# A STUDY ON THE UTILISATION OF PLASTIC WASTES IN STABILISED MASONRY BLOCKS

*A Thesis*

*Submitted by*

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*for the award of the degree*

*of*

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# *Certificate*

*This is to certify that the thesis entitled "A STUDY ON THE UTILISATION OF PLASTIC WASTES IN STABILISED MASONRY BLOCKS" is a report of the original work done by Shri. C K Subramania Prasad, under my supervision and guidance in School of Engineering. No part of this thesis has been presented for any other degree from any other institution.*

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# Declaration

*I hereby declare that the work presented in the thesis entitled "A STUDY ON THE UTILISATION OF PLASTIC WASTES IN STABILISED MASONRY BLOCKS" is based on the original work done by me, under the supervision and guidance of Dr. Benny Mathews Abraham, Professor of Civil Engineering, School of Engineering, Cochin University of Science and technology Kochi, 682022. No part of this thesis has been presented for any other degree from any other institution.*

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// Abstract //

At this era of energy crisis and resource depletion, availability of conventional materials throughout the year in quantity and quality, pose a hectic problem for the builders. Adding fuel to the fire, the demand of these materials increases day by day, since the housing and habitat requirements exponentially increase time to time. There is an international concern over this crisis and researchers are reorienting themselves, so as to evolve appropriate masonry units, using locally available cheap materials and technology. The concept of green material and construction has been well conceived in the research so that marginal materials and unskilled labour can be employed for the mass production of building blocks. In this context, considering earth as a sustainable material, there is a growing interest in the use of it, as a modern construction material. Solid waste management is one of the current major environmental concerns in our country. Our country is left with millions of cubic metre of waste plastics. One of the methods to satisfactorily address this solid waste management and the environmental issues is to suitably accommodate the waste in some form (as fibres). Their employability in block making in the form of fibres (plastic fibre- mud blocks) can be investigated through a fundamental research. Also, the review of the existing literature shows that most studies on natural fibres are focussed on

cellulose based/ vegetable fibres obtained from renewable plant resources except in very few cases, where animal fibre, plastic fibre and polystyrene fabric were used.

At this context, for the plastic fibre-mud blocks to be more widely applicable, a systematic quantification of the relevant physical and mechanical properties of the fibre masonry units is crucial, to enable an objective evaluation of the composite material's response to actual field condition. This research highlights the salient observations from the detailed investigation of a systematic study on the effect of embedded fibres, made of plastic wastes on the performance of stabilised mud blocks.

The study on the influence of composition and block making mechanism on mud blocks described here basically come under four stages viz. (i) The density and the strength (ii) Sorption characteristics such as Water absorption and Sorptivity (iii) Erosion studies and (iv) Study on Mud block masonry. The input variables selected for the study to evaluate the above parameters, are (i) Cement as a chemical stabiliser (ii) Moulding pressure for mechanical stabilization (iii) Plastic fibres from carry bags(Kit fibres) and PET bottles(Bottle fibres) as an embedment or internal reinforcement.

Compared to the raw soil samples, Fibre reinforced Cement stabilized soil samples have shown an increase of 21 to 121% in the

Compressive strength. However in reality, the effect of fibres is pronounced in Kit fibres having 2cm length and 0.1% by weight of the dry Soil. An optimum Cement content of 7.5% by weight of the dry Soil is required to meet the minimum requirement of strength. The maximum quantity of Cement may be limited to 10% by weight of the dry Soil, considering the rate of increase in strength and the cost. Compared to the stabilised samples, the Fibre reinforced stabilised samples showed an increase of 59 to 89 % in the Compressive strength, for a Cement content of 7.5% and 64 to 118%, in the case of a Cement content of 10%, for the range of Moulding pressures varying from 1.25 to 7.5MPa. Stabilised samples and fibre reinforced stabilized samples at higher moulding pressures showed strength values of 3.5 to 4.41MPa when tested on cylindrical samples and 3.7 to 5.5MPa when tested on the moulded soil blocks. These values are conforming to the standards of minimum compressive strength of 3.5MPa for a well burnt brick as per BIS 1077-1992 and minimum compressive strength of soil block for general building construction as per BIS: 1725-1982(reaffirmed in 2002). The Kit fibres exhibit consistent behaviour and produce reliable results on the Soil, which was selected for the study.

One of the major advantages of the addition of fibres is the increase in the Tensile strength. From the observations of failure pattern, it can be concluded that benefits of fibre reinforcement includes both improved ductility in comparison with raw blocks and inhibition of large crack propagation after initial formation. The Compacted Reinforced Cement Stabilized specimens show an increase of 4.5 times the tensile strength of the raw Soil specimen.

The performance of the Masonry prisms made out of these blocks was also studied and a correlation with Masonry strength to Block strength has been made. For given Cement content, the ratio of masonry strength to block strength was found to vary from 0.38 to 0.52 and 0.45 to 0.72, for specimens subjected to low and high Moulding pressure respectively.

The water absorption of the samples with 10 to 15% Cement content was less than the specified value of 15% by weight as per IS 1725-1982(reaffirmed in 2002): Specifications for Soil based blocks used for general building construction. Erosion test indicates that the stabilized plastic reinforced blocks possess adequate resistance against rain erosion. It is also possible that, these stabilised blocks can be used in walls without any water-proof coatings and plaster.

**Key Words**: Mud Blocks, Cement Stabilisation, Moulding Pressure, Plastic Fibres, Compressive Strength, Split Tensile Strength, Mud Block Masonry, Sorptivity, Erosion Studies

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Chapter 1

# INTRODUCTION



## 1.1 General

The provision of good quality housing is recognized as an important responsibility, for the welfare of people in any country. For any such mass housing scheme, masonry is one of the important components and these masonry walls are usually made up of building blocks. These building blocks, technically known as masonry units, are available in variety, as natural, semi natural or artificial in their origin. Lot of work on these units has been done, especially on conventional brick, laterite, solid and hollow concrete blocks which are made of conventional raw materials, i.e. building materials based on natural resources. Some examples for these natural resources are the use of clay for making bricks, and river sand for making cement-sand blocks. The commercial exploitation of these resources often leads to various environmental problems. Extensive sand mining can lower the river-beds and allow salt-water intrusion in land. Therefore, the development of as many alternative walling materials as possible will be of immense benefit to minimize the impact on the environment. One such walling material is earth as mud blocks. Earth as mud bricks, has been used in the construction of shelters for thousands of years and approximately 30% of the population still live in earthen structures.

## 1.2 History of Earthen Construction

A brief state-of art review is given by Walker et al. (2000). Mud wall construction is one of the oldest and remains one of the most widespread forms of wall construction. In the Middle East, for example, remains of adobe (sundried mud blocks) wall construction have been dated back to 8000 BC. Many of these ancient techniques, such as adobe and cob constructions, are still widely practiced in many countries today.

Unstabilised mud construction is associated with two major problems:(1) Loss of strength on saturation and (2) Erosion of soil due to the impact of rain. These problems can be handled by the techniques of soil stabilisation. Compressed earth block or stabilised mud block, as they are commonly called in India, represent, an example of alternative component for masonry construction produced by utilising natural soils, sand and other industrial waste products such as fly ash.

Although adobe blocks have long been tamped into slip form moulds, the dawn of compressed earth block technology is attributed to Francois Cointeraux, who developed a timber block press, based upon a wine press, in Eighteenth century in France. However, it is only in the last so many years that compressed earth blocks have been widely adopted, largely due to the development of soil-cement block technology and invention of CINVA-RAM press in 1952 by Ramirez, a Chilean Engineer.

Mud wall construction in India has centuries of history and even now practiced in rural parts of India. The earliest Indian example of soil-cement buildings probably is to be seen in the refugee-housing programme in and around Karnal in Haryana state. 4000 buildings were constructed in 1948 using the concept of rammed earth soil-cement walls. A couple of problems like cracks and peeling off of cement plaster from the walls were noticed later. These problems may be attributed to inadequate stabilisation of fine-grained soils used for walls. Some of these houses are still in use with minor repairs and modifications. Development of Cinvaram block press in 1952 led to the concept of machine pressed stabilised mud blocks. Number of groups started working on stabilised mud block technology all over the world. The Ellson Block Master, a machine of South Africa origin was manufactured in Rajkot of Gujarat state during early seventies. This is heavier than Cinvaram, having the flexibility of interchangeable moulds. Some buildings were built using this machine in Gujarat, Kerala etc. Major impetus for stabilised mud blocks technology came after the formation of Centre for ASTRA (Application of Science and Technology to Rural Areas) in 1974 at IIISc, Bangalore.

Compressed soil masonry blocks, formed using moist soil compacted mechanically to improve physical characteristics, have gained popularity over the past so many years. Benefits of earth in this manner include improved strength and durability as compared to adobe while maintaining significantly low embodied energy levels than alternative materials. However problems arise from the material's low tensile strength, brittle behaviour and deterioration in the presence of water. Stabilisation by a hydraulic binder such as cement or lime or a combination of the two can significantly improve water resistance and strength to some extent. Also natural fibres have been used in adobe and other traditional forms of earthen construction for many thousands of years, to reduce shrinkage cracking, to improve tensile strength, durability and improved ductility in tension. Apart from that, baking of composite bricks with natural fibres and grain, leaves a porous structure which consequently enhances thermal and acoustical insulation of the finished products. Theoretical models were also developed on composite soil blocks reinforced with fibres subjected to shear. In almost all the above studies, the fibres used are sisal fibres, coconut fibres, vegetable fibres, straw, palm fibre etc.

## 1.3 Motivation to this Study

During the last few years, there has been a growing interest in the use of earth as a modern construction material and also considered as a sustainable material. Some factors contributing to this new interest are the energy crisis, resource depletion, increase in housing and habitat requirements day by day. At this context, for this mud blocks to be more widely applicable, a systematic study on physical and engineering properties is required. The present study aims at evolving few propositions regarding manufacturing of functionally efficient, structurally adequate and cost effective sustainable building blocks.

The motivation factors, which led to the present study, are listed as follows:

- Enormous amount of Plastic throw away.
- Soil by itself cannot stand reasonable loads as a masonry block.
- Natural materials tend towards dramatic depletion.
- Synthetic materials up heave drastically.
- Environmental issues.
- Energy aspects.
- Economic considerations.
- Social commitment.
- Technology based (Appropriate Technology).
- Rural & Mass Housing.

## 1.4 Organisation of the Report

A general introduction of mud block and its classification, a brief history and motivation for the present study have been given in the preceding sections. A critical review of literature on earthen construction with special emphasis on mud blocks , its material, production, physical, mechanical and durability properties, applications and advantages is presented in Chapter 2. The need for the present study along with the objectives and scope are also brought out in this chapter.

Chapter 3 describes the characterisation of the materials used in the present study. Descriptions of the various experimental methods to find out the properties of mud blocks are also explained in Chapter 3. Chapter 4 presents the analysis of results of the experimental investigations covering wide range of compositional parameters to get a conclusive influence of these parameters on the strength of mud blocks and masonry. Analysis of the experimental study on the sorption and erosion characteristics is given in Chapter 5. The conclusions drew from the present research work and the scope for further studies are given in Chapter 6.

Test samples were prepared, for different composition of ingredients and relevant experiments were conducted. Cylindrical specimens were prepared for all the investigations, as these represent the worst condition of stresses. Apart from that, Light compaction tests have been carried out to arrive at the OMC and the max dry density of samples. Hence, the specimens made on these moulds will be more relevant for the study. As masonry units are of blocks, a dismandable mould has been made and the Compressive strength tests have been performed. Interestingly the results are akin to that of the cylinders. There exists a definite ratio between the strengths of the two. Thus the Characteristic curves are drawn for cylinders and the modification factor for blocks has been mentioned in the relevant section (4.4). Tension and erosion tests have been done on cylinders alone. Split tension test has been done and the erosion resistance has been assessed by a spray test set up which is designed and devised to suit the cylindrical samples.

Chapter 2

# REVIEW OF LITERATURE



## 2.1 General

Raw earth was one of the first, oldest and most traditional building materials to be used by man and Earthen architecture has a continuous heritage dating back at least 10,000 years (Singh D L and Singh C S, 2003; Bahar et al. 2004; Mesbah A et al. 2004; Arumala and Gondal, 2007; Binici et al. 2007; Galan-Marin et al. 2010; Chee-Ming C, 2011; Swan et al. 2011). Mud-wall buildings can be seen throughout the world and mud construction techniques are still in vogue in many parts of the world (Reddy and Gupta, 2006). Up to 30% of the world's population continues to live in earthen construction (Binici et al. 2007; Swan et al. 2011, Walker, 2004).

The earliest examples of variously shaped earth ‘‘bricks’’ and of ‘‘plasters’’ are found in the Near/Middle East (dating from X Millennium B.C.). Earth materials were also used in stone constructions, for instance as a constituent of bedding mortars and plasters, and as a filler between stones. Earth was also combined with parts of plant and grasses parts for building huts, as witnessed, for example, by the archaeological findings from the Nuragic civilisation in Sardinia dating back to as early as the Middle Bronze Age (XIV Century B.C.) (Galan-Marin et al. 2010). Earth has always been the most widely used material for building in India and is a part of its culture. Approximately 55% of all India homes still use raw earth for walls (Singh D L and Singh C S, 2003).

## 2.2 Building with Unstabilised Mud

Earth has been used in the construction of ancient houses for thousand years together with others natural materials such as wood and stone. The constructional technologies used for the earth houses change with the geographical zone, topography, climatic condition, needs of different regions and with the historical period (Singh D L and Singh C S, 2003; Piattoni et al. 2011). Different types of earth construction are, Cob (Reddy and Gupta, 2006; Jagadish, 2007; Swan et al. 2011), Bamboo-reinforced mud wall (waffle and daub) (Reddy and Gupta, 2006; Arumala and Gondal, 2007; Jagadish, 2007; Krishnaiah and Reddy, 2008), Rammed earth ‘‘pisè’’ (Singh D L and Singh C S, 2003; Bahar et al. 2004; Reddy and Gupta, 2006; Arumala and Gondal, 2007; Jagadish, 2007; Piattoni et al. 2011; Swan et al. 2011), Adobe (Singh D L and Singh C S, 2003; Bahar et al. 2004; Reddy and Gupta, 2006; Arumala and Gondal, 2007; Jagadish, 2007; Swan et al. 2011), Compressed Earth Blocks. Brief descriptions on all the above mentioned earthen construction are given below.

For Cob walls, wet mud is directly used in wall construction. The well pugged mud is first made into a ball and the ball is placed properly using wooden mallet. The wall thickness can be 45cm or more. Each day the height of wall is raised about 45cm. Bamboo reinforced mud wall is a commonly used traditional technique where bamboo is available in plenty. This technique is similar to the waffle and daub wall technique used traditionally in Europe. It consists of essentially a bamboo frame work with mud filling. The frame work is formed by round bamboos of about 10cm diameter, held vertically at a spacing of about 45 to 60cm. Either split bamboos or 2.5cm diameter round bamboos form the horizontals at a vertical spacing of about 15cm. The horizontal provides two surfaces with the 10 cm bamboo in the middle. The horizontal and vertical are tied together using coir. Wet mud is then applied to the frame to complete the mud wall. Finished thickness is about 15cm.

Rammed earth is traditional mud construction technique known in Europe, Moroco, Peru and in China. It is also practised in Rajasthan and Hariyana in India. It consists of using a mould with two parallel boards to compact the earth inside them such that in situ wall construction is achieved. In traditional technique, wooden moulds are used with manual ramming using different types of rammers. Later on more mechanical techniques have been developed using pneumatic or vibratory rammers. Adobe is a universally adopted technique for making sundried bricks and using them in walls without burning. The blocks are cast in moulds and left to dry in the sun. Once dry, the blocks are built into walls using masonry type construction with mortar. Adobe wall is perhaps one of the best mud walls. It is superior to cob wall since the shrinkage is not there as the adobe bricks are dried before wall construction.

Compressed earth block (CEB) is similar to adobe; however, the blocks are created under pressure, expelling excess water and eliminating the need to sun-dry the blocks, thus resulting in a higher strength block with less curing time (Morel et al. 2007; Swan et al. 2011). The compressed earth block overcomes many of the limitations of above described earth constructions by an increase in block density through compaction using a mechanical press. The water content in soil is low for compaction as compared to the puddle clay required for mud bricks and ensures much greater dimensional stability (Singh D L and Singh C S, 2003). As this block has high density which varies from 1.8 to 2.1gm/cc, giving it more load bearing capacity and improved water resistance and in this compacted form it is suitable for more general low rise masonry construction. Compressed earth blocks are economically and effectively made with the compressed earth block machines. The hydraulic pressure on the blocks that affects the block density can be adjusted to enhance the performance of a variety of soils (Arumala and Gondal, 2007). Compressed earth blocks have gained popularity as an alternative building material that can be used for the construction of walls. For compressed earth blocks, the laterite soil that is widely available in tropical countries can be used. However, other soil types have also been used for various research studies. (Perera and Jayasinghe, 2003). Benefits of using earth in this manner include improved strength and durability as compared with adobe, while maintaining significantly lower embodied energy levels than alternative materials. However problem arises from the materials los tensile strength, brittle behaviour, and deterioration in the presence of water (Mesbah et al. 2004; Walker, 1996).

## 2.3 Advantages and Disadvantages

The technical characteristics of earth as a building material have both advantages and disadvantages depending on the requirements, applications and the context. Some of the main advantages of earth as reported by Walker (2004); Reddy and Gupta (2006); Arumala and Gondal (2007); Bicini et al. (2007); Krishnaiah and Reddy (2008); Chee-Ming (2011) are:

- It is the most readily available and cheap material found everywhere. Making it perhaps the most accessible and economical natural material for making building materials, such as bricks.

- It is easy to work with, requires less skills and as such, it encourages and facilitates unskilled individuals and groups of people to participate in their housing construction on self-help basis.
- It offers a very high resistance to fire and provides a comfortable built living environment due to its high thermal and heat insulation value.
- Earth is recyclable and an environmentally friendly building material offering a number of environmental benefits, including lower embodied energy levels, high thermal mass, reduced use of nonrenewable materials, and maximizing use of locally sourced materials.

Some of the main short comings are (Singh D L and Singh C S, 2003; Bahar et al. 2004; Reddy and Gupta, 2006; Krishnaiah and Reddy 2008):

- Liability to volume changes especially in the case of clayey soils.
- Low mechanical and strength characteristics necessitating larger wall thickness and loss of strength on saturation.
- High maintenance and low durability due to water penetration, erosion of walls at level by splashing of water from ground surfaces, attack by termites and pests. Many failures have been reported after seasonal flooding in many cities.

Traditional wall construction using soil as building material directly, without burning, in any of the forms discussed above has certain disadvantages as mentioned. The performance of these walls is not very satisfactory. The performance of burnt brick walls is quite satisfactory. However, burnt brick walls consume significant amounts of fuel energy. Since the country is already facing an energy crisis, alternatives to wood such as coal, are not cheap either and in any case are desperately needed for other purposes including cooking. Hence there is a need for an alternative way of using soil wall construction (Krishnaiah and Reddy, 2008). Of course these can be corrected by combined chemical and mechanical action, technically known as soil stabilisation (Reddy and Gupta, 2006; Arumala and Gondal, 2007; Krishnaiah and Reddy, 2008). An additional binder, such as cement, may be included to stabilize the mix. Additionally, local fibre reinforcement may be added (Bouhicha et al. 2005; Swan et al. 2011).

## 2.4 Compressed Stabilised Earth Block Technology (CSEB)

One of the drawbacks using earth alone as a material for construction is its durability which is strongly related to its compressive strength (Morel et al. 2001; Guettala et al. 2006; Reddy and Kumar, 2010). But most soil in their natural condition lack the strength, dimensional stability and durability required for building construction. At the same time any material used for wall construction should possess adequate wet compressive strength and erosion resistance. The technique to enhance natural durability and strength of soil defined as soil stabilisation. There are several types of stabilisation: first, mechanical stabilisation; second; physical stabilisation; and third chemical stabilisation (Walker, 1995; Billong et al. 2008; Riza et al. 2011). For stabilising, cementituous admixtures such as cement and lime and bitumen are added. Cement is the most widely used stabilising agent (Walker, 1995; Morel et al. 2000; Forth and Zoorob, 2002; Perera and Jayasinghe, 2003; Bahar et al. 2004; Mesbah et al. 2004; Reddy and Gupta, 2006; Krishnaiah and Reddy, 2008; Galan-Marin et al. 2010). Compacted soil blocks, naturally dried are ecological and economical materials with no air pollution arising from their fabrication process. However uses of these additives also significantly increase both material cost and their environmental impact. (Morel et al. 2000; Mesbah et al. 2004). The properties of stabilised soil can be further improved by the process of compaction. The process of compaction leads to higher densities, thereby higher compressive strength and better erosion resistance can be achieved. Exploring the stabilisation and compaction techniques, a cheap, yet strong and durable material for wall construction is the stabilised pressed block. The merits of this block are: low cost and no burning or firing is required, use of locally available soil, bricks can be made at site with no transportation of blocks, moreover simplicity in manufacture and no special skills required (Krishnaiah and Reddy, 2008).

Over the past 40 to 50 years, there has been an increasing interest in the use of stabilised compressed earth blocks for residential construction (Oliver and Gharbi, 1995; Walker and Stace, 1997). A mixture of soil, sand, stabiliser, and water is compacted using a machine to produce SMBs, also called compressed earth blocks CEB or soil-cement blocks when only cement is used as a binder. Cement and lime are the most commonly used stabilisers in SMBs. Stabilised mud blocks have been used for masonry construction in Australia, France, India, Columbia, Chile, Venezuela, Bolivia, Zambia, Brazil, Thailand, Algeria, Mauritania, Morocco, Upper Volta, the Ivory Coast, and many other countries (Jagadish 1988; Walker et al. 2000; Reddy and Gupta, 2006).

Compaction of moist soil, often combined with 4 to10% cement stabilisation, significantly improves compressive strength and water resistance in comparison with traditional adobe blocks (Morel et al. 2007).

The stabilised compressed earth block has a wide application in construction for walling, roofing, arched openings, corbels etc (Singh D L and Singh C S, 2003).

The two thrust areas in the housing sector are the promotion of building material units using local materials consistent with ecological balance, and the production of building materials with low energy inputs which substitute for energy intensive building materials. Common burnt clay bricks are increasingly becoming costly due to excessive cost of fuel to burn them and not many suitable brick earths are found everywhere. Stabilised mud block could be an economic alternative to the traditional brick (Choudhary, 2004). These blocks maximise utilisation of local materials, require simple construction methods and offer high thermal and acoustic insulation. Typically cement stabilised soil blocks require less than 10% of the input energy used to manufacture similar fired clay and concrete masonry units (Walker, 1995).

The performance specification of CSEB (Compressed Stabilised Earth Blocks) are based on BIS code IS 1725, 1982 and tested in accordance with IS 3495 – 1992.

| | | |
|---|---|---|
| Dimensional Variations | : | +/- 2 mm |
| Wet compressive strength | : | 20 – 30 kg/cm2 |
| Water absorption | : | <15% by weight |
| Erosion | : | <5% by weight |
| Expansion on saturation | : | <0.15% in block thickness |
| Surface characteristics | : | No pitting on the surface |
| Manpower required | : | 1 skilled, 6 – 8 unskilled |

For soil to provide the required level of performance as a walling material the process of stabilisation must improve or impart new properties to the soil. The aims of stabilisation are to

a) increase the wet strength of the soil,

b) provide adequate cohesion,

c) increase volume stability,

d) increase durability, resistance to erosion and frost attack,

e) lower permeability. (Bryan, 1988)

Stabiliser for CSEB is playing an important role in creating bonding between soil-stabiliser mixes. One of the main functions of the stabilising medium is to reduce the swelling properties of the soil through forming a rigid framework with the soil mass, enhancing its strength and durability. Portland cement is the most widely used stabiliser for earth stabilisation. Many research works (Walker, 1995) found that soil with plasticity index below 15 is suitable for cement stabilisation. Typically, cement binder is added between 4 and 10% of the soil dry weight (Mesbah et al. 2004). However, if the content of cement is greater than 10% then it becomes uneconomical to produce CSEB brick. For brick using less than 5% of cement, it often too friable for easy handling (Walker, 1995). For soil that has plasticity index below 15 more suitable to use cement as a stabiliser whether for the soil that has plasticity index above 15 or have clay content, it is suggested to use lime as a stabiliser. Lime can be added to the cement and clay mix to enhance stabilisation process because with the additional lime, the lime-clay ratio will be increased due to the existing of lime in cement and the present of lime attributed to the immediate reduction of plasticity. Although the same trend happen to the soil-cement mixes, the immediate effect of modification more obvious in the soil-lime mixes. When lime added to the clay soil, first it adsorbed by the clay mineral until the affinity of the soil for lime achieved, its call lime fixation and normally the amount between 1 to 3% lime added by weight. The addition of lime after lime fixation contributing to the pozzolanic reaction that created hydrated gel and this process is time dependent where strength developed gradually over long period. When clay soil is blended with Portland cement in the presence of water, hydration reaction will take place. The compound of $C_3S$ and $C_2S$ present in the Portland cement react with water forming complex Calcium Silicate Hydrates (C-S-H) gel. C-S-H gel has beneficial effect in clay material by reduction of deleterious heaving effects such as the growth of ettringite due to the rapid removal of alumina. The formation of ettringite contributes to the increase of porosity and simultaneously decreases the free moisture content. The C-S-H gel formed fill the void spaces and bind the soil particles together thus imparting strength to the soil mixture.

For laterite soil, noted that lime stabilisation of soil is a function of quantity of lime, curing time, environmental condition and testing method. Billong et al. (2008) also observed the potential of using lime and other pozzolanic material to form a binder that can acts as a stabiliser. It is suggested the combination of lime with ground granulated blast furnace (product in the manufacturing of pig iron) that will give better performance compared to the use of cement as the stabiliser. Natural stabiliser as proposed by Mesbah et al. (2004) is more environmental friendly and cheaper. Even though stabilisation with hydraulic binder (cement) significantly improved strength and water resistance but it contributes to negative environmental impact. Guettala et al. (2006) suggested the use of an aqueous dispersion of resin as an additive in earth stabiliser. The additive has increased the strength significantly to 2-3 fold to those indicated by standards for both wet and dry conditions. In general, soil stabilisations enhance quite significant bricks properties as described in section 4. Types of soil played an important role to determine the proper stabiliser for specific properties of brick to be enhanced. Even though the best soil for stabilisation is the soil that has low plasticity, the advantages of using cement for soil with low plasticity can be substituted with lime and other pozzolanic based stabiliser for soil with high plasticity and high clay content. The inventions of new stabilisers whether it from natural or artificial substances have had broaden the range of options to be chosen from. (Riza et al. 2011).

Stabilised soil has been used for the construction of sub bases of roads, pavements and rammed earth walls. Cement stabilised soil can be compacted into a high density block, which can be termed as soil-cement block. Such blocks are used for load bearing masonry structures. Cement-stabilised hand compacted blocks (size: 350X250X150 mm) were used to build 260 houses in Bangalore (India) in 1948 (Jagadish, 2007). CINVA RAM press was the first machine developed to compact soil into a high density block in Columbia during 1952. The construction of a large number of houses using compacted stabilised blocks have come up in many parts of the world. At present there are more than 12,000 buildings spread all over India (Walker et al. 2000). Currently more than 100 types of soil block making machines are available in the world market (Walker, 2004). More details on stabilised mud block technology can be found in the earlier studies (Walker et al. 2000; Walker, 2004) and many other publications. Some of the major findings/recommendations from the earlier studies, regarding production and properties of soil cement blocks have been summarized below:

a) Sandy soils containing predominantly non-expansive clay minerals (like kaolinite) are ideally suited for the production of soil-cement blocks. It is desirable that such soils have sand content >65% and a clay fraction of about 10%. Soils with higher clay fractions can be reconstituted by adding inert materials like sand/stone quarry dust/mine wastes etc. to bring down the clay fraction of the mix.

b) Soil-cement blocks produced using high clay soils are prone for damage due to rain impact and possess poor durability characteristics.

c) Strength of the block is sensitive to its density and preferable to obtain greater than 1.8 g/cc dry density for blocks. Wet to dry strength ratio for the blocks will always be less than unity.

d) Compressive strength of soil-cement blocks increases with the increase in cement content. Soil-cement mixes with 7% cement give sufficient wet compressive strength for the blocks to build two-storeyed load bearing residential buildings. Block strength can be easily manipulated by adjusting the cement content ( Reddy and Guptha, 2006).

According to Ngowi (1997), the strength of the cement-stabilised bricks is 70% higher than the bricks stabilised with lime, as the strength of lime mortar is only a third of the cement mortar. Atzeni et al. (2008) added stabilisers such as hydraulic cements, hydrated lime and polymers (acrylic latex and an aqueous solution of naphthalene–sulphonate), thus increasing compression resistance from 0.9 (unstabilised) to 5.1 (polymer impregnated). Bahar et al. (2004) improved to 4.5MPa with an addition of 10% of cement and up to 6.5MPa with an addition of 20% of cement as stabiliser. Spanish standards indicate maximum values of 3.6MPa with lime stabilisation and 6.6MPa with Portland stabilisation (Galan-Marin et al. 2010).

More details on SMB technology can be found in the studies of Reddy and Jagadish (1995); Walker and Stace (1997); Walker (2004) and in many other publications.

## 2.5 Fibre Reinforced Mud Blocks

Earth is a brittle building material with low tensile strength, and as a result tensile cracks in response to external actions or restrained shrinkage are often observed. As a more sustainable alternative to cement and bitumen, natural fibres, such as straw have of course been used in adobe and other traditional form of earthen construction for many thousands of years, to reduce shrinkage and improve tensile strength and ductility (Chee-Ming, 2011). It should be remembered that the first composite material used by man in Persia was soil reinforced with vegetable fibres (Morel et al. 2000). For instance, the roman introduced to prevent excessive shrinkage, and added natural fibres, like straws and dried grass, to further limit shrinkage cracking (Chee-Ming, 2011). Natural fibres in compressed earth blocks have also been shown to reduce the size of shrinkage cracks and to improve durability and post cracking tensile strength. (Mesbah et al. 2004). The strength of the CSEB can be increased by adding natural fibres where it can improve the ductility in tension. The improvement is by retarding the tensile crack propagation after initial formation and also the shrinkage cracking (Mesbah et al. 2004; Riza et al. 2011). Apart from that, the baking of composite bricks with natural fibres and grains leaves a porous structure which consequently enhances thermal and acoustic insulation of the finished products (Chee-Ming, 2011).

The fibres, which are connected together by mud, provide a tensile strength in mud bricks. The fibre provides a better coherence between the mud layers. The stress-strain relation of mud bricks under compression is very important. The compressive strength of fibre reinforced mud bricks has been found to be higher than that of the conventional fibreless mud bricks, because these fibres are strong against stresses. In the mud brick, there are fibres in both the longitudinal and transverse direction. These fibres prevent the deformations that may appear in the mud brick, thus, preserving the shape of bricks, and preventing the regions near the surface from being crushed and falling off. Where there are fibres in the mud, the transverse expansion due to poisson's effect is prevented by the fibres. The existence of these fibres increases the elasticity of mud bricks. When the mud brick starts to dry, it deforms and contraction/shrinkage takes place. The distribution of fibre is arbitrary, as their number increases, the tensile and elastic property of mud bricks improve. Thus, the mud brick behaves more flexible and mud bricks can store more elastic energy compared to other mud brick types, which renders it more resistant to earthquakes. For the same reason, fibre reinforced mud brick is more advantageous compared to the conventional brick. (Bicini et al. 2009).

Consoli et al. (1998) studied the influence of fibre and cement addition on behaviour of sandy soil. They reported that; the fibre reinforcement increased the peak and residual tri-axial strength and; decreased stiffness; however, the increase in residual strength was more efficacious when the fibre was added to cemented soil. Ghavami et al. (1999) found that inclusion of 4% sisal, or coconut fibre, imparted considerable ductility and slightly increased the compressive strength. It was also found that introduction of bitumen emulsion did not improve the bonding between the soil and fibres; but did significantly improve soil durability (Marandi et al. 2008).

Consoli et al. (2002) worked on engineering behaviour of sand reinforced with plastic waste. They found that, the polyethylene terephthalate fibre reinforcement improved the peak and ultimate strength of both cemented and un-cemented soil and somewhat reduced the brittleness of the cemented sand. In addition, the initial stiffness was not significantly altered by the inclusion of fibres. (Mesbah et al. 2004) proposed development of a direct tensile test for compacted earth blocks reinforced with natural fibres. By using the direct tensile test, it was possible to quantify the tensile reinforcing effects of randomly distributed sisal fibres in earth blocks. Benefits of the inclusion of the natural fibre reinforcement include both improved ductility in tension in comparison with plain earth blocks and the inhibition of tensile crack propagation after initial formation. Prior to cracking, the fibres appeared to have no noticeable effect on the material behaviour (Marandi et al. 2008).

It appears that, the fibre length is more effective in strength increase in comparison with quantity of fibre. In other words, the fibre sliding strength in comparison with their failure strengths controls the increase of the strength and bearing capacity of the specimens. In all experimental tests it was observed that; the behaviour of elements at failure surface was sliding type and no rupture was observed (Marandi et al. 2008).

Plenty of natural materials available have been used as soil reinforcement improving certain engineering properties of soil such as jute, coir, sisal, bamboo, wood, palm leaf, coconut leaf truck, coir dust, cotton and grass etc. Research works are concentrating on limited varieties of materials (Prabakar and Sridhar, 2002) like bamboo, jute, and coir and other materials are presently left without consideration in the field of soil reinforcement. Several investigations have been carried out on the addition of coconut and sisal fibre, which have shown very promising results. The addition of 4% of fibres (weight ratio), reduced significantly the occurrence of visible cracks and gave high ductility in soil blocks (Ghavami et al.1999, Galan-Marin et al. 2010).

Tests done by Bouhicha et al. (2005) proved the positive effects of adding straw in decreasing shrinkage, reducing the curing time and enhancing compressive strength if an optimal reinforcement ratio is used. Flexural and shear strengths were also increased and a more ductile failure was obtained with the reinforced specimen. Straw in the mixture acts not only as reinforcement but also catalyzes homogenous drying. The large amount of clay required in the binding process causes an increase in shrinkage. Straw in the mixture minimizes the shrinkage and prevents cracks in the earthen blocks. A review on the existing literature shows that most studies of natural fibres are focused on cellulose-based/vegetal fibres obtained from renewable plant resources. This is due to the fact that natural protein fibres have poor resistance to alkalis and cement is present nowadays is many building construction material. There are very few studies detailing composites made from protein fibres (animal hairs). Barone and Schmidt (2005) reported on the use of keratin feather fibre as short-fibre reinforcement in LDPE composites and showed that protein fibres have good resiliency and elastic recovery. Besides, protein fibres have higher moisture regain and warmthness, than natural cellulosic fibre properties all related to its possible use in earth material. The keratin feather fibre for these tests was obtained from chicken feather waste generated by the US poultry industry. Wool fibres exist in abundance in Scotland without widespread use in textile industry any more. The feasibility of using these fibres in conjunction with a soil matrix to produce composite soil has been investigated experimentally. Specimens have been prepared with an addition of a small amount (0.5 to 0.25%) of animal fibre, in this case raw, unprocessed wool. It was supplied directly from Scottish sheep and was used, untreated and straight from the animal's skin. This meant that, there were no additives to the wool such as detergents (Galan-Marin et al. 2010).

One of the significant effects of the inclusion of natural fibres in the soil matrix was the prevention of visible shrinkage cracks due to the drying process. The failure mode of the specimen made of natural soil was very quick and almost without warning. In contrast, in the case of the composite material, after the ultimate load was reached the specimens still deformed and fine cracks could be seen on the surface of the specimens. This was the same for all the composite soil material (Galan-Marin et al. 2010).

The stress–strain relationship is linear for all the test series up to maximum load. For the natural soil the final failure occurs immediately after the ultimate load. However, in tests on soil with natural fibres work softening can be seen. This may be explained by considering the redistribution of internal forces from the soil matrix to the reinforcing fibres. After final failure the soil–fibre composite was not disintegrated completely in contrast to natural soil specimens. Also it must be mentioned that the fibres hold soil matrix and together no rupture of fibres occurred although a loss of fibre bond was observed. The bonding between the soil and the wood fibres will be examined at the microstructure level to establish the factors that influence soil-fibre bonds (Galan-Marin et al. 2010).

Synthetic fibres show most success in practical applications and experiments since they show that they have qualities that other fibres do not, such as:

- they are chemically inert
- do not corrode
- allows easy jetting of the concrete

- are lighter than steel fibres of the same number
- they allow a better control of the plastic shrinkage cracking.

Synthetic fibres, in general, have an elastic modulus lower than that of the matrix. They are divided into:

- high modulus fibres (carbon fibres, aramid and acrylic) which are costly;
- low modulus fibres (fibres of polyethylene, polypropylene, polyester and nylon) that do not contribute to the increase of tensile strength but are effective in controlling shrinkage cracking (Foti, 2011).

In this study PET fibres have been obtained in a more simple way, just cutting waste bottles; in this way elaborate and costly manufacturing procedures have been avoided. The present research aims, in fact, to explore the possibility of using fibres made from plastic bottles in the simplest and most economic way. It is therefore part of the research on the re-cycling of a waste material (plastic bottles) that is produced in large quantities and difficult to destroy (Kim et al.2010; Foti, 2011).

The research focuses on the use, as fibre reinforcement, of a waste material that is widely spread and accumulated through the bottles of mineral water and soft drinks. These fibres are made of a synthetic material, polyethylene terephthalate (PET); this kind of material is difficult to completely destroy or re-cycling (Foti, 2011).

The test results have shown, in fact, that the addition of a very small amount of fibres from recycled and shredded PET bottles can have a large influence on the post-cracking behaviour of plain concrete elements. The tests showed that PET fibres in a concrete mixture are likely to increase the ductility of concrete. If it is shown that the addition of these essentially waste materials in fibre form can be beneficial to every-day concrete construction it would provide an attractive method of disposal of otherwise useless hazardous waste materials (Foti, 2011).

The polyethylene terephthalate (PET) fibres were formed by mechanical cutting of lateral sides of PET bottles. The bottlenecks and the bottom of the bottles were discarded. The uniformity of fibres is ensured, especially for the dimensions length and width, by fine adjusting, executed in a semi automatic cutting machine. The fibre dimensions were approximately 2 mm width, 0.5 mm thickness and 35 mm length and their aspect ratio is 31. The Eq. (1) was used to determine the fibres aspect ratio taking into account a fibre equivalent diameter.

$$\lambda = \frac{l}{d_e} = \frac{l}{2 \times \sqrt{\frac{A}{x}}} = \frac{l}{2 \times \sqrt{\frac{b \times c}{x}}}$$

where *l* is the fibre length in mm, de is the equivalent diameter, A is fibre cross section area in $mm^2$, b is the fibre width and c is the fibre thickness (Pereira and Gomes, 2011).

All of the papers listed above have generally shown that, the strength and the stiffness of the soil was improved by fibre reinforcement. Other than the sand characteristics; such as shape, particle size and gradation; and test condition; such as; confining stress, the increase in strength and stiffness was reported to be a function of fibre characteristics; such as; aspect ratio, skin friction, weight fraction; and modulus of elasticity (Marandi et al. 2008).

## 2.6 Sustainability

Earthen construction has a cultural heritage dating back over 10,000 years. As a truly ubiquitous form of construction, an estimated one third of the world's population still live in some form of earth building (Walker, 2004). The onward march of urbanisation and the continuous growth of industrialization throughout the world together with the increasing living standards have turned the creation of the built environment into a rising threat to the natural environment. Buildings account for one-sixth of the world's freshwater withdrawals, one-quarter of its wood harvest and two-thirds of its material and energy flows. The increased consumption of materials and resources together with the associated creation of solid and toxic wastes underscore the need for the construction industry to develop, use and dispose building products in a sustainable manner (Bicini et al. 2007). Renewal of interest in earthen construction in developed countries over the past 30 years has been stimulated by demands for more sustainable forms of built development (Walker, 2004).

Sustainability is “the maintenance of ecosystem components and functions for future generations,” and sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Meadows 2004). From these definitions, sustainable building material can be defined as a material that is harvested, produced, or manipulated to a usable building form in such a way as to have no negative impact on future generations during the material’s life cycle and disposal. With the increase in general and political interest in environmental matters such as peak oil and climate change, the public is asking for more environmental accountability in all matters, including building construction and maintenance (Lippiatt 1999). The building and construction industry accounts for up to 40% of the world’s energy usage (Lippiatt 1999) and approximately 40% of its raw material usage (Meadows 2004; Pulselli et al. 2007).Within these numbers, it has been reported that the structural system accounts for 25% of the building’s environmental impact. Most of a building’s overall impact is during its operation (Zhang et al. 2006). Therefore, if a structural system could also influence this portion of the building’s life cycle, it would be of even greater sustainable significance. Some professionals and builders are trying to meet the public demand and even help create it by constructing “green” buildings. These include builders using materials that have been all but forgotten in the last 50 years for a variety of reasons. Such materials include cob, adobe, rammed earth, and compressed earth block. Building codes and engineering guidelines play an important role in supporting this shift to alternate construction materials (Swan et al. 2011).

Steel, concrete have been tested and approved as the mainstay materials for the building and construction industry. However, each of these materials must be extracted or harvested at one or several sites, transported to a different location for processing, and transported again to the construction site for installation. The amount of energy required for these operations and the material's disposal is called embodied energy. For each of these steps, energy is used and waste is produced, albeit at varying levels depending on which material is harvested. The more popular construction materials such as clay bricks and concrete blocks are of good quality but are energy intensive in production, expensive and are usually based on heavy industries(Arumala and Gondal, 2007; Reddy, 2004). Even environmental concern inhibits the use of burnt bricks, as the firing of these bricks in kiln creates lot of air pollution, as well as these are putting tremendous pressure on the already scarce non-renewable energy sources for producing 60 billion bricks annually which India needs today (Choudhary, 2004).

Earthen construction can be constituted of soils available within a building's footprint. This creates a much different material production path than that of steel, concrete. (Swan et al. 2011). Earth blocks have low embodied energy and are therefore being promoted to reduce the carbon dioxide expelled by conventional fired bricks. (Browne, 2009). A striking contrast between CSEB and conventional bricks is the energy consumed during the production process and carbon emission. CSEB brick creates 22kg $CO_2$/tonne compare to that of concrete blocks (143kg $CO_2$/tonne), common fired clay bricks (200 kg $CO_2$/tonne) and aerated concrete blocks (280to375 kg $CO_2$/tonne) during production. In average, cement stabilised earth bricks consumed less than 10% of the input energy as used to manufacture similar fired clay and concrete masonry unit (Walker, 1995; Riza et al. 2011). Reddy (2004) reports about 70% energy saving when compared to burnt bricks.

In addition, the materials themselves are more energy-efficient within the building envelope. This comparison of the embodied energy and the insulating properties clearly shows that sustainable construction materials are preferable to wood-frame and by extension to concrete or steel. A stabilised compressed earth block, mortar, and stucco wall built to create the same wall area as above has a total embodied energy of 13,213 MJ (Reddy and Jagadish, 2003; Shukla et al. 2009)-roughly 40% that of a wood-frame wall. (Swan et al.2011). It has also been reported that wall constructed out of these blocks have good thermal resistance; thus minimizing the effects of climatic changes within the building (Choudhary, 2004). The reduction of transportation time, cost and attendant pollution can also make CEB more environmentally friendly than other materials. (Deboucha and Hashim, 2011).Thus Unfired clay materials provide a sustainable and healthy alternative to conventional masonry materials, such as fired clay and concrete block, in both non-load-bearing and low rise load-bearing applications. Environmental benefits include significantly reduced embodied energy, thermal mass (Galan-Marin et al. 2010).

## 2.7 Properties of Stabilised Mud Blocks

### 2.7.1 Density

The performance of a soil based building block depends to a considerable extent on its density. Low density blocks are rather porous and will not have good strength. It is hence necessary to densify a soil while making a stabilised block, besides adding a stabiliser. For this purpose, the soil has to be subjected to adequate pressure at suitable moisture content. This process is known as compaction. (Jagadish, 2007). The main objective of soil compaction is to increase the soil density, decrease the voids ratio, reduce the soil porosity, water permeability and water resistance and hence enhance its durability. The densification of the soil mass also makes particle reorientation and formation of cracks more difficult. (Bahar et al. 2004). Three different methods of compaction: dynamic, static and vibro-static were studied and their effect with the percentage of cement on the soil characteristics and performance were investigated by (Bahar et al. 2004). The compaction can be made inside a machine mould to produce a standard size mud block. As a rule, it is desirable to produce a stabilised mud with dry density of 1.80 to 1.85 g/cc (Jagadish, 2007). Block density is largely a function of the constituent material's characteristics, moisture content at pressing and the degree of compactive effort applied (Walker, 1995). Walker (1995) reported that in his tests, the compactive effort for all blocks produced varied from 2 to 3.5 $MN/m^2$, with an average for the majority of consignments of 2.5 $KN/m^2$.

Variation of compaction pressure is not possible in the case of the ASTRAM machine used for making the blocks. Under normal operation the single acting ram develops a compaction pressure of approximately 2 $MN/m^2$ (Walker and Stace, 1997). In ASTRAM machine the mixed soil is compacted at 50kg/cm2 (Krishnaiah and Reddy, 2008). Another study reported in Riza et al (2011) concluded that by increasing the compacting stress from 5 to 20MPa, it will improve the compressive strength up to 70%. His conclusion was strengthened by Bahar et al. (2004) and in his study it was observed that by using dynamic compaction energy dry compressive strength increases by more than 50% but for vibro-static compaction increases slightly for about 5%. Also, it was reported that dry compressive strength increases with the static applied stress. About 60% increase of the dry compressive strength was obtained when the applied static stress increased from 2.1 to 7.3MPa. Effect of fibre content was less pronounced on the density of the specimens where they remained largely unchanged over the range of fibres added (Chee-Ming, 2011). It is observed that cement content has little effect on the block density (Choudhary, 2004).

Compressive strength of compressed earth blocks is strongly related to dry density achieved in compaction. Compressive strength of individual blocks consistently increases as dry density increases. This relationship between strength and density has been consistently proven by test data over the past 20 years. In India block compressive strength is controlled through density Reddy et al. (2003). Prior to production the density and compressive strength of prototype blocks are determined in the laboratory. Subsequently block density, for given compactive effort, is ensured by carefully measuring, by mass, the quantity of material added to the mould (Morel et al. 2007).

## 2.7.2 Compressive Strength

### 2.7.2.1Compressive Strength of Experimental Samples

Apparently, compressive strength is the most universally accepted value for determining the quality of bricks. Factors affecting the CSEB brick strength are cement-content, types of soil (plasticity index), compaction pressure and types of compaction. Optimum cement content for the stabilisation is in the range of 5 to 10% where addition above 10% will affect the strength of the bricks in negative way. Plasticity index of the clay soil is usually in the range of 15 to 25. The best earth soils for stabilisation are those with low plasticity index. But for plasticity index >20, it is not suitable with manual compaction (Walker, 1995). The strength of the CSEB can be increased by adding natural fibres where it can improve the ductility in tension. The improvement is by retarding the tensile crack propagation after initial formation and also the shrinkage cracking (Mesbah et al. 2004; Riza et al. 2011).

Moisture content of blocks at testing has a significant influence on resultant compressive strength. (Jagadish, 2007) reports that the use of dry compressive strength can be very misleading since, the compressive strength is poorly correlated with wet compressive strength unless the clay fraction in the soil is low. Typically, determination of compressive strength in wet condition will gives the weakest strength value. Reduction in compressive strength under saturation condition can be attributed to the development of pore water pressures and the liquefaction of unstabilised clay minerals in the brick matrix (Morel et al. 2007; Riza et al. 2011). The reduction in compressive strength with increasing plasticity can primarily be attributed to the weakening effect of clay minerals on bonding between the cement paste and inert soil matrix. As clay content increases, the sand and fine gravel content decreases and block strengths are reduced. As clay content increases, the effectiveness of cement can also be impaired by the presence of small pockets of unstabilised cohesive soil which may form during wet mixing (Walker 1995; Walker and Stace, 1997).

Morel et al. (2007) reports that blocks are typically tested at oven dry or ambient air dry moisture conditions, reflecting that under service conditions. Walker (2004) also reports that under service conditions, earth blocks will necessarily remain largely dry. Testing blocks in a service or even in an oven-dry condition would therefore seem the most logical approach. For plain soil unstabilised blocks, the compressive strength when saturated, is zero. (Morel et al. 2007; Walker, 2004). Though there is some variation, depending on soil properties and cement content, compressive strength of cement stabilised blocks following water saturation is typically around 50% of that measured under dry conditions (Walker, 1995). Moisture contents of unstabilised materials at testing should ideally reflect in-service conditions. Testing cement stabilised blocks following saturation allows minimum strength to be determined under easily controlled and replicable moisture conditions, though conditions unlikely to be experienced in practice. The inclusion of mortar joint in the RILEM test makes strength determination under saturated conditions difficult, and more typically testing is undertaken under ambient air-dry conditions (Morel et al. 2007). As discussed in the previous section, Compressive strength was also improved by increasing compaction pressure, thereby increasing material density (Walker, 2004).

Strengths are improved by increasing cement content. Data produced by various researchers show strong, often linear, correlation between compressive strength and cement content (Walker and Stace 1997; Walker, 2004; Choudhary, 2004; Reddy and Guptha, 2006; Morel et al., 2007). Choudhary (2004) in his study reports that the compressive strength values at the maturity age of 28 days of the pressure moulded stabilised blocks of all the three mix types are also observed to fall under class 7.5 to class 12.5 of burnt clay bricks according to IS: 1077-1992 and therefore there should be no more hesitation in using blocks as a substitute to conventional burnt clay bricks. The immersion in water for 48 h reduces the compressive strength, by around 60% for cement-stabilised samples and complete disintegration of un-stabilised specimens was observed in few minutes. The reduction in strength was lower with higher cement content up to an optimum level of 10%, which gives the lowest reduction in strength of about 50%. Higher increase in cement content does not give any positive effect in the wet samples. (Bahar et al. 2004). In a study Reddy and Gupta (2006) reports that as the cement content of the blocks is doubled from 6%, the compressive strength increases by 2.3 times. The blocks with higher cement content (SCB2 and SCB3) have a coefficient of variation of about 10%, whereas the blocks with lower cement content (SCB1) have a 16% coefficient of variation. (Reddy and Guptha, 2006).It can be seen that, the increase of the cement content increases the compressive strength because the hydration products of the cement, fill in the pores of the matrix and enhance the rigidity of its structure, by forming a large number of rigid bonds connecting sand particles. (Bahar et al. 2004). Cement undergoes a three-phase stabilising reaction with the clay minerals during hydration (Walker and Stace, 1997).

Fibres increase the compressive strength of earth blocks (Oliver and Gharbi, 1995; Galan-Marin et al. 2010; Bicini et al. 2007; Chee-Ming, 2011) and thus the thickness of the outer load bearing walls can be reduced substantially (Bicini et al. 2007). The behaviour of fibre block is similar to fibre concrete, sisal fibre act as ties or reinforcement to prevent cracks thus increase the natural soil cohesion, and allow a much higher ultimate stress. Raw earth blocks are very brittle, fibre blocks are very ductile and do not show very clear cracks on failure. At the level of material behaviour fibres improve the tensile and compressive strength (Oliver & Gharbi, 1995).

Binici et al. (2005 and 2007) have shown that the utilization of plastic fibres increases the compressive strength in comparison to the use of straw fibres. Some researches highlighted that the increase of straw fibres decrease the compressive strength (Yetgin et al. 2008; Bouhicha et al. 2005) and the weight of the specimens, but the strain capacity (some kind of ‘‘ductility’’) raises. The last result is considerable also for the behaviour of earth structures during the earthquakes (Binici et al. 2005), an important requirement for houses in the areas where these events happen frequently and this structural technology is diffused (i.e. Turkey). The natural fibres do not have a positive effect on the compressive strength; in fact, straw fibres are weakly adherent to the earth matrix and they can slip (Piattoni, 2011). Quality control strength testing of compressed earth blocks has often followed procedures developed for fired clay and concrete block units (Walker, 1996; Morel et al. 2007).

Morel et al. 2007 shows that the compressive strength of an earth specimen raises with the decrement of the aspect ratio, namely, the ratio between the height and the thickness of the sample, this aspect is described in following section. The importance of carefully defining the methodology of test is highlighted by the comparison between the compressive strength on one brick and that obtained with the RILEM test (Morel et al. 2007; Piattoni, 2011). Morel and Pkla (2002) propose a model to measure compressive strength of earth bricks with the three points bending test; the results depend also on the density gradient of the mud brick compacted with only mobile ram.

**2.7.2.2 Compressive Strength of Blocks**

Blocks are generally tested in the direction in which they have been pressed which is also the direction in which they are generally laid. (Morel et al. 2007). Blocks are available at different thickness and depth. Experimental compressive strength of materials such as concrete, stone, fired and unfired clay is a function of test specimen dimensions. Load is normally applied uniformly through two stiff and flat hardened steel platens. As compressive stress increases the test specimen expands laterally, however, due to friction along the interface between the platen and test specimen, lateral expansion of the specimen is confined. This confinement of specimens by platen restraint increases apparent strength of the material (Morel et al. 2007; Piattoni, 2011; Walker, 2004).

To date, the correction factors in use were established for fired clay masonry rather than weaker and non-uniform compressed earth blocks. Geometric effects on compressive strength of compressed earth blocks stem not only from platen restraint, but also influence of friction during block manufacture. Density of blocks produced using single acting ram presses is not constant, but reduces with height away from the ram face due to friction along the mould sides. Experimental studies have confirmed that the apparent unconfined compressive strength value is achieved when the aspect ratio reaches 5. However, beyond an aspect ratio of 1.5 the compressed earth block material is unlikely to be homogeneous, due to friction during manufacture (Morel et al. 2007).

Piattoni (2011) studied the effect of aspect ratios (height divided by shortest size) of the different earthen samples like; blocks = 0.87; bricks = 0.42; and walls = 1.26, and found that with the increment of the aspect ratio the compressive strength decreases and at the value of the biggest aspect ratio (1.26) there is the lowest value of compressive resistance (1.00MPa). This effect come out, as mentioned above, from the presence of the friction between the earthen sample and the upper and lower platen and it is more relevant for samples with low aspect ratio. In fact with the decrement of the aspect ratio there is an increment of the contact surface between the specimens and the platens and therefore there are big values of the tangential force caused by friction.

Experimental variation in wet compressive strength with an aspect ratio (ratio of specimen height to width) is illustrated in a study by Walker (2004). Strength reduction is most marked for aspect ratios less than 2. Typically, the aspect ratio for pressed earth blocks is around 0.5 to 1. Once, the aspect ratio of the cut blocks exceeded 4 to 5, there was little further decrease in measured strength (Walker, 2004). About 20% increase in strength may be expected for a 25% decrease in thickness (Jagadish, 2007). Morel et al. 2007 in their study accommodated the geometric variation of blocks by aspect ratio correction factors, developed for fired clay masonry.

### 2.7.3 Tensile Strength

BVV Reddy and Gupta (2006) report that direct tensile strength of soil-cement block is much lower than the flexural strength (about one third of the flexural strength value). It is in the range of 0.18MPa to 0.46MPa when the cement content is varied from 6 to 12%. There is a linear relationship between tensile strength and cement content and it increases with the increase in cement percentage of the block. There is about 2.5 times increase in tensile strength for a two-fold increase in cement content from 6%. When compared with the compressive strength, the direct tensile strength of the block is in the range of 5 to 6% (Reddy and Guptha, 2006).

By using the split tensile strength test, it was possible to quantify the tensile reinforcing effects of randomly distributed fibres in earth blocks. Benefits of natural fibre reinforcement include both improved ductility in tension in comparison with pain earth blocks and the inhibition of tensile crack propagation after initial formation (Mesbah et al. 2004).

In a study on the strength and ductility of randomly distributed palm fibre reinforced silty-sand soils, it is reported that the slopes of the stress-strain curves of un-reinforced soil are steeper in comparison with reinforced soil and reach a maximum at a failure strain of about 1.3%. While the reinforced soils reach maximum values at 2 to 6% strain (with palm inclusion percentages of 0.25 to 2.50%). The rapid reduction in strength of the un-reinforced soil combined with the initial rapid (relatively) increase to the maximum strength is suggestive of a brittle material, as observed in the compaction of granular and over-consolidated fine-grained soils. It can also be observed that, with an increase in fibre length ($L_f$), the strain failure increases and the stiffness (maximum modulus of elasticity) decreases, or ductility increases. This trend suggests that; adding fibres to a soil medium that exhibits brittle material properties results in greater fibre connection and replacement of a portion of soil by elastic material. The soil becomes softer, the elasticity of the medium increases and as a result; the specimens fail at higher axial strains (Marandi et al. 2008).

### 2.7.4 Failure Pattern

The soil mass shearing strength is the strength of internal unit cross sectional area; which acts against failure or sliding along every internal plane. Adding elements with tensile properties such as fibres, to the soil medium effects the surface failure direction and the shear zone through the activation of tensile forces in the fibres under load. The reflection of these stresses causes higher compression between the solid grains and increases the soil compressive stress. These phenomena combine to have the dual benefit of increasing the shearing strength, and ductility, of the soil medium. Since these two properties are the most distinct parameters for soil medium failure criteria, the failure geometry and shear zone are affected by existence of the fibres. A close examination of the failed un-reinforced samples revealed that, in most cases, the failure surfaces were planar and oriented closely to the surface. As predicted by the Coulomb theory, the failure occurred at, the angle of obliquity or (45± 2). In contrast, the behaviour of the reinforced palm fibre specimens showed that, the trends of surface failures were distinguishable but irregular. Observation during the experimental tests showed that, at a constant palm fibre length, with increase in fibre inclusion, there were a greater number of failure surfaces and the surface orientations were regular with higher angle in respect to the horizontal line. The reason for this behaviour suggests that, increasing the palm fibre inclusion (i.e. the number of filaments per unit volume), improves the homogenous and isotropic properties of the soil medium or the soil medium becomes more uniform. It was also observed that, increasing the palm fibre length, at a constant Wf, the shear surfaces were more irregular but with a higher angle in respect to horizontal line. This suggests that an increase in palm fibre length, at a specific Wf, decreases the number of filaments per unit weight which, decreases the homogeneous and isotropic nature of the soil medium resulting in irregularity in surface failures. Conversely, the soil medium shearing strength increases and results in the increase in the surface failure angle in respect to the maximum principal plane (Marandi et al. 2008).

Raw earth blocks are very brittle, fibre blocks are very ductile and do not show very clear cracks on failure. This behaviour is also seen in tensile tests; the two halves of raw blocks fall apart on breaking, the fibre specimen stay in one piece. At the level of material behaviour fibres improve the tensile and compressive strength (Oliver and Gharbi, 1995).

### 2.7.5 Modulus of Elasticity

Bahar et al. (2004), in a study, report that the cement stabilisation increases the slope of the stress-strain curve and hence the elastic modulus of the material increases from 1.89GPa for un-stabilised soil to 2.5GPa for 10% cement-stabilised soil. It is also reported that the compressive and tensile strength and initial tangent modulus are much higher than those reported on soil stabilised with lime and fly ash.

Presence of the fibres on the non-baked specimens was considered the main reason for the lower strength and stiffness recorded. The soft, flexible and elastic properties of the natural fibres could have caused a creeping effect during compression (Chee-Ming, 2011). The presence of fibres in mud bricks has been reported to provide flexibility to the structures by enhancing their earthquake resistance (Bicini et al. 2005, 2007). In general, a big content of the straw fibre causes small value of the Young's modulus; probably the addition of natural fibres determines a minor homogeneity of the mixture (Piattoni, 2011).

### 2.7.6 Strength of Masonry

The compressive behaviour of masonry is of crucial importance for design and safety assessment purposes, since masonry structures are primarily stressed in compression (Mohamad et al. 2007). Various parameters pertaining to masonry units, mortars, bond between units and mortars, etc. affect the masonry characteristics (Reddy and Gupta, 2006).

In keeping with current recommendations the mortar used for construction was similar to the soil-cement mixture used for block production (Walker and Stace, 1997)). Consistency of the mortar will affect the bond and thus the performance of the masonry. Consistency can be measured by Slump testing which is proved the most reliable means of assessing soil-cement mortar consistency as per Walker and Stace (1997). Both the flow table and cone penetrometer tests were found to be unsuitable. (Walker and Stace, 1997). In a study reported by Reddy and Gupta (2006), flow table tests were conducted on samples of fresh cement-soil mortars collected from different construction sites and reported a flow value of 100%. Hence, a flow of 100% determined as per BS 4551-1980 was used here to investigate various characteristics of mortars as well as masonry using Stabilised mud block (SMB) (Reddy and Gupta, 2006).

Compressive strength of masonry is one of the major factors considered in the design of masonry structures. It is known that the strength of masonry units can be significantly lower than that of dry units (Pietruszczak, Pande, 1994; Walker, 1995, 2004). Masonry compressive strength varied from 34 and 96% of the corresponding unconfined block strength (Walker, 2004). This behaviour is attributed to the fact that the inclusion of a mortar joint in the test specimen alters the specimen format and behaviour. The test is no longer simply on an individual masonry unit, but effectively on a simple stacked bonded masonry prism. The mortar joint, even if made from identical material, is weaker and less stiff than the blocks, due to higher initial moisture content and lack of compaction. In compression greater lateral expansion of the mortar joint places the blocks in a state of compression and biaxial lateral tension (Hendry, 1981; Morel et al. 2007) whereas restraint of the blocks places the mortar joint in a state of tri-axial compression. Inclusion of mortar joint introduces a further variable into the test set up, with performance of specimens also dependent on the quality of work in combining half blocks and mortar joint (Morel et al. 2007). So in the uni-axial compression, masonry typically fails by vertical splitting as a result of lateral tension developed in the units. This vertical tensile cracking is between 50 and 95% of the ultimate load, proceeded by more general crushing of the prism (Walker, 2004).

As the strength of building blocks and the walls are not generally the same, the designers usually depend on guidelines given in codes of practice and other literature. Although block compressive strengths which satisfy the minimum requirements for both fired clay and concrete masonry units are readily attained, stabilised soil blocks are excluded from national standards and codes of practice for load bearing masonry design. There is a general lack of data on the performance of stabilised soil block work. It is also possible to relate the block and masonry strengths by performing tests on blocks and wall panels (Perera and Jayasinghe, 2003). Masonry strength values can be obtained from tests on small assemblages or tests on the components (Mohamad et al. 2007).

A considerable amount of research is on-going in the field of SMB technology. Most of the studies are focused on the production and properties of stabilised mud blocks and issues connected with construction and dissemination of SMB buildings. Very few studies are completely dedicated to the behaviour of SMB masonry using cement-soil mortars. However, there are a few investigations (Reddy and Jagadish 1989; Rao et al. 1995; Rao et al. 1996; Walker and Stace 1997; Walker 2004) related to the compressive strength of soil cement block masonry using cement-soil mortars as a part of the investigations dealing with masonry using other mortars such as cement mortars. For brevity only some of the major observations and important results of these studies are summarized below:

1) Soil-cement block masonry with cement-soil mortar, in certain cases, shows better masonry strength as compared to masonry using cement mortar;
2) Soil-cement block masonry with cement-soil mortar shows higher value of strain at ultimate stress, indicating more softening behaviour; and
3) Very lean cement-soil mortars with 4 to 5% cement containing high clay fraction lead to poor masonry strength and show larger values of strain at ultimate stress for the masonry (Reddy and Gupta, 2006).

Reddy and Gupta (2006) investigated the compressive strength of SMB masonry was determined by testing the masonry prisms. Four-block-high stacks bonded masonry prisms block size 305x143x100 mm and prism size 305x143x460 mm were used. A mortar joint thickness of 12 mm was maintained for all of the prisms. The initial moisture content of the block during the casting of prism specimens can affect the bond strength of masonry. Partially saturated blocks at 75% saturation lead to maximum bond strength (Rao et al. 1996). Thus to avoid the interference of the moisture content of the block with the masonry strength, the blocks were soaked in water for a period of 4 m prior to casting to keep the moisture content constant experiments conducted on these blocks showed that the blocks attain about 75% saturation when soaked in water for 4 minutes. The prisms were cured for 28 days in a moist condition under wet burlap. The masonry prisms were tested after soaking them in water for 48 h in a universal testing machine and the longitudinal compressive strains were measured by using a 200mm demec gauge (Reddy and Gupta, 2006).

Compressive strength of masonry increases with an increase in block strength irrespective of the mortar type. Masonry strength increased by 3.7 times when the block strength increased by 2.3 times from 3.13MPa. Masonry compressive strength is not very sensitive to mortar strength. The prisms failed by developing vertical splitting cracks parallel to the loading direction. A number of studies are available on the strength of burnt-clay brick masonry. (Hendry 1990) reports that the compressive strength of masonry is roughly the square root of the unit strength and very poorly related to mortar cube strength. For brick compressive strength greater than 25MPa, a plot of brickwork strength with brick strength (Hendry 1990) approximately doubles in masonry strength as brick strength is doubled. The results of the study by Reddy and Gupta (2006) where block strength ranges from 3 to 8MPa show that for SMB masonry the compressive strength went up by about 4 times as the block strength is increased by 2.3 times. Masonry strength using cement-soil mortars is more sensitive to the cement content of the mortar mix than the clay fraction. There is a marginal decrease 8 to 10% in compressive strength of masonry prisms when the clay fraction of the mortar is increased from 4 to 16%, irrespective of the cement content, whereas the masonry compressive strength increased by about 20% with an increase in cement content of the mortar from 10 to 15%. Cement mortar (CM), cement-lime mortar (CLM), and cement-soil mortar containing 15% cement content. Test blocks CSMB1, CSMB2, and CSMB3 have nearly the same percentage of cement15% in the mortar mix. Compressive strength values for the masonry using these mortars and SMB3 blocks clearly indicate that composite mortars such as cement-lime mortar and cement-soil mortars have 15 to 25% higher masonry compressive strength compared to the masonry using pure cement mortar. It should be noted here that masonry prisms were cast by keeping the mortar flow at 100% for all the three types of mortars (Reddy and Gupta, 2006).

The modulus of SMB masonry using various combinations of block and mortar lie in the range of 600 to 6,400MPa. The masonry modulus increases with the increase in block strength. The strain at ultimate stress for masonry is more than that for mortars and blocks. The modulus of masonry is not sensitive to the clay fraction of the cement-soil mortar. Masonry using cement-soil mortars has a higher modulus 40 to 50% more than masonry with cement mortar or cement-lime mortar. The study demonstrates that cement-soil mortar, which is cheaper than conventional mortars, can be beneficially used for SMB masonry (Reddy and Gupta, 2006).

In a study (Walker, 1995; Walker, 2004) reported that under uni-axial loading the behaviour of stabilised soil block work is similar to that of conventional masonry. The stiffness of the stabilised soil block work was only approximately one-third of the value expected of similar strength conventional masonry. Similarly the peak strain corresponding to maximum stress, were 3 to 4 times greater than that recorded in concrete brickwork. It is primarily attributed to the soil-cement mortar (Walker, 1995).

In an another study, Walker (2004) measured the surface compressive strains across the section of each prism at load increments up to or close to failure and found that the masonry compressive strength varied from 34 to 96% of unconfined block strength. Prism strength was comparatively influenced little by mortar strength. In general, the stiffness of pressed earth block masonry prisms was lower than that expected of comparable fired clay masonry. The tangent modulus was 25 to 50% of equivalent strength fired clay brickwork and peak strains were 200 to 400% higher (Walker, 2004).

Soil block walls should give sufficient warning before the failure of the panel thus demonstrating the ductile behaviour (Perera and Jayasinghe, 2003). As masonry failure is due to cracks spreading in the whole structure, because the reinforcement reduces the spreading, it has a positive action (Morel et al. 2000). Marandi et al. (2008) after studying the behaviour of fibre reinforced blocks, suggests that, adding fibres to a soil medium that exhibits brittle material properties results in greater fibre connection and replacement of a portion of soil by elastic material. The soil becomes softer, the elasticity of the medium increases and as a result, the specimens fail at higher axial strains. This behaviour of blocks is suggestive of the same behaviour for masonry with fibre reinforced units. A study in this direction is needed.

Information on the strength of SMB masonry is very scanty, and the information available on the strength of SMB masonry using cement-soil mortars is especially limited. Hence, there is a need to understand the properties of SMB masonry, especially with fibre reinforced units and cement-soil mortar masonry, in greater detail. This investigation focuses on the strength and elastic properties of SMB masonry using cement-soil mortars.

### 2.7.7 Sorption Characteristics

Water resistance was studied by measuring water absorption after immersion or by measuring the height of water penetration by capillary (Bahar et al. 2004). Water absorption is a function of clay and cement content and usually related with the strength and durability of earth bricks and therefore it is important to determine the rate of water absorption of earth bricks (Riza et al. 2011; Reddy and Guptha, 2006). It is also a function of compaction pressure and methods ((Bahar et al. 2004; Choudhary, 2004).

Raw specimen disintegrated during water absorption test, clearly suggesting the necessity of cement stabilization, if the blocks were meant for exterior use without protection (Chee-Ming, 2011). Bahar et al. (2004)

have conducted a study on durability of compacted stabilised soil by water absorption and water capillarity test. Stabilisation was done by adding cement and compaction was done by static, vibro-static and dynamic compaction. The combination of dynamic compaction and chemical stabilisation reduces substantially the sorptivity from 11.9% for no cement content to 9.8 and 2.7% when cement content is 5% and 10% respectively. This is lower than the water absorption with only chemical stabilisation. A lower absorption is obtained with a dynamic compaction at 10% cement content than that with 15% of cement without compaction. A similar trend was observed when static compaction using an 8.2MPa stress was used and water absorption decreases from 14.3,10 and 6.6% for respectively 0, 5 and 10% of cement content. However, the static compaction was less efficient than the dynamic compaction in reducing the water absorption. The positive effect of the combination of chemical and mechanical stabilisation seems to have on one hand cemented the soil particles together and filled in the pore space in the soil and on the other hand prevented the reorientation and flocculation of soil particles, which precluded formation of enlarged pores and cracks (Bahar et al. 2004).

In a study by Choudhary (2004) on pressure moulded building blocks with laterite soils, it is observed that percentage water absorption for different mix types varied from 10.32 to 7.62% which is well within the range as prescribed by IS:3495 for the conventional burnt bricks. Further, it is also observed that there is a general decrease in water absorption values of the blocks with increasing cement contents. The higher density values resulting from the pressure moulding of the blocks seem to provide the desired water tightness in these blocks and consequently the water absorption values of these blocks are on the lower side as compared to that of the conventional bricks. This property gets further enhanced with increase in the cement content (Choudhary, 2004).

As observed by Walker (1995) water absorption, as well as porosity, increases with clay content and decreasing cement content. Between cement, lime, cement-lime and cement-resin, combination cement and resin stabilisation show the lowest water absorption both in capillary absorption and total absorption (Guettala, 2006). Freidin and Erell (1995) tried to reduce the water uptake by adding a hydrophobic material, in this case was siloxane polymethyl hydrohen siloxane and combined with slag and fly ash which is highly absorbent and the result showed that the water uptake with the addition of 0.5% siloxane less than a quarter of the water uptake of fly ash-slag without additive.

Reddy and Gupta (2006) studied the initial rate of water absorption of blocks with cement 6% (SCB1), 8% (SCB2) and 12% (SCB3). SCB1 and SCB2 blocks having higher IRA values of 6.5 and 4.9 kg/m$^2$/minute, show a rapid absorption of water, initially after a few minutes of soaking in water. SCB1 and SCB2 blocks show 75% saturation within 1 and 4 minute respectively, whereas SCB3 blocks having low IRA value (1.5kg/m$^2$/minute) needs 12 minutes for 75% saturation. These features indicate that the rate of moisture absorption slows down as the percentage of cement in the block increases. These results also give an idea of soaking duration to partially saturate the blocks during wall construction. The SEM Images show that pore size decreases as the cement content of the block is increased. This can be attributed to the fact that with the increase in cement content, the soil and sand particles are very well coated with cement particles, thus enhancing the bonding among the particles (Reddy and Guptha, 2006).

Water absorption increases with clay content, as a greater proportion of water is adsorbed by the clay minerals, and reducing cement content, as the stabiliser becomes less effective at stabilising the clay minerals. Water absorption is unlikely to be a significant problem for earth block construction, as roof protection for durability,will limit moisture ingress. However, such highly absorbent blocks are, in general, unlikely to prove suitable in applications such as damp proof coursing (Walker and Stace, 1997).

### 2.7.8 Erosion Testing

Erosion from wind-driven rain is often a major concern for unbaked earthen wall construction. Mud walls have a tendency to erode under rain impact and can collapse when exposed to continuous downpour for several hours. The pressed soil blocks offer a better alternative to mud walls. (Reddy and Jagadish, 1983; Walker 1998). In general it has been observed that the erosion of pressed soil blocks by a water spray is due to the absorption of water in the exterior portions of the soil block. The significant loss of strength of the soil due to the absorption of water appears to be the main cause of erosion. It is then apparent that, if the water absorption by the soil block can be prevented/postponed, the erosion of soil can be reduced significantly (Reddy and Jagadish, 1983).

At present, there are a large number of different test procedures available to assess erosion resistance of earth blocks. Broadly speaking test procedures can be defined either as water-spray, water-drip, or wetting and drying cycles. Water spray testing may be considered as a more direct replication of rainfall borne erosion (Walker, 2004).

Spray erosion tests most closely simulate effects of rainfall impinging on the surface of a wall. They are repeatable, effective and quick to undertake (Walker, 1998). Though the spray-jet does not simulate a rain, it is likely that it may provide a relative evaluation of blocks using different soils and soil treatments. Normally the rain drops impinging on a wall surface will be inclined. The angle of incidence will generally vary depending on the velocity and direction of the wind. It is quite possible that the angle of incidence will have a definite effect on the erosion. It would however be difficult to standardize the test procedure by keeping the angle of incidence as a variable. Hence, for the present study, a horizontal water spray is considered in order to standardize and simplify the test procedure. (Reddy and Jagadish, 1983).The test suggested by BIS is also spray erosion test (BIS: 1725 - 1982).

A simple accelerated test using spray erosion, for a relative evaluation of pressed soil blocks and traditional mud walls with reference to rain erosion is discussed in the paper by Reddy and Jagadish (1983). The results of accelerated tests in the laboratory are also compared with the rain erosion results in the field. It has been observed that an increase in dry density will generally lead to better strength in pressed soil blocks.

A few small pits/patches of less than 1 mm depth are seen on the faces of the soil-lime and soil-cement blocks using red soil. There are also small patches of approximately 1 mm depth on the surface of soil-lime block using black cotton soil. This test indicates that pressed soil-lime and pressed soil-cement blocks possess adequate resistance against rain erosion. It is also fairly clear that these stabilised blocks can be used in walls without any water-proof coatings and plaster (Reddy and Jagadish, 1983).

The results of accelerated erosion tests show a complete disintegration of the non-stabilised specimens (Walker, 2004; Bahar et al. 2004). Resistance to erosion improves with cement content (Walker and Stace, 1997; Bahar et al. 2004), compactive effort (Walker, 1998) and reducing clay content (Walker and Stace, 1997). In a study by Bahar et al. (2004), it is observed that compacted stabilised specimens show no visible distress sign on the surface when subjected to erosion studies and hence it was difficult to assess the effect of different compaction methods.

## 2.8 Need for the Study

At this era of energy crisis and resource depletion, availability of conventional materials throughout the year in quantity and quality posed a hectic problem for the builders. Adding fuel to the fire, as the demand of these materials increases, the housing and habitat requirements increase. There is an international concern over this crisis and researchers are reorienting themselves, to evolve appropriate masonry units, using locally available cheap materials and technology. The concept of green material and construction has been well conceived in the present study so that marginal materials and unskilled labour can be employed for the mass production of building blocks. In this context, considering earth as a sustainable material, there is a growing interest in the use of it as a modern construction material.

Solid waste management is one of the major environmental concerns in our country. As our country is left with millions of cubic meter of waste plastics and as one of the methods to satisfactorily address this solid waste management and the environmental issues is to suitably accommodate the waste in some form (as fibres) during the process of making these block units. Their employability in block making in the form of fibres (plastic fibre- mud blocks) can be investigated through a fundamental research. The review of the existing literature shows that most studies on natural fibres are focussed on cellulose based/ vegetable fibres obtained from renewable plant resources except in a few cases, where animal fibres, plastic fibres and polystyrene fabric were used.

At this context, for these plastic fibre-mud blocks to be more widely applicable, a systematic quantification of the relevant physical and mechanical properties is crucial, to enable an objective evaluation of the composite material's response to actual field condition. This study highlights the salient observations from the detailed investigation of a systematic study, on the effect of embedded fibre made out of plastic wastes, in the performance of compressed stabilised mud blocks.

## 2.9 Objectives

The precise objectives of the study are summarized as follows:

- To investigate into the feasibility of utilizing plastic wastes, in the form of fibres in masonry units.
- To identify various plastic wastes compatible with block making.
- To evaluate the performance characteristics of randomly oriented plastic fibre reinforced mud blocks as masonry units.
- To evaluate the performance of masonry using these mud blocks as masonry units.

## 2.10 Pilot Study

To arrive at reasonable test parameters and to finalise the input variables, preliminary investigations have been carried out on soil samples, plastics, and cement at various compositions. The process of the pilot study is given as follows:

- Collection and identification of soil samples.
- Collection and identification of plastic wastes.
- Identification of chemical stabiliser.
- Identification of Test samples / specimens.
- Identification of moulding and making mechanism.
- Identification of soil friendly plastics.
- Identification of plastic friendly soil.

## 2.11 Scope

The overall scope of the work is given as follows:

- Rising demand for Masonry blocks.
- Going towards Energy efficient technology.
- Possible plastic solid waste management.
- Good amount of plastics used in small units of soil.
- Being super structure components, Masonry blocks do not contaminate water unlike plastics in huge mass of soil below ground level.
- Reasonable load bearing units for reasonable cost.

- Use of locally available human resources, materials, skill and methods.
- Technology based traditional materials and methods.
- Cater to environmental friendly, economically viable and socially relevant housing demands.

However the scope of the study is limited to the following with respect to the raw materials used and the methods adopted:

- The study is restricted to a particular type of soil collected from a site, at Palakkad district.
- Studies on properties are limited to density, compressive strength, tensile, sorption and erosion characteristics.
- Only two types of plastic wastes in the form of fibres are used, viz. fibres made out of carry bags (Kit fibre) and mineral water bottles (Bottle fibre).

## 2.12 Present Study

The input variables have been identified and detailed experimental investigations have been carried out on these variables, in all possible compositions. The materials and methods chosen for the study are summarised as follows:

**Materials**

- Locally available Soil in Palakkad.
- 43 grade OPC.
- Two types of Fibres from PET bottles (Bottle Fibre) & Carry bags (Kit Fibre).
- Potable Water.

**Method**

- Determination of OMC & Dry density.
- Addition of Cement and Fibres at different proportions.
- Moulding.
- Compacting at different Moulding load.
- Strength and Durability Tests.

Chapter 3

# MATERIALS AND METHODS



## 3.1 General

The input variables for a detailed study could be identified from the indications of the review of literature and preliminary tests and results that can influence the quality and the performance of the soil blocks. They are listed below.

- Type of soil
- Type and quantity of fibers
- Length of fibers
- Moulding pressure
- Type and quantity of stabilizer

The methodology to be followed in the detailed investigation to derive specific conclusions and salient findings about the soil block performance, with the objectives mentioned above, is shown Fig 3.1.

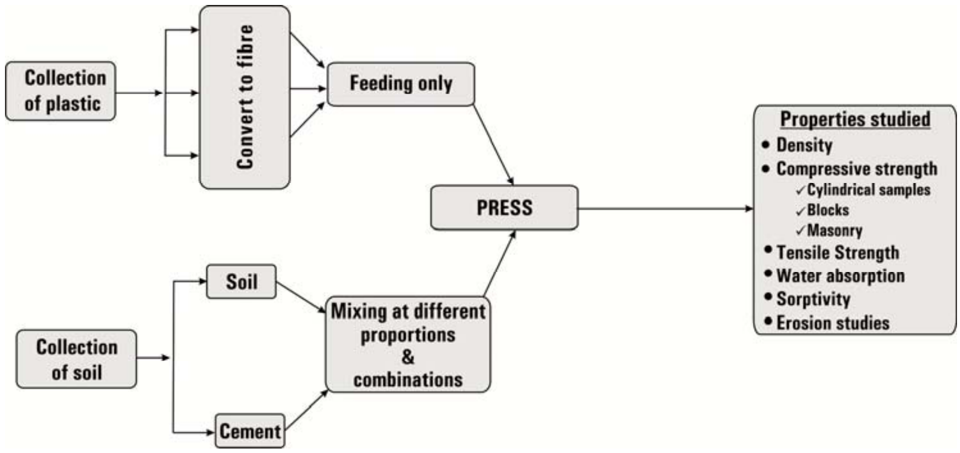



**Fig 3.1 Flow diagram showing the methodology**

## 3.2 Materials and Sample Preparation

### 3.2.1 Materials

Standard classification tests were carried out, on the soil collected for block making and a summary of the test results are given in Table 3.1 and the grain size distribution curve is given in Fig 3.2.

**Table 3.1 Physical properties of the soil used**

| Sl. No. | Property | Value |
|---|---|---|
| 1 | Specific gravity | 2.68 |
| 2 | Grain size distribution | |
| | (a) Clay (<0.002 mm) | 6% |
| | (b) Silt (0.002 – 0.075 mm) | 42% |
| | (c) Sand (0.075 – 4.75 mm) | 52% |
| 3 | Standard Proctor Test Results | |
| | (a) Optimum Moisture Content | 14% |
| | (b) Maximum dry density | 1.84 g/cc |
| 4 | Atterberg limits: Liquid limit<br>Plastic limit | 47%<br>40% |

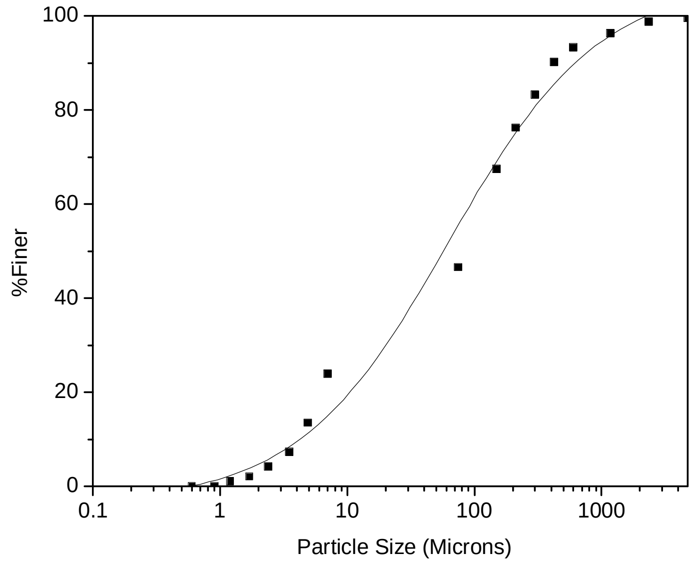



**Fig 3.2 Grain size distribution curve for the Soil**

The approach was to compare the properties and performance of two categories of samples, namely Base samples and Modified samples. Modified samples are different from base samples in their composition like the presence and type of Fibers, the type of additives, the Moulding pressure and the curing of samples. Ordinary Portland cement (OPC, 43grade) at different dosages has been used as the chemical stabiliser. The properties of the Cement used are given in Table 3.2 (BIS 8112-1989). Two types of fibers were used, the one made out of PET bottles and the other from carry bags (Pick up bags) as shown in Fig 3.3, henceforth referred to as 'Bottle fibres' and 'Kit fibres' respectively. Fibres are made out of these plastic wastes by chopping them into small length with almost the same minimal width of 2 to 3mm. The lengths of the fibers used for the investigation were of 1cm and 2 cm. Fibre content was taken as 0.1 and 0.2% by weight of the dry soil used .The investigation has been carried out for possible combinations of the fibres and their lengths with the above percentages of Fibre. Moulding (Compaction) pressure was controlled by a digital Compression testing machine, having a capacity of 1000kN and least count 100N. Experiments were carried out for a Moulding pressure of 1.25 to7.5MPa at 1.25MPa intervals.

**Table 3.2 Properties of Cement used**

| Sl No. | Properties tested | Values | BIS Specifications (BIS 8112-1989) |
|---|---|---|---|
| 1 | Normal Consistency | 32% | - |
| 2 | Initial Setting Time | 42 minutes | Not less than 30 minutes |
| | Final Setting Time | 123 minutes | Not more than 600 minutes |
| 3 | Compressive Strength, 3 days | 25MPa | Not less than 23MPa |
| | Compressive Strength, 7 days | 36MPa | Not less than 33MPa |
| | Compressive Strength, 28 days | 49MPa | Not less than 43MPa |

**(a) Carry bags ('Kit fibre')** **(b) PET bottles ('Bottle fibre')**

**Fig 3.3 Type of fibres**

### 3.2.2 Mixing, Moulding and Curing

Various mixing procedures that are given in literature are reviewed (Walker and Stace, 1997; Morel et al. 2000, Perera and Jayasinghe 2003, Mesbah et al. 2004, Walker 2004, Bahar et al. 2004). Prior to the mixing, the natural soil constituents for block production were prepared by initially air drying, lumps of dried soil were broken down manually and sieving was done to remove particles exceeding 4.75mm. To achieve uniformity, materials were carefully weight batched into the tray prior to compaction. In the case of stabilised soil, a homogeneous mixture was obtained by blending the required amount of Cement with the dry soil in a tray before adding water and further mixing. Then required water was added to the uniform mixture of soil, soil- cement, or soil-cement- fibre as the case may be, to attain the optimum water content (OMC = 14 percentage by weight of soil/soil-cement mixture). Same water content was used for all the block compositions (with and without Cement and Fibre). During the mixing process, the fibres were added by hand in stages, to achieve a homogeneous Soil - Cement - Fibre matrix. Mixing was continued to get a uniform distribution of fibres throughout the above matrix, without aggregation of the fibres, which will result in the congestion and conglomeration of the matrix.

Summary of the input variables used in the experimental investigation is shown in the Table 3.3.

**Table 3.3: Summary of the main constituent materials and input variables used in the Investigation**

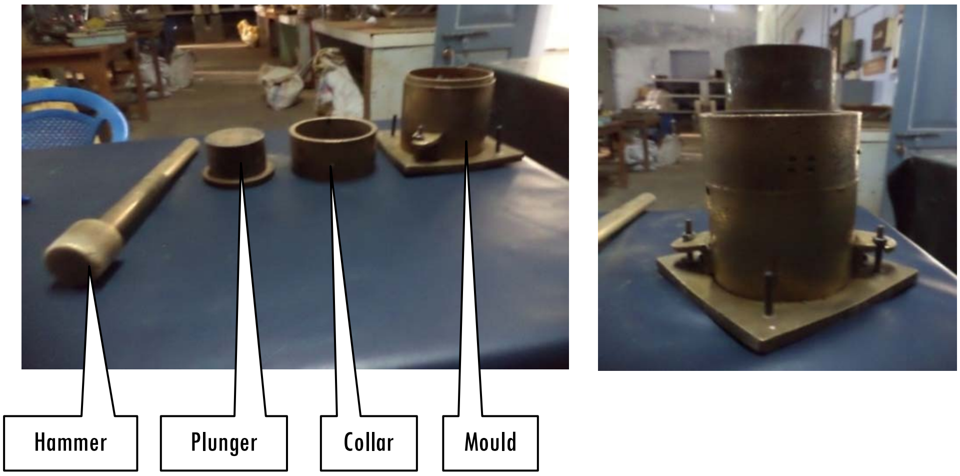
| Symbol | | Input variables | Unit | Quantity | Variation | |
|---|---|---|---|---|---|---|
| Cylinder | Block | | | | Fixed | Variable |
| S | | **Soil** | | | | |
| | | Sand | % | 52 | ✓ | |
| | | Silt | % | 42. | ✓ | |
| | | Clay | % | 6 | ✓ | |
| | | **Stabilizer** | | | | |
| C | | OPC | % | 5 - 15 | | 5C – 15C |
| | | **Mix water** | % | 14 | O M C | |
| P | | **Moulding Pressure** | MPa | 1.25 - 7.5 | | P1-P6 |
| | | **Curing** | | | | |
| | | Duration | Days | 28 | | |
| | | Condition | | Under wet gunny bag | | |
| | | **Fibre** | | | | |
| B | | Bottle ( PET bottle) | % | 0.1 – 0.2 | For a length of 1 cm and 2 cm | 1B1 – 2B2 |
| K | | Kit (Carry bag) | % | 0.1 – 0.2 | | 1K1 – 2K2 |

Note: Specimen Symbol S 10 C P5 1K2 stands for Cement = 10%; Moulding pressure = 6.25MPa; Length of Kit fibre = 1cm; Fibre content = 0.2% (For Cylindrical specimens and Blocks).

The blocks were compacted immediately after the mixing was over. The density of the blocks depends on the Moulding (Compaction) pressure. Constant compaction pressure is only possible in the case of the ASTRAM (Developed by the Department of Civil Engineering, IISC Bangalore in 1979) or similar conventional machines used for making the blocks. Under normal operation, a single acting ram develops a compaction pressure of approximately 2MPa (Walker and Stace, 1997).

Walker (1995) reported that in his tests, the compactive effort for all blocks produced, varied between 2 - 3.5MN/$m^2$, with an average for the majority of consignments of 2.5MN/$m^2$. While Krishnaiah and Reddy (2008) have reported a Moulding pressure of 50 kg/$cm^2$ (5MPa), Walker (1995) reports a compaction pressure of 2-10MPa. Investigations on blocks, by increasing the compacting stress from 5 to 20MPa (Riza et al. 2011) and from 2.1 to 7.3MPa (Bahar et al. 2004), were reported. Preliminary investigations on the performance of blocks reinforced with plastic fibres have shown that the performance of the blocks was reduced in some cases due to the relaxation and slippage of the fibres from the Soil Cement matrix. This defect gets reduced by moulding the samples at higher moulding pressures. In the investigation, a moulding load of 10 to 60kN on the cylindrical samples (corresponding to a moulding pressure of 1.25 to 7.65MPa) has been applied using the Compression Testing Machine. Similar tests were carried out on moulded masonry blocks also by changing the input variables. The tests on cylinders and blocks reveal consistency in results and a constant relation was maintained between cylinder strength and block strength. Cylindrical specimens were subjected to all the listed experiments and the results are correlated to blocks too. As the cylinder strength and block strength have consistent relation, conclusions derived for cylinders are extended to blocks also.

Cylindrical samples were prepared by filling the soil at stages, in a mould of internal diameter of 101.5mm and a height of 117mm with the collar of height 50mm on its top (Fig 3.4). Soil requirement for each sample at a given moulding pressure was arrived by trial and error. To achieve uniformity, materials were carefully weight batched into the mould prior to compaction. Required soil was filled in layers to the mould with the collar, applying conventional tamping. Then the soil in the mould was compressed to the required moulding pressure by using a Compression Testing machine. Then the collar was removed and the excess soil was trimmed to make it level with the top of the mould. After compaction, the specimens were extruded from the mould and stacked for curing. Cement stabilized specimens were moist cured under Jute bags for 28 days before the preparation for testing (Fig 3.5). The unstabilised specimens were air dried in the laboratory, until testing.




**(a) Mould and accessories** **(b) Set up ready for applying the pressure**

**Fig 3.4 Preparation of Test Specimens**

Fig 3.5 Curing of Cylindrical specimens in progress

Blocks measuring 305 x 143 x 100 mm were made by the same procedure given as above by filling the special mould devised for the block making. The stages of evolution of blocks is shown in the Fig 3.6(a) to Fig 3.6(e) with soil, soil-cement or soil-cement-fibre mix at different proportions. Then, the blocks were suitably stacked for curing of 28 days.


Fig 3.6(a) Details of Block making mould

Fig 3.6(b) Block making mould after assembling

Fig 3.6(c) Filled mould with collar ready for compression

**Fig 3.6(d) Application of Moulding pressure using Compression Testing Machine**

**Fig 3.6 (e) Masonry blocks ready for Curing**

## 3.3 Testing Methods and Testing Program

### 3.3.1 General

In order to evaluate the performance of Fibre Reinforced Mud blocks, the following tests shown in Table 3.4 were conducted, details of which are given in the following sections.

**Table 3.4 Tests conducted**

| Sl. No. | Tests conducted | Reference Standards |
|---|---|---|
| 1 | Compressive strength | BIS : 3495, (Part I) 1976 |
| 2 | Split tensile strength | BS 1881, (Part 4) 1970 |
| 3 | Block dry density | BIS 1725 , 1982 |
| 4 | Water absorption | BIS 3495 (Part II) 1976 |
| 5 | Sorptivity | Courtesy Hall (1989) |
| 6 | Durability studies – Spray test | BIS 1725, 1982 ( 2002) |

### 3.3.2 Compressive Strength

#### 3.3.2.1 Cylindrical Specimens and Soil Blocks

Compressive strength test was based on BIS code IS 1725- 1982 (Reaffirmed in 2002) and tested in accordance with IS 3495 – 1992 except that the test was conducted at ambient air dry moisture condition. This is necessary, to facilitate optimum performance of masonry units at service condition. Hence Testing of blocks, in a service condition is most logical and is justified. For unstabilised blocks, compressive strength when saturated is zero. Similar aspects were also discussed by (Walker 2004, Morel et al. 2007).

### 3.3.2.2 Masonry

Procedure of preparing and testing of masonry prisms are as per the details given in Reddy and Guptha (2006). The compressive strength of the mud block masonry was determined by testing masonry prisms. Three blocks of size 305 x 143 x 100 mm were used and they were bonded to get a masonry prism of overall size 305x143x324mm, having a mortar thickness of 12mm. The soil-cement mortar was used for bonding the blocks in the masonry. Consistency could be measured by Slump testing which is proved to be the most reliable means of assessing soil - cement mortar workability as per Walker and Stace (1997). Flow test as per BS 4551, 1980: Methods of testing mortar, screeds and plaster, was conducted (Morel et al. 2007) and it was fixed as a flow of 100%. Studies by Walker and Stace (1997) and Reddy and Gupta (2006) demonstrated that cement-soil mortar, which is cheaper than conventional mortars, can be beneficially used for SMB masonry. Also, studies suggest soil-cement mortars in proportion similar to those used for block production. The water requirement for soil-cement mortar is fixed for a flow of 100%, after the flow test conducted as per BIS 5512, 1983. A mortar joint thickness of 12mm was maintained for all the prisms. The moisture content of the block during the casting of prism specimens can affect the bond strength of masonry. Partially saturated blocks (75% saturation) lead to maximum bond strength (Reddy and Gupta, 2006). Fig 3.7 shows the variation of % water absorption with immersion time for blocks which are used for making the masonry prisms (for 10% cement and 7.5MPa moulding pressure). The maximum % water absorption for each combination is also shown in the figure. It can be seen that 75% of the maximum water absorption is taking place within 9 to 15 minutes. Thus to avoid the interference of the moisture content of the block with the masonry strength, blocks were soaked in water for a period of 15 minutes prior to testing to keep the moisture content constant. The prisms were cured for 28 days in a moist condition under jute bag. The masonry prisms were tested in ambient air dry conditions in a compression testing machine and the longitudinal compressive strains were measured as the movement of the platen by a dial gauge of least count 0.002mm and capacity of 10 mm.

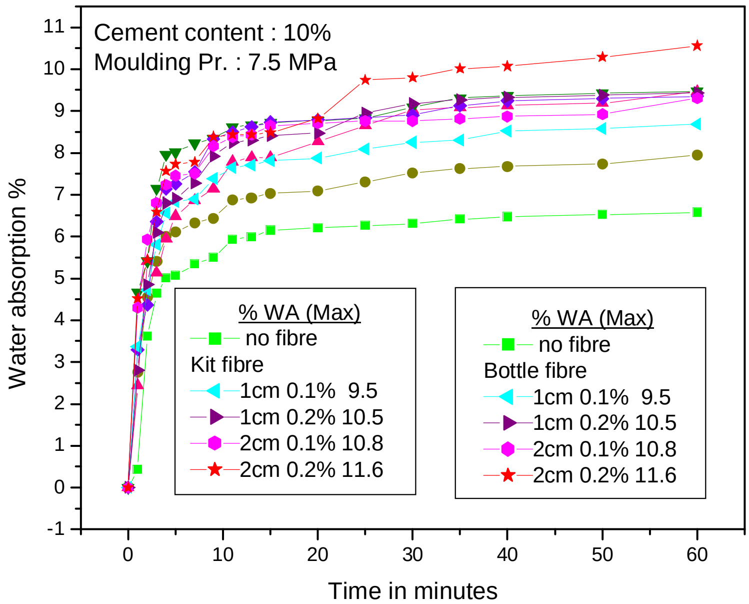



**Fig 3.7 Rate of water absorption**

The Stacking of blocks for curing is shown in Fig 3.8(a) and the test setup is shown in Fig 3.8(b).

**Fig 3.8(a) Masonry prisms stacked for curing, prior to testing**

**Fig 3.8(b) Load Test on prism in progress**

### 3.3.3 Tensile Strength

Tensile strength was measured using Split test on cylindrical specimens. In this test, a soil cylinder, of the type used for compression tests, was placed with its axis horizontal between the platens of the compression testing machine, and the load was increased until failure by splitting along the vertical diameter. If P is the failure load, split tensile strength = $2P/\pi DL$, where D is the diameter and L is the length of the specimen. The test is covered by BS 1881 (Part 4), 1970: Method of testing of concrete for strength.

### 3.3.4 Sorption Characteristics

#### 3.3.4.1 Water Absorption

Water absorption test is based on BIS 1725, 1982 (Reaffirmed in 2002) and tested in accordance with BIS 3495, 1992: the code for the test on burned clay bricks The specimens were wetted in cold water for 24 hours and its weight was determined. Then they were kept outside and air dried for few days. Then it was kept in an oven at a temperature of $105^{o}C$ till a constant weight was obtained. The difference in the two weights is expressed as a percentage of dry weight, gives the water absorption percentage.

### 3.3.4.2 Sorptivity

Capillary absorption of water by the specimens was done using the Sorption test. Sorptivity is an easily measurable property which characterises the tendency of a porous material to absorb and transmit water by capillarity, a main mechanism responsible for the ingress of contaminated water through the surface skin of the unsaturated ground structures. The movement of water into building material is described through classical square-root-time relationship by Hall (1889), $i = A + St^{0.5}$, where $t$ = elapsed time, $i$ = cumulative volume absorbed per unit area of inflow surface, $S$ = sorptivity of the material obtained from the slope of the $i$ versus √t curve using best fit linear regression and $A$ = constant term which is the intercept at $t$=0.

For sorptivity tests, the bottom surface of the cylindrical specimens was made to have contact with water during the test. During this experiment, the water level in the pan was maintained at about 5mm above the base of the specimen. Care has been taken to keep the other contact surfaces with water than the bottom to be water tight, by using epoxy coating. The weight of the specimen was measured using a balance, then the amount of water absorbed was calculated and normalized with respect to the surface area of the specimens exposed to water, at different intervals of time viz. 1, 4, 9, 16, 25, 36, 49, 64, 81, 100 and 121 minutes. The experimental setup is shown in Fig 3.9.

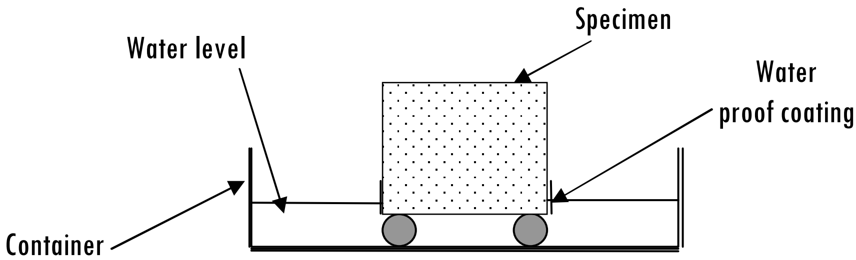




**Fig 3.9 Sorptivity test in progress**

## 3.3.5 Erosion Studies

Erosion studies are based on BIS code IS 1725, 1982(reaffirmed in 2002). Spray erosion tests most closely simulate the effect of rainfall impinging on the surface of a wall. The rain parameters simulated in the spray tests are the (i) Rain drop diameter at impact (2mm for medium intensity and 4mm for high intensity), (ii) Maximum terminal velocity of 6.5m/s at impact, and (iii) Maximum intensity of rainfall 15 to 30mm/h. A spray shower that can produce hard spray all over the exposed surface of the specimen was devised and was used for the test. Diameter of the shower is 100mm with 36 holes of 2 mm diameter. Water was sprayed through these holes at a pressure of 1.5kg/cm$^2$ (which can be measured by a pressure gauge attached to the system), using a centrifugal pump. The test set up is shown in Fig 3.10.

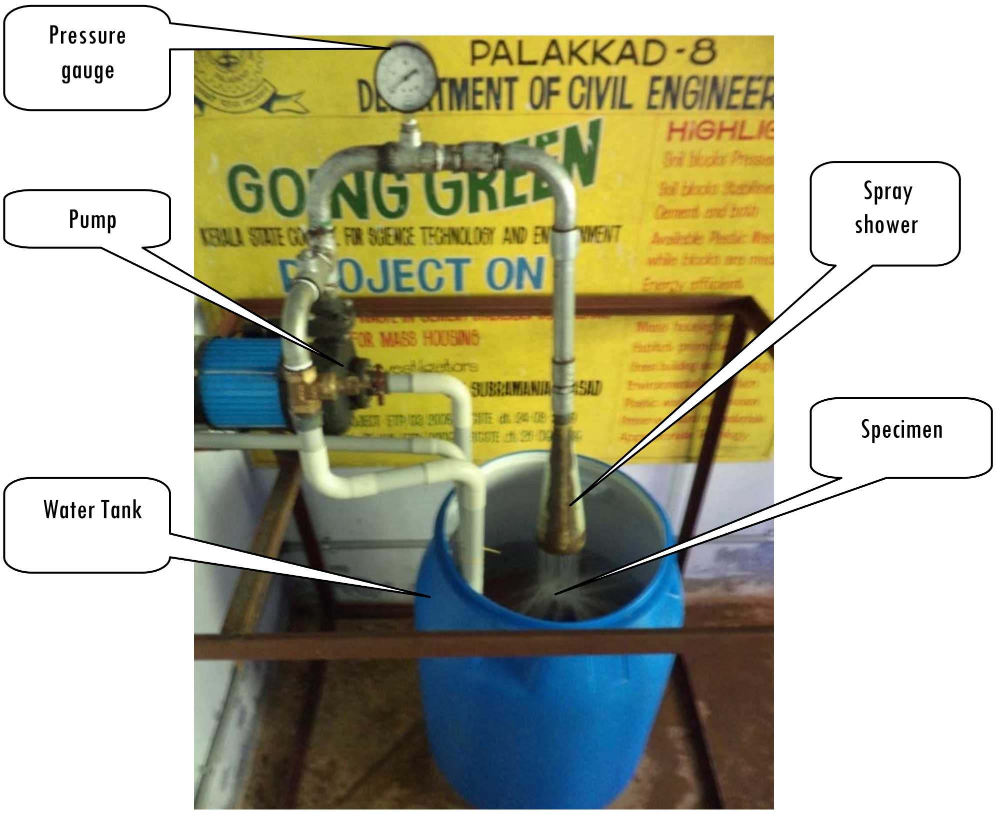



**Fig 3.10 Spray Erosion set up**

The specimen was kept on the support in such a way that one circular face of the specimen is exposed to the spray and at a distance of 180 mm from the spray. The surface was exposed to a shower of two hrs of spray and the surface was inspected for any pitting. Limiting diameter of the pit formed is 10mm and a limiting loss in weight is 5%, for passing the weathering test, as per BIS 1725, 1982 (Reaffirmed in 2002).

## 3.4 Summary

As a preliminary phase, the performance of soil blocks were studied through reviewing the literature and collecting the theoretical knowledge and conducting pilot studies on soil block specimens varying different parameters. From the indications of the preliminary tests and results, all the input variables (for an elaborative systematic study) that can influence the quality and the performance of the masonry unit and the extent of its variation, in service could be identified. The characterisation of various materials used for the experimental investigations are done. The procedures of various tests conducted are also explained. The results of the experimental investigations are analysed in the following chapters.

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Chapter 4

# STRENGTH CHARACTERISTICS OF CYLINDER, BLOCK AND MASONRY



## 4.1 General

This chapter deals with the analysis of experimental investigations conducted to ascertain the influence of combinations and compositions of Soil, Cement, Fibre and Moulding pressure, on the strength characteristics of cylinder, block and masonry. Experiments were conducted for different Moulding pressures, Cement content, types of Fibre, their length and volume to determine the Density, Compressive strength, Tensile strength. The role of each ingredient and its properties, on these variables was investigated. Determination of the Masonry strength has been done using Masonry prisms. Results of the experiments by varying the constituents, their proportions, properties and Moulding pressure are analysed to understand the behaviour of Plastic Fibre Reinforced Soil blocks and that of the masonry system made out of these blocks.

## 4.2 Density

Dry density of samples with different composition (three samples for each composition) is determined after drying it in an oven at a temperature of 105$^{o}$C. The results are analysed for the effect of Moulding pressure, Cement content, Fibre type, its length and volume as described below.

### 4.2.1 Effect of Moulding Pressure

Fig 4.1 shows the effect of Moulding pressure on the dry density. For given Cement content, as Moulding pressure increases, the dry density increases. The marked increase in density witnessed in modified specimens could have been due to the following factors like (i) Pore filling effect (ii) Increased homogeneity (iii) Improved bonding and also (iv) Reduced voids. The measured Density was found to vary between 1.846 to 1.958g/cc. These values are in conformity with the desirable limit, for producing a stabilized mud block, which is specified as 1.8 to 1.85g/cc (Jagadish, 2007). The density was found to be 1.805 to 1.894g/cc, in the preliminary studies on the mud blocks, which were made, using ASTRAM. In the present study, these values correspond to a Moulding pressure of 1.25MPa. There is an increase in density about 6 % when the Moulding pressure is increased from 1.25 to 7.5MPa.

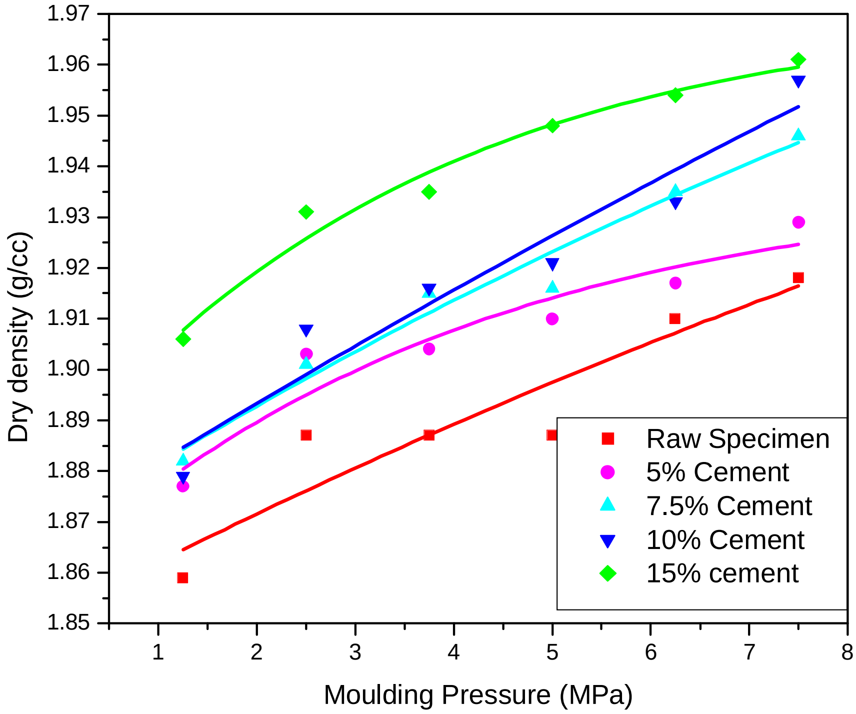


**Fig 4.1 Effect of Moulding pressure and Cement content on dry density**

## 4.2.2 Effect of Cement Content

The effect of Cement content on dry density was investigated, for given Moulding pressure and different Fibre properties. The curves are shown in Fig 4.2(a) which corresponds to a low Moulding pressure of 1.25MPa and for Kit fibres. Fig 4.2(b) corresponds to that of Bottle fibres. The fibres do not contribute much for the improvement of density. Higher the length of fibre or its content, the value of density is reduced. However this reduction is compensated by increasing the Moulding pressure. The rate of increase in density is pronounced when the moulding pressure is increased

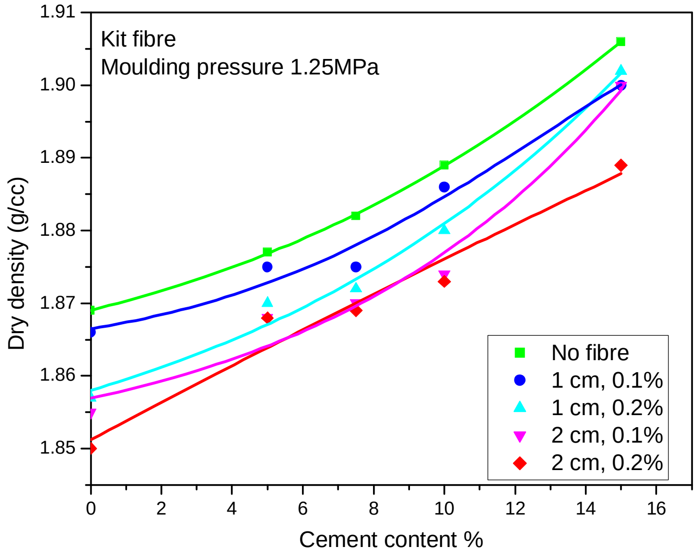


**Fig 4.2 (a) Effect of Cement content on dry density (Moulding pressure 1.25MPa; Kit fibre)**

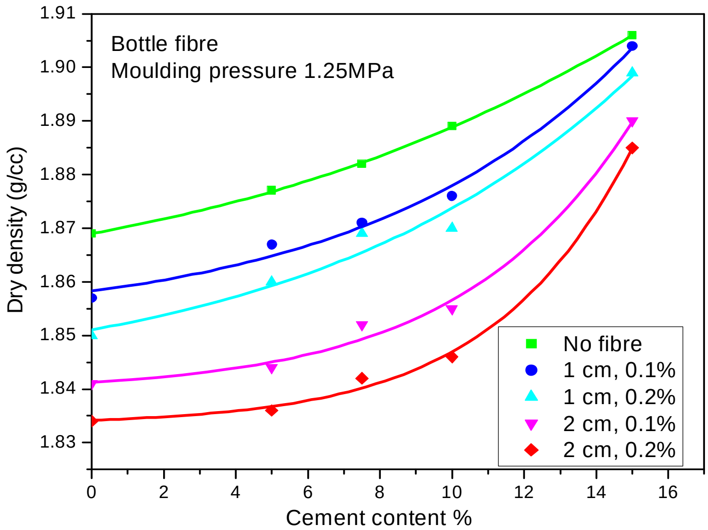


**Fig 4.2 (b) Effect of Cement content on dry density (Moulding pressure 1.25MPa; Bottle fibre)**

Fig 4.2(c) reveals the effect of Moulding pressure as high as 7.5MPa and for the Kit fibre properties on the Density. The effect of the Bottle fibre properties on density is shown in Fig 4.2(d). From these figures, it is evident that increase in the Cement content enables the fibres to recoup density, but not that much as in the case of increase in the Moulding pressure. When the Cement content was increased from 0 to 15%, there was an increase of 2.2 to 3.7% in the density. Choudhary (2004) in a study has reported that Cement content has little effect on the block density. The small increment attained in the study may be due to the higher specific gravity and the use of 43grade Cement.

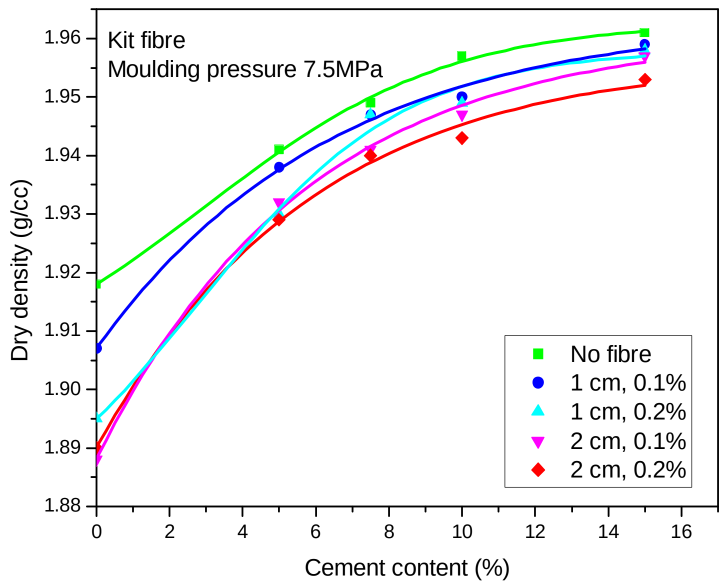


**Fig 4.2 (c) Effect of Cement and fibre content on dry density (Moulding pressure 7.5MPa; Kit fibre)**

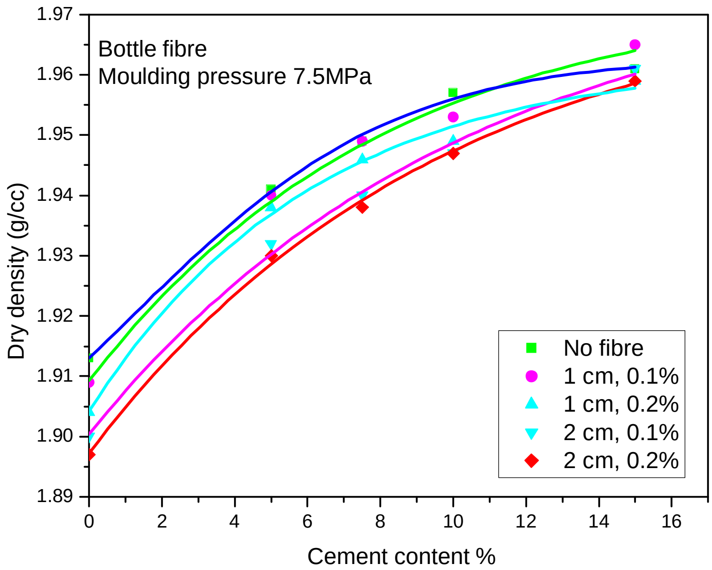


**Fig 4.2 (d) Effect of Cement and fibre content on dry density (Moulding pressure 7.5MPa; Bottle fibre)**

### 4.2.3 Effect of the Type of Fibre, its Length and Content

From Fig 4.2, it is evident that any addition of fibre reduces the density and Table 4.1 gives the percentage reduction in the density, for different type, length and quantity of Fibre. It is clear from the table that effect of the Fibre content was less pronounced on the density of the specimens. However there is only a small decrease in the density, over a range of 0 to 1.87%. This is because of the low specific gravity of the Fibres, the values being 1.10 for Kit fibre and 1.17 for Bottle fibre. Similar type of observation is made by Chee-Ming Chan [2011] in a study using natural fibres in clay bricks. It can be observed from Fig 4.2 and

Table 4.1 that, a maximum reduction of 1.87% in density occurs at a higher content of Bottle fibre, for a low Moulding pressure of 1.25MPa and without Cement. For a higher Moulding pressure of 7.5MPa and a Cement content of 15%, there was no reduction in density. The loose state of fibres at low Moulding pressures and for low Cement content may be the reasons for the decrease in density.

Low moulding pressure, leaves behind air spaces in the specimen, makes the specimens loose and less dense. Higher compacting energy enables the particles to come closer reducing, the voids. The specimens thus become denser. Due to this, the bond between the Fibres and the Soil would be increased in the presence of Cement.

**Table 4.1 Percentage Reduction in Density for different Fibre content and length**

| Cement content (%) | Moulding pressure (MPa) | Type of fibre | Reduction in density (%) for fibre length | | | |
|---|---|---|---|---|---|---|
| | | | 1 cm | | 2 cm | |
| | | | 0.1% | 0.2% | 0.1% | 0.2% |
| 0 | 1.25 | Kit | 0.16 | 0.64 | 0.75 | 1.02 |
| | | Bottle | 0.64 | 1.02 | 1.5 | 1.87 |
| | 7.5 | Kit | 0.47 | 0.73 | 0.94 | 1.09 |
| | | Bottle | 0.57 | 0.94 | 1.56 | 1.46 |
| 15 | 1.25 | Kit | 0.31 | 0.21 | 0.31 | 0.89 |
| | | Bottle | 0.14 | 0.31 | 0.89 | 1.1 |
| | 7.5 | Kit | 0.2 | 0.39 | 0 | 0.39 |
| | | Bottle | 0.39 | 0.25 | 0.2 | 0.41 |

## 4.3 Compressive Strength of Cylindrical Specimens

Cylindrical samples of diameter 101.5mm and height 117mm were prepared and the tests have been carried out. The tests were conducted on cylindrical samples to correlate the values of Compressive strength with that of Tensile strength (by Split Tension test). The sample will be a relevant replica, on the engineering properties of the soil, as the value of dry density and OMC has been found out using Proctor mould for light compaction.

### 4.3.1 Effect of Moulding Pressure

The effect of Moulding pressure on Compressive strength is shown in Fig 4.3.

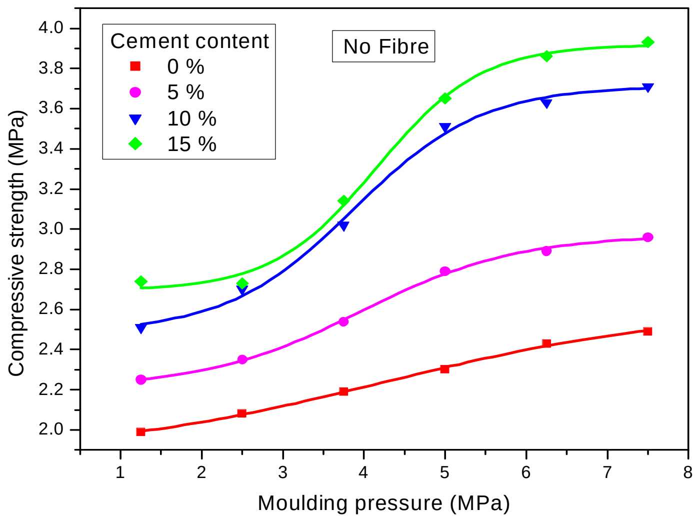


**Fig 4.3 Effect of Moulding pressure on Compressive strength**

In general, as the Moulding pressure is increased, the Compressive strength increases. About 20 to 50% increase in the Compressive strength was observed when the Moulding pressure was increased from 1.25 to 7.5MPa. A study reported by Riza et al. (2011) concluded that by increasing the compacting pressure from 5 to 20MPa, improves the Compressive strength up to 70%. Bahar (2004) in his study reported that dry Compressive strength increases with the Static applied stress. About 60% increase of the dry Compressive strength was obtained when the applied Static stress was increased from 2.1 to 7.3MPa (Bahar, 2004). For given Compaction pressure, as the Cement content is increased, there resulted an increase in the Compressive strength. Effectiveness of Cement content was more at higher Moulding pressures compared to the lower pressures. However, for a Moulding pressure more than 5MPa, the rate of increase in strength reduces. This may be due to a reduced water for the hydration of Cement as it was observed that some water in the samples comes out at higher Moulding pressures. It is seen that, the Compressive strength can be improved from 2.5 to 3.7MPa by increasing the Moulding pressure and with addition of 10% of Cement.

### 4.3.2 Effect of Cement Content

Fig 4.4 shows the variation of Compressive strength of the specimens with Cement content, for different Moulding pressures. There was an increase in the Compressive strength, with an increase in the Cement content for any Moulding pressure. Due to the Cement addition alone, there was an increase of 38 to 58% in the Compressive strength, for Moulding pressures of 1.25 to 7.5MPa. For given Cement content, as Moulding pressure increases, Compressive strength also increases. This increase in Compressive strength is more significant for Cement content up to 10% and beyond 10%, the effectiveness of Cement addition was not substantial for any Moulding pressure. This may be due to the lesser Fibre Cement ratio in the Soil Cement matrix. The final strength of the specimens appears to be more sensitive to changes in Cement content than Moulding pressure. This improved strength may be attributed to the (i) Pore filling effect (ii) Increased homogeneity and (iii) Improved bonding.

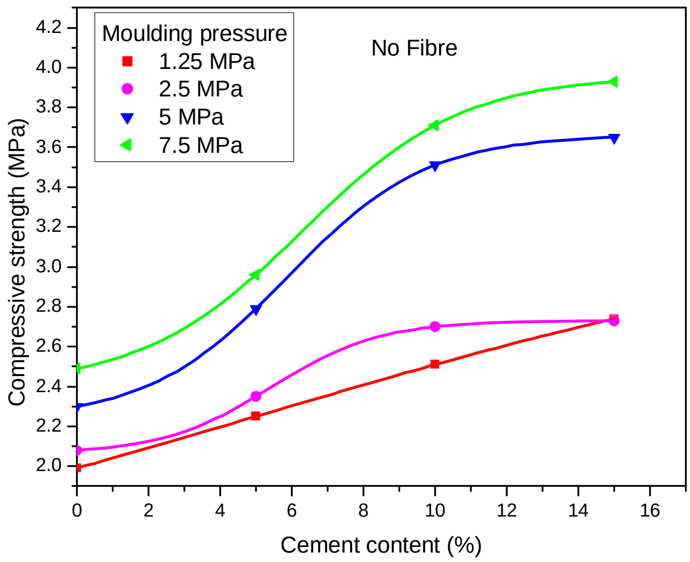


**Fig 4.4 Effect of Cement content on Compressive strength**

### 4.3.3 Effect of Type of Fibre

The effect of the fibre type on the Compressive strength is shown from Fig. 4.5(a) to Fig 4.5(c). Fig 4.5(a) reveals that, any addition of fibre in the raw soil reduces the strength, as all the lines are below the thick line which corresponds to the specimens without fibre, up to a Moulding pressure of 5MPa for Bottle fibres and up to 2.5 to 3.7MPa for Kit fibres. However at higher Moulding pressures, the addition of these fibres improves the strength. There seems an inhibition on the part of fibres, in assisting the soil to take more Compression at low Moulding pressures. The reduction in strength may be due to the lack of proper bond between the fibres and the Soil at low pressures. It also affects the Soil homogeneity, which would have caused a reduction in the strength.

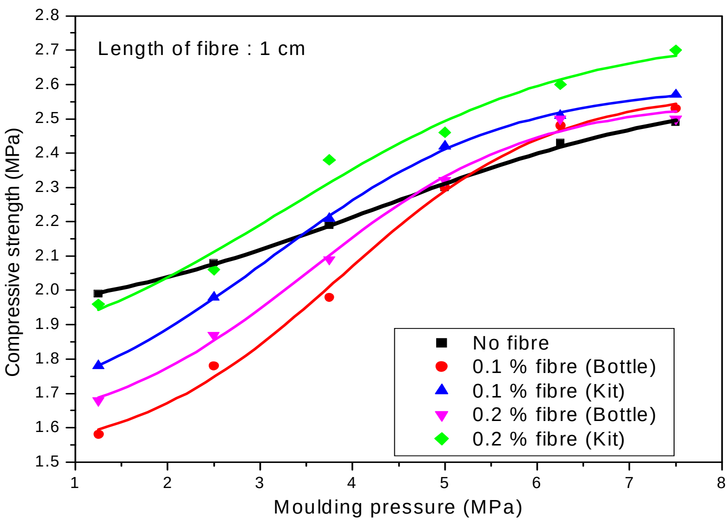


**Fig 4.5(a) Effect of fibre and Moulding pressure on Compressive strength (Raw Soil specimen)**

As Moulding pressure increases, the bond is improved and the strength has increased correspondingly. In the case of specimens stabilised with Cement, all fibres performed better even at lower Moulding pressures which are evident from Fig 4.5(b) and Fig 4.5(c). This may be attributed to an increased bond between the Soil and the Fibres in the presence of Cement. Cement contributes much, for an increase in the Compressive strength. This strength gain is again supported by increasing the Moulding pressure. The presence of fibres adds to the value of Compressive strength, with the help of Cement and Moulding pressure. Even though the role of fibres in increasing the compressive strength is subsequent to that of Cement and Moulding pressure, it contributes a substantial percentage of increase in compressive strength, especially at higher Moulding pressure, and with optimum quantity of Cement.

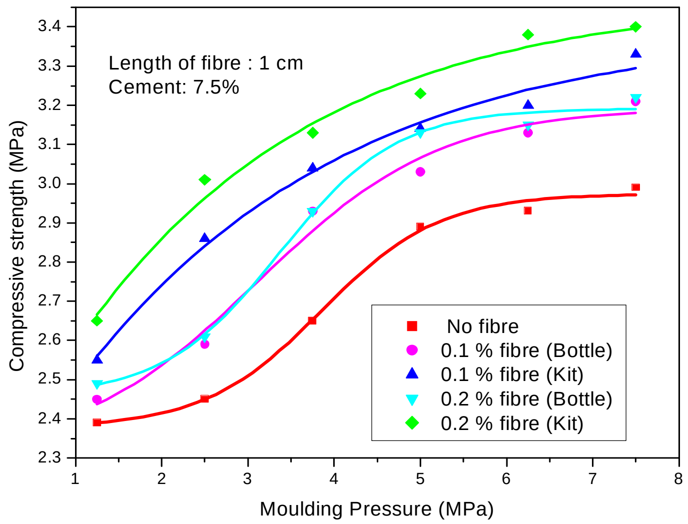


**Fig 4.5 (b) Effect of fibre and Moulding pressure on Compressive strength (7.5 % Cement)**

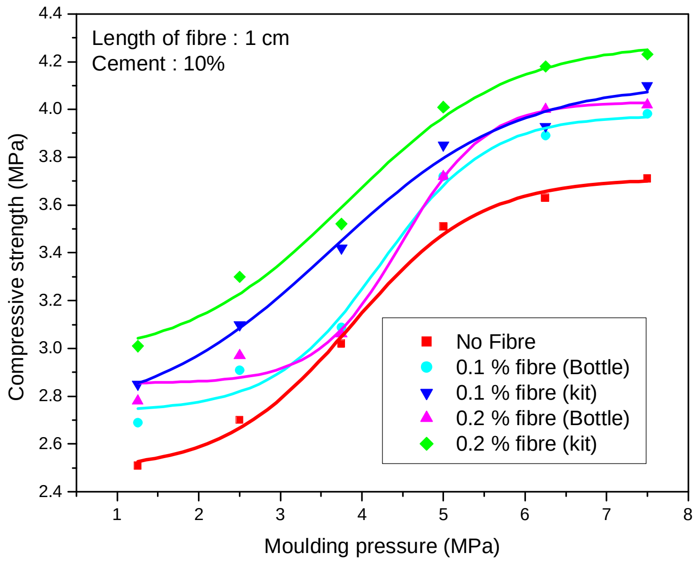


**Fig 4.5 (c) Effect of fibre and Moulding pressure on Compressive strength (10 % Cement)**

Regarding the type of Fibres, those made out of carry bags (Kit fibres) are found to be more effective. Fig 4.5(a) to Fig 4.5(c) establishes this fact. This may be due to the fact that, these fibres are flexible and while making the specimens, they bend and cause better bond in the Soil Cement matrix (Fig 4.6). Lesser efficiency of fibres made out of Bottle (Fig 4.7) may be due to the following reasons: i) The type of surface finish which results in lack of bond with Soil ii) Due to the stiffness of the fibres, during mechanical compression, the soil particles may laterally move apart, leaving behind air spaces between the Fibres and the Soil. This may result in the formation of weaker planes.


**Fig 4.6 Fibres in their loose state**

This relaxation of Fibres may be reduced by moulding the block at higher Moulding pressures and the stabilization of Soil using Cement, as seen from the test results.

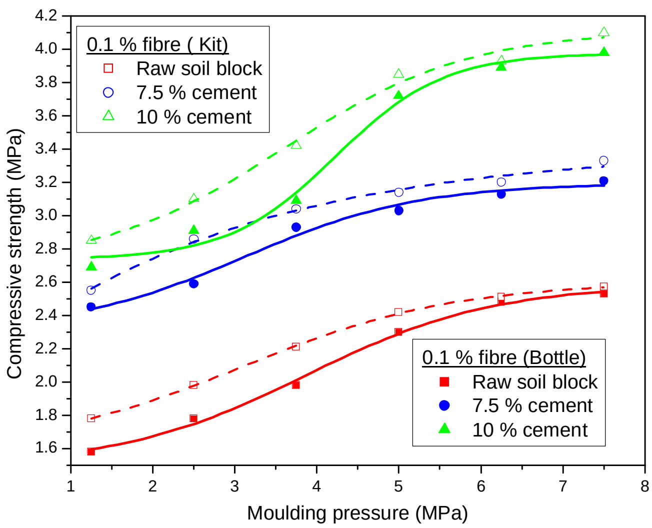


**Fig 4.7 Effect of type of Fibre and Cement content on Compressive strength**

### 4.3.4 Effect of length of the Fibre and its Quantity

The effect of length of the fibre and its quantity on the Compressive strength, for different Moulding pressures is shown in Fig 4.8(a) and Fig 4.8(b). From these figures, it is evident that, the fibres having a length of 2 cm and a weight of 0.2% by the weight of Soil, adversely affect the Strength performance of the specimens considerably. Further, the presence of higher percentage of longer Bottle fibres showed inconsistent results.

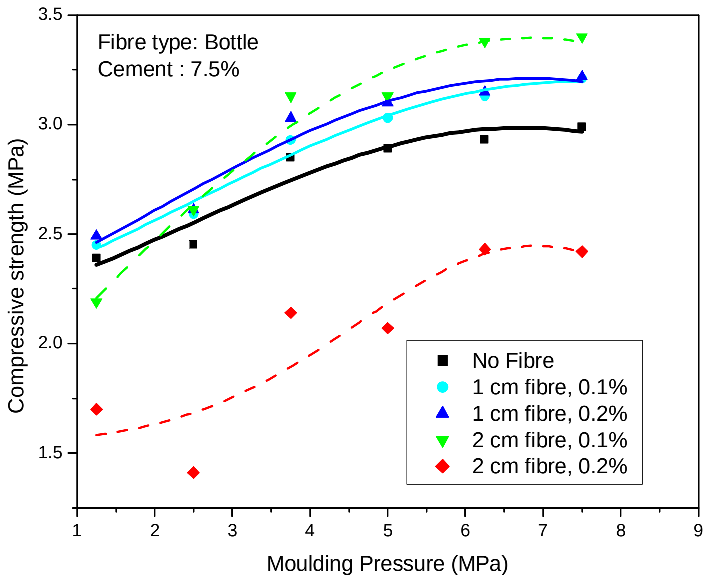


**Fig 4.8 (a) Effect of fibre content and length on the Compressive strength (7.5% Cement and Bottle fibre)**

The Fibres made out of carry bags (Kit fibres) showed better performance when the length is increased. This may be due to the fact that, as the length of fibre is increased from 1 to 2cm, the bond between Fibres and the Soil is increased. This increase in bond is attributed to the fact that, while making the specimens they bend and cause better bond in the Soil Cement matrix, as these fibres are more flexible in nature. For the Kit fibres at higher volumes, there was a reduction in strength even though the behaviour is consistent. This reduction may be due to non-uniform distribution of the large quantity of fibres present in the specimens, thus leading to the formation of weaker planes.

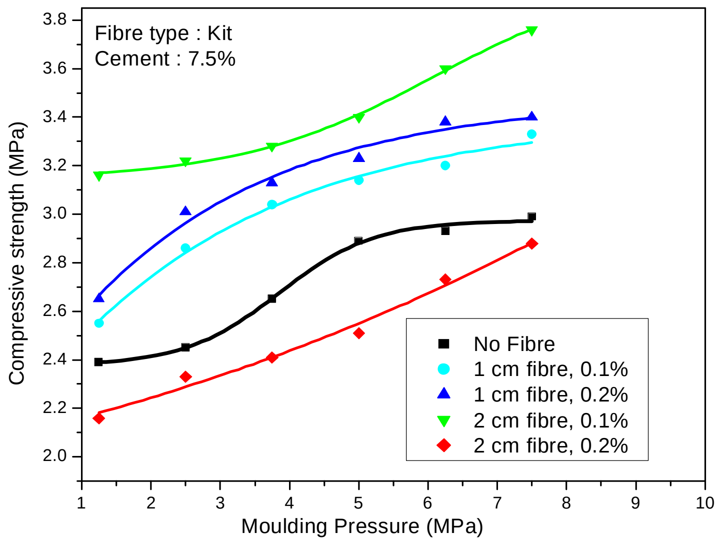


**Fig 4.8 (b) Effect of fibre content and length on Compressive strength (7.5% Cement and Kit fibre)**

### 4.3.5 Percentage Increase in Strength

The Compressive strength of the specimens after 28 days of curing, was found to vary from 1.99 to 4.40MPa for different combinations of the stabilisers (Cement and Moulding pressures), the type of fibres, the length of fibres and their volume. The variation in the Strength in percentage, by the effect of Stabilisation, the addition of Fibres, and the Moulding pressure with respect to that of the raw Soil samples are shown in Table 4.2. The table displays the extremities of values, considering the worst case of using Bottle fibres, 2cm long, 0.2% by weight of the dry Soil and an ideal case of using Kit fibres, 2cm long, 0.1% by weight of the dry Soil.

**Table 4.2 Percentage increase in the Compressive Strength**

| Moulding pressure (MPa) | % increase in Strength compared to raw Soil specimens (1.99MPa) | | | | | |
|---|---|---|---|---|---|---|
| | Fibre Content and Length | Cement C (%) | | | | |
| | | 0 | 5 | 7.5 | 10 | 15 |
| Lower P (1.25) | Nil | 0 | 13 | 20 | 26 | 38 |
| | 2B2 | -16 | -17 | -15 | 9 | 25 |
| | 2K1 | - 6 | 20 | 59 | 64 | 73 |
| Higher 6P (7.5) | Nil | 25 | 49 | 50 | 86 | 97 |
| | 2B2 | 23 | 18 | 22 | 52 | 71 |
| | 2K1 | 50 | 70 | 89 | 118 | 121 |

P→ Moulding pressure of 1.25MPa
2B2→ Bottle fibre 2cm long, 0.2% weight of Soil
2K1→ Kit fibre 2cm long, 0.1% weight of Soil

The role of Cement is significant, at this context, as it acts as an internal reactive stabilizer to enhance the Compressive strength (Primary stabilisation). The applied Compacting or Moulding pressure increases the strength, by acting as an external active stabiliser (Secondary stabilisation). The Fibres could increase the strength, only in the presence of Cement and Moulding pressure, hence they act as internal embedded passive stabilisers (Tertiary stabilisation).

Compared to the raw Soil specimens, the Fibre reinforced stabilized Soil samples have shown an apparent increase of 20 to 121% in the Compressive strength. However in reality, the effect of fibres is pronounced in Kit fibres having 2cm length and 0.1% by weight of the dry Soil. An optimum Cement content of 7.5% by weight of the dry Soil is required to meet the minimum requirement of strength. The maximum quantity of Cement may be limited to 10% by weight of the dry Soil, considering the rate of increase in the strength and the cost. The practical combinations of the variables are given in Table 4.3.

**Table 4.3 Percentage increase in Compressive strength (Kit fibre 2cm long, 01%)**

| Cement Content (%) | Moulding Pressure(MPa) | | | | | |
|---|---|---|---|---|---|---|
| | 1.25 | 2.5 | 3.75 | 5 | 6.25 | 7.5 |
| 0 | -6(NA) | 4.5 | 10 | 15.6 | 22.1 | 25.1 |
| 7.5 | 59 | 62 | 67 | 73 | 81 | 89 |
| 10 | 64 | 71 | 78 | 105 | 116 | 118 |

Compared to the stabilised samples, the Fibre reinforced stabilised samples showed an increase of 59 to 89 % in the Compressive strength, for a Cement content of 7.5% and 64 to 118%, in the case of a Cement content of 10%, for the range of Moulding pressures from 1.25 to

7.5MPa. The Kit fibres exhibit consistent behaviour and produce reliable results on the Soil, which was selected for the study.

Based on the wet Compressive strength, stabilised blocks may be classified in to three grades viz. (i) Grade 4 with strength range 4 to 5MPa (ii) Grade 3 with strength range 3 to 4MPa (iii) Grade 2.5 with range 2.5 to 3MPa (Jagadish, 2007). Stabilised samples and Fibre reinforced stabilised samples at higher Moulding pressure showed strength values of 3.5 to 4.40MPa, a value which is in conformity with that of minimum Compressive strength of 3.5MPa, for a well burnt brick as per BIS 1077-1992. As per BIS 1725-1982, the blocks which are to be used in general building construction when tested in accordance with the procedure laid in the standards, viz. BIS 3495 (Part I), 1976 shall have a minimum average Compressive strength of not less than 20kgf/cm$^2$ for Class 20 and 30kgf/cm$^2$ for Class 30.

### 4.3.6 Effect of Density

Fig 4.9 shows the variation of Compressive strength with the density of the specimens at service condition. Obviously, the Compressive strength increases with the density. For given density, specimens containing fibres made out of carry bag (Kit fibres) showed higher strength compared to those with Bottle fibres. The specimens without fibres showed the least strength for given density. But at lower density level, specimens with Bottle fibres showed lower strength than those without fibre. But specimens containing Kit fibres performed better than other types, for all density level. This observation once again points towards the better performance of Kit fibres compared to that of the Bottle fibres.

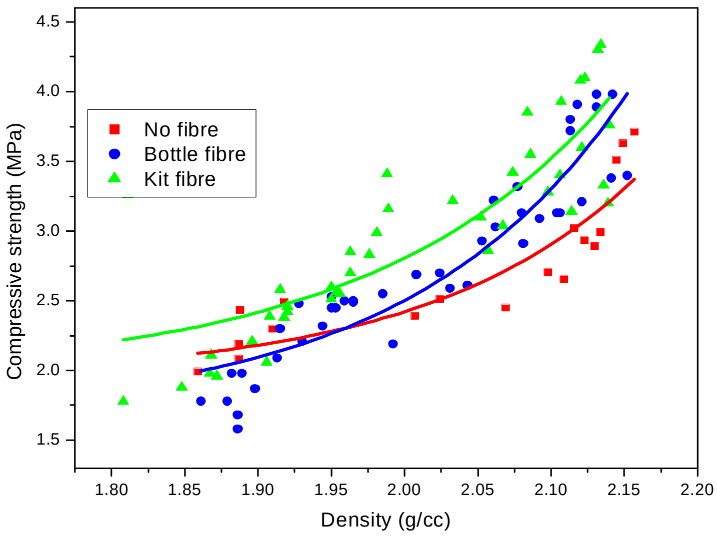


**Fig 4.9 Variation of strength with density**

## 4.4 Compressive Strength of Blocks

Investigations have been done on Unstabilised, Stabilised and Fibre stablised blocks of size 305x143x100mm. The results are very much akin to that of the cylindrical samples. As the characteristic curves are identical to that of the cylindrical samples, with a modification factor, they are not presented here to avoid duplication and repetition. The

Compressive strength of the blocks was found to vary from 1.74 to 5.5MPa for different Cement content, Moulding pressure, type, length and volume of Fibres. Compared to the Compressive strength of cylindrical specimens, all blocks are having higher Compressive strength. The ratio of block strength to cylinder strength ranges from 1.068 to 1.247. This increase in strength (6.8 to 24.8 %) may be due to the platen effect, that is due to friction along the interface between the platen and test specimen, lateral expansion of the specimen is confined. This confinement of specimens by platen restraint increases apparent strength of the material (Walker, 2004; Morel et al. 2007; Piattoni et al. 2011). Also, with the decrement of the aspect ratio, there is an increment of the contact surface between the specimens and the platens (for cylindrical specimens, the contact area is circular with 101.5 mm diameter and for blocks, it is a rectangular area of 305 x 143 mm) and therefore there are big values of the tangential force caused by friction (Piattoni et al. 2011). As the distance between the platens, relative to the specimen thickness (aspect ratio) increases, the platen restraint effect reduces (Morel et al. 2007). Aspect ratio of the cylinders and blocks are 1.153 and 0.70 respectively. Jagadish (2007) reports that about 20% increase in strength may be expected for a 25% decrease in thickness. A sample comparison of Cylinder strength to Block strength , for an optimum Cement content of

7.5%, at different Moulding pressures, without any Fibre, is shown in Fig4.10(a).

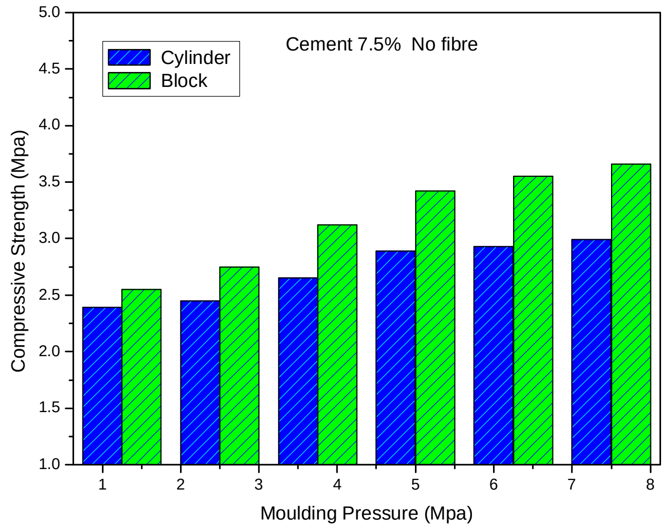


**Fig 4.10(a) Comparison of Cylinder Strength to Block Strength (Cement 7.5%, No fibre)**

To highlight the performance of Kit fibres compared to that of the Bottle fibres, a sample comparison of the Compressive strength of the cylinder and that of the block obtained by using these fibres is shown in Fig 4.10(b) and Fig 4.10(c). From Fig 4.10(b), it is observed that the Bottle fibres, if used in large quantity and at a longer length, affect the strength. As these fibres are stiff, they may exercise a rebound, during the compaction, which would have resulted in a reduction in the Compressive strength. Lack of sufficient bond with Soil Cement matrix may also be another reason. Fig.4.10(c) gives a clear indication of the pronounced influence of Kit fibres, on increasing the Compressive strength. As these fibres are flexible and longer, they bend and curl facilitating better bond with Soil Cement matrix. There will not be a rebound effect during the compaction, since the fibres are not stiff.

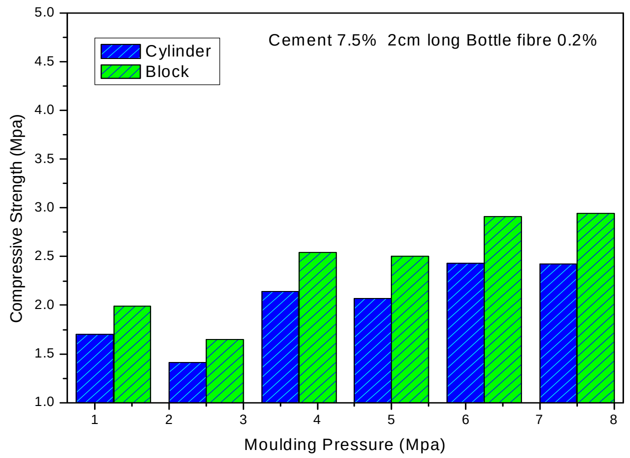


**Fig 4.10(b) Comparison of Cylinder Strength to Block Strength (Cement 7.5%, 2cm long Bottle fibre, 0.2%)**

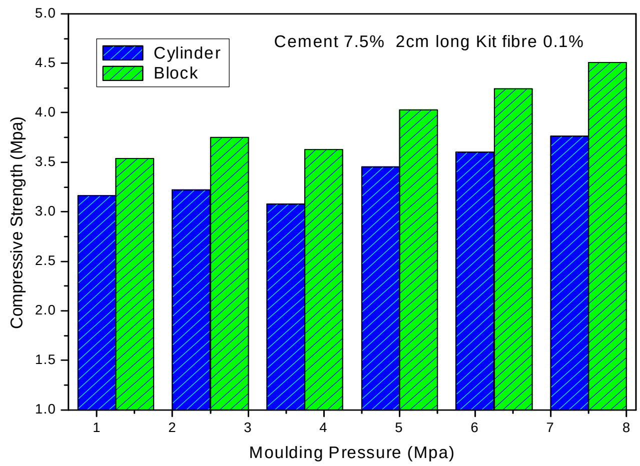


**Fig 4.10(c) Comparison of Cylinder Strength to Block Strength (Cement 7.5%, 2cm long Kit fibre, 0.1%)**

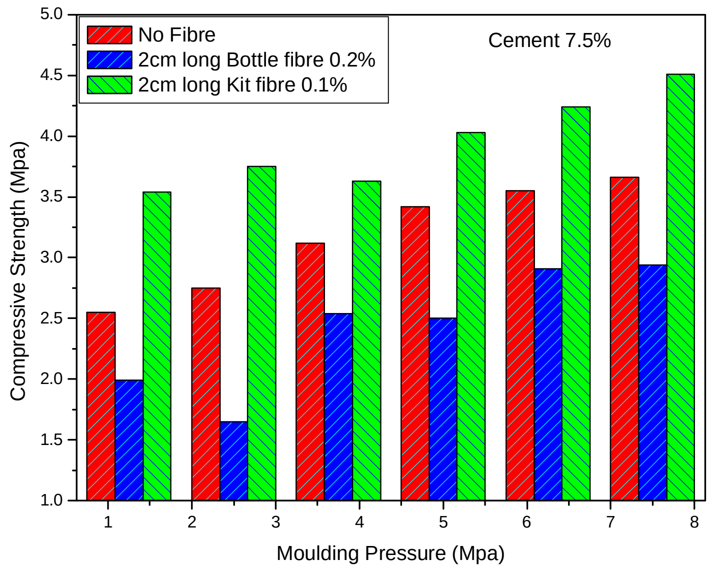


**Fig 4.11 Comparison of Block Compressive Strength (Kit fibres and Bottle fibres)**

Fig.4.11 compares the effect of Fibre properties on the block Compressive strength. As the Kit fibres show better performance compared to that of the Bottle fibres, the extreme values of the two have been taken for the comparison. The performance of Blocks with no addition of fibres is also shown in the figure, to have the reference or base value.

## 4.5 Split Tensile Strength

The effect on the Split tensile strength, by varying Moulding pressure, varying Cement content and varying the type, quantity and the length of Fibres, has been studied. Fig 4.12 depicts the effect of Cement content on the Tensile strength for various Moulding pressures. There results a continuous increase in the Tensile strength corresponding to an increase in the Cement content., When Cement content increases, the Tensile strength increases (Fig 4.13 and Fig 4.14), for given Moulding pressure. There is significant rise in the Tensile strength when the Cement content is increased, and the increase is supported by higher moulding pressures. The rate of increase is higher at higher values of Cement content, unlike in the case of compression, where the rate of increment is less beyond a Cement content of 10%. The rate of gain in Tensile strength is almost constant, in the case of Moulding pressure variation, from lower to higher.

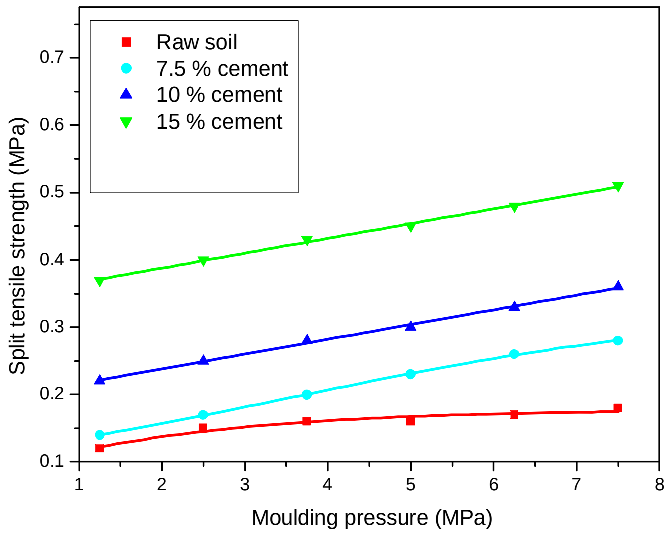


**Fig 4.12 Effect of Cement content on Split tensile strength**

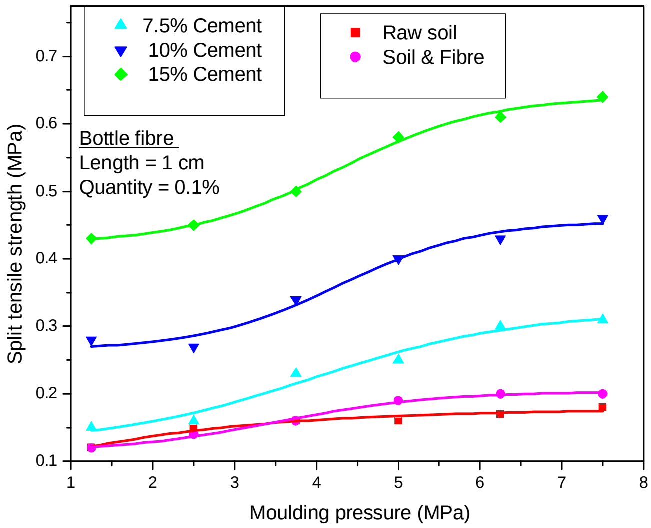


**Fig 4.13 Effect of Cement and Fibre content on Tensile strength (1cm long Bottle fibre, 0.1%)**

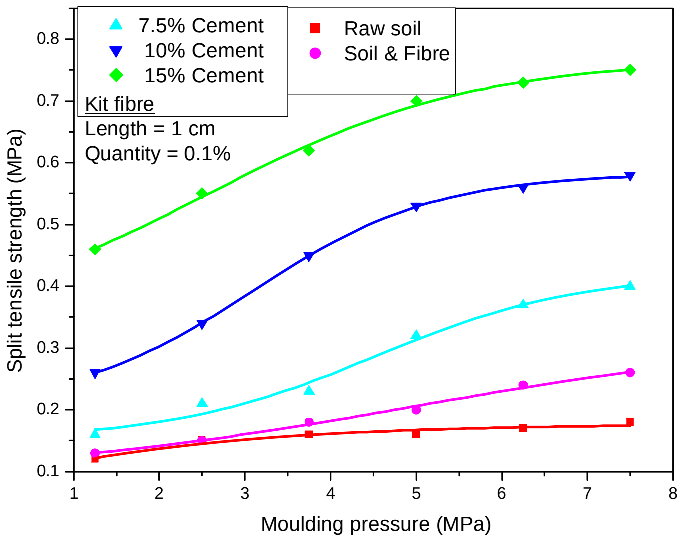


**Fig 4.14 Effect of Cement and Fibre content on Tensile strength (1cm long Kit fibre, 0.1%)**

For low Moulding pressure, even though the fibres fail to increase the Tensile strength of the raw soil specimens, at higher pressures they enhance the Tensile strength even in the absence of Cement, unlike in the case of Compressive strength, where fibres are inert at low Moulding pressures and passive at higher pressures. However, they are partially active in the case of Tension. Fig 4.13 depicts the behaviour of Bottle fibres for smaller quantity and length, for different Cement content and Moulding pressures. Fig 4.14 details the features of Kit fibre for the same condition. Both of them help in improving the tensile properties of the specimens. The rate of increase in the Tensile strength is more for Bottle fibres than that for the Kit fibres.

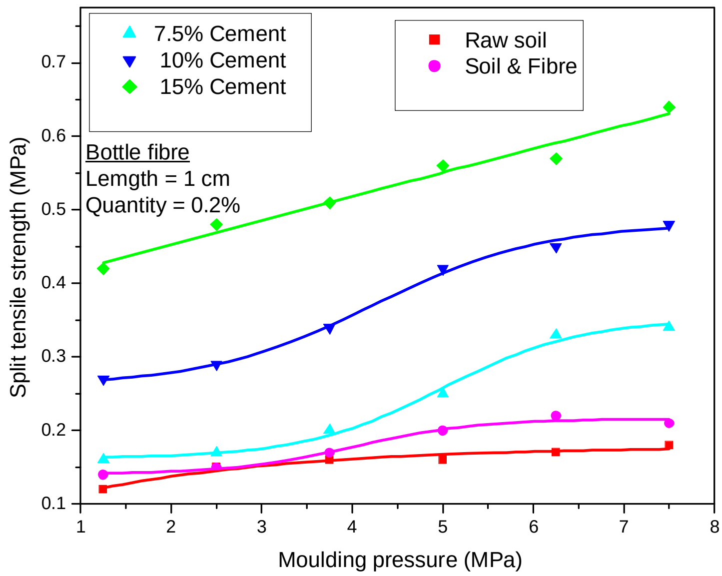


**Fig 4.15 Effect of Cement and Fibre content on Tensile strength (1cm long Bottle Fibre, 0.2%)**

Fig 4.15 shows, how higher percentage of shorter Bottle fibres improves the Tensile strength. There exists an increase in Tensile strength for given length with higher fibre content. This effect is less pronounced in the case of Kit fibres (Fig 4.16). However at lower pressures also, they help the raw specimens to have higher values, once reinforced. Fig 4.17 highlights the role of fewer amount of long Bottle fibres, in enabling the specimens to have high tensile strength values. Raw soil specimens embedded with Bottle fibres take more tension both in low and high Moulding pressures. Longer the fibres, more the effectiveness will be. From Fig 4.18, long Kit fibres perform similar to the Bottle fibres at high Cement content and at higher Moulding pressures. However strength gain in the case of long Bottle fibres is consistent irrespective of magnitude of Cement content and Moulding pressure. Lesser quantity of long fibres picks up strength early, where gain and rate of gain in the strength is considerable. The fibres prove that, they can even replace a certain quantity of Cement, for given value of the Tensile strength. Bottle fibres are versatile in tension and they perform better even at low Moulding pressure and at low Cement content.

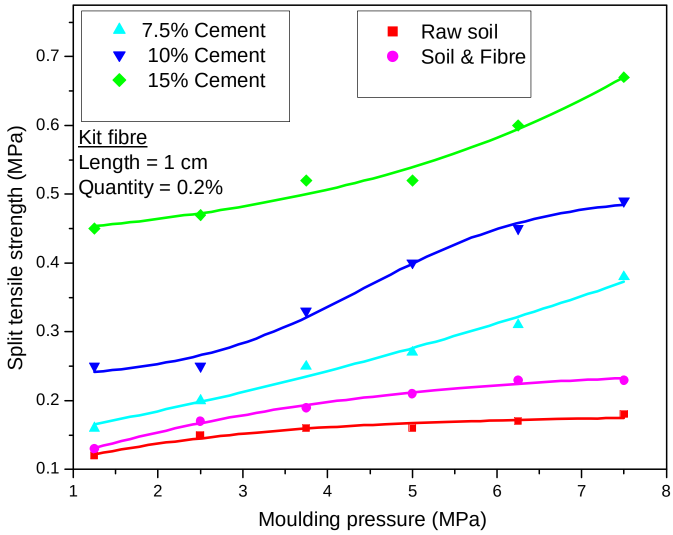


**Fig 4.16 Effect of Cement and Fibre content on Tensile strength (1cm long Kit Fibre, 0.2%)**

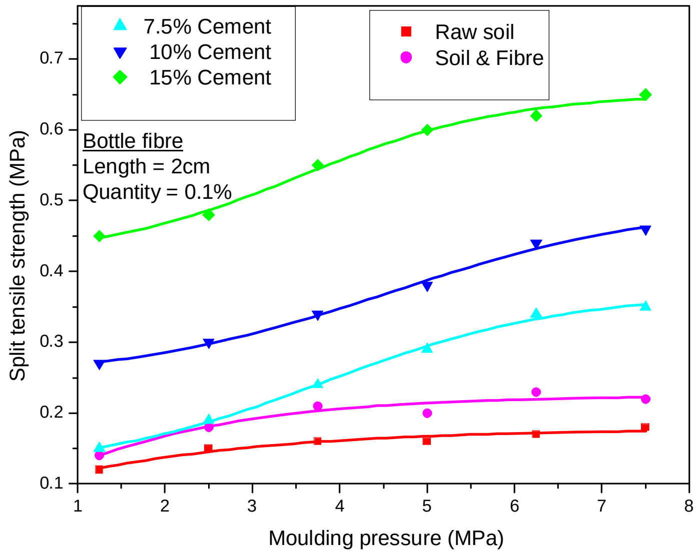


**Fig 4.17 Effect of Cement and Fibre content on Tensile strength (2cm long Bottle fibre, 0.1%)**

Kit fibres enable the raw soil specimen to enhance its Tensile strength, even at low Moulding pressures. When the Moulding pressure is high, there exists a significant rise in the strength value, even in the absence of Cement. Hence the effect of Fibres, on the Tensile property of the specimen, is pronounced. The rate of increase in these values is higher in the presence of Cement. Higher Moulding pressure helps the fibres, to enable the specimens to take more Tension, in the presence of Cement.

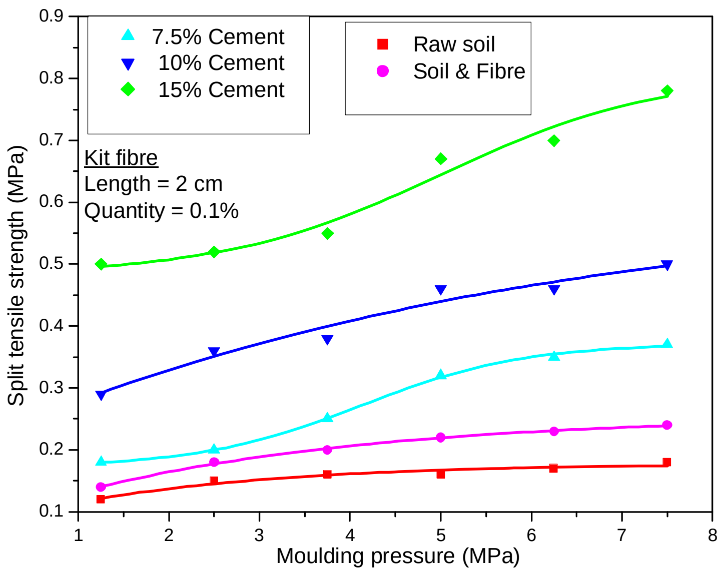


**Fig 4.18 Effect of Cement and Fibre content on Tensile strength (2cm long Kit fibre, 0.1%)**

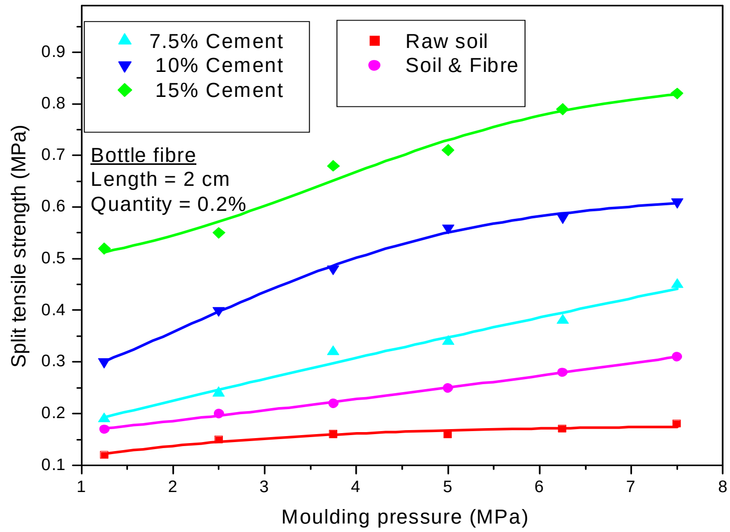


**Fig 4.19 Effect of Cement and Fibre content on Tensile strength (2cm long Bottle fibre, 0.2%)**

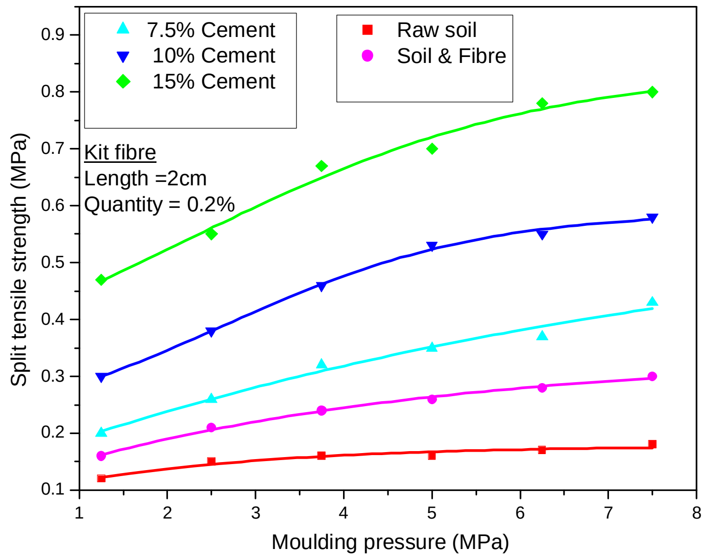


**Fig 4.20 Effect of Cement and Fibre content on Tensile strength (2 cm long Kit fibre, 0.2%)**

Fig 4.19 represents the behaviour of high quantity of long Bottle fibres. The performance of these fibres in Tension is high, unlike that in Compression. Interestingly, the Kit fibres of larger quantity and length behave similarly (Fig 4.20).

The role of Bottle fibres on influencing the Tensile strength is shown in Fig 4.21. The effect of Kit fibre on the Tensile strength is shown in Fig 4.22 and Fig 4.23. From these figures the following observations can be made: As Moulding pressure increases, Split tensile strength increases. Addition of Fibre increases the Split tensile strength. This increase in strength depends upon the Moulding pressure. As Moulding pressure increases, the effectiveness of fibres, in bringing up the Split tensile strength, increases. Similarly as Cement content increases, the effectiveness of fibres in improving the Split tensile strength, is increased. For given fibre length, increase in the percentage of fibre content, improves the Tensile strength. Similarly for given content of fibre, as the length of the fibre increases, tensile strength is increased.

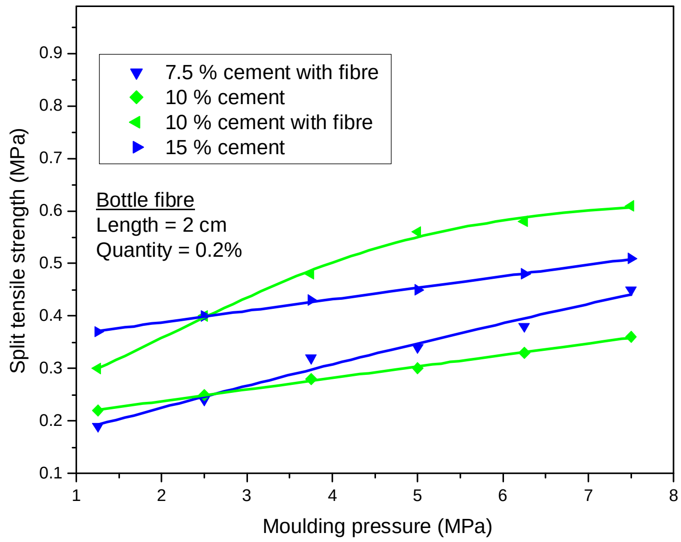


**Fig 4.21 Effect of Fibre content on Tensile strength (2cm long Bottle fibre, 0.2%)**

As far as the tensile behaviour of Plastic Reinforced Soil samples is concerned, it is observed that, both the type of fibres (Kit and Bottle) performed in a similar way, by way of improving the Tensile strength of specimens. Improved bond between the Fibres and Soil Cement matrix due to the increased Cement content, higher Moulding pressure and increased length of fibres are responsible for better performance of Plastic Fibre Reinforced Soil in Tension.

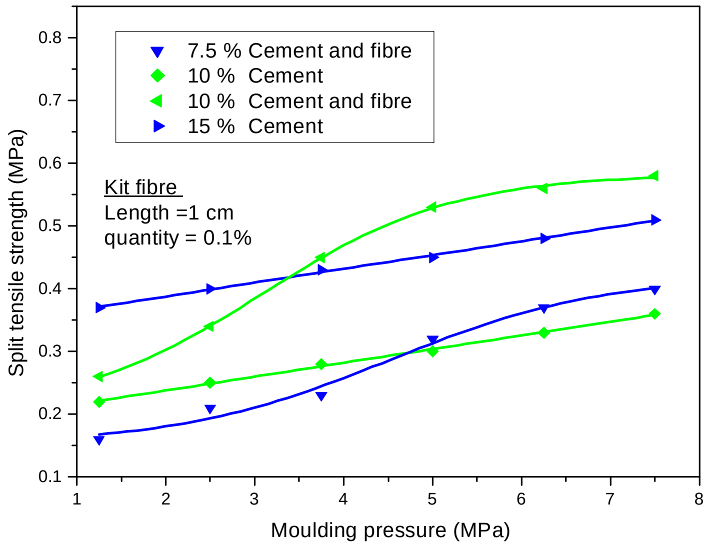


**Fig 4.22 Effect of Fibre content on Tensile strength (1cm long Kit fibre 0.1%)**

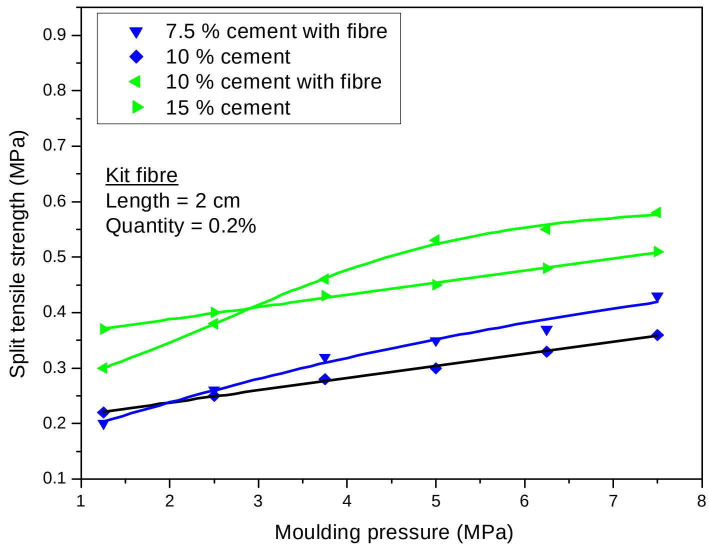


**Fig 4.23 Effect of Fibre content on Tensile strength (2cm long Kit fibre 0.2%)**

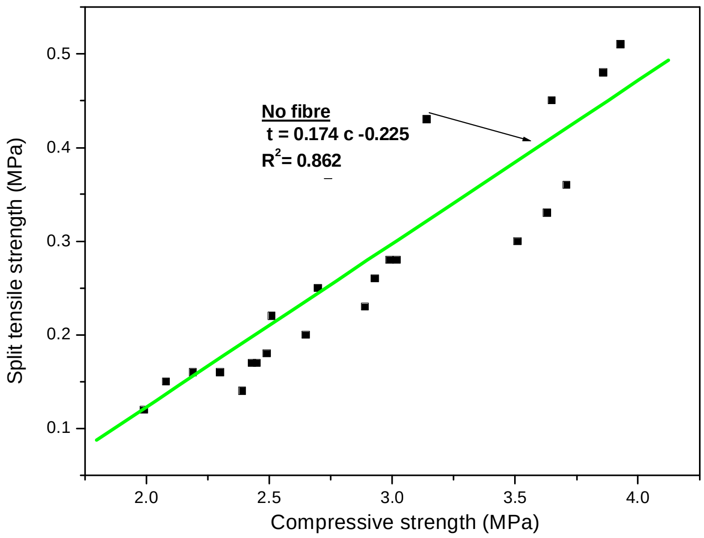


**Fig 4.24 (a) Correlation between Compressive strength and Tensile strength (Specimens without Fibre)**

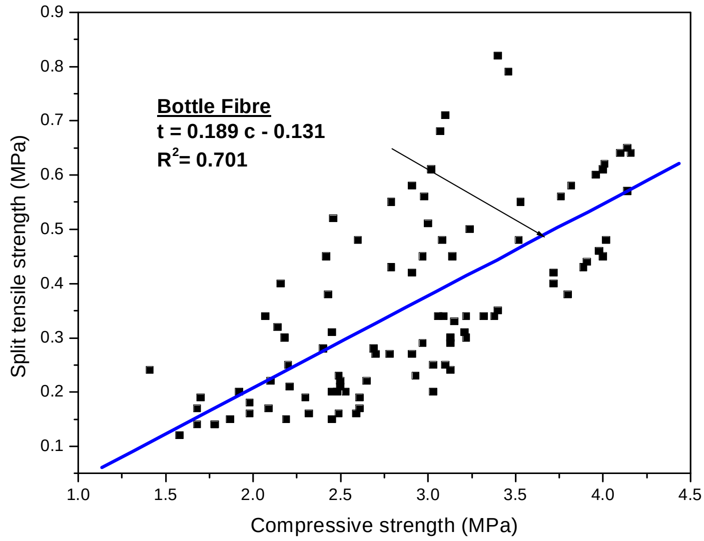


**Fig 4.24 (b) Correlation between Compressive strength and Tensile strength (Specimens with Bottle fibre)**

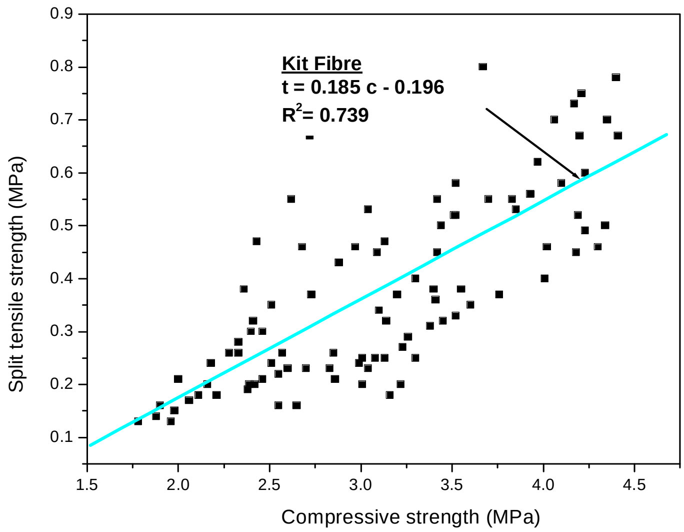


**Fig 4.24 (c) Correlation between Compressive strength and Tensile strength (Soil specimens with Kit fibre)**

In the case of samples without fibre, a good relationship exists between the Compressive strength (c) and the Tensile strength (t) of the samples [Fig 24(a)]. This fact is evident from the regression equation, given as t = 0.174 c - 0.225; ($R^2$ = 0.862). Though scattered, there exists a good correlation between the Compressive strength and the Tensile strength t = 0.189 c - 0.131; ($R^2$ = 0.701) in the case of Bottle fibres[(Fig 24(b)] and t = 0.185 c - 0.196); ($R^2$ = 0.739) for the Kit fibres [Fig 24(c)]. But from the regression equations it can be seen that, for given Compressive strength, samples with fibres gave more tensile strength than that without fibre. A comparison of Tensile strength, achieved by using the fibres is shown in Fig.4.25. Bottle fibres seem to be showing better performance than Kit fibres. This may be due to their higher stiffness and tensile strength than that of the Kit fibres.

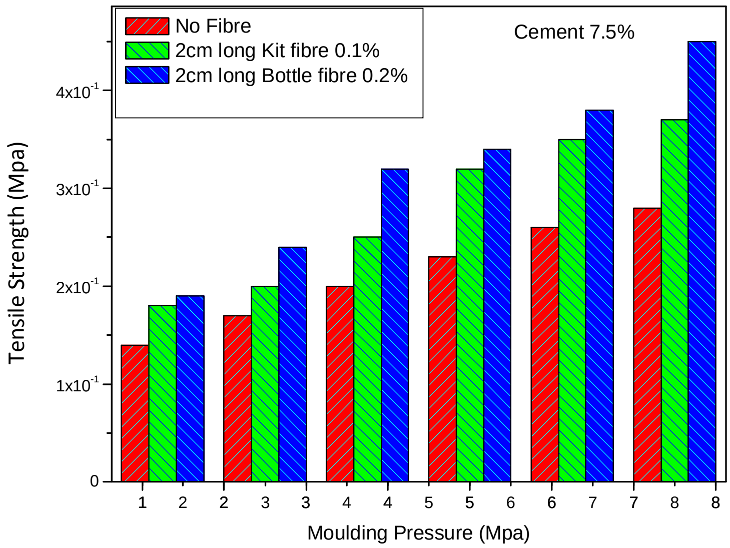


**Fig 4.25 Comparison of Split Tensile Strength (Kit fibres and Bottle fibres)**

The Kit fibres having a length of 2cm and weight 0.1% of the dry soil perform well in both Tension and Compression. Bottle fibres of the same length and the quantity are not contributing to the Compressive strength, where as they impart greater Tensile strength to the specimens. The Compacted Reinforced Cement Stabilised specimens show an increase of 4.5 times the tensile strength of the raw Soil specimen. This is one of the major advantages of adding fibres to the Stablised soil specimens

## 4.6 compressive Strength of Masonry

Results of the Compressive strength of masonry, made out of the blocks of different combination of Cement, Moulding pressure and Fibres are given in Table 4.4 and Table 4.5. The variation in Compressive strength of the masonry as a function of the block strength is shown in Fig 4.26.

**Table 4.4 Relation between masonry and block strength (Cement content10 %, Moulding pressure 1.25MPa)**

| Sl. No. | Details of Fibre in the block | | | Compressive strength (MPa) | | Reduction factor (M / L) | Strain at Ultimate stress of masonry (%) |
|---|---|---|---|---|---|---|---|
| | Type of Fibre | Length (cm) | Fibre content (%) | Block (L) | Masonry (M) | | |
| 1 | No Fibre | - | 0 | 2.94 | 1.23 | 0.42 | 0.34 |
| 2 | Kit | 1 | 0.1 | 3.3 | 1.39 | 0.42 | 0.38 |
| 3 | Kit | 1 | 0.2 | 3.33 | 1.50 | 0.45 | 0.40 |
| 4 | Kit | 2 | 0.1 | 3.59 | 1.87 | 0.52 | 0.43 |
| 5 | Kit | 2 | 0.2 | 2.66 | 1.30 | 0.49 | 0.43 |
| 6 | Bottle | 1 | 0.1 | 3.15 | 1.45 | 0.46 | 0.36 |
| 7 | Bottle | 1 | 0.2 | 3.18 | 1.37 | 0.43 | 0.45 |
| 8 | Bottle | 2 | 0.1 | 3.16 | 1.55 | 0.49 | 0.40 |
| 9 | Bottle | 2 | 0.2 | 2.5 | 0.95 | 0.38 | 0.38 |

**Table 4.5 Relation between masonry and block strength (Cement content 10 %, Moulding pressure 7.5MPa)**

| Sl. No. | Details of Fibre in the block | | | Compressive strength (MPa) | | Reduction factor (M / L ) | Strain at Ultimate stress of masonry (%) |
|---|---|---|---|---|---|---|---|
| | Type Of Fibre | Length (cm) | Fibre content (%) | Block (L) | Masonry ( M) | | |
| 1 | No Fibre | - | 0 | 4.44 | 2.58 | 0.58 | 0.40 |
| 2 | Kit | 1 | 0.1 | 5.09 | 3.05 | 0.60 | 0.56 |
| 3 | Kit | 1 | 0.2 | 5.26 | 3.35 | 0.64 | 0.58 |
| 4 | Kit | 2 | 0.1 | 5.34 | 3.83 | 0.72 | 0.61 |
| 5 | Kit | 2 | 0.2 | 4.33 | 2.93 | 0.68 | 0.62 |
| 6 | Bottle | 1 | 0.1 | 4.85 | 2.94 | 0.61 | 0.54 |
| 7 | Bottle | 1 | 0.2 | 4.98 | 2.90 | 0.58 | 0.61 |
| 8 | Bottle | 2 | 0.1 | 4.86 | 3.06 | 0.63 | 0.58 |
| 9 | Bottle | 2 | 0.2 | 3.66 | 1.64 | 0.45 | 0.56 |

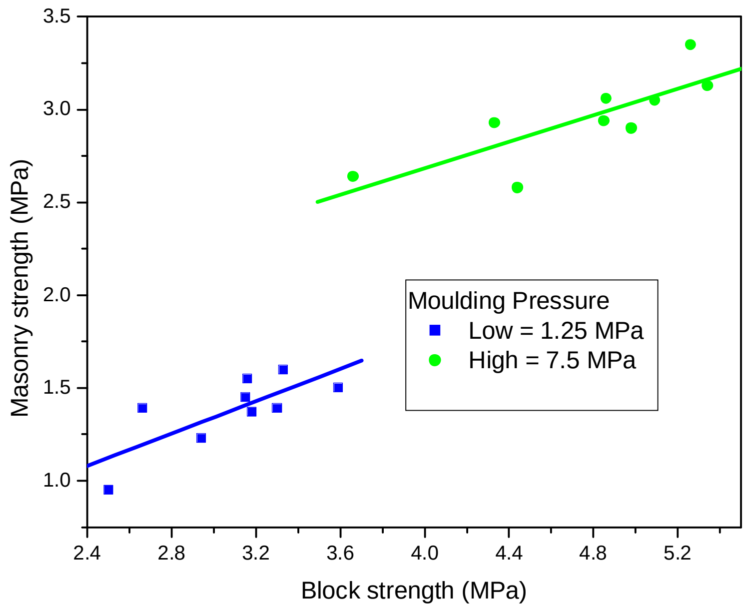


**Fig 4.26 Relation between Compressive strength and block strength**

Compressive strength of masonry increases with an increase in block strength. For given Cement content, the ratio of masonry strength to block strength was found to vary from 0.38 to 0.52 and 0.45 to 0.72 for specimens subjected to low and high Moulding pressure respectively. Similar observations were also made, by Walker (2004) that the masonry Compressive strength varied between 34% and 96% of unconfined block strength. The prisms failed by developing vertical splitting cracks parallel to the loading direction. Hendry (1990) reports that the Compressive strength of masonry is roughly the square root of the unit strength and very poorly related to mortar cube strength. The results of the study by Reddy and Gupta (2006), where the block strength ranges between 3 and 8MPa, show that for Stabilised Mud block (SMB) masonry, the

Compressive strength went up, by about 4 times as the block strength is increased by 2.3 times. That is, the increase in masonry strength is proportional to the increase in the block strength.

Typical stress-strain relationship for the mud block masonry using mud blocks with different fibre length, quantity and types at 10% Cement content and at high Moulding pressure (7.5MPa) is shown in Fig 4.27(a) and Fig 4.27(b). For given Cement content, the ultimate stress increases with the addition of fibre content. Also strains at ultimate stress for masonry are more for blocks containing fibres (Table 4.4 and Table 4.5).

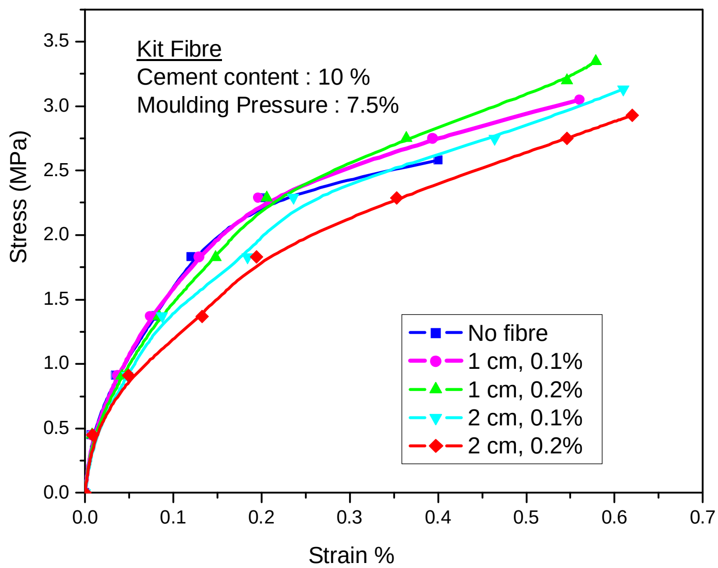


**Fig 4.27(a) Stress strain relationship for masonry prism (Kit fibre)**

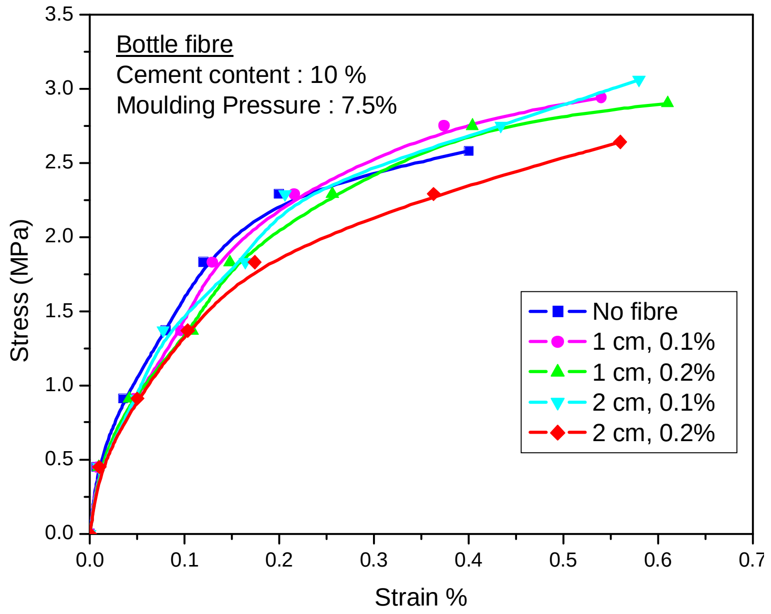


**Fig 4.27 (b) Stress strain relationship for masonry prism (Bottle fibre)**

Above observation shows that the Fibre mud block masonry behaves more ductile and can store more elastic energy compared to the mud blocks without fibre. This renders it more resistance to earthquake forces. Hence the fibre reinforced mud brick is more advantageous compared to the conventional brick. Similar observations were made by Binici et al. (2005).

## 4.7 Analysis of Failure Pattern

The failure of specimens made of raw Soil was very quick without warning both in compression and tension (Fig 4.28), in contrast to the compression test of blocks with fibres. The deformation of these specimens still continued, even after the ultimate load, and fine cracks could be seen on the specimens. Unlike raw Soil specimens, those with fibres showed fine irregular but distinguishable cracks on its surface (Fig 4.29). Similar observations were made by Marandi et al. (2008) in a study on strength and ductility of randomly distributed palm fibre reinforced silty sand soil and by Gelan-Marin et al. (2010) in a study on clay based composites with natural polymer and fibre. After failure, the Soil fibre composite was not disintegrated completely in contrast to the specimens with raw Soil. This behaviour is seen in the split tensile tests, the two halves of raw blocks fall apart on breaking, where as the specimens with fibre reinforcement stay intact (Fig 4.29), similar to the observations made by Oliver and Gharbi (1995). This behaviour was found more evident in samples with Kit fibre as shown in Fig 4.30(a). In the case of samples with Bottle fibres, slipping of the fibres from the soil cement is likely to happen due to poor bond, as seen in Fig 4.30(b) and Fig 4.31. From the observations of failure pattern, it can be concluded that benefits of fibre reinforcement includes both improved ductility and inhibition of large crack propagation after initial formation.

All the prisms have failed by developing vertical splitting cracks parallel to the loading direction. This can be explained as follows. In compression greater lateral expansion of the mortar joint places the blocks in a state of compression and biaxial lateral tension (Walker, 1995; Moral et al. 2007; Hendry, 1990), whereas restraint of the blocks places the mortar joint in a state of tri-axial compression. So in uni-axial compression, masonry typically fails by vertical splitting, as a result of lateral tension developed in the units (Walker, 1995). This vertical tensile cracking is between 50 and 95% of the ultimate load, preceded by more general crushing of the prism (Walker, 2004). It can be observed that the masonry without fibre addition failed with the sudden enlargement of the initially formed crack and failure was all of a sudden without giving any warning (Fig 4.32). But the masonry specimens with fibre, instead of enlargement of a single crack, fine cracks were developed on its surface and the failure is due to cracks spreading in the whole structure giving enough warning before collapse thus demonstrating the ductile behaviour of Masonry (Fig 4.33). Marandi et al. (2008), after studying the behaviour of fibre reinforced blocks, suggests that, adding fibers to a soil medium that exhibits brittle material properties results in greater fiber connection and replacement of a portion of soil by elastic material. They have found that the soil becomes softer, the elasticity of the medium increases and as a result, the specimens fail at higher axial strains. Similar behaviour can be expected in masonry system, which is made out of fibre reinforced blocks.

**Fig 4.28 Failure pattern in Compression and Tension (No Fibre)**

**Fig 4.29 Failure pattern in Compression (samples with Kit fibre)**

**(a) Kit fibre**

**(b) Bottle fibre**

**Fig 4.30 Failure pattern in Tension**

**Fig 4.31 Slipping of Bottle fibre from Soil Cement matrix**

**Fig 4.32 Failure of masonry prism (blocks without Kit fibre)**

**Fig 4.33 Failure of masonry prism (blocks with Kit fibre)**

## 4.8 Summary

The influence of composition (basic parameters) viz. Moulding pressure, Cement content, Fibre type, length and quantity, on the density and strength of mud blocks has been studied. Effect of fibre addition on the Compressive strength of block masonry was also evaluated by studying the stress strain characteristics. Stabilised samples and fibre reinforced stabilized samples at higher Moulding pressure showed a strength values of 3.5 to 4.41MPa in the case of cylinders and up to 3.7 to 5.5MPa in the case of blocks, a value which is highly satisfactory compared to that of minimum Compressive strength of 3.5MPa for a well burnt brick as per BIS 1077 - 1992 and a minimum Compressive strength of Soil block for general building construction as per BIS: 1725 1982. One of the major advantages of addition of fibre is the increase in tensile strength. Above observations and failure pattern show that the fibre reinforced mud block masonry behaves more ductile and masonry can store more elastic energy compared to mud blocks without fibre, which renders it more resistant to earthquakes. A practical Mix of 7.5 to 10% of Cement, Kit fibre (from carry bags) having 2cm length and 0.1% by weight of Soil, 5MPa Moulding pressure, may be treated as the outcome of the test results, for the type of soil mentioned in table 3.3, having a lesser clay content and the percentage of sand high.

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Chapter 5

# SORPTION AND EROSION CHARACTERISTICS



## 5.1 General

Knowledge of the sorption characteristics like absorption and Sorptivity of building materials are of importance as they affect the durability and other properties. In the case of fibre reinforced mud blocks, the moisture movement behaviour becomes more complex as it contains randomly oriented plastic fibres. This chapter deals with the investigation of the sorption related properties of mud specimens as influenced by the Moulding pressure, Cement content, type, length and quantity of Fibres. Results of Water absorption by complete immersion and Sorptivity by capillarity for various specimens with different levels of parameters were analysed. Mud block undergoes deterioration due to the wind driven rain. Hence the erosion characteristics of soil specimens have been studied by changing these variables on cylindrical specimens.

## 5.2 Sorption Characteristics

### 5.2.1 Water Absorption

Test on samples without stabilisation was not successful as they were completely damaged under water. Raw specimens disintegrated during Water absorption test, clearly suggesting the necessity of Cement stabilisation, if the blocks were meant for exterior use without protection (Chee-Ming, 2011). Fig 5.1(a) to Fig 5.1(d) shows the variation of Water absorption with Cement content. It can be observed that there is a general decrease in Water absorption values of the samples with increasing Cement content. Similar observations were made by (Choudhary, 2004; Riza et al. 2011; Reddy and Gupta, 2006). This reduction in Water absorption is attributed to the (i) Decrease in Pore size as the Cement content of the sample is increased (ii) Soil and sand particles are very well coated with Cement particles due to the increase in the Cement content, thus enhancing the bonding among the particles (Reddy and Gupta, 2006).

The effectiveness of Cement in reducing the Water absorption is marginal for Cement content more than 10%. Similar observation was made, in the case of Compressive strength characteristics too. This may be due to the non availability of sufficient water in the specimens prepared at high Cement content and at low initial water content.

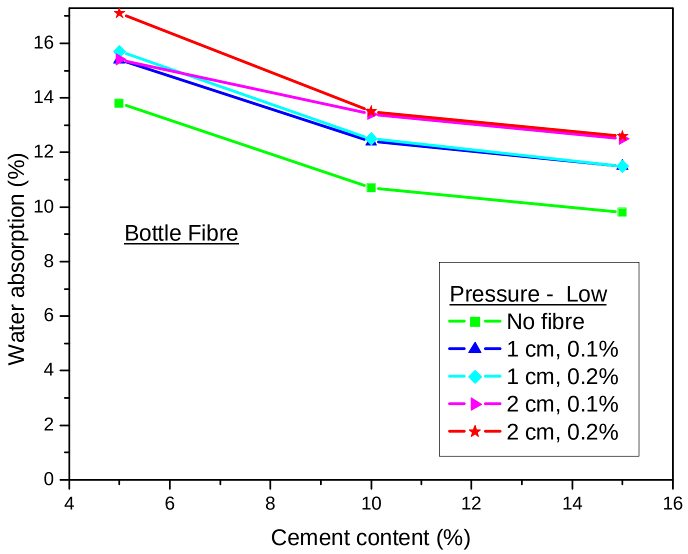


**Fig 5.1 (a) Effect of Cement content on Water absorption (Bottle fibres, Moulding pressure 1.25MPa)**

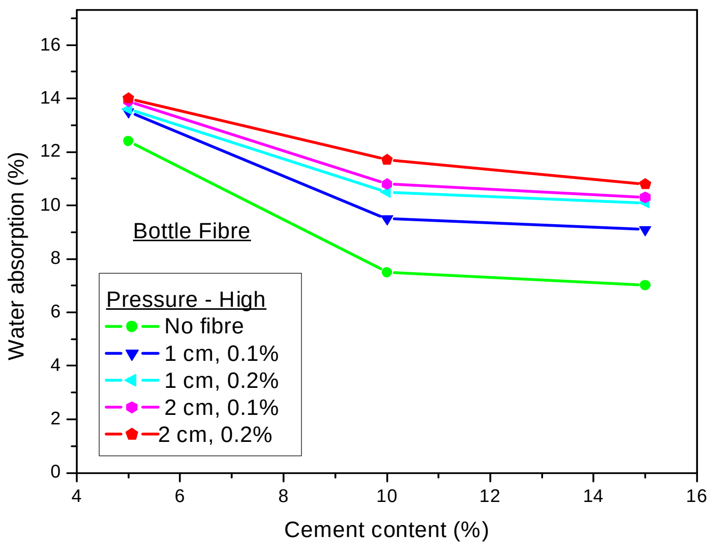


**Fig 5.1 (b) Effect of Cement content on Water absorption (Bottle fibres, Moulding pressure 7.5MPa)**

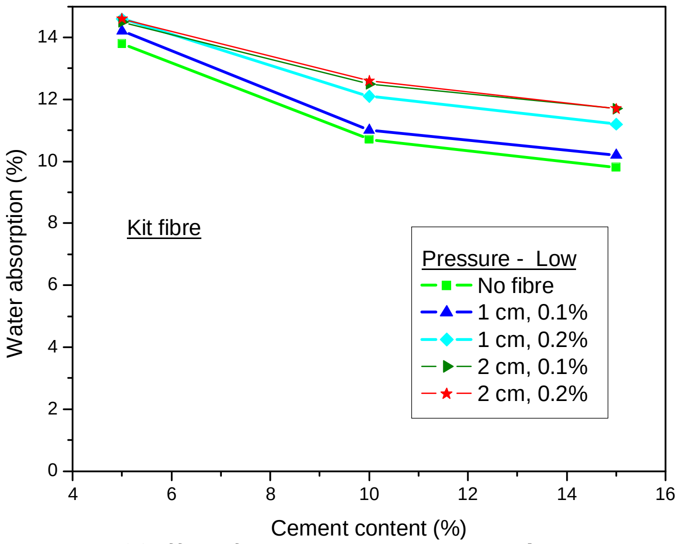


**Fig 5.1 (c) Effect of Cement content on Water absorption (Kit fibres, Moulding pressure 1.25MPa)**

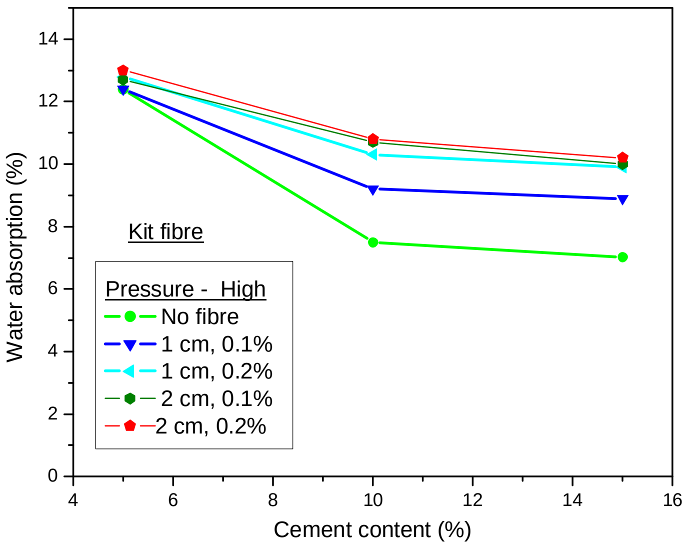


**Fig 5.1 (d) Effect of Cement content on Water absorption (Kit fibres, Moulding pressure 7.5MPa)**

Fig 5.2(a) to Fig 5.2(d) shows the effect of Moulding pressure on the Water absorption. As Moulding pressure increases, Water absorption decreases. The higher density values resulting from the increasing Moulding pressure seem to provide the desired water tightness in these samples and consequently the Water absorption values of these specimens are less, as compared to that of the samples at lower Moulding pressures. This water tightness property gets further improved with the increase in the Cement content. For example, the blocks compacted at a Moulding pressure of 7.5MPa the Water absorption reduces from 12.4 to 7.5%, when the Cement content was increased from 5 to 10%. Further increase of Cement, as in the case of 15%, this reduction is only 7%. Hence for a higher Moulding pressure, addition of Cement more than 10% is not justified, for reducing Water absorption. At the same time, at a lower Moulding pressure of 1.25MPa, the Water absorption reduces from 13.8 to 10.7% when the Cement content is varied from 5 to 15%.

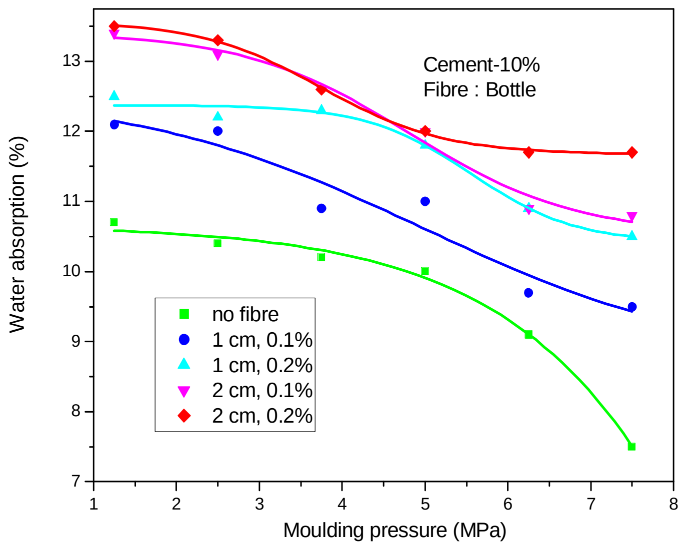


**Fig 5.2 (a) Effect of Moulding pressure on Water absorption (Bottle fibre, Cement 10%)**

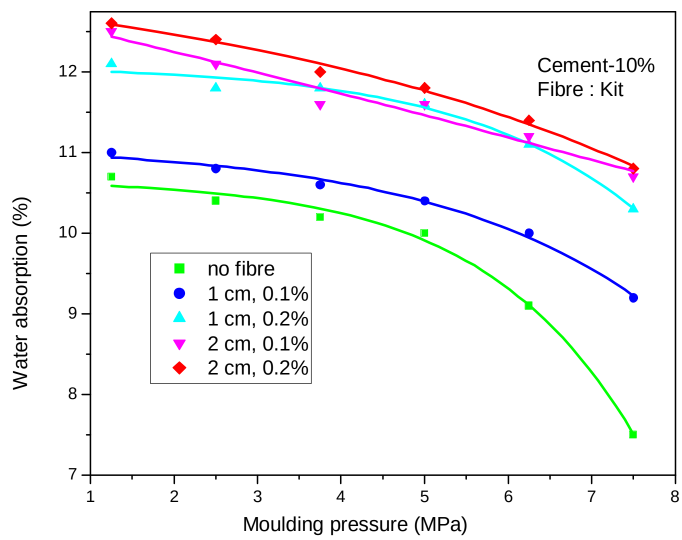


**Fig 5.2 (b) Effect of Moulding pressure on Water absorption (Kit fibre, Cement 10%)**

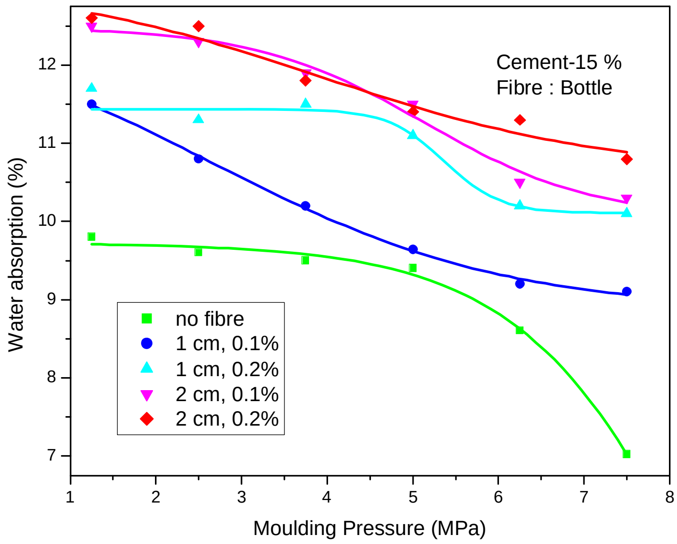


**Fig 5.2 (c) Effect of Moulding pressure on Water absorption (Bottle fibre, Cement 15%)**

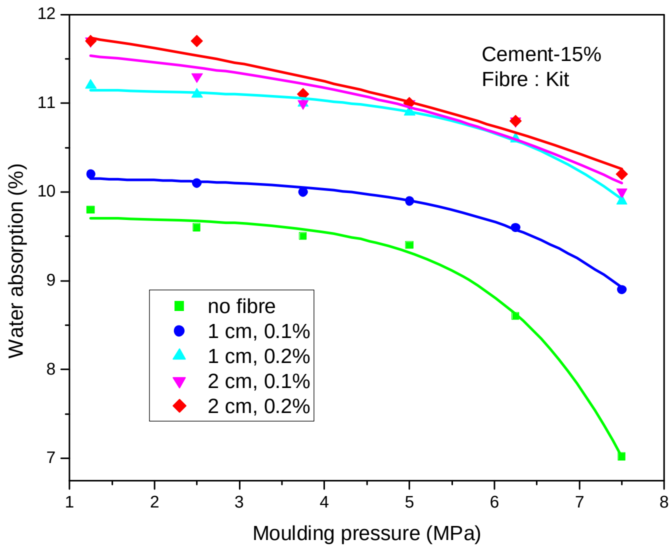


**Fig 5.2 (d) Effect of Moulding pressure on Water absorption (Kit fibre, Cement 15%)**

The Chemical and Mechanical stabilisation, have helped in cementing the soil particles together and filling the pore spaces. It prevents the reorientation and flocculation of soil particles, which precluded formation of enlarged pores and cracks (Bahar et al. 2004).

It can be seen from Fig 5.2(a) to Fig 5.2(d), that the addition of fibres increases the Water absorption. As the percentage of fibre increases, Water absorption increases. Length of fibres also increases the Water absorption. These observations show that, fibres form interconnected channels leading to an increase in the Water absorption when the specimens are completely submerged in water.

Water absorption is found to be more in samples with Bottle fibres, which is evident in Fig 5.3.

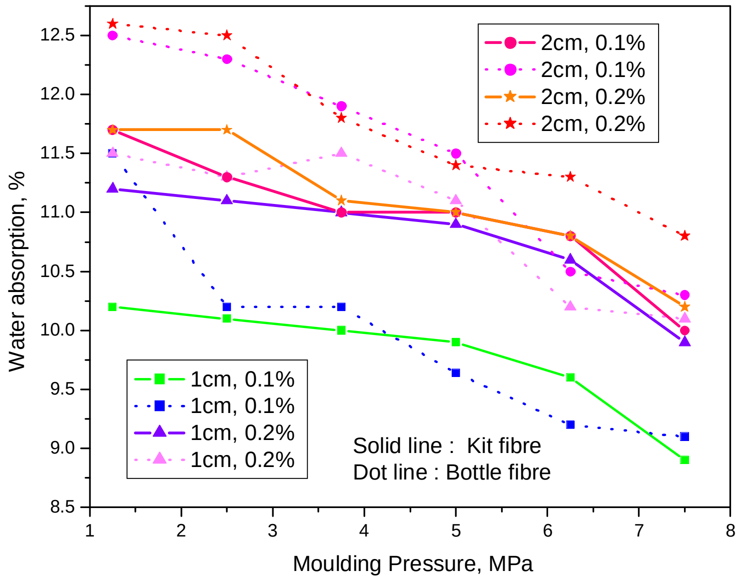


**Fig 5.3 Influence of fibre type on Water absorption**

This may be due to the following reasons: (i) The type of surface finish which results in lack of bond with the soil and hence slips from the soil (ii) The soil particles may laterally move apart leaving behind air spaces between the stiff Fibres and the Soil, thereby creating weaker planes, during mechanical compression. In the case of specimens with Fibres, as Moulding pressure increases Water absorption decreases. This may be due to the increased compaction of soil and also due to the considerable reduction of the air space between the Fibres and the Soil at high Moulding pressures. In any case, the Water absorption of specimens, stabilised with 10 and 15% Cement, was less than the permissible value of 15% by weight as per IS 1725-1982: Specifications for Soil based blocks used for general building construction.

### 5.2.2 Sorptivity

The variation of sorption with square root of time is shown in Fig 5.4(a) to Fig 5.4(c). The slope of the linear fit is taken as the Sorptivity. The Sorptivity values are found to reduce from 0.984 to 0.304 $mm/min^{0.5}$ for different Cement content and fibre properties. Tests on samples without stabilisation were not successful, as they were completely disintegrated when kept in water. Effect of Cement content on Sorptivity for various compaction pressures is shown in Fig 5.5. It is clear from the figure that Sorptivity decreases with Cement content and the reduction is of the order of 28% when Cement content is increased from 5 to 15%, at a low Moulding pressure of 1.25MPa. At the same time, for the same increase of Cement content, the reduction in Sorptivity values is as high as 50 %, at the higher Moulding pressure of 7.5MPa. This may be due to the fact that the soil particles become closer as the Moulding pressure increases and are cemented together by the chemical stabilisation. However, beyond a Cement content of 10% the effectiveness was reduced considerably. Similar observation was made, also in the case of Water absorption and Compressive strength. For a given Cement content, the variation of Sorptivity with Moulding pressure is shown in Fig 5.6(a) to Fig 5.6(d). There was a reduction in Sorptivity with an increase in the Moulding pressure. For given Cement content, the Sorptivity got reduced by 28 to 50%, when the Moulding pressure was increased from 1.25 to 7.5MPa. This may be due to the reduction in pores due to stabilisation by compaction. The combination of mechanical and chemical stabilisation has resulted in a reduction of Sorptivity by 63 to 69% in specimens without fibre addition. Similar observations regarding the positive effect of mechanical and chemical stabilisation on Sorptivity was reported by Bahar et al. (2004).

Fibre addition increases the Sorptivity as it increases the inter-connecting channels. This observation was significant, when the fibre content was less. Compared to the specimens containing Kit fibres, those containing Bottle fibres showed more Sorptivity. But when the fibre percentage was increased and at higher fibre length, the Sorptivity was less, even less than the samples without fibres, as shown in Fig 5.6 (a) to Fig 5.6(d). This exceptional behaviour may be due to the increased path length for capillary water, by the large amount of randomly oriented fibres. Due to this delay in capillary rise, the amount of water absorbed in unit time is reduced and resulted in the decrease of Sorptivity.

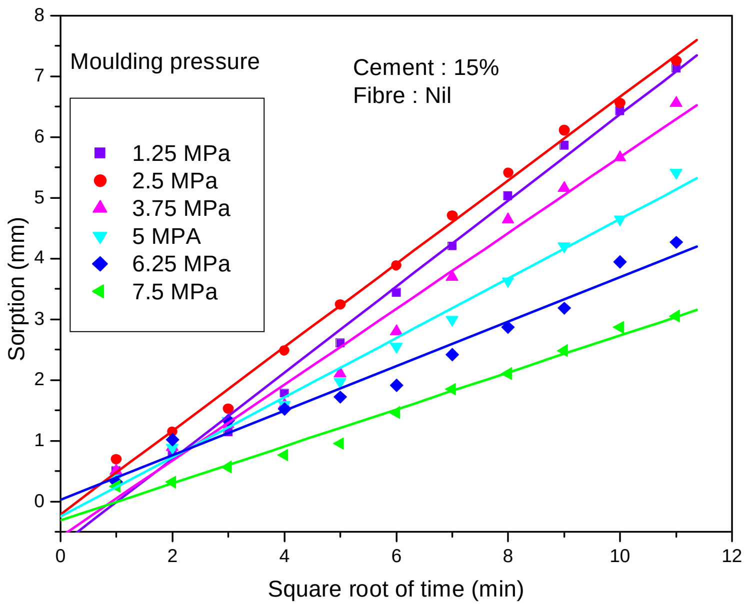


**Fig 5.4 (a) Variation of sorption with square root of time (No Fibre)**

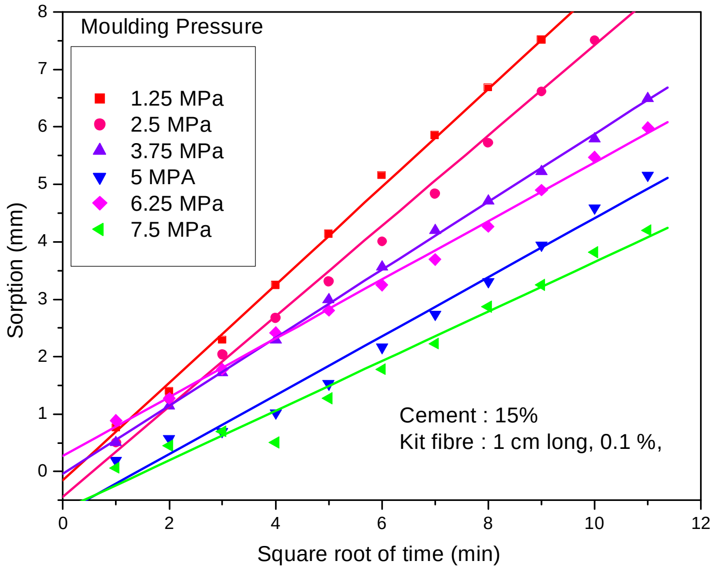


**Fig 5.4 (b) Variation of sorption with square root of time (Kit fibre 0.1%)**

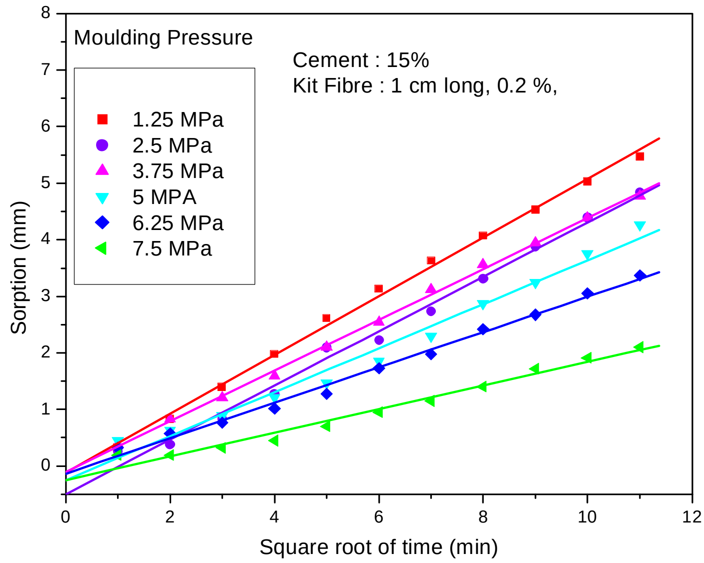


**Fig 5.4 (c) Variation of sorption with square root of time (Kit fibre 0.2%)**

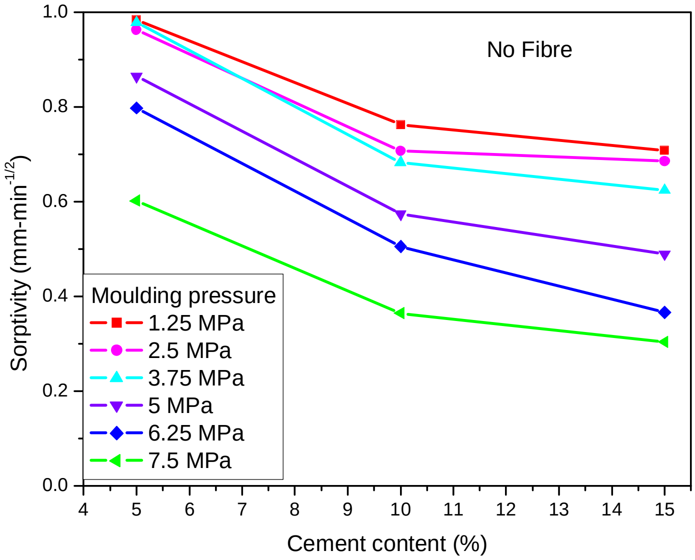


**Fig 5.5 Effect of Cement content on Sorptivity**

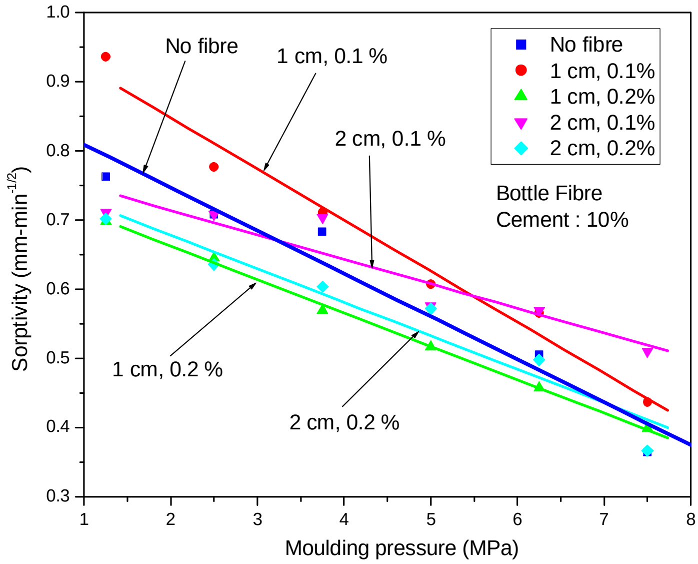


**Fig 5.6 (a) Variation of Sorptivity with Moulding pressure (Bottle fibre Cement 10 %)**

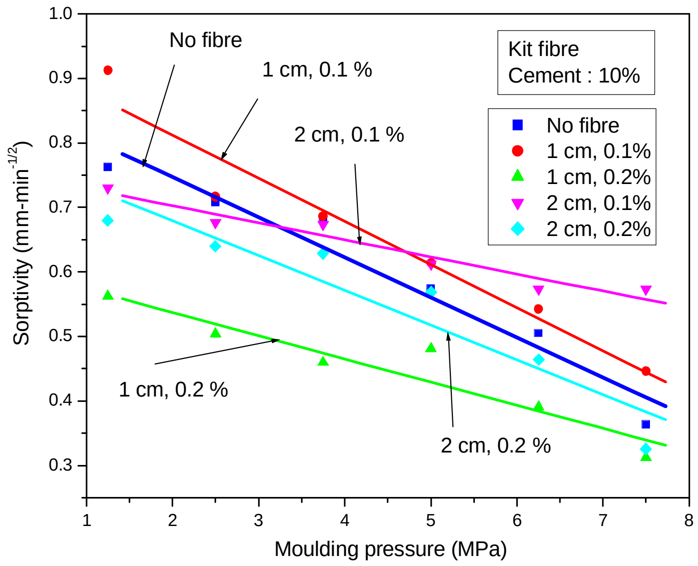


**Fig 5.6 (b) Variation of Sorptivity with Moulding pressure (Kit fibre Cement 10 %)**

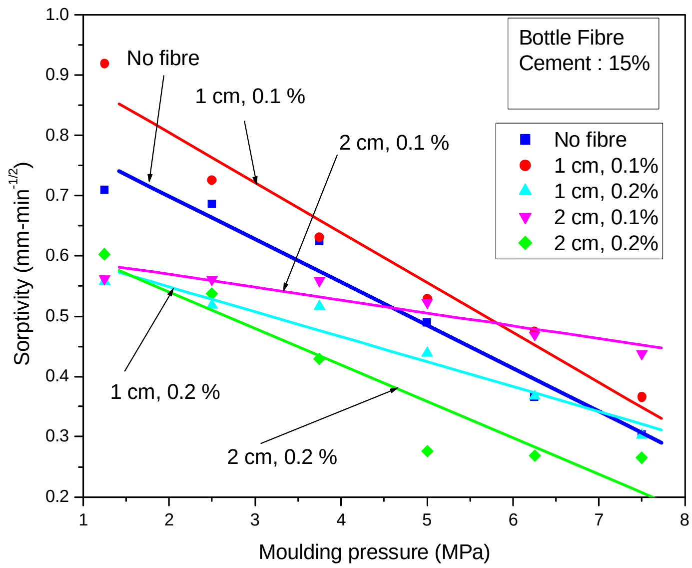


**Fig 5.6 (c) Variation of Sorptivity with Moulding pressure (Bottle fibre Cement 15 %)**

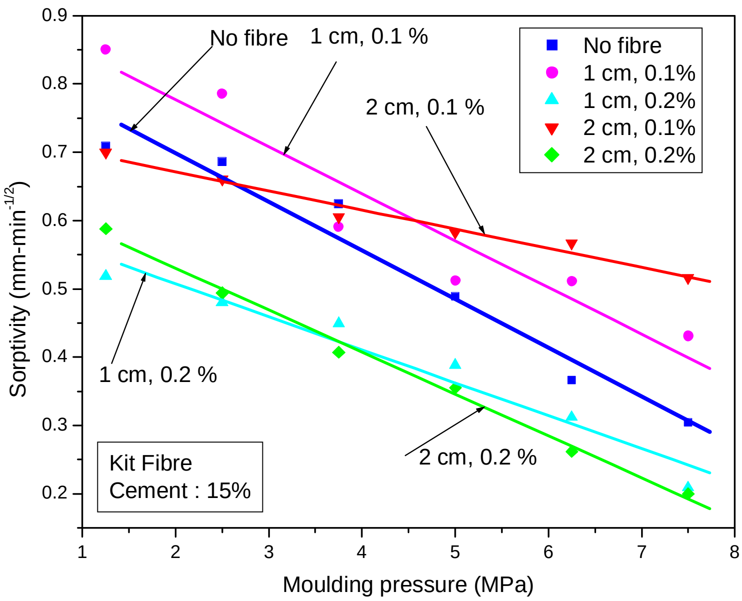


**Fig 5.6 (d) Variation of Sorptivity with Moulding pressure (Kit fibre Cement 15 %)**

## 5.3 Erosion Studies

Pressed Soil - Cement Fibre reinforced blocks posses adequate strength. However they should have good erosion resistance for satisfactory performance in service. Therefore these blocks were tested for erosion by exposing the specimen surface to the standard spray test (BIS 1725 1982) for 120 minutes. Cylindrical specimens were tested as the shower designed for the spay test is for a circular surface. Spray erosion tests most closely simulate the effects of rainfall impinging on the surface of a wall. The relevant rain parameters simulated in the spray tests are the (i) Diameter of the rain droplet at impact (2mm for medium intensity and 4mm for high intensity), (ii) maximum terminal velocity of

6.5m/s at impact, and (iii) maximum intensity of rainfall 15-30mm/h. Diameter of the shower used for the present erosion study is 100mm with 36 holes of 2mm diameter (Fig 5.7). Water is sprayed through these holes at a pressure of 1.5kgf/cm$^2$, which can be measured by a pressure gauge attached to the system, using a pump (Fig 3.10).

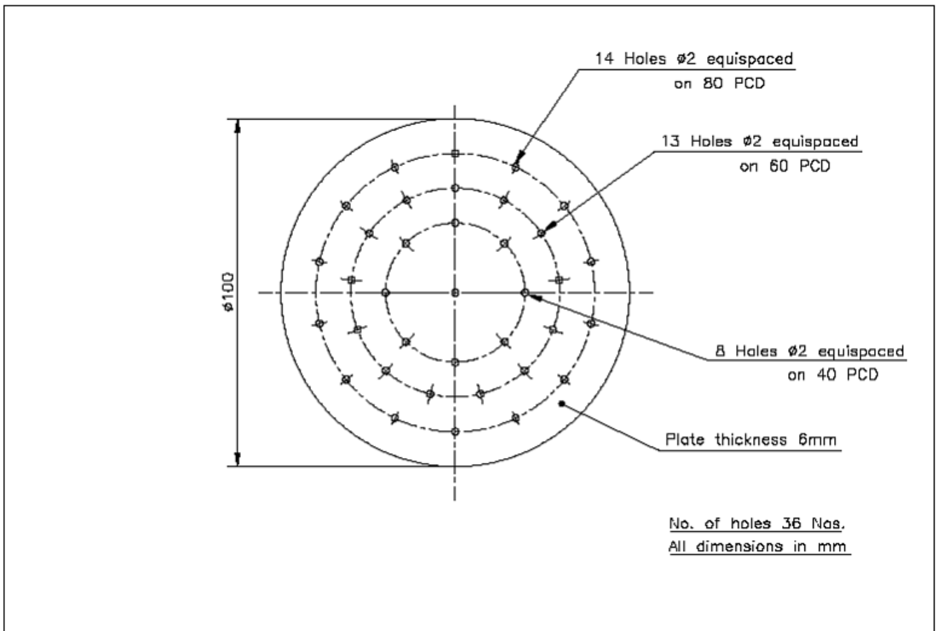


**Fig 5.7 Details of Spray shower**

Fig 5.8 to Fig 5.10 shows the photograph of the exposed face of specimens after the Spray erosion test. The unstabilised specimens prepared at higher Moulding pressures exhibited pitting damage on their surface during accelerated erosion test, by a continuous spray of water for two hours. Similar observations were made by Walker (1998, 2004), Bahar et al. (2004). No measurable pitting or other damage was observed in any other samples which were stabilised or stabilised and fibre reinforced. A few small pits/patches were seen on the faces of the samples which are reinforced with 0.2% Bottle fibre and compacted at low Moulding pressure of 1.25MPa, as seen in Fig 5.10(a). These patches/pits are reduced as the Cement content is increased from 5 to 15%. All the samples satisfy the weathering test criteria specified by IS 1725 1982, the maximum loss of weight shall not be more than 5% and the diameter of the pit formed shall be within 1 cm. In samples, which were reinforced with Kit fibres, especially when the fibre content is 0.2% and at low Moulding pressure, the fibres which were sticking on the surface become loose and start projecting outside as shown in Fig 5.10(a). Small pitting was observed when Bottle fibres were used. The cause for this small pitting by the removal soil cover may be due to the force exerted by the stiff Bottle fibre on the soil particles. There may be a small loss of strength in the soil cover due to the absorption of water. Similar to the observations of few earlier researchers, resistance to erosion improves with Cement content (Walker, 1997; Bahar et al. 2004) and Compactive effort (Walker and Stace, 1997).

**(a) No Fibre** **(b) Kit Fibre** **(c) Bottle Fibre**

**Fig 5.8 Specimens subjected 2 hours of spray erosion test (Raw soil, Moulding pressure 7.5MPa)**

**(a) Cement 5%** **(b) Cement 10%** **(c) Cement 15%**

**Fig 5.9 Specimens subjected 2 hours of spray erosion test (Raw soil, Moulding pressure 1.25MPa)**

**(a)Cement : 5%** **(b) Cement : 10%,** **(c) Cement : 15%**

**Fig 5.10 Specimens subjected 2 hours of spray erosion test Kit fibre, Moulding pressure 1.25MPa)**

**(a) Cement : 5%** **(b) Cement : 10%** **(c) Cement : 15%**

**Fig 5.11 Specimens subjected 2 hours of spray erosion test (Bottle fibre, Moulding pressure 1.25MPa)**

**a). Cement : 5%,** **(b) Cement : 10%,** **(c) Cement : 15%**

**Fig 5.12 Specimens subjected 2 hours of spray erosion test (Kit fibre, Moulding pressure 7.5MPa)**

**(a) Cement : 5%** **(b) Cement : 10%** **(f) Cement : 15%**

**Fig 5.13 Specimens subjected 2 hours of spray erosion test (Bottle fibre, Moulding pressure 7.5MPa)**

This test indicates that the Stabilised Plastic Reinforced Blocks possess adequate resistance against rain erosion. It is also fairly clear that these stabilised blocks may be used in walls without any water-proof coatings and plaster.

## 5.4 Summary

Water intake and transport behaviour in mud blocks have been studied with the help of Water absorption by immersion and Sorptivity by capillarity. Weathering of mud blocks by wind driven rain have been studied by simulation of the rain, using a Spray erosion set up, designed and devised for the purpose. In any case, the Water absorption of samples with 10 to 15% Cement stabilisation was less than the specified value of 15% by weight as per IS 1725-1982: Specifications for Soil based blocks used for general building construction. The Spray test indicates that the stabilised plastic reinforced blocks possess adequate resistance against rain erosion. It is also fairly clear that these stabilised blocks can be used in walls without any water proof coatings and plaster.

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# Chapter 6
# CONCLUSION

6.1 Summary and Conclusions
6.2 Scope for Future Work

## 6.1 Summary and Conclusions

The salient conclusions arising out of this research work are summarized in this section. The study on the influence of composition and block making mechanism on mud blocks described here basically come under four stages viz. (i) density and the strength of blocks (ii) studies on mud block masonry (iii) sorption characteristics such as the water absorption and the sorptivity; (iv) erosion studies. (v) suggested mix proportion. The conclusions from the experimental investigations are grouped under these sections, which are applicable to the characteristics of materials used and that of the parameters investigated.

### 6.1.1 Density

- Measured density of the specimens was found to vary from 1.846 to 1.958g/cc. These values are above the desirable limit for producing a stabilized mud block which is specified as 1.8 to 1.85 g/cc

- When the cement content varied up to 15 %, there is an increase of 2.2 to 3.7 % in density.
- For given cement content, as moulding pressure increases, the dry density increases. There is an increase of density of about 6 % when the moulding pressure is increased from 1.25 to 7.5MPa.
- The marked increase in the density witnessed in modified specimens could have been due to the salient factors like (i) Pore filling effect (ii) Increased homogeneity (iii) Improved bonding and (iv) Reduced voids.
- Effect of the fibre content was less pronounced on the density, where there is only small change in the density (0 to1.87%) over the range of fibres added.

### 6.1.2 Compressive Strength

- Compared to raw soils blocks, fibre reinforced cement stabilized soil blocks have shown an increase of 20 to 121% in compressive strength.
- Compared to the stabilized samples, the Fibre reinforced stabilized samples showed an increase of 59 to 89 % in the Compressive strength, for a Cement content of 7.5% and 64 to 118%, in the

case of a Cement content of 10%, for the range of Moulding pressures from 1.25 to 7.5MPa.

- The effect of fibres is pronounced in Kit fibres having 2cm length and 0.1% by weight of the dry Soil.
- An optimum Cement content of 7.5% by weight of the dry Soil is required to meet the minimum requirement of strength.
- The maximum quantity of Cement may be limited to 10% by weight of the dry Soil, considering the rate of increase in strength and the cost.
- About 20 to 50% increase in the compressive strength was observed, when the moulding pressure was increased from 1.25 to 7.5MPa. This shows that along with cement stabilisation, higher moulding pressure also was found to influence the strength of the fibre-blocks.
- Influence of fibres on the compressive strength was found to be significant, the increase in strength was in the order of about 45%, when stabilised with cement. This shows that cement, acting as the binder of the composite material, was found to influence the strength of the fibre-blocks along with fibre type, length and volume.

- The plastic fibres chopped from carry bags perform better than that from PET water bottles in enhancing the compressive strength. Lower effectiveness of fibres made out of bottle may be due to the following reasons: (i) the type of surface finish which result in lack of bond with soil and slips from soil, (ii) due to the stiffness of the fibres, during mechanical compression, the soil particles may laterally move apart leaving air space between the fibres and that of soil creating weaker planes.

- Stabilised cylindrical specimens and fibre reinforced stabilized cylindrical specimens at higher moulding pressure showed a strength values of 3.5 to 4.41MPa, a value which is highly satisfactory compared to that of minimum compressive strength of 3.5MPa for a well burnt brick as per BIS 1077 and minimum compressive strength of soil block for general building construction as per BIS:1725 – 1982

- Compressive strength of the blocks varied between 3.8 to 5.5MPa for the range of stabilizers and fibres added. Compared to the compressive strength of cylindrical specimens, all blocks are having higher compressive strength. The ratio of block strength to cylinder strength varied from 1.068 to 1.247. This increase in strength (6.8 to 24.8 %) may be due to the platen effect that is due to friction along the interface between the platen and test specimen resulting in confinement to lateral expansion of the specimens.

### 6.1.3 Split Tensile Strength

- For given moulding pressure, as cement content increases, the tensile strength increases.
- Fibre addition increases the split tensile strength. This increase in strength, also depends upon the moulding pressure.
- Compared to raw specimens, compacted reinforced cement stabilized specimen shows an increase of 4.5 times in its tensile strength. This is one of the major advantages of addition of fibres, to the compressed stabilised specimens.
- From the observations of failure pattern it can be concluded that the benefits of fibre reinforcement includes both improved ductility and inhibition of large crack propogation after initial formation.

### 6.1.4 Compressive Strength of Masonry

- For given cement content, the ratio of masonry strength to block strength varied from 0.38 to 0.52 for low and 0.45 to 0.72 for high moulding pressure.

- For given cement content, the ultimate stress increases with the addition of fibres. The strains at ultimate stress for masonry are more for blocks containing fibres.

- Above observations and failure pattern show that the fibre reinforced mud block masonry behaves more resilient and ductile, so that the masonry can store more elastic energy compared to mud blocks without fibre, which renders it more resistant to earthquakes.

### 6.1.5 Water Absorption

- Raw specimens were disintegrated during water absorption test, clearly suggesting the essentiality of cement stabilisation, if the blocks were meant for exterior use without protection

- When static compaction using 7.5MPa stress was used, water absorption reduces from 12.4 to 7% when the cement content is increased from 5 to 15%. At the same time, at lower moulding pressure of 1.25MPa, the water absorption reduces from 13.8 to 10.7%, when the cement content is increased from 5 to 15 %.

- The positive effect of the combination of chemical and mechanical stabilisation seems to have on one hand, cemented the soil particles together and filled in the pore space in the soil and on the other hand, prevented the reorientation and flocculation of soil particles, which precluded formation of enlarged pores and cracks

- Fibre addition increases the water absorption. As percentage of fibre increases water absorption increases. Water absorption increases with length of fibre also. These observations show that fibre forms interconnected channels and helps in increased water absorption when the specimens are completely submerged in water.
- But in the blocks containing fibre, as moulding pressure increases water absorption decreases. This may be due to the more compaction of soil and due to the considerable reduction of the air spaces between fibres and soil at high moulding pressure.
- More water absorption is observed in blocks, made out of bottle fibres. This may be attributed to the gap between fibre and soil resulted from the poor bond and lateral movement of fibres after releasing the moulding pressure because of the stiffness of bottle fibres.
- In any case, the water absorption of samples with 10 to 15% cement stabilisation was less than the specified value of 15% by weight as per IS 1725-2002: Specifications for Soil based blocks used for general building construction.

### 6.1.6 Sorptivity

- The sorptivity values varied from 0.984 to 0.304mm/√min, for different combinations of stabilizers and fibres.
- The combination of mechanical and chemical stabilization has resulted in a reduction in sorptivity by 63 to 69% in soil specimens without fibre addition.
- Fibre addition increased the sorptivity as it increases the inter-connecting channels. This observation was found, especially when the fibre content was lower. Compared to kit fibre, bottle fibre showed more sorptivity.
- But when fibre percentage was increased and at higher fibre length, the sorptivity was less, even less than that of the specimens without fibres. This exceptional behaviour may be due to the increased path length for capillary water because of the obstruction due to large amount of randomly oriented fibres.

### 6.1.7 Erosion Studies

- The unstabilised specimens prepared even at higher moulding pressure exhibited pitting damage upon accelerated erosion test.
- No measurable pitting or other damage was observed in any of the samples which were stabilised or stabilised and fibre reinforced. A

few small pits/patches were seen on the faces of the samples which were reinforced with 0.2% bottle fibre and compacted at low moulding pressure.

- But all of these specimens satisfy the weathering test criteria specified in IS 1725-1982, which says that when tested as per the code, the maximum loss weight shall not be more than 5% and the limiting diameter of the pit formed is to be within 1 cm for passing this weathering test.
- Spray erosion test indicates that the stabilized plastic reinforced blocks possess adequate resistance against rain erosion and these stabilized blocks can be used in walls without any water-proof coatings and plastering.

### 6.1.8 Suggested Mix Proportion

For the type of soil selected for the study which is more sandy in nature, the following mix proportion may be considered.

- Soil at a max dry density of 1.84g/cc
- Cement 7.5%
- Fibres made out of carry bags (Kit fibres) 0.1% by weight of dry soil having length of 2cm
- Moulding pressure 5MPa
- Potable water to achieve an Optimum Moisture Content of 14%

## 6.2 Scope for Future Work

This study forms an initial part in the ensuing long-term investigations on mud blocks. The areas on which continued research can be undertaken to provide a better understanding of the material and thus be of more use to the construction industry are:

- Similar studies on different types of soils are to be done to get a wide sustainable construction application of this technology
- Study on the microstructure to understand better the bond between soil matrix and fibre and an investigation on the effect of fibre orientation inside the soil matrix is required.
- This work has focused on mechanical and weathering properties (wind-driven rain erosion) of stabilized earth. Further tests such as drying shrinkage, thermal conductivity, long term durability studies to understand resistance to other degradation factors, are to be done in order to assess sustainability and practicality of extending its use to any environmental and climatic conditions
- Research is needed on improvements to the standard mix designs. Potential research options include alternative stabilizing agents or reinforcing options.

- Investigations on the bond, compressive strength and deformations characteristics of mud block masonry with different types of masonry mortar is also required
- A theoretical study (analytical and numerical) to facilitate the design process, and to allow the inclusion of these materials in building codes and engineering design standards, is required.
- As the Kit fibres are versatile in imparting better Compressive strength, where as the Bottle fibres assist more in imparting the Tensile strength of the Compressed Stabilised Earth Blocks, a combination of these two fibres at definite proportions may probably lead to interesting results.

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