Engineering properties and carbon footprint of ground granulated blast-furnace slag-palm oil fuel ash-based structural geopolymer concrete


Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

HIGHLIGHTS

- Normal weight and lightweight structural green concrete could be produced by using POFA and GGBS with low binder content.
- Manufactured sand could be used as an ideal replacement for conventional mining sand.
- In ambient cured conditions, 96% of the compressive strength of OPSGC could be achieved in 7 days.
- The usage of OPSGC could reduce the density by 20% compared to NWGC.

ABSTRACT

Engineering properties of geopolymer concrete developed using palm oil fuel ash and slag as binders, manufactured sand and quarry dust as replacement materials for fine aggregate, and oil palm shell (OPS) as coarse aggregate were investigated along with carbon footprint. The use of binder content of 425 kg/m³ with OPS based lightweight concrete produced the highest compressive strength of 33 MPa. Ultrasonic pulse velocity of normal weight geopolymer concrete (NWGC) shows it as "good quality". The development of structural grade OPS geopolymer concrete comparable to NWGC shows its potential application for structural purposes. OPS geopolymer concrete has lower carbon footprint of 50–60% compared to conventional concrete.

1. Introduction

The term structural concrete indicates any type of concrete that is used in structural applications, which may be plain, reinforced, pre-stressed, or partially pre-stressed concrete [1]. For structural concrete, generally, the pragmatic requirement is that any lightweight aggregate that is suitable with a crushing strength sufficient to have reasonable resistance to fragmentation while enabling concrete strengths in excess of 20 N/mm² [2]. The density of structural lightweight aggregate concrete can range from approximately 1200–2000 kg/m³ compared to 2300–2500 kg/m³ for normal weight concrete (NWC) [2]. The oven-dry density range, as specified in EN 206-1 [3] for lightweight concrete and NWC are 800–2000 kg/m³ and 2000–2600 kg/m³, respectively. Concrete with a density that exceeds 2600 kg/m³ is known as heavyweight concrete. The minimum strengths for structural lightweight concrete, as identified by several codes, are shown in Table 1 [2].

As known, concrete is the most widely used construction material in the world, with the current consumption of 1 m³ per person per year [4]. The concrete industry is said to be one of the contributors to global warming due to the use of ordinary Portland cement (OPC), which is the main component in the production of concrete and other cement based construction materials. The carbon dioxide (CO₂) emissions from the production of OPC constitute approximately 5% to 7% of global anthropogenic emissions [5,6]. It has been reported [7] that 1 tonne of cement produces about 1 tonne of CO₂.

Every year millions of tons of industrial waste are generated of which most are either unutilised or underutilised. Furthermore, these wastes cause environmental issues due to storage problems and pollution of the surrounding fields. In recent years, there has been increasing awareness concerning the quantity and diversity of hazardous solid waste generation and its impact on human health. The quarrying of natural sand has a sizeable and
irreversible environmental impact [8], as it causes a reduction in the groundwater, which affects the moisture content of the soil. Due to the drop in river water level, drinking water is badly affected, especially during the dry season, and saltwater intrusion becomes a potential problem. In addition, sand mining causes the erosion of nearby land leading to instability in the ecosystem [9].

Currently, the need for environmentally friendly construction materials for sustainable development is an important environmental issue in the construction industry. An alternative cementitious binder, termed “geopolymer”, comprising alkali-activated palm oil fuel ash (POFA) and ground granulated blastfurnace slag (GGBS) binders could be considered as a substitute for OPC. Geopolymer was first described by Davidovits [10] as an inorganic material that is rich in silicon (Si) and aluminium (Al), and reacts with alkaline activators to become cementitious. Yusuf et al. [11] investigated the microstructure analysis of POFA–GGBS based geopolymer paste and found that the optimum content of GGBS was about 20% in POFA, which could produce a compressive strength of 44.57 MPa at 28 days. Geopolymer concrete is well-suited to manufacture precast concrete products that can be used in both infrastructure developments [12] and main building structures [13]. The University of Queensland’s Global Change Institute (GCI), Australia, is the world’s first building to successfully use slag/fly ash-based geopolymer concrete for structural purposes Fig. 1 [13].

The recent research works on the utilisation of palm oil fuel ash (POFA) as the source material opens a new avenue in the development of geopolymer concrete [14–16] as well as normal concrete [17–19]. Aldahdooh et al. [18] reported that POFA could be used to produce high strength fibre reinforced concrete of about 158 MPa at 90 days. Mijarsh et al. [14] developed geopolymer mortar using 65 wt.% of POFA and found a compressive strength of 47 MPa after 7 days of curing. It is reported [19] that the smaller size of POFA particles is more potential than that of the larger size of POFA particles due to the filler effect. Kupaei et al. [20] developed fly ash based lightweight geopolymer concrete using OPS as lightweight coarse aggregate. OPS based structural lightweight cement-concrete has also been developed [21] in the recent years. Kanadasan and Razak [22] reported that another potential waste from palm oil mill called palm oil clinker, which can be directly incorporated into concrete as replacement for natural aggregates.

<table>
<thead>
<tr>
<th>Code</th>
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<th>Prestressed</th>
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<tr>
<td>BS 8110</td>
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<td>30° and 40°</td>
</tr>
<tr>
<td>BS 5400</td>
<td>25</td>
<td>Not permitted</td>
</tr>
<tr>
<td>ACI 318</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>ENV 1992-1-4</td>
<td>12</td>
<td>25° and 30°</td>
</tr>
<tr>
<td>AS 3680</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>NS 3473</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>JASS 5</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

* Post-tensioned.
* Pre-tensioned.

Table 1 Minimum strengths for structural lightweight concrete [2].

Fig. 1. (a) Queensland’s University GCI building with 3 suspended floors made from structural geopolymer concrete, (b) precast slag/fly ash – based geopolymer concrete floor parts, Australia [13].
To the best knowledge of the authors, no research work has been carried out using GGBS–POFA as the source materials and OPS as the lightweight coarse aggregate to develop structural concrete. The aim of this research, therefore, was to develop a structural lightweight geopolymer concrete using POFA and GGBS as the binder with OPS as coarse aggregate. The effect of different fine aggregates, such as mining sand (NS), manufactured sand (MS) and quarry dust (QD) was also investigated and reported by keeping other parameters, such as water and activator contents, constant.

2. Experimental programme

2.1. Materials

2.1.1. Binder

POFA (Fig. 2a) with a specific surface area and specific gravity of 172 m²/kg and 2.14, respectively, was used in this investigation. The grinding of POFA was carried out for 30,000 cycles over 16 h to obtain the desired level of fineness (>66%). ASTM: C618-12a stipulates that the mass of fly ash and natural pozzolan passing through a 45-μm by wet sieving should be at least 66%; POFA exceeded this target as 87% passed through the sieve.

Ground granulated blast-furnace slag (GGBS) (Fig. 2b) obtained from YTL Cement Marketing Sdn Bhd, Malaysia, was used along with POFA as the source material in the development of geopolymer concrete. The slag activity index of GGBS was 62% and 108% for 7 and 28 days, respectively. The particle size distribution, chemical composition and physical properties of POFA and GGBS are shown in Fig. 3, Tables 2 and 3, respectively. The binder contents for normal weight geopolymer concrete (NWGC) and lightweight geopolymer concrete (LWGC) were 220 kg/m³ and 425 kg/m³, respectively. Fig. 4 shows the particle size distribution of mining sand, manufactured sand and quarry dust.

2.1.2. Fine aggregate

Three different fine aggregates (Fig. 5) were used to produce concrete mixtures. Conventional local mining sand (NS) with a maximum nominal size, specific gravity and fineness modulus of 4.75 mm, 2.61 and 2.69, respectively, was used for comparison purpose.

Two other local waste materials, namely, manufactured sand (MS) and quarry dust (QD) were used to study the feasibility of these materials in the development of sustainable lightweight geopolymer concrete; their physical and mechanical properties were investigated and compared with the conventional mixes using mining sand. The maximum nominal size of 4.75 mm was kept constant for all fine aggregates. The specific gravity and fineness modulus of MS were found to be 2.60 and 3.19, respectively; however, QD with irregular and flaky particles had a higher specific gravity and fineness modulus of 2.64 and 3.84, respectively. The particle size distribution and physical properties of all three fine aggregates are shown in Fig. 4 and Table 4, respectively.

2.1.3. Coarse aggregate

Conventional crushed granite aggregate as shown in Fig. 6(a) was used for comparison purpose. The other coarse aggregate, OPS used in this study was collected from the local palm oil factory with maximum size of 14 mm (Table 5). Generally, the raw OPS collected from the factory has an oily surface that could affect the bond. Hence, the OPS was washed and then air-dried in the laboratory to a saturated surface dry (SSD) condition; for the crushed OPS, the cleaned OPS was crushed to the required size.

The uncrushed OPS (Fig. 6b) have more concave and convex surfaces of which the outer convex surface is smoother compared to the concave surface. The crushed OPS as shown in Fig. 6(c) has more spiky edges than the uncrushed OPS (Fig. 6b) [24]. The physical properties of the uncrushed and crushed OPS, along with the conventional crushed granite aggregate are given in Table 5. Both the crushed and the uncrushed OPS have a lower aggregate impact value (AV) and bulk density than the crushed granite aggregate. The OPS content in all the OPSC GC mixes was kept constant at 255 kg/m³; while for the NWGC, crushed granite of 994 kg/m³ was used. The 24 h water absorption of OPS was found to be about 25%.

2.1.4. Alkaline activators

A combination of sodium silicate (Na₂O = 12%, SiO₂ = 30%, and water = 57% by mass) and sodium hydroxide solution (NaOH) was used as the alkaline activator. The solution of 12 molarity (M) NaOH prepared with 99% purity, such that 361 g of pellets were dissolved in 1 kg of solution [25]. The ratio of Na₂SiO₃/NaOH was kept constant at 2.5 for all the mixtures and the mixture containing additional water. The specific gravity of the combined alkaline activators was found to be about 1.57; while the specific gravities for Na₂SiO₃ and NaOH were 1.65 and 1.38, respectively. The specific gravity of the NaOH solution varied depending on the molarity of the solution. An increase in concentration of NaOH solution increased the specific gravity and vice-versa. The formula for the combined specific gravity is as follows:

\[
\frac{G_{\text{NaOH}}}{1 + 2.5} + \frac{G_{\text{Na₂SiO₃}}}{1 + 2.5} = 1.57
\]

where \(G_{\text{NaOH}}\) and \(G_{\text{Na₂SiO₃}}\) are the specific gravities of NaOH and Na₂SiO₃, respectively.

2.2. Mix proportions

A total of nine mixes were prepared using variables of three different coarse aggregates (crushed granite, uncrushed and crushed OPS), three fine aggregates (NS, MS and QD) and two different curing conditions, namely, oven and ambient curing. The effect of the three fine aggregates on the fresh and hardened concrete properties was observed. In addition, a comparison of the mechanical properties

### Table 2

<table>
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<tr>
<th>Chemical compounds</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>MgO</th>
<th>Na₂O</th>
<th>SO₃</th>
<th>P₂O₅</th>
<th>K₂O</th>
<th>TiO₂</th>
<th>MnO</th>
<th>Fe₂O₃</th>
<th>SrO</th>
<th>Cl</th>
<th>CuO</th>
<th>LOI</th>
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<tbody>
<tr>
<td>GGBS</td>
<td>45.83</td>
<td>32.52</td>
<td>13.71</td>
<td>3.27</td>
<td>0.25</td>
<td>1.80</td>
<td>0.04</td>
<td>0.48</td>
<td>0.73</td>
<td>0.35</td>
<td>0.76</td>
<td>0.08</td>
<td>0.02</td>
<td>-</td>
<td>0.60</td>
</tr>
<tr>
<td>POFA</td>
<td>4.34</td>
<td>63.41</td>
<td>5.55</td>
<td>3.74</td>
<td>0.16</td>
<td>0.91</td>
<td>3.78</td>
<td>6.33</td>
<td>0.33</td>
<td>0.17</td>
<td>4.19</td>
<td>0.02</td>
<td>0.45</td>
<td>6.54</td>
<td>6.20</td>
</tr>
</tbody>
</table>

Fig. 2. Binders (a) palm oil fuel ash (POFA), (b) ground granulated blast-furnace slag (GGBS).
from the experimental results with the code of practice and published results was also performed. A normal weight geopolymer concrete (NWGC) using crushed granite aggregate was prepared as a control mix to compare the mechanical properties of the OPSGC.

The mix proportions and experimental parameters of all the concrete mixes are shown in Tables 6 and 7, respectively. A graphical representation of fresh concrete properties of POFA–GGBS based geopolymer concrete developed using OPS as coarse aggregate. The OPS used had two forms – crushed and uncrushed – the sizes of which varied in the range of 5–10 mm and 5–14 mm, respectively.

### 3. Results and discussion

#### 3.1. Workability

As mentioned in Table 7, the solution to binder ratio was kept constant at 0.4 for all mixes; the water/binder ratios were 0.64 and 0.30 for NWGC and OPSGC, respectively. The workability of the concrete measured using the slump test shows the values of 5–12 mm and 50–63 mm, respectively, for NWGC and OPSGC (Table 8). The mixtures using fine aggregate as quarry dust (QD) produced slightly lower workability compared to the mixes with conventional mining sand and MS, which might be attributed to the angular edges of the aggregate, coarser particle size, high silt and dust content in the QD [27]. The setting of NWGC was found to be faster compared to OPSGC, which could be attributed to the dry condition of NWA; it should be noted that the OPS was pre-soaked for about 24 h in water before use; the workability of the OPSGC mixes was found to be medium [28]. Although most of the mixes did not produce high workability, the cohesive concrete mixes achieved sufficient compaction upon vibration using vibration table. The smooth surface of the OPS aggregate also enhanced the workability compared to the conventional coarse aggregate, as reported in previous studies [29]. It can be concluded that the slump values do not reflect the actual workability for the cohesive geopolymer concrete, and that suitable workability tests as designed for self-compacting concrete (SCC) have to be formulated.

#### 3.2. Density

Table 8 shows the test results for the 24 h oven dry density (ODD) for all mixes from which it can be seen that the OPSGC produced a density in the range of 1900–1935 kg/m³. EN 206-1 [3] defines lightweight concrete (LWC) as concrete having an oven-dry density (ODD) of not less than 800 kg/m³ and not more than 2000 kg/m³ that is produced using lightweight aggregate for all or part of the total aggregate. As seen in Table 8, all the OPSGC in this investigation produced ODD of less than 2000 kg/m³ and thus could be categorised as LWC.

#### 3.3. Development of compressive strength in geopolymer concrete

##### 3.3.1. Development of compressive strength between 3 and 28 days

Table 8 shows the compressive strength developed between 3 and 28 days expressed as a percentage. The 28-day compressive strength was used as the reference and the ratios achieved in...
the strength for 3 and 7 days were calculated. The 3-day compressive strengths of 35, 30 and 28 MPa were obtained for A1, B1 and C1, respectively, and these values were 92%, 94% and 93% of the 28-day strength, as shown in Table 8. Most of the specimens achieved 90% of the 28-day strength at 3 days for OD curing, while the AD curing specimens achieved 57–82%; however, the final strength of the AD curing specimens were found to be slightly higher than the corresponding OD cured specimens at 28 days.

The 7-day compressive strength of geopolymer concrete (GC) reached 92–100% and 81–97% of the 28-day compressive strength, respectively, for OD and AD curing.

Table 9 shows the chemical composition of binder based on 60% of GGBS and 40% of POFA and the additional composition of Na2O, SiO2 and H2O from the activator solution and the additional water are as follows (based on solution to binder mass ratio (s/b) and water to binder mass ratio (w/b) are 0.40 and 0.3, respectively, and NaOH solution of 12 M):

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Mining sand</th>
<th>Manufactured sand</th>
<th>Quarry dust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum size (mm)</td>
<td>4.75</td>
<td>4.75</td>
<td>4.75</td>
</tr>
<tr>
<td>Specific gravity (SSD)</td>
<td>2.63</td>
<td>2.60</td>
<td>2.65</td>
</tr>
<tr>
<td>24 h water absorption (%)</td>
<td>1.10</td>
<td>1.80</td>
<td>1.87</td>
</tr>
<tr>
<td>Fineness modulus</td>
<td>2.69</td>
<td>3.19</td>
<td>3.84</td>
</tr>
<tr>
<td>Grading zone (BS882:1992)</td>
<td>F</td>
<td>M</td>
<td>C</td>
</tr>
</tbody>
</table>

For the formation of early high-strength polysialate geopolymers, the oxide-mole ratios proposed by Davidovits [10] and the experimental mixes (based on the binder, activator solution and added water contents) is shown in Table 10.

The molar ratios proposed by Davidovits [10] are for the formation of high strength concrete while the experimental molar ratios in this research are based on the 30 grade concrete, and, hence, the ratios of \( \text{H}_2\text{O}/\text{M}_2\text{O} \) and \( \text{M}_2\text{O}/\text{SiO}_2 \) fall short of the proposed values by Davidovits [10]. Hardjito and Rangan [30] reported that, as the \( \text{H}_2\text{O}/\text{Na}_2\text{O} \) molar ratio increases, the compressive strength of geopolymer concrete decreases. The high early strength might be attributed to the addition of GGBS in the presence of alkalisis as it could generate more heat due to the calcium and alumina contents, as was reported in earlier studies [31]. During mixing, the \( \text{Ca}^{++} \) reacts with \( \text{OH}^- \) in the alkaline aqueous system to form \( \text{Ca(OH)}_2 \), which then reacts with \( \text{CO}_2 \) in the atmosphere, forming calcite, \( \text{CaCO}_3 \). At the same time, the dissolution of alumina–silica precursor continues to take place. In essence, these reactions produce the high early strength as reported by Davidovits [10]. Based on the scanning electron microscopy image (SEM) analysis, it is reported that a high volume of GGBS (50% replacement by cement) produces more ettringite (\( \text{CaO·Al}_2\text{O}_3·3\text{SO}_3·32\text{H}_2\text{O} \)) at an early age, which results in the higher early strengths [32].

The development of the compressive strength between 7 and 28 days seems to be lower compared to that between 3 and 7 days, as shown in Figs. 8 and 9. This could be attributed to the geopolymerization that happens at the early age [26,33]. The rate of development of strength between 7 and 28 days for NWGC was found to be higher compared to that of OPSCG (NWGC: 2–9% for OD curing and 15–21% for AD curing; OPSCG: 0–7% for OD curing and 3–7% for AD curing). This could be due to the stronger bond between the NWA and the matrix. In contrast, the convex surface of the OPS leads to a poor bond that reduces the compressive strength [34].

### 3.3.2. Failure modes of cubes

This sub-section explain the failure mode of concrete cubes as specified in standard code BS EN 12390-3 [35] and the experimental specimens.

The satisfactory failure mode(s) of the 100-mm cubes, as specified in [35], and the experimental 100-mm cube specimens, are shown in Fig. 10a and b, respectively. As can be seen in Fig. 10b, all four exposed faces failed similar to that shown in BS EN 12390-3 [35].
3.3.3. Effect of curing on the compressive strength

The 3-, 7-, and 28-day compressive strengths of the ambient and oven-cured concrete specimen mixes are shown in Table 8. As can be seen in Table 8, the compressive strengths of the oven-cured mixes at early ages of 3 and 7 days were found to be higher than the corresponding specimens cured in ambient conditions. However, the 28-day strength of the ambient cured specimens was found to be slightly higher than that of the oven-cured specimens (Table 8 and Fig. 11). The increase of the ambient cured specimens was found to be between 3% and 10%. Davidovits [10] opined that the slag based geopolymer mortar cured under heat and non-heat conditions achieves similar strength at a later age of 28 days compared to the early 3- and 7-day strength. Geopolymerization starts with the depolymerisation (break down, cleavage of Si–O–Si–O– and others in the aluminosilicate structures of the raw materials: slag (melilite) or metakaolin). This step requires energy (heat) or time (at room temperature). However, ultimately, the chemical mechanism remains the same.

The difference in the increase of the compressive strength of the specimens cured in OD and AD conditions shows 2.63–5.0% for NWGC. However, for OPSGC with crushed and uncrushed OPS it was found to be in the range of 0–6.90% and 6.70–10%, respectively (Table 8).

Based on the compressive strength development of both the OD and AD of the OPSGC, it can be concluded that the AD cured specimens produce nearly 95% of the 28-day strength in 7 days and is preferred over the OD specimens. This also reduces the energy required for the elevated temperature in oven curing and thus reduces the cost.

3.3.4. Effect of three types of fine aggregate on the compressive strength

Table 8 shows the compressive strength development for the mixes with three different types of fine aggregate, namely, conventional mining sand (control mix), MS and QD. The 28-day compressive strength of the control mixes A1, B1 and C1, which were prepared using conventional mining sand and initially 24 h cured in the oven were 38, 32, 30 MPa, respectively. In contrast, the compressive strengths of the mixes A2, B2 and C2 prepared using MS were 40, 33 and 29 MPa, respectively, which were comparable to the control mixes. Similar findings are shown in the case of AD curing (Table 8). All the mixes (A3, B3 and C3) with QD produced a slightly lower strength compared to the other mixes with mining sand and MS. Reddy [37] investigated both in mortar and concrete specimens using NS and MS, and found that the specimens prepared using MS had higher strength. The slight difference among the mixes with three different fine aggregate shows that MS could be considered to be an ideal replacement for the conventional sand. However, QD with angular and flaky particles, could lead to a reduction in compressive strength and workability [38].

Raman et al. [27] reported that the compressive strength of self-compacting concrete (SCC) slightly decreased after 20% replace-
ment of QD due to the non-uniform grading of QD and also due to the large amount of fine particles smaller than 150 μm and 300 μm sieve sizes in QD. Thus, the use of MS could be more appropriate as a replacement material for conventional mining sand.

3.3.5. Relationship between 28-day compressive strength of NWGC and OPSGC under AD and OD curing

Fig. 12 shows a linear relationship between the compressive strength of the specimens cured under oven and ambient curing;
the trend line shows a strong correlation between those two curing regimes.

Based on the experimental results the following equations could be obtained to relate the compressive strengths of the specimens cured under two different regimes:

NWGC,

\[ y_{(OD)} = 0.9656x_{(AD)} \quad R^2 = 0.94 \quad (2) \]

OPSGC,

\[ y_{(OD)} = 0.9557x_{(AD)} \quad R^2 = 0.95 \quad (3) \]

Atiş and Bilim [39] proposed the following equations for normal Portland cement (NPC) concrete and GGBS concrete.

NPC concrete:

\[ y_{(dry)} = 0.94x_{(wet)} \quad R^2 = 0.87 \quad (4) \]

GGBS concrete (up to 80% replacement of cement):

\[ y_{(dry)} = 0.85x_{(wet)} \quad R^2 = 0.89 \quad (5) \]

Shafigh et al. [40] reported the following relationship between OPSG concrete containing GGBS up to 50% replacement of cement under two different curing conditions (air-dry and wet curing):
\[ y_{\text{dry}} = 0.80x_{\text{wet}} \quad R^2 = 0.94 \]  

A similar type of equation proposed by Shafigh et al. [40] shows that a good correlation could be established between the compressive strengths of specimens cured under two different environments. The following equation is proposed for predicting the compressive strength for OPS concrete containing fly ash up to 50% replacement of cement:

\[ f_{c_{\text{dry}}}(\text{dry}) = 0.81f_{c_{\text{wet}}} \quad R^2 = 0.93 \]  

Based on the above equations for two different lightweight concretes – OPSGC and OPSC – the relationship between the oven and air cured specimens of OPSGC shows a stronger relationship compared to the air and wet cured specimens. This could be attributed to the geopolymerization of the specimens cured in the oven and ambient conditions. For OPSC, the compressive strength depends on the hydration of cement and subsequent formation of C-S-H gel, while for the OPSGC, the strength development is dependent on the formation of calcium–silicate–hydrate (C-S-H) and aluminosilicate-hydrate (A-S-H), which enhances the compressive-strength [26,41]. In the presence of an alkaline activator and calcium from the GGBS, the additional SiO\(_2\) and Al\(_2\)O\(_3\) could react and form C-S-H or C-A-S-H and N-A-S-H gels and lead to a higher strength geopolymer [42].

### 3.3.6. Effect of uncrushed and crushed OPS on compressive strength

Figs. 13 and 14 show the 28-day compressive strengths of OPSGC prepared using crushed and uncrushed OPS and cured under OD and AD conditions. The results show that OPSGC with crushed OPS achieved a slightly higher compressive strength compared to the corresponding mixes prepared using uncrushed OPS cured in OD and AD conditions, and in the ranges of about 7–14% and 3–7%, respectively.

Previous studies [24,43] reported that OPSC with crushed aggregate produced a higher compressive strength compared to...
OPC with uncrushed aggregate. Crushed OPS is hard and has a strong physical bond with the hydrated cement paste. The crushing of OPS reduces the smooth concave and convex surfaces and increases the rough and spiky broken edges of OPS. This enhances the bond between the OPS and the cement paste. Alengaram et al. [43] reported that the convex smooth surfaces of larger OPS particles produce a weaker interfacial bond strength. Mannan et al. [44] reported that the failure of concrete specimens in compression is initially due to the failure of the adhesion between the OPS and the cement paste.

### 3.4. Comparison of workability and strength development with previous studies

Slump test is the most commonly used test to measure the workability for conventional concrete but as mentioned earlier (Section 3.1) it might not be an appropriate test for sticky and cohesive geopolymer concrete. The slump value depends on the variations of materials and its fineness, quantity and type of liquid, mixing time, etc. Although there are some variations in the materials and mix proportions, some comparison with previous studies can be drawn in the following at ambient curing (Table 11).

As shown in Table 11, the alkaline activator was about 40% of total binder and the ratio of Na$_2$SiO$_3$ solution to NaOH solution was kept constant at 2.5 for all the mixes. The molarity of NaOH solution used in this study was 12 M compared to 14 M in the studies as shown in Table 11 [45–47]. The fine and coarse aggregates for all the mixes used was mining sand and crushed granite, respectively. The principal difference between the present study and the previous studies [45–47] is the binder content. Previous studies used fly ash with varying GGBS [45,46] and OPC [47]. On the contrary, current study used POFA and GGBS as binders and the total alkaline activator and free water in this study were 88 kg/m$^3$ and 141 kg/m$^3$, respectively. However, the previous studies used only alkaline activator of about 160 kg/m$^3$ and no free water was added. As can be seen in Table 11, the alkaline activator used in this study was only 55% of earlier studies [45–47]. It has to be noted that the increase in molarity requires more NaOH pellets/flakes, which increases the cost of the production as well. Though there have been few positives in the present research based on lower binder and activator contents, the slump value is much lower as compared to previously reported geopolymer concrete prepared using normal weight crushed granite aggregates (Table 11). The lower slump value in this investigation could be attributed to higher GGBS content that increases calcium quantity. The addition of POFA also plays an important role in low workability as it has high loss on ignition (LOI) and irregular shape; further its porous structure absorbs water that could also affect the workability [17,48].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Concrete mix quantity (kg/m$^3$)</th>
<th>Previous studies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current study</td>
<td>Previous studies</td>
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<tr>
<td>OPC</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>POFA</td>
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<td>0</td>
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<tr>
<td>Fly ash</td>
<td>0</td>
<td>360</td>
</tr>
<tr>
<td>GGBS</td>
<td>132</td>
<td>80</td>
</tr>
<tr>
<td>Sand</td>
<td>884</td>
<td>651</td>
</tr>
<tr>
<td>Granite</td>
<td>994</td>
<td>1209</td>
</tr>
<tr>
<td>NaOH solution</td>
<td>25 (12 M)</td>
<td>45.7 (14 M)</td>
</tr>
<tr>
<td>Na$_2$SiO$_3$ solution</td>
<td>63</td>
<td>114.3</td>
</tr>
<tr>
<td>Water</td>
<td>141</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 11

Comparison of workability and strength development with previous studies.

- **Slump test**
  - **Compressive strength obtained at the age of 7- and 28-day and comparison of 7 and 28-day strength (%)**
  - **7-Day**
    - **OPC** 220
    - **POFA** 1878
    - **Fly ash** 229
    - **GGBS** 10
  - **28-Day**
    - **OPC** 32
    - **POFA** 39
    - **Fly ash** 82
    - **GGBS** 82
  - **(%) 7-Day of 28-day**
    - **OPC** 15
    - **POFA** 26
    - **Fly ash** 58
    - **GGBS** 63

---

*a* Total aggregate contents (fine and coarse aggregates).

*b* Solution (NaOH solution + Na$_2$SiO$_3$ solution + water).
As can be seen from the results in Table 11, the mixes with lower GGBS contents in D1 (100% fly ash and 0% GGBS) and B1 (90% fly ash and 10% GGBS), the addition of 10% GGBS did not affect the workability but increases the early strength. The development of early compressive strength is higher due to increase in the GGBS content and this is constructive as it could hasten the construction and reuse of formwork.

3.5. Ultrasonic pulse velocity (UPV)

The ultrasonic pulse velocity (UPV) test (Fig. 15) of concrete is based on the pulse velocity method to provide information concerning the uniformity of concrete, cavities, cracks and defects. The pulse velocity in a material depends on its density and its elastic properties, which, in turn, are related to the quality and the compressive strength of the concrete. It is easy to use and the results can be quickly obtained on site. The UPV of a homogeneous solid can be easily related to its physical and mechanical properties.

UPV is an indicator of the compressive strength of concrete and the quality of the aggregates used [49]. A low UPV value indicates the presence of the internal voids or porous aggregate in the concrete.

The UPV values for all the mixes were found to be within the range of 3.19–3.76 km/s, as shown in Table 12. Geopolymer concrete is very cohesive, which makes the compaction of concrete more difficult compared to that of normal concrete; thus, inappropriate compaction is likely to cause voids within the concrete leading to reduced UPV values.

The mixes with normal weight aggregate (NWA) produced 28-day UPV values between 3.51 and 3.76 showing that the quality of the concrete is “good” [50]. Bogas et al. [51] reported that in LWC with more porous aggregate and rich mortar there is a greater relative variation for UPV than for the compressive strength. In this investigation, all the mixes with OPS produced UPV values of 3.19 and 3.48 for 100-mm concrete cubes at 28 days, which is lower than for NWGC and proves that OPSGC contains more porous aggregate compared to NWGC; thus, showing that the quality of the concrete is “medium” [50].

3.6. Splitting tensile strength (STS)

The splitting tensile strengths of NWGC and OPSGC are shown in Tables 13 and 14, and the relationship between the splitting tensile and compressive strengths are shown in Figs. 16 and 17, respectively. The tests were conducted in accordance with BS EN 12390-6 [52]. It can be observed that the splitting tensile strength increases with the increase in compressive strength. The experimental 28-day splitting tensile strength was found to be in the range of 2.61–2.94 MPa for NWGC, 1.88–2.44 MPa for OPSGC with crushed OPS, and 1.92–2.94 MPa for OPSGC with uncrushed OPS. It is found from the experimental results that irrespective of the OPS coarse aggregate (crushed or uncrushed), the mixtures containing conventional mining sand (NS) produced higher tensile strength compared to the splitting tensile strengths of the mixtures prepared with MS and QD.

The mixes A3, B3 and C3 produced lower tensile strengths of about 11%, 23% and 30% compared to A1, B1 and C1, respectively. This might be due to the angular and flaky particles of QD that could influence the bond between the aggregate and matrix in the interfacial transition zone (ITZ), which has a significant role in the tensile strength of concrete.

The empirical formulae proposed in Eq. (8) shows the relationship between the compressive strength ($f_c$) and splitting tensile strength ($f_t$) [54].

$$f_t = k f_c^n$$  \hspace{1cm} (8)

where $f_t$ is the splitting tensile strength (MPa); $f_c$ is the compressive strength (MPa); $k, n$: constants.

The constants $k$ and $n$ are obtained through a regression analysis of the experimental data. In general, the value of $n$ ranges between 0.5 and 0.75.

3.6.1. Splitting tensile strength for NWGC

Based on the basic equation, ACI 363R-92 [55] and CEB-FIP [56] suggest the models as expressed in Eqs. (9) and (10) to predict the cylinder splitting tensile strength ($f_t$) from the compressive strength of the cylinder for normal weight concrete. In addition, Ryu et al. [57] proposed a formula to predict the cylinder splitting tensile strength from the cylinder mean compressive strength for fly ash-based geopolymer concrete, as shown in Eq. (11).

ACI 363R-92: $f_t = 0.590 \sqrt{f_c}$ (for 21 MPa $< f_c < 83$ MPa)  \hspace{1cm} (9)

CEB-FIP: $f_t = 0.301 (f_c)^{0.5}$  \hspace{1cm} (10)

Ryu et al.: $f_t = 0.170 (f_c)^{0.5}$  \hspace{1cm} (11)

The comparison of the experimental results and the formulae proposed by ACI 363R-92 [55], CEB-FIP [56] and other researchers [57] is shown in Table 13 and Fig. 16. It is found that the splitting tensile strength obtained from the experimental results for POFA-GGBS-based geopolymer concrete is lower than that of the values calculated using the proposed formula by ACI 363R-92 [55]; however, closer values were obtained from the equations proposed by CEB-FIP. Ryu et al. [57] proposed an equation to predict the splitting tensile strength for fly ash based geopolymer normal weight aggregate concrete; the experimental results of GGBS-POFA based

<table>
<thead>
<tr>
<th>Mix</th>
<th>Mean compressive strength, $f_c$ (MPa)</th>
<th>Splitting tensile strength, $f_t$ (MPa)</th>
<th>$\left( \frac{f_t}{f_c} \times 100 \right)$%</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>38</td>
<td>2.94</td>
<td>7.74</td>
</tr>
<tr>
<td>A2</td>
<td>40</td>
<td>2.87</td>
<td>7.18</td>
</tr>
<tr>
<td>A3</td>
<td>36</td>
<td>2.61</td>
<td>7.25</td>
</tr>
</tbody>
</table>

*Conversion factor to convert the cube compressive strength to the cylinder compressive strength. The lower value of conversion for 100 mm cube compressive strength to 150 mm diameter cylinder was taken based on previous data from published researchers [53].
geopolymer concrete produced higher splitting tensile strength than that using the equation proposed by Ryu et al. [57]. The difference between the splitting tensile strengths of specimens prepared using MS and NS is negligible compared to the specimens with QD. As mentioned earlier in Section 3.3.4, the QD particles have angular and flaky particles that could result in more air voids being entrapped surrounding the QD, and, hence, the interfacial zone is weaker compared to the specimens with MS and NS.

3.6.2 Splitting tensile strength of lightweight OPSGC

The ratio of the 28-day splitting tensile strength to the compressive strength expressed as percentage of the crushed OPSGC was found to be in the range of 6–8%; while the uncrushed OPSGC produced slightly higher values of 7–9%. The lower range for the crushed OPSGC might be due to the large quantity of OPS used in these mixes. The smaller size of crushed OPS leads to a larger number of crushed OPS particles compared to that of uncrushed OPS for a given weight of OPS. Generally, the splitting tensile strength of normal weight concrete (NWC) is 8–14% of the compressive strength [58]. In comparison to NWC, the tensile/compressive strength ratio is lower for LWAC of equivalent grade [59]. This could be due to the weaker bond between the OPS and the matrix than that of NWC.

Fig. 18 shows the experiment for the splitting tensile strength and the failure of the specimen after the test; it can be seen that, generally, the bond failure between the OPS and the matrix occurred along with failure of the OPS itself. However, the tensile/compressive strength ratio of OPSGC obtained in this study is comparable with that of the OPS concrete (not geopolymer, but lightweight OPS concrete prepared from OPC) containing fly ash of an equivalent grade, as reported by Shafigh et al. [40].

The following equation was suggested to predict the splitting tensile strength from the compressive strength of OPS normal concretes made from OPC [60].

\[ f_t = 0.49 \sqrt{f_c} \]  
(12)

where \( f_t \) is the splitting tensile strength obtained from 100 × 200-mm cylinders and \( f_c \) is the 100-mm cube compressive strength at 28 days.

For OPS normal concrete containing fly ash, the following equation is proposed to predict the splitting tensile strength based on the compressive strength [40].

\[ f_t = 0.23f_c^{0.644} \quad R^2 = 0.91 \]  
(13)

![Fig. 16. Relationship between splitting tensile and compressive strengths of NWGC at 28-day.](image1)

![Fig. 17. Relationship between splitting tensile and compressive strengths of OPSGC at 28-day.](image2)

![Fig. 18. (a) Splitting tensile testing; and (b) specimen after testing.](image3)
Gesoğlu et al. [61] suggested the following equation for structural lightweight aggregate normal concrete made of an artificial lightweight aggregate, namely, cold-bonded fly ash, to predict the splitting tensile strength from the compressive strength (compressive strength in the range of 21–47 MPa):

\[
f_t = 0.27f_c^{0.67}
\]  

(14)

Table 14 and Fig. 17 show the comparison among the experimental results with the formulae proposed by other researchers (Eqs. (12)–(14)). The results show that the splitting tensile strength produced by the POFA–GGBS-based OPSGC based on the compressive strength is lower than that provided by the formulae in Eqs. (12) and (14) and is comparable with the formulae in Eq. (13). It should be noted that the specimens prepared in this investigation has two variables, namely, the crushed and uncrushed OPS and three different types of sand (NS, MS and QD). The equations proposed by researchers are for the lightweight concrete prepared with OPC, conventional sand, OPS and cold bonded lightweight fly ash aggregate.

It is worth noting that, according to ASTM: C330, a minimum splitting tensile strength of 2.0 MPa is a requirement for structural grade lightweight aggregate concrete. It can be seen that according to this criteria, all mixes, except B3 and C3, fulfilled the criterion for minimum splitting tensile strength.

3.7. Flexural strength

The flexural strength of NWGC and OPSGC and the comparison with the compressive strength are shown in Table 15. The flexural test was conducted in accordance with BS EN 12390-5 [62]. Generally, for conventional concrete having a compressive strength of more than 25 MPa, the ratio of flexural strength to compressive strength, expressed as a percentage, is in the range of 8–11% [63]. As can be seen in Table 15, this ratio was found to be within this range for all the mixes.

In this investigation, the flexural/splitting tensile strength ratios for the A1, A2 and A3 mixes were found to be 1.23, 1.33 and 1.23, respectively; while for the B1, B2, B3, C1, C2 and C3 mixes, the ratios were 1.23, 1.45, 1.48, 1.13, 1.35 and 1.53, respectively.

Alengaram et al. [64] reported that the ratio \( f_r/f_c \times 100 \) for OPC based OPS concrete was between 1.4 and 1.7. In general, as reported by Zheng et al. [65], the flexural strength of concrete is 35% higher than the splitting tensile strength.

The mixes A1, B1 and C1 using conventional mining sand show flexural strengths of 3.62, 3.00 and 3.10 MPa, respectively. In contrast, the flexural strengths of the mixes using MS (A2, B2, C2) and QD (A3, B3, C3) were 3.83, 3.03, 3.19 and 3.20, 2.79, 2.94, respectively

Table 16

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Mean compressive strength, ( f_c ) (MPa)</th>
<th>Flexural strength, ( f_r ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental</td>
<td>Predicted by Eq. (15)</td>
</tr>
<tr>
<td>A1</td>
<td>38</td>
<td>2.94</td>
</tr>
<tr>
<td>A2</td>
<td>40</td>
<td>2.87</td>
</tr>
<tr>
<td>A3</td>
<td>36</td>
<td>2.61</td>
</tr>
<tr>
<td>B1</td>
<td>32</td>
<td>2.44</td>
</tr>
<tr>
<td>B2</td>
<td>33</td>
<td>2.09</td>
</tr>
<tr>
<td>B3</td>
<td>29</td>
<td>1.88</td>
</tr>
<tr>
<td>C1</td>
<td>30</td>
<td>2.74</td>
</tr>
<tr>
<td>C2</td>
<td>29</td>
<td>2.37</td>
</tr>
<tr>
<td>C3</td>
<td>27</td>
<td>1.92</td>
</tr>
</tbody>
</table>

Fig. 19. (a) Flexural strength testing; and (b) specimen after testing.
respectively. The results show that the mixes A2, B2 and C2 are 6%, 1% and 3%, respectively, higher than the corresponding mixes using conventional mining sand. In contrast, the corresponding mixes using QD show 12%, 7% and 5% lower flexural strength compared to the corresponding mixes using conventional mining sand. Hence, it can be concluded that the use of MS could be considered as an ideal replacement for conventional mining sand.

Fig. 19 shows that bond failure occurred between the OPS and the mortar, which could be due to the smooth surface of the OPS. In addition, as explained in Section 3.6.2, OPS failure along the failure plane is visible, which is due to the weaker stiffness of OPS. The weaker bond and OPS failure result in lower value for the flexural strength of OPSGC compared to NWGC.

Previous researchers have proposed the following relationships to predict the flexural strength from the compressive strength of OPS concrete.

Alengaram et al. [64] have reported OPS concrete with compressive strength ranging from 15 to 37 MPa and the relationship with the flexural strength can be expressed as follows:

$$ f_r = 0.30 \sqrt{f_c} $$

Meanwhile, Lo et al. [66] have reported expanded clay lightweight aggregate concrete with cube compressive strength ranging from 29 to 43 MPa and the relationship with the flexural strength can be expressed as follows:

$$ f_r = 0.69 \sqrt{f_c} $$

Smadi and Migdady [67] reported high strength lightweight concrete with compressive strength of 60 MPa, which was prepared with Tuff lightweight aggregate and the relationship with the flexural strength can be expressed as follows:

$$ f_r = 0.58 \sqrt{f_c} $$

Shafigh et al. [40] investigated OPS concrete with compressive strength ranging from 30 to 44 MPa, with 0–50% fly ash replacement with cement and the above relationship expressed as follows:

$$ f_r = 0.09f_c $$

Table 16 and Fig. 20 show the comparison of flexural strengths for the experimental results with the formulae proposed by other researchers [40, 64–67]. The results show that the flexural strength produced by the POFA–GGBS-based OPSGC, based on the compressive strength is lower than that provided by the formulae Eq. (16) [66] and comparable with the formulae Eqs. (15) and (17) and slightly higher than the Eq. (18). The higher difference between the formulae in Eq. (16) and the experimental results could be

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Mean compressive strength, $f_c$ (MPa)</th>
<th>$\rho_{28-d}$ (kg/m$^3$)</th>
<th>Poisson’s ratio</th>
<th>Elastic modulus, $E$ (GPa)</th>
<th>Predicted by Eq. (19)</th>
<th>Predicted by Eq. (20)</th>
<th>Predicted by Eq. (21)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>38</td>
<td>2341</td>
<td>0.19</td>
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<td>27.60</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>A2</td>
<td>40</td>
<td>2285</td>
<td>0.27</td>
<td>14.80</td>
<td>28.00</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>A3</td>
<td>36</td>
<td>2320</td>
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<td>27.20</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>B1</td>
<td>32</td>
<td>1970</td>
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<td>21.95</td>
<td>10.70</td>
<td>10.70</td>
</tr>
<tr>
<td>B2</td>
<td>33</td>
<td>1949</td>
<td>0.16</td>
<td>8.93</td>
<td>21.82</td>
<td>10.58</td>
<td>10.58</td>
</tr>
<tr>
<td>B3</td>
<td>29</td>
<td>1957</td>
<td>0.16</td>
<td>8.51</td>
<td>20.62</td>
<td>10.21</td>
<td>10.21</td>
</tr>
<tr>
<td>C1</td>
<td>30</td>
<td>1948</td>
<td>0.16</td>
<td>10.08</td>
<td>20.78</td>
<td>10.24</td>
<td>10.24</td>
</tr>
<tr>
<td>C2</td>
<td>29</td>
<td>1934</td>
<td>0.17</td>
<td>8.05</td>
<td>20.14</td>
<td>9.98</td>
<td>9.98</td>
</tr>
<tr>
<td>C3</td>
<td>27</td>
<td>1940</td>
<td>0.17</td>
<td>7.36</td>
<td>19.56</td>
<td>9.80</td>
<td>9.80</td>
</tr>
</tbody>
</table>

Note: NA – not applicable.
attributed to the formula proposed for high strength concrete (Eq. (16)) (cube compressive strength ranging from 29 to 43 MPa). In addition, the aggregate used in this study was crushed and uncrushed OPS and three different types of sand (NS, MS and QD), as discussed earlier in Section 3.6, while the equations proposed by the researchers [66] are for the lightweight concrete prepared with OPC, conventional sand, and expanded clay lightweight aggregate.

3.8. Relationship of splitting tensile strength to flexural strength

In the splitting tensile strength test the failure can be initiated anywhere in the portion of the diametric plane that is in tension; however, in the flexural strength tests, failure is controlled by the strength of the concrete at the tension surface of the beam. Hence, based on the size effect principle, it is expected that the splitting tensile strengths would be lower than the flexural strength. In this study (Fig. 21) for POFA–GGBS based lightweight OPSGC and NWGC, it was found that the splitting tensile strength is about 75% and 79% of the flexural strength, respectively, for a centre-point loading. It is specified in ASTM STP 169D that this value for conventional concrete is about 65%. Alengaram et al. [64] found that the splitting tensile strength of OPS based cement concrete is about 60–70% of its flexural strength.

3.9. Modulus of elasticity (E-value)

The modulus of elasticity (MOE) or $E$-value of concrete is one of the most important parameters for structural concrete as it is required when assessing deflections and cracking of a structure. Table 17 shows the experimental and predicted static moduli of elasticity ($E$) for all mixes. The Young’s modulus test was conducted in accordance with ASTM: C469/C469M-10.

The moduli of LWA particles are generally lower than NWA and although most LWA concretes contain higher cement content it follows that the overall moduli of lightweight aggregate concretes will be lower than that of normal weight concretes [2]. Generally, for LWAC with natural and artificial LWA, the value of the static MOE ranges between 10 and 24 kN/mm² [68].

The experimental $E$-values for the OPSGC and NWGC vary in the range of 7.4–11.12 GPa and 13.74–16.86 GPa, respectively (Table 17), and the MOE increases as the compressive strength increases (Fig. 22). The $E$-values of OPSGC are lower than the values obtained for NWGC; as stated, NWA has higher stiffness and establishes a stronger bond between the aggregate surface and the matrix compared to the OPS. The $E$-values of OPSGC depend on the stiffness of the aggregate, the hardened cement matrix, the bond between the OPS and the cement matrix and the quantity of OPS. A higher LWA content lowers the modulus value, because the concrete stiffness decreases [8,68]. Alengaram et al. [34] opined that the use of higher OPS content in mixes reduces the $E$-values. They reported values ranging between 5.5 and 7.1 kN/mm². The $E$-values reported in this investigation were higher than the values reported by Alengaram et al. [34] for OPSC, which could be attributed to reasons such as water to binder (w/b) ratio, sand to binder (s/b) ratio and the quantity of OPS in the OPSGC.

3.9.1. Effect of aggregates on $E$-value of geopolymer concrete

It can be seen in Table 17 that the $E$-values obtained using conventional mining sand are 16.86, 11.2 and 10.08 GPa for mixes A1, B1 and C1, respectively. In comparison, the $E$-values obtained using MS to the corresponding mixes are 14.80, 8.93 and 8.05, which are 12%, 19% and 20% lower than the values obtained for mixes with NS. One possible explanation for this difference could be due to the low stiffness of OPS and the bond between the aggregate and

![Fig. 22. The relationship of MOE and compressive strength at 28-day.](image)

![Fig. 23. Stress–strain curve.](image)
Kosmatka et al. [58] reported that for structural lightweight conventional concrete the MOE varied between 7 and 17 GPa.

Alengaram et al. [34] established for OPS lightweight normal concrete incorporated cement, fly ash and silica fume, the MOE can be expressed as:

$$E_c = \left(\frac{\rho}{2400}\right)^2 \times (f_c)^{1/3} \times 5.0$$  

(21)

Based on the Young’s modulus comparison between the experimental and the three equations (Eqs. (19)–(21)), it could be concluded that the equation proposed by Alengaram et al. [34] (modified based on FIP manual) predicts the $E$-values closer to the experimental; the difference between the experimental and predicted values are 0.16–2.44 MPa.

3.10. Stress–strain relationship

Fig. 23 shows the stress–strain relationship for all nine mixes including NWGC. The draft European Code [70] gives special provisions for lightweight aggregate concrete. It defines an idealised bilinear stress–strain diagram for concrete, with a peak stress of 0.77 times the design strength of the concrete in most situations. For normal weight concrete, the factor is 0.85. The transition from the linearly increasing portion of the curve to the uniform is at a strain of 0.00135 for normal weight concrete, but increases to 0.0022 for lightweight aggregate concrete. The ultimate strain for most structural concretes is approximately 0.0035, irrespective of the strength of the concrete [71].

It can be seen in Fig. 23, that, in the beginning, as the load is applied, the stress–strain curve is approximately linear, irrespective of the type of concrete; both NWGC and OPSGC behave almost as an elastic material with virtually a full recovery of displacement if the load is removed. Eventually, the curve is no longer linear and the concrete behaves more and more as a plastic material. The peak stress of the geopolymer concrete (GC) using conventional mining sand is higher compared to the concrete using MS and QD, but MS gives a good result compared to QD. Fig. 23 shows that the stress–strain relationship of OPSGC is more linear compared to NWGC. It is reported that lightweight aggregate concretes are typically linear to levels approaching 90% of the failure strength, indicating the relative compatibility of the constituents and the reduced occurrence of micro-cracking [72].

3.11. Poisson’s ratio

The ratio of the lateral strain to the longitudinal strain is called Poisson’s ratio (Fig. 24). If the lateral and longitudinal strain is $\Delta x$ and $\Delta y$, respectively, the Poisson’s ratio can be expressed as:

$$\mu = \frac{\Delta x}{\Delta y}$$  

(22)

where $\mu$ is the Poisson’s ratio.

Table 18

<table>
<thead>
<tr>
<th>Concrete producing materials</th>
<th>Emission factors (t CO2-e/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>0.82</td>
</tr>
<tr>
<td>GGBS</td>
<td>0.143</td>
</tr>
<tr>
<td>POFA</td>
<td>0.0459</td>
</tr>
<tr>
<td>Crushed granite/MS/QD</td>
<td>0.0139</td>
</tr>
<tr>
<td>Mining sand</td>
<td>1.915</td>
</tr>
<tr>
<td>Na2SiO3 manufacture</td>
<td>1.514</td>
</tr>
<tr>
<td>NaOH manufacture</td>
<td>0</td>
</tr>
<tr>
<td>OPS</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 19

<table>
<thead>
<tr>
<th>Label</th>
<th>Binder content</th>
<th>CO2-e/t from binder</th>
<th>Crushed granite</th>
<th>OPS</th>
<th>CO2-e/t from coarse aggregate</th>
<th>Fine aggregate</th>
<th>Alkali activator (solid)</th>
<th>CO2-e/t from Alkali activator of concrete</th>
<th>Total CO2-e/m3 of concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWC</td>
<td>335</td>
<td>0</td>
<td>0</td>
<td>0.2747</td>
<td>1303</td>
<td>0</td>
<td>0.0598</td>
<td>0</td>
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</tr>
<tr>
<td>NWGC</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>0</td>
<td>132</td>
<td>88</td>
<td>0.0189</td>
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<td>0</td>
<td>0.0456</td>
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<tr>
<td>A2, A3</td>
<td>0</td>
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<td>88</td>
<td>0.0189</td>
<td>994</td>
<td>0</td>
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<td>0.0406</td>
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<td>OPSGC</td>
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<td></td>
</tr>
<tr>
<td>B1, C1</td>
<td>0</td>
<td>255</td>
<td>170</td>
<td>0.0365</td>
<td>0</td>
<td>0</td>
<td>1064</td>
<td>0</td>
<td>0.0148</td>
</tr>
<tr>
<td>B2, B3, C2, C3</td>
<td>0</td>
<td>255</td>
<td>170</td>
<td>0.0365</td>
<td>0</td>
<td>0</td>
<td>1064</td>
<td>0</td>
<td>0.0488</td>
</tr>
</tbody>
</table>
The values of Poisson’s ratio for OPSGC (mixes B1, B2, B3, C1, C2 and C3) were found to be within the range of 0.15–0.17, while in the case of NWGC (mixes A1, A2 and A3), the ratio shows slightly higher values of 0.19–0.27, as shown in Table 17. The mixes with uncrushed OPS coarse aggregate show a slight increment in the Poisson’s ratio (5.9–6.3%) compared to the mixes using crushed OPS (0.15–0.16), which could be attributed to the higher strains in the uncrushed OPS. The OPSGC with conventional mining sand shows Poisson’s ratio values of 0.15 and 0.16 for the mixes B1 and C1, respectively, while the corresponding mixes using MS and QD show only 0.16–0.17 in both cases.

There is no published literature available on the Poisson’s ratio of OPS based geopolymer concrete. Depending on the properties of aggregate used, the Poisson’s ratio of concrete lies generally in the range of 0.15–0.22 [28]. Neville [28] reported that for lightweight aggregate conventional concrete the Poisson’s ratio could be of lower value compared to NWA concrete.

The Poisson’s ratio effect has a considerable influence in construction. Due to the Poisson’s ratio effect the concrete may laterally expand and shorten its length. If a single slab concrete highway is cast without any expansion joint, it may show cracking within a short time due the effect of the Poisson’s ratio. The impact strength in compression is improved by the use of aggregate with a low Poisson’s ratio [28]. A higher Poisson’s ratio could lead to splitting. In each material, the vertical compression results in a lateral expansion due to the Poisson’s ratio effect.

3.12. Carbon footprint

A carbon footprint is historically defined as “the total sets of greenhouse gas emissions caused by an organisation, event, product or person”. The total carbon footprint cannot be calculated because of the large amount of data required and the fact that carbon dioxide can be produced by natural occurrences. The calculation on the amount of CO₂ emission (CO₂-e) for a particular component of concrete was based on 1 m³ of concrete. In this investigation, the estimation of CO₂ emission for the manufactured sand (MS) and quarry dust (QD) is taken the same as that of crushed granite aggregate. This could be justified due to the fact that the MS/QD is the by-product of crushed granite aggregate and needs electricity for further processing [73]. As the POFA and OPS are also an industrial by-product, the CO₂ emission was not considered in the calculation of the carbon footprint for OPSGC.

The CO₂-e for manufacturing of concrete producing materials is shown in Table 18, in which the process of decomposition of lime, grinding and heating in kiln, as well as the transportation were accounted for [74].

<table>
<thead>
<tr>
<th></th>
<th>NaOH (kg/m³)</th>
<th>Na₂SiO₃ (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NWGC</td>
<td>25 × 0.361 = 9.025</td>
<td>63 × 0.43 = 27.09</td>
</tr>
<tr>
<td>OPSGC</td>
<td>49 × 0.361 = 17.689</td>
<td>122 × 0.43 = 52.46</td>
</tr>
</tbody>
</table>

Table 19 shows the estimated CO₂-e for NWC, NWGC and OPSGC of grade 30 concrete mixtures. It can be seen that CO₂-e from NWGC (A1, A2, A3) is 52–61% lower compared to NWC, while OPSCG (B1, C1, B2, C2, B3, C3) is 42–52% lower compared to NWC of similar grade. A significant reduction of CO₂ emission was observed in the development of geopolymers. McLellan et al. [77] investigated over Australian geopolymer concrete and found an estimated 44–64% reduction in greenhouse gas emissions over OPC, while the cost of these geopolymers can be up to twice as high as OPC.

4. Conclusion

Based on the experimental work reported in this study, the following conclusions are drawn:

(a) POFA and GGBS could be used as the source material in the development of low to moderate structural grade lightweight and normal weight geopolymer concrete. The development of grade 30 concrete using OPS and crushed granite aggregate of ambient cured specimens also reduces the need for oven curing, which is normally employed for geopolymer concrete.

(b) The oven-dry densities of all the OPSGC specimens were found to be within the range of 1900–1935 kg/m³ and hence fulfilled the requirement for LWC as stipulated in EN206-1.

(c) Although the usage of 40% POFA in the total binder content of 425 kg/m³ in the development of 30 grade structural lightweight OPSGC is higher than the total binder content of 220 kg/m³ used in NWGC of similar grade, its density reduction of 20% is crucial.

(d) The mixture containing quarry dust produced slightly lower mechanical strength compared to the mixes with conventional mining sand and manufactured sand.

(e) The higher mortar demand in the mixes of OPSGC specimens prepared using crushed OPS aggregate resulted in lower slump values compared to the mixes with uncrushed OPS aggregate.

(f) The OPSGC with crushed OPS aggregate produced a higher compressive strength of about 7–14% and 3–7% cured in OD and AD, respectively, compared to the corresponding mixes with uncrushed OPS aggregate.

(g) Most of the specimens of geopolymer concrete produced 90% of the 28-day compressive strength at 3 days for OD curing, while the AD curing specimens reached 57–82%; however, the final strength of the AD curing specimens were found to be slightly higher than the corresponding OD cured specimens at 28 days.

(h) The early strength development of 92–100% and 81–97% of 28-day compressive strength, respectively, for OD and AD curing at 7 days for both the OPSGC and NWGC points to geopolymerization at an early age. The rate of increase in compressive strength in the oven-cured specimens after 7 days is not significant.

(i) The mixes with MS and conventional mining sand fulfilled the minimum requirement for splitting tensile of about 2 MPa for OPSGC prepared using both crushed and uncrushed OPS. The failure of specimens in splitting and flexural tensile strengths is governed by the failure of the bond between the OPS and the matrix, and the OPS itself.

(j) The splitting tensile and flexural strengths of POFA–GGBS based geopolymers were found to be in the range of about 6–9% and 9–11% of the compressive strength, respectively.

(k) The low stiffness of OPS resulted in reduced E-value of POFA–GGBS based OPSGC compared to NWGC. However, the E-values obtained for the OPSGC in the range of 8–11 are comparable to the E-values of OPC based lightweight OPSC concrete [34]. The usage of a high content of OPS in the OPSGC resulted in lower values for the Poisson’s ratio of about 0.15–0.17 compared to 0.19–0.27 for NWGC.
The usage of 60% of GGBS and 40% of POFA both in NWGC and OPSCG was found to have 52–61% and 42–52% reduction in carbon dioxide emission, respectively compared to NWC of similar strength.

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