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Experimental and Computational Analysis of Compressive Strength of Bricks with Granite Powder and Fibres as Binder to Soil

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Authors' contributions

This work was carried out in collaboration between both authors. Author PPY designed the study, performed the experiment and the analysis, wrote the protocol and wrote the first draft of the manuscript. Author CKK edited the manuscript and made immense contribution. Both authors read and approved the final manuscript.

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ABSTRACT

The effect of incorporating granite powder and fibres (oil palm and polyethylene plastic) into soil for sun dried brick production was investigated. Initial tests were conducted on the soil and the granite powder so as to obtain all the relevant index properties of the materials to be used. Fifteen percent granite powder, by weight of the soil was added to the soil as a binder and palm and plastic fibres as enhancer for sun dried bricks production. The bricks were tested for their compressive strength and validated with Finite Element Numerical Model. It was observed that at 1.0% fibre addition, the compressive strength increased, by 17% and 29.7% for the palm and plastic fibre respectively. At 1.5%, fibre content the corresponding values were even higher at 28.6% and 38.3% increase over the control brick without fibres. The granite powder soil brick with the highest weight fraction of fibre were found to provide the best correlation between the Finite Element Analysis (FEA) model and the experimental observation in relation to both the loading path and maximum strength. The FEA predicted the real behaviour well, and the composite action between the fibres and the soil could be seen largely as an enhancement through a tensile strength provided by the fibres to

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contain and retain the soil in place to continue to carry the compressive force. Further work is recommended to continue with the validated numerical model tool to design a fibre - enhanced granite powder soil brick with required performance characteristic for practical use in construction.

Keywords: Fibre; soil; granite powder; numerical model; sun dried brick.

1. INTRODUCTION

Developing countries are faced with great housing problem for their citizens. This is largely due to the progressive escalating cost of building materials, most of which are imported into the countries at exorbitant hard currencies [1]. Furthermore, developing countries are faced with efficient waste management challenges. There are a whole lot of local waste materials that are left unharnessed, thereby posing serious environmental challenges. Such local waste materials could be effectively used to produce, enhance or supplement construction materials, especially for masonry units.

Soil bricks have continuously been used as masonry units by most cultures due to their outstanding physical and engineering properties [2]. The principal properties of soil bricks that make them superior building units are: their strength, fire resistance, beauty and satisfactory bond performance with mortar [3]. However, soil bricks have low resistance to abrasion, water absorption and so on. Some of the means of improving the engineering properties of soil brick are: stabilising it with chemical binders, subjecting it to a high temperature, compressing it under high pressure and so on. Chemical stabilisers are expensive for most rural dwellers in developing countries. The technological set up for the brick firing is expensive for the impoverished rural and urban inhabitants in these poor countries. It is therefore prudent that current research focuses on investigating materials that are cheap, affordable and readily available to stabilise soil brick in order to attain desirable engineering properties [4,5,6,7,8,9,10]. Therefore this study investigates how waste materials could be used as stabiliser for bricks. The waste materials for this study are granite powder (GP) and fibres (synthetic and natural). The motivation for using granite powder and fibre among other things are as follows: environmental friendly, low cost and readily available.

The increase in the popularity of using environmental friendly, low cost and durable construction materials in the building industries have brought about the need to investigate how these materials can be used to benefit the environment and maintain the requirement affirmed in standard practices.

Granite powder constitutes a huge volume of solid wastes (dust) generated daily by quarries in the developing world [1]. This waste generally poses a serious environmental hazard to the public. Quarry waste is used in different applications in the construction industry, for example as a source of material for calcium silicates in road construction, as aggregates in concrete and asphalt, and as an additive in cement and other building materials [11,12]. The main chemical composition of waste from the quarry industry is calcium oxide, magnesium, ferrous, silicon, and aluminium oxides [5]. Quarry dust incorporated in the matrix of fired clay brick has proven to be very efficient in improving the mechanical properties of the brick [12].

The mechanical properties of a masonry unit depend on the orientation of the bed joints, the shear modulus and stiffness of the masonry structural elements. Hence, improving the shear modulus and the stiffness of the brick itself would further enhance the masonry unit. One of the materials that is likely to improve the stiffness of the brick is fibre. Findings from past studies on the use of fibre in soil bricks are conflicting. Studies by Souza et al. [13] and Aouba et al. [14] have shown that the use of fibre in clay bricks improved the strength and the durability of the soil brick, Tonnayopas et al. [15] on the other hand reported a decrease in durability (water absorption resistance) for brick with fibre addition. Hence, further studies need to be conducted on the performance of fibre as a stabiliser to soil bricks.

Existing studies on masonry units focused on the use of granite powder as stabiliser for soil in burnt bricks production [16]. The present study looked at fibre as an enhancer to sun dried bricks with granite powder as soil stabiliser. The results were validated using Finite Element Analysis Model. The motivation for conducting computational analysis was threefold: firstly to improve the understanding of the performance of granite power soil bricks enhanced with fibres, secondly to assess whether the magnitude of the stresses were within the permissible limits (after comparing the computed deformation with the experimental values) and thirdly, when confidence in the finite element result has been established, the finite element model can be used to more rapidly investigate effects of changes to the soil brick geometry, material and configuration.

2. MATERIALS USED AND TESTING METHODS

2.1 Materials

The bricks for this study were produced from ordinary soil that is normally used in the brick industry; the fibres consisted of oil palm fibres and polyethylene fibres, while granite powder was obtained from a quarry site.

2.2 Testing Methods and Procedures

2.2.1 Physical and chemical properties of soil and GP

Sieve analysis of the soil was conducted in accordance with BS 1377-1 [17] and BS 1377-2: [18] requirements.

A three kilogram of soil sample was dried in an oven, at a constant temperature of 110°C for 24 hours (BS1377-1) [17]. Soil particles were crumbled between the palms of the hands so that when the particles were sieved on the specific test sieve only individual particles were retained. The soil was sieved using a standard stack of test sieves with aperture sizes of 37.5, 20, 10, 5, 4, 2.36, 1.18, 0.6, 0.3 and 0.15 mm. The results of the particle distribution test are presented in the results Section.

In a similar manner, the particle size distribution was determined for the granite powder sample. Multi-element determinations of GP were carried out using an energy-dispersive polarizing X-ray Fluorescence Spectrometer. Table 2 shows the chemical composition of the granite powder.

2.2.2 Atterberg limits

The liquid and plastic limits tests on the soil were conducted in accordance with BS 1377 [18]. The liquid limit expresses the moisture content corresponding to a cone penetration of 20 mm.

Approximately 500 g of soil in the natural state was taken from soil sample that had passed through the 425 µm test sieve. The soil was placed on a flat glass plate and was mixed thoroughly with distilled water using two palette knives until the mass became a thick homogeneous paste. The paste was placed in an air tight container and allowed to stand for 24 hours to enable the water permeates through the soil.

A portion of the mix was forced into a cup with a palette knife to make sure air was not trapped. Excess soil was stroke off with the straight edge to give a smooth level surface. The soil sample was then placed on the cone penetrometer apparatus for testing (Fig. 1).

The supporting assembly of the penetration cone in the raised position was lowered so that the tip of the cone touched the surface of the soil. The stem of the dial gauge was lowered to contact the cone shaft and the initial reading of the dial gauge was recorded to the nearest 0.1 mm. The cone was then released for five seconds and the reading on the dial gauge was recorded.

The cone was then lifted and thoroughly clean. A little more wet soil was added to the cup, taking care that air was not trapped and the surface was smoothened. The above experiment was repeated. The average of the two readings of cone penetration was recorded. About 10g of the soil within the area penetrated by the cone was taken and the moisture content determined according to BS1377-2 [18].

2.2.3 Compaction test

Compaction of the soil specimen was done in accordance with BS 1377-1 [17] and BS 1377-4 [19].

The mould was weighed with base plate attached (M_1). The extension of the mould was attached and placed on the base of the compaction testing machine. A quantity of moist soil was placed in the mould such that when compacted it occupied a little over one-third of the height of the mould. Twenty seven blows from the rammer (as recommended by BS 1377-4 [19] were dropped from the height of 300 mm above the soil by a motorised means.

The process was repeated twice with additional soil, so that the amount of soil used was sufficient to fill the mould. The extension of the mould was removed and the excess soil was stroke off and the surface of the compacted soil was levelled at the top of the mould using a straight edge. Any coarse particles that were removed during the process of levelling was replaced with finer material from the soil sample and well pressed into the soil sample. The soil and the mould with base plate was then weighed (M_2) (see Fig. 2).

The compacted soil was removed from the mould and placed in a metal tray. A representative sample of the soil was taken for determination of moisture content.

2.2.4 Linear shrinkage test

The soil in its natural state was tested for linear shrinkage and was conducted in accordance with BS 1377-1 [17]; BS 1377-2] [18].

The determination of linear shrinkage was carried out on 500 g of soil that had passed through the 425 µm test sieve. The soil was mixed thoroughly with distilled water using palette knives till the mass became a smooth homogeneous paste with the moisture content at about the liquid limit of the soil. Four brass moulds were smeared with silicon grease and soil paste was added to each, ensuring that there was no air bubble present. The surfaces were smoothened using a straight edge. The moulds were then placed on a table where the wet soil could air dry slowly until the soil had shrunk away from the walls of the moulds. The drying was completed by placing the sample in an oven, first at a temperature 60°C until shrinkage had largely ceased, and then at a temperature of 105°C for 24 hours to complete the drying. Shrinkage was considered complete when three successive measurements showed no change in length. Details of the measurements were recorded.

2.2.5 Organic content test

An oven-dried soil sample of approximately 10 g was placed in the container and covered. The sample, container and the lid were weighed together. The container with the sample was heated on a gas stove which resulted in fume generation. The heating continued until there was no visible fume. The container together with the lid and the soil sample was again weighed and the organic content was thus calculated.

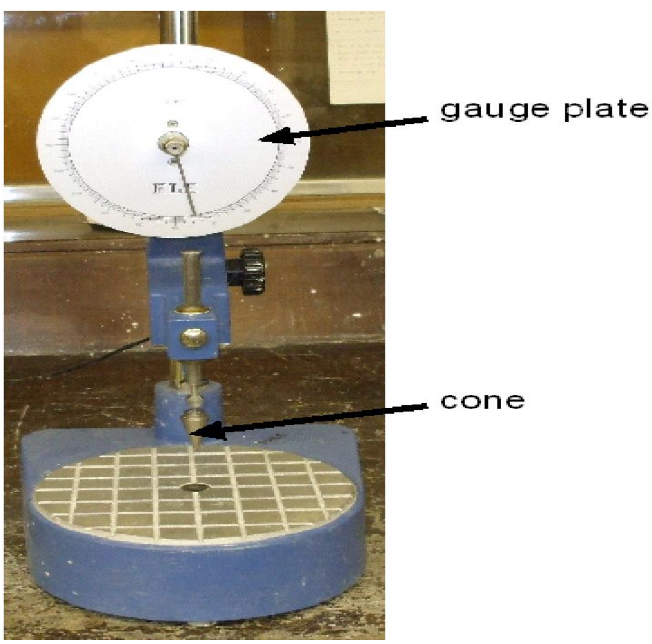


Fig. 1. Cone penetrometer

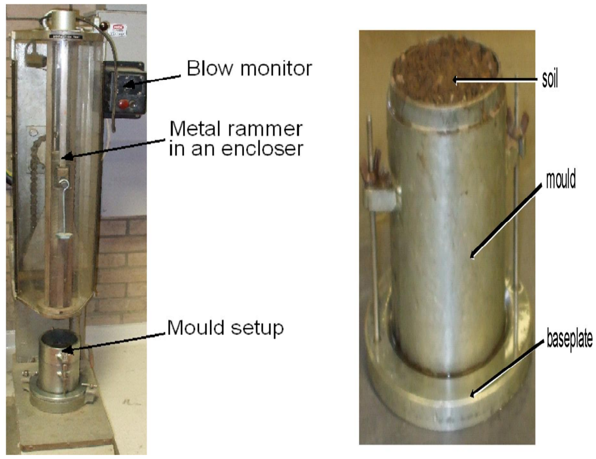


Fig. 2. Compaction test set up

2.2.6 Triaxial test

The optimum aim of conducting the triaxial test was to obtain the maximum stresses from three sets of test samples and use the result to further calculate Modulus of Elasticity E, Cohesion coefficient C′ and Angle of shear resistance Φ from the Mohr's circle diagram. The Poisson's ratio v, was calculated from the dimensions of the soil test specimen before and after the test was completed (see Fig. 3). The modulus of elasticity, shear modulus and Poisson's ratio were used in the numerical modelling.

The procedure for mounting of triaxial test specimen was according to BS EN 17892-9 [20]. A saturated porous disc was placed on a layer of water on the triaxial base pedestal thus making sure air was not trapped and excess water removed. The specimen was placed on the disc without delay and without trapped air. An identical disc was placed on top of the specimen. After surplus water was allowed to drain from the soaked membrane, the membrane was placed around the specimen. The base pedestal was sealed with two rubber O-rings. The back pressure valve was opened to moisten the top cap, which was then fixed onto the porous disc without entrapping air. The membrane on top of the cap was then sealed with another two O-rings. The air in the triaxial cell was displaced by filling the cell with de-aerated water. Castor oil was introduced on top of the water to act as a lubricant to the piston and to reduce leakage around the piston. The setup is shown in Fig. 3.

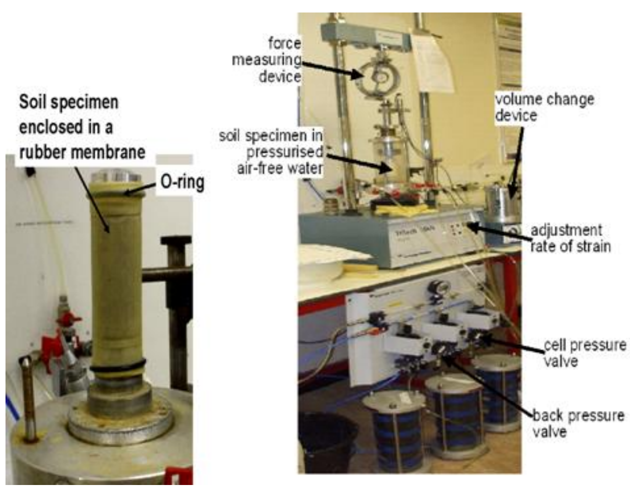


Fig. 3. Mounting of soil specimen for triaxial test

2.3 Preliminary Experimentation on Soil Brick Stabilised with Granite Powder

Preliminary experiment was conducted on soil bricks stabilised with various percentages of granite powder ranging from five to thirty. The results from the preliminary experiment indicated that 15% granite powder increased the compressive strength of the bricks by 32%. Again it was noted that the addition of granite powder beyond 15% did not improve the properties under consideration. The preliminary results then implied that 15% granite powder was the optimum percentage content for stabilising soil for bricks production.

On the basis of the results from the preliminary studies on bricks with granite powder as stabiliser to soil, this study used 15% of granite powder as stabiliser to soil in brick production, with the inclusion of 0.75%, 1.0% and 1.5% (by weight of granite powder) of natural and synthetic fibres. Compressive strengths, was analysed after 28-days of air curing. The materials mix proportions are in Table 1.

A BREPAK earth block press (see Fig. 4) was used to produce the soil bricks with 15% granite powder and various fibre weight fractions at a pressures of 35 N/mm^{2} ¨ The size of the brick was 200cm x75cm x50 cm. Based on the results of the shrinkage test, the bricks were covered with polyethylene sheet in the first three days after moulding and then cured in open air for further 25 days (see Figure 5).

2.4 Compressive Strength Test

Compressive strength test on the bricks were conducted in accordance with BS EN 12390-3 [21]. Three bricks from each batch were selected after four weeks of curing. These bricks were gently wiped with non-absorbent cloth in order to remove any dust or loose matter stuck to them and the compressive strength for each brick was determined using a universal testing machine with accessories which could record the stress and strain values. Fig. 6 shows the setup of compressive tests. The average of the compressive strength for each batch was calculated for analysis.

2.5 Finite Element Simulation

It was assumed that all the fibres had the same dimensions and orientation and were uniformly distributed. The soil and the fibre materials were assumed to be isotropic in stiffness. The representative element of the brick, shown in Fig. 6 had a tetrahedron mesh for the soil and this included the cylindrical enhancement fibre. An orthogonal cartesian coordinate system was used as reference with 0x, 0y and 0z axis aligned with the main dimensions of the brick. The longitudinal axis of the enhancement fibre was placed perpendicular to the uniaxial loading direction [22].

Finite element mesh of the brick composite of 200mm x 75mm x 50 mm in size was generated using the MSC/PATRAN program. The soil together with fibre was modelled as ''Halpin-Tsai'' discontinuous fibre composite material. This was a two phase composite in which the matrix phase was isotropic and the fibres were uniform, discontinuous, cylindrical, and transversely isotropic. The resultant composite was therefore considered as transversely isotropic [23]. A predicted 3D displacement and stress diagram at a fully deployed state is exhibited in Fig. 7b.

Table 1. Mix proportion

Sample	Soil (kg)	Fibres (kg)	GP (kg)	Water (kg)	No of bricks
A	7.5	0	1.2	0.75	5
$B_{0.75}$	7.5	0.009	1.2	0.75	5
$B_{1.0}$	7.5	0.012	1.2	0.75	5
$B_{1.5}$	7.5	0.018	1.2	0.75	5
$C_{0.75}$	7.5	0.009	1.2	0.75	5
$C_{1.0}$	7.5	0.012	1.2	0.75	5
$C_{1.5}$	7.5	0.018	1.2	0.75	5

A -control sample, Bx-sample with x% oil palm fibres, Cx - sample with x% plastic fibres

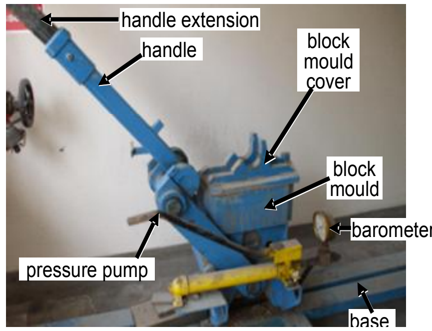


Fig. 4. BREPAK block machine

Fig. 5. Curing of bricks

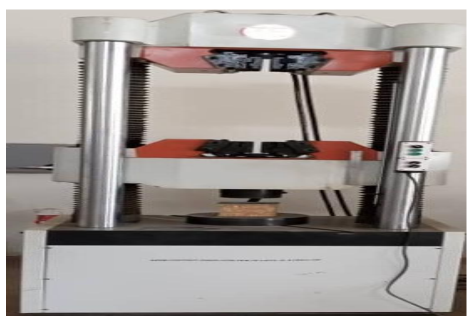
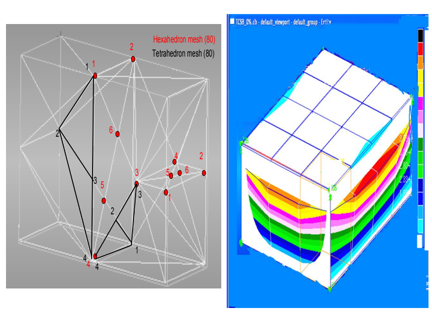


Fig 6. Compressive test setup



a **b**

Fig. 7a. Soil block geometry and FE mesh
Fig. 7b. A predicted 3D stress displacement

3. RESULTS AND DISCUSSION

3.1 Classification of Soil and Granite Powder

The sieve analysis and Atterberg limits were used to classify the soil in this study.

3.1.1 Physical and chemical properties of soil and GP

The effective size D_{10} (the particle size where 10% of particles are finer also known as effective size) was 0.125 mm (see Fig. 8a). D_{60} (the particle for which 60% of particles are finer) was 2.5 mm.

As shown in Equations 1 and 2, the soil's coefficient of uniformity and gradation were 20 and 0.56 respectively. This soil was thus within the limit for well-graded intermediate clay content and gravel, making it ideal for soil bricks,

Uniformity coefficient, U

$$U = \frac{D_{60}}{D_{10}} = \frac{2.5}{0.125} = 20 \quad (1)$$

That is well graded soil

Coefficient of Gradation or curvature C_g of GP

$$C_g = \frac{(D_{30})^2}{D_{60} \, xD_{10}} = \frac{0.5^2}{2.5 \times 0.125} = 0.8 < 3 \quad (2)$$

That is uniformly graded GP.

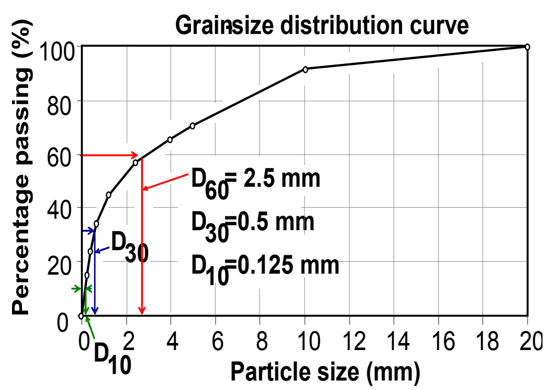


Fig. 8a. Particle size distribution

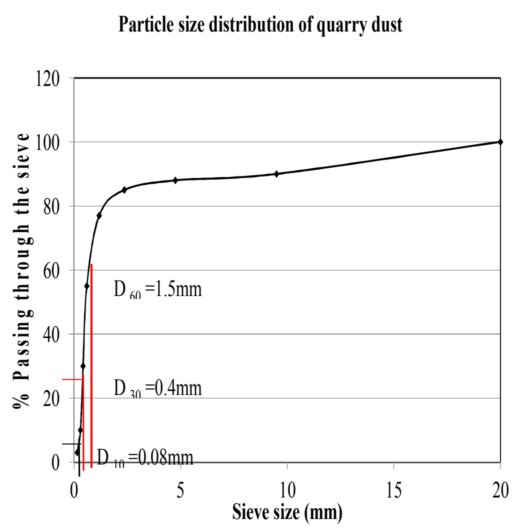


Fig. 8b. Particle size distribution of GP

Coefficient of Uniformity Cu

$$C_u = \frac{D_{60}}{D_{10}} = \frac{1.5}{0.08} = 18.75 \quad \text{(3)-well graded}$$

Coefficient of Gradation GP

$$C_g = \frac{(D_{30})^2}{D_{60} \, x \, D_{10}} = \frac{0.4^2}{1.5x0.8} = 1.3 < 3 \quad (4)$$

uniformly graded

The granite powder had coefficient of uniformity and gradation of 18.75 and 1.3 respectively making the GP uniformly and well graded (see equations 3 and 4, Fig. 8b).

3.1.2 Chemical composition of GP

The SiO_2, Al_2O_3 and the Fe_2O_3 contents in the GP were 62.68%, 18.72% and 6.54% respectively (Fig. 2). The total amount of reactive of SiO_2, Al_2O_3 and the Fe_2O_3 content in the GP was 90% making the GP a binder according to BS EN 450-1 [24].

3.1.3 Linear shrinkage

From the results, shrinkage increased rapidly within the first three days and then the increase slowed down. The maximum percentage of linear shrinkage at age seven days was 2.18mm (Fig. 9). The rapid shrinkage during the first three days drew the attention that particular care should be taken for curing during the first three days of the moulded brick. Hence the bricks were covered with a polythene sheet for the first three days of curing and this was beneficial in reducing drying shrinkage and cracking.

Table 2. Chemical properties of granite powder

Chemical composition	%
Silicon oxide (SiO_2)	62.68
Aluminum oxide (Al_2O_3)	18.72
Ferric oxide (Fe_2O_3)	6.54
Calcium oxide (CaO)	4.83
Magnesium oxide (MgO)	2.53
Potassium oxide (K_2O)	3.81
LOI	1.33

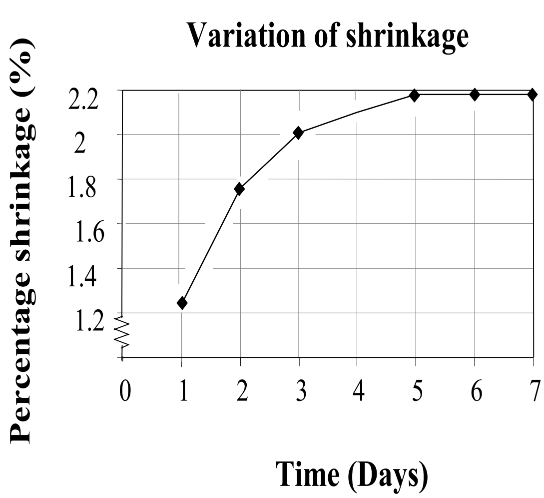


Fig. 9. Effect of time on development of shrinkage

3.1.4 Atterberg limits

The soil had a liquid limit (W_L) of 35%, plastic limit (W_P) of 24% and plasticity index of 11% hence the soil was classified as moderately plastic clay according to the plasticity chart of [25] (see Fig. 10).

$$\text{Plasticity index} = W_L - W_p = 35 - 24 = 11 \quad (5)$$

3.1.5 Compaction test

The results indicated that the most favourable water content for soil without granite powder was 10% (by weight of soil) with maximum dry density of 1762 kg/m^3. Soil with some amount of granite powder had most favourable moisture content of 9%. This low water content could be explained that the fine particle of granite powder filled the void of the soil matrix, hence fewer voids needed to be filled by water. It could be seen from Table 3 that the addition of granite powder increased the dry density of soil. The improvement in density could be ascribed to the finer nature of the granite powder that might have generated a matrix of interlocking crystals that covered any void between the soil particles and eventually provided a higher density and better stability.

3.1.6 Loss on ignition

The soil was found to have organic content of 1.9% (Table 4). Houben and Guillard (1994) [26] expressed the view that organic matter up to 2% of the soil has little influence on the mechanical performance of the soil brick. Hence the soil used was appropriate for soil brick production.

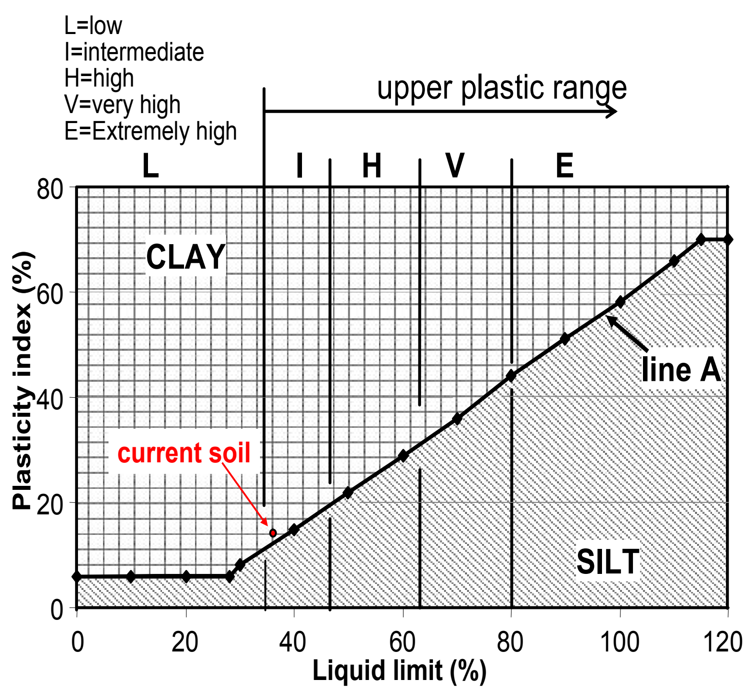


Fig. 10. Plasticity chart for soil classification

Table 3. Optimum moisture content and maximum dry density of the soil used

Specimen	OMC (%)	MDD (kg/m^3)
A (soil without granite powder)	10	1762
B (soil with 7% granite powder)	9	1820
C (soil with 8% granite powder)	9	1813
D (soil with 9% granite powder)	9	1804
E (soil with 10% granite powder)	9	1797

Table 4. Percentage of organic content determination by ignition

Weight readings	Values
Mass of container + lid (m_1)	61.5 g
Mass of container + lid + soil sample (m_2)	71.7 g
Mass of soil sample before ignition $m_3 = m_2 – m_1$	10.2 g
Mass of container + soil sample after ignition (m_4)	71.5 g
Mass of organic materials $m_5 = m_2 – m_4$	0.2 g
Percentage of organic content $\frac{m_5}{m_3} = \frac{0.2}{10.2} x\ 100$	1.9 %

Table 5. Shear force data

Stage	Average Pore pressure (kPa)	Average strain
At the saturated stage	30	0.1
Consolidated stage	277	5.2
Compression stage	400	5.8
Failure stage	700	6.4

3.1.7 Shear strength test of soil

The elastic modulus E, Poisson ratio v, cohesion coefficient C and Angle of shear resistance Φ of the soil, were required to generate the results of the FEA model. Data were determined using triaxal soil test. The properties of the soil are listed in Table 5 and 6.

Modulus of elasticity, Poisson ratio and shear modulus are expressed in equations 6, 7 and 8 respectively.

Modulus of elasticity

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{700-30}{6.4-0.1} = \frac{6\ 70}{6.3} x\ {}^{1}/_{10} = 10.6\ mPa \quad (6)$$

Poisson ratio

$$v = \frac{\epsilon x}{\epsilon y} = \frac{0.026}{0.06\ 1} = 0.33 \quad (7)$$

Shear modulus

$$G = \frac{E}{2(1+v)} = \frac{10.6}{2(1+0.33)} = 3.98 \approx 4mPa \quad (8)$$

3.2 Compressive Strength of Bricks

The compressive strength of the soil brick containing granite powder and fibres was tested using a universal testing machine. Figs. 11a and 11b show stress-strain results of the bricks. Granite powder soil brick without addition of fibres had the lowest compressive strength of 17.5 N/mm^2 as compared with those with fibres addition. In the case of granite powder soil brick with fibre enhancement, the compressive strength increased with increase in weight fraction of fibre content. At the lowest level of 0.75% of oil palm fibre and plastic fibre addition, compressive strength was 6.8% and 12.5% respectively higher than granite powder soil brick without fibre. At 1.0% fibre addition, the compressive strength increased, by 17% and 29.7% for the palm and plastic fibres respectively. At 1.5%, the corresponding values were even higher at 28.6% and 38.3% increase. It was noted that the strength values obtained were very respectable strengths for building bricks. It could be seen that within the range of straining applied, the granite powder soil brick had a fairly linear response even for strains up to 40%. Moreover, these granite powder soil bricks could have achieved higher strength values before ultimate failure. The presence of granite powder was adequate to generate amply high compressive strengths for even soil brick without fibre (e.g. 17.5MPa at 40% strain). The advantage of fibre additions was therefore actually not so much in the higher strengths achievable (though the strength increased with the addition of fibres) but in the ability to achieve high stresses at lower strains. For increase in fibres content from 0.75% to 1.5% (i.e. an increase of 50% of fibre content) the compressive strength increased by only about 20% to 23%. The advantage was thus the higher stiffness generated by the fibre enhancement.

3.3 Stiffness

The use of plastic fibres as opposed to the palm fibres consistently produced higher stiffness. For the same fibre content of 0.75%, 1.0% and 1.5% by weight of soil, the strength at 40% strain of bricks C_x was about 5.4%, 11% and 6%

respectively higher than bricks B_x. This could be expected since the plastic fibres were both stiffer and stronger than the natural palm fibres. The stiffness of the brick was much improved for bricks with fibre addition. For example, a stress of 15MPa was achieved at about 10.4% and 29.5% lower strain for 1% and 1.5% palm fibre, when compared with the soil brick without fibre. The corresponding lower strain value for plastic fibres was about 33%. There was thus a clear advantage in adding fibres to the current newly proposed granite powder soil brick. The stiffness of the brick could improve the stiffness of the masonry unit, hence, the shear stresses and ductility of the masonry unit.

3.4 Finite Element Numerical Model Analysis

The predicted results from finite element numerical model showed a similar behaviour to that of experimental results. The FE analysis showed that granite powder soil brick model without addition of fibres as an enhancement had the lowest compressive strength of 14.3 MPa as compared to those with fibre addition. In the case of fibre enhanced granite powder soil bricks, the compressive strength increased with increase in weight fraction of fibre content as shown in Fig. 12a.

The compressive strength was 24.7% higher for the lowest level of 0.75% fibre addition compared to the granite powder soil bricks without fibre. At 1.0% levels of fibre addition, the compressive strength increased by 27% and 33% respectively for oil palm fibre (B_{10}) and plastic fibre (C_{10}) enhanced granite powder soil brick model. At 1.5% levels of fibre addition, the corresponding figures were increases of 36% and 46% (Fig 12b-g).

Table 6. Characteristics of soil

Properties	Values
Angle of shear resistance Φ	21°
Elastic modulus E	10.6 MPa
Poisson ratio v	0.33
Moisture content	10%
Liquid limit	35%
Plastic limit	24%
Plasticity index	11%
Maximum shrinkage at 6 days	2.18%
Organic content	1.9%
Maximum dry density	1762 kg/m^3
Moisture content	12%
Clay content – intermediate	11%

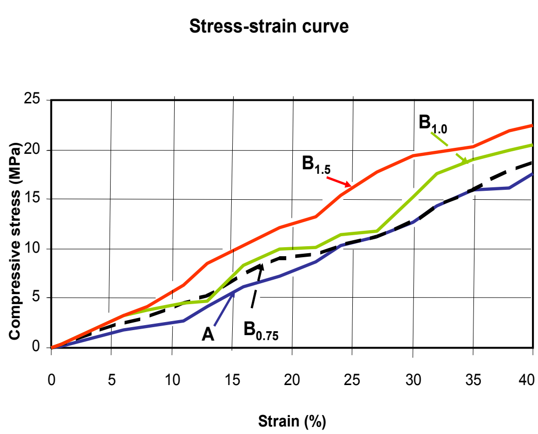


Fig. 11a. compressive stress vs strain Bx

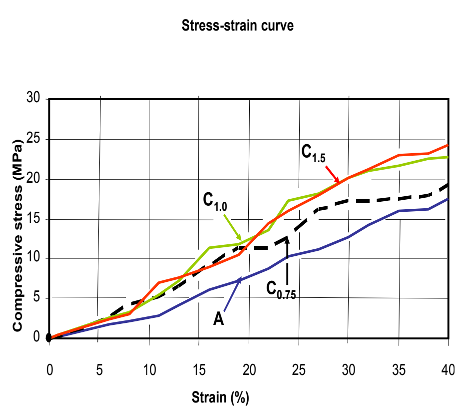


Fig. 11b. compressive stress vs strai Cx

(NB: B_x refers to bricks with palm fibre; C_x refers to bricks with plastic fibre)

Both sets of results indicated that granite powder soil brick with fibre had higher strength than those without any fibre addition, and that strength increases with increase in fibre content (at least up to 1.5% by weight of soil). Furthermore, results from both experimental studies and the finite element numerical model prediction showed that at the same weight fraction of fibres, granite powder soil brick enhanced with plastic fibre performed slightly better than those enhanced with oil palm fibres. It could be seen from Figs. 13a-g that the predicted and measured results were in good agreement. However, it was observed from the experimental results that, up to a strain of about 13% the experimentally measured stress increase was very small with a fairly rapid increase in strain. Thus, it was hypothesised that the discrepancies observed in this study might be attributed to poor compaction of the soil bricks.

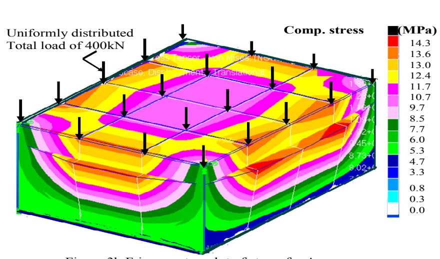


Fig. 12a. Fringe brick plot of stress for A

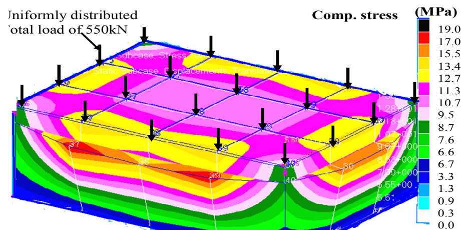


Fig. 12b. Fringe brick plot of stress for $B_{0.75}$

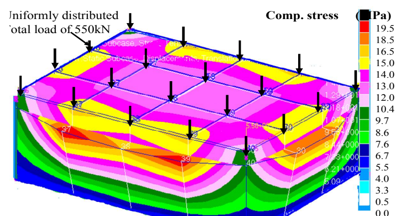


Fig. 12c. Fringe brick plot of stress for $B_{1.0}$

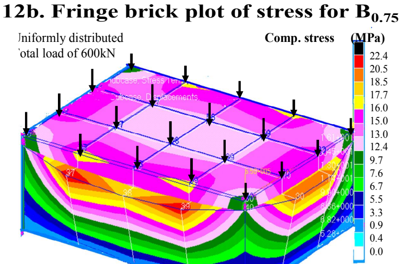


Fig. 12d. Fringe brick plot of stress for $B_{1.5}$

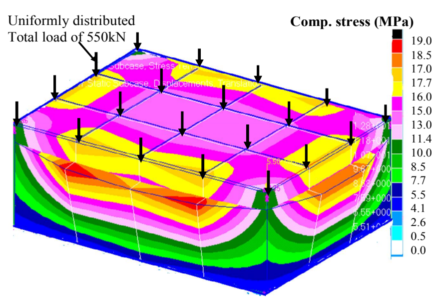


Fig. 12e. Fringe brick plot of stress for $C_{0.75}$

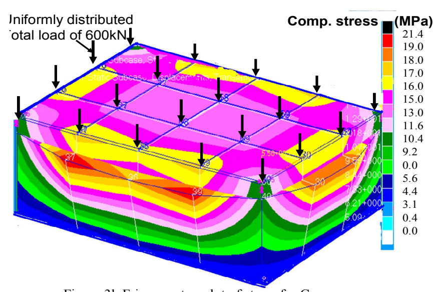


Fig. 12f. Fringe brick plot of stress for $C_{1.0}$

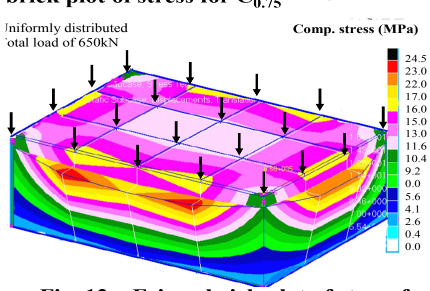


Fig. 12g. Fringe brick plot of stress for $C_{1.5}$

Fig. 12 a-g. Compressive strength for finite element numerical model

For granite powder soil brick without any fibre, the maximum stresses in the vertical direction, at a strain of 40% were 14.3 MPa for predicted and 17.5 MPa for measured. This gave 18% stress increase of the experimental value over that of predicted by the numerical model, though for 75% of the loading range, the experimentally measured stress was lower (Fig. 13). The strength values for granite powder soil brick enhanced with 0.75% of oil palm fibre (at a strain of 40%) were 18.6 and 19 N/mm^2 for measured and numerical model predicted respectively. This gave a small difference of 0.4 N/mm^2 between the two. The equivalent difference between the measured and numerical prediction, for granite powder soil brick enhanced with 1.0% and 1.5% of oil palm fibre were variations of 0.9 and 0.1 N/mm^2 respectively. It was clear that the FEA predicted the real behaviour well. The same trend occurred in granite powder soil brick enhanced with plastic fibre. The differences here were 0.3, 1.3 and 0.3 N/mm^2 between experimental and numerical results for fibre contents of 0.75%, 1.0% and 1.5% respectively. The agreement between the predicted and experimental results was clearly good. However, the applied loads for the numerical results were generally between 15 and 36% higher than the experimentally applied load to obtain the same failure strain of 40 %. This again could be due to lack of good compaction in the experimental samples. The bricks with the highest weight fraction of fibre were found to provide the best correlation between the FEA and the experimental observation in relation to both the loading path and maximum strength, as shown in Fig. 13a-g.

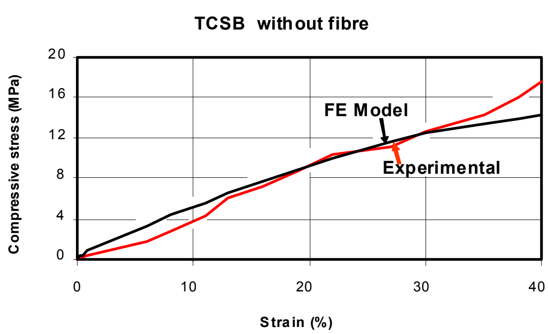


Fig 13a. Comparison of FEA Model with test data (A)

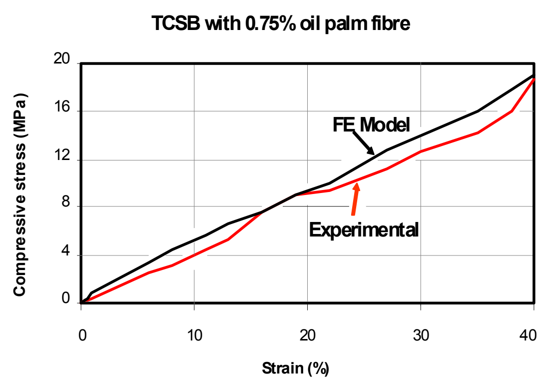


Fig. 13b. Comparison of FEA Model with test data ($B_{0.75}$)

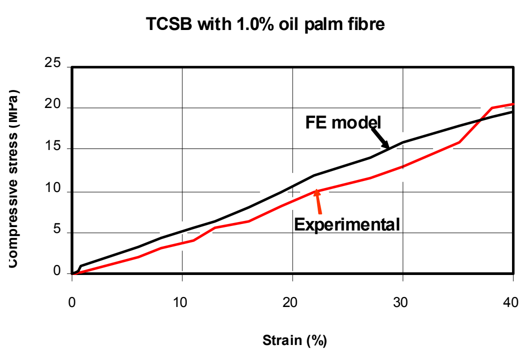


Fig. 13c Comparison of FEA Model with Test Data ($B_{1.0}$)

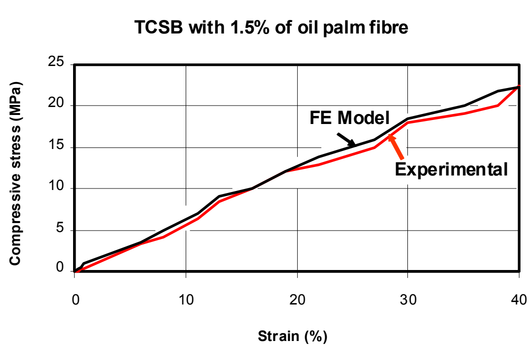


Fig.13d. Comparison of FEA Model with Test Data ($B_{1.5}$)

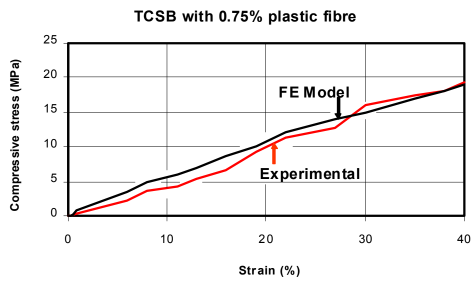


Fig. 13e. Comparison of FEA Model with Test Data ($C_{0.75}$)

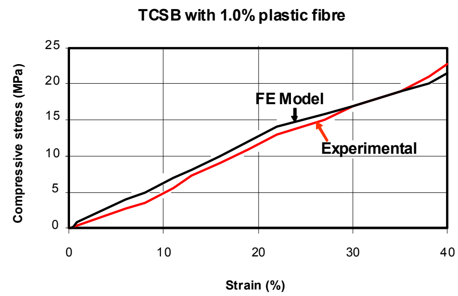


Fig.13f. Comparison of FEA Model with Test Data ($C_{1.0}$)

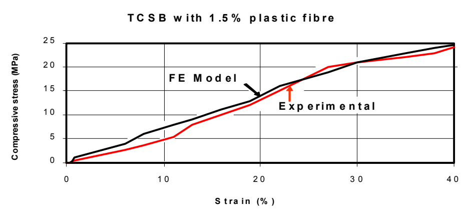


Fig. 13g. Comparison of FEA Model with Test Data ($C_{1.5}$)

4. CONCLUSION

Very good agreement was achieved between the numerical predictions and experimentally measured. The granite powder soil bricks with the highest weight fraction of fibre were found to provide the best correlation between the FEA and the experimental observation in relation to both the loading path and maximum strength. It was also clear that the FEA was predicting the real behaviour well, and the composite action between the fibres and the soil could be seen largely as an enhancement through a tensile strength provided by the fibres to contain and retain the soil in place to continue to carry the compressive force.

5. RECOMMENDATIONS

Further study on the durability of the natural fibre is recommended to ensure the newly propose alternative building material is suitable for construction of low cost housing.

Work should continue with the validated numerical model tool to design a granite powder soil brick with required performance characteristic for practical use in construction.

There is a limitation on the modelling of the interface between the fibre and the soil. This needs to be examined further before recommending the finite element model, as a reliable tool for validation of the masonry units.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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