The effect of steel fibres on the enhancement of flexural and compressive toughness and fracture characteristics of oil palm shell concrete

Kim Hung Mo, Kathy Khai Qian Yap, U. Johnson Alengaram *, Mohd Zamin Jumaat
Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

Abstract
This effect of steel fibre on the toughness characteristics such as flexural toughness, fracture parameters and compressive toughness of steel fibre oil palm shell concrete (SFOPSC) is described in this paper. In the post-peak regions of the bending specimens, the addition of steel fibres significantly increased both the fracture energy and flexural toughness of the SFOPSC up to 16 times. The compressive toughness of SFOPSC specimens with 0.75% steel fibre of about 864 kN mm was 6 times higher than the specimens without fibres. The pre-peak response through the mechanical property tests shows an increase of up to 178%, 88% and 41% for splitting tensile, flexural and direct tensile strengths, respectively.

1. Introduction
Oil palm shell (OPS) is considered as a waste material produced from the extraction of palm oil in South East Asian countries, such as Indonesia, Malaysia, and Thailand. Most of the wastes that emanate from the production of palm oil are dumped in the vicinity of the factories. The excessive dumping of these wastes including OPS leads to pollution in the surrounding environment. Research works on utilizing the oil palm wastes such as OPS, palm oil fuel ash (POFA) and palm oil clinker paved way to develop sustainable materials. The utilization of OPS as lightweight coarse aggregates resulted the development of structural grade lightweight oil palm shell concrete (OPSC) with a reduction in the density of about 15–33% [1–3] compared to the normal weight concrete (NWC) of density of about 2400 kg/m³. Thus the reduction of concrete density significantly increases the strength to density ratio of the concrete; this allows the design flexibility of structural members and further reduces transportation and fabrication costs.

The cube compressive strength of the OPSC varies in the range of 15–45 MPa; however, one of the shortcomings of the OPSC is the low tensile strength. As known, most of the lightweight aggregate concrete is inferior in the tensile strength [4] as well as higher brittleness compared to NWC of the same strength [5–7]. Recently, Shafigh et al. [8] have researched on enhancing the compressive strength of OPSC by varying the size of the OPS and developed high strength OPSC with a cement content of 550 kg/m³. The increase in the compressive strength, however, will be offset by the increased brittleness of the concrete [6–10]. The brittleness of concrete is more prone towards catastrophic failure that occurs without much warning, and could be hazardous to the surroundings. In addition, the OPSC has a relatively low modulus of elasticity [4,9,11] compared to NWC which might lead to acceleration of crack development [12]. The cracks in concrete provide easy routes for deleterious agent and that could lead to durability issues. The
addition of fibres in the concrete enhances both the tensile strength and the ductility of the concrete.

It has been reported that the addition of specified quantity of steel fibres is known to increase the tensile capacity of the fibre reinforced concrete (FRC) along with its post-failure ductility [13–15]. The post-failure ductility is extremely useful in cases where tensile strength is not adequate to characterize the mechanical response of concrete [16]. After the cracking of matrix, the steel fibres function as a crack bridging mechanism, in which the fibres undergo fibre pull-out, thus delaying the crack formation and limit the crack propagation [17,18]. De-bonding and pulling out of fibres from FRC require higher amount of energy, resulting in the increased toughness and ductility of concrete. Since the toughness characteristic is essential for FRC, codes of practice in some countries incorporated this aspect to measure this property. The commonly used codes of practice for the measurement of flexural toughness tests of FRC are ASTM C1018-92 and JCI SF-4 and these are widely reported in literatures [5,19–21]. However, the toughness indices as proposed in these standards have been questioned as these are not material properties [22].

On the other hand, the fracture behaviour of concrete is the fundamental to understand the basics of reinforced concrete structures through the application of fracture mechanics. One of the vital fracture properties for the design of concrete structures is the fracture energy ($G_f$) and this is the most accepted and commonly used in numerical models [23]. Another characteristic namely, fracture toughness ($K_{fc}$) has also been found to be a fracture mechanics parameter to describe the resisting property of concrete to cracking [24].

There have been many research works carried out on the mechanical, thermal, durability and structural behaviour of OPSC [9,25]. In addition, a low cost house along with a foot bridge constructed using OPS as a lightweight aggregate in Malaysia is being monitored for structural performance [26]. A low aggregate impact value (AIV) implies high resistance to impact. Thus, owing to its high impact resistance, OPS could be used in road blocks, crash barriers, etc. In addition, pavement blocks, drain culverts, etc. are some other possible applications. Research works on potential structural application of OPSC in reinforced concrete beams and impact-resistant panels had been carried out. Alengaram et al. [27] reported that the ductility of reinforced OPSC beam was about 2 times higher than the corresponding reinforced NWC beam; Mo et al. [28] investigated the impact resistance of OPSC panels due to the improved AIV of OPS compared to conventional granite aggregates; the AIV of the OPS was found 2 times lower than the crushed granite aggregate. In order to promote the potential application of the OPSC, the structural behaviour with respect to fracture behaviour needs to be investigated. Thus the study on the influence of steel fibre in OPSC (SFOPSC) would pave way in understanding the material properties, toughness and fracture energy of the concrete for further application.

In this investigation, the relationship of steel fibre content and post crack toughness as well as the mechanical properties of SFOPSC is investigated and reported. In addition, the post-crack response of SFOPSC with varying steel fibre content (0–1.0%) was also compared through flexural toughness test; the fracture parameters of SFOPSC are quantified via a fracture energy test. Another aim of this investigation is the emphasis of a greener and sustainable concrete through 50% replacement of ordinary Portland cement (OPC) using ground granulated blast furnace slag (GGBS) as binder for all the SFOPSC mixes. The comparison of the mechanical properties between the OPSC with 100% OPC and OPSC with a replacement of 50% OPC replacement through GGBS is also analysed and reported.

2. Experimental program

2.1. Materials

2.1.1. Binder

Ordinary Portland Cement (OPC) with specific gravity and specific surface area of 3.10 and 352 m$^2$/kg, respectively was used in all mixes. The ground granulated blast furnace slag (GGBS) supplied by YTL Cement Sdn Bhd was used as partial cement replacement; the specific gravity and specific surface area of the GGBS used was 2.90 and 405 m$^2$/kg, respectively.

2.1.2. Aggregates

Manufactured sand passing through 5 mm and retained on 300 μm was used as fine aggregate. OPS with specific gravity of 1.30 were used as coarse aggregates, with size ranging between 2.36 and 14 mm. The OPS collected from a local crude palm oil mill were washed, air-dried and used in saturated surface dry (SSD) condition. Physical properties of OPS are listed in Table 1.

2.1.3. Superplasticizer and water

A polycarboxylic-ether (PCE) based superplasticizer (SP), commercially known as Glenium Ace 388 and supplied by BASF (Malaysia) Sdn Bhd was used to reduce the water and enhance the workability of the mixes. Potable water, free from contaminants and impurities was used for mixing.

2.1.4. Steel fibre

Hooked-end type steel fibres of length 60 mm with aspect ratio of 80 were used as steel fibres with high aspect ratio were reported to have better flexural performance [29]. The steel fibres used had minimum tensile strength of 1100 MPa as specified by the manufacturer.

2.2. Mix proportion and procedure

A total of five mixes were prepared with binder: water: sand: aggregate ratio of 1:0.33:0.65:1.70 for all mixes. The binder content was fixed at 550 kg/m$^3$ with 50% GGBS replacement (by mass) used for K series mixes (K1, K2, K3 and K4) while 100% OPC was used for mix N1. The steel fibre content was varied at 0% (K1), 0.5% (K2), 0.75% (K3) and 1.0% (K4) volume fractions. The SP used in all the mixes was kept constant at 1.0% by mass of binder.

The OPS and manufactured sand were mixed in the rotary drum mixer for about 3 min, followed by the addition of OPC and GGBS for another 6 min. After the addition of mixing water along with the SP, the mixing was continued for another 8 min. Finally, steel fibres were evenly distributed into the mixture and mixed. The concrete was then poured into moulds and compacted. All the specimens were demoulded after 24 h and moist cured until the day of testing. The testing plan was presented in Table 2.

2.3. Test methods

2.3.1. Mechanical properties

The mechanical properties tests on compressive strength (BS EN 12390-3: 2002), splitting tensile (BS EN 12390-6: 2009) and flexural strength (BS EN 12390-5: 2009) tests were performed on 100 mm cube, 100 mm φ × 200 mm height cylinder and 100 mm × 100 mm × 500 mm prism at the age of 28-day respectively. The static modulus of elasticity test was conducted on 150 mm φ × 300 mm height cylinders at the age of 28-day based on ASTM C469-10. In addition, the compressive strength test results performed at the ages of 1-, 3- and 7-day are reported.

2.3.2. Direct tensile test

The direct tensile test was performed based on RILEM TC 162-TDF. In this modified test, notched specimen with 100 mm φ and 200 mm height cylinder was used (Fig. 1). The depth of the notch was sawn to 7.5 mm in order to ensure the failure occurred in the mid-section of the specimen. The effective cross-sectional area was therefore reduced from 7854 to 5675 m$^2$. In the report by Barragan et al. [30], no significant influence of geometry characteristics of the test specimen was noticed in the direct tensile test.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Physical properties of OPS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical properties</td>
<td>OPS</td>
</tr>
<tr>
<td>Speciﬁc gravity (saturated surface dry)</td>
<td>1.30</td>
</tr>
<tr>
<td>Bulk density (compact) (kg/m$^3$)</td>
<td>635</td>
</tr>
<tr>
<td>Water absorption (24 h) (%)</td>
<td>538</td>
</tr>
<tr>
<td>Water absorption (24 h) (%)</td>
<td>24.4</td>
</tr>
</tbody>
</table>
Three LVDT were placed around the specimen at equal distances to measure the toughness ratio. The tests on direct tension, fracture and flexural toughness were conducted for 0%, 0.5%, and 0.75% of steel fibres. The addition of steel fibres up to 1.0% slightly increased the UPV (Fig. 5), and this justified that sufficient compaction and uniform mix could be produced using the steel fibres. Gencel et al. [32] reasoned that the minor variation in the measured and the predicted ODD could be attributed to uniform distribution of steel fibres in the SFOPSC mixes.

### 3.2. Ultrasonic pulse velocity (UPV)

The UPV test is done to assess the quality of the concrete; the higher the UPV, the superior the quality of concrete. The measurement of UPV is therefore useful for assessing strength of concrete, particularly on-site where destructive strength test is not applicable. The relationship between the UPV and the cube compressive strength measured at the ages of 1-, 7-, 28-day is shown in Fig. 4. It can be seen that the UPV of the SFOPSC generally increased with the increase in the compressive strength and the values were found within the range of 3.0–4.25 km/s (Fig. 4). The UPV measurement is also indicative of presence of cracks, voids and inhomogeneity of concrete. Although the addition of large quantity of steel fibres with high aspect ratio was known to cause clogging of fibres, improvement in the UPV is an indication of uniformity of the concrete mix.

### 3.3. Mechanical properties

#### 3.3.1. Compressive strength

As shown in Table 3, the increase in the steel fibre content improved the compressive strength of the OPSC. The addition of

<table>
<thead>
<tr>
<th>Mix</th>
<th>Mechanical properties test</th>
<th>Direct tensile test</th>
<th>Fracture and flexural toughness test</th>
<th>Compressive toughness test</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>100 mm cube (compressive strength test), 100 mm φ × 200 mm height cylinder (splitting tensile strength test), 100 mm × 100 mm × 500 mm prism (flexural strength test), 150 mm φ × 300 mm height cylinders (modulus of elasticity test)</td>
<td>100 mm φ × 200 mm height cylinder with notch depth of 7.5 mm</td>
<td>100 mm × 100 mm × 500 mm prism with bottom notch depth of 30 mm</td>
<td>100 mm φ × 200 mm height cylinder</td>
</tr>
<tr>
<td>K2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>K3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>K4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

in which

\[ g(\alpha) = \frac{1 - \alpha^2(2 - \alpha)}{\sqrt{\pi(1 + 2\alpha(1 - \alpha))}} \]

where \( R = \alpha/D, \beta = \text{maximum load + self-weight of specimen (kg)}, S = \text{span length (m)}.\)
steel fibres of 0.5%, 0.75% and 1.0% resulted in the increase of the compressive strength of about 10%, 30% and 37%, respectively. In the case of lightweight aggregate concrete, the cracks occur in the coarse aggregate before extending into the cement paste. When sufficiently good bond exists between fibres and cement paste, the steel fibres act as crack growth arrestors, thus increasing the ultimate compressive strength of concrete [19]. Further, in the case of fibres with high aspect ratio where fibres are stiffer, there is a better control of micro-crack development [33]. This could lead to a delay in coalescence of micro-cracks to form macro-cracks, and might enable the concrete to sustain additional loads. The ability of steel fibres to arrest both micro and macro-cracks in the pre-peak region could therefore be the contributing factor to the improvement in the compressive strength of the SFOPSC. The increase in the compressive strength of steel fibre reinforced concrete using OPSC was also reported by Shafigh et al. [34]. In their studies using other lightweight expanded clay as coarse aggregates, Chen and Liu [10] and Campione et al. [35] reported that the addition of steel fibre resulted in the increase in the compressive strength. Wang and Wang [15] found that the increase of compressive strength up to 23% with the addition of 2.0% steel fibre volume using lightweight shale aggregate. Lee and Song [36] found that the 1.0% addition of steel fibre increased the compressive strength of lightweight cellular expanded shale concrete by 37%. On the other hand, Balendran et al. [5] and Kayali et al. [37] reported that there was no significant effect of steel fibres on the compressive strength for Lytag and sintered fly ash aggregate concrete. The influence of steel fibre and GGBS on the compressive strength of SFOPSC can be seen from Fig. 6. The 28-day compressive strength was found about 23% higher than that of 7-day for 1.0% of fibre volume. This could be attributed to the presence of GGBS in addition to the increase in fibre content. The hydration of GGBS is slower at the earlier ages, and it could have contributed to weaker bonding of steel fibres with the binder matrix at 7 days. The increased in the GGBS hydration at 28 days could have led to stronger fibre–matrix bond, and thus effect of steel fibre was more pronounced at this stage.

The comparison of the compressive strength up to 90 days between the OPSC with 100% OPC and the OPSC with 50% GGBS as cement replacement is presented in Table 4. The 1-day compressive strength of the mix N1 was almost 83% higher compared to the mix K1. However, the difference in the strength between the two mixes reduced to 52%, 27%, 26% and 18% at 3-, 7-, 28-, and 90-day respectively. The reduction was due to the delayed hydration of GGBS, and as the by-product of calcium hydroxide from hydration of OPC was required for the GGBS to show its binding property [38]. The mix N1 had only 1% increment in compressive strength whereas 8% increase was found for the mix K1 and this showed that the hydration of OPC was almost completed at this stage while the GGBS hydration process still continues in the mixes with GGBS.

### 3.3.2. Modulus of elasticity (MOE)

The modulus of elasticity (MOE) is one of the most important material properties used in the design of concrete structures as it provides useful information on the ability of concrete to deform elastically. The 28-day MOE of the OPSC was found to increase with the addition of steel fibre as shown in Table 2 and similar finding is reported by other researchers [19,32,39–41]. The enhancement of MOE with the addition of steel fibre may be attributed to the effect of fibres in arresting the original shrinkage cracks in the concrete [19] and hence the fibres enhanced the stress redistribution and reduced the localized strain, thus giving a steeper slope in the stress–strain curve [32]. The increase of the MOE for the mixes with 0.5%, 0.75% and 1.0% of steel fibre was found to be about 10%, 52% and 58%, respectively. As seen from this result, the increase of the steel fibre from 0.75% to 1.0% has negligible effect in the enhancement of MOE of SFOPSC. It could be inferred that the use of 0.75% volume of steel fibre has the maximized potential in the stress transfer during the initial elastic stage of the SFOPSC. The effectiveness of 0.75% of steel fibre volume in the enhancement of MOE was also reported by Kurugol et al. [41], albeit using pumice stone as lightweight aggregate. As the MOE is a function of compressive strength of concrete, as seen from Fig. 7, a good correlation is established between these two parameters. The following equation is proposed to relate the cube compressive strength and MOE of SFOPSC:

\[
E = 6.31f_c^{1/2} - 26.90
\]

where \(E\) = MOE (GPa), \(f_c\) = cube compressive strength (MPa).
The MOE of the control mix N1 without the addition of GGBS was found to be about 35% higher than that of the mix K1 as indicated in Table 3. As known, the hydration of GGBS based concrete is slow at the early age and pores are not filled with the CSH gel. This might cause weak matrix with pores and results in low compressive strength. Therefore, the mix N1 was found to have higher MOE than the mix K1 as lower porosity leads to higher MOE [42]. Since the MOE is a function of the compressive strength, the lower MOE of GGBS-based OPSC could be due to the lower compressive strength compared to OPSC with plain OPC [43].

3.3.3. Splitting tensile strength

The splitting tensile test is an indirect and easier method to determine concrete tensile strength. The determination of concrete tensile strength is necessary to provide information on the maximum tensile load that a concrete member can sustain before cracking. In this investigation, it was found that the addition of steel fibre greatly improved the splitting tensile strength of the concrete. As found from this experimental investigation, the addition of 0.5%, 0.75% and 1.0% steel fibre volume enhanced the splitting tensile strength up to 93%, 133% and 178% respectively compared to the control concrete. When significant amount of tensile stress was introduced in concrete, micro-cracks and subsequently macro-cracks were formed. The increase in the load induces critical crack growth at the tip of macro-cracks which eventually led to failure of concrete [44]. The steel fibres act as a means of stress transfer whereby the tensile stress was transferred across fibres, which subsequently delayed the propagation of macro-cracks and improved the splitting tensile strength of concrete [32]. The relationship between the compressive strength and splitting tensile strength for SFOPSC at the age of 28-day was correlated in Fig. 8 and an equation for the relationship is proposed as follow:

\[
f_{t} = 4.22f_{c}^{1/2} - 21.47
\]

where \( f_{t} \) = splitting tensile strength (MPa).

The replacement of 50% OPC with GGBS was found to decrease the 28-day splitting tensile strength of OPSC. As seen from Table 3, the splitting tensile strength of the mixes K1 and N1 were found as 2.49 and 3.07 MPa, respectively. Kou et al. [45] also found that the use of GGBS decreased the splitting tensile strength due to delayed hydration that leads to the decrease in both the splitting and compressive strengths.

3.3.4. Flexural strength

The use of steel fibre with high aspect ratio is known to have more pronounced effect on the flexural performance of concrete [19]; this is attributed to longer length of steel fibres as it is more effective in delaying the crack propagation [17]. It was found in this study that the addition of steel fibre of 0.5%, 0.75% and 1.0% led to improvement in flexural strength to about 25%, 45% and 88%, respectively. The flexural strength as high as 8.90 MPa was recorded for SFOPSC with the addition of 1.0% steel fibre, which was significantly higher than for the OPSC as reported by Shafigh et al. [34]. The steel fibres with long length offer more resistance to pull out of fibres due to better bond characteristics [21]. Further, higher volume of steel fibre enables the fibres to cross the flexural cracks, thus giving rise to the efficiency of fibres in arresting the cracks. Thus, the failure load was increased to cause more cracks for failure, leading to a higher flexural strength [46]. The relationship between the compressive strength and flexural strength of SFOPSC is illustrated in Fig. 8 and the following equation is proposed for the relationship:

\[
f_{\text{flex}} = 4.02f_{c}^{1/2} - 18.63
\]

where \( f_{\text{flex}} \) = flexural strength (MPa).

Similar to the observation for splitting tensile strength, the mix K1 showed the decrease in flexural strength compared to corresponding control mix, N1 and the reasons attributed to low splitting tensile strength apply to flexural strength as well. However, it was worth noting that the ratio of flexural to compressive strength of the mix K1 was 6% higher than that for the mix N1. This proved that the use of GGBS slightly increased the flexural tensile strength of OPSC at a given compressive strength.

3.4. Direct tensile strength

Direct tension test was conducted as it is the most direct method in evaluating the tensile strength of concrete. It is an established fact that the tensile strength obtained from a direct tension test is usually lower than that of the result from an indirect splitting tensile test, while the flexural test gives the highest tensile strength.
values of energy absorption and is considered more suitable in comparing the ductility performance of FRC. The load–deflection curve for the SFOPSC specimens investigated in this study is shown in Fig. 10 and the calculated flexural toughness values are presented in Table 5. The control concrete produced the lowest final deflection and hence the area under the load–deflection curve used for the flexural toughness was calculated based on the final deflection of about 2.15 mm. The addition of steel fibre was found to have significant effect as it dramatically increased the toughness of the OPSC, with increase of about 6, 9 and 17 times higher than that of the control concrete for the specimens with the addition of 0.5%, 0.75% and 1.0% of steel fibres, respectively. As seen from Fig. 10, not only the peak load was increased with the addition of steel fibres, but the post cracking response was found to be totally different for the control specimens compared to the specimens with fibres. In the control concrete, after the attainment of the tensile capacity, the load dropped drastically, giving a steep falling branch in the load–deflection curve. On the other hand, the post-cracking falling branch of the SFOPSC specimens was relatively horizontal and the specimen, SFOPSC with 1.0% steel fibre exhibited the least steep falling branch. This progressive failure is attributed to the presence of steel fibres as the cracks that start at the soffit of the prism extend slowly to the top of the specimen[48] and the energy required to pull out of fibres gives rise to increase in the tensile strength of the concrete.

It should be noted that the increase in the direct tensile strength with the addition of 1.0% steel fibre was only 41%, as compared to 178% and 88% for splitting tensile and flexural strengths, respectively. One possible explanation for low tensile strength could be the orientation of certain fibres; some of the fibres might be oriented parallel to the crack and reduced crack bridging effect in the concrete [30]. The relationship between the direct tensile and splitting tensile strength is characterised by a strong R² value as shown in Fig. 9 and represented by the following equation:

\[ f_{	ext{dt}} = 9.43f_{	ext{sp}} - 5.19 \]  
\[ \text{R}^2 = 0.996 \]  

where \( f_{\text{dt}} \) = direct tensile strength (MPa).

### 3.5. Flexural toughness

One of the significant benefits on the addition of steel fibre in concrete is its improved post-cracking response. ASTM C1609-12 specifies the determination of flexural toughness through absolute

#### Table 4

<table>
<thead>
<tr>
<th>Mix</th>
<th>Compressive strength (MPa)</th>
<th>Splitting tensile strength (MPa)</th>
<th>Flexural strength (MPa)</th>
<th>Modulus of elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>33.51</td>
<td>2.49</td>
<td>4.73</td>
<td>9.71</td>
</tr>
<tr>
<td>K2</td>
<td>36.78</td>
<td>4.80</td>
<td>5.91</td>
<td>10.65</td>
</tr>
<tr>
<td>K3</td>
<td>43.57</td>
<td>5.80</td>
<td>6.88</td>
<td>14.79</td>
</tr>
<tr>
<td>K4</td>
<td>45.96</td>
<td>6.94</td>
<td>8.90</td>
<td>15.31</td>
</tr>
<tr>
<td>N1</td>
<td>42.28</td>
<td>3.07</td>
<td>5.62</td>
<td>13.16</td>
</tr>
</tbody>
</table>

Table 4: Strength gain for K1 and N1 mixes.

Note: Values in parentheses represent percentage in compressive strength gain.

![Fig. 6. Relationship of steel fibre volume with 7- and 28-day compressive strength.](image)

![Fig. 7. The relationship of compressive strength and 28-day MOE.](image)
energy required to create a unit area of crack surface, measured by the area under the load–deflection graph and calculated based on Eq. (1). The fracture energy for the control specimen, K1 with a 28-day compressive strength of 35 MPa was found as 555 N/m. Cui et al. [49] used area under load–CMOD curve to determine the fracture energy for NWC and lightweight expanded shale concrete with the compressive strength of 55 MPa and 45 MPa, respectively and reported the values as 1680 and 935 N/m. The comparison between the fracture energy of the OPSC and the lightweight expanded shale concrete shows that the former with a lower compressive strength of 35 MPa produced 60% of the fracture energy of the latter.

In contrast to the plain concrete specimens, the addition of steel fibre was found to enhance the fracture energy of SFOPSC. This could be attributed to the role of steel fibres that divert the crack paths and also prevent direct propagation of the cracks. And this increases the fracture area and the work of fracture. The increase of steel fibre content from 0.5% to 0.75% and 0.5% to 1.0% enhanced the fracture energy by approximately 1.5 and 2.9 times, respectively. Sahin and Koksal [18] used NWC of grade 45 and steel fibres of aspect ratio of 80, and found the increase of fracture energy by about 2.2 and 3.6 times for the addition of steel fibres from 0.33% to 0.67% and 0.33% to 1.0%, respectively.

The fracture energy alone is not sufficient to characterize brittleness or ductility of concrete. In addition, the characteristic length is used as a measure of brittleness since it includes the influence of material and size of structure [16]. The characteristic length is proportional to fracture energy; higher characteristic length leads to tougher concrete. It can be seen from Table 5 that the characteristic length of OPSC increased from 869 to 1288, 1914 and 2568 mm with the addition of 0.5%, 0.75% and 1.0% steel fibre, respectively. Hence, it can be shown that the addition of steel fibre greatly improved the toughness and ductility of OPSC, especially with 1% of steel fibre.

### Table 5

<table>
<thead>
<tr>
<th>Mix</th>
<th>Flexural toughness (N mm)</th>
<th>Toughness ratio</th>
<th>Fracture energy, Gf (N/m)</th>
<th>Fracture toughness, Kc (MPa m(^{1/2}))</th>
<th>Characteristic length, lch (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>3364</td>
<td></td>
<td>555</td>
<td>0.563</td>
<td>869</td>
</tr>
<tr>
<td>K2</td>
<td>18,983</td>
<td>5.64</td>
<td>2786</td>
<td>0.865</td>
<td>1288</td>
</tr>
<tr>
<td>K3</td>
<td>29,956</td>
<td>8.90</td>
<td>4354</td>
<td>1.266</td>
<td>1914</td>
</tr>
<tr>
<td>K4</td>
<td>56,032</td>
<td>16.66</td>
<td>8080</td>
<td>1.877</td>
<td>2568</td>
</tr>
</tbody>
</table>

Fig. 8. Relationship between compressive strength and tensile strengths (splitting tensile and flexural strengths).

Fig. 9. Relationship between the direct tensile and splitting tensile strength of SFOPSC.

![Fig. 8.](image)

![Fig. 9.](image)

![Fig. 10.](image)

![Fig. 11.](image)
The fracture toughness, $K_{IC}$, is determined by the value of critical stress intensity factor, as this is measure of the crack propagation. The $K_{IC}$ obtained for the control OPSC is 0.563 MPa m$^{1/2}$, which is slightly lower than the range of 0.61–0.82 MPa m$^{1/2}$ obtained by Eskandari et al. [50] using self-compacting concrete with compressive strength of 45 MPa. It should be noted that the use of OPSC with lower compressive strength of 35 MPa managed to achieve similar $K_{IC}$ value to those of self-compacting concrete with higher compressive strength. However, with the addition of steel fibres, the fracture toughness improved to 0.865, 1.266 and 1.877 MPa m$^{1/2}$ for 0.5%, 0.75% and 1.0% volume fraction, respectively. The enhancement of the fracture toughness in the SFOPSC could be due to the mechanism of fibres undergoing de-bonding, sliding against matrix and stabilization of the matrix cracks by exerting closure traction on crack surfaces [51].

3.7. Compressive toughness

The load-deformation graphs for the mixes K1, K2 and K3 are presented in Fig. 12. It was observed that the addition of steel fibre slightly increased the peak compressive load of the OPSC, but greatly enhanced the post-peak compressive ductility of OPSC. The compressive toughness values calculated using the area under the load-deformation curves by integration were found to be 147, 433 and 864 kN mm, respectively for the mixes K1, K2 and K3. This shows that the addition of 0.5% and 0.75% steel fibre improved the compressive toughness of the OPSC by almost 3 and 6 times, respectively. It can be seen from Fig. 12 that the area under the peak load of the SFOPSC specimens was higher than the corresponding area of the control specimen and this is an indication of higher energy absorption of SFOPSC even before the peak load. One possible explanation for high energy absorption of the SFOPSC specimens could be due to the effective micro-cracks bridging of steel fibre that increases the stress and deformation capacity of concrete prior to peak load. In the post-peak region, the control mix K1 exhibited much steeper falling branch compared to the mixes K2 and K3 as in the SFOPSC, the presence of steel fibre delayed the propagation of micro-cracks to form macro-cracks through its crack bridging mechanism as explained earlier. Hence, this mechanism allowed the SFOPSC to sustain more load with higher deformations, leading to an increased energy absorption capacity and compressive toughness of concrete.

4. Conclusions

The effect of steel fibres addition by 0.5%, 0.75% and 1.0% in SFOPSC on the density, UPV, mechanical properties, direct tensile strength, fracture parameters, flexural toughness and compressive toughness was investigated. The following conclusions are drawn from the investigation:

(i) The ODD of SFOPSC specimens that contained steel fibres up to 0.5% ODD was found to be within the limit of lightweight concrete as stipulated in EN206-1. However, a slight increase in the ODD was found for mixes with 0.75% and 1.0%.

(ii) The homogeneity of the concrete was not affected by the addition of steel fibres as UPV values were generally found to increase with addition up to 1.0% steel fibre. The UPV values of above 4.00 km/s for the mixes with steel fibres show that the concrete is of good quality and the fibres had no impact on the compaction of concrete that is generally encountered while using fibres.

(iii) The overall effect of fibres in arresting the crack and its propagation enhanced the mechanical properties of OPSC such as compressive strength, splitting tensile strength, and flexural strength. Further, the contribution of fibres to stress redistribution caused lower strain and improved the MOE as for the same stress level the strain produced in the OPSC was higher compared to the SFOPSC.

(iv) The direct tensile strength obtained in this investigation gave lower values of concrete as compared to the splitting tensile and flexural strengths. The direct tensile strength of SFOPSC was found to increase with the increase in steel fibre volume. Despite the increase in steel fibre content, the enhancement in the direct tensile strength was found lower compared to the splitting tensile and flexural strengths.

(v) The addition of 1.0% of steel fibre significantly improved the flexural toughness of the SFOPSC by up to 16 times compared to OPSC. The improvement is attributed to better post-crack response as the steel fibres are effective in imparting ductility to the concrete.

(vi) The fracture parameters such as fracture energy, fracture toughness and characteristic length investigated for the SFOPSC indicate improved performance due to addition of steel fibres. The fracture energy was enhanced by almost 3 times when steel fibres were added from 0.5% to 1.0% volume fraction.

(vii) The ductility of the SFOPSC of cylindrical specimens under compression measured as compressive toughness shows significant improvement by about 3 and 6 times with the addition of 0.5% and 0.75% of steel fibre, respectively.

Acknowledgements

This research work was funded by the University of Malaya under the High Impact Research Grant (HIRG) No. UMC/HIR/MOHE/ENG/02/D000002-16001 (Synthesis of Blast Resistant Structures). The authors are grateful to YTL Cement Sdn Bhd for the supply of GGBS used in this study.

References


