Effect of Natural Fibres Inclusion in Clay Bricks: Physico-Mechanical Properties

Chee-Ming Chan

***Abstract*—**In spite of the advent of new materials, clay bricks remain, arguably, the most popular construction materials today. Nevertheless the low cost and versatility of clay bricks cannot always be associated with high environmental and sustainable values, especially in terms of raw material sources and manufacturing processes. At the same time, the worldwide agricultural footprint is fast growing, with vast agricultural land cultivation and active expansion of the agro-based industry. The resulting large quantities of agricultural wastes, unfortunately, are not always well managed or utilised. These wastes can be recycled, such as by retrieving fibres from disposed leaves and fruit bunches, and then incorporated in brick-making. This way the clay bricks are made a 'greener' building material and the discarded natural wastes can be reutilised, avoiding otherwise wasteful landfill and harmful open incineration. This study examined the physical and mechanical properties of clay bricks made by adding two natural fibres to a clay-water mixture, with baked and non-baked conditions. The fibres were sourced from pineapple leaves (PF) and oil palm fruit bunch (OF), and added within the range of 0.25-0.75 %. Cement was added as a binder to the mixture at 5-15 %. Although the two fibres had different effects on the bricks produced, cement appeared to dominate the compressive strength. The non-baked bricks disintegrated when submerged in water, while the baked ones displayed cement-dependent characteristics in water-absorption and density changes. Interestingly, further increase in fibre content did not cause significant density decrease in both the baked and non-baked bricks.

***Keywords*—**natural fibres, clay bricks, strength, water absorption, density.

I. Introduction

EARTH is readily and abundantly available, making it perhaps the most accessible and economical natural material for making building materials, such as bricks. Advancement in material engineering has yet to render earth obsolete as a building material, especially in financially and resources challenged places [1]. It is also most likely the most ancient building material known, with records of earth bricks dating back to 10,000 BC in Mesopotamia [2]. However, Man soon learned that earth alone is not suitable for the production of enduring bricks, and that the cohesion property of clay is essential as a natural binder for composites. For instance, the Romans introduced sand in the clay-water mixture to enhance the material's workability and to prevent excessive shrinkage, and added natural fibres, like straws and dried grass, to further limit shrinkage cracking [3]. Population growth is always accompanied by land acquisition for the construction of new dwellings and infrastructure. The vast natural land depletion is contributed by agricultural land cultivation and agro-based industry's expansion too, to support the survival needs of the human race [4]. The production and manufacturing processes inadvertently generate large quantities of natural wastes, such as fibres, pulps and grains, which are disposed of in landfill and open burning. Besides, the accumulation of unmanaged or improperly managed wastes has raised significant environmental and sustainable concerns [4, 5]. An on-going effort to counter this vicious cycle is by interception: to recycle and incorporate these natural wastes in the construction industry, especially in the manufacturing of building materials. A particularly potential area for the reuse of these wastes is brick-making. Adding natural fibres in clay bricks has been reported to improve the compressive strength and flexibility [6]. 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 [7, 8, 9].

For these fibre-bricks 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 conditions. Better understanding of the inter-relationship between the different properties can aid in future material selection and improve mix designs to produce fibre-bricks with desirable qualities. It was on this basis that the present study was conducted, to examine the main physical and mechanical properties of bricks made of a clay-fibre-cement mixture, baked and non-baked, and to establish the interaction of these key parameters, which manifest the combined properties and characteristics of the raw materials of a composite.

II. Materials and Methods

The clay soil used was collected in bulk from the test site of the Research centre for Soft Soils (RECESS), in the main campus of Universiti Tun Hussein Onn Malaysia. Standard soil classification tests were carried out based on the British Standards, BS 1377-2: 1990 [10], and a summary of the test results can be found in Table 1. Chemical properties of the clay are presented in Table 2. In order to keep a constant mixing water content for the brick specimens, the clay was first air-dried, then crushed and ground into powder form. Only the portion passing 63 μm was later used in preparing the test specimens. The fine clay powder was to ensure sufficient

Chee-Ming Chan is with the Research Centre for Soft Soils (RECESS), Universiti Tun Hussein Onn Malaysia, and is currently a Visiting Scholar at the Port and Airport Research Institute of Japan (corresponding author phone: +81-80-4345-1905; fax: +81-46-844-0618; e-mail: chan@uthm.edu.my).

plasticity for a uniform mix when added with the other components of the mixture.

TABLE I
PHYSICAL PROPERTIES OF CLAY

Percentage passing 63 μm sieve	44.7 %
Specific gravity, G_s	2.71
Natural water content, w_{NAT}	73.10 %
Liquid limit, w_{LL}	45.85 %
Plastic limit, w_{PL}	22.38 %
Plasticity Index, PI = w_{LL} - w_{PL}	23.47 %
Soil description	Greyish clay with medium plasticity

TABLE II
CHEMICAL PROPERTIES OF CLAY

Al_2O_3	27.50 %
CaO	0.18 %
Fe_2O_3	3.66 %
K_2O	1.96 %
MgO	1.09 %
SiO_2	59.10 %
SO_3	5.25 %
TiO_2	0.63 %
Na_2O	0.39 %

TABLE III
LIST OF SPECIMENS
(DUPLICATE SPECIMENS FOR BAKED AND NON-BAKED ONES)

Cement, C (%)	Fibres, F (%): PF or OF			
	0	0.25	0.50	0.75
0	•	•	•	•
5	•	•	•	•
10	•	•	•	•
15	•	•	•	•

The pineapple leaf fibres (PF) were retrieved by initially soaking and softening the leaves, followed by scraping to extract the cellulose fibres (Fig. 1). The fibres were then left to dry naturally at room temperature. The oil palm fruit bunch fibres were provided by the local palm oil processing plant, where they were found at the end of the fruit bunch harvesting process (Fig. 2). Both fibres were cut into lengths of 10 mm for inclusion in the specimens. The specific length was 1/10 of the length of the brick specimen (100 mm), chosen to avoid interference with uniform mixing in preparing the specimens. Ordinary Portland cement was added up to 15 % to serve as a binder to the mixtures.

Fig. 1 Pineapple leaf fibres, PF: raw (left) and dried (right)

Fig. 2 Oil palm fibres (OF)

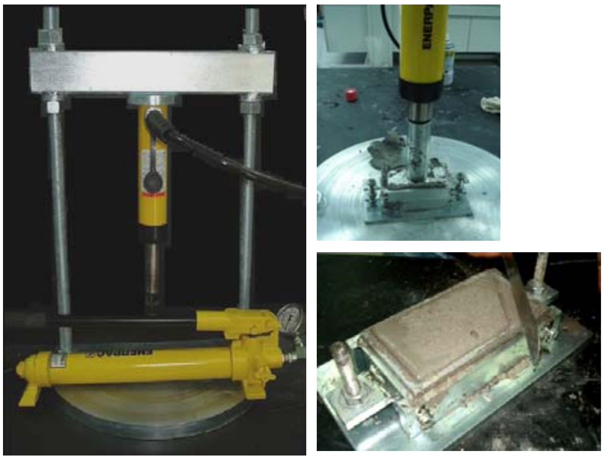


Fig. 3 The hydraulic press setup and brick specimen mould

The raw materials were thoroughly mixed in a conventional kitchen mixer to form a uniform paste. 40 % of water (based on dry weight of the clay) was added to all mixtures. Note that this water content is approaching the liquid limit of the clay (see Table 1), and hence facilitated ease in mixing with the addition of other raw materials, particularly cement. The paste was next transferred to a steel mould measuring 100 mm x 50 mm x 30mm, which represented an approximate 50 % scale-down of the dimensions a conventional brick. In order to maintain a standard specimen preparation procedure, the amount of material placed in the mould, regardless of the mixture's consistency, was kept constant for all specimens. Using an ENERPAC RC101 hydraulic hand jack fitted to a loading piston (Fig. 3), the paste was compacted at 100 bar, or equivalent to 10 MPa. The hydraulic press method was adopted to achieve higher strengths in the specimens [11], where higher density could be expected. Excess material beyond the mould rim was trimmed to the intended specimen height. The specimen was then removed from the mould and stored for further treatment or tests. The specimen list is given in Table 3.

Next, the specimens were prepared in 3 categories to examine the effect of curing temperature on the mixtures. All specimens were first air-dried for 7 days, then transferred to an electric oven for further drying under gradually increased temperature, from 40^{o}C to 200^{o}C, in the ensuing 7 days. Specimens in the 'air-dried' category were only subjected to the first stage of drying process, while the 'oven-dried' specimens underwent the first and second stages. As for the 'baked' specimens, subsequent firing in a furnace, gradually up to 800°C, was carried out for another 5 days. Incremental temperature in the oven and furnace was necessary to avoid severe cracking of the specimens due to non-uniform heat propagation through the specimen's thickness. Similar practice was reported by Demir et al. [12] in baking clay bricks added with kraft pulp production residues. Also, the firing temperature was not raised to 1000°C as preliminary trials showed that such intense heat could weaken the brick structure and cause disintegration in some cases.

The brick tests conducted in this study were the compression, water absorption and efflorescence tests. All tests were performed in accordance with the prescription of the British Standards, BS3921:1985 [13] and the Malaysian Standards, MS76:1972 [14]. These tests were carried out on the baked and non-baked specimens only. The oven-dried ones were considered intermediate specimens and were prepared only for evaluating the induced heat effect on the clay-fibre mixtures, as mentioned in earlier paragraphs.

As for the water absorption test, the specimens were kept submerged in a water bath, heated to boiling point for 1 hour, followed by 5 hours of boiling, and then cooled at room temperature in 19 hours. Difference between the initial and saturated mass gives an indicator of the water absorption tendency of the specimen. For easier comparison, the water absorption ratio (WAR) was computed by dividing the water absorption value of a particular specimen with of the clay only specimen, which was referred to as the datum. Lower WAR suggests low water infiltration of a specimen, hence higher durability when exposed to rain water, for instance [15].

The compression test was conducted with a conventional universal testing machine, with the long base (length x width) facing upwards. The specimens were compressed to failure at loading rate of no greater than 35 N/mm^2, and the peak strength was taken as the compressive strength, simply by dividing the failure load with the loading area. The stiffness or Young's modulus was also derived with the secantial method: from the gradient of a straight line drawn from the origin to the peak of the load-displacement curve.

The efflorescence test is essentially a visual examination and detection of salt deposits, powdering or flaking on the exposed surface of the test specimen. The observation is described as nil, slight, moderate, heavy or serious. The test was conducted by subjecting a single face of the brick specimen to a twin-cycle of wetting and drying process. With all surfaces sealed except one, a wide mouth bottle with known area was filled with distilled water and placed inverted on top of this exposed surface for 48 hours. Then the bottle was removed and the exposed surface was left to dry naturally for 9 days. The procedure was repeated for another 16 days in the second cycle, before the visual inspection was carried out at the end of it.

III. Results and Discussions

The density of specimens was found to increase slightly with heat treatment, i.e. dried in the oven at 200°C and fired in the furnace at 800°C (Fig. 4). The plot does not differentiate between the mix ratios or fibre type, but as marked out by the dashed lines, the upward trend is unmistakable. Marginal increase in density has also been observed with prolonged firing of the clay bricks [16].

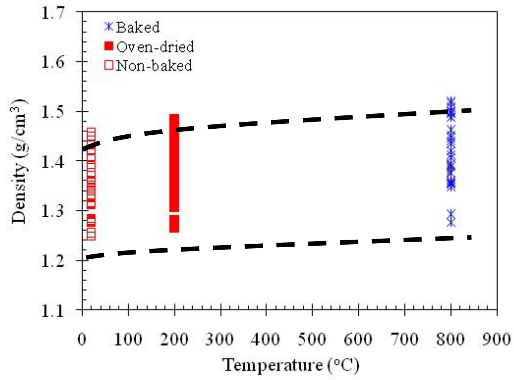


Fig. 4 Changes in density with temperature

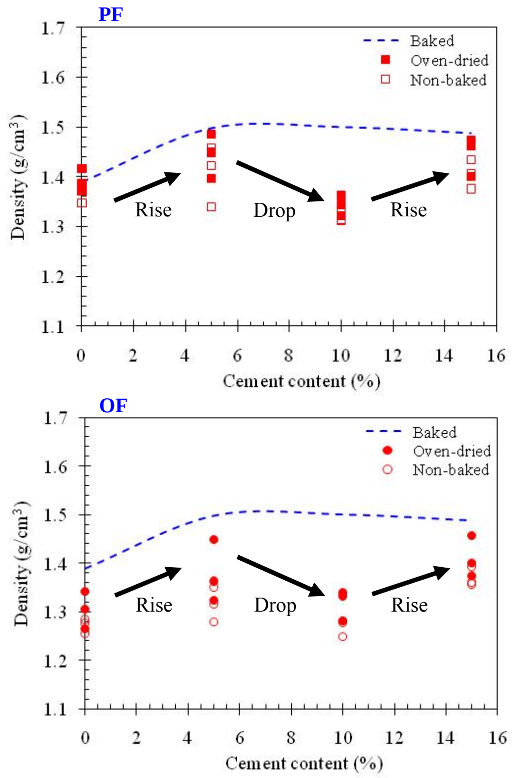
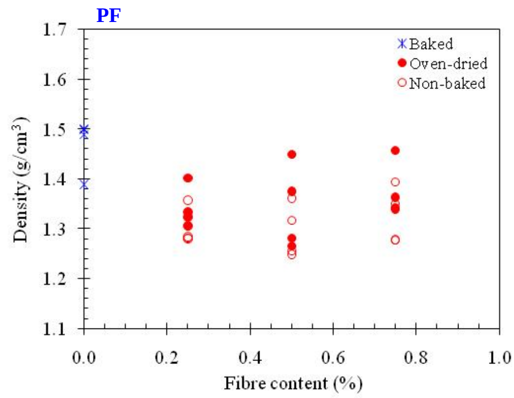


Fig. 5 Density of specimens with PF and OF additions: cement content effect



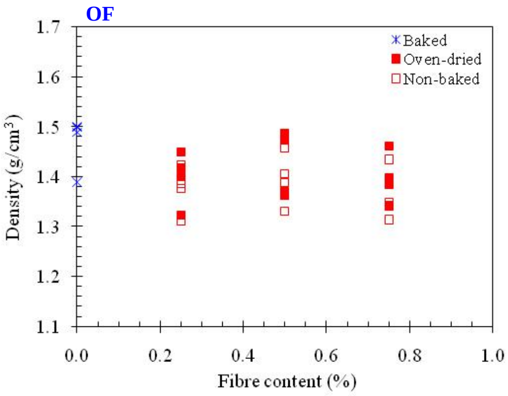


Fig. 6 Density of specimens with PF and OF additions: fibre content effect

More details were revealed when the same data was plotted with respect to the cement content, as shown in Fig. 5. The baked specimens had the highest densities, followed by the oven-dried and non-baked specimens, corresponding with earlier reference to Fig. 4. The non-baked specimens did not undergo obvious density change as compared to their baked counterpart, not unlike findings by Marín et al. [11]. Baking seemed to be more beneficial for the PF specimens, where the gap between the density of baked and oven-dried specimens was larger compared to the OF specimens. At 10 % cement addition, however, the density suffered a significant drop in both the PF and OF specimens. This density reduction appeared to be halted with increased cement dosages, as depicted by the second rise of both plots in Fig. 5. This phenomenon was attributed to the interaction between water and the solid phase of the mixture. From 0 to 5 % cement addition, the mixture was in a semi-plastic state most suitable for compaction by pressing. At 10 % cement content however, it is probable that the compaction energy was resisted by the drier mixture, hence resulting in lower densities of the specimens. Such drops in density are in fact not uncommon in compacted sandy soils, where surface tension causes the solid particles to repel one another [17]. Subsequent increase in the cement content could have overwhelmed the resistance against compaction by the drier mixtures, and effectively bound the soil-fibre matrix into denser solid forms, as illustrated by the second rise in density.

Effect of the fibre content was less pronounced on the density of the specimens, where they remained largely unchanged over the range of fibres added (Fig. 6). Natural fibres are known for their affinity towards water and are inclined to be water-absorbent, hence contributing to quicker drying of the mixture [18]. Unless the induced curing temperature evaporates the entrapped water, the increased brick mass due to water retention within the fibres would consequently cause a rise in the brick density. On the other hand, previous work has generally reported on density reduction due to the loss of natural fibres or components when subjected to baking [12, 19 and 20]. As the organic inclusions are burnt away, voids are formed in the specimen, giving it a porous and lighter appearance. Inclusions like these are also known to be added intentionally to form pores in bricks, mainly to avoid cracking during the drying process by reinforcing the mixed mass [21]. This is, however, not necessarily a desirable feature, considering high porosity encourages high water infiltration and adsorption rates, both detrimental to the long term durability of bricks [15]. From subsequent compression tests where the specimens were crushed or broken, it was observed that the baked specimens had no remnants of fibres intact, and that the highest compressive strengths were of the baked specimens. Therefore it was thought that baking did cause loss of the fibres through ignition, but sintering of the clay led to reduced porosity, increased density and enhanced strength. The high temperature during baking could have caused edges of the clay particles to soften and mould into the gaps left by the burnt out fibres and fill them up, resulting in specimens with higher density and strength. On the contrary, fibre-bricks with low densities are potentially useful for thermal isolation of buildings, especially in regions with extreme climatic changes [5 and 22].

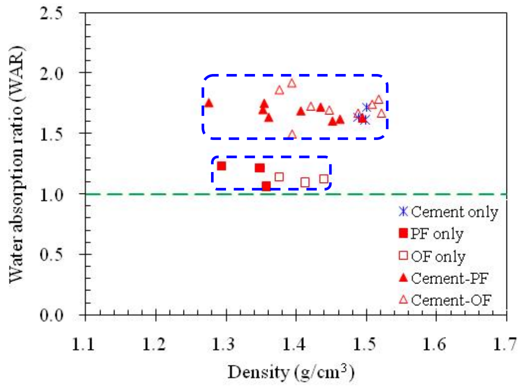


Fig. 7 Relationship between water absorption ratio and density

Fig. 7 shows the relationship between water absorption ratio (WAR) and density. The horizontal dashed line represents the unity WAR of 1 or datum, as computed from the water absorption capacity of the clay specimen. Note that only data from the baked specimens are included in the plot as the non-baked specimens disintegrated during the water absorption test, clearly suggesting the necessity of baking if the bricks were meant for exterior use without protection, in particular. From Fig. 7, the dominance of cement on WAR is apparent, where the binder seemed to cause more water to infiltrate the specimens: a sign of increased porosity. The addition of fibres slightly reduced the specimen density too, as the data points lie to the left of those with the only cement added. This is attributed to the adverse affect on the bonding ability of the mixture with the presence of alien materials, such as the fibres [15]. It can also be seen that the WAR data points form distinct clusters based on cement addition, as marked out in boxes in the figure. Within the same density range, where the two boxes overlaps, WAR can be twice higher. This cautions against the prediction of a specimen's water absorption tendency from its density alone, as the notion of WAR being inversely related to density, as proposed in [5] and [7], may not always be true.

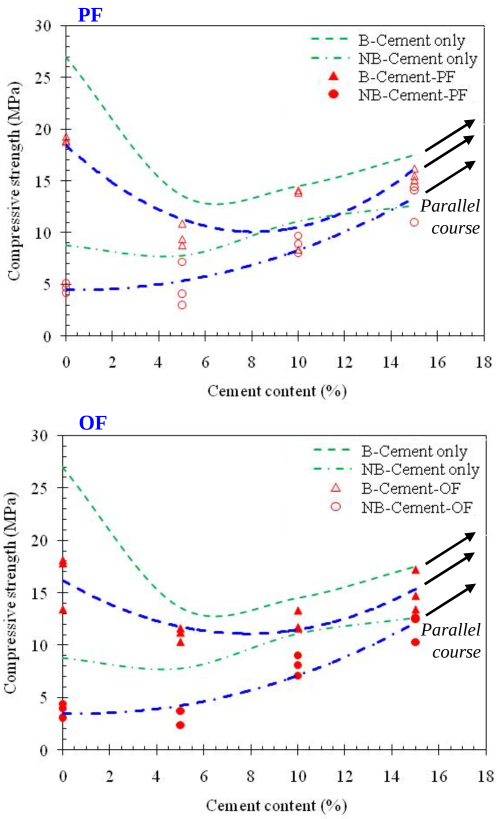


Fig. 8 Compressive strength: cement content effect

The effect of cement content on the compressive strength of the brick specimens is illustrated in Fig. 8. The thicker trend lines were plotted for the specimens with fibre addition. Both cement-PF and cement-OF specimens, baked (B) or non-baked (NB) displayed similar strength characteristics with regard to cement addition: (1) Cement generally increased the compressive strength in non-baked specimens, but caused a significant strength reduction in the baked specimens. The threshold cement content before strength was effectively enhanced appeared to be approximately 6 % in both cases. (2) The continuous drop in strength for the baked specimens up to 6 % cement addition almost coincided with the strength of the non-baked specimens at the same cement content, as can be seen in the 'necking' section between the trend lines. Then the trend lines diverge slightly before running parallel to each other at higher cement dosages. Russ et al. [7] experimented with spent grains as a pore-forming agent in fired clay bricks and reported unchanged flexural strength in comparison with the control specimen (no spent grains added). This concurs with the 'necking' effect observed in Fig. 8, though higher cement dosages helped maintain higher strengths of the baked specimens. (3) The non-baked specimens had proportionate strength gain with increased cement content, as shown by the parallel trend lines for both specimens, with and without fibre addition, where the trend line of the non-baked specimens lies consistently below that of the baked specimen's. This emphasizes the positive effect of baking on these fibre-bricks. (4) Apart from the non-baked specimens without fibre addition, the other trend lines can be projected along an approximately parallel course from 10 % cement content onwards, in the strength-wise sequence of B-Cement only > B-Cement-PF/OF > NB-Cement-PF/OF. As the natural fibres are relatively soft and hollow, they are unlikely to contribute much to the compressive strength of non-baked fibre-bricks [8]. Cement clearly plays the primary role of providing strength to the fibre-bricks, while fibres tend to weaken the composite's micro-structure. Similar observations can be found in previous work, e.g. [8], [19] and [12]. (5) The non-baked specimens without fibre addition clearly could not sustain higher compression even with increased cement dosages, as depicted by the plateau of the NB-Cement trend line. This highlights the benefits of having fibre inclusion in the composite bricks under non-baked conditions.

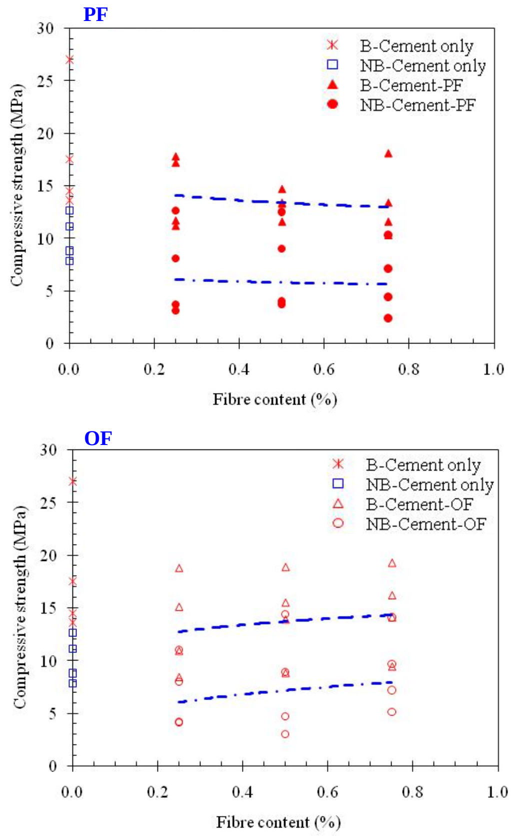


Fig. 9 Compressive strength: fibre content effect

The fibre content effect on the compressive strength of these fibre-brick specimens was less pronounced, though baking clearly enhanced the strength in both fibre addition cases (Fig. 9). On average, difference between the compressive strength of the baked and non-baked specimens was consistent from 0 % fibre addition. This difference was carried through as the fibre content increased. Interestingly, higher percentage of OF produced a marginal increase in strength, whereas there appeared to be a gradual drop in strength for the PF specimens. Taking into account experimental errors, in spite of 3 specimens tested for each mix, it is postulated that regardless of whether the fibre-bricks were baked or not, the strength would remain largely unchanged. This, therefore, points to the dominance of cement in bonding the composite's matrix for enhanced strength.

Referring to the Malaysian Standards for bricks, MS76: 1972 [14], a brick with compressive strength ≥ 70 N/ mm^2 qualifies for the highest category of Class A Engineering Brick. The relevant British Standards, BS 3921: 1985 [13], are less stringent, stipulating ≥ 50 N/ mm^2 as the minimum strength requirement for the same category. While none of the specimens made the class, all fulfilled the minimum compressive strength of 5.2 N/ mm^2 for conventional bricks. Judging from Fig. 8, a significant cement dosage is necessary to attain higher strengths.

Fig. 10 shows how stiffness (i.e. Young's modulus, E) is related to the compressive strength (Q) for the fibre-brick specimens. Data points of the baked specimens lie above those of the non-baked specimens. They were also stiffer at the same strength compared to the non-baked specimens. Presence of the fibres in 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, as represented by a much gentler rise of the load-deformation curve [8]. Turgut and Yesilata [5] demonstrated similar decline in stiffness with increased crumb rubber addition in their brick specimens, using a non-destructive ultrasonic pulse velocity tester. Admittedly rubber has higher energy absorption capacity on its own, while natural fibres tend to have better tensile resistance. The baked specimens, on the other hand, probably contained minute voids left by the burnt out fibres before being subjected to the compression test. However, when compressive load was applied, these voids collapsed and brought the composite mass into closer contact at microscopic level, therefore increasing the strength and stiffness.

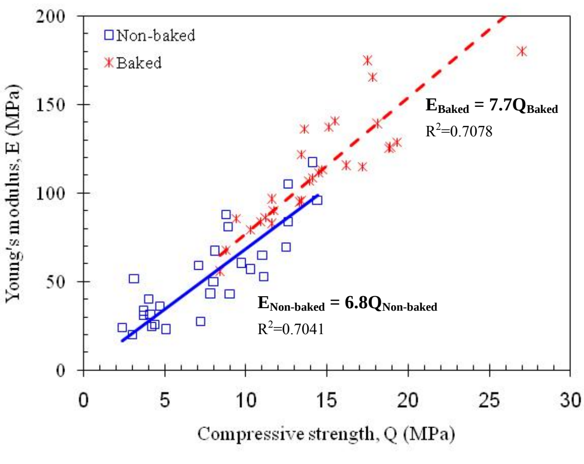
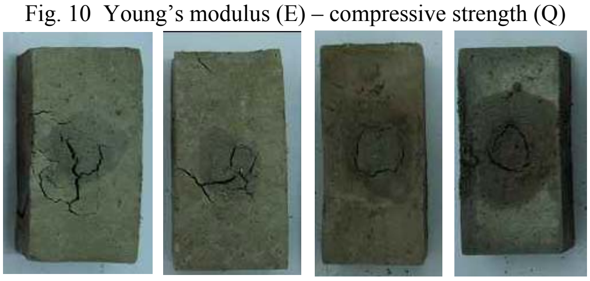


Fig. 10 Young's modulus (E) – compressive strength (Q)



Non-baked specimens: severely damaged during tests

Baked specimens:
"heavy" (left) and "nil" (right)

Fig. 11 Efflorescence test results

The efflorescence tests were feasible only on the baked specimens, as the non-baked ones formed severe deterioration in the duration of the tests (Fig. 11). The PF addition specimens had more results in the 'heavy' category compared to the OF ones, where ≥ 50 % of the water-soaked surface showed salt deposit and/or accompanied by flaking or powdering. Nevertheless no distinct pattern can be deduced from the overall results. Interestingly though, observations of the PF-added specimens seemed to agree with those of the density-cement content plot (Fig. 5), where the specimens registered 'nil' for efflorescence when the density rose at 5 and 15 % cement additions, and identified as 'heavy' when the density dropped at 10 %. This can be explained, theoretically, that the denser specimens were less likely to leach salt compounds due to the lower void ratio, which impeded water infiltration and salt migration.

IV. Conclusion

Baked and unbaked bricks made with the mixture of clay, cement and pineapple leaf fibres (PF) or oil palm fruit bunch fibres (OF) at different ratios were examined, with focus on the density, water absorption, compressive strength and efflorescence. In general, specimens with higher density had corresponding higher strength and water absorption capacity. Cement, acting as the binder of the composite material, was found to govern the strength of the fibre-bricks, both baked and unbaked. The prevailing benefits of fibre inclusion were evident in the non-baked specimens, where the strength gain surpassed that of non-baked cement-added only specimens (i.e. at cement content ≥ 15 %).

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