Evaluation of sustainable metakaolin-geopolymer concrete with crushed waste clay brick

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Abstract. In the last decades, with the speed up of urban construction and infrastructure, the large amounts of new concrete and, at the same time a huge quantity of construction and demolition waste are generated every year. Therefore, the sustainability of concrete technology and building industry has taken priority with respect to, CO2 emission during cement manufacturing, natural resources depletion, environmental pollution and ecology unbalance. This study aims to assess the possibility of produce a more eco-friendly geopolymer concrete using Iraqi metakaolin (MK) and crushed waste clay brick (CWCB) as coarse aggregate, regarding the highest compressive strength and more sustainable curing method. The variations in the mechanical properties of MK-based geopolymer concrete with different contents (0%, 10%, 20%, and 30%) of waste clay brick as a replacement by volume of natural coarse aggregate were investigated. The fresh density and mechanical properties (compressive, splitting and flexural strengths), also the dry density was evaluated at age of 7 and 28 days. The results showed that all mixes with CWCB had lower fresh and dry densities. Geopolymer concrete mix with 30% CWCB showed a reduction in fresh and dry densities of 3.22% and 6.30% respectively relative to the concrete mix without CWCB. Also, the compressive and splitting tensile strength reduce with the increase of CWCB content, the percentage reduction is 53.37% and 45.09% for 30% CWCB replacement level respectively relative to reference specimens (0% CWCB aggregate). On the other hand, specimens with 10% of CWCB showed a slight improvement in flexural strength, while with 20 and 30% CWCB there is a reduction in flexural strength. Generally, production of moderate strength MK-geopolymer concrete incorporates waste clay brick as coarse aggregate will improve the sustainability and lead to open wide areas for civil engineering applications.

Keywords: Sustainability, Geopolymer concrete, Metakaolin, Crushed waste clay brick, Mechanical properties.

1. Introduction
In present days, the sustainability in construction and building sector become a vital issue related to environmental pollution, climate change and preserve natural sources. Concrete is one of the most used man-made construction materials in the world. The negative impact of concrete on the environment comes from Portland cement, the main binder ingredient in concrete. Portland cement industry not only consumes high energy and large amounts of raw materials, but its responsible for emission huge quantity, up to 1.5 billion tons of CO2 annually, which amounts 5-8% of the total global CO2 emission and this rate may increase up to 10-15% by 2020 [1], [2]. To mitigate these drawbacks, many efforts have been focused on developing an eco-friendly innovative alternative to normal concrete with zero cement content, which commonly known as Geopolymer Concrete. Geopolymer
concrete, which firstly introduced by Davidovits in 1978, is synthesized by geopolymerization the aluminosilicate materials (e.g., metakaolin, fly ash and slag) with alkaline activators that usually sodium hydroxide and sodium silicate [1].

Furthermore, the concern regarding the environmental impact of the construction and demolition waste (CDW) has increased. More than 25% of the total solid wastes consist of CDW; the brick residues contribute 50% of these wastes. Just in the European Union, the CDW amount is nearly 0.8–1 billion tons per year [3], [4]. Most of those wastes are thrown away as a landfill material or dumped illegally, which not cause economic losses only but also serious environmental problems. Thus, recycling and re-use of clay brick waste as a source of aggregate in concrete production has become more common recently[5]. There are many researches available on the use of the crushed clay bricks as aggregate in the normal concrete [6, 7, 8]. Most of these studies were focused on the mechanical properties, and durability of concrete [9]. On the other hand, a few studies had investigated the characteristics of geopolymer concrete with recycled coarse aggregate obtained from a construction and demolition waste, which were usually recycled concrete aggregate[1, 3, 10]. Currently, there are no results exist on the mechanical properties of the metakaolin based geopolymer concrete, which contents a crushed waste clay bricks as a coarse aggregate. Hence, the objectives of this study are to manufacture geopolymer concrete using Iraqi metakaolin (MK) as source material, and present the results of the physical and mechanical properties of MK-geopolymer concrete made by substituted the natural coarse aggregate by crushed waste clay bricks at different volume rates (0, 10, 20, and 30)%. This research will be finding a great way to utilize the waste clay brick as an economy source to produce more eco-friendly geopolymer concrete, that helping to enhance the sustainability and minimize the greenhouse gas emission, and depletion of natural resources.

2. Experimental Approach

2.1. Materials

2.1.1. Metakaolin.

Iraqi kaolin clay was calcined at 700 °C for two hours to produce the metakaolin that used as source material for synthesis geopolymer concrete. Physical properties and chemical composition of metakaolin according to the results of X-Ray Fluorescence (XRF) are presented in Table 1. The results shown in Table 2 indicate that the obtained metakaolin is comply the requirements of ASTM C618-2017[11] as a natural pozzolan Class N.

| Oxide% | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₃ | Na₂O | K₂O | LOI |
|--------|------|-------|-------|-----|-----|-----|------|-----|-----|
| MK     | 54.20| 39.0  | 0.92  | 1.37| 0.15| 0.45| 0.22 | 0.27| 0.71|

**Table 1.** The chemical composition and physical properties of metakaolin compared with ASTM C618-17

**Physical Properties of MK**

| Property | Value  |
|----------|--------|
| Specific gravity | 2.64   |
| Specific surface area (m²/kg) | 14300 |
| 7 days pozzolanic activity index, (%) | 113.3  |
Table 2. Natural pozzolan class N requirements according to ASTM C618-2017.

| Items                                      | Test results | ASTM C618-17 requirements |
|--------------------------------------------|--------------|---------------------------|
| $(\text{SiO}_2+\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$% | 94.12%       | Min. 70%                  |
| $\text{SO}_3$(%)                           | 0.45%        | Max. 4.0%                 |
| Loss on ignition (%)                       | 0.71%        | Max. 10%                  |
| Amount retained when wet-sieved on 45 μm (No. 325) sieve (%) | 18.2% | Max. 34%                  |
| Strength activity index at 7 days (%)      | 113.3        | Min. 75%                  |

2.1.2. Alkali Activator.
The alkali solution used in this study was a combination of sodium silicate $(\text{Na}_2\text{SiO}_3)$ and sodium hydroxide $(\text{NaOH})$. The pellets form with 98% purity of NaOH was dissolved in distilled water to prepare a solution with 14 molarity. The commercial grade of sodium silicate $(\text{Na}_2\text{SiO}_3)$ which contents (54% $\text{H}_2\text{O}$, 32.5% $\text{SiO}_2$, and 13.5% $\text{Na}_2\text{O}$) was mixed with (NaOH) solution at ratio (2:1). The final solution left 24 hours to be cool at room temperature before using.

2.1.3. Aggregates.
The coarse aggregate was natural and crushed with size 5–14 mm, while the fine aggregate was natural sand zone 1 with fineness modulus of 3.3. The crushed waste clay brick aggregate (CWCB) was prepared by crushing the residue of non used hollow bricks (usually quarters and half pieces) from different sites using crusher machine. Then the crushed clay brick was graded on electrical sieves shaker to comply with the natural coarse aggregate which used in this study (size 5-14mm) as shown in Figure 1. The properties of aggregates are illustrated in Table 3 below.

Figure 1. Crushed waste clay brick aggregate

Table 3. Properties of the coarse natural, fine, and CWCB aggregates.

| Property                        | Coarse Natural Aggregate | Fine Aggregate | CWCB Aggregate |
|---------------------------------|--------------------------|----------------|----------------|
| Dry rod density (kg/m$^3$)      | 1595                     | 1787           | 940            |
| Bulk specific gravity           | 2.61                     | 2.58           | 1.57           |
| Absorption %                    | 1.3                      | 1.6            | 24.0           |
| $\text{SO}_3$%                  | 0.034                    | 0.063          | 0.83           |
2.1.4. Admixture and Extra water.
High-range water reducing admixture superplasticizer (Conplast 2000) was used to improve the workability of fresh geopolymer concrete. Also, extra tap water was added to enhance the mixing process.

2.2. Mixing Procedure, Casting and Curing of Specimens for the Geopolymer Concrete
The mix proportions of geopolymer concrete are shown in Table 4. For all mixes, the ratios were fixed as the alkaline solution to binder = 0.65, Na₂SiO₄:toNaOH = 2:1 with 14 molarity concentration, while the dosage of superplasticizer and extra water were 2% and 10% by weight of MK respectively. The natural coarse aggregate was partially replaced with CWCB at percentages of 0, 10, 20, and 30 by volume. All aggregates were prepared to be in saturated surface dried (SSD) condition. Firstly, the coarse, fine and CWCB aggregates were mixed with MK together in an electrical pan mixer for four minutes. Then, the alkali solution, superplasticizer, and extra water were added gradually to the dry mixture to be mixed together for 7 to 8 minutes, included one-minute rest to clean the blades. After the mixing process, the homogenous fresh geopolymer concrete was cast into the required molds in two layers. Each layer was tamped 30 times with a standard steel rod and then followed by 15-30 second on the vibration table.

| Materials          | CWCB aggregate content (%) |
|--------------------|-----------------------------|
| Metakaolin         | 0                           |
| Coarse Agg.        | 10                          |
| Fine Agg.          | 10                          |
| WCB Agg.           | 10                          |
| Alkaline Solution  | 10                          |
| Extra Water        | 10                          |
| Superplasticizer   | 10                          |

Immediately after casting, the samples were covered with plastic film to reduce water loss by evaporation, and left in ambient condition for 24 hours. Then, the specimens were demolded and cured by sealed it with a thick plastic bags and placed in an oven at 60 °C for 4-5 hours followed by exposure to sunlight in the summer season at 35-49 °C until the testing time.

2.3. Test Methods
To recognize the characteristics of MK-based geopolymer concrete which containing different percentages of CWCB as coarse aggregate, several tests were carried out according to the following specifications: Fresh density test according to ASTM C138-2017 [12], dry density test according to ASTM C642–2013 [13], compressive strength test according to BS. 1881: Part 116:1983 using cube specimens of 100 mm [14], flexural strength test comply with ASTM C78 –2018 using prisms of100×100×400mm [15], and splitting tensile strength test on cylinders of 100 mm diameter and 200 mm high, as in ASTM C496–2017 [16]. For each experimental test, three specimens at 7 and 28 days were used to calculate the result as an average value.

3. Results and Discussions
3.1 Fresh Density
The results of fresh density for MK-geopolymer concrete with respect to various percentages replacement of CWCB aggregate are shown in Figure 2. As can be seen, the fresh density decreases with the increase in the amount of crushed waste clay brick as coarse aggregates. The dropped in fresh density was from 2360 kg/m³ for the mix with 0% CWCB to be 2284 kg/m³ for mix with 30% CWCB. This behavior is similar to that for normal concrete containing the crushed clay brick as coarse
aggregate. The reduction is attributed to the lower density and specific gravity of CWCB aggregate compared with natural coarse aggregate [5, 17, 7, 8 and 9].

![Figure 2](image)

**Figure 2.** Fresh density of MK-geopolymer concrete with varying CWCB aggregate contents

### 3.2 Dry Density

Figure 3 presents the dry density values of MK-geopolymer concrete with different CWCB aggregate contents at 7 and 28 days. For all mixes, the dry density at 28 day was higher than that at 7 days due to the continuity of the geopolymerization process. The dry density decreases with the increase in replacement level of CWCB. At 28 day, the dry density of specimens with 10, 20 and 30% CWCB are 2193, 2151 and 2067 kg/m³ respectively. The lower density and lower specific gravity of recycled brick aggregate caused this decrement in the dry density of geopolymer concrete, but still MK-geopolymer concrete with different CWCB aggregate prepared in this investigation is classified as normal weight concrete.

![Figure 3](image)

**Figure 3.** Dry density of MK-geopolymer concrete with varying CWCB aggregate contents

### 3.3 Compressive Strength

The influence of incorporating CWCB on the compressive strength of MK-geopolymer concrete at 7 and 28 days is presented in Figure 4. Generally, the compressive strength of all geopolymer specimens tends to increase with time [18], [19]. The MK-geopolymer concrete with CWCB had a lower compressive strength than the reference specimens (with 0% CWCB). It was observed that as the CWCB substitution levels increased, the compressive strength decreased by 3.13%, 31.27% and 53.37% for specimens containing 10, 20 and 30% CWCB aggregate at 28 days respectively. This reduction in compressive strength of MK-geopolymer concrete is similar to that for normal concrete.
which incorporated recycled waste brick as coarse aggregate as indicated in previous researches, this may be attributed to the lower in strength and hardness of brick aggregate [8], [6],[10].

![Figure 4. Compressive strength of MK-geopolymer concrete with varying CWCB aggregate contents](image)

3.4 Splitting Tensile Strength
Figure 5 shows the splitting tensile strength of MK-geopolymer concrete versus the replacement levels of CWCB aggregate. The splitting tensile strength ranged from 2.55 to 0.66 MPa between 0% and 30% dosage of CWCB at 7 and 28 days. The splitting tensile strength of all geopolymer concretes increased with time. As in compressive strength, the splitting strength decreases with the increase of the replacement level of CWCB. This could be due to the relatively low strength of recycled clay brick aggregate compare to that for natural aggregates. It is clear from Figure 5, that the optimum content of CWCB is 20%, which has the minimum reduction in splitting strength of 8.62% relative to specimens with 0% CWCB, while the reduction is 27.05% and 45.1% for specimens with 10% and 30%CWCB at 28 days respectively.

3.5 Flexural Strength
The flexural strength values of MK-geopolymer concrete with and without CWCB aggregate at 7 and 28 days are illustrated in Figure 6. Due to the continuous geopolymerization process, the results at 28 day are higher than those at 7 days. As shown in Figure 6, up to 10% replacement of natural coarse aggregate with CWCB aggregate, the flexural strength increases by 34.62% and 27.27% at 7 and 28 days respectively, compared with specimens not containing CWCB. This enhancement related to the angular shape and surface roughness of crushed brick which improved the bond between the CWCB aggregates and the paste [6], [17]. The increase of CWCB aggregate content to 20% and 30% causes a decline in the flexural strength of about 25.75% and 40.91% at 7 and 28 day age respectively.
4. Conclusions

Based on the results found in this study, the most important conclusions can be summarized as follows:

• MK-geopolymer concrete with recycled waste brick aggregates showed a decrease in fresh and dry densities, thus it is appropriate for applications where self-weight are a problem.
• By increasing the CWCB aggregate content, the compressive strength decreases. The highest reduction was 53.37% for 30% replacement level at 28 days, while specimens with 10% CWCB showed the superior performance with the lowest drawback by only 3.13% related to specimens with 0% CWCB at 28 days.
• The use of CWCB aggregate increases the loss in the splitting tensile strength up to 45% for 30% CWCB aggregate content at 28 days. The optimum content of recycled brick aggregate was 20% with minimum reduction of 8.6% compared to specimens with 0% CWCB aggregate.
• MK-geopolymer concrete with 10% dosage of CWCB aggregate shows improvement in flexural strength of 27.27% compared to that for specimens with 0% CWCB aggregate.
• In spite of the decrement in the mechanical properties of MK-geopolymer concrete with crushed waste clay brick aggregate, but the minimum strength still provides a moderate performance concrete which can apply in a limited structural application and some manufactured elements such as precast elements, interlocking paving units, masonry units, and sidewalk.
• To confirm these results, further studies are suggested to investigate the microstructure characteristics, long-term durability performance, and time-dependent deformations (creep and shrinkage).
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