Structural behaviour of reinforced concrete beams containing a novel lightweight aggregate

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Abstract: This paper reports the results of an experimental investigation into the structural behaviour of reinforced concrete beams incorporating a novel EPS-based lightweight aggregate (LWA) called stabilised polystyrene (SPS) aggregate. Four concrete mixtures with water to cement (W/C) ratio of 0.8 were used. The replacement levels of natural aggregate by SPS were 0%, 30%, 60% and 100%. The volume ratio to manufacture SPS aggregate was 8:1:1 (80% waste EPS: 10% cement: 10% clay). A total of 24 beams were cast and tested at 28-day age. Three types of tension reinforcement were used: 2 bars, 3 bars and 2 bars + shear links. There were no compression bars at the top for all beams. Four point-loading flexural tests were conducted up to failure. In general, it can be observed that the structural behaviour of SPS concrete beams is similar to that of other types of lightweight aggregate concretes used around the world.

Keywords: waste polystyrene; lightweight aggregates; LWA; compressive strength; structural behaviour; deflection; reinforced concrete beam.


Biographical notes: Bengin Masih Awdel Herki was awarded a PhD scholarship in 2011 and his academic career began as a research student at the University of Wolverhampton, UK. He moved to Soran University in Kurdistan, Iraq as a Lecturer in 2014 then as the Head of Civil Engineering Department. He became the Dean of the Faculty of Engineering at the Soran University in 2015. His current research focuses on the utilisation of waste and recycled materials in producing high quality construction materials.

Jamal M. Khatib is a Professor of Civil Engineering (Construction/Structural Materials) – Faculty of Science and Engineering at the University of Wolverhampton. Prior to the present post, he was a Senior Lecturer at Sheffield Hallam University and a Research Fellow at the Universities of South Wales

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and Aberdeen. He obtained his MSc in Structural Engineering from Liverpool University. He obtained his PhD in Concrete/Structural Materials from Aberdeen University. His research area is in the general field of construction materials and management and innovative use of industrial by-product, waste, recycled and novel materials in construction. He had 15 PhD completions, currently supervising more than ten PhD students and over 20 PhD examinations. He has published more than 300 papers in the field of sustainable construction/structural materials. He has an ISI Web of Knowledge H-index of 15 and more than 2,400 citations.

1 Introduction

Expanded polystyrene (EPS) is a thermoplastic material and is mainly used as packaging and insulating products in various industrial fields around the world. A large quantity of EPS is disposed of as waste and left as stockpiles, landfill material or illegally dumped in selected areas. It has been reported that more than 112,000 tons of EPS were used for post-consumer protective packaging in the USA only in 1996. It has also been reported that around 300,000 tons of waste EPS are disposed of in landfill in the UK each year; because up to 95% of EPS is air, it occupies 38,000,000 m$^3$ of space in landfill, which is enough to fill 15,000 Olympic-sized swimming pools! This will ultimately cause pollution and is harmful to the ecosystem. National and international environmental regulations have also become more inflexible, causing this waste to become increasingly expensive to dispose. Therefore, utilising waste polystyrene in place of natural aggregate in lightweight aggregate (LWA) concrete production not only solves the problem of disposing this ultra-light solid waste but also helps preserve natural resources (Bhutta et al., 2011; Glenn and Orts, 2001; Polymelt, 2013). However, EPS beads are extremely light with very low densities which can cause segregation in mixtures. In addition, EPS beads are hydrophobic, which results in poor bonding to cement paste. Hence, some researchers (Noguchi et al., 1998; Guan et al., 2007; Miskolczi et al., 2006; Amianti and Botaro, 2008; Asaad and Tawfik, 2011; Batayneh et al., 2008; Kan and Demirboğa, 2009) have conducted experiments to improve the properties and resistance to segregation including adding some bonding additives such as aqueous epoxy emulsions and aqueous dispersions of polyvinyl propionate, chemically pre-treated EPS beads, adding ultra-fine SF to improve the bonding between EPS and cement paste, using super-plasticisers to increase the workability of concrete, and thermal modification, etc. However, these techniques may not be sustainable, environmentally friendly and readily available around the world. The novel technique used in the present study to produce a novel LWA will improve the resistance to segregation of EPS beads, increase the utilisation of waste materials and contributes towards sustainable development.
2 Previous work

The bond performance of reinforced EPS concrete using glass fibre reinforced polymer (GFRP) bars was examined earlier (Tang et al., 2008). They used three surface treatment methods for the bars:

1. smooth and circular GFRP bar
2. smooth and elliptical GFRP bar
3. sand-coated circular GFRP bar.

They observed that the type 3 bar (sand-coated circular bar) obtained the highest bond strength. The bond strength increased with an increase in the compressive strength and density of EPS concrete.

Researchers (Teo et al., 2006) investigated the flexural behaviour of reinforced LWA concrete beams containing oil palm shell. The beams with varying reinforcement ratios were tested and their strength, cracking, deformation and ductility behaviour were examined. The investigation revealed that the flexural behaviour of reinforced concrete beams made from oil palm shell aggregate was comparable to that of other lightweight concretes (LWC) and the experimental results satisfied the serviceability requirements of the Codes of Practice.

Researchers (Tang et al., 2006) investigated the characterisations of structural behaviour of reinforced LWA concrete beams made with polystyrene aggregate strengthened with near surface mounted (NSM) GFRP bars. The parameters examined in their investigation were type of concretes (control and polystyrene concretes), type of reinforcing bars (GFRP and steel), and type of adhesives. The modes of failure, moment-deflection response and ultimate moment capacity of the beams were examined. The results showed that beams with NSM GFRP bars showed a reduction in ultimate deflection and an improvement in flexural stiffness and bending capacity, depending on the polystyrene aggregate content. In general, beams strengthened with NSM GFRP bars overall showed a significant increase in ultimate moment ranging from 23% to 53% over the corresponding beams without NSM GFRP bars. The influence of epoxy (adhesive) type was found conspicuously dominated the moment-deflection response up to the peak moment.

Others (Sabaa and Ravindrarajah, 1997) studied engineering properties of EPS aggregate concrete by partially replacing natural coarse aggregate with equal volume of the chemically coated polystyrene at the levels of 30%, 50% and 70%. They found that compressive strength, unit weight and modulus of elasticity decreased and drying shrinkage and creep increased with increasing EPS aggregate replacement in concrete.

According to the literature, the primary use of concrete containing EPS has been in the manufacture of non-structural components for buildings (e.g., roof insulation, partition walls, etc.). However, the structural use of this concrete has been prevented due to the lack of knowledge on its structural properties. This paper presents the results of an experimental investigation into the structural behaviour of reinforced concrete beams incorporating an EPS-based LWA called stabilised polystyrene (SPS) aggregate using a novel technique.
3 Experimental program

3.1 Materials

The cement used was Portland cement. The chemical (composition) characteristics of cement are given in Table 1. The natural aggregate used was a low cost aggregate with bulk density of 1,673 kg/m$^3$, water absorption of 1.1%, specific gravity of 2.65, saturated surface dry (SSD) specific gravity of 2.67 and 0–8 mm in sizes conforming to the British standard requirements. The particle size distributions (sieving) details of natural aggregate according to British Standards Institution, BS EN 933-1 (1997) are presented in Figure 1. The properties of natural aggregate are presented in Table 2. A novel waste EPS-based aggregate called SPS was also used to replace natural aggregate partially and totally in the concrete mixtures.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Chemical compositions of the cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constituent</td>
<td>SiO$_2$</td>
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<tr>
<td>Value (%)</td>
<td>22.8</td>
</tr>
</tbody>
</table>

Figure 1: Particle size distributions of natural and SPS aggregates

3.1.1 Manufacturing process of SPS aggregate

The general description of manufacturing process of this novel LWA is shown in Figure 2. In the present study, and in order to improve the resistance to segregation of EPS particles, a new technique has been used. The crushed waste polystyrene, clay and cement were mixed with water then formed into ‘cake’ which was then dried (cured in the controlled laboratory environment of 20 ± 2°C and 60%–70% relative humidity (RH) for 14 days) and re-crushed into a novel LWA called SPS. A volume ratio of 8:1:1:1.5 (80% waste EPS: 10% clay powder: 10% Portland cement: water) was adopted. Although no detailed study was conducted on the effect of bond between binder (coating) and EPS; it was found that the proportion; 80%(EPS)-10%(cement)-10%(clay) has given the best proportions in terms of working with the materials and increasing the utilisation of waste EPS (i.e., the best thickness of the coating that densifies the materials and enhances the
bond between EPS particles and mortar without using too much cement). The water to cement + clay ratio (W / (C + C)) was 0.75. The enhanced cohesiveness of the binder at the time of wet mixing avoided the problem of very light particles separating and floating to the top of the mix. The particle size distributions (sieving) details of SPS aggregate according to British Standards Institution, BS EN 933-1 (1997) are presented in Figure 1. The properties of SPS aggregate are presented in Table 2.

Figure 2 Manufacturing process of SPS LWA (see online version for colours)

Table 2 Properties of natural and SPS aggregates

<table>
<thead>
<tr>
<th>Properties</th>
<th>SPS aggregate</th>
<th>Natural aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density (Kg/m³)</td>
<td>457</td>
<td>1,673</td>
</tr>
<tr>
<td>Specific gravity (SSD)</td>
<td>0.80</td>
<td>2.67</td>
</tr>
<tr>
<td>Water absorption 24 h (%)</td>
<td>13.0</td>
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</tr>
</tbody>
</table>

For this experimental program, four concrete mixtures with three different reinforcement types were carried out consisting of 24 reinforced concrete beams with rectangular cross-sections of 100 mm width × 150 mm depth × 700 mm length. The cement content and the W/C ratio were kept constant at 320 kg/m³ and 0.8, respectively. The control mixture had a proportion of 1 (cement): 6 (natural aggregate).

Each mix comprised six beams; the first two beams containing two tension reinforcement steel bars only without shear reinforcement (without stirrups) (Type 1), two beams containing three tension reinforcement steel bars only without shear reinforcement (without stirrups) (Type 2) and the last two beams containing two tension reinforcement steel bars with shear reinforcement (with stirrups) (Type 3). Compression reinforcement was not used for any of the concrete beams. The first mixture, which is the control mixture, comprised natural aggregates and the remaining mixes were partially and fully replaced with an increasing amount of SPS aggregates by volume. The percentage replacements were 0%, 30%, 60%, and 100%. Table 3 illustrates the details of concrete mixtures. The reinforcement details of concrete beams are presented in Table 4.

Table 3 Details of mixtures

<table>
<thead>
<tr>
<th>Series no.</th>
<th>W/C</th>
<th>Mix no.</th>
<th>SPS (%)</th>
<th>Mixture constituents (kg/m³)</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cement</td>
</tr>
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<td>1</td>
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</tr>
<tr>
<td>3</td>
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<td>4</td>
<td>100</td>
<td>4</td>
<td>320</td>
<td>256</td>
</tr>
</tbody>
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Note: SPS – stabilised polystyrene, (% by volume); NA – natural aggregate.
<table>
<thead>
<tr>
<th>Beam code</th>
<th>Tension reinf. no. and size</th>
<th>Compre. reinf. no. and size</th>
<th>Shear links no.</th>
<th>Beam size B × D (mm)</th>
<th>Area of tensile steel, As (mm²)</th>
<th>As / h × d (%)</th>
<th>Tensile steel weight (g)</th>
<th>Shear links weight (g)</th>
<th>Total steel weight used (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M5-1A</td>
<td>2ø8</td>
<td>0</td>
<td>0</td>
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<td>1,817.0</td>
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</table>
Experimental work comprised of structural tests was conducted on three types of reinforcement for concrete beams containing varying amounts of SPS aggregate. The beams are simply supported and tested under two-point loading (Figure 3). The beams were loaded in 2 kN increments until failure and the following structural observations were made:

- load-deflection behaviour at mid-span for each increment
- mode of failure, crack pattern and load at first crack
- strain distribution at mid-span for load increment and the corresponding change in the neutral axis position.

For each mixture six cubes were cast and tested just after each beam was tested to determine the concrete’s compressive strength.

Figure 3  Loading set-up for the reinforced concrete beam specimens

### 3.2 Beam specifications

A total of 24 reinforced concrete beams were cast from four different mixtures as stated previously (Table 4). There were no compression bars at the top for all beams, but those in tension consisted of two and three for each mix combination. The variation in the number of bars on the tension side was used to obtain more data which could be used to maximise the efficiency/performance of reinforced concrete beams for low-cost housing and reduce the overall dead load of construction. The tension bars were 8 mm diameters. The shear links (stirrups) were also 8 mm diameters and were used for type 3 beams only. In type 3 beams, there were no shear links (stirrups) between two loading points (200 mm) but they were instead placed at 50 mm from the sides towards the loading points (between supports and loading points). The reinforcement arrangement for types 1, 2, and 3 is shown in Figures 4, 5 and 6, respectively. The steel reinforcement bars were already cut to size by the manufacturer. The steel stirrups were also bent to the appropriate dimensions; consequently for the type 3 reinforcement cage, the reinforcement and steel stirrups were then assembled using traditional wires.
3.3 Mixing, casting and curing of beams

A plywood mould was used for the casting of beams whereas steel moulds conforming to British Standards Institution, BS EN 12390-1 (2012) were used for the cubes. Before casting began, the moulds were visually inspected and cleaned thoroughly. Thereafter, a thin layer of oil was applied to the inside surfaces of the moulds for easy de-moulding.

The concrete mixer was then cleaned and slightly damped with a wet cloth to avoid any absorption of water by the concrete mixer. The natural aggregate, cement and SPS aggregates were then gently poured into the mixer according to their required quantities. Once all the dry materials were inside the mixer, water was then poured in little by little (1/3) while mixing. After 3–5 minutes of thorough mixing until the required texture of the concrete was obtained, the mixing process was stopped and a slump test was carried
out in accordance with British Standards Institution, BS EN 12350-2 (2009a) to test the fresh concrete properties such as concrete consistency and the workability.

In the meantime the pre-prepared reinforcement was gently placed into the moulds and appropriate cover (20 mm) was provided for top and bottom along with both sides. Using a shovel, concrete was poured in two layers; each layer was compacted using a vibrating table. The vibrating table was used instead of the poker vibrator due to the lightweight nature of the polystyrene material. Subsequently, using a trowel the top surface was levelled and neatly trimmed as best as possible.

Along with the beams, six cubes of 100 mm from each mix combination were also prepared to determine the compressive strength comply with British Standards Institution, BS EN 12390-3 (2009b) of concrete; concrete was poured into the steel moulds in three equal layers, then compacted using the vibrating table to a smooth finish and top surface. The completed beams and cubes were then left to settle down for approximately 24 hours at room temperature. The following day they were de-moulded and marked with the corresponding mixture propositions. The beams and cubes were wrapped with plastic sheets then cured at room temperature (at about 20ºC). They were in the curing process for 28 days.

4 Results and discussions

4.1 Workability and density

The slump values for concretes containing varying amounts of SPS aggregate are presented in Figure 7. The slump values were in the range of 3–36 mm. Without the use of super-plasticiser and with other factors (including W/C ratio and cement content) kept constant, the workability of the concrete increased with the increase in SPS content up to 60% before starting to decrease. At 100% SPS the slump was lower than that of 60% SPS (Figure 7). The decrease in concrete workability with higher percentages of SPS aggregate (100% SPS) may be due to increasing surface area or the absorption of a significant amount of water and cement paste by SPS aggregate. However, the pre-wetted method of SPS aggregate (wetted with the compensated aggregate absorption) mitigated this loss of mixture workability to a small extent. If EPS aggregate content is increased, the fresh concrete mix became rubbery, harsh, and difficult to place and compact (Sabaa and Ravindrarajah, 1997).

The density of concrete containing varying amount of SPS aggregate is presented in Figure 8. The densities for SPS lightweight aggregate concretes (LWAC) were in the range of 1,009–2,074 kg/m³. The SPS volume with the density of lower-than-natural aggregate in the mixes had a great effect on the concrete density. The density of the concretes decreased with the increase in SPS aggregate replacement (Sabaa and Ravindrarajah, 1997; Kan and Demirboğa, 2007). The concrete with 100% SPS aggregate was shown to produce a LWAC that can float on water. As we know the density of concrete significantly affects the mechanical properties of concrete. The density of SPS aggregate was much less than that of natural aggregate.
4.2 Compressive strength

The compressive strength of concrete containing varying amounts of SPS aggregate at 28-day curing period is presented in Table 5. The results show that the incorporation of SPS aggregates caused a reduction in the compressive strength of concrete depending on the level of replacement with natural aggregate. The compressive strength of the concretes decreased between 29%–78% compared to the control concrete. According to the study (Shafigh et al., 2012) LWC can be produced with an oven-dry density range of approximately 300–2,000 kg/m$^3$ and with corresponding cube compressive strengths from approximately 1 to over 60 MPa. In the present study, a LWC containing a novel LWA called SPS has been produced with an oven-dry density of 1,009–2,074 kg/m$^3$ and cube compressive strength of 4.56–16.66 MPa.

Table 5 Compressive strength of concrete containing varying amounts of SPS aggregate

<table>
<thead>
<tr>
<th>Mix</th>
<th>SPS (%)</th>
<th>Compressive strength (MPa)</th>
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</thead>
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<tr>
<td>6</td>
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<td>16.43</td>
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<tr>
<td>8</td>
<td>100</td>
<td>4.56</td>
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</tbody>
</table>

4.3 Flexural behaviour

As previously stated in the methodology, the beams were tested as a simply supported beam under a point loading test. For each test, two beams with the same SPS aggregate content and reinforcement type were prepared. The beams were painted white to make cracks easier to detect.
Figure 9  Load-deflection curves for concrete beams containing varying amounts of SPS aggregate for, (a) type 1 (2 bars) (b) type 2 (3 bars) (c) type 3 (2 bars + shear links) reinforcement
4.3.1 Deflection of beams

4.3.1.1 Effect of SPS aggregate

Figure 9 shows the load-deflection curves for beams containing 0% (control), 30%, 60% and 100% SPS aggregate for beams with Figure 9(a) 2 steel bars, Figure 9(b) 3 steel bars and Figure 9(c) 2 steel bars + shear reinforcement. Generally, for all beams the load tended to increase sharply and linearly until the first crack appeared with a small increase in deflection. The first cracks were mainly influenced by the concrete’s flexural strength, probably due to the low elastic modulus of SPS concretes and their high degree of compressibility compared with the control concrete. The cracks observed in SPS concretes were less wide and finer than in control concrete (Tang et al., 2006). The slope of the load-deflection curves decreased after the first crack has occurred and the relationship was still approximately linear until the steel started yielding. Beyond the yield point there was a large increase in deflection associated with a small increase in load. The experimental results also suggest that the incorporation of SPS aggregate had an effect on the load deflection behaviour. Generally, as the replacement levels of SPS aggregate in mixtures increased, the deflection also increased, which was largely consistent for all three types of reinforcements. The increase in deflection is an indication of increased ductility. The presence of SPS tends to reduce the failure loads. It can be interpreted that EPS beads (80%) in the SPS aggregate resulted in a substantial decrease in the concrete toughness (Sadrmomtazi et al., 2012). For example, the load at the failure point is lower for beams containing SPS and the higher the SPS aggregate content, the lower the load. However, the deflection of 100% SPS mixtures is higher than that of other mixtures (0%, 30% and 60% SPS) for all three different types of reinforcement.

4.3.1.2 Effect of reinforcement type

Figure 10 shows the load-deflection curves for beams with different types of reinforcement (2 steel bars, 3 steel bars and 2 steel bars + shear reinforcement) containing Figure 10(a) 0% SPS (control), Figure 10(b) 30% SPS, Figure 10(c) 60% SPS and Figure 10(d) 100% SPS aggregate. As the load increased, deflections also increased and it was observed that the beams with 2ø8 tension reinforcement + shear links deflected more under smaller loads as opposed to beams with 2ø8 and 3ø8 tension reinforcements without shear links. For example, at 10 kN load, the deflection for beams containing varying amounts of SPS aggregate and reinforced with 2ø8 bars + shear links was in the range of 0.18–0.63 mm, whereas for the beams with 2ø8 and 3ø8 tension reinforcements, the deflection was in the range of 0.19–0.48 mm and 0.14–0.39 mm, respectively. This is consistent with the findings of researchers (Adom-Asamoah and Afrifa, 2011) which investigated the flexural behaviour of phyllite LWA and reported that the beams with less reinforcement deflected more under smaller loads than beams with more reinforcement. It was also observed that the beams with 3ø8 tension reinforcement without shear reinforcement (links) deflected less.
Figure 10  Load-deflection curves for concrete beams with different reinforcements for,
(a) 0% SPS (b) 30% SPS (c) 60% SPS (d) 100% SPS
4.3.2 Mode of failure

Figure 11 shows the load at first crack for beams containing varying amounts of SPS aggregate for different types of reinforcement. For type 1 reinforcement (2 steel bars), as the SPS content increased, the load (18 kN) at which the first crack appeared was the same for control, 30% and 60% SPS replacements, and decreased to 10 kN for 100% SPS aggregate, indicating that the tensile strength of concrete decreases more for high replacement levels (100% SPS). For type 2 reinforcement (3 steel bars) as the SPS content increased, the load (24 kN) at which the first crack appeared was the same for control and 30% SPS aggregate, but decreased to 22 kN for 60% SPS and to 10 kN for 100% SPS replacements. For type 3 reinforcement (2 steel bars + shear links) as the SPS content increased, the load (16 kN) at which the first crack appeared decreased. However, the first crack load (14 kN) for concrete with 30 and 60% SPS content was the same and for 100% SPS was 12 kN. It is well known that a decrease in compressive strength leads to a decrease in tensile strength. The results suggest that up to 60% replacement level, the benefit to the first crack loads was not greatly affected by increasing the content of SPS aggregate, but it was greatly affected at 100% replacement. For example, the decrease in the first crack load for the concrete with 60% SPS replacement was 0%, 8% and 12.5% for reinforcement types 1 (2 bars), 2 (3 bars) and 3 (2 bars + shear links), respectively compared to the control concrete. The results shown in Figure 11 indicate that the load at first crack for concrete beams containing 0%, 30% and 60% SPS aggregate with 3 steel bars is higher than the other types of reinforcement, but for concrete beams containing 100% SPS aggregate with 2 bars + shear links, the first crack load is the highest, which shows the effect of stirrups at first crack load for concretes with high contents of LWA.

The cracks forming on the surface of the beam were mostly flexural cracks. For the beams containing varying amounts of SPS aggregate with 2ø8 steel bars as tension reinforcement, initial cracking occurred at about 69%–90% of its failure load, whereas for the beams with 3ø8 steel bars as tension reinforcement and 2ø8 bars + shear links, initial cracking occurred at 62%–84% and 36%–60% of its failure loads, respectively. This indicates that for lower reinforcement ratios, the first crack occurs at a higher percentage of the failure load as shown in Figure 12. This view is consistent with the findings of researchers (Teo et al., 2006) who found that different ratios of reinforcement have an influence on the initiation of the first crack with regard to its failure load. With continuous load increments, the cracks started to take a diagonal shape towards the compression zone of the beams. In general, it can be observed that SPS aggregate concrete beams demonstrate similar behaviour to that of other lightweight concrete beams such as those observed by earlier studies (Teo et al., 2006; Alengaram et al., 2008; Alengaram et al., 2011) on lightweight oil palm shell concrete beams. However, for SPS concrete to be accepted for structural applications, further investigations need to be conducted.

The experimental results of the present work also show that there is a decrease in the beams’ failure loads with an increase in SPS aggregate content for all three reinforcement types as shown in Figure 13. The failure load for concrete beams with 2 bar tension reinforcement and containing 0%, 30%, 60% and 100% SPS was 26.08, 22.58, 20.01 and 14.03 kN, respectively. The failure load for concrete beams with 3 bar tension reinforcement and containing 0%, 30%, 60% and 100% SPS was 37.13, 32.84, 25.95 and 15.10 kN, respectively. The failure load for concrete beams with 2 bar tension reinforcement + shear links and containing 0%, 30%, 60% and 100% SPS was 36.32,
30.91, 27.75 and 17.75 kN, respectively. The results obtained show that the beams with type 1 (2 bars) reinforcement recorded the lowest failure load for all SPS replacement levels compared with other types of reinforcement. The beams’ failure loads with type 2 (3 bars) reinforcement are higher than types 1 (2 bars) and 3 (2 bars + shear links) at 0 and 30% SPS contents, indicating enhancement of the bond strength between the concrete and steel for lower SPS replacement levels. The results also show that the beams’ failure loads in type 3 (2 bars + shear links) are higher than types 1 (2 bars) and 2 (3 bars) at 60 and 100% SPS content, indicating the positive effect of shear reinforcement (stirrups); thus compensating for the low compressive strength of SPS and enhancing the bond strength between the concrete and steel for higher SPS replacement levels. Generally, decreasing tension reinforcements (from 3 bars to 2 bars) and using shear links, the failure load decreased for control and 30% SPS concretes but increased for 60 and 100% SPS.

**Figure 11** Load at first crack of concrete beams containing varying amounts of SPS aggregate with different reinforcements

![Figure 11](image1.png)

**Figure 12** Percentage of first crack load to failure load of concrete beams containing varying amounts of SPS aggregate with different types of reinforcement

![Figure 12](image2.png)
Figures 14 to 20 show the mode of failure for concrete beams containing varying amounts of SPS aggregate (0%, 30%, 60% and 100% SPS) with different types of reinforcement (2 bars, 3 bars and 2 bars + shear links). The beams failed in the form of a diagonal crack which started in the tension side of the beam and, with progressive loads, propagated towards the compression side under the loads. The mode of failure for concrete beams containing varying amounts of SPS with different types of reinforcement was shear failure, except for beams with 2 bars + shear links where it was shear/compression (concrete crushing in the compression zone) failure. The yielding of the tensile reinforcement happened before the crushing of the compression concrete in the pure bending zone. A similar observation has been reported by Teo et al. (2006). For concrete beams containing 100% SPS the failure occurred near or at the support point.

Figure 13  Failure load of concrete beams containing varying amounts of SPS aggregate with different types of reinforcement

Figure 14  Mode of failure of beams containing 0% SPS (control) with 2 bars, 3 bars and 2 bars + shear links reinforcement (see online version for colours)
Figure 15 Mode of failure of beams containing 30% SPS with 2 bars, 3 bars and 2 bars + shear links reinforcement (see online version for colours)

Figure 16 Mode of failure of beams containing 60% SPS with 2 bars, 3 bars and 2 bars + shear links reinforcement (see online version for colours)

Figure 17 Mode of failure of beams containing 100% SPS with 2 bars, 3 bars and 2 bars + shear links reinforcement (see online version for colours)
**Figure 18** Mode of failure of beams with 2 bars reinforcement containing 0%, 30%, 60% and 100% SPS (see online version for colours)

**Figure 19** Mode of failure of beams with 3 bars reinforcement containing 0%, 30%, 60% and 100% SPS (see online version for colours)

**Figure 20** Mode of failure of beams with 2 bars + shear links reinforcement containing 0%, 30%, 60% and 100% SPS (see online version for colours)
Figure 21 Strain distribution of beams containing varying amounts of SPS aggregate with 2 bars reinforcement (see online version for colours)
Figure 22  Strain distribution of beams containing varying amounts of SPS aggregate with 3 bars reinforcement (see online version for colours)
Figure 23  Strain distribution of beams containing varying amounts of SPS aggregate with 2 bars + shear links reinforcement (see online version for colours)
Figure 24 Strain distribution of beams containing 0% SPS aggregate (control) with different reinforcements (see online version for colours)
Figure 25  Strain distribution of beams containing 30% SPS aggregate with different reinforcements (see online version for colours)
Figure 26  Strain distribution of beams containing 60% SPS aggregate with different reinforcements (see online version for colours)
Figure 27  Strain distribution of beams containing 100% SPS aggregate with different reinforcements (see online version for colours)
Figure 28 Neutral axis depth of beams with different reinforcements for, (a) 0% SPS (b) 30% SPS (c) 60% SPS (d) 100% SPS
4.3.3 Strain distribution

Figures 21 to 27 show the strain distribution diagrams and Figures 28 and 29 show the neutral axis depth for concrete containing varying amounts of SPS with different types of reinforcement. The strain distribution for load increments and the corresponding change in the neutral axis position was measured using a DEMEC strain gauge at various positions along the depth of the beam. The strain values of beams with different types of reinforcement increased with an increase in the SPS content. Generally, the neutral axis depth for concrete beams containing 0%, 30%, 60% and 100% with different types of
reinforcement was between 57–95, 60–95, 72–95 and 92–105 mm; this decreased with an increase in SPS content in concrete. As the load increased, the neutral axis shifted upwards towards the compression zone, which means the depth of the compression zone decreased for all concrete beams and types of reinforcement except for 100% SPS beams with 3 bars. The neutral axis depth for 100% SPS beams reinforced with 3 bars shifted downwards towards the tension zone, which means it increased and recorded the maximum depth compared with other concrete beams. The change in neutral axis position towards the compression zone indicates that the tension zone of the beam increased and the compression zone decreased.

5 Conclusions

The results show that as the replacement levels of SPS aggregate in mixtures increased, the deflection also increased, which was consistent for all three types of reinforcements (2 bars, 3 bars and 2 bars + shear links). The increase in deflection is an indication of increased ductility. The mode of failure for concrete beams containing varying amounts of SPS with different types of reinforcement was shear failure, except for beams with 2 bars + shear links which was shear/compression (concrete crushing in the compression zone) failure. In general, it is possible to use SPS LWA in concrete-based applications and the performance is comparable to other types of LWAC currently used around the world. The concrete containing 30% SPS aggregate with 16.43 MPa strength and 1,814 kg/m³ density can comply with the structural LWA concrete applications (e.g., beams) requirements of RILEM classification. The engineering properties of SPS concrete can be improved by decreasing W/C ratio and adding super-plasticiser, adding natural coarse aggregate, and increasing the amount of cement content. However, sustainability issues (economic-environment-social) should be taken into consideration.

The main recommendation for further possible work is to investigate the resistance of SPS aggregate to chemicals and how the clay content in the SPS aggregate affects the final concrete strength using different methods of curing.

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References


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