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-Marín 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
Chapter 2

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, cementitious 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 to 10% 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
Review of Literature

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 C₃S and C₂S 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.
Chapter 2

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-Marín 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-Marín 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 everyday 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, \(d_e\) 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).
Chapter 2

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
Review of Literature

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.
Chapter 2

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/m², with an average for the majority of consignments of 2.5 KN/m².

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/m² (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

2.7.2.1 Compressive 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
Review of Literature

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,
Review of Literature

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 unstabilised 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-Marín 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 cement 15% 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 uniaxial 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 Ereell (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/m²/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/m²/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:
Chapter 2

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.