Sustainable metakaolin based pervious geopolymer concrete with recycled concrete aggregate

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Abstract. Production of Portland cement causes many environmental problems. Whereby, about seven percent by the gross weight of CO2 emissions resulted from cement production factories. Therefore, the usage of geopolymer binder, to produce pervious concrete, instead of Portland cement considers the one solution towards conserving the environment by reducing emission of carbon dioxide. In this paper, we investigate the production of local metakaolin (MK) as a geopolymer binder to produce Pervious Geopolymer Concretes (PGC). Also, the inclusion of recycled construction materials wastes as aggregates (RA) for production of (PGCs) was studied. PGC was produced from local metakaolin (MK), sodium hydroxide (NaOH) solution, sodium silicate (Na2SiO3) solution, and recycled concrete (RC) as a volumetric partial replacement from the natural coarse aggregate (NA). All PGC specimens cured at a temperature of 50°C for five hours after 24 hours from casting and tested after 28 days. Compressive strength, total void content, splitting tensile strength, flexural strength, dry density and coefficient of water permeability for the PGCs were investigated. The results of mechanical properties were ranged from (12.23, 1.81 and 2.5) to (9.86, 1.3 and 1.95) MPa for compressive, splitting tensile and flexural strengths, respectively. The results articulate that the recycled concrete (RC) can be used as recycled coarse aggregates with a partial replacement for producing PGC with acceptable properties.

1. Introduction
Pervious concrete PC which is named as a porous concrete or permeable concrete consists from cement, coarse aggregate with single size, with low content or without of fine aggregate, some admixtures if needed and water. A small layer of cement paste was formed around aggregate particles when these components were mixed together. So, the permeability of pervious concrete will be enhanced that resulted from voids created between particles of aggregate [1].

Generally, the pervious concretes have water-cement ratio from 0.26 to 0.45 and fine aggregate between 0% and 10% [1]. Connecting voids in pervious concrete ranging in size between 2 and 8 mm and voids ratio between 15% and 35% with water permeability of 2–12 mm/s [2]. The high voids ratio of pervious concrete leads to compressive strength less than that of conventional concrete and it is ranging from 3 to 28 MPa [1,3].

Ongoing decades indicated wide thoughtfulness regarding pervious concrete as the consequence of its ecological favourable circumstances, for example, lessening storm water spill over, water contamination expulsion, keeping up groundwater level, decreasing the requirement for maintenance...
lakes and other expensive tempest water controlling, expanding air and water capacity to achieve foundations of trees. [1,4].

Huge quantities of construction wastes are produced every year. In numerous countries, all these waste construction materials are sent to landfills or commonly deliver illegally. There are many environmental and social problems resulting from disposal of these construction waste materials. Therefore, the recycling process of construction waste materials and utilization in new concrete manufacturing projects can decrease the problems [5]. Likewise, the utilization of recycled aggregate minimizes the consumption of natural aggregate. The mechanical strengths of concrete that contains recycled aggregates are reduced as the quantity of these recycled aggregate increases. The recycled aggregate is usually low in abrasion resistance and density, and high in porosity and absorption due to the attachment of mortar and cement paste around the surfaces of aggregate [6].

Geopolymers may be produced by polymerization of materials with high silicate and alumino oxides together with alkali poly-silicates yielding Si–O–Al chains [7]. The geopolymer binder consists of two main ingredients of source materials and alkaline liquids. The alkaline liquids are commonly solutions of potassium or sodium. The source materials used in geopolymer must be rich in aluminum (Al) and silicon (Si) from by-product or geological origin materials such as fly ash, clays, metakaolin and slag. The usage of geopolymer lead to a lower amount of greenhouse gas. Therefore, it is considered as an ecological friendly material when compared to the normal Portland cement [8]. In addition, geopolymer possesses many superb properties such as excellent mechanical properties, high early strength, low shrinkage and creep and good resistance to sulfate and acid attacks [9]. Firing of kaolin clay with controlled condition was resulting to produce an amorphous alumina-silicate material (metakaolin) that is reactive in concrete. The metakaolin geopolymer concrete has compressive strengths higher than Portland cement concrete. The enhancement of characteristic is resulted from the high compressive strength of the binder material [10].

The process of using or merging of construction and demolition material wastes as aggregates in pervious geopolymer concrete make this type of concrete more sustainable. Here, sustainability achieved in three directions. Firstly, the advantages of using pervious concrete (purification and high permeability of water, thermal and acoustic insulation and light in weight) in constructions. Secondly, the process of replacing Portland cement by geopolymer binder reduces all greenhouse gases emission resulting from Portland cement production. Finally, the reduction of construction wastes and the consumption of natural aggregate in environment.

There are very little works carried out for investigating the properties of PGPCS with construction waste materials. In this investigation, the dry density, splitting tensile, flexural and compressive strengths, water permeability and void content were determined. This study will surely be beneficial for the use of pervious geopolymer concrete in future for construction using recycled waste concrete as a coarse aggregate with volumetric partial replacement from coarse aggregate.

2. Materials

2.1. Source Material (Metakaolin)
Iraqi metakaolin (MK) as a local source material brought from Al-Anbar region was used in this investigation. Air blast was used to grind kaolin clay and burn at a temperature of 700 ± 20 °C, for 2 hrs, and cooled to room temperature for 24 hrs. The surface area of MK was 14300 m²/kg, strength activity index was 113 and specific gravity was 2.54. The results of chemical tests for this local metakaolin was conforming to ASTM 618 [11].

2.2. Coarse Aggregate
Normal crushed coarse aggregate of 10mm maximum single size, 2.66 specific gravity and absorption of 0.56% was used in this investigation. The crushed recycled concrete used has the same grading of
normal weight aggregate with specific gravity of 2.46. These crushed concrete was brought from wastes of concrete found in the Laboratory of concrete.

2.3. Alkali Liquid
The hydroxide sodium (NaOH) with purity of 98 % in flake form was used in this work. The solids liquefied in distilled water to make a solution with constant concentration of 12 morality. The ratio of sodium silicate to sodium hydroxide was kept constant at the value of 2.

2.4. Superplasticizer
In this study, Conplast SP2000 was used. It is a free from chloride high range water reducing admixture. These chemical admixture causes enhancement in workability and strength of concrete. Conplast SP2000 congruent with Type G, ASTM C494.

3. Details of Mixing, Casting and Mix Proportion of PGCs
The crush coarse aggregate in saturation surface dry (SSD) condition was prepared for all mixes. The Alkaline / metakaolin ratio was 0.6, metakaolin / coarse aggregate MK: CA ratios were 1:5 and 1:6, the dosage of SP was 2.0 by metakaolin weight, with 10% of extra water by weights of MK to enhancing workability. Crushed waste concrete as a recycled aggregate was used as a partial volumetric replacement of 10, 20 and 30% by volume of coarse aggregates. All mix proportions details of pervious geopolymer concrete PGC are shown in Table 1.

The coarse aggregate with SSD condition mixed with local metakaolin powder in a 0.1m3 capacity pan mixer for few minutes. After that, the alkali liquid with extra water and the dosage of SP was added to the ingredients. All these materials were mixed until the PGC mixture became homogeneous. After process of mixing, the fresh mixture of PGC was placed in three molds with width and height equal to 100 mm and 400 mm long for test of flexural strength, three cubic molds with 100mm for test of compressive strength, and three cylindrical mold with diameter equal to100 mm and height equal to 200 mm. Then, all these molds were compacted by using vibrating table. Thin plastic sheet was used to cover all these specimens to minimize and prevent moisture loss and were stayed at room temperature for 24 hrs. Then, all the samples cured for 5 hrs. at temperature of 50°C and they were stored under the direct sunlight for 28 days. Figure 1 represents the fresh and casting mold of PGPC.

![Figure1](https://example.com/image1.png)

**Figure1.** a. Fresh PGPC mix  b. Molds of PGC after casting
| Mixes | Mk: CA ratio | AL / MK ratio | R.C/CA (%) | water by weight of MK (%) | NaOH (m) |
|-------|--------------|---------------|------------|--------------------------|---------|
| Mix 1 | 1: 5         | 0.6           | 0          | 10                       | 12      |
| Mix 2 | 1: 5         | 0.6           | 10         | 10                       | 12      |
| Mix 3 | 1: 5         | 0.6           | 20         | 10                       | 12      |
| Mix 4 | 1: 5         | 0.6           | 30         | 10                       | 12      |
| Mix 5 | 1: 6         | 0.6           | 0          | 10                       | 12      |
| Mix 6 | 1: 6         | 0.6           | 10         | 10                       | 12      |
| Mix 7 | 1: 6         | 0.6           | 20         | 10                       | 12      |
| Mix 8 | 1: 6         | 0.6           | 30         | 10                       | 12      |

4. Details of Testing

4.1. Oven Dry Density and Total Voids Content
The total void content and dry density of pervious geopolymer concrete PGCs was determined as per ASTM C1754/C1754M − 12 [12]. The results of average three 100 × 200 mm cylindrical specimens was calculated at age 28 days for all mixes. The dry density of the PGC specimens calculated by using the equation below:

\[
\text{Density} = \frac{K \times A}{D^2 \times L}
\]  

where:
A = the mass of specimen (gm) after oven-drying.
D = samples diameter (mm) as average of many measurement.
L = samples length (mm) as average of many measurement and
K = 1 273 240.

The equation below was used in calculating samples void content:

\[
\text{Voids Content} = \left[ 1 - \left( \frac{K \times (A - B)}{\rho_w \times D^2 \times L} \right) \right] \times 100\%
\]  

where:
B = samples mass in (gm) under water.
\(\rho_w\) = the density of water kg/m³.
A, L, D and K having the same meaning as in equation of density above.

4.2. Water Permeability Test
The water permeability of pervious concrete was measured by a simple falling head permeameter as observed in figure 2 [13] in this test; latex membrane was used to enclosed the specimen to prevent flowing of water along the specimen sides. This test was achieved by addition of water in to the cylinder until the draining pipe and specimen cell filled. The preconditioned of the specimen is achieved by permit water to drainage from pipe till the levels in the cylinder become the same with top of drainage pipe, then the valve was closed, and the cylinder was filled with water. Then opened the valve, and time (t) in second required to fall the water from (h1) initial head to (h2) second head is measured. These device was calibrated for an h1 of 290 mm and h2 of 70 mm. The coefficient of water permeability (k) in (mm/s) expressed as:

\[
k = \frac{A}{t}
\]  

where A is constant (190mm).
4.3. Compressive Strength Test
The measuring of pervious geopolymer concrete compressive strength was carried out according to British Standard, BS 1881 part 116:1983 [14] by a 2000 kN capacity compression machine, usage cubic specimens with 100 mm. The average of results for three samples at 28 days age was calculated for all mixes.

4.4. Splitting Tensile Strength Test
The measuring of pervious concrete splitting tensile strength achieved accord to ASTM C496-04 [15] using 100*200 mm cylinder specimens. The average results of three cylinders calculated at 28 days for all mixes.

4.5. Flexural test
Based on ASTM C78-002 [16], the flexural test was carried out, this method of test covers the determining of pervious concrete flexural strength by the use of (100*100*400) mm prism samples, with third-point loading. Result of average three prisms was calculated after age 28 days for all mixes.

5. Results and Discussion
The results of tests for density, total void content, permeability of water, splitting tensile and compressive strengths of pervious geopolymer concrete with and without waste aggregates are shown in Table 2.

| Mixes | Density (kg/m$^3$) | Void content (%) | Permeability k (mm/s) | Splitting tensile strength (MPa) | Flexural strength (MPa) | Compressive strength (MPa) |
|-------|-------------------|------------------|-----------------------|---------------------|---------------------|---------------------|
| Mix1  | 1921              | 24               | 9.14                  | 1.81                | 2.50                | 12.23               |
| Mix2  | 1916              | 24               | 9.60                  | 1.76                | 2.40                | 12.10               |
| Mix3  | 1876              | 24.3             | 10.00                 | 1.71                | 2.35                | 11.16               |
| Mix4  | 1830              | 25               | 11.29                 | 1.64                | 2.30                | 10.76               |
| Mix5  | 1846              | 26               | 16.00                 | 1.45                | 2.25                | 11.03               |
| Mix6  | 1831              | 26.5             | 17.00                 | 1.42                | 2.20                | 10.46               |
| Mix7  | 1791              | 27               | 19.00                 | 1.4                 | 2.05                | 10.20               |
| Mix8  | 1768              | 27.3             | 21.33                 | 1.3                 | 1.95                | 9.86                |

5.1 Dry Density
The densities of Metakaolin Pervious Geopolymer concretes (MPGPCs) with and without recycled concrete aggregates ranged from 1921 to 1768 kg/m$^3$ which were smaller than that of normal concrete due to the high voids in porous concrete. Also, the results in Table 2 show a slight reduction in density that achieved when the natural coarse aggregate replaced by recycled concrete aggregate, this is because these waste material has lower specific gravity compared with natural coarse aggregate, all these effects are shown in figure 3. On the other hand, the results illustrated the dry density of MPGPC decreases accordingly with the increase in content of coarse aggregate for all mixes. This is because MPGPCs become highly porous with high coarse aggregate content.

5.2. Compressive Strength
Table 2 and figure 4 show the effects of crushed concrete as a recycled aggregate and MK:CA ratios on the compressive strength of PGCs at age of 28 days. In this investigation, all the compressive strength was in the range from 12.23 to 9.86 MPa. In addition, as shown in the result the compressive strength depends directly on the MK to CA ratio. For instance, the increase in percentage in compressive strength results when MK paste content increased from 16.6% to 20% was 10.87%. The reason is that the high paste content ratio led to increase the thickness of the paste that surrounds coarse aggregate and led to enhancement in compressive strength of PGCs. In contrast, the low content of MK paste led to a thin layer of paste surrounds the coarse aggregate and increase air voids in the concrete body, this causes reduction in the mechanical properties of PGCs. As shown in figure 4, the replacement of natural coarse aggregates by 10, 20 and 30% of recycled crushed concrete as volumetric ratio led to a decrease in the compressive strength by 2%, 8% and 12% and 5%, 7.5% and 10% for (1:5 and 1:6) MK:CA ratios, respectively. This is expected as the incorporation of recycled concrete aggregate normally reduces the mechanical strengths of concrete [17].

5.3. Splitting Tensile Strength
Table 2 and figure 5 illustrate the splitting tensile strength for all mixes. These results show a direct relationship between the compressive and splitting tensile strengths of PGC mixes. The results show that the splitting tensile strength increases as MK past content increased, and it was ranging from 1.81 to 1.3 MPa for all mixes. The MPGPC splitting tensile strength slightly reduces as recycled waste concrete aggregate replacement level increased. The replacement of natural coarse aggregate by 10, 20 and 30% recycled waste concrete aggregate led to reduce of splitting tensile strength by 3, 5.5 and 9% and 2, 3.5 and 10% for (1:5 and 1:6) MK :CA ratios, respectively. Also the results show that the ratios of splitting tensile to compressive strengths are in the range from 13 to 15% with average ratio of 14%, which was little higher than of 8 to 14% for normal concrete with waste materials as aggregates [18]. This is resulted from the denser interfacial transition zone (ITZ) between aggregates and geopolymer paste compare with Portland cement because of using soluble silicate [19].
5.4. Flexural Strength
The results of flexural strength for metakaolin pervious geopolymer concrete with and without recycled concrete aggregate are shown in Table 2 above. The results illustrated that the flexural strengths of all MPGC mixes ranging from (2.5 to 1.95) MPa. Also, its found that the flexural strength of MPGC slightly decreased when the recycled concrete aggregate incorporate as a partial replacement up to 30% by natural aggregate. Whereby, the flexural strength reduced from (2.5 to 2.4, 2.35 and 2.3 MPa) and (2.25 to 2.20, 2.05 and 1.95 MPa) as a (10, 20 and 30 %) partial replacement level of waste concrete instead of natural coarse aggregate for mixes (1:5 and 1:6) MK:CA ratios, respectively. All these reduction are shown in figure 5 bellow. Also, the results of this test show the flexural strength effected by MK:CA ratio.

![Figure 5](image1.png)

**Figure 5.** Effects of different content recycled concrete aggregate and MK: CA ratios on splitting tensile strengths of MPGPCs

![Figure 6](image2.png)

**Figure 6.** Effects of MK: CA ratios and different content of recycled concrete aggregate on flexural strengths of MPGPCs

5.5. Void Content and Water Permeability
The results of coefficient permeability of water and total void content for MPGPC illustrated in Table 2 and Figure 7,8. The total void content of MPGPCs is in the range from 24% to 27.3% which are within the typical values of ACI 522 (15–35%). This led to permeability coefficient in the range from 9.14 to 21.33 mm/s. Normally, the total void content ordinary portland cement porous concrete effected by the aggregate gradation and compaction methods that adopted [26]. However, in this investigation, the method of compaction and the aggregate gradation for all mixes kept constant.

The results illustrate that the slightly increases in total void content in this investigation with increasing the replacement level of recycled concrete aggregate from the total coarse aggregate. For instance, the total void content of MPGPCs with 0, 10, 20 and 30% replacement level are 24, 24, 24.3 and 25.5% and 26, 26.5, 27 and 27.3% for (1:5 and 1:6) MK:CA ratios respectively. From the results, it can illustrated that there is a direct relationship between void content and water permeability of MPGPCs. Similar to the results of total void content, the permeability of water tended to increase when the coarse aggregate content and recycled concrete aggregate replacement level are increased.

The water permeability of MPGPCs increased by 5, 9 and 23 % and 6, 18 and 33% when the recycled concrete replacement level are 10, 20 and 30% for (1:5 and 1:6) MK:CA ratios respectively relative to specimens without recycled concrete aggregate.
Figure 7. Effects of recycled concrete aggregate and ratios of MK:CA on water permeability of MPGPCs.

Figure 8. Effects of recycled concrete aggregate and ratios of MK:CA on the total void content of MPGPCs.

6. Conclusions

From the results and discussion, may be found the following conclusions:

1. The recycled concrete aggregate as a waste materials can be used as a partial replacement of natural coarse aggregates for production of PGCs using metakaolin as a binding material.
2. MPGPCs with partial replacement of natural coarse aggregate by waste concrete gave lower flexural, splitting tensile and compressive strengths than those containing natural coarse aggregate.
3. The split tensile strength to the compressive strengths ratio were ranged from 13 to 15 with an average ratio of 14 which was slightly higher than of 8 to 14% for conventional and recycled aggregate concrete.
4. The density of MPGPCs slightly reduces accordingly when the total coarse aggregate and partial replacement of recycled waste concrete aggregate in mixture increased.
5. There are direct relationship between water permeability and void content and they increase as the amount of coarse aggregate and recycled waste concrete aggregate content increased.
6. Finally, the PGCs can produced by using local metakaolin as a binding material and sodium silicate with sodium hydroxide as alkaline solution.

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