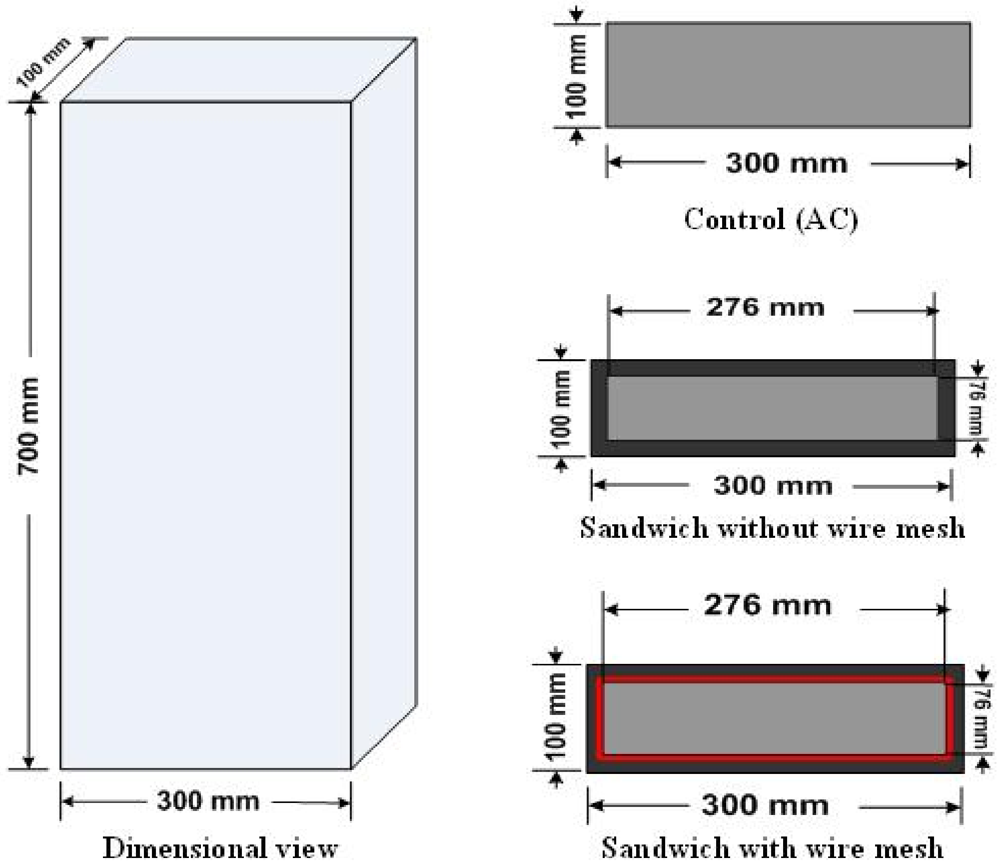


Figure 3.6: Dimensions and cross sections of wall elements (700 mm x 300 mm x 100 mm)

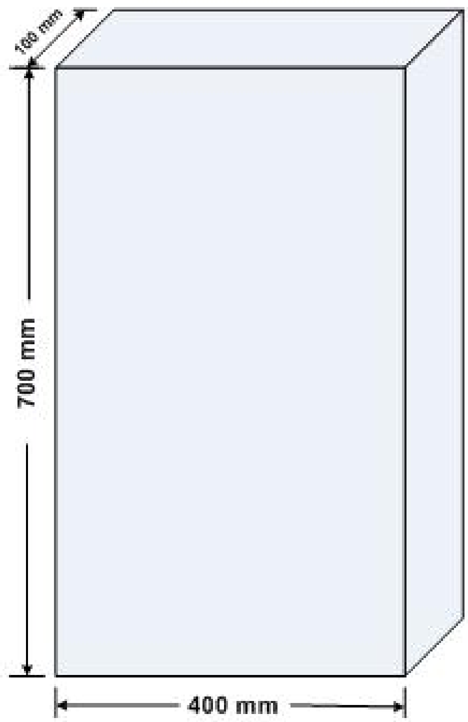


Figure 3.7: Dimensions of wall elements
(700 mm x 400 mm x 100 mm)

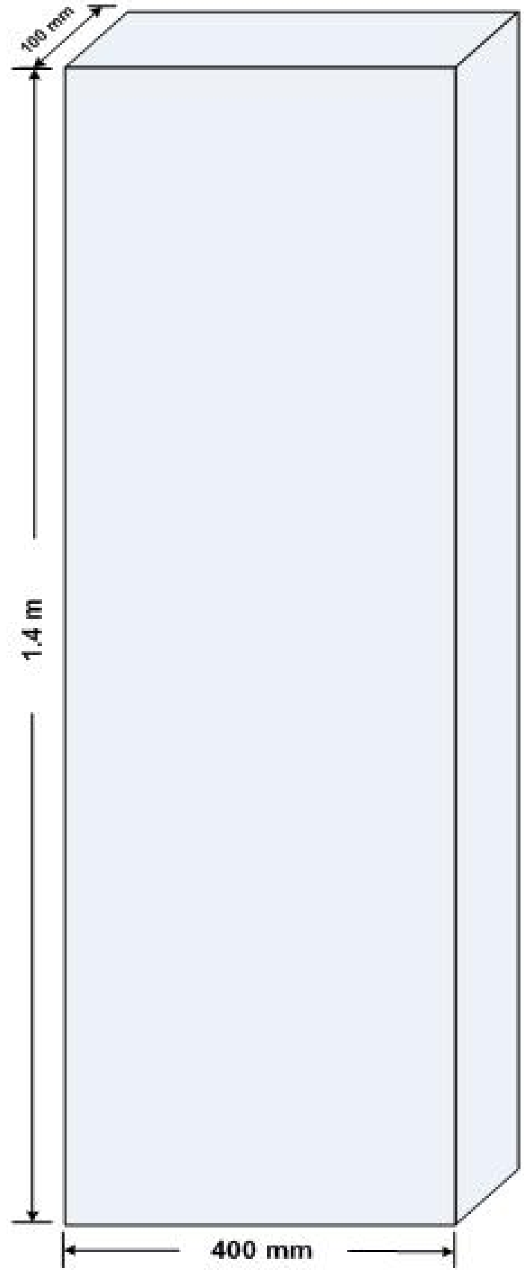


Figure 3.8: Dimensions of wall element
(1400 mm x 400 mm x 100 mm)

3.3 Materials

All the raw materials used throughout this study complied with the standard specifications of ASTM, BS and Malaysian Standards.

3.3.1 Cement

Ordinary Portland Cement (OPC) of 'SELADANG' brand from Tenggara Cement Manufacturing Sdn. Bhd. was used during the study. The OPC used complied with the Type I Portland Cement as in ASTM C150-05 (2005) and BS 12 (1991) which is equivalent to Malaysian Standard MS 522: part I (2003). The chemical composition of the cement is given in Table 3.1.

Table 3.1: Chemical composition of OPC and GGBFS

Chemical Composition	OPC	GGBFS
Silicon dioxiode (SiO_2)	20.1	28.2
Aluminum oxide (Al2O_3)	4.9	10.0
Ferric oxide (Fe_2O_3)	2.5	1.8
Calcium oxide (CaO)	65.0	50.4
Magnesium oxide (MgO)	3.1	4.6
Sulphur oxide (SO_3)	2.3	2.2
Sodium oxide (Na_2O)	0.2	0.1
Potassium oxide (K_2O)	0.4	0.6
Titanium Oxide (TiO_2)	0.2	-
Phosphorus Oxide P_2O_2	<0.9	-
Loss of ignition (LOI)	2.4	0.2
Carbon content (C)	-	-

* All values are in percentage

3.3.2 Ground Granulated Blast Furnace Slag (GGBFS)

GGBFS was obtained from YTL Cement Sdn. Bhd.,Pasir Gudang, Johor. The GGBFS used complied with the requirements in ASTM C989-05 (2005), which is equivalent to BS 6699 (1992) and MS 1387 (1995). The chemical composition of slag is given in Table 3.1.

3.3.3 Fine Aggregate

Locally available hill sand passing through 1.18 mm sieve was used as fine aggregate in mortar for encasement. Initially the sand was dried in an oven at the temperature of 105 ^{0}C ± 5 ^{0}C. After that it was sieved accordingly. The sand used was as per the specifications of ASTM C778-02 (2002) and gradation was in accordance with the specifications of ASTM C33-03 (2003) and IFC-10 (2001). The fineness modulus was found to be 2.36.

For aerated concrete the sand was sieved from 600 micron sieve as per the recommendations of Arreshvhina (2002).

3.3.4 Superplasticizer

The superplasticizer of trade name SIKAMENT NN was used as the chemical admixture during this study. It was type F high range water reducing admixture complying with ASTM C494-05a (2005). It was from group Sulphonated Naphthalene Formadehyde condensates (SNF) in dry powder form.

3.3.5 Aluminum Powder

The aluminum powder type Y250 was used as the gas-forming agent in producing the slag cement based aerated lightweight concrete. The specifications and chemical composition of the aluminum powder used are given in Table 3.2.

Table 3.2: Specifications and chemical composition of Aluminum powder

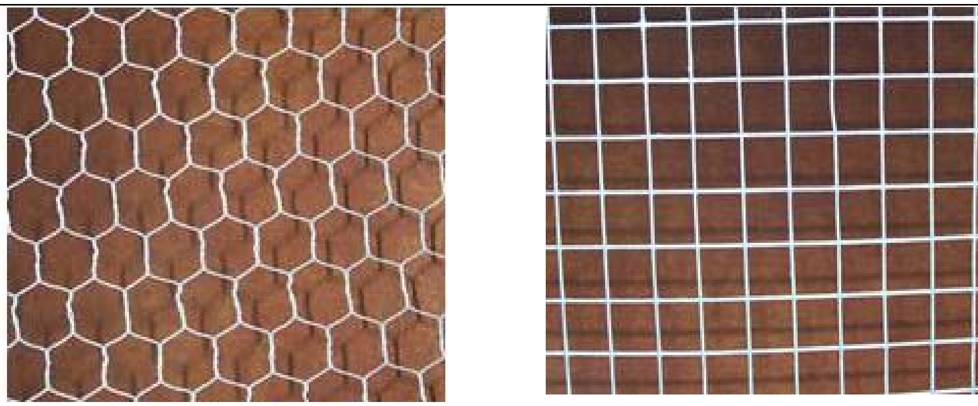
Specification	No.300
Colour	Silver
Particle Size	Mesh 250
Reactivity of Aluminum (%)	-
Chemical composition (%)	
Aluminum	Min. 99.3
Copper	Max. 0.1
Iron	Max. 0.4
Silica	Max .0.2

3.3.6 Wire Meshes

Square welded wire mesh and hexagonal chicken wire mesh locally available in the market were used as the reinforcement in ferrocement box. The properties of the wire mesh are given in Table 3.3. Figure 3.9 depicts the photographic view of wire meshes used.

Table 3.3: Properties of wire meshes

Wire mesh type	Properties	Values
Square mesh	Average diameter	0.9 mm
	Opening size of mesh	12.2 mm x 12.2 mm
	Yield strength	410 MPa
Chicken (Hexagonal) mesh	Average diameter	0.45 mm
	Opening size of mesh	13 mm x 15 mm
	Yield strength	290 MPa



Chicken mesh **Square mesh**

Figure 3.9:. Wire meshes

3.3.7 Water

Water is one of the most important constituents without which concrete cannot be produced. It should not contain any substance, which can be harmful to the process of hydration of cement and durability of concrete. In general, water, which is acceptable for drinking, is also suitable for the concrete mixing. In this study tap water was used for the manufacture of the concrete.

3.4 Mix Proportion

3.4.1 Mortar for Encasement

Mix proportion for ferrocement mortar was selected from the test results of phase-1. Table 3.4 shows the details of the proportion.

Table 3.4: Mix proportion of mortar for encasement

Binder : Sand	1:2
OPC	50% of total binder by weight
GGBFS (as partial replacement of (OPC)	50% of total binder by weight
Sand	Passing through sieve size # 16
Water-binder ratio	Adjusted to 136±3% flow value
Superplasticizer	0.2% of total binder by weight
Design compressive strength	About 50MPa

3.4.2 Aerated Concrete

In principle the mix proportion for aerated concrete (sand: binder) adopted was the same as that of aerated concrete developed earlier at UTM by Arreshvhina (2002). However substantial modifications in the dosage of superplasticizer and aluminum powder were applied as per the requirement. Table 3.5 presents the mix proportion of the aerated concrete used during this study.

Table 3.5: Mix proportions of slag cement based aerated concrete.

Binder : Sand	1: 1
OPC	50% of total binder by weight
Sand	Passing through sieve size 600 micron
Slag Replacement	50%
Water-dry mix ratio	0.23
Aluminium Powder	0.1% of total dry mix by weight
Superplasticizer	0.55% of total binder by weight
Average density	1100- 1200 kg/m^3

3.5 Specimens Casting

The specimens of various sizes and shapes as mentioned in section 3.1 were prepared and tested during the experimental part of this study. All the specimens were cast and tested in accordance to the specifications of the appropriate standards. Guidelines established by various authors were adopted wherever the procedures in certain cases were not found in the standards like, casting of ferrocement thin sheets, aerated concrete, and sandwich specimens. Following is the brief account of the casting procedures adopted for these specimens.

3.5.1 Ferrocement Thin Sheets

Thin ferrocement elements of 6mm, 8mm, 10mm, and 12mm thick, 200mm wide and 600mm high containing one layer of square wire mesh inside were cast in vertical upright direction with random values of water-binder ratio by keeping mix proportions constant. A trial-and-error method was applied by adjusting the water content, in order to determine the minimum water-binder ratio required to cast the proposed ferrocement box by the method of pouring the mortar instead of manual plastering of the wire mesh layers. Table vibrator was used during the casting of thin sheets.

Tests were conducted for different mix proportions and were repeated for three times for each mix. Details of mix proportions and results are discussed in chapter 4. Figures 3.10 and 3.11 show the mould and a few thin ferrocement elements cast respectively while Figure 3.12 depicts the view of one of the ferrocement elements containing wire mesh encapsulated with mortar.

Figure 3.10: Mould used to cast thin FC elements

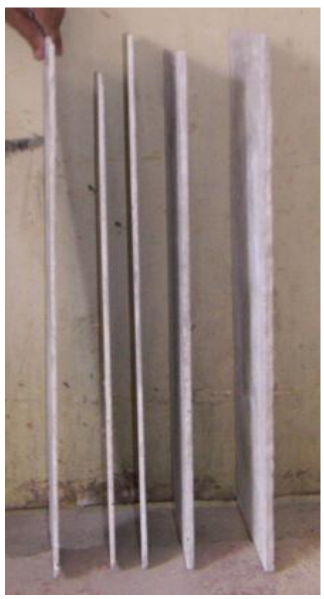


Figure 3.11: View of a few thin FC elements cast

Figure 3.12: FC element showing wire mesh inside

3.5.2 Mortar Cubes

All materials including water were weighed prior to mixing of the materials. The mixing was performed in accordance to ASTM C305-99 (1999). Initially sand and binder (OPC and GGBFS) were mixed in an electrically operated mortar mixer at 285 ± 10 rpm for about 3-5 minutes to ensure uniformly mixed. Figure 3.13 shows the mixer used. Then water was added slowly into the dry mix and mixing of the mortar mix continued for about 3 minutes in order to achieve the uniform mix. Then cube specimens of standard size were cast as per the specifications of ASTM C109-05 (2005). The moulds were covered in a plastic sheet with wet gunnysacks at the top to provide humidity during the hardening process. After 24 hours, the specimens were demoulded and cured accordingly.

Since mortar for ferrocement sandwich elements was large in quantity to be mixed in electrically operated mixer, hence it was mixed in the drum mixer with similar procedure adopted for the cube mortars.

Figure 3.13: Mixer (electrically operated)

3.5.3 Aerated Concrete Specimens

Firstly, sand cement and slag were weighed and added and were mixed thoroughly in a mixer (electrically operated mixer/ drum mixer) for about 3-5 minutes. Aluminum powder and SP were then added and mixed about three minutes until all the constituents were evenly mixed. Then water was added and again mixed for about 5 minutes or until a uniform mix was achieved. Figure 3.14 shows the AC mix after attaining the uniform state.

Figure 3.14: AC uniform mix

Then the mix was poured in the moulds approximately up to 80% of their height. This can be viewed from Figure 3.15.

Figure 3.15: AC filled in moulds up to 80%.

Immediately after pouring the mix in mould, expansion convened and continued for next 30-45 minutes. The specimens became hard enough after 3-4 hours of casting and were ready to be trimmed the expanded portion above the top of the specimens. After 24 hours the specimens were demoulded and were placed in the curing regime (if the control) and the core specimens were processed further to cast the sandwich. Figures 3.16 -3.18 illustrate the pictorial views of expanded, trimmed and demoulded aerated concrete specimens.

Figure 3.16: AC specimens after expansion

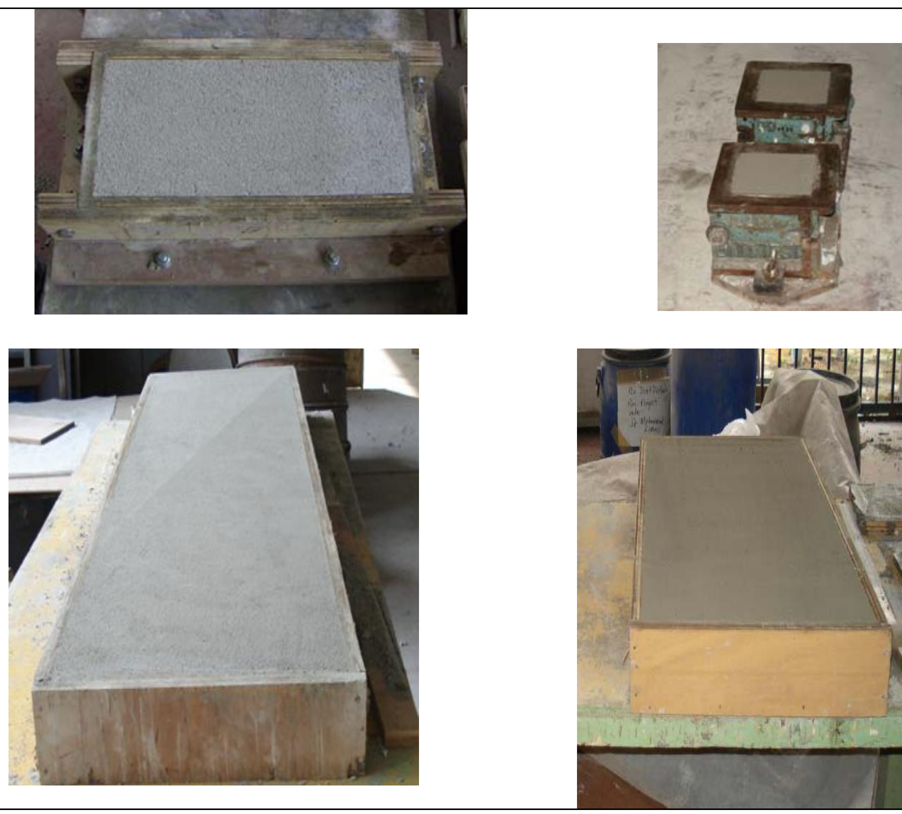


Figure 3.17: AC specimens after trimming

Figure 3.18: AC specimens after demoulding.

3.5.4 Sandwich

The wire mesh was cut from the roll as per requirement of the specimens and it was wrapped over the core in layers (as required) followed by the casting of the ferrocement box in single operation. Table vibrator was used during the casting of the ferrocement encasement. Figures 3.19-3.22 present the pictorial views of the various stages of the casting of the sandwich elements. The stages are; wrapping of wire mesh, specimens ready to cast encasement, after casting, and the demoulded specimens ready for curing. At the time of casting the ferrocement encasement, three companion mortar cube specimens of standard size were also cast to determine the ultimate compressive strength of mortar on the day of the testing the corresponding batch.

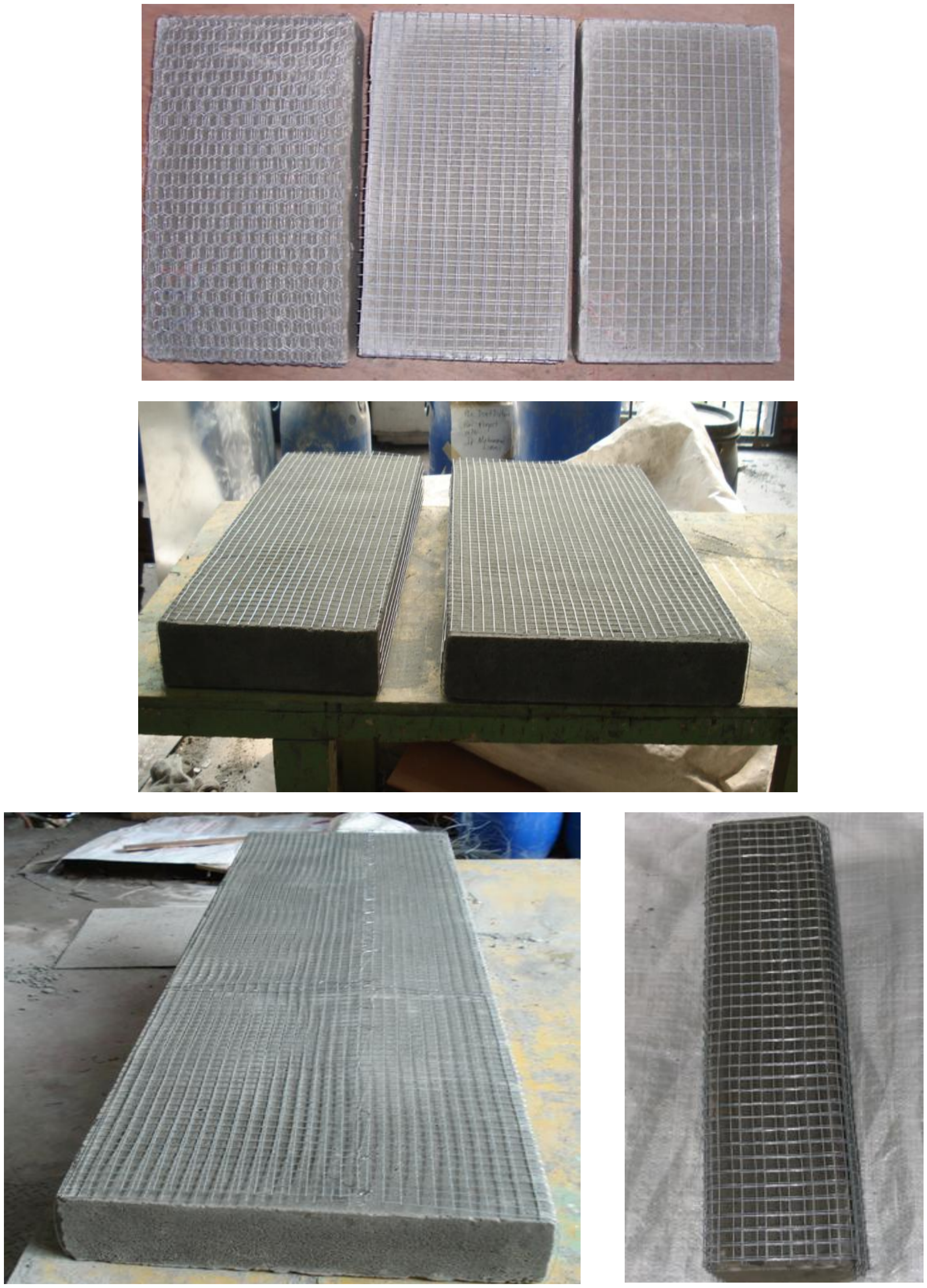


Figure 3.19: AC core specimens after the wrapping with wire mesh

Figure 3.20: Sandwich specimens ready to cast encasement

Figure 3.21: Sandwich specimens after casting of encasement

Figure 3.22: Sandwich specimens under curing process

3.6 Experimental Procedures and Setup

3.6.1 Flow Tests

Flow table test in accordance to ASTM C230-03 (2003) was applied in order to determine the mortar flow. The flow is defined as the resulting increase in the base diameter of a mortar mass expressed as a percentage of the original base diameter after being vibrated on a flow table. First of all the constituents were mixed thoroughly to achieve uniform mix. The mix is filled in the standard mould on the flow table in 2 layers compacted in each layer with 20 numbers of blows with a 25mm diameter mild steel bar. The tamping pressure was just sufficient to ensure uniform filling of the mould. After filling, the mould was removed and the flow table was vibrated, by dropping it from standard height of 12.5mm at the rate of 25 drops in 15 seconds.

Lastly, the result of increased base diameter of mortar mass is measured and divided by the original diameter to get the flow. Figure 3.23 presents the pictorial views of the flow test.

Figure 3.23: Flow table test

3.6.2 Compression

Compressive strength is the major test done during this study. Three types of specimens were tested under compression; cubes, blocks and wall elements. The cubes and block specimens were tested using TONIPAK 300 compressive testing machine of capacity 3000 KN installed in the structures and materials laboratory, FKA UTM. The tests were conducted as per the specifications of ASTM C109-02 (2002) and EN 679 (1993) at the prescribed age of the testing. The specimens were withdrawn from the specific curing regime just 15 minutes before the testing and cleaned properly with dry cloth to remove foreign particles if any.

Before conducting the test, all the specimens were checked for any kind of deformation such as broken edges and cracks. Then the specimens were placed at the center of the cleaned platens of the machine followed by the application of gradual and without shock loading. The rate of loading was maintained at a constant value 0.3 KN/mm^2 per second until the failure of the specimens. During test, the visible cracking and the failure mode were monitored carefully and the load corresponding to first visible crack and the ultimate failure were recorded. Figures 3.24 and 3.25 show the test setup for compression tests of cubes and block specimens.

Figure 3.24: Test setup for cubes.

Figure 3.25: Test setup for blocks

Lastly the compressive strength was calculated by following formula:

$$f_{ci} = \frac{F_i}{A_{ci}} \qquad 3.1$$

Where:

$f_{ci} =$ Compressive strength (MPa)

$F_i =$ Ultimate load (N)

$A_{ci} =$ Cross-sectional area perpendicular to loading direction (mm^2)

Sandwich wall elements were tested with special testing arrangement suited for the specimen dimensions and expected load carrying capacity accordingly. The test set up used for the wall elements are shown in Figures 3.26 and 3.27. All the specimens were tested in vertical position. Before testing, the panels were painted white so that crack pattern could be observed easily. The specimen was placed in the loading frame in the correct position. A leveling ruler was used to ensure the proper leveling of the panel. A total of 10 LVDTs were used in each specimen for lateral and axial deformations, out of which six LVDTs, three being on either side were used to measure lateral deformation, while the remaining four were used to measure axial deformations by installing two on either side.

Figure 3.26: Test setup-I for wall panels under compression

Figure 3.27: Test setup-II for wall panels under compression.

The instruments were checked and adjusted properly, before applying the load. A small load of around 1 KN was first applied to make sure that all the instruments were working. The load is then increased gradually with an increment of approximately 10 KN till the failure of the specimen. At each load stage, the readings were recorded automatically using a Data Logger connected to a computer. The crack pattern was also noted at each load stage. Cracks were marked on the surface of the specimen the general behaviour of the specimen was carefully observed.

3.6.3 Flexural (Bending)

The bending strength is of value in estimating the load under which cracking will develop. Flexural strength specimens were in the form prisms 100 x 100 x 500 mm in dimensions, to asses the modulus of rupture. A symmetrical, two point loading (third-point / middle third loading) in accordance to ASTM C78-02 (2002), which produces a constant bending moment between the load points, was used until to failure. Three LVDTs; one at centre and two at load points, were installed at the bottom of the prisms to study the load-deflection behaviour. The load was applied in uniform increments of about 400N/s until failure. During the test in progress, the development of crack and the cracking pattern of specimens up to failure were closely observed. At each load stage, the readings were recorded automatically using a Data Logger connected to a computer. Figure 3.28 depicts the pictorial view of the test arrangement.

Figure 3.28: Test setup for prism beams under flexure (bending)

The flexural strength values of all prisms can be calculated using the modulus of rupture formulae using the ultimate load values as follows.

$$MOR = \frac{PL}{bd^2} \qquad \text{(When, } a > \frac{L}{3}\text{)} \qquad 3.2$$

$$MOR = \frac{3Pa}{bd^2} \qquad \text{(When, } a < \frac{L}{3}\text{)} \qquad 3.3$$

Where

P	=	Load at failure
L	=	Span length

b	=	Average width of specimen
d	=	Average depth of specimen
a	=	Average distance between line of fracture and the nearest support measured in the tension surface of the beam

Sandwich wall elements were tested in a testing frame. The frame was anchored to a strong floor. All the specimens were tested in the horizontal position. The panels were simply supported on two shorter sides and subjected to two-line lateral loads as shown in Figure 3.29. The force introduced to the jack was generated by a hydraulic pump.

Figure 3.29: Test setup for walls under flexure (bending)

The force was transferred from the jack through the I-beams to the specimen. All the specimens were tested till failure. The panels were painted white so that crack patterns could be easily observed. The specimen was then placed in the loading Frame in the correct position. The LVDTs and strain gauges were placed at the proper locations. Before application of the load, the instruments were checked and adjusted properly. A small load of around 0.5 KN was first applied to make sure that all the instruments were working. The load is then increased gradually with an increment of approximately 1 KN till the failure of the specimen. At each load stage, strains in concrete and the deflections were recorded automatically using a computerized data acquisition system. The crack pattern was also noted at each load stages. Cracks were marked on the surface of the specimen and general behaviour of the specimen was carefully observed during the load application. The failure load is identified when excessive cracking occurs at the bottom the applied load drops and the deflection increases.

3.6.4 Water Absorption Test

Water absorption test was conducted as per the specifications of BS 1881: Part 122, (1983). This method is also known as water immersion method. Three representative specimens from each batch were oven dried at 105±5 ^{0}C for 72±2 hours. Upon removal from the oven, all specimens were cooled for 24±0.5 hours in a dry airtight vessel. Then the specimens were weighed and immediately immersed in water tank to a depth ensuring 25±5mm of water over the top of specimens. The specimens remained in water for 30±0.5 minutes, followed by their withdrawal from the water. Then the specimens were dried with a cloth in order to remove surplus water on the surfaces and were weighed. The water absorption value was then calculated as the increasing in the mass resulting from the immersion process expressed as a percentage of the mass of the dry specimen. The calculations were made as per the formula specified in BS 1881: Part 122 (1983), as follows:

$$W_a = \frac{W_w - W_d}{W_d} \times 100 \qquad 3.4$$

Where

$W_a =$ Percentage of water absorption

$W_w =$ Weight of wet specimen

$W_d =$ Weight of dry sample

Accordance to Concrete Society Technical Report No. 31 (1988), the typical values of the water absorption of concretes rating the type of concrete cured in water and tested at 28 days as per the recommendations and test procedures of BS 1881 BS 1881: Part 122 (1983), are defined as:

Very low absorption concrete	< 3%
Low absorption concrete	3 – 4%
High absorption concrete	> 4%

3.6.5 Initial Surface Absorption Test (ISAT)

BS1881: Part 5 (1970) clause 6 describes a method of determining the initial surface absorption of concrete which was developed and tested by Levitt, (1970). The test is non-destructive test and a measurement of the surface concrete properties and is of interest in relation to concrete performance criteria like permeability thereby the durability. The clause defined the initial surface absorption test as the rate of flow of water into concrete per unit area after a stated interval from the start of the test and at constant applied head and temperature.

All the ISAT samples were oven dried in well-ventilated oven at 105±5^{0}C for about 24 hours in order to achieve constant weight. Then the specimens were placed in a suitable airtight cooling cabinet until the time of testing where the temperature was equivalent to the room temperature.

In this method a cap with a minimum surface area of 5000mm^2 is sealed to the concrete surface and filled with water. Figure 3.30 illustrates the schematic diagram of the tests. The rate at which water is absorbed into the concrete under constant pressure head of 200mm is measured by movement of water along a capillary tube attached to the cap. The readings were recorded at the time intervals; 10 minutes, 30 minutes, I hour and 2 hours after the starting of test.

The observed values are then calculated accordingly and the results are given as 'K' (ml/m^2/s). Finally the specimens are classified by comparing the values observed with the classification criteria proposed by Levitt (1970) as presented in Table 3.6.

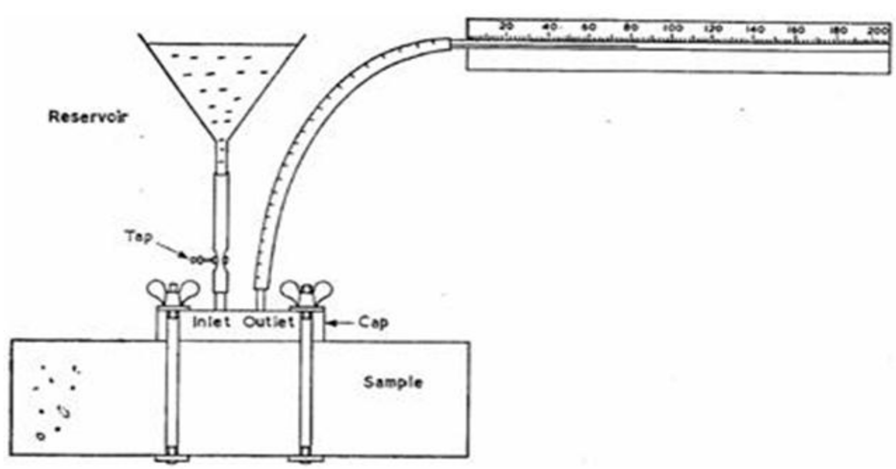


Figure 3.30: Schematic diagram of ISAT

Table 3.6: Typical results of ISAT (Levitt, 1970)

Comments	ISAT ml/m^2/s			
	Time after starting the test			
	10 minutes	30 minutes	60 minutes	120 minutes
High	> 0.50	>0.35	>0.20	>0.15
Average	0.25-0.50	0.17-0.35	0.10-0.2	0.07-0.15
Low	< 0.25	< 0.17	< 0.10	< 0.007

3.6.6 Ultrasonic Pulse Velocity (UPV) Test

The purpose of this test is to check the uniformity in the prisms. According to Neville (2003), this test is useful as a measure of uniformity of concrete and is great value in checking the quality of material throughout a structure, or in the manufacturing of pre-cast sections. Figures 3.31 show the testing points marked on one of the wall elements while Figure 3.32 depicts the UPV test in progress. The sensitivity of this method was very useful in determining the uniformity of the prisms by checking its surface hardness at age day-28.

The test was performed as per the specifications of ASTM C597-02 (2002) the test was conducted across the thickness of the wall element; thus, the distance between the two transducers was 100 mm (thickness of wall element) through out the test. Whereas, a total of 43 readings (testing points as shown in Figure 3.31) along the height of each wall element were recorded. The readings were in terms of effective transit time of pulse waves between the two transducers. Finally pulse velocity was calculated by a formula described by ASTM C597-02 (2002) as follows:

$$V = \frac{L}{T} \qquad 3.5$$

Where

$V =$ Pulse velocity (m/s)

$L =$ Distance between transducers (m)

$T =$ Effective transit time (s)

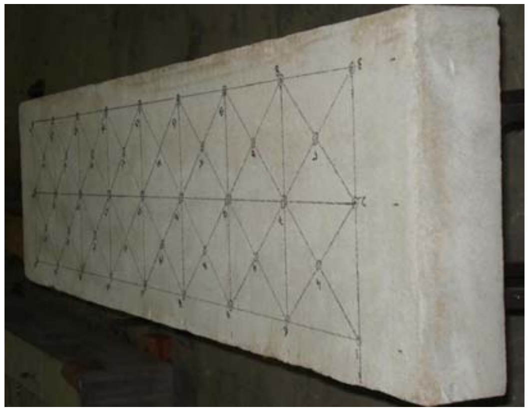


Figure 3.31: A view of point marking for UPV test

Figure 3.32: A pictorial view of UPV test in progress

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSIONS (PHASE-I)

4.1 General

This chapter discusses the results of phase-I of the experimental program as described in chapter three. The experimental investigations were aimed to develop high workability and high performance slag cement based mortar to cast the ferrocement encasement over aerated concrete core in order to produce proposed ferrocement encased aerated concrete sandwich wall elements.

A stepwise strategy for this phase of experimental study was adopted, as mentioned in methodology of the study described in chapter three. The results and their comparisons are described through tables and figures as following. Finally the experimental results are summarized at the end of the chapter.

4.2 Minimum Mortar Flow Value

Table 4.1: Details of thin ferrocement elements cast by the method of pouring the mortar with minimum flow required

S. No	**Thickness of thin FC Elements (mm)**	**Mix**	**SP (%)**	**w/b***	**Flow* (%)**	**Average (%)**
1	6	1:2	0	0.6	140	140
		1:2	0.1	0.57	139	
		1:2.5	0.2	0.64	140	
		1:2.5 (50% GGBFS)	0.1	0.65	140	
2	8	1:2	0.0	0.59	138	137
		1:2	0.1	0.56	137	
		1:2.5	0.2	0.62	136	
		1:2.5 (50% GGBFS)	0.1	0.64	137	
3	10	1:2	0.0	0.58	135	135
		1:2	0.1	0.55	135	
		1:2.5	0.2	0.61	134	
		1:2.5 (50% GGBFS)	0.1	0.6	134	
4	12	1:2	0.0	0.57	132	133
		1:2	0.1	0.54	133	
		1:2.5	0.1	0.59	132	
		1:2.5 (50% GGBFS)	0.1	0.6	133	
					Range	7
					Mean	136
					SD	3

* All the values are average of three-test values.

4.3 Maximum Dosage of Superplasticizer

Table 4.2: Details of the test results for optimum dosage of superplasticizer

SP (%)	Mix					
	1:2		0.5:0.5:2.5		0.5:0.5:3	
	w/b	Flow* (%)	w/b	Flow* (%)	w/b	Flow* (%)
0.0	0.60	140	0.70	140	0.79	137
0.1	0.56	139	0.66	140	0.76	139
0.2	0.53	138	0.64	139	0.74	137
0.3	0.50	136	0.61	138	0.72	138
0.4	0.48	137	0.59	138	0.69	135
0.5	0.47	138	0.57	136	0.68	134
0.6	0.46	129	0.56	132	0.67	126
0.6	0.47	136	0.57	136	0.68	133
0.7	0.46	124	0.56	128	0.66	116
0.7	0.47	131	0.57	134	0.68	129

*All the values are average of three tests values.

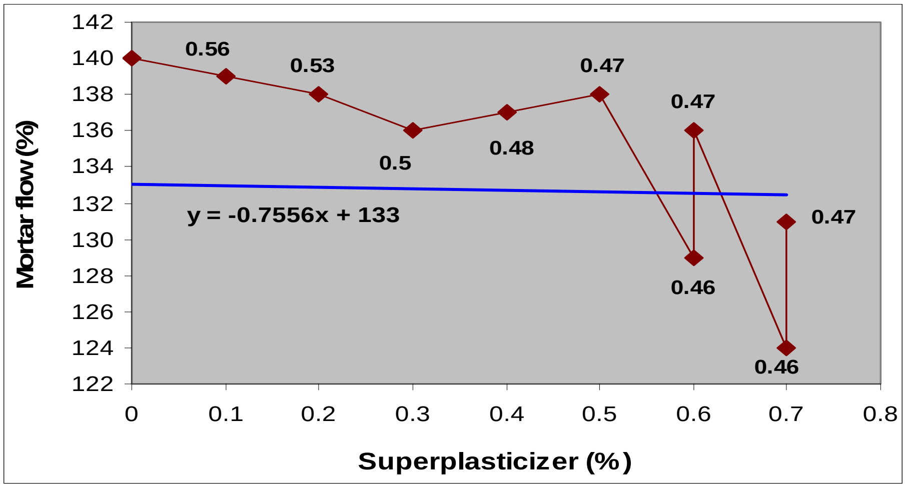


Figure 4.1: Superplasticizer versus flow value (mortar 1:2)

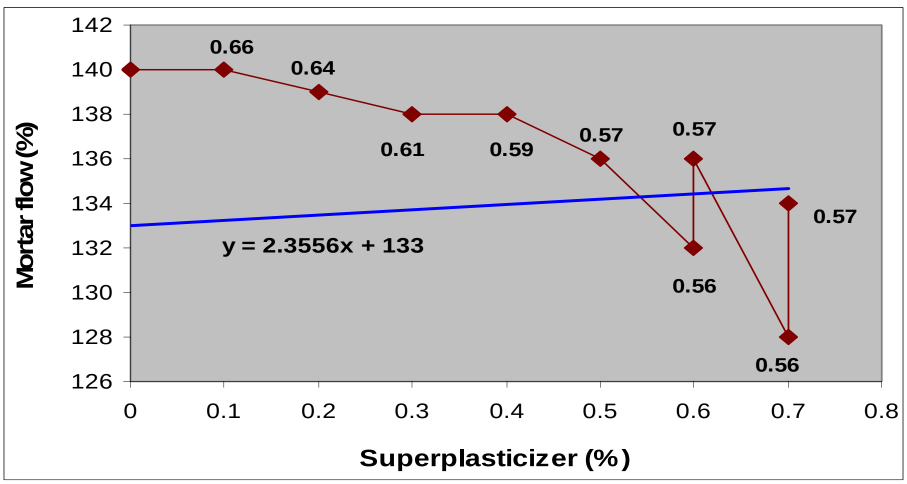


Figure 4.2: Superplasticizer versus flow value (mortar 1:2.5, 50% GGBFS)

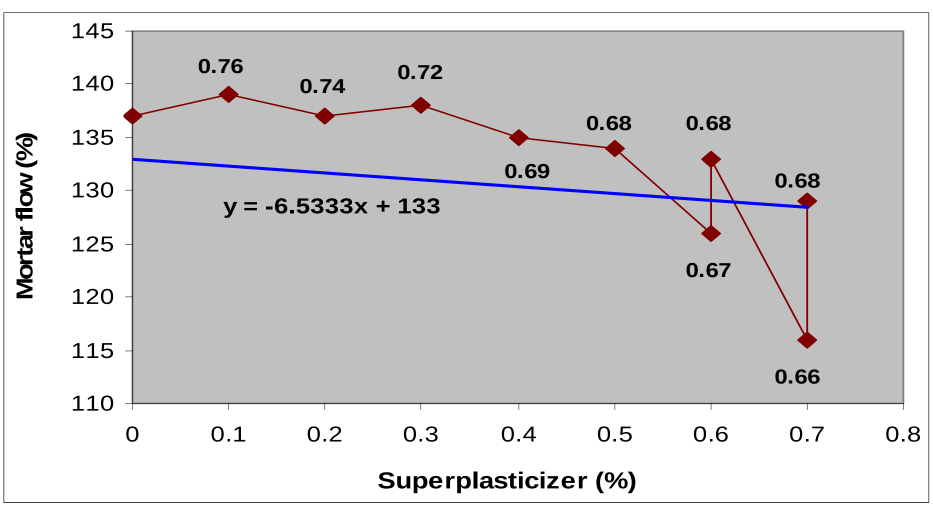


Figure 4.3: Superplasticizer versus flow value (mortar 1:3, 50% GGBFS)

4.4 Flow Value versus Mix Proportions of Mortar Mix

Table 4.3: Comprehensive flow tests results.

Mix	SP (%)	OPC		50% GGBFS		60% GGBFS	
		w/b	Flow (%)	w/b	Flow (%)	w/b	Flow (%)
1:2	0.0	0.59	138	0.59	139	0.60	140
	0.1	0.56	139	0.56	139	0.56	138
	0.2	0.53	138	0.53	137	0.54	138
	0.3	0.50	136	0.50	138	0.51	136
	0.4	0.48	137	0.48	137	0.49	136
	0.5	0.47	138	0.47	137	0.48	136
1:2.5	0.0	0.69	138	0.69	139	0.70	138
	0.1	0.65	139	0.66	139	0.66	139
	0.2	0.63	137	0.64	139	0.64	137
	0.3	0.60	137	0.61	138	0.62	139
	0.4	0.57	135	0.59	138	0.59	136
	0.5	0.55	135	0.57	136	0.57	135
1:3	0.0	0.79	138	0.79	137	0.80	139
	0.1	0.75	139	0.76	139	0.75	137
	0.2	0.73	137	0.74	137	0.73	136
	0.3	0.71	138	0.72	138	0.71	136
	0.4	0.69	135	0.69	135	0.70	137
	0.5	0.68	135	0.68	134	0.69	135

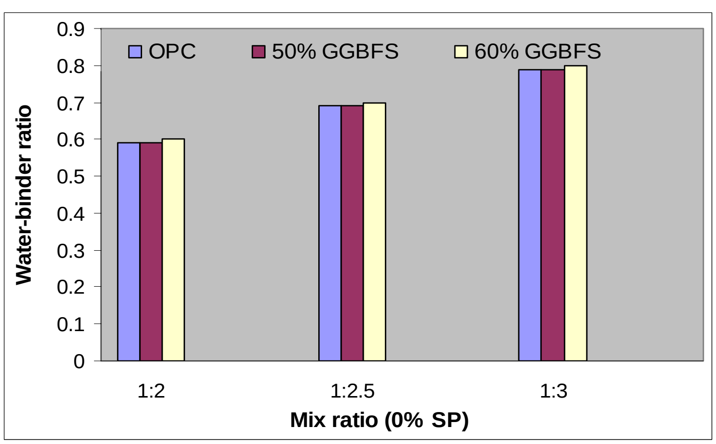


Figure 4.4: GGBFS versus water-binder ratio (136±3% mortar flow, without SP))

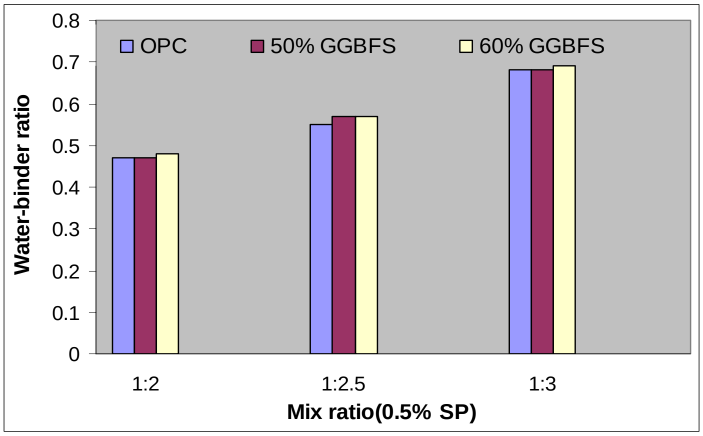


Figure 4.5: GGBFS versus water-binder ratio (136±3% mortar flow, 0.5% SP)

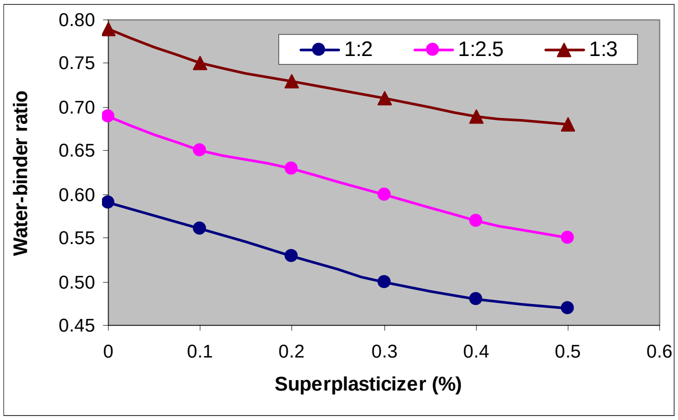


Figure 4.6: Superplasticizer versus water/binder ratio (OPC mortar, 136±3% mortar flow)

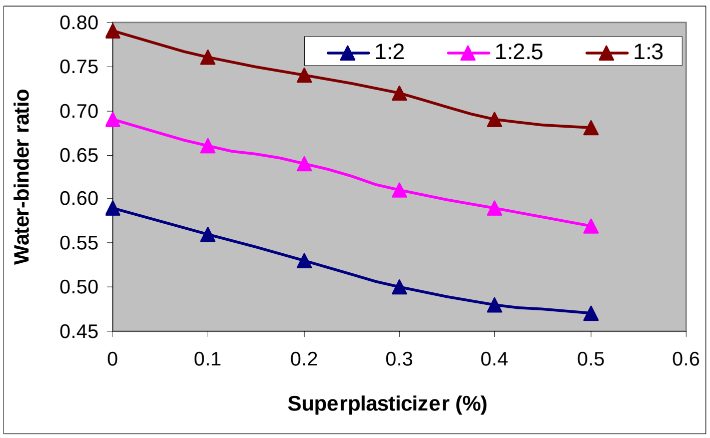


Figure 4.7: Superplasticizer versus water/binder ratio (50% GBFS mortar, 136±3% mortar flow)

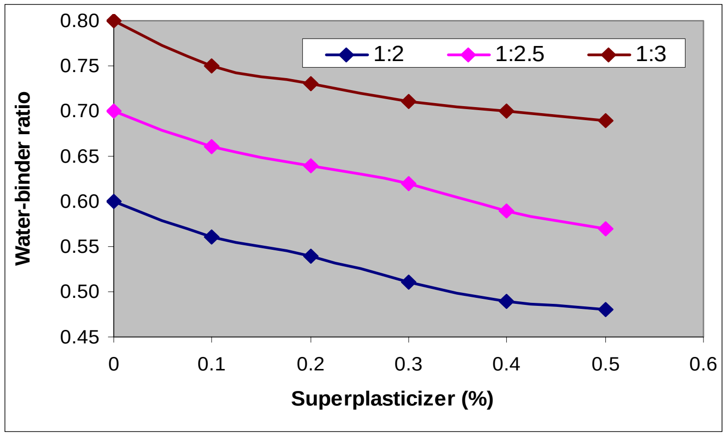


Figure 4.8: Superplasticizer versus water/binder ratio (60% GGBFS mortar, 136±3% mortar flow)

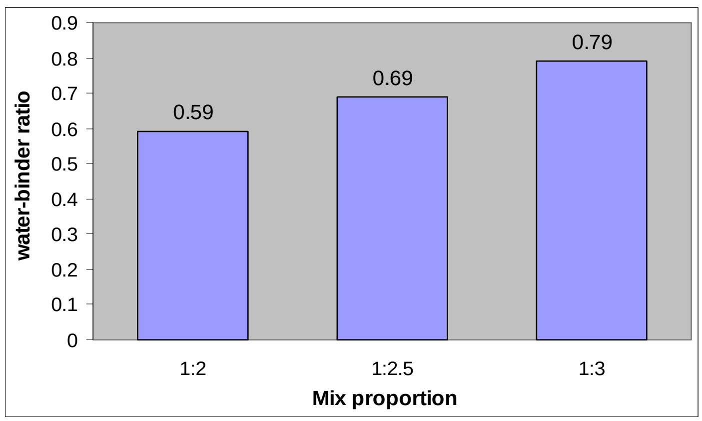


Figure 4.9: Mix proportion versus water/binder ratio (OPC, 0% SP, 136±3% mortar flow)

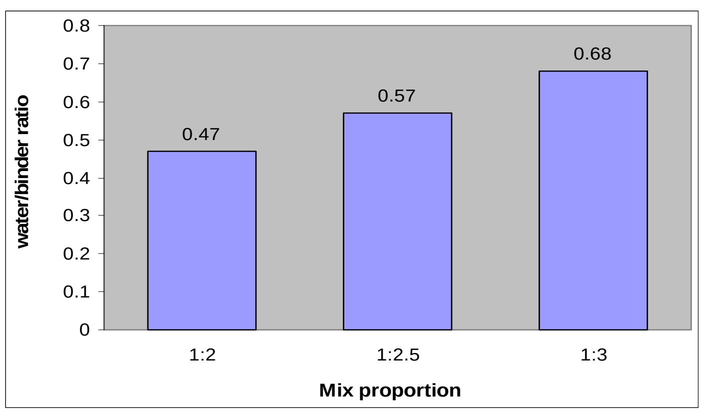


Figure 4.10: Mix proportion versus water/binder ratio (50% GGBFS, 0.5% SP, 136±3% mortar flow)

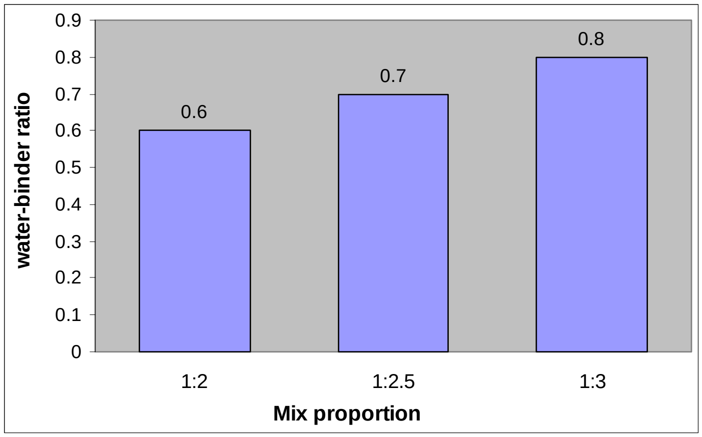


Figure 4.11: Mix proportion versus water/binder ratio (60% GGBFS, 0% SP, 136±3% mortar flow)

4.5 Characteristics of High Workability Slag Cement Mortar

4.5.1 Compressive Strength

Table 4.4: 28 days compressive strength of 54 mixes (136±3% mortar flow)

Mix	% of SP	OPC	50% GGBFS		60% GGBFS	
		f_{cu} (MPa)	f_{cu} (MPa)	Difference of f_{cu} (% OPC)	f_{cu} (MPa)	Difference of f_{cu} (% OPC)
1:2	0.0	43.0	45.8	6.5	43.2	0.5
	0.1	45.3	50.4	11.3	46.0	1.5
	0.2	48.7	53.9	10.7	48.3	-0.8
	0.3	51.3	55.8	8.8	50.4	-1.8
	0.4	52.7	56.7	7.6	51.8	-1.7
	0.5	54.0	56.5	4.6	52.0	-3.7
Mean		49.17	53.18		48.62	
SD		4.33	4.31		3.49	
1:2.5	0.0	33.6	36.4	8.3	34.8	3.6
	0.1	36.2	40.7	12.4	36.9	1.9
	0.2	37.9	42.5	12.1	38.8	2.4
	0.3	40.0	43.9	9.8	40.4	1.0
	0.4	41.9	45.0	7.4	40.7	-2.9
	0.5	42.6	45.0	5.6	41.7	-2.1
Mean		38.7	42.25		38.88	
SD		3.47	3.30		2.61	
1:3	0.0	26.8	30.0	11.9	28.1	4.9
	0.1	28.5	32.7	14.7	29.9	4.9
	0.2	30.5	35.1	15.1	31.8	4.3
	0.3	32.1	36.3	13.1	32.9	2.5
	0.4	33.1	36.7	10.9	33.3	0.6
	0.5	33.9	37.0	9.1	33.5	-1.2
Mean		30.82	34.63		31.58	
SD		2.76	2.76		2.16	

- f_{cu} = Compressive strength
-

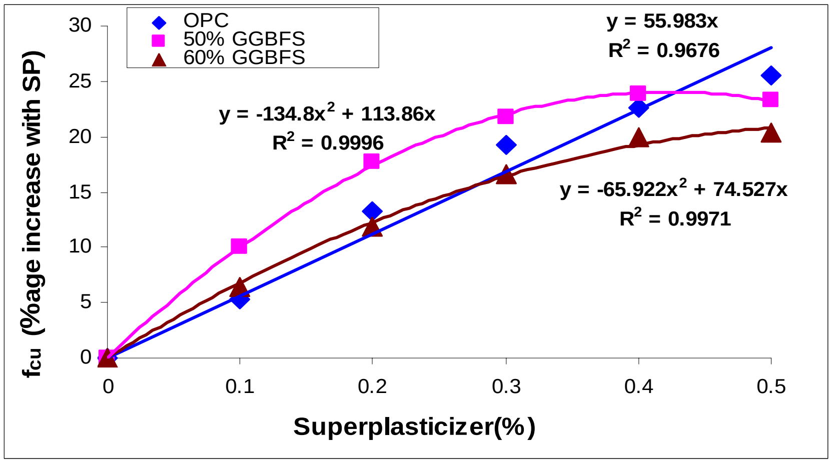


Figure 4.12: Percentage increase in compressive strength for mix 1:2 versus SP (136±3% mortar flow)

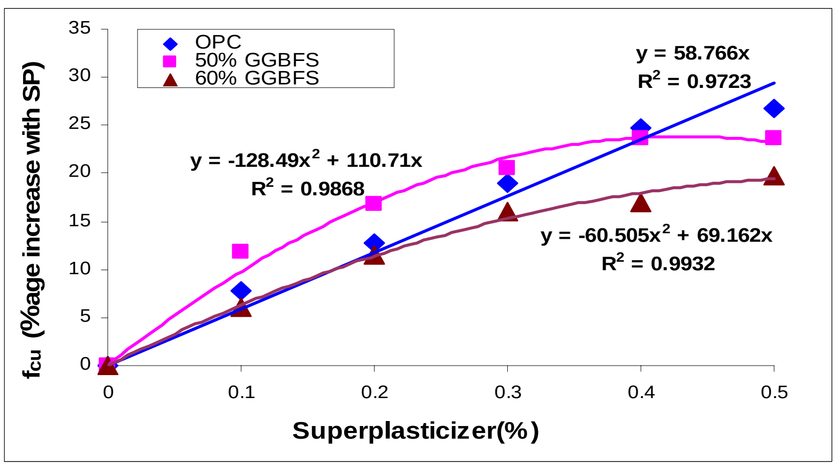


Figure 4.13: Percentage increase in compressive strength for mix 1:2.5 versus SP (136±3% mortar flow)

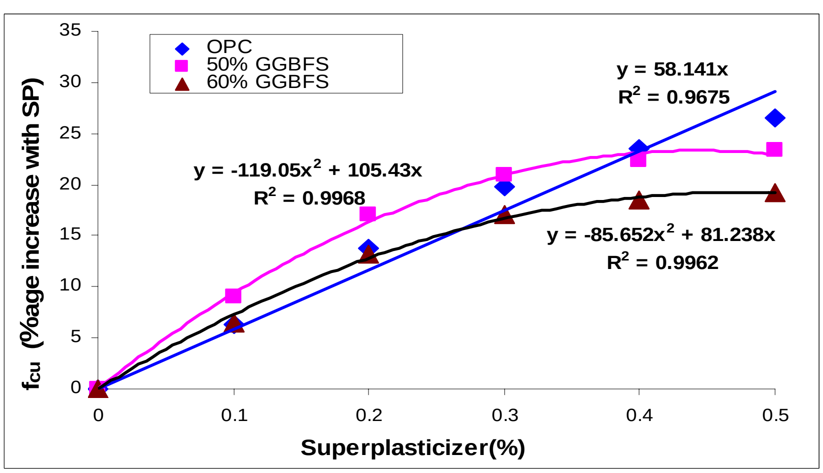


Figure 4.14: Percentage increase in compressive strength for mix 1:3 versus SP (136±3% mortar flow)

4.5.2 Unit Weight

Table 4.5: Details of unit weight 54 mortars (136±3% mortar flow)

Mix	% of SP	OPC	50% GGBFS	60% GGBFS
		Unit weight (kg/m^3)	Unit weight (kg/m^3)	Unit weight (kg/m^3)
1:2	0.0	2207	2155	2117
	0.1	2240	2193	2164
	0.2	2236	2188	2174
	0.3	2245	2236	2188
	0.4	2269	2228	2202
	0.5	2288	2217	2240
Mean		2248	2203	2181
1:2.5	0.0	2146	2164	2122
	0.1	2183	2202	2183
	0.2	2221	2198	2188
	0.3	2188	2207	2174
	0.4	2250	2202	2207
	0.5	2245	2212	2188
Mean		2206	2198	2177
1:3	0.0	2146	2174	2155
	0.1	2193	2183	2174
	0.2	2188	2179	2183
	0.3	2188	2150	2179
	0.4	2198	2202	2155
	0.5	2193	2202	2179
Mean		2184	2182	2171
Gross Mean Density : 2194 kg/m^3				
Range (Gross values) : 117 kg/m^3				

Since, this study was aimed to investigate the ferrocement sandwich elements, and it is well known fact that the end product of thin ferrocement elements depends upon the properties of the mortar, particularly compressive strength and porosity.

Moreover, the compressive strength becomes more pronounced factor when the elements are subjected to axial compression. Thus, on the basis of the results presented and the discussion made herein, it was imperative to select mix 1:2 as the principal mix. However, one mix 1:2.5 with higher dosage of SP was also selected for further study just for comparison purposes. Table 4.6 shows the details of seven mortar mixes selected for further investigations.

Table 4.6: Mortars selected for strength development (136±3% mortar flow)

Mix Designation	Mix ratio	GGBFS (%)	SP (%)
M1	1:2	OPC	0
M2	1:2	50	0
M3	1:2	50	0.1
M4	1:2	50	0.2
M5	1:2	60	0.1
M6	1:2	60	0.3
M7	1:2.5	50	0.4

4.5.3 Strength Development

Table 4.7: Strength development of mortars at various ages (136±3% mortar flow)

Age (Days)	Compressive strength (MPa)						
3	25.5	18.9	28.2	32.1	25.6	27.3	19.1
7	33.8	34.2	40.3	43.4	35.5	39.9	35.4
28	42.8	44.3	51.1	54.1	45.1	50.8	43.7
90	47.9	52.7	61.9	66.1	53.5	59.9	51.9
180	48.8	54.1	63.3	67.7	54.8	60.9	52.4
Mix	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**

Table 4.8: Strength development of mortars expressed as percentage of 28-day compressive strength (136±3% mortar flow)

Age (Days)	**Strength development as percentage of 28 days**						
3	59.6	42.6	55.2	59.3	56.8	61.1	63.2
7	79.0	77.2	78.9	80.2	78.7	81.0	81.0
28	100	100	100	100	100	100	100
90	111.9	119.0	121.1	122.2	118.6	120.0	115.6
180	114.1	122.2	123.9	125.1	121.6	122.1	119..8
Mix	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**

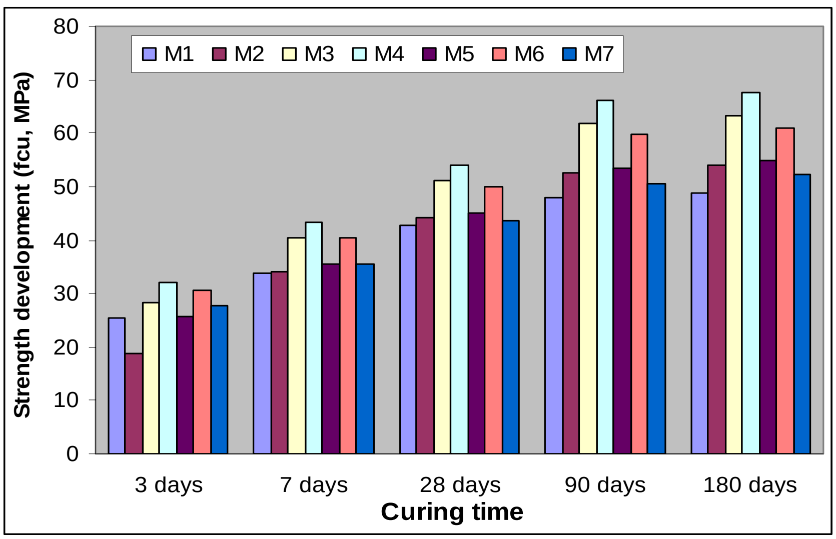


Figure 4.15: Compressive strength versus curing regime of selected mortars (136±3% mortar flow)

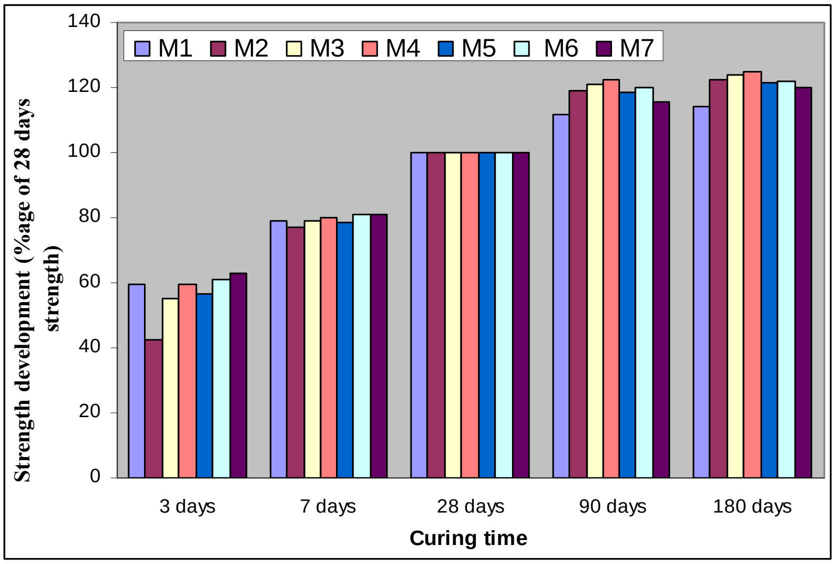


Figure 4.16: Strength development as %age of 28 days strength (136±3% mortar flow)

4.5.4 Water Absorption

Table 4.9: Water absorption test results of mortars (136±3% mortar flow)

Mix designation	**Water absorption (%)**	**Water absorption expressed as %age of M-1**
M1	4.69	100
M2	4.44	95
M3	3.67	78
M4	2.98	64
M5	4.12	89
M6	3.49	74
M7	4.21	90

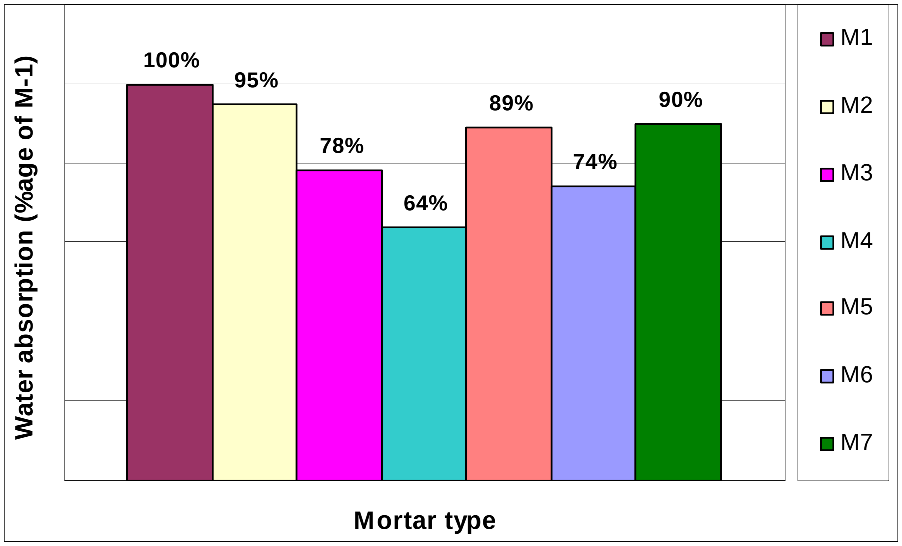


Figure 4.17: Water absorption of selected mortars (136±3% mortar flow)

4.5.5 Initial Surface Absorption Test, ISAT (Permeability Test)

Table 4.10: ISAT results of mortars (136±3% mortar flow)

Time after test started	**ISAT (ml/m^2/s)**						
	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**
10 minutes	0.220	0.2050	0.1558	0.1147	0.1470	0.1129	0.2230
30 minute	0.130	0.1210	0.0929	0.0641	0.0862	0.0558	0.1370
60 minutes	0.070	0.0600	0.0510	0.0282	0.0430	0.0248	0.0766
120 minutes	0.009	0.0084	0.0062	0.0032	0.0053	0.0041	0.0110

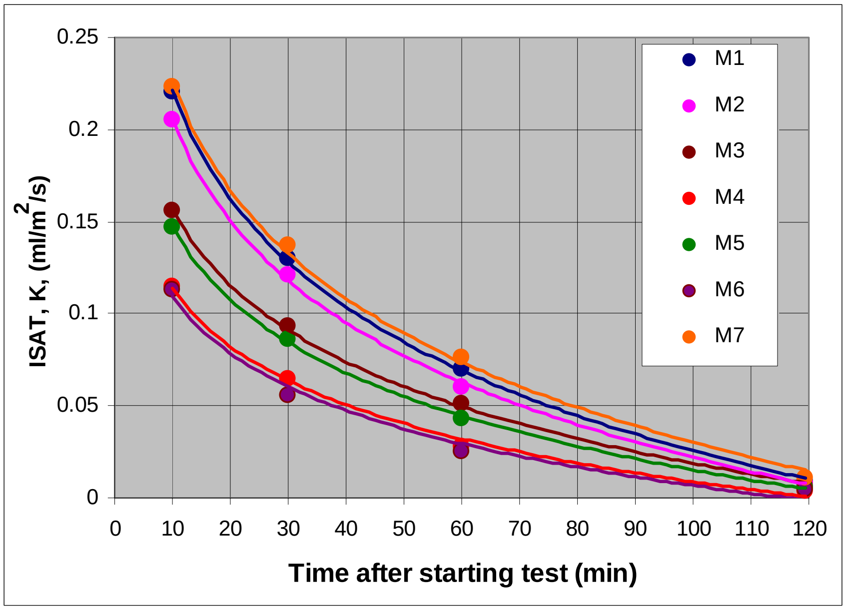


Figure 4.18: ISAT values of mortars (136±3% mortar flow)

4.5.6 Effect of Curing Regime

It was supposed that for the present studies, the compressive strength of mortar at 28 days should be 50MPa for the casting of thin ferrocement box of proposed sandwich wall elements and keeping in view the results of other characteristics presented before, two mortar mixes M3 and M4 were chosen to determine the effect of curing regime on compressive strength characteristics.

Table 4.11: Effect of curing conditions on compressive strength of mortars (136±3% mortar flow)

Mix	Age (Days)	Compressive strength (MPa)		
		Wet	Air	Natural weather
M3	3	29.1	23.6	25.2
M4	3	31.7	28.1	30.4
M3	7	41.5	31.2	32.1
M4	7	44.7	34.3	37.5
M3	28	52.6	39.9	40.8
M4	28	55.4	44.2	47.2
M3	90	63.6	39.4	44.6
M4	90	67.5	46.6	53.7
M3	180	63.6	39.4	44.6
M4	180	67.5	46.6	53.7

Table 4.12: Compressive strength expressed in %age of 28 days strength of mortars cured under various curing regimes (136±3% mortar flow)

Mix	Age (Days)	Compressive strength expressed as %age of 28 days strength		
		Wet	Air	Natural weather
M3	3	29.1	55.3	61.8
M4	3	31.7	57.2	64.4
M3	7	41.5	78.9	78.7
M4	7	44.7	80.7	79.4
M3	28	52.6	100	100
M4	28	55.4	100	100
M3	90	63.6	120.9	109.3
M4	90	67.5	121.8	113.8
M3	180	63.6	125.7	112.5
M4	180	67.5	126.9	116.9

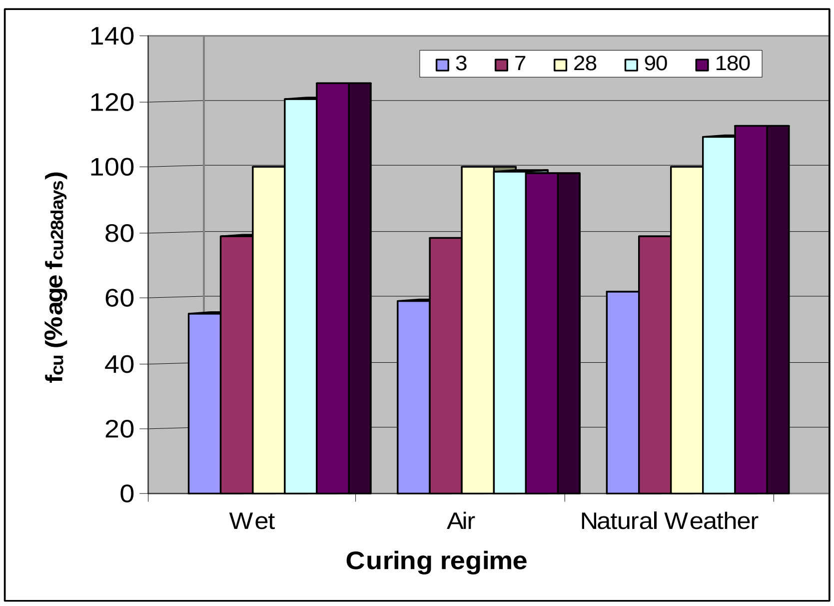


Figure 4.19: Effect of curing regime on strength development mortar M2 (1:2, 50% GGBFS, 0.1% SP and 136±3% mortar flow))

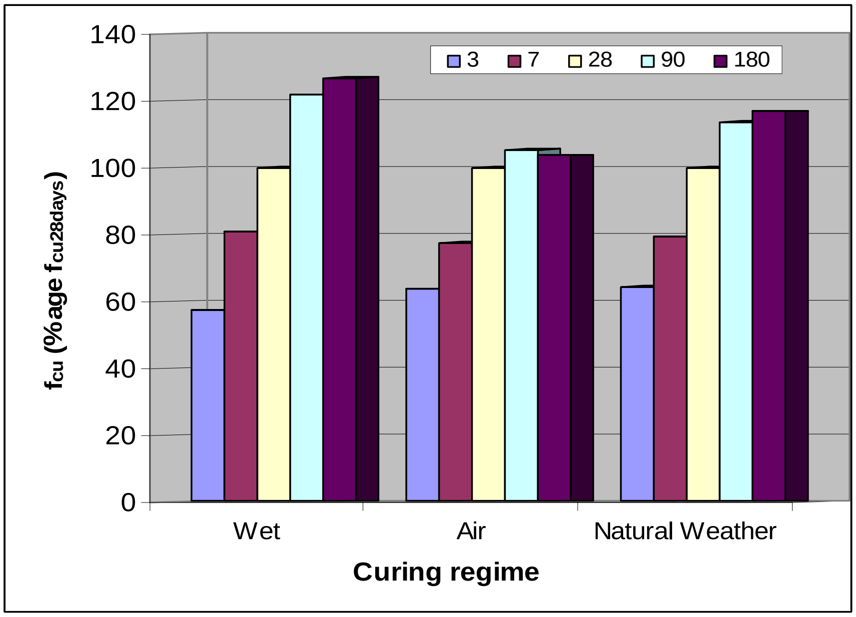


Figure 4.20: Effect of curing regime on strength development mortar M3 (1:2, 50% GGBFS, 0.2% SP and 136±3% mortar flow))

4.6 Summary

As the matrix in ferrocement has 95% or more pronounced influence on the behaviour of the final product. The selection of the constituent materials such as fine aggregates, cement content, water-cement ratio, and the mineral admixtures are the major influencing parameters in determining the performance of the mortars rather final products regarding strength and other characteristics like durability etc. Moreover, the ferrocement is thin walled cement based composite and the common practice of construction is done by plastering the wire mesh manually in three stages thus it renders it as, not only labour and cost intensive but also a non uniform final product leading towards the poor performance. This is why, this phase of study was conducted, the details of which are already presented. This study led to the development of a criterion for a high workability and high performance mortar to cast thin FC elements with the technique of pouring the mortar similar to that applied for the casting of RC members without compromising on the performance of mortar in terms of strength, water absorption, strength development and ISAT. The results of the study can be briefly concluded as follows:

(a) Mortar flow value of 136±3 % is adequate to cast ferrocement elements ranging from 6mm to 12 mm thickness. In general for each 2mm thickness difference flow may be adjusted inversely proportional by 3%.

(b) Water-binder ratio required to ensure the flow of mortar at 136±3 % depends upon the mix proportion and the dosage of the superplasticizer as water reducing agent.

(c) Water-binder ratio can be controlled by the addition of superplasticizer but the maximum dosage of the SP applicable in this case was found to be 0.5% of the total binder by weight and this reduced the water-binder ratio by 1.2 when compared to that of same mix without SP.

(d) An increase of water/binder ratio by 17% is observed with each increment of sand content by 25% of the sand in the mix 1:2 in order to maintain constant flow.

(e) Mineral admixture GGBFS adopted as cement replacement did not affect the flow properties in all the mortars and at all the dosages of superplasticizer applied.

(f) A wide range of compressive strength ranging about 27MPa to 57MPa was exhibited by high workability mortars depending on the mix proportion, GGBFS level and superplasticizer dosage adopted. A value as high as 56.7MPa of compressive strength at 28 days was achieved in case of mortar 1:2 including 50% GGBFS and 0.4% of SP. The lowest compressive strength was achieved for mortar 1:3 without GGBFS and SP.

(g) Addition of superplasticizer and GGBFS contributed towards the strength enhancement ranging 5-15% over their OPC mortars depending upon the mix proportion, GGBFS replacement level and dosage of superplasticizer. However likewise ordinary concrete and mortars, the optimum level of GGBFS is found to be 50% of total binder weight in this case also. While superplasticizer dosage up to 0.2% yielded the pronounced effect on compressive strength.

(h) Trend regarding strength development of high workability mortars was identical to that of normal workability concretes and mortars that, at early age's strength development of mortars with GGBFS was slower than OPC. Nevertheless, the early age strength of slag cement based mortars could be ensured similar to that of the OPC mortar by adopting appropriate proportioning of mortar constituents and dosage of superplasticizer.

(i) Although all the high workability mortars exhibited low rate of water absorption whereas, mortar mix 1:2 with 50% GGBFS and 0.2% SP exhibited the lowest. Similar trend to that of water absorption was obtained for ISAT (permeability). The values were quite lower than those fixed as low limit by previous researcher.

(j) Curing conditions influence the compressive strength and strength development of high workability mortars. The mortars cured under wet condition obtained remarkably higher and consistent strength development compared to the mortars of same mix proportions cured under air and natural weather conditions. Thus, likewise ordinary concretes and mortars wet/moist curing condition is essential for high workability mortars also. The mortar 1:2 with 50% GGBFS and 0.2% SP exhibited strength gain more than 25% over its 28 days strength, when cured for 6 months in water. It is believed that in 10 years the concretes with appropriate replacement level of GGBFS and the mix proportioning may attain strength about 2.5 times as high as 28 days strength (Shi 2004).

Based on the results presented, discussions made during the analysis of results and the conclusions cited above, it was decided to select mortar mix 1:2 with 50% GGBFS as partial replacement and 0.2% superplasticizer as high workability and high performance mortar for the casting of ferrocement encasement to produce 'Ferrocement Encased Aerated Concrete Sandwich Elements' during next phase of the experimental investigations.

CHAPTER 5

EXPERIMENTAL RESULTS AND DISCUSSIONS (PHASE-II)

5.1 General

As described in chapter three, this phase of the experimental study comprised of two parts where the wall elements of relatively large size were manufactured and tested in the step of this study. Likewise phase-I, stepwise approach was adopted during this phase of the study too. Following are the details of the results of the experimental study conducted.

5.2 Results and Discussions of Part I

During this part of the study, an intensive experimental programme with large number of variables and different sizes of specimens was carried out either to determine the non-parametric properties like optimizing various variables such as overall weight of sandwich elements, water absorption, and ISAT, and to optimize the various variables; core-encasement volumetric ratio and type and number of mesh layers of wire mesh to be adopted for further studies carried out in part II. The entire specimens were cast and tested with the standard procedures described in Chapter Three. Following are the results and discussions.

5.2.1 Compressive Strength

Table 5.1: Details of specimens tested for compressive strength

Specimens type and batch designation			Description
Cubes A (CA) 70.6*	Cubes B (CB) 100*	Blocks (B) 400x200x100*	
CAC	CBC	BC	Control specimens made of aerated concrete
SWCA0	SWCB0	SWB0	Sandwich specimens without mesh
SWCACM1	SWCBCM1	SWBCM1	Sandwich specimens with one layer of chicken mesh
SWCACM2	SWCBCM2	SWBCM2	Sandwich specimens with two layers of chicken mesh
SWCACM3	SWCBCM3	SWBCM3	Sandwich specimens with three layers of chicken mesh
SWCACM4	SWCBCM4	SWBCM4	Sandwich specimens with four layers of chicken mesh
SWCASM1	SWCBSM1	SWBSM1	Sandwich specimens with one layer of square mesh
SWCASM2	SWCBSM2	SWBSM2	Sandwich specimens with two layers of square mesh
SWCASM3	SWCBSM3	SWBSM3	Sandwich specimens with three layers of square mesh
* All the dimensions are in mm.			

Table 5.2: Compressive strength (cubes A)

Batch	Compressive strength (MPa)	Increase w.r.t CAC (%)	Increase w.r.t SWCA0 (%)	Increase w.r.t. no. of layers (%)
CAC	6.5	-	-	
SWCA0	20.3	212.3	-	
SWCACM1	22.3	243.1	9.9	9.9
SWCACM2	23.6	263.1	16.3	5.8
SWCACM3	24.3	273.8	19.7	3.0
SWCACM4	25.1	286.2	23.6	3.3
SWCASM1	25.4	290.8	25.1	25.1
SWCASM2	27.0	315.4	33.0	6.3
SWCASM3	27.9	329.2	37.4	3.3

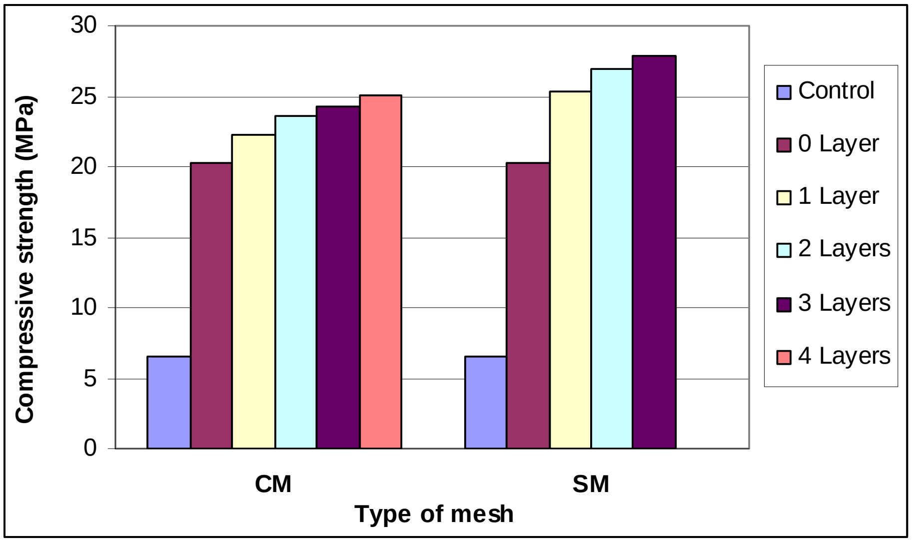


Figure 5.1: Compressive strength of cubes A

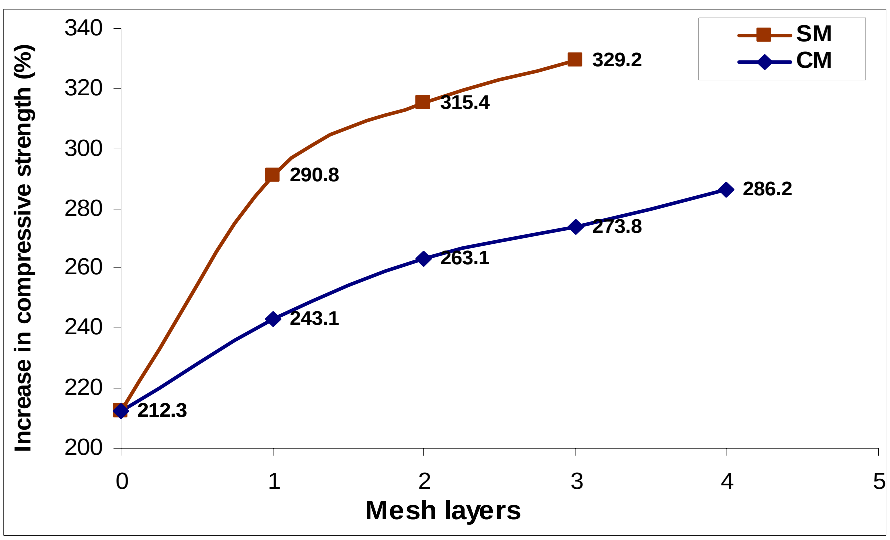


Figure 5.2: Comparison of compressive strength increase between CM and SM for cubes A

5.2.1.2 Compressive Strength of Cubes B

Table 5.3: Compressive strength (cubes B)

Batch	Compressive strength (MPa)	Increase w.r.t CBC (%)	Increase w.r.t SWCB0 (%)	Increase w.r.t no. of layaers (%)
CBC	7.4	-	-	
SWCB0	15.3	106.8	-	-
SWCBCM1	15.9	114.9	3.9	3.9
SWCBCM2	16.9	128.4	10.5	6.3
SWCBCM3	17.8	140.5	16.3	5.3
SWCBCM4	18.1	144.6	18.3	1.7
SWCBSM1	20.3	174.3	32.7	32.7
SWCBSM2	21.7	193.2	41.8	6.9
SWCBSM3	22.4	202.7	46.4	3.2

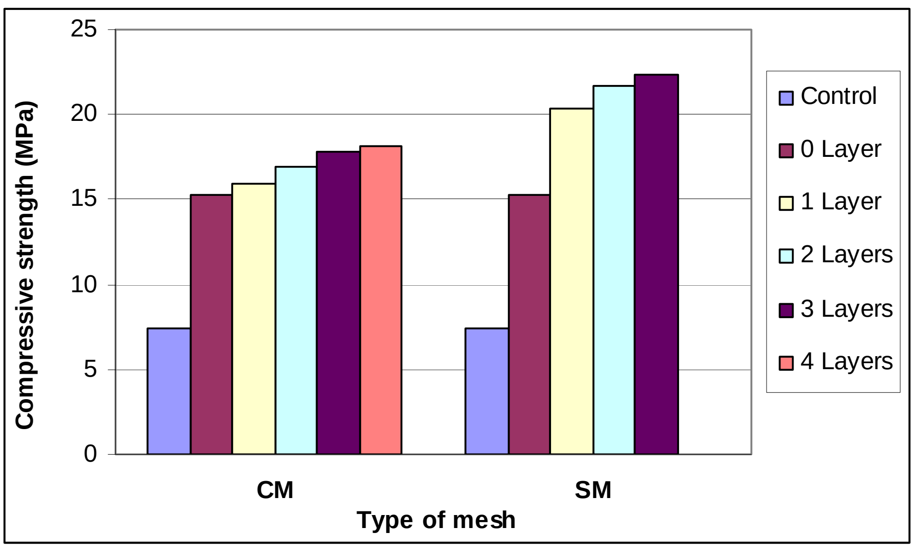


Figure 5.3: Compressive strength of cubes B

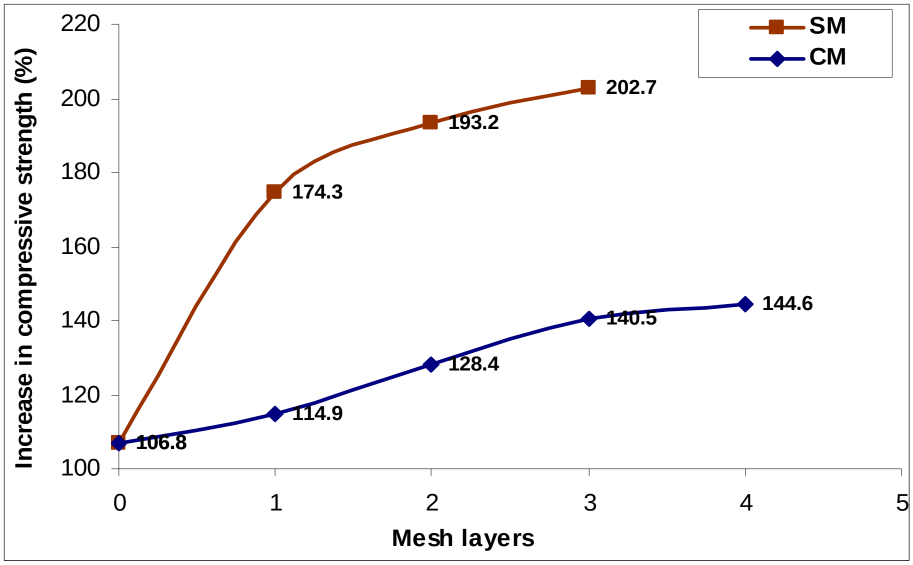


Figure 5.4: Comparison of compressive strength increase between CM and SM for cubes B

5.2.1.3 Compressive Strength of Blocks

Table 5.4: Compressive strength (blocks)

Batch	Compressive strength (MPa)	Increase w.r.t BC (%)	Increase w.r.t SWB0 (%)	Increase w.r.t. no. of layers (%)
BC	7.7	-	-	
SWB0	10.8	40.3	-	
SWBCM1	12.2	58.4	13.0	13.0
SWBCM2	13.0	68.8	20.4	6.6
SWBCM3	13.7	77.9	26.9	5.4
SWBCM4	12.9	67.5	19.4	-5.8
SWBSM1	15.5	101.3	43.5	43.5
SWBSM2	16.4	113.0	51.9	5.8
SWBSM3	16.9	119.5	56.5	3.0

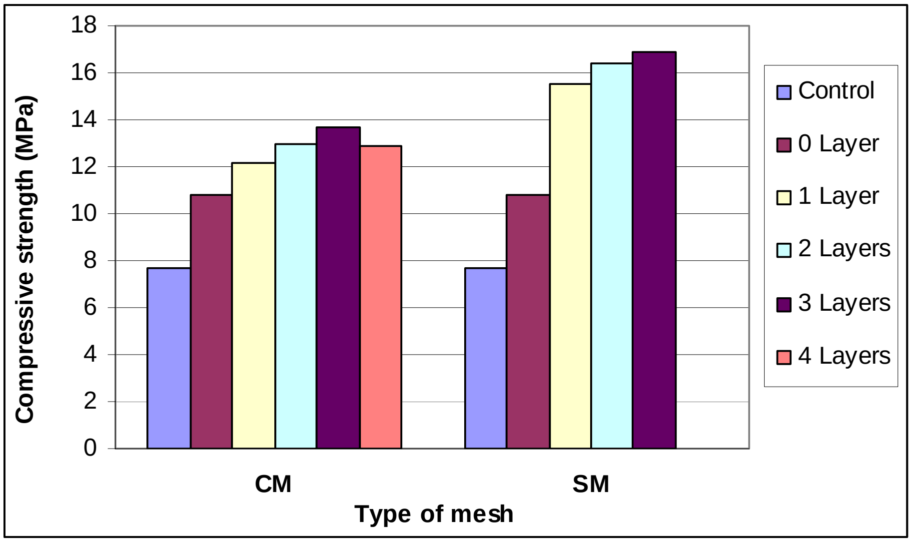


Figure 5.5: Compressive strength of blocks

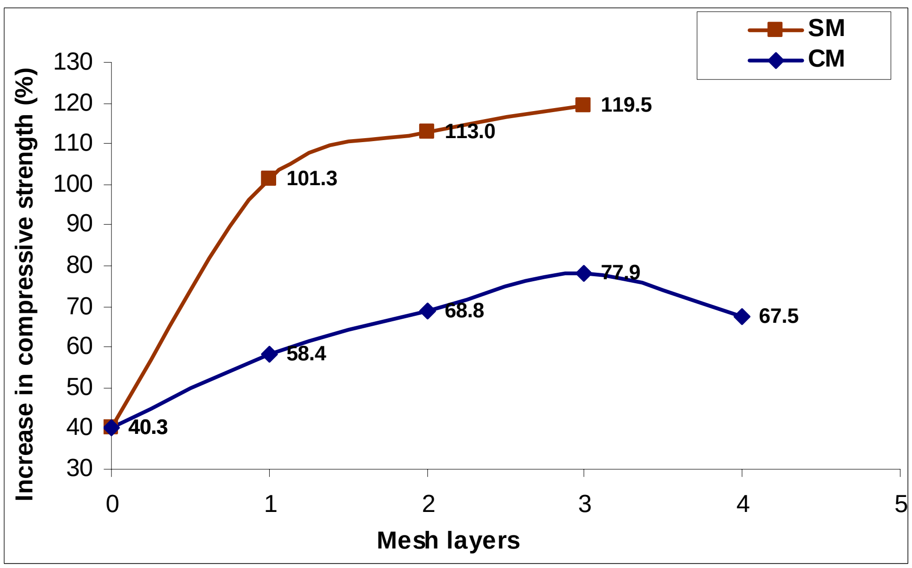


Figure 5.6: Comparison of compressive strength increase between CM and SM for blocks

5.2.2 Encasement Effectiveness towards Compressive Strength Based on Its Direction to the Loading Direction

Table 5.5: Compressive strength of specimens tested by holding encasement perpendicular to loading direction

Number of mesh layers (square mesh)	**0**	**1**	**2**	**3**
Cubes B (100mm)				
Compressive strength encasement hold perpendicular to loading direction (MPa)	14.8	13.3	12.4	11.1
Compressive strength encasement hold parallel to loading direction (MPa)	15.3	20.3	21.7	22.4
Decrease in compressive strength (%age of encasement hold in loading direction)	3	53	75	102
Blocks				
Compressive strength encasement hold perpendicular to loading direction (MPa)	10.5	9.7	9.3	8.7
Compressive strength encasement hold parallel to loading direction (MPa)	10.8	15.5	16.4	16.9
Decrease in compressive strength (%age of encasement hold in loading direction)	3	60	76	94

5.2.3 Compressive Strength Based on Core-Encasement (c-e) Volumetric Ratio

Table 5.6: Core-encasement (c-e) volumetric ratio of cubes and blocks

Description	**Cubes A (CA)**	**Cubes B (CB)**	**Blocks (B)**
Specimen dimensions*	70.6 x 70.6 x 70.6	100 x 100 x 100	400 x 200 x 100
Core dimensions*	70.6 x 46.6 x 46.6	100 x 76 x 76	376 x 200 x 76
Total volume** (V)	351896	1000000	8000000
Core volume** (V_c)	153312	577600	5715200
Encasement Volume** (V_e)	198584	422400	2284800
Core-to-encasement ratio (c-e)	0.77	1.37	2.50
Core as %age of total volume	44	58	71
Encasement as %age of total volume	56	42	29

* All dimensions sizes are in mm **volume is in mm^3

Table 5.7: Comparison between compressive strength enhancement and c-e volumetric ratio

Description	**Cubes A (CA)**	**Cubes B (CB)**	**Blocks (B)**
Core-to-encasement (c-e) ratio	0.77	1.37	2.50
Core volume (V_c)as %age of total volume	44	58	71
Encasement volume (V_e) as %age of total volume	56	42	29
Compressive strength of control (MPa)	6.5	7.4	7.7
Average increase in compressive strength due to encasement with CM including 0 layers (%)	258	127	63
Average increase in compressive strength due to encasement with SM including 0 layers (%)	287	169	94

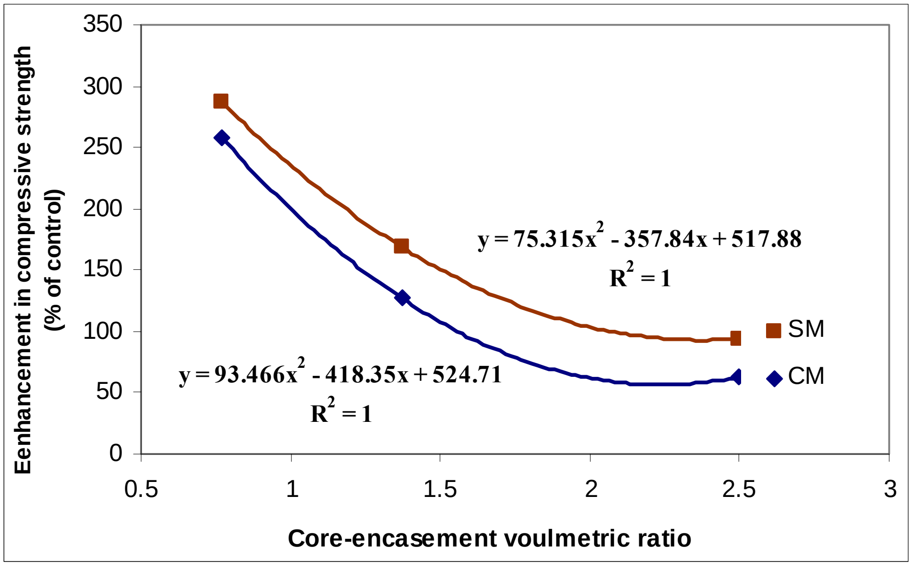


Figure 5.7: Compressive strength variation versus c-e volumetric ratio.

An identical trend for both the types of meshes incorporated in FC encasement is evident from the figure. The reduction in strength enhancement is not linearly proportional to the increase in c-e ratio, however; the relationship between the two is governed by quadratic equation with R^2 equals to 1 (Figure 5.7). Nevertheless, it is worth noting that, within the scope of this study, the variation between compressive strength with the change in c-e value may be predicted by following equation to the maximum possible degree of accuracy i.e.1 (100%).

$$\Delta f_{c(SM)} = 75.315\left(\frac{V_c}{V_e}\right)^2 - 357.84\left(\frac{V_c}{V_e}\right) + 517.88 \qquad 5.1$$

$$\Delta f_{c(CM)} = 93.466\left(\frac{V_c}{V_e}\right)^2 - 418.35\left(\frac{V_c}{V_e}\right) + 524.71 \qquad 5.2$$

Where $\Delta f_{c(CM)}$ and $\Delta f_{c(SM)}$ are the average increase in compressive strength due to FC encasement containing square and chicken mesh within encasement and $\left(\frac{V_c}{V_e}\right)$ is the c-e volumetric ratio.

5.2.4 Unit Weight (Density)

Table 5.8: Unit weight

Description		c-e volumetric ratio	Average density (kg/m^3)		Increase in density (%age of control)		Average increase (%age of control)	
			CM	SM				
Cubes A (CA)	Control	--	1199	1199	**CM**	**SM**	**CM**	**SM**
	SW0	0.77 (V$_c$**=44% of total volume)	1823	1823	52	52	53	54
	SW1		1831	1836	53	53		
	SW2		1839	1849	53	54		
	SW3		1845	1857	54	55		
	SW4		1848	-	54	-	**Av. ≈ 54**	
Cubes B (CB)	Control	--	1208	1208	**CM**	**SM**	**CM**	**SM**
	SW0	1.37 (V$_c$ = 58% of total volume)	1722	1722	43	43	44	45
	SW1		1734	1742	44	44		
	SW2		1744	1753	44	45		
	SW3		1750	1766	45	46		
	SW4		1754	-	45	-	**Av. ≈ 45**	
Blocks (B)	Control	--	1205	1205	**CM**	**SM**	**CM**	**SM**
	SW0	2.5 (V$_c$ = 71% of total volume)	1562	1562	30	30	32	33
	SW1		1588	1603	32	33		
	SW2		1597	1623	33	35		
	SW3		1613	1642	34	36		
	SW4		1623	-	35	-	**Av. ≈ 33**	

*SW = Sandwich, 0,1,2,3,4 = number of mesh layers and ** V$_c$ = core volume

5.2.5 Unit Weight Increase versus Compressive Strength Enhancement

Table 5.9: Comparisons between the variations in compressive strength, unit weight and c-e volumetric ratio.

Description of sandwich specimens	c-e volumetric ratio	Average increase in compressive strength (%age of control)		Average increase In density (%age of control)
		CM	SM	
Cubes A (CA)	0.77 (V$_c$* = 44% of total volume)	258	287	54
Cubes B (CB)	1.37 (V$_c$ = 58% of total volume)	127	169	45
Blocks (B)	2.5 (V$_c$ = 71% of total volume)	63	94	33

*V$_c$ = core volume

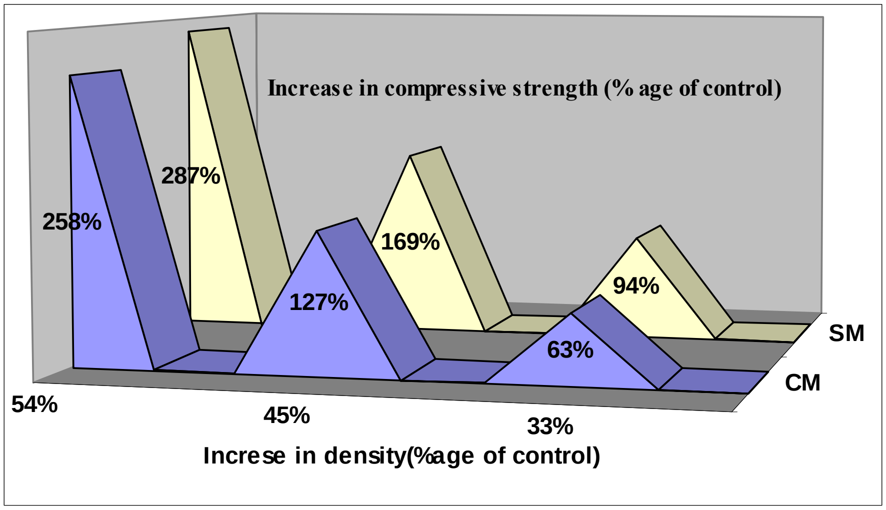


Figure 5.8: Comparisons between the variations in unit weight, and compressive strength.

5.2.6 Classification of Sandwich Based on Average Unit Weight

Table 5.10: Classification of sandwich specimens based on unit weight.

Description of sandwich specimens	**c-e volumetric ratio**	**Average unit weight of sandwich (Kg/m^3)**	**Classification of sandwich (ASTM C90-06b)**
Cubes A (CA)	0.77 (V_c* = 44% of total volume)	1839	***Medium weight*** (1682-2002 kg/m^3)
Cubes B (CB)	1.37 (V_c = 58% of total volume)	1743	***Medium weight*** (1682-2002 kg/m^3)
Blocks (B)	2.5 (V_c = 71% of total volume)	1601	***Lightweight*** (<1682 kg/m^3)

5.2.7 Flexural Strength

5.2.7.1 Modulus of Rupture (Flexural Strength of Sandwich Prism Beams)

Table 5.11: Details of results of prism beams tested in flexure (bending)

Batch	Average ultimate load (KN)	Average MOR* (MPa)	Increase in MOR (%age of PBC)	Increase in MOR (%age of SWPB0)	Increase in MOR w.r.t no. of layers (%)
PBC	3.7	1.5	--	-	-
SWPB0	6.1	2.5	68	..	-
SWPBCM1	7.3	2.9	100	19	19
SWPBCM2	8.8	3.5	142	44	21
SWPBCM3	9.9	4.0	172	36	12
SWPBCM4	11.8	4.7	222	92	18
SWPBSM1	8.2	3.3	125	34	34
SWPBSM2	14.1	5.6	287	130	71
SWPBSM3	18.0	7.2	393	194	28

*MOR = Modulus of rupture

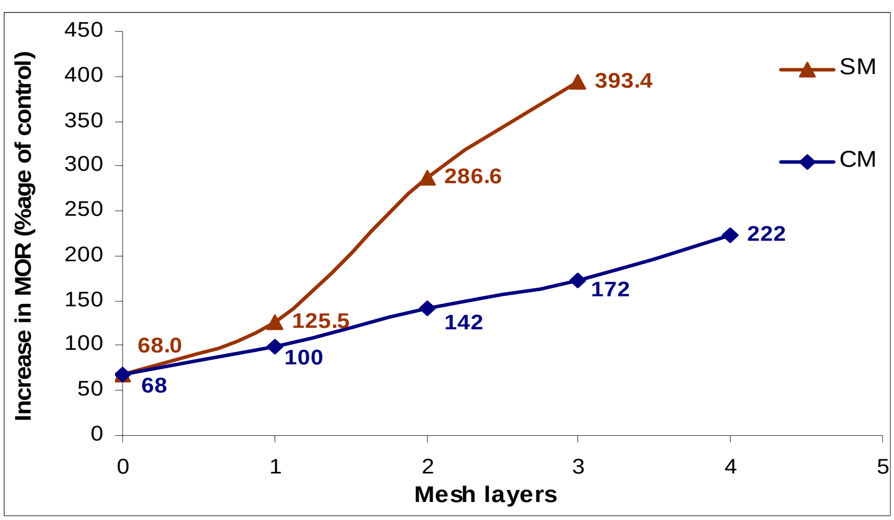


Figure 5.9: Comparison of increase in MOR with CM and SM

5.2.8 Failure Mode of Cubes, Blocks and Prism Beams Specimens

During the compressive strength and flexural strength tests in progress, the development of first crack and the other cracking pattern along with the failure mode of specimens at ultimate load, were closely monitored. The details of the failure mode are as under;

5.2.8.1 Failure Mode under Compression

Figure 5.10: Failure mode of control specimen in compression

Figure 5.11: Failure mode of sandwich specimens without mesh in compression

Figure 5.12: Failure mode of sandwich specimens with wire mesh in compression

5.2.8.2 Failure Mode under Flexure

Figure 5.13: Failure mode of control prism beam in flexure

Figure 5.14: Failure mode of **s**andwich prism beam without wire mesh in flexure

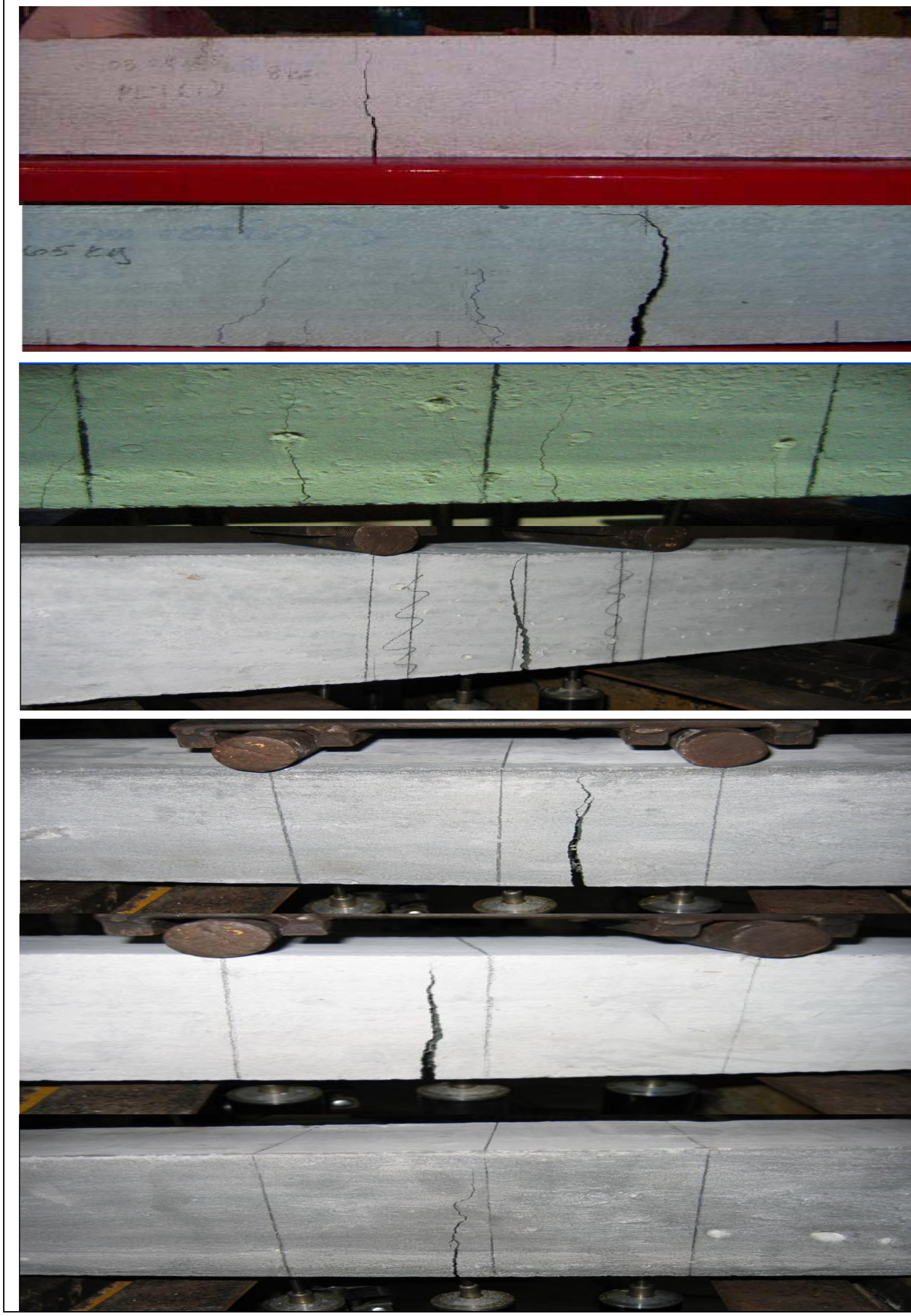


Figure 5.15: Failure mode of sandwich prism beams with wire mesh in flexure.

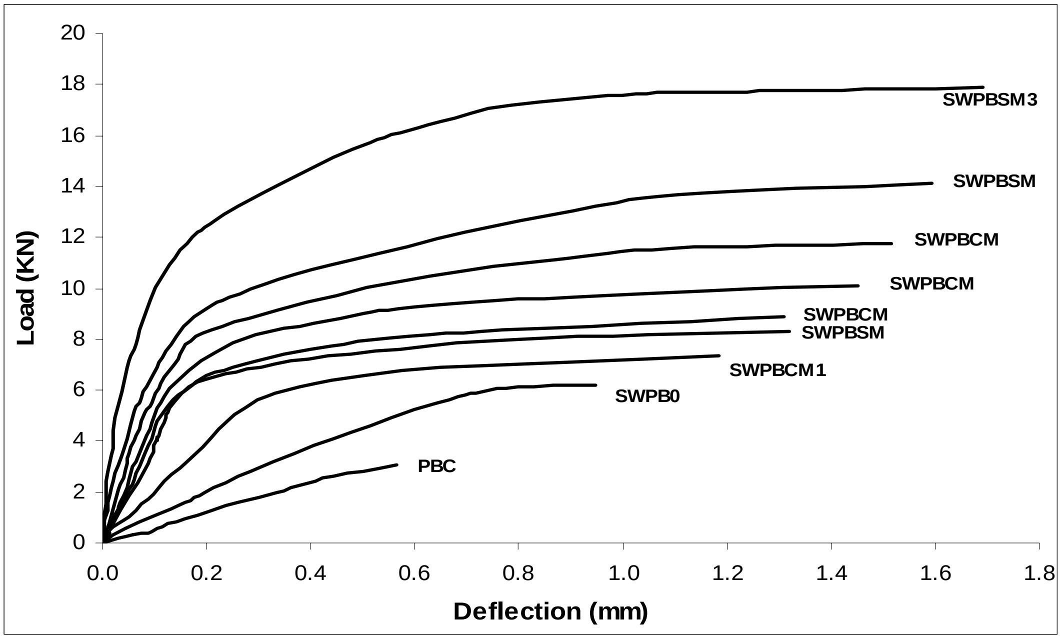


Figure 5.16: Load deflection curves of prism beams in flexure

Figure 5.17: Composite failure at interface of core and FC encasement of prism beam tested in flexure

5.2.9 Water Absorption of Sandwich

Table 5.12: Water absorption

Batch	Average W_a^* (%)	$\frac{W_{aSW}^{**}}{W_{aC}^{***}}$	$\frac{W_{aSWM}^{****}}{W_{aSW0}^{*****}}$
Control	16.72	--	-
SW0	4.15	0.25	-
SWCM1	3.94	0.24	0.95
SWCM2	3.74	0.22	0.90
SWCM3	3.86	0.23	0.93
SWCM4	3.91	0.23	0.94
SWSM1	3.79	0.23	0.91
SWSM2	3.31	0.20	0.80
SWSM3	3.6	0.22	0.87
Average		**0.23**	**0.90**

$*W_a$ = Water absorption, ** SW = sandwich, ***C= Control
****SWM sandwich with mesh *****SW0 = sandwich without mesh

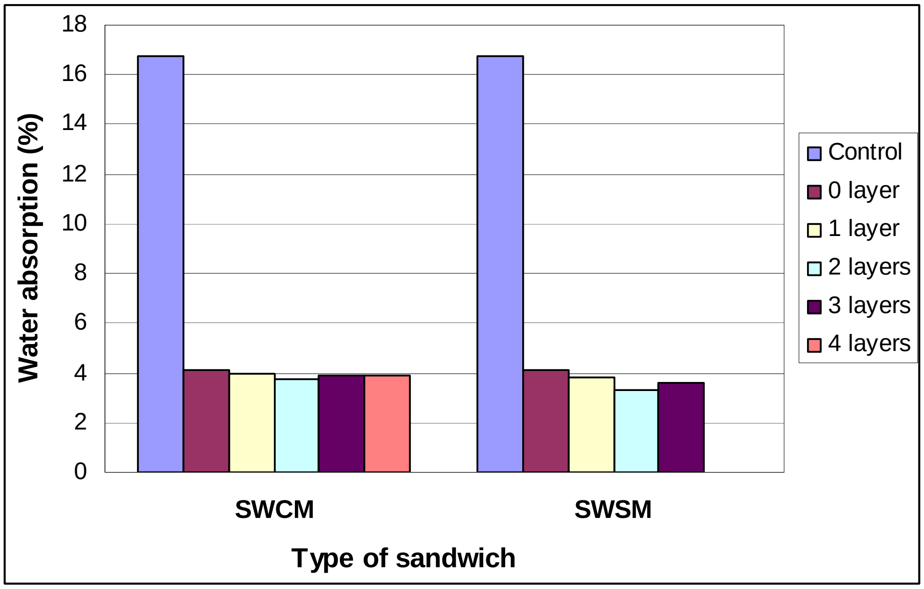


Figure 5.18: Water absorption

5.2.10 Initial Surface Absorption Test, ISAT (Permeability Test) of Sandwich

Table 5.13: ISAT (Permeability)

Batch designation	ISAT (ml/m^2/s)			
	10 minutes	30 Minutes	I hour	2 hours
Control	The actual ISAT values at any time interval could not be recorded because of excessive flow of water beyond the limits of maximum value and instrument			
SW0	0.1181	0.0660	0.0290	0.0033
SWCM1	0.1164	0.0650	0.0286	0.0032
SWCM2	0.1152	0.0569	0.0253	0.0042
SWCM3	0.1229	0.0687	0.0302	0.0034
SWCM4	0.1418	0.0792	0.0349	0.0040
SWSM1	0.1140	0.0637	0.0280	0.0032
SWSM2	0.1118	0.0564	0.0250	0.0041
SWSM3	0.1170	0.0654	0.0288	0.0033

5.3 Results and Discussions of Part II

This was the last part of the experimental study chalked out in order to investigate the characteristics of ferrocement encased aerated concrete sandwich wall elements, the details of which were presented in methodology explained in Chapter Three. As mentioned before, the study was aimed to investigate lightweight sandwich panels, thus, on the basis of the comparison made before, between c-e volumetric ratio and average unit weight of sandwich elements, the c-e value was fixed at about 2.5 (core volume about 70% or more of the total volume). Since the wall elements are primarily subjected to axial loading, therefore, the effect of slenderness ratio and aspect ratio of the wall elements under compression were also considered as variables during this part of study.

It is important to mention that during this phase of study an additional reinforcement (steel bars of 5mm diameter and yield strength 455MPa, and steel strips 0.4mm thick and 20mm wide and yield strength 650MPa) was incorporated along with the square mesh layer in FC box of respective sandwich wall elements. This was adopted in order to investigate their effect of on the compressive strength of sandwich wall elements. Figures 5.20 and 5.21 present the sectional and pictorial views of the sandwich specimens with steel bars and strips incorporated in FC box respectively.

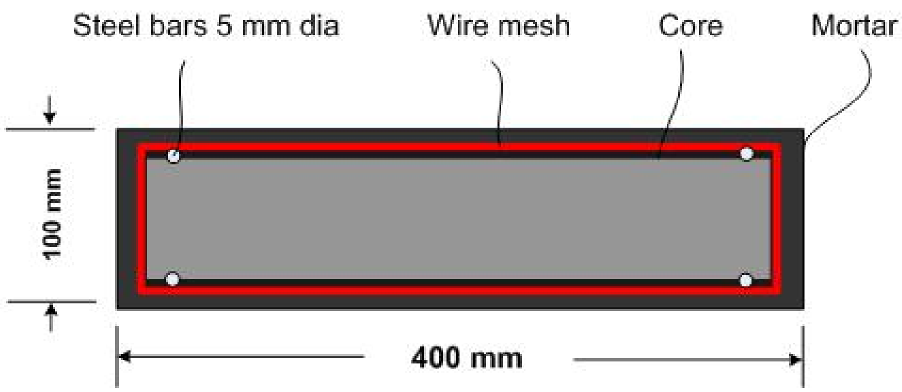


Figure 5.20: Wall cross-section showing steel bar reinforcement

Figure 5.21: Wall elements with steel strips

Table 5.14 describes the details of the sandwich wall elements and their variables investigated under compressions. The specimens are arranged in three series; A, B and C according to the variation in their various properties. Addition tests; flexural and uniformity (UPV), were also conducted on large size wall panel elements designated as series A in Table 5.14. The details of test results are discussed later on, in their respective sections.

Table 5.14: Details of wall elements

Group	Sandwich wall elements	Reinforcement details of encasement	Dimensions (mm) (H x L x t)	c-e volumetric ratio	$\frac{H}{t}$	$\frac{H}{L}$
A	**control**	AC without encasement	1400x400x100	2.5 (C_V = 71% of total volume	14	3.5
	SWA-1	Without mesh				
	SWA-2	1 layer SM				
	SWA-3	1 Layer SM, Horizontal. strips				
	SWA-4	1 layer SM, 4 vertical steel bars				
B	**SWB-1**	Without mesh	700x300x100	2.3 (C_V = 70% of total volume	7	2.3
	SWB-2	1 layer SM				
	SWB-3	1 Layer SM, Horizontal. strips				
	SWB-4	1 layer SM, 4 vertical steel bars				
C	**SWC-1**	Without mesh	700x400x100	2.5 (C_V = 71% of total volume	7	1.8
	SWC-2	1 layer SM				
	SWC-3	1 Layer SM Horizontal. strips				
	SWC-4	1 layer SM, 4 vertical steel bars				

5.3.1 Compression (Wall Elements)

5.3.1.1 Ultimate Load

Table 5.15: Ultimate load of wall elements in compression

Group	**Sandwich wall elements**	**First crack load** $P_{ucr.}$ (KN)	**Experimental ultimate load** $P_{u\exp.}$ (KN)	**Ultimate load (KN/m)**
A	**control**	198	198	495
	SWA-1	309	329	823
	SWA-2	335	465	1163
	SWA-3	343	463	1158
	SWA-4	324	498	1245
B	**SWB-1**	265	279	930
	SWB-2	269	384	1280
	SWB-3	277	379	1263
	SWB-4	254	416	1387
C	**SWC-1**	327	352	880
	SWC-2	324	483	1208
	SWC-3	344	484	1210
	SWC-4	323	513	1283

5.3.1.2 Load- Lateral Deformation Behaviour

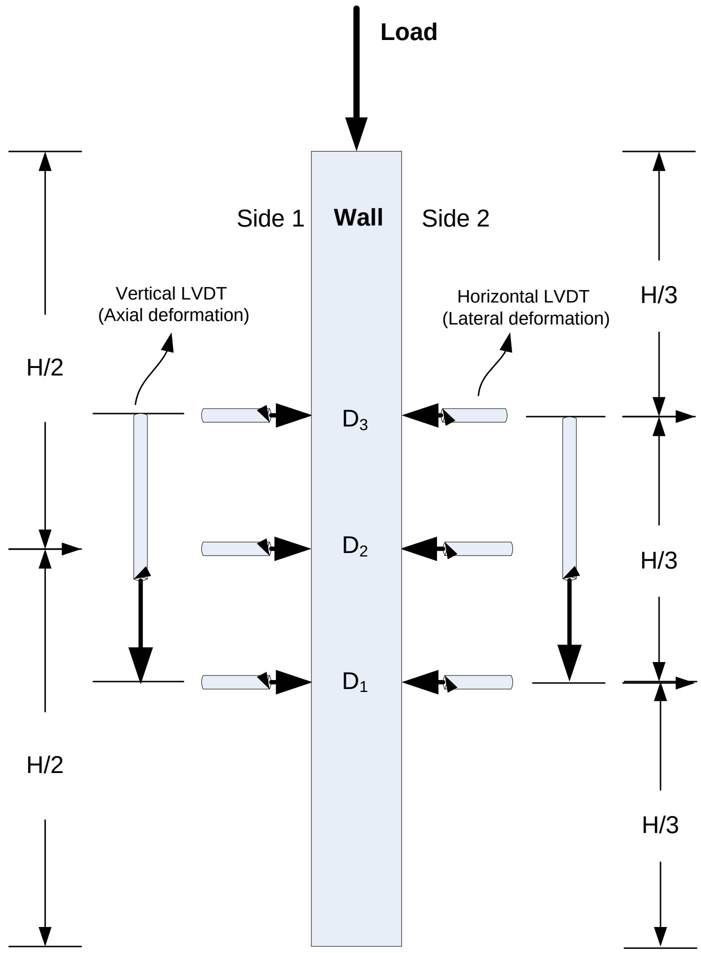


Figure 5.22: Schematic diagram of instrumentation on wall under compression

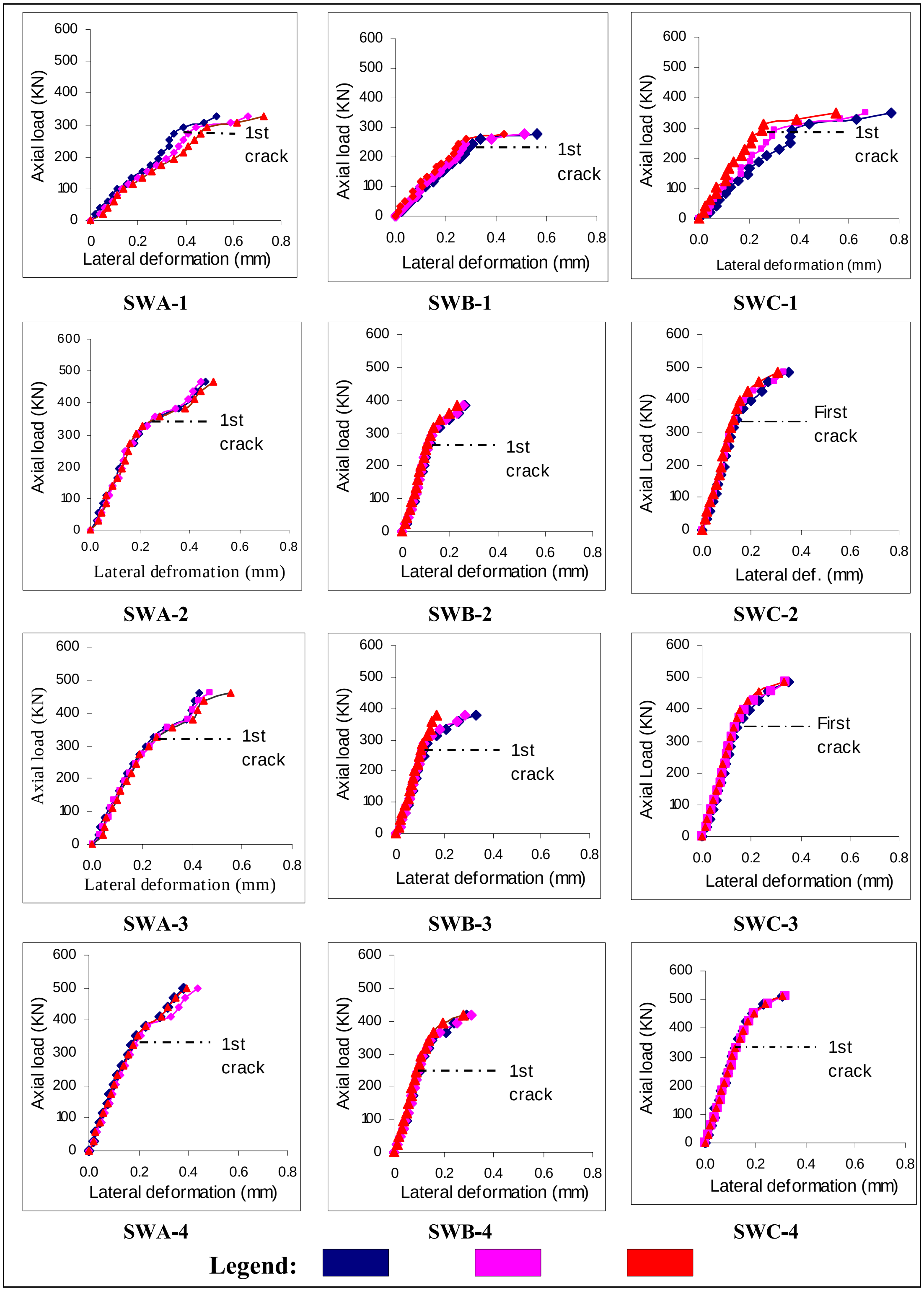


Figure 5.23: Axial load-lateral deformation curves of wall elements

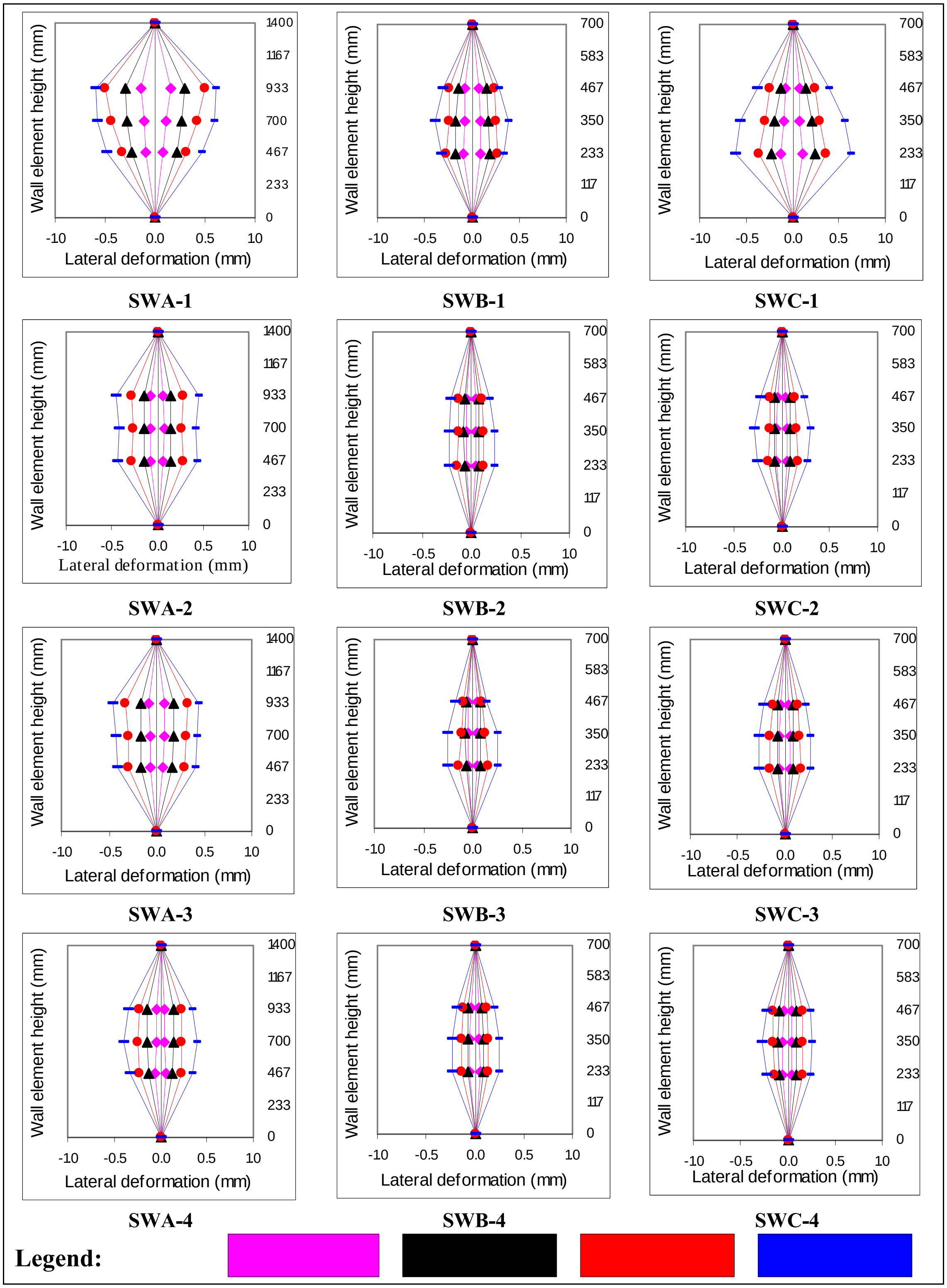


Figure 5.24: Comparison between lateral deformations along the two sides of sandwich wall elements under compression.

5.3.1.3 Load-Axial Deformation Behaviour

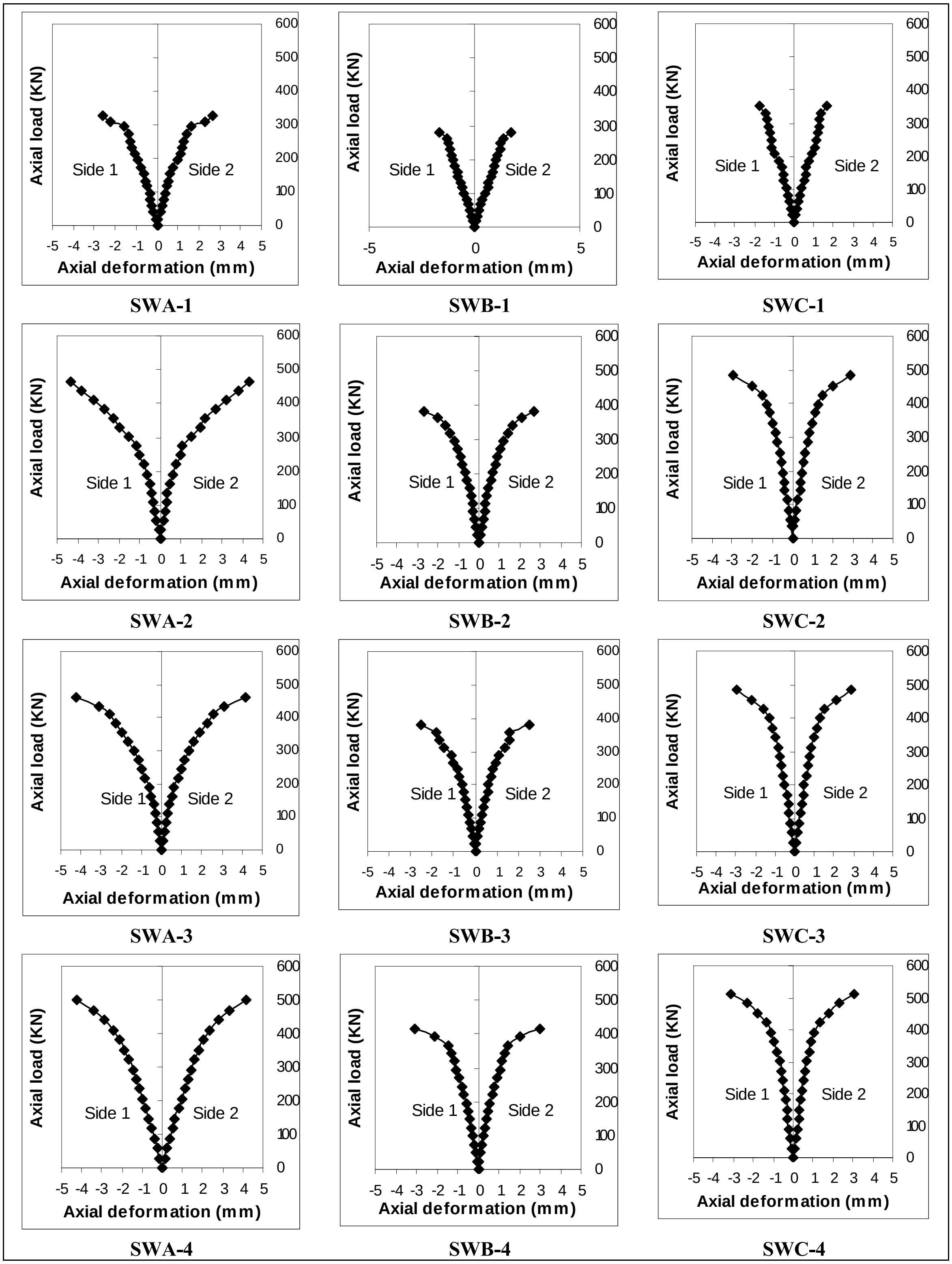


Figure 5.25: Axial deformations of sandwich wall elements along the two sides of sandwich wall elements

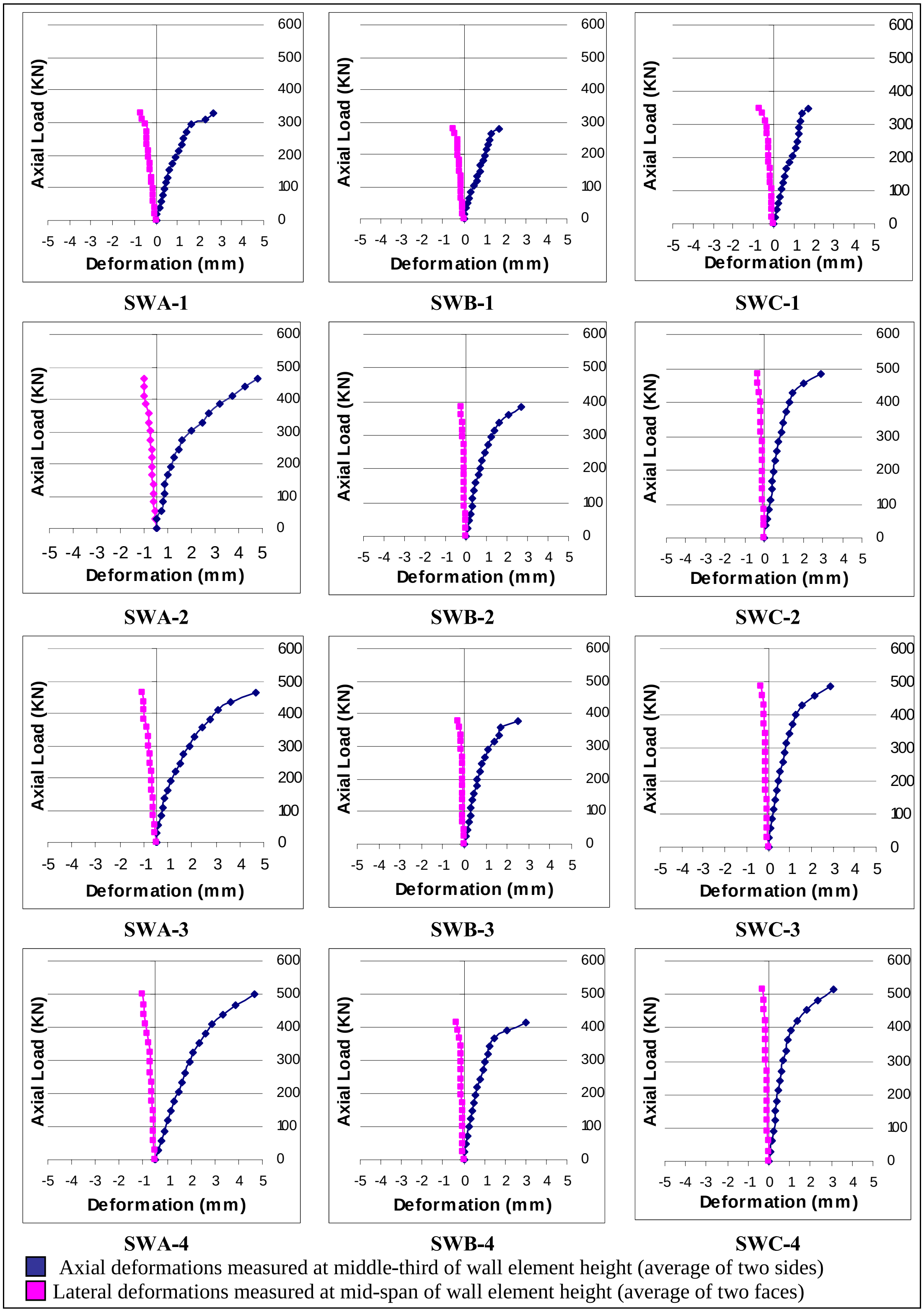


Figure 5.26: Comparison between axial and lateral deformations of sandwich wall elements

5.3.1.4 Failure Mode of Walls in Compression

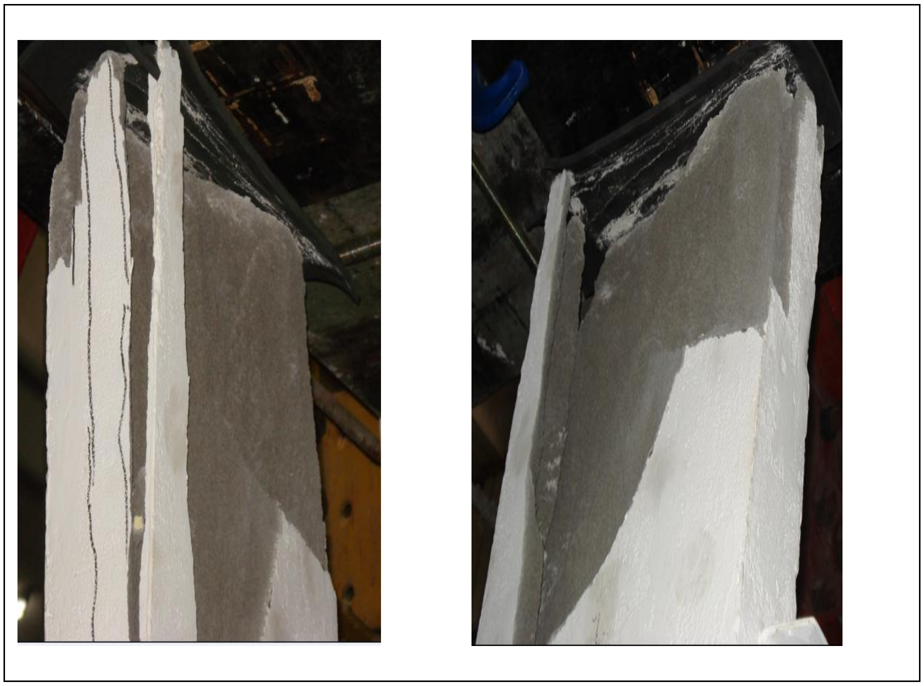


Figure 5.27: Failure mode of control wall elements in compression

Figure 5.28: Failure mode of sandwich wall elements without wire mesh in compression

Figure 5.29: Failure mode of sandwich wall elements with reinforcement (wire mesh and others) in compression

5.3.2 Flexure (Bending) of Wall Elements

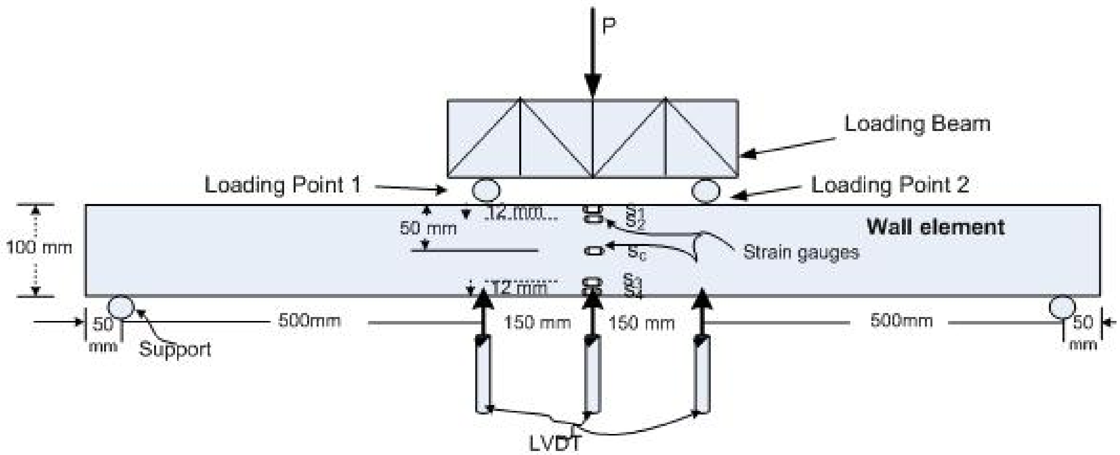


Figure 5.30: Schematic diagram of instrumentation and testing of wall elements

As described before, the main objective of this study was to investigate the sandwich wall elements and in fact, the wall panels are subjected to the compression loading. This is why; a detailed study was carried in order to investigate the panels under compression. Nevertheless, it was deemed appropriate to carry additional flexural tests on only largest size sandwich elements, in order to study the behaviour of sandwich wall elements under flexure because a detailed investigation on the prism beams under flexure considering a large number of variables is already reported in the previous sections. Hence, only series A of the sandwich specimens described in Table 5.14 was considered during this set of test series. The details of the results are as follows.

5.3.2.1 Ultimate Load

Table 5.16: Ultimate load of sandwich wall elements in flexure

Wall element	Ultimate Load (KN)	First crack load (KN)
Control	1.6	1.6
SWA-1	4.9	4.6
SWA-2	7.4	6.1
SWA-3	7.2	5.7
SWA-4	11.9	7.2

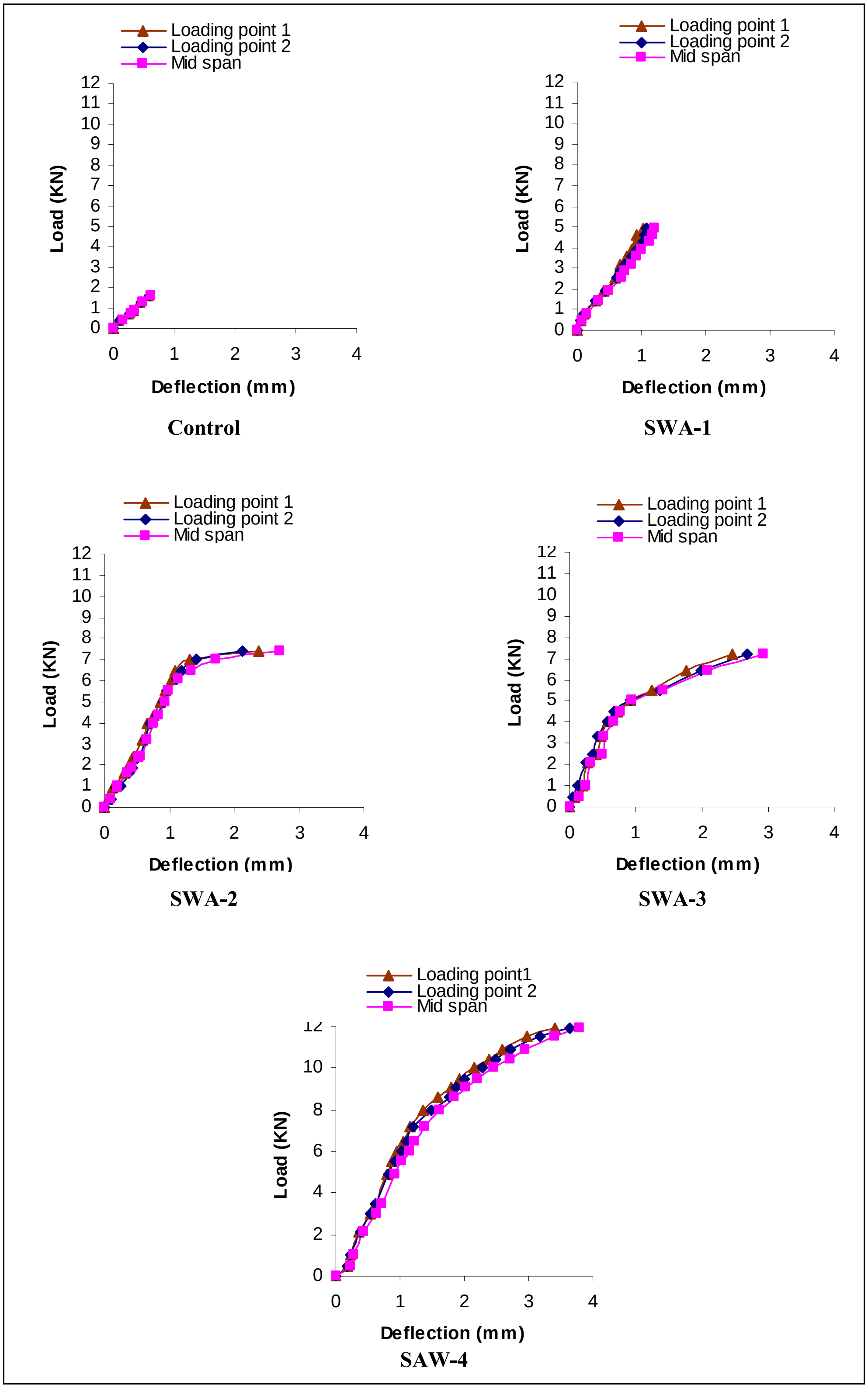


Figure 5.31: Load-deflection variations of sandwich wall elements in flexure

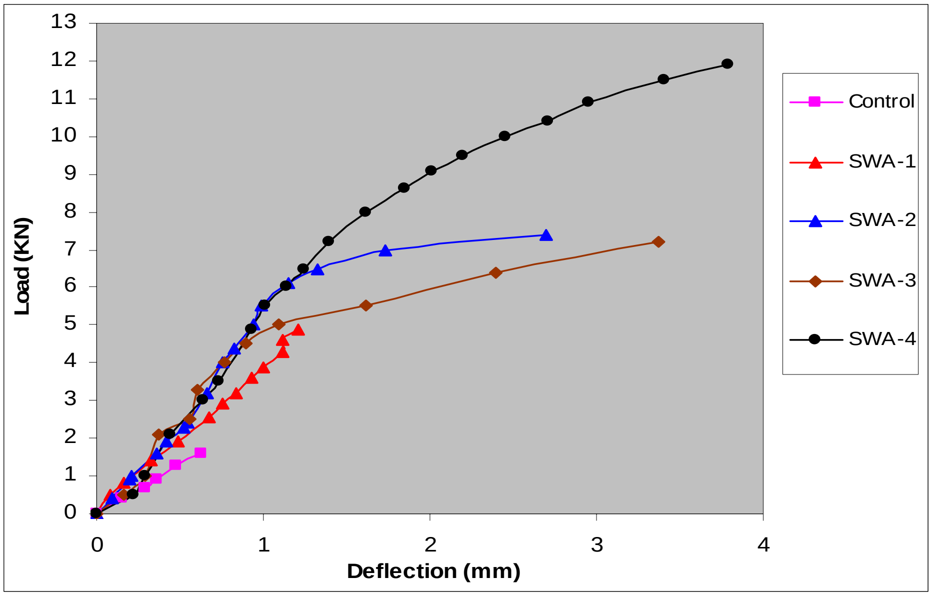


Figure 5.32: Mid-span deflections of wall elements in flexure

5.3.2.2 Load-Strain Behaviour.

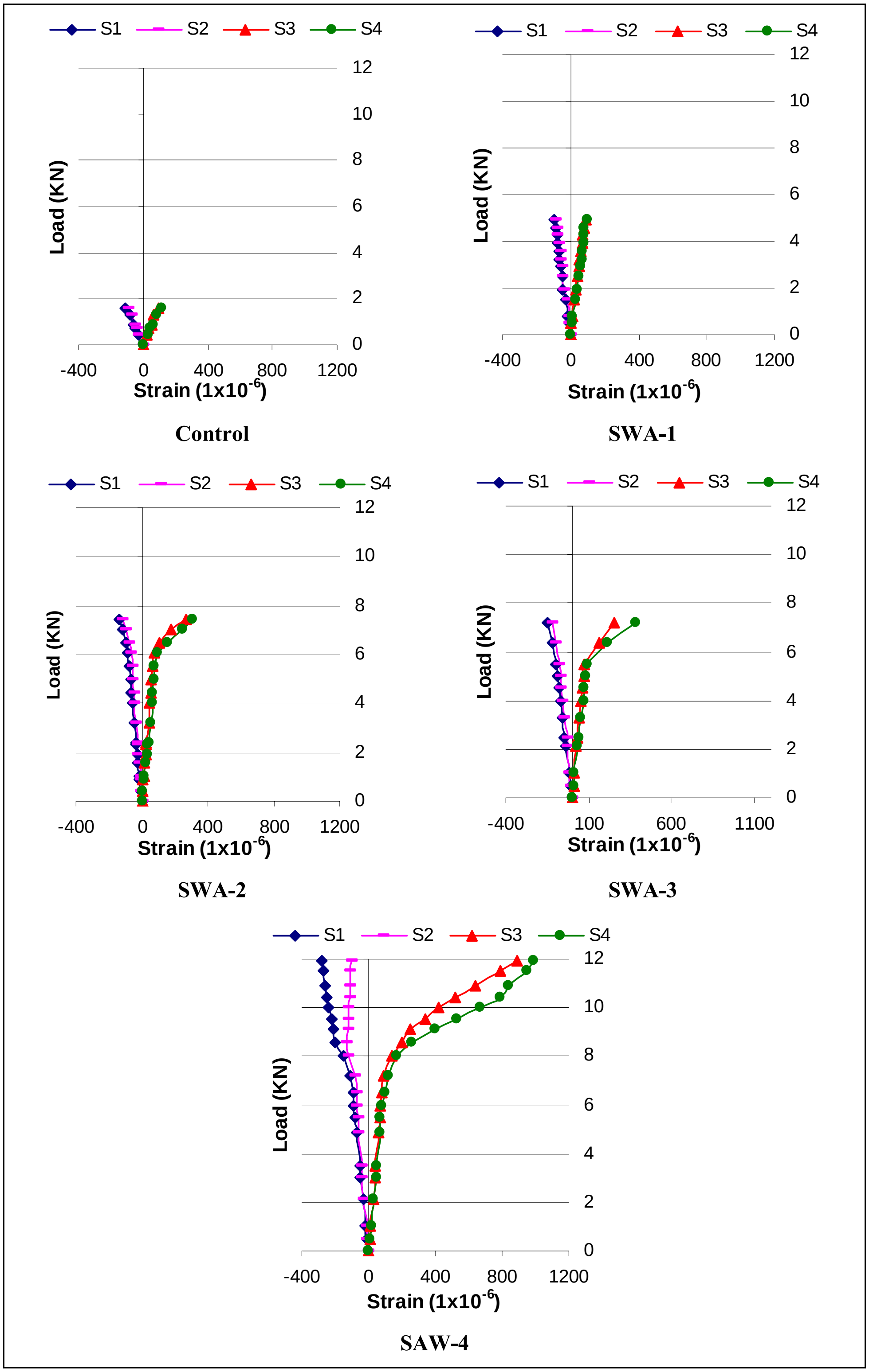


Figure 5.33: Load-strain curves of sandwich wall elements in flexure

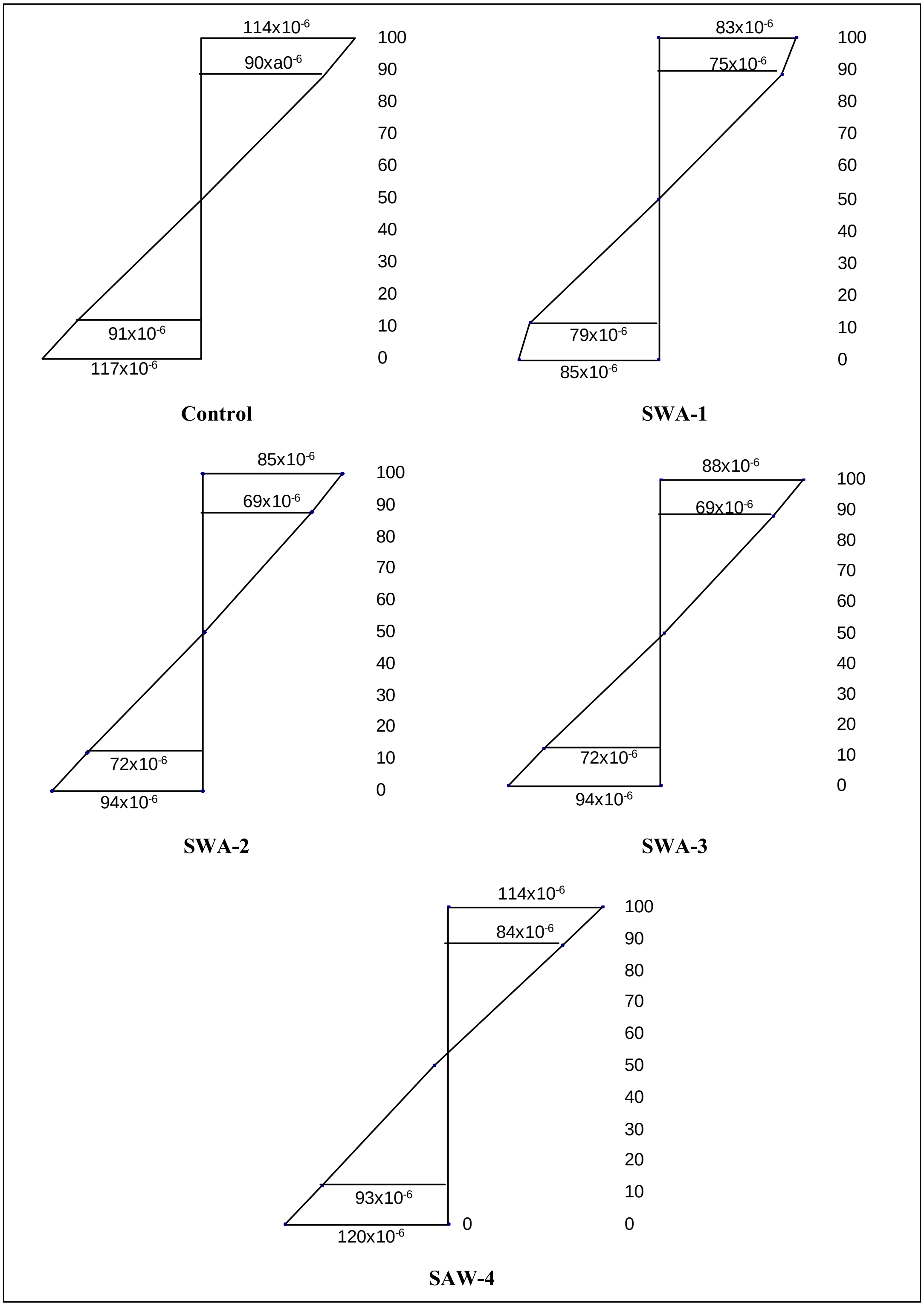


Figure 5.34: Strain distribution along the section of sandwich wall elements in flexure

5.3.2.4 Failure Mode of Wall Elements in Flexure

Figure 5.35: Failure mode of control wall element in flexure

Figure 5.36: Failure mode of sandwich wall element without wire mesh in flexure

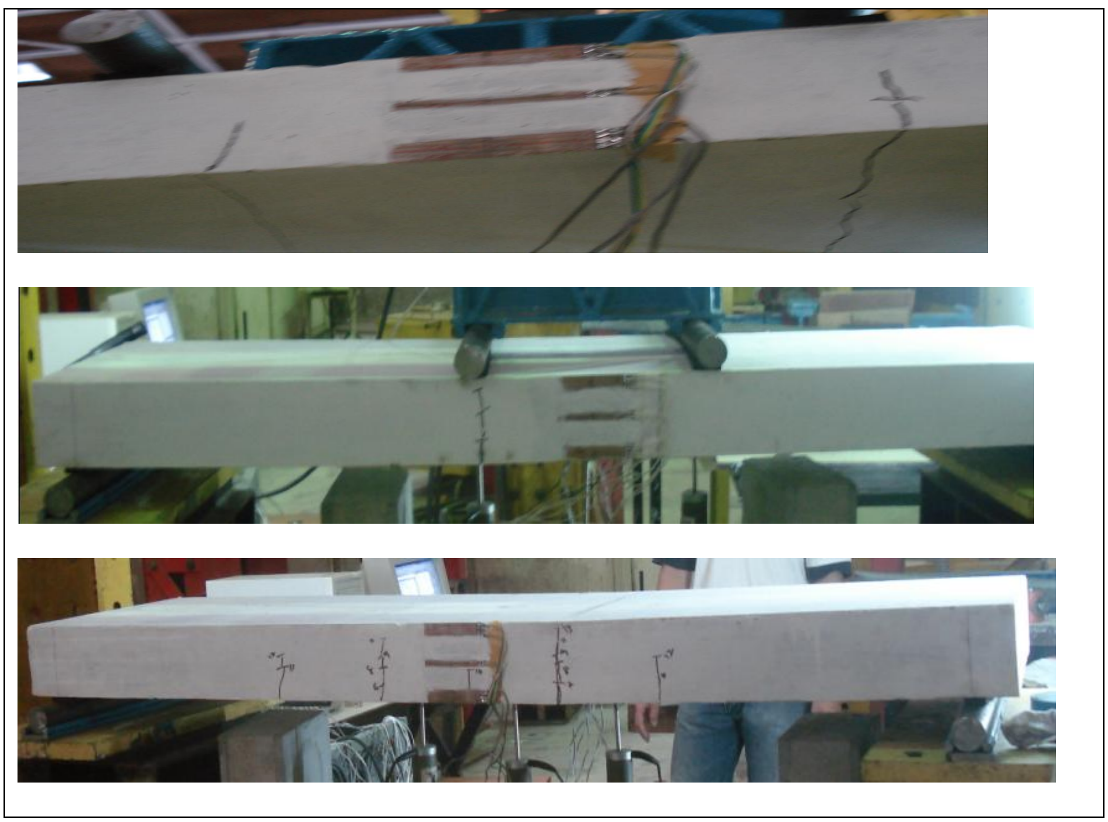


Figure 5.37: Failure mode of sandwich wall element with reinforcement (wire mesh and others) in flexure

5.3.3 Ultrasonic Pulse Velocity (UPV) Tests (Uniformity)

Table 5.17: UPV (uniformity) test results of wall elements.

Wall element	Control	SWA-1	SWA-2	SWA-3	SWA-4
Average distance between transducers (wall thickness) (mm)	100	100	100	100	100
Average time measured (µs)	38.3	32.0	29.5	29.8	29.3
Average pulse velocity (Km/s)	2.61	3.12	3.39	3.36	3.41
Standard deviation (S.D)	0.21	0.17	0.28	0.41	0.37

5.4 Summary

The modern and innovative techniques, approaches and systems are being adopted by the construction industry in order to produce sustainable housing particularly in developing countries like Malaysia and Pakistan. . Precast and prefabrication of the lightweight structural members is much more discussed subject of the day, one of the efficient techniques in this regard is the sandwich construction. A number of the issues associated to sandwich construction have been addressed by various researchers which were discussed earlier in chapter two. However, the development of sandwich elements by encasing the lightweight core with high performance encasing material has not yet been investigated. This is why this study was undertaken to investigate the characteristics of ferrocement encased aerated concrete sandwich wall elements. An extensive experimental programme was chalked out and conducted by addressing a large number of variables. The discussions are already made which can be summarized as under.

- A remarkable enhancement in compressive strength was obtained due to the encasement of lightweight aerated concrete.

- Although, the compressive strength of the sandwich increased with the increased number of mesh layers but the relation between the two was not proportional. It was significant with one and two layers of square and chicken wire meshes respectively and its effect diminished with the further addition wire mesh layers. This led to the conclusion that the in terms of compressive strength, the number of wire mesh layers should be kept at possible minimum number.

- Both the wire meshes; square and chicken wire mesh contributed to the enhancement of strength; however the enhancement due to square wire mesh within the FC encasement was more significant to that exhibited by chicken wire mesh. This observation was in agreement to the previous investigations reported. This inferred that square wire mesh could be suitable choice between square and chicken wire mesh in terms of compressive strength.

- The FC encasement direction to the loading direction was found to be as primary parameter towards the compressive strength enhancement. The enhancement in compressive strength could only be expected when FC encasement is hold parallel to the loading direction, otherwise it causes the deterioration of compressive strength when hold perpendicular to the loading direction.

- Overall unit weight of the sandwich specimens increased due to the encasement. However, it was independent of any significant effect of wire mesh layers incorporated in the FC encasement.

- The unit weight was emerged to be a function of core-encasement volumetric ratio. In other words, the core volume governs the over all unit weight of the sandwich elements, particularly when those are produced by encasing lightweight core material where the difference of unit weight between core and an encasement material is more pronounced.

- The classification of sandwich elements based on their weight entirely depends upon the core-encasement volumetric ratio when lightweight core is encased with high density FC encasement. Higher the c-e ratio; lower the overall unit weight of sandwich. In our case, c-e value 2.5 rendered sandwich element to be classified as lightweight sandwich element.

- Nevertheless, it was worth noting that, due to the encasement, the compressive enhancement was manifold as compared to the increase in unit weight of corresponding specimen, when both, the compressive strength and unit weight increase of same sandwich specimen were compared to the corresponding control specimen. This implied the suitability of ferrocement encasement in terms of compressive strength versus unit weight. Where, the compressive strength enhancement is the major parameter without compromising on unit weight at large.

- All the control and sandwich specimens without wire mesh exhibited sudden and brittle failure under compression. However, the sandwich specimens with wire mesh layers showed significant ductile behaviour where the fine cracks appeared at about 60%-80% of their ultimate load depending on the type and layers of wire mesh. This led to the conclusion that, FC encasement over aerated concrete transforms the otherwise brittle failure mode of aerated concrete in a ductile failure due to the presence of wire mesh within ferrocement box. This property is more significant when the design of structural elements in earthquake prone areas like Pakistan, is in consideration.

- A residual compressive strength of the order of 20%-30% of the corresponding ultimate load was obtained for FC sandwich specimens which imparts the some sort of the warning period prior to the complete failure of the elements.

- Identical behavioural trends to that reported for sandwich specimens in compression were observed when sandwich prism beams were tested in flexure (bending). However, the contribution of number of mesh layers towards MOR (flexural strength) was more significant compared to that in case of compressive strength. Where, MOR increased with the increase in mesh layers. Nevertheless, the effectiveness of mesh layers was dependent on the encasement thickness, because a large number of mesh layers caused the congestion of the reinforcement in thin FC section leaving no room for quality casting leading towards the deterioration in compressive strength. Thus, it was concluded that the number of mesh layers should be optimized depending upon the thickness of FC encasement even in the case of flexural strength where steel reinforcement plays key role in the performance of structural element.

- Water absorption and ISAT values of aerated concrete were drastically reduced due to its FC encasement. In fact, water absorption and ISAT are considered as the measure of porosity and permeability. Hence, FC encasement transformed a very poor aerated concrete into a good material in terms of water absorption, porosity and permeability and has great viability to be employed in aggressive and hostile environments like Malaysia.

- Slenderness ratio and aspect ratio factors were found to influence the ultimate load of sandwich wall elements in compression and these factors should be accounted when the development of a mathematical model to predict the ultimate compressive load, is in consideration.

- During the testing of wall elements in compression, the incorporation of steel bar reinforcement in the direction of loading showed its contribution towards the ultimate load. However, this parameter could further be investigated properly with different variables like diameter of bar and the spacing. Nevertheless, it is important to note that, as the bars were embedded inside the wire mesh without lateral links but no bending of steel bars was observed in any case. This was because of the uniform and closely distributed wires of mesh in transverse direction which acted as the lateral reinforcement around the bar. This deduced the good combination of wire mesh and steel bar reinforcement in sandwich wall elements in compression.

- The axial and lateral deformations of wall elements in compression were almost linear in all the cases. However, their magnitude in case of sandwich specimens without wire mesh was greater than those of the sandwich specimens with wire mesh. For FC sandwich specimens wire mesh arrested the deformation of the wall elements thus exhibiting some sort of toughness.

- The lateral deformations obtained on the two sides of the sandwich wall elements were almost very small and uniform in magnitude which is actually the sign of composite action exhibited by the wall element. This was due to the wrapping of the wire mesh. This concludes that the FC encasement could be suitable option to produce sandwich elements which act as composite element in compression.

- The load-strain relationship of sandwich wall elements tested in bending was linear up to first crack load. Except the sandwich wall element without wire mesh, in all other cases, the strains in tension and compression zone were in good linear trend up o first crack which was broken with further loading beyond the first crack load. This indicated the composite behaviour of the sandwich wall elements with wire mesh in flexure up to the first crack. In fact the composite action is considered as major parameter along with the strength when sandwich elements are in consideration to design as structural elements. This concluded the feasibility of FC encasement of aerated concrete to produce sandwich element where the wire mesh due to the method of wrapping over AC renders the sandwich element to act as fully composite up to the first crack.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 General

This chapter presents the conclusions on the findings including the contribution of the work to the body-of-knowledge and lastly the recommendations for future work. Since, the experimental study of this research was undertaken in two phases and the details of the results and their summary have been presented in Chapter 4 and Chapter 5. Detailed conclusions drawn from the results and discussions of each phase have been presented in the end of respective chapter. At this stage it is appropriate to identify the major findings in relation to the original objectives of this research.

6.2 Conclusions

A brief account of the conclusions drawn, in the context of original objectives, set for this research study, is summarized as follows:

(1) To investigate the minimum flow value (flow table) of cement mortar capable to be poured during the casting of thin ferrocement encasement.

- Mortar with flow value of 136±3% is adequate to cast 6mm-12mm thick ferrocement encasement.
- Flow value should be inversely adjusted by 3% with 2mm variation in the thickness of ferrocement encasement.
- Water-binder ratio required to ensure 36±3% mortar flow is adjustable depending on mix proportion and superplasticizer dosage.

(2) To establish the optimum high workability and high performance mortar with slag and superplasticizer.

- High workability mortar of compressive strength ranging between 27MPa and 57MPa were developed

- Mortar mix 1:2 with 50% GGBFS and 0.1%, and 0.2% SP were found to be high performance in terms of compressive strength, strength development, water absorption and ISAT (permeability).
- Water curing is the suitable curing regime to achieve high performance of high workability mortars.

(3) To study the behaviour of ferrocement encased aerated concrete sandwich specimens.

- Encasement of aerated concrete resulted in pronounced enhancement in compressive strength and flexural strength.
- Square mesh is the better option amongst the square and chicken wire mesh to incorporate in ferrocement encasement where layer of the square mesh is the optimum number of layers for specimen in compression.
- Failure mode transformed from pure brittle and sudden mode to the highly ductile and gradual mode of failure retaining substantial residual strength also due to the ferrocement encasement.
- Core-encasement (c-e) volumetric ratio governs the strength and density of the sandwich.
- Ferrocement encasement produces the lateral confinement to the core of the sandwich leading to the high compressive strength of sandwich.

(4) To investigate the behaviour of ferrocement encased lightweight aerated concrete sandwich wall elements of relatively large size in compression with addition flexural and UPV tests.

- Slenderness ratio and aspect ratio affect the load carrying capacity of the wall elements.
- Lateral and axial deformations of sandwich specimens particularly with wire mesh remained very small and uniform.
- Steel bars contributed to the ultimate load of sandwich in compression when embedded inside the wire mesh within the ferrocement encasement.

- Sandwich walls exhibited highly composite behaviour up to 90% of their ultimate load and fist crack loading subjected to compression and bending respectively.
- High degree of material uniformity attained by the sandwich due to method of pouring adopted to cast ferrocement encasement.
- Replacement of the conventional labour intensive manual method of ferrocement elements manufacture with the new mechanized method of the pouring the high workability mortar altogether with the partial replacement of cement with industrial byproduct GGBFS leads to the cost effectiveness of the final product of sandwich wall elements.

(5) To develop mathematical models

(a) Compressive strength of high workability slag cement based mortar for ferrocement

In all four mathematical expressions were developed.

$$f_{cm28} = 93.313 - 86.619(w/b) \quad \text{(A)}$$

$$f_{cm28} = 97.402 - 86.322(w/b) \quad \text{(B)}$$

$$f_{cm28} = 90.364 - 80.427(w/b) \quad \text{(C)}$$

$$f_{cm28} = 94.997 - 85.546(w/b) \quad \text{(D)}$$

Equations A–C predict the compressive strength of high workability OPC, 50%GGBFS and 60% GGBFS mortars with an accuracy of the values up to about 97%. Equation D is the generalized equation which predicts the compressive strength of high workability slag cement based mortars. The predicted values were in good agreement with the experimental values. The average deviation of predicted values was just about 4.6% of the experimental values.

(b) Ultimate load of ferrocement encased aerated concrete sandwich wall elements in compression

A comprehensive and classified mathematical equation was developed to determine the compressive strength of ferrocement encased sandwich wall elements. The equation is also applicable to the sandwich block specimens.

$$P_U = 0.4\left(f_c A_c + f_{cm} A_{cm}\right)\left[1-\left(kH/40t\right)^2\right] + 0.67\left(f_{my} A_m + f_{sy} A_s\right) + \frac{2A_p C_m}{D_c}\left(0.3t_f\sqrt{f_{cm}} + \frac{25\pi d_w n}{g_{wL}}\right) \quad \text{(E)}$$

Equation E entertains a wide variety of variables like slenderness ratio, type of wire mesh, number mesh layers, steel bar reinforcement and c-e ratio. The aspect ratio also could be included by multiplying the factor A_r, determined from following equation

$$A_r = \left[1.2-\left(H/10L\right)\right] \qquad A_r \text{, is applicable when, } H/L. < 2 \qquad \text{(F)}$$

The predicted values of the compressive strength of sandwich wall elements and block elements are averagely 98% accurate to the experimental values.

From the above mentioned achievements it can be concluded that the main aim of this research has been successfully achieved.

6.3 Contribution of the Research

The research has embarked and paved the way to adopt a novel and potential approach of ferrocement encasement of lightweight non-autoclaved aerated concrete to produce lightweight sandwich composite. The sandwich elements produced are high performance in compressive strength, flexural strength and ductility where as the water absorption and ISAT values were very low leading to the durability of the elements particularly in aggressive environment like in Malaysia. These sandwich composites are potential to be applied in earthquake prone areas like Pakistan. Their lightweight properties and precast, and prefabrication approach of construction can lead to the industrialization of the building system. The equations developed have laid the base to predict the design values of ultimate loads of encasement mortar and the sandwich composite in compression without bothering a lot on the experimental studies.

6.4 Recommendations for Future Work

As a result of the work undertaken for this research, it is suggested to extend the work further with respect to the following aspects,

(a) It is highly recommended that the concept of this study should be extended towards the development of sandwich elements for their application in floors and slabs and the extent of the contribution of mesh layers in terms of flexural strength should be optimized.

(b) Since the steel bar reinforcement was adopted as additional parameter during this study. A systematic study investigating various variables like diameter of bars, spacing of bars, is recommended for future work.

(c) It is believed that after a certain value of slenderness ratio, wall elements experience the lateral instability which affects the load carrying capacity of the wall elements drastically. Hence, it is highly recommended that an experimental study based on full height wall elements be planned and the safe limits of the slenderness ratio against lateral instability of wall elements be characterized accordingly. Also if necessary, the slenderness factor in the proposed mathematical model could be modified accordingly.

(d) The mathematical model to predict the compressive strength of high workability mortars with slag has been developed based on only the results of this research. The author wishes the further generalization of the model by considering the effect of other replacement materials like PFA, POFA, and RHA and the slag replacement levels other than used during this study.

REFERENCES

Abang, A.A.A. (1995). Application of Ferrocement as a Low Cost Construction Material in Malaysia. *Journal of Ferrocement*. 25(2):123-128.

Abang, A.A.A. (1999). Advances in Construction Systems and Technology. *Proceedings of the Worlds Engineering Congress.99- Specialize Conference on Industrialized Building System*. July 19-22. Kuala Lumpur, Malaysia. UPM.

Abdullah, and Mansur, M.A. (2001). Effect of Mesh Orientation on Tensile Response of Ferrocement. *Journal of Ferrocement*. 31(4): 289-298.

Abdullah, and Takiguchi, K. (2002a). Strength and Behaviour of Concrete Confined by Ferrocement Boxes. *Journal of Ferrocement*. 32(3): 193-203.

Abdullah, and Takiguchi, K. (2002b). Strength and Behaviour of Concrete Confined by Ferrocement Boxes. *Journal of Ferrocement*. 32(4): 304-314.

ACI Committee 226-87 (1987). Ground Granulated Blast-Furnace Slag as Cementitious Constituent in Concrete. *ACI Materials Journal*. 327-342.

ACI Committee 233R (2003). Slag *Cement in Concrete and Mortar,* American Concrete Institute, Farmington Hills,ACI 233R-03.

ACI Committee 308 (1998). *Recommended Practice for Curing Concrete*, MCP, American Concrete Institute, Farmington Hills, USA, ACI 308-98.

ACI Committee 363 (1984). Satae of the Art report on High strength Concrete, ACI 363 R-84. *ACI Materials Journal*. 364-41.

ACI Committee 5492R (2004). *Report on Thin Reinforced Cementitious Products*, Farmington Hills, Michigan. ACI 5492R-04.

ACI Committee 549R (1997). *State-of-the-Art Report on Ferrocement*, Manual of Concrete Practice, ACI, Farmington Hills, Michigan ACI 549R-97.

Ahmed, S.F.U. and Nimityogsku,l P. (1998). Improvement of Punching Shear Resistance in Ferrocement Slabs. *Journal of Ferrocement*. 28(4): 325-336.

Alkubaisy, M.A. and Jumaat, M.Z. (2002). Punching Shear Strength of Bolted Ferrocement Sandwich Panels, *Journal of Ferrocement*. 32(1): 1-17.

Al-Kubaisy, M.A. and Nedwell, P.J. (1999). Behavior and Strength of Ferrocement Rectangular Beams in Shear. *Journal of Ferrocement*. 29(1): 1-16

Allen, H.G. (1996). *Analysis and Design of Structural Sandwich Panels*. London. Pergamon Press.

Al-Noury, S.I and Haq S. (1988). Ferrocement in Axial Tension. *Journal of Ferrocement.* 18(2): 111-137.

Al-Rifai, W.N and Mohammad, K.A. (2000). Strength of Ferrocement-Brick Composite Columns. *Journal of Ferrocement.* 30(1): 69-83

Al-Rifai, W.N, Al-Shukur, A.H.K. (2001). Effects of Wetting and Drying Cycles in Fresh Water on the Flexural Strength of Ferrocement. *Journal of Ferrocement*. 31(2): 101-108.

Al-Rifai, W.N. (2006). Ferrocement Wall: Penetration Testing, *Proceedings of Eight International Symposium and Workshop on Ferrocement and Thin Reinforced cement Composites*. 06-08 February, Bangkok Thailand, IFS, 177-185.

Al-Sulaimani, G.J, and Basunbal, I.A. (1991). Behaviour of Ferrocement under Direct Shear. *Journal of Ferrocement*. 21(2): 109-117.

American Society for Testing and Materials (1999). *Standard Practice for Mechanical Mixing of Hydraulic Pastes and Mortars of Plastic Consistency*. Philadelphia, ASTM C305-99.

American Society for Testing and Materials (2002). *Standard Specifications for Standard Sand*. Philadelphia, ASTM C778-02.

American Society for Testing and Materials (2002) *Standard Test Method for Pulse* Velocity Through Concrete. Philadelphia, ASTM C597-02.

American Society for Testing and Materials (2002). *Standard Test Method for Flexural Strength of Concrete (Using Simple Beams with Third-Point Loading*) Philadelphia, ASTM C78-02.

American Society for Testing and Materials (2003). *Standard Specifications for Concrete Aggregates*. Philadelphia, ASTM C33-03.

American Society for Testing and Materials (2003) *Standard Specifications for flow Table for Use in Tests of Hydraulic Cement* Philadelphia, ASTM C230-03.

American Society for Testing and Materials (2005). *Standard Specifications for Portland Cement*, Philadelphia, ASTM C 150-05.

American Society for Testing and Materials (2005) *Standard Specifications for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars*. Philadelphia, ASTM C989-05.

American Society for Testing and Materials (2005). *Standard Specifications for Chemical Admixtures for Concrete*. Philadelphia, ASTM C494-05a

American Society for Testing and Materials (2005). *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars*. Philadelphia, ASTM C109-05.

American Society for Testing and Materials (2006). *Standard Specifications for Load Bearing Concrete Masonry Units.* Philadelphia, ASTM C 90-06b.

American Society for Testing and Materials (2006). *Standard Test Method for Linear Drying Shrinkage of Concrete Masonry Units*. Philadelphia, ASTM C426-06.

An, C. (2004*)*. *Strength Evaluation of Honeycomb FRP Sandwich Panels with Sinusoidal Core*. Department of Civil and Environmental Engineering West Virginia University, PhD Thesis.

Araffa, M. and Balaguru, P.N. (2006). Flexural Behaviour of High Strength-High Temperature Laminate Sandwich Beams. *Proceedings of Eight International Symposium and Workshop on Ferrocement and Thin Reinforced cement Composites*. 06-08 February, Bangkok Thailand, IFS.189-201.

Arif, M., Akhtar S., Masood, A., Basi, F. and Garg, M. (2001).. Flexural Behaviour of Fly Ash Mortar Ferrocement Panels for Low Cost Housing. *Journal of Ferrocement*. 31(2): 125-135.

Arif, M., Pamkaj, and Kuasik, S.K. (1999). Mechanical Behavior of Ferrocement Composites: An Experimental Investigation. *Cement and Concrete Composites,* 21(4): 301-312.

Arreshvhina, N., Zakaria, F., Warid, H.M. and Roswadi G.S. (2005). Microstructural Investigations on Slag Cement Based Aerated Concrete. *Proceedings of Seminar Kebangsaan Penyelidikan Kejuruteraan Awam*, 5-6 July, JB. Malysia, FKA.UTM.

Arreshvhina, N. (2002). *Application of Slag Cement Based Aerated Lightweight Concrete In Non-Load Bearing Wall Panels*. FKA. UTM., Malaysia Masters Thesis.

Arreshvhina, N. and Zakaria, F. (2002). Drying Shrinkage and Water Absorption of Slag Cement Based Aerated Lightweight Concrete Wall Panels. *Proceedings of the Research Seminar on Materials and Construction*, Johor Bahru.118-134.

Ashrabove, A.A. (2006). Structural Behaviour of Eccentrically Loaded Precast Sandwich Panels. *Construction and Building Materials*. 20 (9) 713–724.

Austriaco, R.L. (2006). Researches and Innovations on Ferrocement in the New Millenium: Global perspective. *Proceedings of Eight International Symposium* *and Workshop on Ferrocement and Thin Reinforced cement Composites. 06-08 February, Bangkok Thailand,* IFS, 77-86.

Awal, A.S.M.A (1987). Ferrocement: A Unique Material of Construction and Its Use in Agriculture. *Bangladesh Journal of Agricultural Engineering*. 1(2): 35-40

Barnett, S.J, Soutsos, M.N., Millard, S.G, and Bungey, J.H. (2006). Strength development of mortars containing ground granulated blast furnace slag: Effect of curing temperature and determination of apparent activation energies. *Cement and Concrete Rresearch,* 36(3): 434-440.

Bave, G. (1980). Aerated Lightweight Concrete-Current Technology. Proceedings of the Second International symposium on Lightweight Concretes. London.

Benayoune, A., Samad, A.A.A., Abang, A.A.A. and Trikha, D.N. (2007a). Response of Precast Reinforced Composite Sandwich Panels to axial Loading. *Construction and Building materials.* 21(3): 677-685.

Benayoune, A., Samad, A.A.A., Abang, A.A.A., Trikha, D.N. and Ashrabov, A.A. (2006). Structural Behaviour of Eccentrically Loaded Precast Sandwich Panels. *Construction and Building Materials*. 20 (9): 713-724.

Benayoune, A., Samad, A.A.A., Trikha, D.N., Abang, A.A.A. and. Ellinna, S.H.M. (2007b). Flexural Behaviour of Pre-Cast Concrete Sandwich Composite Panel-Experimental and Theoretical Investigation. *Construction and Building Materials* In Press, Available online on www.sciencedirect.com.

Bhatacharyya, P., Tan, K.H. and Mansur, M.A. (2003). Flexural Moment Capacity of Ferrocement Hollow Sandwich Panel System. *Journal of Ferrocement*. 33(3): 183-189.

Bitzer, T. (1997). *Honeycomb Technology*. London: Chapman and Hall;:

Bottcher, M. and Lange, J. (2006). Sandwich Panels with Openings. *Composite Construction in Steel and Concrete*, 186(14): 137-46.

British Standard Institution (1970). *Method for Initial Absorption Test*. London. BS1881 Part 5.

British Standard Institution (1983). *Water Method for Determination of Absorption Water Immersion Method.* London. BS1881 Part 122.

British Standard Institution (1991). *Specifications for Portland Cement*. London. BS12.

British Standard Institution (1992). *Specification for Ground Granulated Blast Furnace for Use with Cement*. London. BS6699.

Buekett, J. and Jennings, B.M. (1996). Reinforced Autoclaved Aerated Concrete. *The Concrete Society Technical Report*. London. The Concrete Society Limited.

Bush, T.D. and Zhiq, Wu (1998). Flexural Analysis of Prestressed Concrete Sandwich Panels with Truss Connectors. *PCI Journal*.43 (5):76–86.

Cabrillac, R., Fiorio, B., Anne-lise, B., Dumontet, H. and Ortola S. (2006). Experimental Study of the Mechanical Anisotropy of Aerated Concretes and the Adjustment Parameters of the Introduced Porosity. *Construction and Building Materials*. 20(5): 586-295.

Cairncross, C. (1972) *Ferrocement Boat Construction*. International Marine Publishing Company, Marine.

Carmichael, J (1986). Pumice Concrete Panels. *Concrete International.* 8(11): 31–32.

Christos, G.P (2003). *High Temperature Structural Sandwich Panels.* The State University of New Jersey. PhD Thesis.

Einea, A., Salmon, D.C., Tadros, M.K and Culp, T. (1995). Partially Composite Sandwich Panel Deflection. *ASCE Journal of Structural Engineering*. 121(4): 778–83.

El Debs, M.K., Machado, J E.F., Hanai, J.B. and Takeya, T. (2000). Ferrocement Sandwich Walls. *Journal of Ferrocement.* 30(1): 45-51.

Ergul, Y., Cengiz, D.A., Aleaettin, K. and Hassan, G. (2003). Strength and Properties of Lightweight Concrete Made with Basaltic Pumice and Fly Ash. *Materials Letters.* 57(15): 2267-2270.

Escalante, J.I., Go´mez, L.Y., Johal, K.K., Mendoza, G., Mancha,H. and Me´ndez, J. (2001). Reactivity of Blast-Furnace Slag in Portland Cement Blends Hydrated Under Different Conditions. *Cement and Concrete Research* 31(10): 1403– 1409.

Eswaranmoorthi, P. and Subramanian, K. (2006). Impact Resistance of Fibrous Ferrocement Slabs. *Proceedings of Eight International Symposium and Workshop on Ferrocement and Thin Reinforced cement Composites*. 06-08 February, Bangkok Thailand, IFS, 133-140.

European Standards (1993). *Determination of the Compressive Strength of Autoclaved Aerated Concrete*. London. EN 679.

Fabiana, L.D.O. and De Hanai, J.B. (2002). Experimental Analysis of Concrete Block Masonry Walls with Rectangular Openings Strengthened by Ferrocement Overlays. *Journal of Ferrocement*. 32(3): 179-191.

Feichtinger, K.A. (1998). Test Methods and Performance of Structural Core Materials-I. Static Properties. *Fourth Annual Aasm International/Engineering Society of Detroit Conference*. Michigan, Detroit.1-11.

Frostig, Y. and Thomson, O.T. (2005). Non-Linear Behavior of Delaminated Unidirectional Sandwich Panels with Partial Contact and a Transversely Flexible Core. *International Journal of Non-Linear Mechanics* 40 (5): 633 – 651.

Grove, S.M., Popham, E. and Miles M.E. (2006). An Investigation of the Skin/Core Bond in Honeycomb Sandwich Structures Using Statistical Experimentation Techniques. *Composites.* Part A 37(5) 804–812.

Hago, A.W., Al-Jabri, K.S., Al-Naumi, A.S., Al-Moqbali, H., and Al-Kubaisy, M.A. (2005). Ultimate and Service Behavior of Ferrocement Roof Slab Panels. *Construction and Building Materials*. 19(1): 31-37.

Hanecka, K., Koronthalyova, O. and Matiasovsky, P. (1997). The Carbonation of Autoclaved Aerated Concrete. *Cement and Concrete Research*. 27(4): 589-599

Hawalder, M.N.A, Mansur, M.A. and Rahman, M. (1990). Thermal Behaviour of Ferrocement. *Journal of Ferrocement*. 20(3): 231-239.

Hossainan, M.Z. and Inoue (2000). A Comparison of the Mechanical Properties of Ferrocement Elements under Compression for Square and Chicken Meshes. *Journal of Ferrocement.* 30(4): 319-343.

Houst, Y., Alou, F., and Witman, FH. (1983). Influence of Moisture Content on the Mechanical Properties of Autoclaved Aerated Concrete. *Autoclaved Aerated Concrete. Moisture and Properties*. Elsevier. Amsterdam 219-233.

International Ferrocement Society, (2001). *Ferrocement Model Code*. Thailand, IFS-10.

Isu, N., Ishida, H. and Mitsuda, T. (1995). Influence of Quartz Particle Size on the Chemical and Mechanical Properties of Autoclaved Aerated Concrete-Tobermorite Formation. *Cement and Concrete Research*. 25(2): 243-248.

Juan, C., Serrano, P., Uday K., Vaidya, A., and Nasim U. (2007). Low Velocity Impact Response of Autoclaved Aerated Concrete/CFRP Sandwich Plates. *Composite Structures.* 80 (4): 621-630.

Kandaswamy, S. and Ramachandraiah, A. (2002). Sound Transmission Performance on Ferrocement Panels. *Journal of Ferrocement*. 32(1): 59-67.

Khan, B.M., Ong, K.C.G. and Paramasivam, P.(1999). Behavior of Ferrocement Slabs under Low velocity Projectile Impact. *Journal of Ferrocement*. 29(4): 255-266.

Korkmaz, H.H. and Tankut, T. (2005). Performance of Precast Concrete Beam-to-Beam Connection Subject to Reverse Cycling Loading. *Engineering Structures*. 27(9): 1392-1407.

Kus, H. and Carlson, T. (2003). Micro Structural Investigations of Naturally and Artificially Weathered Autoclaved Aerated Concrete. *Cement and Concrete Research*. 33(9): 1423-1432.

Lee, B.J. and Pessiki, S. (2006). Thermal Behavior of Precast Prestressed Concrete Three-Wythe Sandwich Wall Panels. *AEI, ASCE*. 190(3): 1-15.

Levitt, M. (1970). Non Destructive Testing of Concrete by the Initial Surface Absorption Method. *Proceedings of Symposium on Non-destructive Testing f Concrete and Timber*, London. ICE.

Liang, S. and Chen, H.L. (2006). Investigation on the Square Cell Honeycomb Structures under Axial Loading. *Composite Structures*. 72 (4): 446–454.

Liborio, J.B.L. and Hanai, J.B. (1992). Ferrocement Durability: Some Recommendations for Design and Production, *Journal of Ferrocement*. 22(3): 265-271.

Lim, C.H.,.Samad, A.A.A, Abang, A.A.A. and Trikha, D.N. (2000). Behaviour of Ferrocement Shallow Box Beams as Wall Elements. *Journal of Ferrocement*. 30(1): 19-30.

Lim, C.T.E., Paramasivam, P., and ONG, K.C.G. (2001). Push Out Shear Strength of Ferrocement-Concrete Interface, *Journal of Ferrocement*, 31(4): 299-310

Lim, J.H and Kang, K. (2006). Mechanical Behavior of Sandwich Panels with Tetrahedral and Kagome Truss Cores Fabricated from Wires. *International Journal of Solids and Structures.* 43 (17) 5228–5246.

Lindasy, A.D.M. (2003). *Partially Composite Sandwich Panels*. University of Alberta. Master Thesis.

Loudun, A.G. (1983). The Effect of Moisture Content on Thermal Conductivity, Autoclaved Aerated Concrete, Moisture and Properties, *RILEM International Symposium On Autoclaved Aerated Concrete*, Swiss Developments In Civil Engineering, 6:131-142.

Mahfuz, H., Muhammad, S.I., Vijaya,,K.R, Mrinal, C.S. and Shaik J. (2004). Response of Sandwich Composites with Nanophased Cores under Flexural Loading. *Composites: Part B Engineering* 35 (6-8): 543–550.

Mahyuddin, R. and Wahab, I. (1994). Ferrocement in Affordable Housing Construction, the Malaysian Experience. *Journal of Ferrocement*. 24(1): 17-22

Malaysian Standards (2003) *Standard Specifications for Portland Cement: Ordinary and Rapid Hardening.* Malaysia MS 522: Part I.

Malaysian Standards (1995). *Standard Specifications for Ground Granualted Blast Furnace Slag for use with Portland Cement.* Malaysia, MS 1387-1993.

Mannan, M.A, Basri, HB, Zain, M.F.M.and Islam, M.N. (2002). Effect of Curing Conditions on the Properties of OPS-Concrete. *Building and Environment* 37(11):1167–71.

Mansur, M.A. (1988). Ultimate Strength Design of Ferrocement in Flexure. *Journal of Ferrocement* 17(4): 385-395.

Mansur, M.A. and Paramasivam, P. (1986). Cracking Behaviour and Ultimate Strength of Ferrocement in Flexure. *Journal of Ferrocement*. 16(4): 405-415.

Mansur, M.A. and Abdullah (1998). Constitutive Laws of Ferrocement under Biaxial Tension-Compression. *Journal of Ferrocement*. 28(1): 1-25.

Mansur, M.A. and. Kiritharan, T. (2001). Shear Strength of Ferrocement Structural Sections, *Journal of Ferrocement*. 31(3): 195-211.

Mansur, M.A., Ahmed, I. and Paramasivam, P. (2001). Punching Shear Strength of Simply Supported Ferrocement Slabs. *ASCE Journal of Materials in Civil Engineering.* 13(6): 418-426.

Mansur, M.A., and Ong, K.G.C. (1987). Shear Strength of Ferrocement Beams. *ACI Structural Journal.* 84(1):10-17.

Mansur, M.A., and Ong, K.G.C. (1991). Shear Strength of Ferrocement I-Beams. *ACI Structural Journal.* 88(3): 458-464.

Mansur, M.A., Paramasivam, P., Wee, T.H., and Lim, H.B. (1996). Durability of Ferrocement-a Case Study. *Journal of Ferrocement*. 26(1): 11-19.

Mantei, D.G. (1994). Investigation into the Hydraulic Activity of Five Granulated Blast Furnace Slags with Eight Different Portland Cements. *ACI Materials Journal*. September-October: 471-477.

Masood, A., Arif, M., Akhtar, S. and Haque, M. (2003). Performance of Ferrocement Panels in Different Environments. *Cement and Concrete Research.* 33(4): 555-562.

Mehta, P.K (1980). Durability of Concrete in Marine Environment-A Review. *Performance of Concrete in Marine Environment.* ACI, Detroit, 1-20.

Methews, M.S., Sudhakumar, J. and Thomas, A.V. (1992). Behaviour of Ferrocement Roofing Panels under Periodic Heat Flow Conditions. *Journal of Ferrocement*. 22(2): 125-133.

Mirza, J., Mirza, M.S. and Laponite, R. (2002). Laboratory and Field Performance of Polymer-Modified Cement-Based Repair Mortars in Cold Climates. *Construction and Building Materials.* 16: 365-374.

Montesinos, G.P. and Naaman, A.E. (2004). Parametric Evaluation of the Bending Response of Ferrocement and Hybrid Composites with FRP Reinforcements. *Journal of Ferrocement*. 34(2): 341-352.

Mostafa, N.Y. (2005). Influence of Air-Cooled Slag on Physicochemical Properties of Autoclaved Aerated Concrete. *Cement and Concrete Research***.** 35(7): 1349-1357.

Mouli, M. and Khelafi, H. (2006). Strength of Short Composite Rectangular Hollow Section Columns Filled with Lightweight Aggregate Concrete. *Engineering Structures.* Article in Press, Available Online on www.sciencedirect.com**.**

Naaman, A.E. (2001). Ferrocement and Thin Fiber Reinforced Cement Composites: Looking Back, Looking Ahead. *Journal of Ferrocement*. 31(4): 267-280.

Naaman, AE. (2000). *Ferrocement and Laminated Cementitious Composites.* Ann Arbor, Michigan, USA: Techno Press.

Narayanan, N. and Ramamurthy, K. (2000a). Structure and Properties of Aerated Concrete: A Review. *Cement and Concrete Composites.* 22(5): 321-329.

Narayanan, N. and Ramamurthy, K. (2000b). Micro Structural Investigation on Aerated Concrete. *Cement and Concrete Research.* 30(3): 457-464.

Nasim, U., Shelar, V.K. and Fouad, F. (2006). Impact Response of Autoclaved Aerated Concrete/FRP Sandwich Structures. *Structures Congress USA. ASCE*; 201-214.

Nedwell, P.J. (2000). Ferrocement Research at UMIST. *Journal of Ferrocement*. 30(4): 379-388.

Nedwell, P.J. (2002). National Progress Report –UK. *Journal of Ferrocement*, 32(4):333-339.

Nemat-Nasser, S., Kang, W.J, Mc Gee, J.D., Guo, E.G. and Isaacs (2007). Experimental Investigation of Energy-Absorption Characteristics of Components of Sandwich Structures. *International Journal of Impact Engineering*, 34(6): 1119-1146.

Nervi, M. (1981). Ferrocement Applications in the Developing Countries. *Proceedings of International symposium on Ferrocement, Edited by G.oberti and S.P. Shah, Bergamo* Italy. IFS. A49-A51.

Neville, A.M. (2003). *Properties of Concrete.* 4th Edition, Essex ,England. Pearson Education Limited.

Onet, T., Magureanu, C. and Vescan, V. (1992). Aspects Concerning the Behavior of Ferrocement in Flexure, *Journal of Ferrocement*. 22(1): 1-9.

Paramasivam, P and Santosh, S. (2006). Behaviour of Steel-FRC Sandwich Plates under Hard Lateral Impact. *Proceedings of Eight International Symposium and Workshop on Ferrocement and Thin Reinforced cement Composites*. 06-08 February, Bangkok Thailand, 203-216.

Paramasivam, P. and Ravindrarajah, S.R. (1988). Effect of Arrangements of Reinforcements on Mechanical Properties of Ferrocement. *ACI Structural Journal.* 85(5): 3-11.

Paramasivam, P., Ong K.C.G., Tan, K.H., and Lee, S.L. (1990). Rainwater Storage Using Ferrocement Tanks in Developing Countries. *Journal of Ferrocement*. 20(4): 377-384.

Parmasivam, P. and Tan, K.H. (1993). Punching Shear Strength of Ferrocement Slabs. *ACI Structural Journal.* 90(3): 294-301.

PCI Committee (1997). Pre-Cast Concrete Sandwich Wall Panels, State of the Art of Precast/Prestressed Sandwich Wall Panels. PCI 97 *PCI Journal.* 42(2): 92–133.

Pheerphan, T., Joyklad, P., and Pichai, N. (2006). Experimental Study on Blast Load Resistance of Ferrocement Panels. *Proceedings of Eight International Symposium and Workshop on Ferrocement and Thin Reinforced cement Composites*. 06-08 February, Bangkok Thailand, IFS, 355-364.

Pillai, S.U. and Parthasarathy, C.V. (1977). Ultimate Strength and Design of Concrete Walls. *Building Environment*. 9: 12:25.

Prasad, S. (1993). *Investigation of Debonding and Crack Kinking in Foam Core Sandwich Beams*. College of Engineering, Florida Atlantic University, Florida, Masters Thesis.

Precast/Prestressed Concrete Institute (1985). *Design Handbook-Precast And Prestressed Concrete.* Third Edition, Chicago, PCI-85.

Precast/Prestressed Concrete Institute (1989). *Architectural Precast Concrete.* Chicago, PCI-89.

Rajamane, N.P. Ramachandarmurthy, D.S and Ravi, S. (2003). Application of Ferrocement and Polymeric Materials for Repair of Corrosion Damaged Hyperboloid Overhead Water Tank Structure, *Journal of Ferrocement*. 33(1): 43-54.

Rajesh, G. K. (2001). Behaviour of High Strength Concrete Confined With Ferrocement Shell in Addition to Lateral Ties. *Journal of Ferrocement*. 31(3): 213-222.

Rao, P.K. (1992). Stress-Strain Behavior of Ferrocement Elements under Compression. *Journal of Ferrocement*. 22(4), 343-352.

Rao, K.C.B. and Rao, K.A. (1986). Stress-Strain Curve in Axial Compression and Poisson's Ratio of Ferrocement. *Journal of Ferrocement*. 16(2): 117-128.

RILEM. (1993). *Autoclaved Aerated Concrete – Properties, Testing And Design*. Recommended Practice. , London. E&FN SPON Rivas, H.W. (1994). Low Cost Housing Built with Ferrocement Precast Elements. *Journal of Ferrocement*. 24(1): 29-34.

Russo, A., and Zuccarello, B. (2006). Experimental and Numerical Evaluation of The Mechanical Behaviour of GFRP Sandwich Panels. *Composite Structures* Article in Press. Available Online on www.Sciencedirect.com**.**

Salimullah, M. (1994). Ferrocement Roofing Elements: The Solution of the Middle and Low Income Housing-The Bangladesh Experience. *Journal of Ferrocement*. 24(1): 51-56.

Santosh, S., Alwis, W..A.M. and.Paramasiwam, P. (2003). Steel-Ferrocement Sandwich Plates Under Hard Lateral Impact. *Journal of Ferrocement*. 33(1): 29-41.

Schubert, P. (1983). Shrinkage Behavior of Aerated Concrete, Autoclaved Aerated Concrete, Moisture and Properties. *Proceedings of RILEM International Symposium On Autoclaved Aerated Concrete, Swiss Developments in Civil Engineering* Switzerland, RILEM 6: 207-218.

Seckin, M. and Fu, H.C. (1990). Beam–Column Connections in Precast Reinforced Concrete Construction. *ACI Structural Journal*; 87(3): 252–61.

Sehu, D.R. (2000). Flexural Behaviour of Ferrocement Confined Reinforced Concrete (FCRC) Simply Supported Beams, *Journal of Ferrocement*. 30(3): 261-274.

Serrano, P. J.C, Uday, K.V. and Nasim, U. (2007). Low Velocity Impact Response of Autoclaved Aerated Concrete/CFRP Sandwich Plates. *Composite Structures.* 80(4): 621-630.

Shi, C. (2004). Steel-Slag-Its Production, Processing, Characteristics and Cementitious Properties. *Materials in Civil Engineering.* 16(3): 230-236.

Somayaji, S. and Naaman, A.E. (1981). Stress-Strain Response and Cracking of Ferrocement in Tension, *Journal of Ferrocement*. 11(2): 127-142.

Soubra, K, Wight, J.K. and Naaman, A. E. (1991). Fiber Reinforced Concrete Joints for Precast Construction in Seismic Areas. *ACI Structural Journal*. 88(1): 214–21.

Soubra, K, Wight, J.K. and Naaman, A. E. (1993). Cyclic Response of Fibrous Castin-Place Connections in Precast Beam–Column Subassemblies. *ACI Structural Journal.* 90(3): 316–23.

Suksawang, N., Nassif, H.H. and Sanders, M. (2006). Analysis of Ferrocement-Laminated Concrete Beams. *Proceedings of Eight International Symposium and Workshop on Ferrocement and Thin Reinforced cement Composites*. 06-08 February, Bangkok Thailand, IFS, 141-150.

Sun, H.L., (1999). *Corrosion Protection of Reinforcement in Concrete using Galvanized Steel Bar and Blended Cements*, FKA, UTM Master Thesis.

Suresh, V. (2004). Application of Ferrocement for Cost-Effective Building Construction. *Journal of Ferrocement*. 34(4): 445-455.

Swamy, R.N. (1989). Superplasticizers and Concrete Durability, Superplasticizers and other Chemical Admixtures in Concrete. *Proceedings of Third International Conference* Ottawa, Canada: 361-382.

Swamy, R.N. and Ammar, B. (1990). Some Engineering Properties of Slag Concrete as Influenced by Mix Proportioning and Curing. *ACI Materials Journal.* 87(3): 210-220.

Swamy, R.N., and Shaheen, Y.B.I. (1990). Tensile Behaviour of Thin Ferrocement Plates. *Proceedings of Thin-Section Fiber Reinforced Concrete and Ferrocement*, USA. American Concrete Institute, Detroit, MI.

Tada, s. and Nakano, S. (1983). *Micro Structural Approach to Properties of Moist Cellular Concrete, Moisture and Properties.* Amsterdam: Elsevier, 71-89.

Takiguchi, K. and Abdullah (2000). Experimental Investigations on Ferrocement as an Alternative Material to Strengthen Reinforced Concrete Columns *Journal of Ferrocement*. 30(2): 177-190.

Takiguchi, K.and Abdullah (2004). Ferrocement as Strengthening and Repairing Material for R/C Columns. *Journal of Ferrocement*. 34(4): 433-444.

Tat, L.S and Qian, H C. (2000). Elastic Stiffness Properties and Behaviour of Truss-Core Sandwich Panel. *ASCE Journal of Structural Engineering*. 126(5): 552-559.

Thandavamoorthy, T.S. (2000) Ferrocement Jacketing for the Repair of Offshore Platforms. *Journal of Ferrocement.* 30(4): 363-378.

Villanueva, GR and Cantwell, W.J. (2004). The High Velocity Impact Response of Composite and FML-Reinforced Sandwich Structures. *Composite Science and Technology* 64(1): 35-54.

Waleed, A.T., ,Jaafar M.S., Razali, M., Kadir, A., Abang, A.A.A., Trikha, D.N. and Najm (2004). Development of an Innovative Interlocking Load Bearing Hollow Block System in Malaysia. *Construction and Building Materials*. 18(6): 445-454.

Waliuddin, A.M and Rafeeqi, S.F.A. (1994). Study of the Behaviour of Plain Concrete Confined with Ferrocement. *Journal of Ferrocement*. , 24(2): 139-151

Witman, F.H. (1983). *Development in Civil Engineering; Autoclaved Aerated Concrete, Moisture and Properties.* Elsevier; Netherlands.

Xiong, J.G., and Singh, G. (1997). Review of the fatigue Behaviour of Ferrocement in a Corrosive Environment, *Journal of Ferrocement*. 27(1): 7-18.

Zakaria, F. (1997). *Engineering Properties and Behaviour of Fiber Reinforced Slag Cement Mortar*. FKA, UTM, Malaysia. PhD Thesis.

LIST OF PUBLISHED PAPERS

A. Journal Papers

1. Noor Ahmed, M., Salihuddin R.S., and Mahyuddin R. (2007) **"Performance of High Workability Slag-Cement Mortar for Ferrocement**, Building and Environment, 42(7): 2710-2717.

2. Noor Ahmed, M., Salihuddin R.S., and Mahyuddin R. (2007) **"Ferrocement Encased Lightweight Aerated Concrete: A Novel Approach to Produce Sandwich Composite",** Materials Letters, 61(19-20): 4035-4038.

3. Noor Ahmed, M., Salihuddin R.S., and Mahyuddin R. (2007) **"Study of Flowability and Strength of Ferrocement Mortar",** Mehran University Research Journal of Engineering and Technology, 26(2): 157-166.

4.. Noor Ahmed, M., Salihuddin R.S., and Mahyuddin R. (2006) **"Lightweight Aerated Concrete Incorporating Various Percentages of Slag and PFA**", Journal of Applied Sciences, 6(7):560-1565.

5. Noor Ahmed, M., and Salihuddin S.R. (2006) **"Ferrocement: A Versatile Composite Structural Material"** 2006, Mehran University Research Journal of Engineering and Technology, 25(1): 9-18.

6. Noor Ahmed, M., and Salihuddin S.R. (2006) **"Study of Ground Granulated Blast Furnace Slag as Cementitious Material In Mortar Mix"**, Mehran University Research Journal of Engineering and Technology, 25(2): 89-96.

7. Noor Ahmed, M., Salihuddin R.S., and Mahyuddin R. (2006) **"Ferrocement Encased Lightweight Aerated Concrete Sandwich with Variable Core Size and Wire Mesh Layers"**, Journal of Ferrocement, Accepted for Publication.

8. Noor Ahmed, M., Salihuddin R.S., and Mahyuddin R. (2006) "**Strength and Behaviour of Lightweight Ferrocement-Aerated Concrete Sandwich Blocks",** Malaysian Journal of Civil Engineering, 18(2): 99-108.

B. Conference Papers

9. Noor Ahmed, M., Salihuddin R.S., and Mahyuddin R. (2006) **"Strength and Behaviour of Aerated Concrete Encased with Ferrocement Box"**, Proceedings of Ferro-8, 8th International Symposium and Workshop on Ferrocement and Thin Reinforced Cement Composites, Bangkok, Thailand, pp.153-164.

10. Noor Ahmed, M., Salihuddin R.S., and Mahyuddin R. (2006) **"Behaviour of Ferrocement-Aerated Concrete Sandwich Prism Beams",** Proceedings of *6th* Asia Pacific Structural Engineering and Construction Conference *(APSEC 2006)*, Kuala Lumpur, Malaysia.

11. Noor Ahmed, M., Salihuddin R.S., Mahyuddin R, and Leney S.J. (2006) **"Suitability of MBC Mortars as Skin to Produce Sandwich Blocks with Aerated Concrete",** Proceedings of SEPKA 2006, National Seminar on Civil Engineering Research, Johor, Malaysia, S6: 1-10.

12. Noor Ahmed, M., Salihuddin R.S., and Mahyuddin R. (2006) **"Non-Autoclaved Lightweight Aerated Concrete With PFA And GGBFS",** NRMCA International concrete convention, Genting Highlands.

13. Noor Ahmed, M. and Salihuddin R.S. (2005) **"Evolution of Cement - Based Composites"**, Proceedings of Third International conference on Innovation in Architecture, Engineering and Construction (AEC), 15-17 June, Rotterdam, Netherlands. 1: 303-310.

14. **Noor Ahmed, M., Salihuddin R.S., and Mahyuddin R. (2005)** "Flow Characteristics of Mortar Mix for Ferrocement"**, 2005, Proceedings of Seminar Kebangsaan Penyelidikan Kejuruteraan Awam, SEPKA 2005, FKA, UTM, Malaysia, pp. 489-497.**