Effect of aggregate-binder proportion and curing technique on the strength and water absorption of fly ash-based one-part geopolymer mortars.

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Abstract. This paper investigated the effects of binder-aggregates proportion on the performance of one-part geopolymer mortars. High calcium fly ash together with sodium metasilicate have been utilized as the binder, the powdered sodium metasilicate activator was kept at 12% by weight of the fly ash. Three types of mortars were produced with a different binder to fine aggregates proportions (B: A) of 1: 0.5, 1:1, 1:2. The strength properties of the one-part geopolymer mortars (OPGM) which comprises compressive, flexural, splitting tensile strength and water absorption have been investigated. At 28 days of outdoor curing, the OPGM exhibited compressive strength of 50 MPa and 43 MPa at ambient curing. The flexural strength of the OPGM represents 16 – 17 % of its compressive strength. Regardless of the curing techniques, the strength properties of the OPGM is almost the same. The optimum OPGM was found to be at 1: 0.5 binder-aggregates proportions at outdoor curing.

1. Introduction
Over the past three decades geopolymer has been developed and its utilizations in civil infrastructures begin to gain reputation by replacing cement materials with the greener material [1, 2]. Geopolymer is regarded as an encouraging sustainable and environmentally favorable material substitute to Ordinary Portland cement (OPC) in building applications. The polymerization system of geopolymer constitute of an intensely accelerated chemical reaction under alkaline medium on Si-Al minerals that yields a 3-dimensional polymeric sequence as well as a ring framework composed of Si-O-Al-O bonds [1, 3, 4].

Geopolymer has tremendous ability to reduce CO₂ emissions and the use of natural resources linked to conventional concrete OPC production. In geopolymers, the reaction mechanism is distinct from a well-known OPC hydration reaction. The source materials used to produce geopolymers are triggered in an alkaline condition and the major components of the geopolymers dissolve first in the alkaline environment and then undergo speciation, gelation, reorganization and polymerization till they form a binder with cementing characteristics [5]. Despite this potentiality exhibited by geopolymer, it is applications has been restricted to precast construction due to the need of curing at elevated temperature and low strength development when cured at ambient temperature [6-8]. Moreover, dealing with large volumes of highly corrosive and viscous alkaline solutions may be awkward and time consuming for bulk production of geopolymer concrete, and therefore limits its large-scale applications [9]. However, alkaline solution-activated geopolymers do not appear to be a
viable substitute for OPC in the construction industry, despite its enormous environmental benefits and excellent engineering properties owing to its complexity in mixing and handling. In order to address these problems, dry mixture is needed in such a way that only water will be added to the materials similar to that of OPC binders [10, 11]. Therefore, one-part geopolymers can be well suited for both in-situ and precast applications.

Ke et al. [12], have produced one-part geopolymers using thermally treated mud as the source materials. The red mud was calcined with NaOH pellets at 800 °C to promote the development of fresh hydraulic compounds, along with a partially ordered aluminosilicate structure C₃A and C₃S calcium-rich phases. They have reported a compressive strength of 7.5 – 10 MPa at 7 days curing. However, the strength drastically deteriorates after 1 week, at 4 weeks, the compressive strength was reduced to less than 2 MPa. Ye et al. [13], have reported increase in compressive strength of OPG binder using Bayer red mud blended with 20 – 30 % of silica fume (SF). Their reason for the increased in strength with the addition of SF was due enhancement in Si/Al ratio which result to a more stable structure particularly at lower w/b ratio. They conclude that, their developed one-part geopolymer could be suitable for construction purposes, it could potentially replace ordinary clay bricks for interior wall or back bricks and other building materials that are non-load bearing. Sturm et al. [14], have produced one-part geopolymer from rice husk ash (RHA). They obtained a compressive strength of 30 MPa after 1 day of 80 ºC oven curing. Hajimohammadi et al. [6], have also produced one-part geopolymer binder using low calcium fly ash. They have achieved high compressive strength of 65 MPa after 3 weeks of curing at 40 ºC. However, the requirements for oven curing make it unsuitable for cast-in-situ applications.

Panda et al. [15], have reported increase in strength of fly ash/ slag based OPG activated with solid potassium silicate for 3D concrete printing. The developed binder exhibited orthotropic mechanical properties. The developed one-part geopolymer can be used for load bearing applications. Due to the layer-wise manufacturing strategy used in concrete printing, the printed geopolymers showed anisotropic mechanical efficiency relative to the mould cast samples. The findings is in agreement with that of [16]. Because of the advantages of one-part geopolymer binders and GGBS as a calcium-rich aluminosilicate material, numerous attempts have been made to produce one-part alkali-activated slag binders [17, 18]. GGBS based OPG binders however have some weaknesses, which include volumetric instability and high shrinkage compared to OPC based binders. The high shrinkage of GGBS based OPG contributes to the development of cracks on its surface which negatively influence its long-term performance [19]. Based on the extensive literature search, there is limited studies on the use of C-class fly ash in the production of one-part/ in-situ geopolymer mortars. In view with that the paper is aimed to determine the influence of binder-aggregate proportion and curing methods on the strength and water absorption behaviours of the one-part geopolymer mortars.

2. Experimental methods

2.1 Materials

Class C fly ash conforming with requirement of ASTM 618-10 has been utilized as the source material in this investigation. The oxide content of fly ash was obtained by X-Ray fluorescence (XRF) and presented in Table 1. Powdered anhydrous sodium metasilicate (50 % of Na₂O, 46% of SiO₂ and 4 % of H₂O) has been utilized as the activator. The granular activator has been used at 12% by mass of the fly ash according to previous work [3, 20]. In this investigation, natural river sand was utilized as the fine aggregate.

| Oxide  | (%)   |
|--------|-------|
| CaO    | 17.1  |
| Al₂O₃  | 14.9  |
2.2 Preparation of one-part geopolymer mortar mixtures
Three types of one-part geopolymer mortars (OPGM) have been produced with a different binder to aggregates proportions (B: A) of 1: 0.5, 1:1, and 1:2 respectively. The preparation of one-part geopolymer mortars (OPGM) involve blending of granular sodium metasilicate and fly ash with the aid of a mechanical Hobart mixer for about 3 minutes to obtain a uniform dry geopolymer cement. River sand was then added and mix again for about 3 minutes, water was then poured to the dry mixture and continue mixing for additional 3 minutes until a consistent mixture of OPGM was formed. The fresh mixture of the OPGM mixture has been placed into the moulds of 50 mm cube and compacted using vibrating table. The freshly formed OPGM were then removed from the moulds after 24 hours and then subjected to two curing methods, namely, ambient and outdoor curing till the testing periods of 3, 7, 28 and 90 days respectively. The mixture proportion of the OPGM was shown in Table 2.

Table 2. Experimental design parameters

| Mixture Identification | Fly ash Kg/m³ | Dry Na₂SiO₃ activator (%) | Fine aggregate (Kg/m³) | w/b ratio | B: A |
|------------------------|---------------|----------------------------|------------------------|-----------|------|
| OPGM1                  | 1235.43       | 0.12                       | 617.71                 | 0.25      | 1:0.5|
| OPGM2                  | 960.89        | 0.12                       | 960.89                 | 0.25      | 1:1  |
| OPGM3                  | 665.23        | 0.12                       | 1330.46                | 0.25      | 1:2  |

3. Result and discussion
3.1 Compressive strength of OPGM
The influence of binder aggregate proportion on the compressive strength of the OPGM is illustrated in Figure 1. As expected, the compressive strength of the OPGM increases with age of curing. Figure 1(a) illustrates the compressive strength development of laboratory cured OPGM. At early age of curing, the strength of OPGM1 and OPGM2 is almost the same while that of OPGM3 increases by 23.3% and 13.4% at 3 and 7 days respectively. At 28 and 90 days, the compressive strength of OPGM1 significantly increases compared to OPGM2 and OPGM3. The improvement in the strength is attributed to the continued pozzolanic reaction of the binder at later ages and enhancement of bonding between the geopolymer paste and the river sand particles. Figure 1(b) illustrate the compressive strength growth of outdoor cured OPGM. It is interesting to note that there is no
significance difference between the ambient and outdoor cured OPGMs particularly at early age. All the developed OPGMs specimens achieved more than 20 MPa at 7 days and almost 50 MPa was achieved at 28 days of outdoor curing. At 28 days of outdoor curing, the compressive strength of OPGM1 (1: 0.5) was significantly higher than that of OPGM2 and OPGM3 by 24.1 % and 26.8 % respectively. Moreover, it should be noted that the compressive strength of the developed OPGM demonstrated continuous strength development over a prolonged curing period. This finding is consistent with the reported literatures [3, 21, 22]. It is interested to note that at 90 days of curing, there is insignificant difference between the two curing regimes considered.

![Figure 1. Compressive strength of one-part geopolymer mortar (a) ambient cured (b) outdoor cured.](image)

3.2 Splitting tensile strength of OPGM

Figure 2 represent the effect of binder aggregate proportion on the splitting tensile strength of the OPGM. As expected, the tensile strength of the developed OPGM follows similar pattern with the compressive strength that is it increased with age of curing. Figure 2(b) illustrated the splitting tensile strength of ambient cured OPGM. As shown in Figure 2(b), the split tensile strength of almost 3 MPa and 3.25 MPa was obtained at 28 and 90 days for OPGM2 sample. For OPGM1 and OPGM3, the splitting tensile strength of 2.45 MPa and 2.72 MPa was realized at 28 days of ambient curing. Similarly, at 90 days, the tensile strength of 3.22 and 2.86 MPa was achieved. The tensile strength of the OPGM2 samples outperformed their OPGM1 and OPGM3 counterpart. Moreover, Figure 2(b) shows the strength growth of the outdoor cured OPGM. It is worth to mention that there are no significant discrepancies between the ambient (indoor) and outdoor curing and the strength growth follows the same trend.
3.3 Flexural strength

The flexural strength of the OPGM samples could also be utilized as its tensile strength. Nevertheless, the flexural strength usually indicates a higher strength result than the split tensile strength. As presented in Figure 3, the flexural strength of the OPGM follows similar trend with that of the compressive strength. Figure 3(a) and Figure 3(b) shows the flexural strength growth of ambient and outdoor cured OPGM. The highest flexural strength of 5.83 MPa and 6.11 MPa was achieved at 28 days for ambient and outdoor curing methods respectively. At 90 days, the strength continues to increase gradually. The flexural strength of the developed OPGM represents 16 – 17 % of its compressive strength values. These values are high compare to the OPC based mortars. It is noted that the flexural strength decreased with the increased in the fine aggregate proportion in the OPGM. The strength enhancement at lower aggregate content could be attributed to the sustained pozzolanic reaction of fly ash at a later age by generating more calcium alumina silicate hydrate (C-A-S-H), thus enhancing its strength properties [23]. Regardless of the curing methods, the flexural strength of the OPGM is almost the same, even though the outdoor cured OPGM exhibited slightly higher flexural strength than the ambient cured one-part geopolymer mortar.

Figure 2. Splitting tensile strength of one-part geopolymer mortar (a) ambient cured (b) outdoor cured
3.4 Water absorption of OPGM

The water absorption behaviour of OPGM was presented in Figure 3. The water absorption values of OPGM obtained in this investigation were obtained in the range of 6.19 – 3.94 % at 28 and 90 days of ambient curing. It has been revealed from Figure 3 that the water absorption decreased with increased in the aggregate content and vice versa. This explained that as the aggregate content in the mixes increases the water absorption decreased. Regardless of the curing condition, the water absorption of the OPGM is almost the same. The high-water absorption could be attributed to the high binder content within the OPGM mixtures [23]. At higher paste content, there exist a multiple number of micro-cracks on the surface of the concrete which is associated to the drying shrinkage mechanism of the OPGC. The micro-cracks tend to absorb extra water resulting in the increase of water absorption of the OPGC at higher paste volume.
4. Conclusion
The study reported experimental investigation on the influence of binder-aggregate proportion and curing methods on the strengths and water absorption behaviours of the one-part geopolymer mortars. Based on the experimental work performed in this investigation, the following findings can be outlined:

1. The compressive strength of the one-part geopolymer mortars decreases with the increase in the aggregate proportion similar to OPC-based mortars. At early age of curing, there is no significance difference in strength between the ambient and outdoor cured OPGM.
2. The flexural strength of the developed OPGM are very promising in comparison with the OPC based mortars. The obtained flexural strength of the OPGM represents 16 – 17 percent of their compressive strength values. The outdoor cured samples exhibited higher strength than the ambient cured samples.
3. The water absorption of the developed OPGM1 and OPGM2 is almost the same while that of OPGM3 decreases significantly by 34.3% and 37.1% respectively.
4. The optimum OPGM was found to be at 1: 0.5 binder-aggregates proportions at outdoor curing.

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