Thermal Insulation Enhancement of Metakaolin-Based Geopolymer Concrete Using Waste Clay Brick

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Abstract. Geopolymer concrete is one of the sustainable building materials that has a low energy production and a minimum carbon footprint. In this study, the effect of utilization waste clay brick on the thermal conductivity (TC) of Metakaolin geopolymer concrete (MK-GPC) was investigated. The waste of clay brick was used in two series of mixes, first one included clay brick waste powder (BP) as partial replacement of Metakaolin (MK) at weight dosage 10%, 15%, and 20%, while the second group of mixes contained crushed clay brick waste aggregate (CBA) at replacement level of 10%, 20% and 30% by volume of natural coarse aggregate. In addition to (TC), all the specimens were tested to determine the ultrasonic pulse velocity (UPV), and voids content at 7 and 28 days. The results of the samples with 10% and 15% BP have shown higher UPV and less voids content, while the incorporation of CBA aggregate at 20% and 30% caused reduction in UPV and increased the voids in MK-GPC mixture. Furthermore, the addition of the waste clay brick in both forms (powder and aggregate) has improved the results of thermal insulation. Conclusively, reusing of waste clay brick as ingredients in MK-GPC will provide a super-sustainable geopolymer concrete with advanced thermal insulation properties.

1. Introduction

The growing of awareness about the environmental problems and energy consumption has made the sustainability in the sector of building and construction as an importance issue worldwide. The increasing demand on building materials, especially Ordinary Portland Cement (OPC) concrete and clay brick units has caused negative impacts related to energy consumption, environmental pollution and depletion of natural recourses. The global demand of OPC was over 3 billion tones in 2012, and this number will increase to 4.4 billion tones by the year 2050 [1]. In the production process, each ton of OPC releases one-ton of carbon dioxide (CO2). This is directly contribute to the emission of greenhouse gases approximately 5-8%, and this amount could jumped up to 15% by 2020 [2]. Thus, many endeavor have been attentive on developing an eco-friendly innovative alternative to ordinary Portland cement commonly known as “Geopolymers” which firstly coined by Davidovits in 1978. Geopolymer concrete can be manufactured by chemical reaction of alkaline solution liquid; usually consist of sodium silicate (Na2SiO3) and sodium hydroxide (NaOH), with rich aluminosilicate-based powder materials such as fly ash, slag, red mud, and rice husk ash; or metakaolin (MK). On the other hand, the clay brick has considered as a second level of building materials after concrete. Huge amounts of waste clay brick are generating during the manufacturing, construction and demolition activities, and this type of waste has treated as C&D waste. Most of waste brick are left as landfill or illegally dumped, and become a serious environmental problem [3]. Another environmental drawback of construction field has come from high energy consumption for cooling and heating (thermal comfort) of the buildings, which is depending on thermal conductivity value of construction materials.
Kim and Lee [5] have reported great (TC) value of 0.46 W/m.K and compressive strength 16.2 MPa at 28 days for fine ground bottom ash geopolymer samples. Meanwhile, Jaya et al. [6] have depended on optimum Na$_2$SiO$_3$/NaOH ratio to produce metakaolin geopolymers with 32 MPa compressive strength and (TC) up to 0.82 W/m.K. Hence, the novelty of this research is toward minimizing the waste clay brick pollution throw reusing and recycling it as ingredients in synthesis more thermal insulation geopolymer concrete. The objectives of this study are to investigate the effects of different contents of BP and CBA aggregate on the (TC), (UPV) and voids content of MK-GPC specimens, and show the feasibility of production superior green-thermal insulation geopolymer concrete on the way to developing the sustainable construction industry.

2. Experimental Procedure

2.1. Materials

Iraqi kaolin clay was burning at 700 °C for 2 hours to produce metakaolin that used in this study as source binder. The alkaline activator was obtained from mixing 14M solution of (NaOH) with (Na$_2$SiO$_3$) at ratio of 1:2 for all mixes. The (BP) and (CBA) have produced by crushing the residual of non-used units of hollow clay brick into small pieces using crushing machine. The crushed particles with size 5-14 mm have collected separately and grading on electrical sieves shaker to be used as coarse aggregate, while the finer materials were re-grinded by cyclone machine to produce BP as shown in Figure 1 and 2 respectively. The chemical composition and physical properties for MK and BP are illustrated in Table 1. For all mixes, natural coarse aggregate with 14 mm maximum size; and natural sand with 3.3 fineness modulus were used. Also, extra tap water and superplasticizer (Conplast 2000) were added to improve the workability and mixing process.

![Figure 1. Clay brick waste aggregate (CBA).](image1)

![Figure 2. Clay brick waste powder (BP).](image2)

| Oxide % | SiO$_2$ | Al$_2$O$_3$ | Fe$_2$O$_3$ | CaO | MgO | SO$_3$ | Na$_2$O | K$_2$O | L.O.I |
|---------|---------|-------------|-------------|-----|-----|--------|---------|-------|-------|
| MK      | 54.20   | 39.0        | 0.92        | 1.37| 0.15| 0.45   | 0.22    | 0.27  | 0.71  |
| BP      | 56.82   | 11.36       | 2.36        | 20.20| 3.02| 0.83   | 0.86    | 0.86  | 1.19  |

| Physical Properties | MK | BP |
|---------------------|----|----|
| Specific gravity    | 2.64 | 2.84 |
| Specific surface area (m$^2$/gm.) | 14.3 | 0.462 |
| 7 days pozzolanic activity index, (%) | 113.3 | 89.2 |

2.2. Mix proportions and specimens preparation

The mix design for reference mixture was based on several trial mixes to produce MK-geopolymer concrete with compressive strength reach up to 40 MPa at age of 7 days. For all mixes, the alkaline solution to binder ratio was fixed at 0.65, while the dosage of superplasticizer and extra water were 2% and 10% by weight of metakaolin respectively. As summarized in Table 2, two series of mixes were prepared to understand the effect of waste clay brick on reference mix, the first one included replacing the weight of MK with BP at dosage of 10%, 15% and 20%, while the second series incorporated the CWCB aggregate as partial volumetric replacement of natural coarse aggregate at levels of 10%, 20%...
and 30%. All specimens were cured by sealing it with a thick nylon bags, then placed in an electrical oven at 60 °C for 4-5 hours, and exposed to sun light in summer season at 36-48 °C until the test time.

Table 2. Mix proportions of all MK-GPC mixtures.

| Mixes       | Materials (kg/m³) | Compressive Strength at 7 Day (MPa) |
|-------------|------------------|-------------------------------------|
|             | MK   | BP   | CBA | Coarse Agg. | Fine Agg. |                        |
| Ref. MK-GPC | 415  | 0    | 0   | 1240        | 475        | 40.39                  |
| Series I    |       |      |     |             |            |                        |
| 10% BP      | 373.5| 41.5 | 0   | 1240        | 475        | 22.09                  |
| 15% BP      | 352.75| 62.25| 0   | 1240        | 475        | 29.26                  |
| 20% BP      | 332  | 83   | 0   | 1240        | 475        | 25.36                  |
| Series II   |       |      |     |             |            |                        |
| 10% CBA     | 415  | 0    | 73.08| 1116        | 475        | 39.0                   |
| 20% CBA     | 415  | 0    | 146.16| 992        | 475        | 26.83                  |
| 30% CBA     | 415  | 0    | 219.24| 868        | 475        | 20.0                   |

2.3. Test methods
The details of experimental tests required to recognizing the properties of all MK-GPC mixes are reported in Table 3. For each tests, three specimens were used to calculate the average of final result.

Table 3. Details of testing methods.

| No. | Type of test            | Geometry of sample                  | The Standards          |
|-----|-------------------------|-------------------------------------|------------------------|
| 1   | Ultra Pulse Velocity (UPV) | Prism of 100×100×400 mm               | ASTM C597-2015 [7]    |
| 2   | Voids content           | Fractured part of the tested prisms | ASTM C642-2013 [8]    |
| 3   | Thermal Conductivity    | Prism of 75×75×300 mm               | ASTM C 1113-2013 [9]  |

3. Results and discussion

3.1. Ultrasonic pulse velocity
The the (UPV) test was conducted at 7 and 28 days to evaluate the matrix uniformity of MK-GPC mixes that containing different forms and percentages of waste clay brick. The results of UPV test for series I and series II are shown in Figure 3 and 4 respectively. With continuous of geopolymerization process the microstructure would enhance, thus the UPV values for all mixes have increasing with time.

Figure 3. UPV of MK-GPC with BP.

As appeared from Figure 3, the pulse velocity of 10% and 15% BP mixes were slightly higher than reference mix. This is because of the filling effect of waste brick powder and facilitated pore refinement of the geopolymer matrix. On the other hand, Figure 4 shows that the mix of 10% CBA has a smooth increase in UPV result, on contrary of that, the incorporate of 20% and 30% CBA declined the pulse velocity of reference mix up to 4.25% and 17.24% respectively. This behaviour attribute to the porous structure of crushed clay brick aggregate and weakness of inartificial transition zone.

Figure 4. UPV of MK-GPC with CBA.
3.2. Voids content
Voids content data of MK-GPC containing BP and CBA are shown in Figure 5 and 6 respectively. It can be seen that voids content for all mixes are decreased with time due to continuous geopolymerization activity and development of the microstructure of binder paste. The voids content in mixes with 10%, 15% and 20% BP are less than that of reference mix by 21.19%, 30.64% and 18.35% respectively. These outcomes are because of filling action of BP and the formation of compacted binder in the geopolymer matrix [10], that is comply with the UPV findings. In same trend, the incorporation of 10% CBA has minimized the voids in MK-GPC by 5.87%, while the dosages of 20% and 30% of CBA has increased the voids content of control mix up to 11.56% and 27.98% respectively. The porous and cellular structure of CBA has produced more voids in MK-GPC matrix.

![Figure 5. Voids content of MK-GPC with WBP.](image)

![Figure 6. Voids content of MK-GPC with CBA.](image)

3.3. Thermal conductivity
Figure 7 is given the thermal conductivity values for all MK-GPC mixes at age of 28 days. Thermal conductivity of reference mix (0% waste clay brick) was 1.5295 W/m.K. This value decreased by 42.90%, 45.00%, and 46.27% for mixes with 10%, 15% and 20% BP, respectively.

![Figure 7. Results of thermal conductivity for all MK-GPC mixes.](image)

In spite of the voids content results which indicate that BP-mixes have less voids and pores, but the incorporation of BP in MK-GPC has minimized the thermal conductivity. This can be attributed to the nature and insulation characteristic of the clay brick powder compared with metakaolin. Furthermore, with replacement natural coarse aggregate by CBA, the thermal conductivity of control mix has intensively declined up to 43.44%, 46.02% and 54.07%, for mixes with 10%, 20% and 30% CBA, respectively. In compared with natural coarse aggregate, the CBA has lower coefficient of thermal conductivity [11], more porous and cellular structure. This will produced more pores and voids in the
concrete matrix, leading to lowering (TC) of reference mix and enhanced the thermal insulation. Although the MK-GPC was a normal weight concrete, but the obtained (TC) for all mixes were in close to lightweight geopolymer concrete which range between 0.620 to 0.957 W/m.K [12].

4. Conclusions
In this study, the waste clay brick was utilized as a part of source binder and coarse aggregate to produce sustainable geopolymer concrete. The main findings of using waste clay brick powder in MK-GPC at optimum ratio 15wt.%, are improvement of the pulse velocity and minimization the voids content in the geopolymer paste. On contrary of that, the using of waste brick aggregate has a negative effect on the MK-geopolymer matrix, and that led to reduce the ultrasonic velocity and increase the voids content in the paste. Moreover, the results of thermal conductivity shows a great enhancement when the waste clay brick has added to the MK-GPC mix. The replacement of MK at 20wt. % of BP has provided the best level in thermal insulation results, whereas the dosage of 30 vol. % of CBA has the optimum minimizing of the thermal conductivity to reach 0.7025 W/m.K. The key findings of this investigation confirm the importance of using the waste of clay brick as a main material to synthesis more sustainable geopolymer concrete with superior performance in thermal insulation. This will reduce energy consumption during manufacturing and life cycle of the buildings, as well as, minimize the environmental pollution, CO₂ emission and exhaustion of raw materials. Further researches on micro-scanning structure, durability performance and time dependent deformation for MK-GPC with waste clay brick are suggested to be investigated comprehensively.

5. References
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