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## Theoretical assessment of using ceramic tiles as replacement of Ordinary Portland Cement and sand

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**Abstract:** Using of industrial wastes as replacement of cement and/or other components of concrete is very attractive in concrete industry especially when this replacement leads to a reduction in the cost of concrete. This study investigates the feasibility of using two forms of ceramic tile wastes, naming: waste ceramic powder (WCP) and ceramic fine aggregate (CFA) as replacement of ordinary Portland cement (OPC) and river sand (RS), respectively. Twelve mortar mixtures incorporating various dosages of WCP and/or CFA were prepared to compare Carbon dioxide (CO<sub>2</sub>) emission, cost effectiveness, and energy consumption of the different mortar mixtures. Results showed that the use of WCP as replacement of OPC significantly reduces the CO<sub>2</sub> emission, cost effective and energy consumption of the mortar mixtures. A replacement of 60% by weight of OPC by WCP resulted in a reduction of approximately 50%, 40% and 30% in CO<sub>2</sub> emission, energy consumption, and cost respectively. The replacement of RS by different levels of CFA (up to 100%) had a marginal influence on the CO<sub>2</sub> emission and energy consumption, while it moderately decreased the effective cost of the mortar mixtures. Results of using WCP as a partial replacement of cement are very encouraging and should be gathered with laboratory results about the effect of the replacement on properties of concrete to have a clear vision about selecting the appropriate materials of replacement for cement.

**Keywords:** Cost effective, environment benefits, sustainable materials, tile ceramic wastes.

### 1. Introduction

A significant amount of greenhouse gases' (GHG) emissions and environmental pollution (both critical drivers of climate change) are produced during the manufacturing of all types of cement. In an attempt to minimise this environmental damage, researches are continuously looking for greener construction materials to replace either partially or totally cement [1-3]. Cement is used for the manufacturing of concretes and mortars, giving that one tonne of greenhouse gas is emitted when every tonne of cement is consumed (accounting for around 8% of GHG emissions globally). The high temperature of the cement clinker processing is the main problem. Ecological systems across the globe are thus being strained by the continuous production of cement at its existing rate [4, 5].



There has been significant development in the use of promising alternatives, such as those exist in industrial wastes from construction. The fact that these solutions are environmentally better, readily available, and available at relatively low cost has made these alternatives attractive as replacement of cement [6-8]. Using of the industrial wastes leads to a decrease in the depletion of the natural resources and subsequently the sustainability is boosted and waste management is became more effective [9-11].

A range of wastes are being used to substitute cement, and a series of core factors – from economic viability and market stability, to material durability, environmental responsiveness and sustainability were investigated. Sustainability as a concept practised in the construction industry, in addition to ‘green manufacturing’, require the use of alternative wastes as replacements of natural resources, including extra-cementitious materials. The call for sustainability in construction has prompted the emergence of new materials for a range of uses, all of them cost-reducing and environmentally geared. Ceramic tiles, as a key example, are made at high temperatures using fire clay, feldspar and quartz [12].

Sustainability in construction also comes into play in terms of behavioural aspects and how waste materials are used in applied practice [13-15]. In the accessible literature, there was very limited research pertaining to the environmental merits of using Waste Tile Ceramics (WTC) mortar as a replacement of cement and/or natural river sand (RS).

The present study thus made a series of mortar types using ceramic waste to investigate the feasibility of using WTC as replacement of cement and/or sand in mortars. The study sourced the ceramic waste locally and deployed it to assess whether sustainable mortars could be developed for construction projects. The sustainability performance metrics for the as-prepared mortar samples were assessed using a range of analyses including greenhouse emissions, energy efficiency and cost analysis.

## 2. Methodology

### 2.1 Raw materials

In accordance with ASTM C150, Type I OPC (specific gravity of 3.15) at a strength class of 42.5 was used to prepare all mortar mixtures. Initially, the ceramic tiles were crushed to produce fine particles of various shapes and sizes. Thereafter, crushed ceramic tiles were sieved – as per the ASTM C33– to remove the oversize particles. A consistent volume of fine aggregate was reached, and thereafter the fine aggregate (at 4.0 kg every time) was grounded for four hours in a Los Angeles abrasion test machine, in order to achieve the ground waste ceramic powder (WCP). The process was continued until the point at which about 95% of the WCP passed the 45 µm-opening sieve, as per ASTM C618. The physical and chemical properties of the OPC and WCP are shown in Table 1. As per ASTM C618 and owing to the overall content of silica, aluminium and iron oxides (above 70%), the WCP can be classed as Pozzolan materials. The physical properties of natural river sand and ceramic fine aggregates (CFA) are depicted in Table 2. Figure 1 shows the process of making the WCP and ceramic fine aggregate (CFA).



*2.2 Mix proportions*

Preparation of the materials and mix proportions of different types of mortars used in this study was according to ASTM C1329. As per ASTM C320, water to cement ratio of 0.48 was selected to have an adequate flowability and strength. A total of twelve batches (mortar mixtures) were prepared and used in this study. Mixture (WCPM0) was used as a control mixture as it contains zero ceramic tiles whether as a cement replacement and/or river sand. Six mortar mixtures were prepared with various dosage of WCP (10%, 20%, 30%, 40%, 50% and 60% by weight) as a partial replacement of OPC. Four mortar mixtures were prepared having different percentages (25%, 50%, 75% and 100% by weight) of ceramic fine aggregate CFA as a replacement of river sand. The last mortar mixture (WCP-CFAM) consisted of 40% partial replacement of OPC by WCP and 100% replacement of river sand by CFA. Mix proportions of the used twelve mixtures are provided in Table 3. After 24 hours of casting, all concrete specimens were unmolded and cured in water ( $27 \pm 2$  °C) for 7 days.

**Table 1:** Chemical characteristics and physical properties of WCP and OPC

| Materials                     | WCP   | OPC   |
|-------------------------------|-------|-------|
| Chemical contents (% by mass) |       |       |
| Calcium oxide                 | 1.13  | 68.30 |
| Silica oxide                  | 74.10 | 16.40 |
| Aluminium oxide               | 17.80 | 4.24  |
| Potassium oxide               | 0.44  | 0.22  |
| Iron oxide                    | 3.58  | 3.53  |
| Sulfur trioxide               | 0.023 | 4.39  |
| Magnesium oxide               | 1.24  | 2.39  |
| Loss of ignition (LOI)        | 0.10  | 2.40  |
| Physical properties           |       |       |
| Specific gravity              | 2.35  | 3.15  |
| % Passing through 45 μm sieve | 99    | 90.0  |
| Medium particle size (μm)     | 35    | 40    |

**Table 2.** Physical properties of RS and CFA

| Properties  | RS   | CFA  |
|---|------|------|
| Mass passing 75 $\mu\text{m}$ sieve (%)                 | 0.0  | 0.0  |
| Oven dry basis, bulk density ( $\text{kg}/\text{m}^3$ ) | 1624 | 1450 |
| Specific gravity  | 2.62 | 2.38 |
| Water absorption at 24 h (%)                            | 1.8  | 1.3  |

**Table 3.** Mix proportions of mortar mixtures

| Mix ID   | Binder ( $\text{kg}/\text{m}^3$ ) |     | Fine aggregates ( $\text{kg}/\text{m}^3$ ) |      |
|----------|-----------------------------------|-----|--|------|
|          | OPC                               | WCP | RS   | CFA  |
| WCPM0    | 550                               | --  | 1460                                       | --   |
| WCPM10   | 495                               | 55  | 1460                                       | --   |
| WCPM20   | 440                               | 110 | 1460                                       | --   |
| WCPM30   | 395                               | 165 | 1460                                       | --   |
| WCPM40   | 330                               | 220 | 1460                                       | --   |
| WCPM50   | 275                               | 275 | 1460                                       | --   |
| WCPM60   | 220                               | 330 | 1460                                       | --   |
| CFAM25   | 550                               | --  | 1095                                       | 365  |
| CFAM50   | 550                               | --  | 730  | 730  |
| CFAM75   | 550                               | --  | 365  | 1095 |
| CFAM100  | 550                               | --  | --   | 1460 |
| WCP-CFAM | 330                               | 220 | --   | 1460 |

### 2.3 Greenhouse emission, energy efficiency and cost analysis

More environmentally friendly products can be made when construction materials are manufactured using recycled solid wastes. These waste-based materials need to be obtained at a competitive price, however, in order for them to be made viable options in the industry. It is also desirable that they have ecological benefits to construction projects. This study explored the GHG emissions, production costs and energy consumption rates of the recycled ceramic mortar (RCM) to explore its sustainability. These indicators were chosen because they form the primary rationale for using RCM. Other features including technical application issues, leaching, water usage factors, harmful material constituents, emissions of environmentally dangerous gases of another kind, can also be important factors in the selection of the appropriate waste materials.

Both the effects made by the feedstock and binder manufacturing processes, and the transport, must be factored in an environmental benefit analysis. This study does not factor in the mixing, laying, curing and emissions features of the various mortars over the entire working lifetime because they are considered to be similar. The proposed method will likely give an analogous life cycle of effects rather than an absolute one. The study established the various materials' energy consumption figures, production costs and GHG emission rates. The various phases in preparing the OPC, WCP, CFA and RS are displayed in Table 4.

A transportation fee of 1 t/km was applied for all the materials, and these were incorporated into the net cost. Details of the machinery and materials are provided in Table 5. An assumed price of 0 Ringgit Malaysia (RM) was assigned to the ceramic waste, which was acquired for free from industrial sources. By factoring in the capacity of the engine and the duration of the operation, the overall cost of

electrical consumption for the equipment was estimated, depending on the materials' life cycles. The estimations were premised on Malaysian electricity price rates for October 2020, as shown in Table 6.

To calculate CO<sub>2</sub> the equivalent amount for 1 tonne of cement, the following equation was used.

$$\text{Total GHG released: } \sum_{i=1}^n mi((di * ei) + pi), \tag{1}$$

Where:

di: is the transportation distance, which is dependent on the direction of the transport;

ei: is the emission factor for the different methods of transportation;

pi: is the emission per unit mass of each material.

$$\text{Total CO}_2 \text{ emissions} = \sum_{i=1}^n mi [(di \times Di \times k1i) + (Ei \times k2i)] \tag{2}$$

Where:

mi is the mass of component i (t/m<sup>3</sup>), di is the transport distance (km), Di is the diesel consumption (L/km), k1i is the CO<sub>2</sub> emission for 1 L of diesel (t), Ei is the total electricity consumption (kwh), and k2i is the CO<sub>2</sub> emission for 1 kwh electricity (t).

$$\text{Total energy consumption} = \sum_{i=1}^n mi [(di \times Di \times k3i) + (Ei \times k4i)] \tag{3}$$

Where:

k3i is the energy consumption for 1 L of diesel (GJ), Ei is the total electricity consumption (kwh), and k4i is the energy consumption for 1 kwh of electricity (GJ).

$$\text{Total cost} = \sum_{i=1}^n mi [(di \times Di \times DPi) + Ti + (Ei \times EPI)] \tag{4}$$

where

DPi is the diesel cost (RM/L), Ti is the transport charge for 1 m<sup>3</sup> (RM/km), and EPI is the electricity cost (RM/kwh).

$$\text{Electricity consumption of component } I (Ei) = \sum_{i=1}^n (MEi \times MPi) \tag{5}$$

Where:

MEi is the machine capacity (t/h), and MPi is the machine power (kwh).

**Table 4.** WCP, OPC, CFA and RS preparation stages.

| Materials | Type       | Collection | Transportation | Crush | Sieve | Grind |
|-----------|------------|------------|----------------|-------|-------|-------|
| WCP       | waste      | yes        | yes            | yes   | yes   | yes   |
| OPC       | commercial |            |                |       |       |       |
| CFA       | waste      | yes        | yes            | yes   | yes   | -     |
| RS        | natural    | yes        | yes            | -     | yes   | -     |

**Table 5.** Details of the machinery and materials in Malaysia [16].

| Items  | Amount  |
|--|---------|
| Volume of truck, m <sup>3</sup>                      | 12      |
| Speed of truck, km/hr                                | 80      |
| Consumption of diesel, litter/km                     | 0.09    |
| Diesel price, RM/litter                              | 2.18    |
| Transport charge of 1 m <sup>3</sup> , RM/km         | 0.75    |
| WCP density, kg/m <sup>3</sup>                       | 1470    |
| CFA density, kg/m <sup>3</sup>                       | 1440    |
| Transport distance of WTC, km                        | 35      |
| RS density, kg/m <sup>3</sup>                        | 1750    |
| Transport distance of river sand, km                 | 62      |
| Crushing machine power, watt                         | 435     |
| Crushing machine capacity, m <sup>3</sup>            | 0.08    |
| sieving machine power, watt                          | 250     |
| sieving machine capacity, m <sup>3</sup>             | 0.05    |
| Oven power, watt                                     | 1200    |
| Oven capacity, m <sup>3</sup>                        | 0.18    |
| Grinding machine power, watt                         | 750     |
| Grinding machine capacity, m <sup>3</sup>            | 0.45    |
| CO <sub>2</sub> release for 1 kwh electricity, ton   | 0.00013 |
| CO <sub>2</sub> release for 1 L diesel, ton          | 0.0027  |
| Energy consumption for 1 L diesel, GJ                | 0.0384  |
| Energy consumption for 1 kWh electricity, GJ         | 0.0036  |
| Portland cement CO <sub>2</sub> release, tonne/tonne | 0.904   |
| Energy consumption, GJ/tonne                         | 5.13    |

**Table 6.** The October 2020' electricity cost in accordance with the consumption rate.

| Consumption<br>(Watt) | The unit<br>(RM/kWh) |
|-----------------------|----------------------|
| 0 to 199              | 0.218                |
| 200 to 299            | 0.334                |
| 300 to 599            | 0.516                |
| 600 to 899            | 0.546                |
| 900+                  | 0.571                |

Drawn from the data (in Tables 4, 5 and 6), the study ascertained the energy consumption and production costs for each batch. Comparisons between mortar mixtures WCP-CFAM and WCPM0 were made regarding energy consumption, costs, cost of production and GHG emissions. This was performed to reach a compressive strength of 30 MPa to meet the requisite for Portland cement of 460 kg/m<sup>3</sup>. By ascertaining production costs, GHG emissions and energy consumption levels for WCP, CFA, OPC and RS, the study evaluated the sustainability and environmental merits of the mortars, as shown in Table 7. A far greater quantity of energy was required to process OPC, associated with higher costs and higher GHG emissions, when contrasted with the WCP. A 5.13 GJ/ton energy expenditure emerged for OPC, as contrasted with 1.12 GJ / tonne for the WCP (four times less). Accordingly, OPC produced GHG emissions of 0.904 ton / ton, relatively high compared to WCP which was 0.045 ton/ton. The production costs for OPC were also the highest amongst the samples. The manufacturing process for OPC required high levels of energy, and transporting the material required far greater effort. In the case of OPC, production costs sat at 600 RM / ton, whereas for WCP

the cost stood at 170 RM / ton. To reduce energy consumption levels and production cost, in addition to GHG emissions, OPC needed to be applied at lower contents for mortar samples.

**Table 7.** WCP, OPC, CFA, and RS production process' greenhouse gas emissions, cost effective and energy consumption

| Materials | Greenhouse gases (ton/ton) | Cost (RM/ton) | Energy consumption (GJ/ton) |
|-----------|----------------------------|---------------|-----------------------------|
| WCP       | 0.045                      | 170           | 1.12                        |
| OPC       | 0.904                      | 600           | 5.13                        |
| CFA       | 0.003                      | 10            | 0.111                       |
| RS        | 0.009                      | 35            | 0.134                       |

### 3. Results and discussion

#### 3.1 Greenhouse emission

Figure 2(a) shows GHG emissions (CO<sub>2</sub> emissions) calculated for the control mortar mixture and those incorporated WCP as a partial replacement of OPC. It can be noted that as the dosage of WCP increases, the CO<sub>2</sub> emission decreases. The gas emission was reduced from 0.51 t/m<sup>3</sup> to about 0.24 t/m<sup>3</sup> as a result of using 60% of WCP as a partial replacement of OPC. The rate of reduction in the gas emission was linearly related to the dosage of the replacement. These drastically lowered GHG emission levels when using WCP as the binder demonstrate that there is a viable argument for using WCP as a sustainable material for mortar sample production. The CO<sub>2</sub> emission of the control mortar mixture and those incorporating CFA as replacement of river sand (RS) are shown in Figure 2(b). It can be observed that the GHG emission was slightly trended to decrease with increasing CFA content. Figure 2(c) illustrates a comparison between the CO<sub>2</sub> emission of the control mortar mixture and three other mortar mixtures naming: CFAM100 (mortar with 100% replacement of RS by CFA), WCPM40 (mortar with 40% replacement of OPC by WCP) and WCP-CFAM (mortar mixture with 40% replacement of OPC by WCP and 100% replacement of RS by CFA). The figure clearly shows the positive effect of using WCP as a replacement of OPC in reducing the GHG emission on one hand while the incorporation of CFA had very limited effect, if any, on the emission of GHG on the other hand.

#### 3.2 Cost analysis

The cost of cubic meter of mortar mixture was calculated for the control mortar mixture and those having various dosages of WCP as a partial replacement of OPC and results are illustrated in Figure 3(a). The figure clearly shows that the reduction in the cost is directly proportional to the level of WCP used as a partial replacement of OPC. The rate of reduction was approximately linear. The cost of 1 m<sup>3</sup> of mortar was reduced by about 30% as a result of using 60% of WCP as a partial replacement of OPC. This significant reduction in the cost is owing to the relatively affordable cost of manufacturing the WCP compared to that of the OPC. This reduction is expected to have a big influence on the decision of selecting the replacement materials of cement giving that the properties of the new mixture is technically accepted

In Figure 3(b), the impact of replacing RS by CFA on the costs of mortars is shown. This replacement caused a moderate cost reduction. The preparation phases for the materials, that affect the cost of the mixes, were used as the basis of the price calculations by weight. The figure shows that the



entire replacement of RS by CFA decreased the cost of the  $1\text{m}^3$  of mortar from 380 RM to about 340 RM.

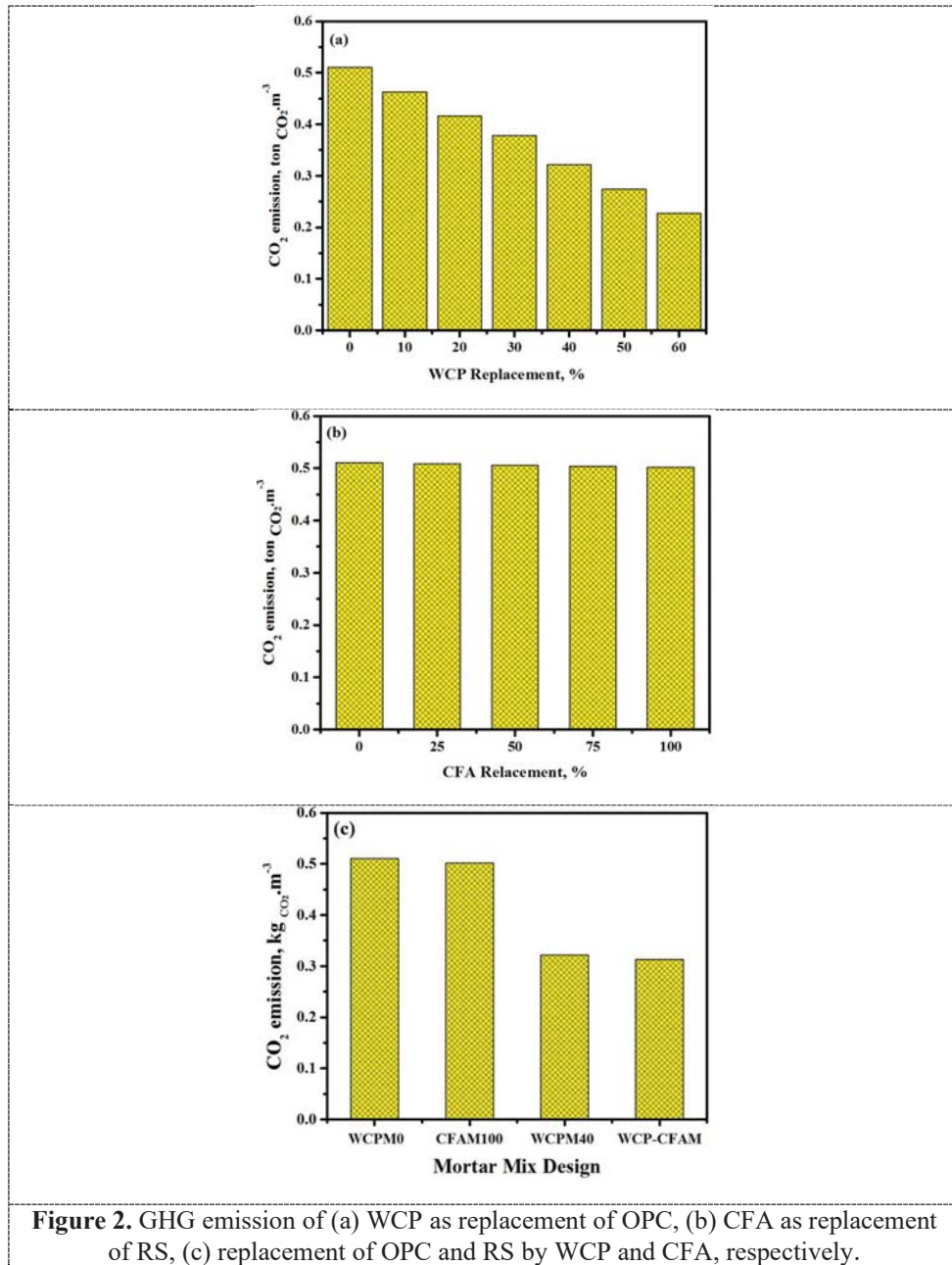
The production costs of mortar mixtures WCPM0, CFAM100, WCPM40, and WCP-CFAM were compared as shown in Figure 3(c). It can be seen that the cost of the later mortar mixture (WCP-CFAM), which has 40% replacement of OPC by WCP and 100% replacement of RS by CFA, was decreased by about 35% compared to that of the control mortar mixture. In other words, the incorporation of both materials WCP and CFA as a replacement of OPC and RS, respectively can lead to a significant reduction in the cost of mortar. It should be noted that technical results, such as effect of replacement dosage on mechanical properties of mortar and concrete, should be gathered with these results to determine the optimum replacement level.

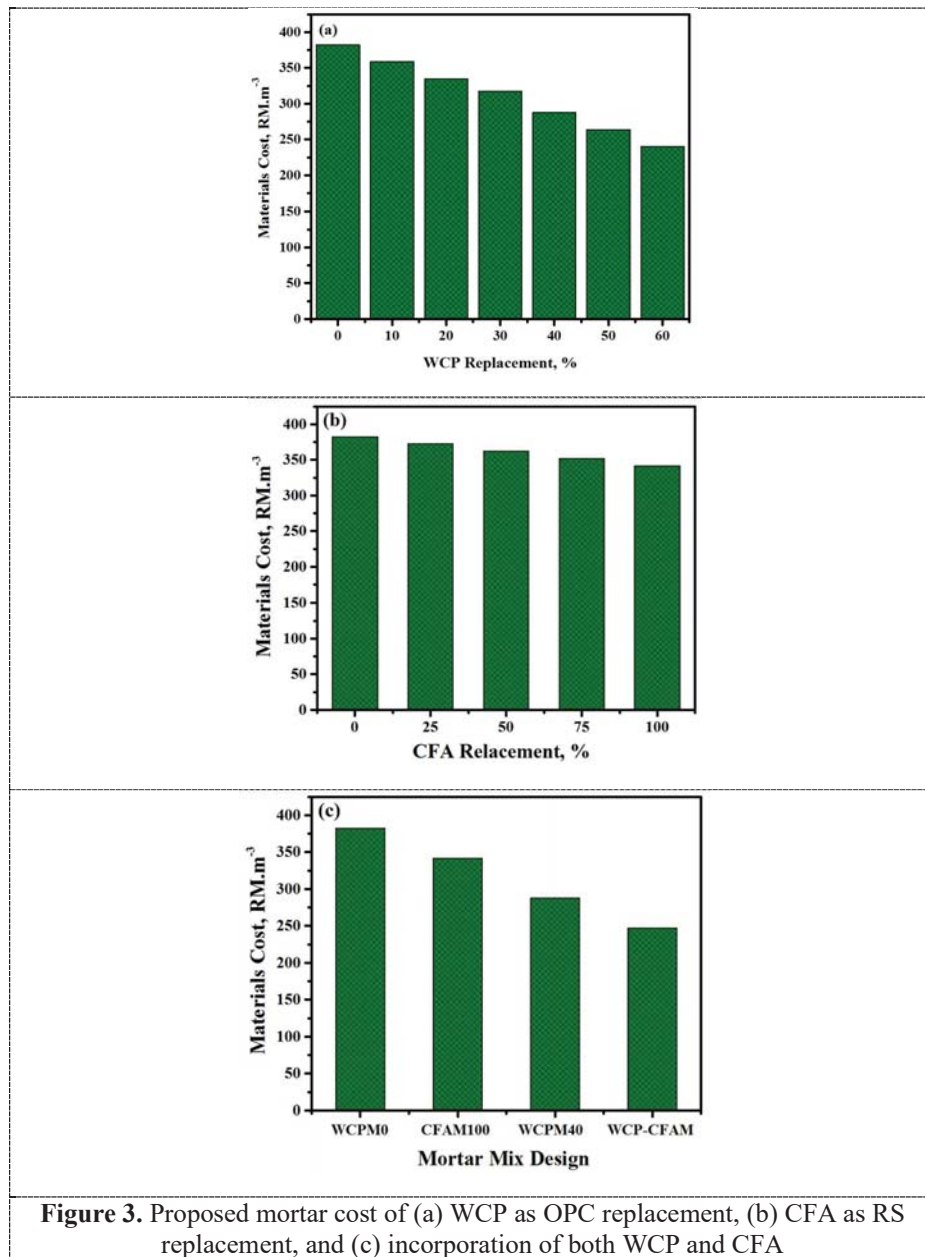
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In Figure 3(b), the impact of replacing RS by CFA on the costs of mortars is shown. This replacement caused a moderate cost reduction. The preparation phases for the materials, that affect the cost of the mixes, were used as the basis of the price calculations by weight. The figure shows that the entire replacement of RS by CFA decreased the cost of the  $1\text{m}^3$  of mortar from 380 RM to about 340 RM.

The production costs of mortar mixtures WCPM0, CFAM100, WCPM40, and WCP-CFAM were compared as shown in Figure 3(c). It can be seen that the cost of the later mortar mixture (WCP-CFAM), which has 40% replacement of OPC by WCP and 100% replacement of RS by CFA, was decreased by about 35% compared to that of the control mortar mixture. In other words, the incorporation of both materials WCP and CFA as a replacement of OPC and RS, respectively can lead to a significant reduction in the cost of mortar. It should be noted that technical results, such as effect of replacement dosage on mechanical properties of mortar and concrete, should be gathered with these results to determine the optimum replacement level.



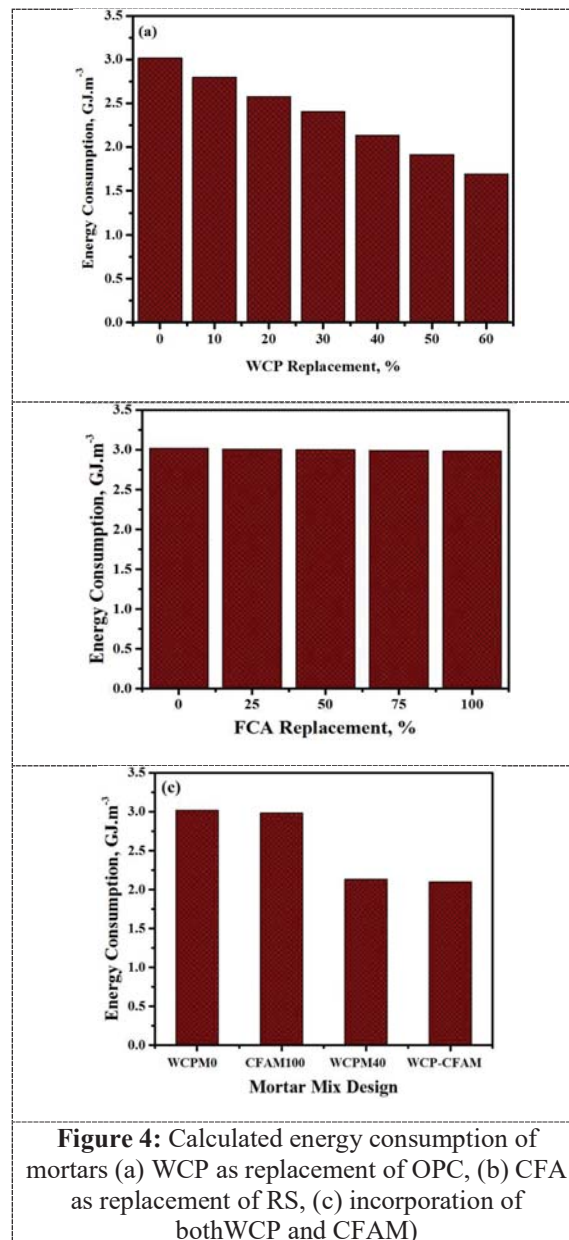


### 3.4 Energy efficiency

By measuring the energy consumption and life cycles of the materials used to manufacture each batch, the overall energy consumption levels in the production of the mortar mixtures were calculated. Results were provided in Figures 4(a), (b) and (c). As it can be noted in Figure 3(a), the incorporation of WCP as a partial replacement of OPC resulted in a significant reduction in the energy consumption compared to that of the control mortar mixture. The energy consumption was decreased by approximately 40% as a result of using 60% replacement of OPC by WCP. Similar to the effect of WCP on the GHG emission and cost, the reduction rate was approximately linear. In other words, each mortar mixture contained a specific amount of WCP in turn consumed lower amounts of energy

compared to the control mortar mixture. This can be partially attributed to the reduced cost of diesel and electricity used in the preparation of WCP. Figure 4 (b) shows that the replacement of RS by CFA has a very marginal effect on the energy consumption. This can be logically attributed to the existing low energy usage level associated with RS.

The incorporation of both WCP and CFA as replacement of 40% OPC and 100% RS, respectively caused a reduction in energy consumption approximately comparable to that of mortar mixture WCPM40. This means that the use of CFA as a replacement of RS has very little effect, if any, whether it was used alone in mortar mixture as a replacement of RS or with mortars having WCP as a partial replacement of OPC.



#### 4. Conclusions

The Carbone dioxide emission, cost and energy consumption of twelve mortar mixtures incorporating two forms of waste ceramic tile (WCP and CFA) were calculated. Based on results of this study, the following conclusions were drawn.

1. The GHG emission, cost and energy consumption of OPC production are approximately 20, 4 and 4 times as high as those of WCP
2. The incorporation of various levels of WCP (10 to 60% by weight) as a partial replacement of OPC resulted in a significant decrease in GHG emission, effective cost and energy consumption of the mortar mixtures.
3. Although the use of CFA as replacement of RS led to a decrease in the effective cost of the mortar mixtures, the effect of the replacement was very marginal on both GHG emission and the energy consumption of the mortar mixtures.
4. The use of WCP and CFA as replacement of OPC and RS, respectively in the same mortar mixture had comparable effect on GHG emission and energy consumption to that of using only WCP in the mortar mixture.

It is worthy stating that laboratory investigation on the effect of using WCP and CFA on the mechanical properties of mortars and concrete should be carried out and gathered with those of this study to complete the entire picture and support the decision of selecting the appropriate replacement materials either for cement or other components of mortars or concrete.

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