Development of thermally efficient fibre-based eco-friendly brick reusing locally available waste materials

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HIGHLIGHTS

• Focus is on development of thermally efficient wall material for hot and humid climate.
• The bricks were developed utilizing locally available sustainable waste material.
• Physical, mechanical and thermal performance of newly developed bricks is assessed.
• Effect of oil palm fibres on physical and thermal properties is assessed.
• Microstructural examination is performed to understand interaction between the raw materials.

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ABSTRACT

Currently there are several kinds of building wall thermal insulation materials commercially available in Malaysia, however the issue with all these materials is that they are not eco-friendly. This paper attempts to reduce the dependence on non-eco-friendly insulation material by developing thermally efficient eco-friendly bricks. The prototype brick developed by incorporating locally available sustainable waste material was subjected to initial investigation on physical, mechanical, thermal and microscopic studies. The investigations revealed that the thermally efficient prototype mix design using glass powder and palm oil fly ash along with lime as binder is able to provide strength to the bricks. Also, usage of oil palm fibres were beneficial in lowering the thermal conductivity of bricks. At incorporation of 1% wt of OPF, compressive strength was found out to be 7.21 MPa and thermal conductivity was 0.39 W/mK, which indicates the proposed bricks can be an alternative to non-eco-friendly commercial common bricks. The advantage of the proposed bricks is two-fold: having low thermal conductivity will make it an energy efficient option, second is the usage of sustainable resources makes it an eco-friendly product.

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1. Introduction

The building sector consumes a significant amount of energy during its operational stage contributing to an ever increasing amount of greenhouse gas emissions. A key consideration in order to improve the energy efficiency of the building sector is to provide thermal insulation to the building envelope for the purpose of lowering its heating/cooling load. There are several kinds of insulating materials commercially available in Malaysia such as Fibreglass—urethane, Fibreglass (rigid), Urethane (rigid), Perlite, Extruded Polystyrene and Urethane [1]. But the problem with all these materials is that they are not eco-friendly materials. Due to the environmental concerns, there is an urgent need to develop and utilize materials that have eco-friendly features. A material having sustainable features along with optimum insulating properties can eventually contribute to addressing key environmental concerns, such as leading to reduction in greenhouse gas emissions. In addition, better insulation of the building envelope reduces mechanical energy dependency for cooling and heating purposes, eventually contributing to the betterment of the environment.

The amount of raw materials consumed by the construction industry is approximately 24% of the global raw material resource [2]. Thus, for achieving the goal of sustainable development in the construction industry, the selection of building material plays a pivotal role. There have been continuous efforts to research on the viability of reusable waste materials as alternative building materials. Efforts have been ongoing to utilize demolition waste, municipal solid waste, agricultural waste and industrial waste in...
building materials [3–6]. However, most of the studies while studying the incorporation of waste material have failed to address the thermal insulation characteristics of such material for improving energy efficiency needs and mechanical performance.

To a great extent the solid waste industrial by-products have been researched for more than a few decades as a form of pozzolanic material. Glass powder is one of such materials having pozzolanic behaviour because of its high silica content. In Malaysia, waste glass amounts for 3% of total municipal solid waste generated every year causing serious environmental concerns [7]. In 2008, for supporting recovering activity in Malaysia, 119 solid waste recyclers were licensed. These companies provides alternative resources by recovering solid waste and reduce dependency on natural resources. There is scope of utilizing recycled glass from recovered solid waste and incorporate it as a supplementary cementitious material [8]. There are various types of glass based on its chemical composition: soda-lime glass, vitreous glass, borosilicate glass, lead glass, barium glass, etc. Most commonly used glass is soda-lime glass consisting of approximately 73% SiO₂, 13–18% Na₂O and 10% CaO [9]. Thus, based on chemical composition powdered glass can qualify as pozzolanic material as per ASTM C618 [10]. There has been much research undertaken with encouraging results regarding mechanical performance and durability criteria for construction materials while incorporating glass powder [11–13]. However, high amount of alkali makes it vulnerable to alkali silica reaction if it is used as a supplementary cementitious material [13,14]. Several studies suggest that ground fine glass powder which has a particle size below 300 μm shows very good pozzolanic reactivity without ASR expansion [15,16]. Also, to reduce the chances of disruption due to alkali silica reactivity, Byars et. al. [17] in his research has suggested the combined use of supplementary cementitious material such as fly ash, silica fume, etc.

Palm oil fly ash (POFA) is available in abundance in Malaysia and possesses pozzolanic behaviour [18]. Each palm oil fruit bunch produces 21% palm oil, 6–7% palm kernel, 14–15% fibres, 6–7% shell and 23% empty fruit bunch on an average [19]. It is estimated that, a single kilogramme of palm oil results in 4 kg of dry biomass [20]. The Malaysian oil palm industry generates 3 million tons of POFA in the year 2007 and it is estimated that production rate will increase due to the expansion of oil palm sector [21]. Several researchers [22–24] have studied the usefulness of POFA as a supplementary cementitious material for enhancing mechanical performance as well as durability of concrete products. Thus, the combined use of glass powder along with POFA as pozzolanic materials can be treated as a sustainable step within the local construction industry.

Enhancement of thermal performance can be done by introducing pores in the matrix of the material. Studies have found that fibrous material possesses cellular pores structure which can reduce the heat transfer rate significantly [25–27]. Coconut coir fibre, durian fibre, straw bale, cotton stalk fibre, and bamboo fibre has been tried and tested before for developing thermally insulated composites. Also, studies there have been conducted on oil palm fibre for insulating applications [28]. On the backdrop of waste disposal issue of Malaysian oil palm industry as discussed earlier, oil palm fibres can be utilized as a pore forming agent in proposed material.

The objective of this research is to understand the physical, mechanical and thermal performance of bricks developed from the locally available waste material which can be procured easily. The research is more inclined towards the thermal performance of bricks as the proposed material is supposed to be thermally efficient. As all the raw materials are mostly by-product of industrial & municipal activity, the proposed product provides a sustainable alternative to existing energy consumptive fired clay bricks.

2. Prototype development

The constituent material for developing thermally efficient bricks are glass powder, palm oil fly ash, oil palm fibres, crusher dust, lime, and water.

2.1. Raw materials

(i) Glass powder: Scrap of broken glass were procured from local dump yard. This broken glass was brought for preconditioning where it was crushed for in a ball mill for 2 hours at 60 rpm speed to form a finely ground glass powder. Furthermore, it was sieved using 90 μm sieve to keep its particle sizes in check. Chemical composition by using X-ray Florescence (XRF) technique is shown in the Table 1. Physicochemical properties such as specific gravity, fineness, soundness, initial and final setting time, drying shrinkage, and determination of flow were determined and it is shown in the Table 2. The scanning electron microscopy (SEM) image of powdered glass is shown in Fig. 1(a). Also, X-ray diffraction (XRD) was carried out which points out to the fact that no substantial crystalline phase was detected as shown in Fig. 3.

(ii) Palm Oil Fly ash: The palm oil fly ash was collected from oil palm industry located at Kluang, Johor, Malaysia. The ash collected was having a certain percentage of moisture content, to remove moisture it was subjected to oven drying at 110 °C. The dried ash was further sieved using 90 μm sieve size. Furthermore, physical, mechanical and chemical characterization of palm oil fly ash were conducted similarly to that of glass powder (GP). The XRD pattern shown in Fig. 2 suggests the presence of quartz mineral which is rich in silica, also proven by chemical composition represented in Table 1.

(iii) Oil palm fibres: The oil palm fibres were also collected from same company where palm oil fly ash was procured. As the fibres were in hydraulic compressed form, their physical properties were also determined. The Table 2 shows the physical properties of POFA and glass powder.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Physical properties</th>
<th>PFOA</th>
<th>GP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Fineness (cm²/g)</td>
<td>1348</td>
<td>1862</td>
</tr>
<tr>
<td>2.</td>
<td>Specific gravity</td>
<td>2.21</td>
<td>2.67</td>
</tr>
<tr>
<td>3.</td>
<td>Soundness</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>4.</td>
<td>Setting time</td>
<td>166</td>
<td>144</td>
</tr>
<tr>
<td>5.</td>
<td>Drying shrinkage</td>
<td>1.805</td>
<td>1.801</td>
</tr>
<tr>
<td>6.</td>
<td>Determination of flow (cm)</td>
<td>15.5</td>
<td>19.6</td>
</tr>
</tbody>
</table>

Table 1

Chemical composition of glass powder and palm oil fly ash.

<table>
<thead>
<tr>
<th>Chemical composition</th>
<th>SiO₂ (%)</th>
<th>Al₂O₃ (%)</th>
<th>MgO (%)</th>
<th>Na₂O (%)</th>
<th>CaO (%)</th>
<th>Fe₂O₃ (%)</th>
<th>Cl (%)</th>
<th>P₂O₅ (%)</th>
<th>K₂O (%)</th>
<th>LOI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass powder (GP)</td>
<td>68.89</td>
<td>4.147</td>
<td>2.717</td>
<td>16.938</td>
<td>5.904</td>
<td>0.52</td>
<td>0</td>
<td>0</td>
<td>0.568</td>
<td>0.316</td>
</tr>
<tr>
<td>Palm oil fly ash (POFA)</td>
<td>61.663</td>
<td>5.13</td>
<td>4.17</td>
<td>0.49</td>
<td>9.869</td>
<td>5.299</td>
<td>0.162</td>
<td>3.716</td>
<td>8.427</td>
<td>1.074</td>
</tr>
<tr>
<td>Lime</td>
<td>3.94</td>
<td>1.37</td>
<td>0.32</td>
<td>0.01</td>
<td>88.7</td>
<td>0.09</td>
<td>–</td>
<td>–</td>
<td>0.02</td>
<td>3.53</td>
</tr>
</tbody>
</table>
Fig. 1. Scanning electron microscopy (SEM) images of (a) glass powder (50 μm); (b) palm oil fly ash (50 μm); (c) c/s of oil palm fibres (100 μm).

Fig. 2. XRD pattern of palm oil fly ash (POFA).

Fig. 3. XRD pattern of grounded glass powder (GP).
preparation of fibres was initially done using Natural Fibre Processing Machine. Then it was washed by using tap water to remove any kind of impurities present on the surface. Furthermore, to enhance fibre-matrix adhesion in bricks, mercerization or alkaline treatment of fibres was done using Sodium Hydroxide (NaOH) solution. This treatment removes the hydrogen bonding in the network structure as shown in Eq. (i).

\[
\text{Fibre}-\text{OH} + \text{NaOH} \rightarrow \text{Fibre}-\text{O}^- \text{Na}^+ + \text{H}_2\text{O} \tag{i}
\]

Fibres were immersed in 2% dilute NaOH solution for an hour, afterwards, it was sun dried. The Physical properties if oil palm fibres are shown in the Table 3. The cross-section of fibres was observed by using scanning electron microscopy (SEM) images shown in Fig. 1(c), in which it is evident that oil palm fibres have cellular porous structure.

(iv) Crusher dust: In the experiment, the filler material obtained from quarry industry provides a sustainable alternative to river sand. It was procured from nearby locally available quarry industry located at Minyak Beku Batu Pahat, Johor. It was further sieved by using sieve size of 2.38 mm.

(v) Lime: In preparation of bricks, lime as a sustainable alternative to cement as a binder was selected. Chemical composition of lime is shown in Table 1.

(vi) Water: The water used for experiments were taken from UTHM, Johor. The pH of the water was 6.9.

2.2. Material preparation

The mix design for the preparation of thermally efficient bricks is done by utilization of the locally available waste material i.e. glass powder, palm oil fly ash, and oil palm fibres. Also, crusher dust and lime were used as filler and binding materials respectively. Mix design was adopted from L16 orthogonal array technique used in Taguchi's method [29] shown in Table 4, where glass powder (GP), palm oil fly ash (POFA) and oil palm fibres (OPF) is varied as per the L16 orthogonal array technique. Oil palm fibres were introduced as a percentage of the binder as it was having very low density. Lime as a binder material was kept constant.

Initially, all the raw materials were batched and dry mixing was done to distribute fibres evenly. All the mixing procedure was conducted in a mechanically operated concrete mixer. Dry mixing was followed by wet mixing which was done over a time span of for 2–3 min. The whole wet mix was poured to segregate and distribute fibres evenly. The material was filled up in a mould and the material was compacted using vibration technique. The removal of the sample was done from the mould after 24 h. Further, it was dried for a couple of days which was followed by continuous curing for 28 days. The whole brick manufacturing process is similar to that of conventional brick making process used for preparation of unfired bricks, except the inclusion of pre-processing of raw materials. The prototype samples of developed thermally efficient brick is shown in Fig. 4.

2.3. Testing procedure

To analyse the developed thermally efficient brick sample, the testing procedure as per standard requirements is very crucial.

### Table 3
Physical properties of oil palm fibres.

<table>
<thead>
<tr>
<th>Fibre properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. fibre length (mm)</td>
<td>25</td>
</tr>
<tr>
<td>Avg. Diameter (μm)</td>
<td>19.4</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>35.33</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>0.05</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.13</td>
</tr>
<tr>
<td>Water absorption 24 h (%)</td>
<td>0.79</td>
</tr>
</tbody>
</table>

### Table 4
Mix designs for thermally efficient brick.

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Glass powder (% wt)</th>
<th>Palm oil fly ash (% wt)</th>
<th>Crusher dust (% wt)</th>
<th>Lime (% wt)</th>
<th>Oil palm fibres (% wt of binder)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>20</td>
<td>20</td>
<td>45</td>
<td>15</td>
<td>0.25</td>
</tr>
<tr>
<td>M2</td>
<td>25</td>
<td>25</td>
<td>35</td>
<td>15</td>
<td>0.25</td>
</tr>
<tr>
<td>M3</td>
<td>30</td>
<td>30</td>
<td>25</td>
<td>15</td>
<td>0.25</td>
</tr>
<tr>
<td>M4</td>
<td>35</td>
<td>25</td>
<td>25</td>
<td>15</td>
<td>0.25</td>
</tr>
<tr>
<td>M5</td>
<td>20</td>
<td>25</td>
<td>40</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>M6</td>
<td>25</td>
<td>20</td>
<td>40</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>M7</td>
<td>30</td>
<td>35</td>
<td>20</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>M8</td>
<td>35</td>
<td>30</td>
<td>20</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>M9</td>
<td>20</td>
<td>30</td>
<td>35</td>
<td>15</td>
<td>0.75</td>
</tr>
<tr>
<td>M10</td>
<td>25</td>
<td>35</td>
<td>25</td>
<td>15</td>
<td>0.75</td>
</tr>
<tr>
<td>M11</td>
<td>30</td>
<td>20</td>
<td>35</td>
<td>15</td>
<td>0.75</td>
</tr>
<tr>
<td>M12</td>
<td>35</td>
<td>35</td>
<td>15</td>
<td>15</td>
<td>0.75</td>
</tr>
<tr>
<td>M13</td>
<td>20</td>
<td>35</td>
<td>30</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>M14</td>
<td>25</td>
<td>30</td>
<td>30</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>M15</td>
<td>30</td>
<td>25</td>
<td>30</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>M16</td>
<td>35</td>
<td>20</td>
<td>30</td>
<td>15</td>
<td>1</td>
</tr>
</tbody>
</table>
Essential parameters such as compressive strength, bulk density, water absorption, porosity, thermal conductivity and initial rate of suction were determined. Water absorption, bulk density, and porosity were conducted on samples having size $210 \times 100 \times 100$ mm$^3$ as per the ASTM C20 [30] standard. Also, compression test was conducted as per standard ASTM C67 [30] by using compressive testing machine having a capacity of 3000 KN. The flexural strength of bricks were determined using universal testing machine of 10,000 KN capacity as per IS 4860 [31]. Determination of initial rate of suction was done as per BS 3921 [32]. Also, Microscopic examination including Energy-dispersive X-ray spectroscopy (EDS) was conducted by using analytical scanning electron microscope, for determination of the phases developed during the reactions X-ray diffraction (XRD) analysis was performed.

To determine the thermal performance of bricks, thermal conductivity readings were calculated using the relation between dry density ($D_d$) and thermal conductivity ($T. C.$) of material [33] by using formula given below in Eq. (ii):

$$T.C. = 0.0559 e^{0.0014D_d} \quad (i)$$

Also, to validate the theoretical results, experimentation to determine thermal conductivity was performed by using hot guarded plate method [34]. For conducting experimentation, a test rig was used, a schematic diagram of which is shown in fig. In this, test rig heat was induced from the top portion which flows downward, as the sample is placed between two plates, unidirectional heat flow occurs. The heat flow at various points is being observed by using thermocouples as shown in Fig. 5. The readings are recorded in a data logger system. The formula used for calculating thermal conductivity of material is given below:

$$q = -kA \frac{dt}{dx} \quad (iii)$$

where, $q$ is the steady-state flow, $k$ is thermal conductivity, $A$ is the cross-sectional area of the sample and $dt/dx$ is the temperature gradient.

3. Results and discussion

3.1. Physical properties of developed bricks

3.1.1. Effects of fibres on porosity, bulk density, and water absorption

The effect of porosity and density for developed thermally efficient bricks is shown in Fig. 6, it is evident from the graph that porosity and bulk density for the developed thermally efficient bricks are in an inverse correlation. The porosity values for developed bricks was in the range of 19%–27% as compared to the bulk density of (1628.02–1338.7) kg/m$^3$. A low density brick is the result of pores, voids spaces occurred due to fibre inclusion. Both porosity and density are affected largely because of the ratio of oil palm fibres. The structure of oil palm fibres observed during microscopic study reveals its cellular porous structure. Thus increase in fibre content increases void in the material. Lowest value of density was observed for a mix M15 with a value of 1338.7 kg/m$^3$. As the low density bricks benefit the structural system as it lowers the self-weight of the structure. But due to porous nature and the void spaces within the material, water absorption capacity of bricks is hugely compromised. From Fig. 7 it is clear that rate of increase in water absorption capacity shows a similar
trend as that of porosity. This can be interpreted that the amount of water absorbed is directly proportional to pores occurred due to the inclusion of fibre content. The water absorption reported was well within the range of \( \leq 18\% \) as per ASTM C67 [30].

### 3.1.2. Effect of fibres on initial rate of suction

The capillary suction effect that draws the water from the mortar during the interaction of freshly laid mortar and brick units can be analysed using initial rate of water absorption (IRA). The initial rate of water absorption plays a significant role in bonding between mortar and brick units. From Fig. 8, the initial rate of water absorption is below 1 kg/m²/min. for mix M1-M4, which has lowest fibre content among all mixes. As the fibre content is increasing the IRA also increases. If initial rate of absorption is too low brick may tend to flow on mortar mix, which eventually affects masonry flexural strength, water tightness, and durability. On the contrary, if the absorption is too high it may damage the mortar-brick bonding by absorbing water from freshly laid mortar causing a reduction in water cement ratio (w/c) for mortar for its gain of strength. Drysdale et al. [36] suggested that initial rate of absorption (IRA) should neither too high nor too low, it should be in the range of \((0.25 \leq IRA \leq 1.5)\) kg/m²/min. The values of IRA for developed thermally efficient bricks are well within the range 0.2–5 kg/m²/min. given by AS/NZS 4456.17 [37]. Mix M9, M13, M14, M15, and M16 shows values higher than 1.5 kg/m²/min. whilst, M13 is recorded IRA value is 2.47 kg/m²/min., highest amongst all mixes.

### 3.2. Mechanical performance of developed bricks

Fig. 9 shows average compressive strength of each mix proportion for developed thermally efficient bricks. The values of compressive strength range between \((15.39–7.21)\) MPa for all mixes. The gain of strength in the material is attributed to the chain of reactions occurring between the pozzolans i.e. glass powder (GP), palm oil fly ash (POFA), lime and water. The amorphous structure of glass powder stimulates the pozzolanic reactivity, as the alkaline activators such as Lime, cement, and alkalis (Sodium and Potassium) acts as a catalyst. The amorphous SiO₂ present in glass powder forms low basicity calcium silicate hydrate gel (C-S-H). The presence of CaO in both glass powder and POFA react with water to form a hydrated gel. Palm oil fly ash (POFA) also acts as a source of siliceous and aluminous material forms silicate and aluminate hydrates when reacted with calcium hydroxide in the presence of moisture, which develops strength in the matrix according to ASTM 618 [10]. Also, restricting the particle size of glass powder and palm oil fly ash helped the reactivity to attain higher strength. The reaction occurred during the hydration process is as follows:

\[
\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2 \quad (\text{iv})
\]

\[
\text{Ca(OH)}_2 + \text{SiO}_2 + \text{H}_2\text{O} \rightarrow \text{C} - \text{S} - \text{H} \quad (\text{V})
\]

\[
\text{Ca(OH)}_2 + \text{Al}_2\text{O}_3 + \text{H}_2\text{O} \rightarrow \text{C} - \text{A} - \text{H} \quad (\text{vi})
\]

The influence of fibre content was very significant affecting the strength of the developed thermally efficient bricks. From the Fig. 9 it is evident that with the increase in fibre content reduces the strength of material. The reduction in strength may be explained due to the fact that the fibre inclusion introduces pores which eventually reduces the density of material as the packing of fibres becomes difficult. Also, the poor adhesive bond between fibre-matrix which can be affected by dimension, surface condition and amount of fibres in given volume, lowers the strength.

The highest value of compressive strength was observed at 15.39 MPa for mix M4. It can also be observed that when the proportion of glass powder (GP) increases compressive strength also increases within mixes having same fibre content. Thus, it can be interpreted that glass powder comparatively is more significant than palm oil fly ash (POFA) for strength development. The compressive strength of bricks complies with MS 76:1972 [38] and BS 3921:1985 [32] for a load bearing bricks, however, bricks are proposed for non-load bearing applications only.

Fig. 10 shows the flexural strength of newly developed thermally efficient bricks. Graph shows that there has been gradual increase in flexural strength as the fibre content is increasing, however, for Mix M13-M16, it shows slightly downward trend. The highest value of flexural strength was for M12 mix with an average value of 1.625 MPa, whereas, M1 mix has 1.12 MPa lowest among all. The reason behind the increase of flexural strength is reinforce-
ment of the matrix with the OPF fibres which distributes its tensile strength to the composite thereby resisting more tensile stresses. Fibres acts as energy absorbing mechanism (bridging action) and delays micro-crack formation [39]. The Fig. 11(a) shows the failure pattern of the brick whereas, Fig. 11(b) shows us the bridging mechanism of fibres in the composite which probably responsible for increase in flexural strength with the increase in fibre content.

3.3. Thermal performance of developed bricks

The addition of oil palm fibres in the mix proportion introduced the complexity in heat transfer process. As it is well known that porous microstructure of fibres lowers the heat transfer rate through a material. Heat transfer through fibrous material is attributed to its pore geometry. In case of newly developed thermally efficient bricks porosity, pore sizes and its distribution plays a vital role which has solid matrix and pores consisting of fluid (water or air) which ultimately influences the heat transfer through conduction, convection and radiation. In the matrix of newly developed bricks due to inclusion of fibres, the heat transfer process comprises of: Heat conduction in solid matrix/particles; Heat conduction through pore fluid (air); Heat conduction in micro-gaps that exist between particles; Particle contact heat conduction; Heat transfer through pore fluid; Radiation from solid surfaces of pores (particle to particle radiation in pores). [40]

Fig. 12 illustrates the thermal conductivity calculated theoretically by using Eq. (ii) as well as determined experimentally by hot guarded plate apparatus for developed thermally efficient bricks. The values for theoretical thermal conductivity which is function of dry density complies with the experimental values. The highest thermal conductivity was observed for a mix M2 having 0.543 W/m K value. Whereas, the most thermally efficient mix proportion was mix M13 with thermal conductivity of 0.389 W/m K. It is evident from Figs. 12 and 6 that thermal performance of brick follows similar pattern as that of density which points out to the fact that the proportion fibre content is significant in lowering heat transfer rate through material. As the fibre have cellular porous structure, the heat transfer through porous fibre may reduce to 0.025 W/m K (conductivity of still air: $k = 0.024 \text{ W/m K}$). The relationship

![Fig. 10. Avg. flexural strength of bricks for different mix proportions.](image1)

![Fig. 11. Flexural testing of developed brick showing (a) the failure pattern, (b) the bridging effect of oil palm fibre (OPF).](image2)

![Fig. 12. Experimental and theoretical thermal conductivity of bricks for different mix proportions.](image3)

![Fig. 13. Relationship between porosity and thermal conductivity of developed bricks for different mix proportions.](image4)
between thermal conductivity and porosity shown in figure proves that more the porosity lower the heat transfer rate. As the pore enhancement in this experiment can be attributed to inclusion of fibre, thus affecting overall thermal conductivity of material.

Thermal Conductivity as a function of porosity for all mix proportions of proposed material examined in the study is plotted in Fig 13. The data depicted in Fig. 13 suggests a correlation between thermal conductivity and porosity influenced by fibre addition. The percentage change in porosity for developed brick is around 27.6% as compared to thermal conductivity 29.4% which suggests that the influence of pores in thermal performance is most significant for developed bricks.

Compressive strength is most vital parameter for analysing the mechanical performance of building materials. Fig. 14 gives the relationship between the thermal conductivity and compressive strength. The mechanical and thermal performance of proposed material should obliged to standards is crucial. The low thermal conductivity and high compressive strength is generally targeted.

The benefits of thermally efficient fibre based eco-friendly bricks enables lowered heat transfer rate which enhances the thermal comfort of occupants within the building envelope. In addition to this, due to the lowered heat transfer rate, the energy requirement for heating and cooling load reduces, thus increasing the savings on energy costing. Indirect reduction in overall all energy consumption has a significant impact on the carbon emission of the building during its utilization phase of building. As the energy...
utilization is closely related to carbon emission. The reduction in carbon emission or energy usage in modern era contributes towards environmental sustainability. Thus, the thermally efficient fibre based eco-friendly bricks contributes to the sustainability aspect of building material indirectly by enhancing the thermal performance of wall system.

3.4. Microstructural examination

Fig. 15 shows scanning electron microscopy and Energy dispersive X-ray (EDX) analysis for the newly developed thermally efficient brick. To understand the interaction between pozzolanic material and lime as a binder SEM-EDX were conducted. In EDX spectra hydrated matrix shown in graph the peak height is proportional to the amount of element present. The portion analysed is rich in silica, calcium, alumina and traces of magnesium. The hardened gel consists of calcium silicate hydrate (C-S-H) and calcium alumino hydrate (C-A-S-H) which have formed during the reaction with calcium hydroxide Ca(OH)$_2$ as predicted earlier. The main crystalline phases which were identified for the developed hybrid brick sample are quartz, calcite, calcium silicate hydrate and calcium aluminosilicate hydrate as shown in Fig. 16. The presence of calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) is confirmed by XRD analysis of the hybrid brick material which is responsible for gain of strength. The formation of calcium aluminosilicate hydrate (C-A-S-H) is caused by reaction between the silica and alumina with calcium hydroxide. Similarly, the formation of calcium silicate hydrate gel is produce due to the presence of silica in glass powder and POFA which must be left unre-acted. The amount of high calcite content can be explained by the reaction between the Ca(OH)$_2$ and CO$_2$ present in the atmosphere.

4. Conclusion

The prototype brick developed by incorporation of additives (glass powder, palm oil fly ash, oil palm fibres) proves to be sustainable alternative for conventional clay bricks. The developed proportions for the hybrid brick shows promising signs for the development of thermally insulated building material. The following conclusions can be drawn from this research:

1. The investigation reveals that the addition of fibres had significant effect on the enhancement of thermal performance of brick lowering it to a level of 0.38 W/m K for mix M4 having oil palm fibre content of 1% wt Lowered heat transfer rate would definitely be helpful in reducing the indoor temperature, whilst reducing the cooling load of building envelope.

2. However, addition of fibres has detrimental effect on the compressive strength of bricks although at maximum incorporation level of fibres (i.e. 1% wt), it satisfy the criteria for load bearing brick as per standard. The lowest and highest of compressive strength were recorded for Mix M13 and M4 having values 15.39 MPa and 7.21 MPa respectively.

3. The glass powder and palm oil fly ash used as additives were responsible for gain of strength for the thermally efficient bricks. The combination of lime, glass powder and palm oil fly ash was proved to form C-S-H and C-A-S-H gel which gave strength to developed material.

4. The developed bricks also satisfies the water absorption criteria as per standard. The minimum water absorption was recorded for mix M4 having a value of 11.48%. Also, from the recorded density of bricks which were in the range of 1355.2 kg/m$^3$–1764.1 kg/m$^3$, it is evident that bricks have lower density as compared to some of the commercially available bricks which eventually reduce the dead weight of structure as well as it will ease the handling procedure.

5. However, the higher values of initial rate of absorption proves to be area of concern. The initial water absorption for developed proportions of hybrid wall material ranges from 0.72 to 2.47 kg/mm$^2$/min.

6. The developed bricks focuses on the eco-friendly aspect in masonry material. The sustainability (indirectly and directly) is achieved in the newly developed bricks by incorporation of waste materials and indirectly reducing carbon footprints in the utilization phase of building.

The developed thermally efficient bricks shows encouraging signs for commercial manufacturing. Lower density, good thermal performance, satisfactory Mechanical performance by the brick provides an alternative for energy consuming, unsustainable fired clay bricks. The waste material incorporated as basic raw material for the brick provides a sustainable, energy efficient alternative.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.conbuildmat.2016.12.055.

References
