Technical note

Shear behaviour and mechanical properties of steel fibre-reinforced cement-based and geopolymer oil palm shell lightweight aggregate concrete

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HIGHLIGHTS

- Shear behaviour of steel fibre cement-based and geopolymer OPS LWAC investigated.
- Mechanical properties comparison of steel fibre cement-based and geopolymer LWAC.
- Tensile strength and toughness increase more evident for cement than geopolymer LWAC.
- Shear capacity improved with fibres and existing prediction equations are conservative.

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ABSTRACT

The shear behaviour and mechanical properties (compressive, splitting tensile and flexural strengths) as well as the flexural toughness of steel fibre-reinforced cement-based and geopolymer oil palm shell lightweight aggregate concrete (OPS LWAC) were experimentally investigated in this paper. Steel fibres were added at various volume fractions for the cement-based OPS LWAC (0%, 0.5% and 1.0%) and geopolymer OPS LWAC (0%, 0.5%). Test results showed that steel fibre improved the mechanical properties of concrete, particularly for the splitting tensile strength whereas flexural toughness enhancement with the use of steel fibres was more evident for the cement-based OPS LWAC than the geopolymer concrete. The shear resistance of OPS LWAC beams was also found to improve with the addition of steel fibres and existing prediction equations for shear capacity of steel fibre-reinforced lightweight concrete was determined to be conservative for the steel fibre-reinforced cement-based and geopolymer OPS LWAC.

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1. Introduction

Utilization of lightweight aggregate concrete (LWAC) exerts certain advantage over normal concrete (NC) in structural members, such as reduction in self-weight, favourable effects towards seismic forces and foundation of buildings supported by soil with low bearing capacity [1]. Commonly used lightweight aggregate includes expanded clay and expanded shale while recent researches in South East Asia also suggested the alternative of incorporating oil palm shell (OPS) – a solid waste material from agriculture industry – as lightweight aggregate to produce structural LWAC [2]. The potential saving in transportation costs for pre-fabricated LWAC members has since encouraged the development of geopolymer OPS LWAC [3]. This is because apart from the elimination of cement usage, one of the greatest benefits of geopolymer concrete is the short curing time and early strength gain, which is suitable for pre-fabricated concrete products.

However, LWAC often failed in a more brittle manner than NC. Shear failure of LWAC members is known to be one of the major problems that cause collapse of structures [4]. Besides that, the use of weaker lightweight aggregate is likely to cause reduction in aggregate interlocking effect in LWAC which could further reduce the shear capacity of reinforced concrete member [5]. Smooth shear failure paths were observed in LWAC [4] due to reduced aggregate interlocking effect as a result of cleavage of lightweight aggregate [6]. Kim and Jang [7] also found that the shear strength of LWAC beam reinforced with FRP bars were lower compared to the corresponding NC beam. Therefore, it is desired to increase the ductility of LWAC through the incorporation of steel fibres. Combination of steel fibres with reinforcement is ideal due to the enhanced toughness of material which reduces crack width and increases tension stiffening [1].
In the past, it was found that the inclusion of steel fibres had beneficial effects in enhancing the flexural toughness of LWAC, such as those from expanded clay [8] and sintered pulverized fuel ash aggregates [9]. Moreover, steel fibre-reinforced LWAC was found to exhibit superior mechanical properties than plain LWAC, particularly the splitting and flexural tensile strengths. It was reported that the enhancement in the splitting and flexural tensile strengths to range between 61–140% and 117–200%, respectively when steel fibre of between volume fractions of 0.5–2.0% were added into concrete prepared with lightweight coarse aggregate such as pumice [10], shale [11], expanded clay [12] and cold-bonded fly ash [13]. When reinforced concrete structural beam was considered, Kang et al. [14] observed a 30% increment in the shear strength capacity of LWAC beams when 0.75% steel fibres were added. Swamy et al. [15] found out that the increase in shear capacity of lightweight concrete I-beams could be increased between 60 and 210% in the presence of 1.0% steel fibres. Shoiab et al. [6] also reported that the shear failure was more ductile and experienced greater crack widening in the case of steel fibre-reinforced LWAC beam compared to the beam without fibres. This was attributed to the pulling out of the steel fibres from the cement matrix and such ductile failure could provide important warning about the imminent shear failure.

Past researches have shown similar encouraging performances of steel fibre-reinforced OPS cement-concrete as well as the resultant reinforced concrete structures [16]. On the other hand, there are only limited literature available regarding the performance of steel fibre-reinforced geopolymer concrete, with Ganesan et al. [17] and Ng et al. [18] carried out research work on enhancing the mechanical properties and shear capacity of geopolymer NC, respectively through the use of steel fibres. There is no previous research done on improving the shear behaviour of OPS LWAC as well as the corresponding geopolymer concrete through the use of steel fibres. Hence, this paper describes a comparative study on the shear behaviour of cement-based and geopolymer OPS LWAC with and without added steel fibres. In addition, the relevant mechanical properties and flexural toughness of the concretes are discussed.

2. Research significance

LWAC is known to have lower shear capacity compared to NC and hence this study aims to explore the effectiveness of steel fibre in enhancing the shear capacity of concrete made with local OPS waste as lightweight aggregate. While there are some studies of steel fibre-reinforced NC and other types of LWAC, it is important to ascertain the efficiency and thus the feasibility of incorporating steel fibres in OPS LWAC. In addition, with the growing trend of research in sustainable cement-less geopolymer concrete, the investigation of the effect on the shear and mechanical performances due to the addition of steel fibres could provide a platform for the development of geopolymer concrete as a future construction material.

3. Experimental programme

3.1. Materials and mix proportion

Coarse and fine aggregate used for this study were crushed OPS aggregate (2.36–9 mm) and local mining sand (0.3–5 mm), respectively. The sieve analysis of OPS aggregate and local mining sand is shown in Fig. 1. The specific gravity of the coarse and fine aggregates was 2.35 and 2.60, respectively. Crushed OPS were pre-soaked in water and used in saturated surface dry condition for casting of concrete.

For the cement-based OPS LWAC, the binding material was ordinary Portland cement (OPC) while the binding material for the geopolymer OPS LWAC was Class-F fly ash, activated with the combination of 14 M NaOH and liquid Na2SiO3 at a ratio of 2.5. Laboratory pipe water was used as mixing water for both mixes and a polycarboxylate ether-based superplasticizer (SP) was added in the case of cement-based OPS LWAC to facilitate workability.

Hooked-end shape steel fibres of 35 mm length and aspect ratio of 65 were used as fibre reinforcement. High-yield steel bar of grade 500 MPa with diameter of 12 mm was used as main reinforcement in reinforced concrete beam.

Table 1 shows the mix proportions of the cement-based and geopolymer OPS LWAC, respectively. The mix proportions were chosen based on trial mixing to obtain targeted cube compressive strength of 30 MPa for the concretes without fibres. For the cement-based OPS LWAC, there are three different steel fibre contents, namely 0%, 0.5% and 1.0% addition by volume whereas for the geopolymer OPS LWAC, there is the control specimen without fibre and specimen with 0.5% steel fibre volume. Based on trial mixing, due to the viscosity of the geopolymer OPS LWAC, it is impractical to incorporate 1.0% steel fibre volume and hence such mix was omitted from the investigation. Fig. 2 shows the preparation of geopolymer concrete.

3.2. Specimen testing

After demoulding, the cement-based OPS LWAC specimens were subjected to water-curing for 28 days before testing while the geopolymer OPS LWAC specimens were heat-cured for 24 h at temperature of 65 °C followed by air-curing in laboratory conditions until day 28 for testing.

Mechanical properties tests such as cube compressive strength, splitting tensile and flexural strength tests were carried out in accordance with BS EN 12390-3: 2002, BS EN 12390-6: 2000 and BS EN 12390-5: 2000, respectively. Prism specimens measuring 100 × 100 × 500 mm³ were tested for flexural toughness based on ASTM C1108-97.

For the testing of the shear behaviour, reinforced concrete beam with cross-section area of 150 mm × 150 mm and length of 1300 mm was cast. The longitudinal reinforcement consisted of 2 steel rebar of 12 mm diameter and the concrete cover was 25 mm. No shear link was provided for the beam. The loading arrangement for the shear-crucial reinforced concrete beam is shown in Fig. 3. Loading from actuator was transferred to the beam via a spreader beam of 700 mm length. The loading rate was fixed at 2 mm/min and the mid-span deflection of the beam was measured using a LVDT.
4. Results and discussion

4.1. Mechanical properties

The 28-day mechanical properties of steel fibre-reinforced cement-based and geopolymer OPS LWAC are presented in Table 2. It was found that the inclusion of steel fibres generally improved the mechanical properties of the OPS LWAC. The increment in the compressive strength, however, was to a lower extent compared to the splitting and flexural tensile strengths. This is because the fibres do not contribute actively in load-sharing in the direction of compression loading as stretching and straining of fibres are not experienced [19]. The increment was found to be about 7% and 14% when 0.5% and 1.0% steel fibres were added to the cement-based OPS LWAC, respectively. This corresponds well with the previously published results on steel fibre-reinforced OPS LWAC [20,21]. For equal fibre volume, it was found that the increment in the com-

![Table 1](image1)

**Table 1**

Mix proportion of cement-based and geopolymer OPS LWAC.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Content (kg/m³)</th>
<th>Volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement</td>
<td>Fly ash</td>
</tr>
<tr>
<td>C0</td>
<td>540</td>
<td>–</td>
</tr>
<tr>
<td>C0.5</td>
<td>540</td>
<td>–</td>
</tr>
<tr>
<td>C1.0</td>
<td>540</td>
<td>–</td>
</tr>
<tr>
<td>G0</td>
<td>–</td>
<td>635</td>
</tr>
<tr>
<td>G0.5</td>
<td>–</td>
<td>635</td>
</tr>
</tbody>
</table>

![Figure 2](image2)

**Fig. 2.** (a) Addition of alkaline solution to dry-mixed materials (b) Mixing of geopolymer concrete (c) Fresh geopolymer concrete after casting and vibration.

![Figure 3](image3)

**Fig. 3.** Shear test of reinforced concrete beam.

![Table 2](image4)

**Table 2**

28-day mechanical properties results.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Compressive strength (MPa)</th>
<th>Splitting tensile strength (MPa)</th>
<th>Flexural strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0</td>
<td>34.04</td>
<td>3.155</td>
<td>4.241</td>
</tr>
<tr>
<td>C0.5</td>
<td>36.63</td>
<td>4.607</td>
<td>5.392</td>
</tr>
<tr>
<td>C1.0</td>
<td>38.85</td>
<td>6.124</td>
<td>6.180</td>
</tr>
<tr>
<td>G0</td>
<td>25.92</td>
<td>2.129</td>
<td>2.948</td>
</tr>
<tr>
<td>G0.5</td>
<td>27.79</td>
<td>3.352</td>
<td>3.182</td>
</tr>
</tbody>
</table>
pressive strength was similar for the case of the geopolymer OPS LWAC, which was 7% for the addition of 0.5% steel fibres. Similar increment was also reported by Ganesan et al. [17] and Kim et al. [22] for steel fibre-reinforced geopolymer and alkali-activated NC, respectively. In addition, Ganesan et al. [17] reported little difference in the compressive strength increment of cement-based and geopolymer NC when similar amount of steel fibres were added.

On the other hand, the beneficial effects of steel fibres were more apparent in increasing the splitting and flexural tensile strength of the OPS LWAC. For instance, splitting tensile strengths were improved by 46% and 94% when 0.5% and 1.0% steel fibres were added in the cement-based OPS LWAC, respectively. The increase was similar for the corresponding geopolymer OPS LWAC whereby the increment was 57% when 0.5% of steel fibres by volume were added. The enhancement in the splitting tensile strength could be attributed to the crack bridging ability of the fibres, whereby tensile stress was transferred across the fibres and delayed propagation of cracks, giving rise to tensile strength of the concrete. Past investigations on steel fibre-reinforced geopolymer NC showed that the increment in splitting tensile strength was lower, which ranged between 12 and 17% when 0.5% steel fibres were added [17,19] while the increment was 6% for the case of alkali-activated slag NC [23]. Nevertheless, it was also reported in the past that the increment in splitting tensile strength due to steel fibre addition between geopolymer and cement NC [17] as well as between alkali-activated and cement NC [23] was similar.

In the case of flexural strength, the increment was about 27% and 46% when steel fibres of 0.5% and 1.0% were added in the cement-based OPS LWAC, respectively, whereas the increment was only about 8% when 0.5% steel fibres were added in geopolymer OPS LWAC. The increment for the latter was in a slightly lower range compared to reported results of between 11 and 22% for geopolymer NC [17,19].

4.2. Flexural toughness

Fig. 4 shows the load-deflection relationships of prism specimens under third-point loading. The flexural toughness was calculated using the area under the load-deflection graph. The flexural toughness of the C0, C0.5 and C1.0 were determined to be 0.54, 25.72 and 34.58 kNmm, respectively. For the geopolymer OPS LWAC specimens, the flexural toughness was 0.30 and 13.66 kNmm for the mixes G0 and G0.5, respectively. According to ASTM C1018, the toughness parameters can be determined through the toughness indices I5, I10 and I20. The calculated toughness indices are given in Fig. 5. It was found that the toughness indices obtained in the study correspond well to those reported in the past for steel fibre-reinforced LWAC [16,24]. The inclusion of steel fibres was found to significantly enhance the ductility of both types of concrete, as reflected in the increased flexural toughness and toughness indices. Unlike specimens without fibres which failed abruptly, the presence of steel fibres facilitated widening of cracks through the action of fibres in stitching the macro-cracks, and allowed progressive failure through pulling out of the fibres (Fig. 6). Pulling out of fibres thus enabled the specimens to absorb more energy and giving rise to ductility of the concrete. It is interesting to note that the steel fibres could be a better proposition for toughness enhancement in the cement-based OPS LWAC compared to geopolymer OPS LWAC. From Fig. 4, it can be seen that for specimens reinforced with 0.5% steel fibres, the reduction in flexural load for the cement-based OPS LWAC was more gradual compared to the geopolymer concrete and this could be due to the weaker bonding between geopolymer matrix with steel fibres compared to that for cement matrix.
4.3. Shear behaviour

All of the reinforced concrete beams experienced shear failure upon formation of diagonal crack (Fig. 7). No tensile splitting along longitudinal reinforcement was observed. Such failure mode was also observed by Shoaib et al. [6] in steel fibre-reinforced expanded clay LWAC. Broken specimens revealed that there was partial fracture of OPS aggregate while some of the cracks were between the matrix-OPS interface (Fig. 8), suggesting that the OPS lightweight aggregate could exhibit aggregate interlocking effect to a certain extent. On the other hand, the crack pattern for both cement-based and geopolymer OPS LWAC beams with and without fibres showed little difference. Crack patterns are usually affected by the shear span/depth ratio rather than the type of concrete [25].

The load-deflection behaviours of the shear-critical reinforced concrete beams are plotted in Fig. 9. It was found that the steel fibre addition enhanced the shear resistance of the beams for both cement-based and geopolymer OPS LWAC. The maximum shear force of the cement-based OPS LWAC beams was 50.7 kN whereas addition of steel fibres at 0.5% and 1.0% volume fraction resulted in increase of 51% and 68% to 76.6 kN and 85.0 kN, respectively. For the geopolymer OPS LWAC beams, the shear resistance was increased by 37% from 36.5 kN to 50.1 kN when 0.5% steel fibres were added. In order to take into account the difference in compressive strength of concrete, the normalized shear capacity is taken as:

\[ \mu = \frac{V_u}{\left( b d f_{cu}^{0.5} \right)} \]  

where \( \mu \) is the normalized shear capacity, \( V_u \) is the ultimate shear capacity (kN), \( b \) is the width of beam (mm), \( d \) is the effective depth of beam (mm) and \( f_{cu} \) is the cube compressive strength of concrete (MPa).

The normalized shear capacity was determined as 0.97, 1.42, 1.53, 0.80 and 1.06 for mixes C0, C0.5, C1.0, G0 and G0.5, respectively. The higher shear capacity of the fibre-reinforced concrete beams was largely due to the improvement in tensile strength of concrete due to addition of fibres. Besides that, the steel fibres provided tension resistance towards diagonal crack surfaces. In addition, the deflection at failure was significantly increased when steel fibres were added, indicating enhanced ductility of the beams. This was largely contributed by the bridging of macro-cracks by the fibres, allowing greater deformation of the beams before failure. As shown in Fig. 6, because of the fibre bridging action, the diagonal crack width was larger at failure for the fibre-reinforced concrete beams.

It is also noted that the normalized shear capacity for the cement-based OPS LWAC was higher than the corresponding geopolymer concrete. This might be attributed to the weaker geopolymer matrix-OPS aggregate interface which reduced the aggregate interlocking effect in the geopolymer concrete beams. Besides that, the geopolymer concrete beams were observed to experience higher deflection at the same load level than the cement-based concrete beams, and this could be attributed to the lower stiffness of the geopolymer concrete beams.

Comparison in Table 3 shows that these modified equations were still conservative for OPS LWAC, and this was due to the assumption taken for the splitting tensile strength of the concrete. When the actual splitting tensile strength was substituted into Eqs. (4) and (5), it was found that the difference between the predicted and actual shear resistance of the OPS LWAC was much closer (Table 3), and the Eq. (4) by Kwak et al. [27] gave the best prediction of the shear strength of OPS LWAC beams.

5. Conclusion

Based on the investigation carried out, it is concluded that the presence of steel fibres brings upon enhancement in the mechanical properties, flexural toughness and shear resistance of both cement-based and geopolymer OPS LWAC. In terms of the mechanical properties, addition of steel fibres had greater effect in enhancing the tensile strength compared to the compressive strength of the concretes. Flexural test results highlighted the enhanced ductility of the concretes with added fibres, and this effect is more apparent in the cement-based than the geopolymer OPS LWAC. Similarly, the shear resistance of the cement-based OPS LWAC beams is found to be greater compared to the corresponding geopolymer OPS LWAC; nevertheless existing equations can be used conservatively to predict shear capacity of the concretes investigated.

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References


