

*Full Length Research Paper*

# Comparison of mechanical and bond properties of oil palm kernel shell concrete with normal weight concrete

U. Johnson Alengaram\*, Hilmi Mahmud and Mohd Zamin Jumaat

Department of Civil Engineering, Faculty of Engineering, University of Malaya, Malaysia.

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The comparison of the fresh, mechanical and bond properties of grade 30 lightweight concrete, namely oil palm kernel shell concrete (OPKSC) with normal weight concrete (NWC) of similar strength is presented in this paper. Oil palm kernel shell (OPKS), an industrial waste has been used as lightweight aggregates (LWA) in the OPKSC. In addition, mineral admixtures, 10% of silica fume and 5% fly ash have been used. The OPKSC produced a density reduction of about 20% compared to NWC. The addition of silica fume enhanced the compressive strength and thus OPKSC produced 28-day compressive strength up to 37 MPa. The bond stress of the OPKSC was found about 86% of the corresponding NWC; however, there was no slip failure between OPKSC and the reinforcement. Further, the ultimate experimental bond stress of OPKSC was found nearly 2½ times higher than the theoretical values calculated based on BS standards.

**Key words:** Oil palm kernel shell concrete, mineral admixtures, density, mechanical properties, bond stress.

## INTRODUCTION

The manufacture and use of lightweight aggregates (LWA) from wastes such as expanded pelletized fly ash aggregates, sintered fly ash aggregates, expanded slag gravel, blast furnace slag etc. have in fact demonstrated the effectiveness of waste utilization in industrially advanced countries. In addition, production of LWA from the municipal and dredging wastes in the USA, Russia, Japan and other developed nations is a very significant development (Short and Kinniburgh, 1978; Chandra and Berntsson, 2003). The modern design procedures in the industrially advanced countries speak volumes about the expertise available in terms of knowledge, research and experience. Hence, the large-scale development of new types of LWA is more rapid.

In many developing and underdeveloped countries in Asia and Africa, the researches on the use of industrial waste materials such as oil palm shell (OPS) or oil palm kernel shell (OPKS) as LWA have shown that OPKS can

be used as potential LWA. Especially, in the agro-based developing countries such as Malaysia and Nigeria, there has been awareness on the utilization of agricultural and industrial wastes into potential construction materials. Abdullah (1984) was the first one to use OPKS as LWA in Malaysia and proved that complete replacement of normal weight aggregate (NWA) with OPKS is a possibility. In Nigeria, Okafor (1988) conducted further study on using OPKS and found out that similar to normal weight concrete (NWC), water to cement (w/c) ratio affects the mechanical properties of palm kernel shell-aggregate concrete. The 28-day compressive strength of OPKS concrete varied between 5 and 25 MPa based on mix design. Subsequently, other researchers (Okpala, 1990; Olanipekun et al., 2006; Mannan and Ganapathy, 2002; Alengaram et al., 2008; Jumaat et al., 2009) investigated physical, mechanical and structural properties of OPKS and have shown its behaviour similar to that of NWC.

Malaysia is the second largest oil palm exporting countries in the world. The demand for vegetable oil in the international market is on the rise. Every year, palm oil industries produce large volume of OPKS as waste

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\*Corresponding author. E-mail: [ujohnrose@yahoo.com](mailto:ujohnrose@yahoo.com).



(a) Oil Palm kernel shell



(b) Granite aggregate.

**Figure 1.** Coarse aggregates. (a) Oil Palm kernel shell (b) Granite aggregate.

material after the production of palm oil. Ramli (2003) stated that nearly 5 million ha of oil palm trees is expected by the year 2020 in Malaysia alone. This will increase the production of both palm oil and its wastes. Normally, the OPKS is attained by breaking the palm kernel. They are lightweight, but hard and come in different shapes and sizes. OPKS are not fully utilized and it has contributed to pollution. This kind of waste material can be utilized to substitute the conventional coarse aggregate to produce the LWC. Near the rural area where the palm oil factories are located, OPKSC can be used to build houses, drain segment etc. to replace the conventional normal weight concrete (NWC). This would pave way for sustainable construction as the depletion of natural resources such as granite or conventionally used coarse aggregates is on the rise.

The use of LWC permits greater design flexibility and substantial cost savings, reduce dead load, improved cyclic loading structural response, longer spans, better fire ratings, thinner sections, smaller size structural members, less reinforcing steel and lower the foundation costs. OPKSC is one of the structural lightweight concretes. From the previous studies done by the other researches, it has been found that the air-dry density of the PKSC was found in the range of 1725 to 1900 kg/m<sup>3</sup> (Abdullah, 1984; Okafor, 1988; Mannan and Ganapathy, 2002; Olanipekun et al., 2006; Alengaram et al., 2008; Jumaat et al., 2009). However, the compressive strength was found between 5 and 25 MPa. Though the compressive strength of OPKSC fulfils the requirement for LWC, higher strength of about 30 MPa is preferred for medium strength structural members.

The smooth surfaces of OPKS resulted in weaker bond, which in turn affected the mechanical properties. Thus, OPKSC produced compressive strength of about 20 to 25 MPa (Abdullah, 1984; Mannan and Ganapathy, 2002; Olanipekun et al., 2006). In order to produce OPKSC of grade 30 and above, the bond between the smooth convex surfaces of OPKS and cement matrix has to be improved. This necessitates the use of mineral

admixture in the OPKSC. Generally, silica fume (SF) has been used to produce high strength concrete and SF particles are 100 times smaller than cement particles. The extremely very fine SF particles have the ability to be located in the very close proximity of the aggregate particles (Neville, 1996). Thus the zone between aggregate and cement paste interface, which is called zone of weakness, could be strengthened by the use of SF.

The objective of this investigation was to improve the mechanical properties of OPKSC by incorporating 10% of silica fume and 5% of fly ash as additional and cement replacement materials, respectively. In addition, the bond property of OPKSC was investigated. Fresh and hardened concrete properties of both OPKSC and NWC were investigated. The mechanical properties studied include the following: compressive strength, modulus of rupture, splitting tensile strength and modulus of elasticity. These properties were compared with NWC of similar grade concrete.

## MATERIALS AND METHODS

### Cement and mineral admixtures

Ordinary Portland cement conforming to MS 522: Part-1:2003 with specific gravity and surface area of 3.10 and 335 m<sup>2</sup>/kg, respectively was used for all mixes. The residue on 45 and 90  $\mu$ m were respectively 6.8 and 0.6%. Class - F fly ash (FA) obtained from Lafarge Malayan Cement with SiO<sub>2</sub> content about 65% and relative density of 2.10 was used. 5% of FA on weight of cement was used as cement replacement material. 10% of silica fume (SF) in densified form with specific gravity of 2.10 was used as additional cementitious material for all mixes. About 1% of superplasticizer (SP) on cement weight was used for all mixes.

### Fine and coarse aggregates

Figure 1 shows the OPKS and crushed granite aggregates which were used as normal weight aggregates (NWA). The particle size distribution curves of fine and coarse aggregates are shown in

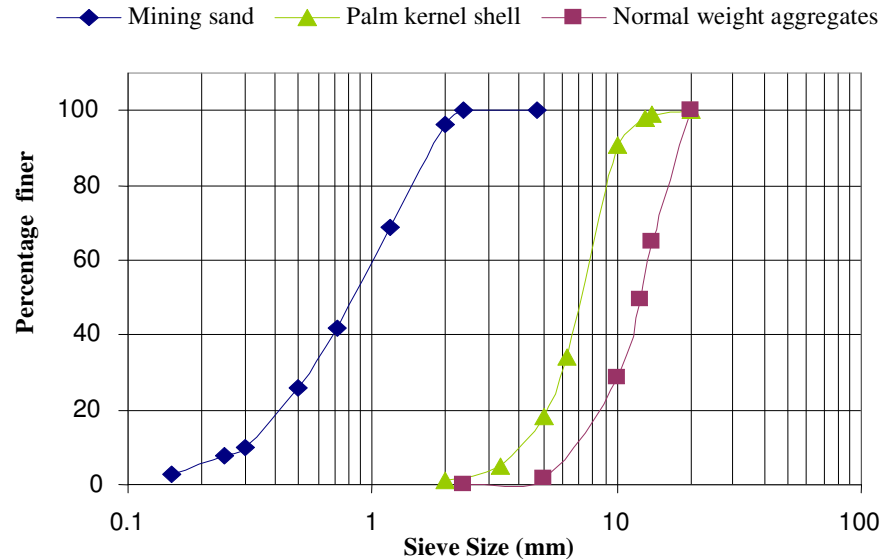


Figure 2. Particle size distributions of fine and coarse aggregates.

Figure 2. Mining sand with particle density of 2.7 was used as fine aggregates. OPKS were obtained from local crude palm oil producing mill. Since OPKS are waste materials, these are normally stockpiled in open fields, thus subject to varying climatic conditions.

As Malaysia is a tropical country with unpredictable rainfall throughout the year, the shells are bound to absorb moisture during such storage conditions; also during sunny days, the surface moisture may be dried out leaving some moisture inside the pores of OPKS. Hence the water absorption characteristics of OPKS were determined. Table 1 shows the comparison of properties of both OPKS and NWA. It can be seen from the results that NWA are superior in every aspect. However, the AIV of the OPKS is lower compared to NWA. Thus, OPKS has good shock absorbing characteristics. Higher water absorption of OPKS shows that pre-soaking is necessary or higher water content must be used to compensate for loss of water due to absorption.

### Preparation of specimens

Table 2 shows the mix proportions of both the OPKSC and the NWC. Two mixes in each case have been prepared for the following tests: 100 mm cube for compressive strength; 100 × 100 × 500 mm prism for flexural strength and 150 mm diameter × 300 mm cylinder for the determination of splitting tensile strength and modulus of elasticity. Specimens of 100 mm diameter and 200 mm height cylinder were used for pull-out test. The mixing was done in the following order: firstly OPKS in saturated surface dry condition was added with dry sand and mixed in mixer for about 2 min. Then one-half of cement and cementitious materials were added and part of water with superplasticizer was added. Then remaining materials were added and mixed. Specimens cast in moulds were demoulded after 24 h and cured in water till testing.

The preparation of pull-out test specimens is shown in Figure 3. The 12 mm diameter high yield strength deformed bar used in the pull-out specimen had yield strength ( $f_y$ ) of about 500 MPa. The ends of the reinforcement were provided with an un-bonded length of about 30 mm by means of plastic sheathing. A linear variable voltage transducer (LVDT) was used to determine the slip of the reinforcement. The pull-out specimens were tested at the age of 28 days in a 100 kN Instron testing machine. A linear variable voltage

transducer (LVDT) was used to determine the slip of the reinforcement in the pull-out test.

### Testing of specimens

#### Workability and density tests

Slump and flow table tests were used to measure the workability of concrete. While, both the tests were used for the OPKSC, slump test alone was used for NWC. The slump and flow table tests were conducted in accordance with BS EN 12350-2 and BS EN 12350-5 (BSI, 2000), respectively. The flow table test was developed in Germany and it has a hollow frustum of a cone with the dimension 200 mm diameter of the base, 130 mm diameter of the top and 200 mm height was used as a mould to form the test specimen. A 700 × 700 mm flow table which is made from a flat plate was used to carry out this test. The flow table is hinged to a rigid base onto which it can fall from a fixed height. A 40 mm square section and length of 200 mm tamping bar was used to tamp 10 times on each layer.

After the mould was raised vertically, raise the table top and let the table top fall freely. This cycle was repeated to give a total of 15 drops, each cycle taking not less than 2 or more than 5 s. The maximum dimension of concrete spread in two directions was measured and the flow value was obtained by taking the average value for the dimension of concrete spread in two directions. The fresh density of concrete were measured based on BS1881 - 107 (BSI, 1983).

#### Mechanical properties tests

**Cube compression test:** The compressive strength of concrete was determined in accordance with BS EN 12390-3 (BSI, 2002). The load was applied at a constant rate of 0.25 MPa/s on the specimen by a testing machine. The compressive strength, also known as crushing strength was obtained by dividing the maximum load applied over the concrete contact surface area.

**Splitting tensile test:** A 150 mm diameter and 300 mm height cylinder was used in this test. The specimen was placed with its

**Table 1.** Comparison of properties of aggregates.

Properties	NWA	PKS
Thickness (mm)	15	≈3.00
Bulk density (kg/m <sup>3</sup> )	1510	620
Specific gravity (SSD)	2.67	1.27
Fineness modulus	6.57	6.24
Water absorption - 1 h (%)	<1	10 - 12
Water absorption - 24 h (%)	<1	25
Aggregate impact value (AIV) (%)	16.78	3.91

**Table 2.** Mix proportion of concrete.

Mix details	Target density (kg/m <sup>3</sup> )	Ratio			Cement content (kg/m <sup>3</sup> )	Percentage on cement weight		
		Water/bin der (w/b)	Sand/cement (s/c)	Aggregate/cement (a/c)		Silica fume	Fly ash	Superplasticizer
OPKSC	1850	0.35	1.20	0.80	510	10	5	1.0
NWC	2400	0.65	3.35	2.63	315	NA	NA	0.5

**Figure 3.** Preparation of pull-out specimens.

axis horizontal between the platens of a testing machine according to BS EN 12390-6 (BSI, 2000). The load was applied on it until failure by indirect tension in the form of splitting along vertical diameter takes place.

**Flexural strength test:** This test was carried out by following BS EN 12390-5 (BSI, 2000). In this test, a plain concrete beam with 100 × 100 × 500 mm length prism was used. The prism was subjected to two-point loading until failure. The load positions were spaced at one-third of the span.

**Modulus of elasticity:** A specimen of cylinder 150 mm in diameter and 300 mm in height was used in this test according to BS 1881:

Part 121 (BSI, 1983). At the same time, three or more specimens shall be used to determine the mean compressive strength of the concrete. The compressive strength determines the stress that will be applied on the specimen. The strain measurement apparatus was placed in the test specimen. Initially the basic stress of 0.5 N/mm<sup>2</sup> was applied on the specimen. The load was increased steadily until it reached one-third of the compressive strength ( $f_c$ ) of the concrete.

#### **Bond behaviour**

The pull-out specimens were tested at the age of 28 days in a 100 kN Instron testing machine. The set-up of the loading and slip measurement is shown in Figure 4. The load was applied at an interval of 2 kN using the control panel of Instron. A linear variable voltage transducer (LVDT) was used to determine the slip of the reinforcement in the pull-out test. The data logger connected to the Instron and LVDT measured slip and load at every 2 kN load increment.

## **TEST RESULTS AND DISCUSSION**

### **Density**

Table 3 shows the saturated density of both OPKSC and NWC. The fresh density of the OPKSC was found approximately 1880 kg/m<sup>3</sup>, while for the NWC the fresh density was about 2335 kg/m<sup>3</sup>. The density reduction of the OPKSC was about 20 % on NWC. Normally for the lightweight concrete, the fresh density should be less than 2000 kg/m<sup>3</sup>. The density of the concrete depends on the particle density, sand content and type of sand used. The higher specific gravity of granite aggregate and higher sand content in the NWC resulted in higher concrete density. It can be seen from the Table 1 that in



Figure 4. Pull-out test set-up.

Table 3. Fresh and hardened concrete properties.

Concrete	Workability (mm)		Hardened concrete properties as of 28 days				
	Slump	Flow	Saturated density (kg/m <sup>3</sup> )	Compressive strength (N/mm <sup>2</sup> )	Splitting tensile strength (N/mm <sup>2</sup> )	Modulus of rupture (N/mm <sup>2</sup> )	Modulus of elasticity (kN/mm <sup>2</sup> )
NWC-1	65	NA	2335	31.83	2.85	4.21	30.71
NWC-2				33.04	2.65	4.42	31.08
OPKSC-1	105	400	1880	37.41	2.10	3.83	11.15
OPKSC-2				36.70	1.95	3.50	10.05

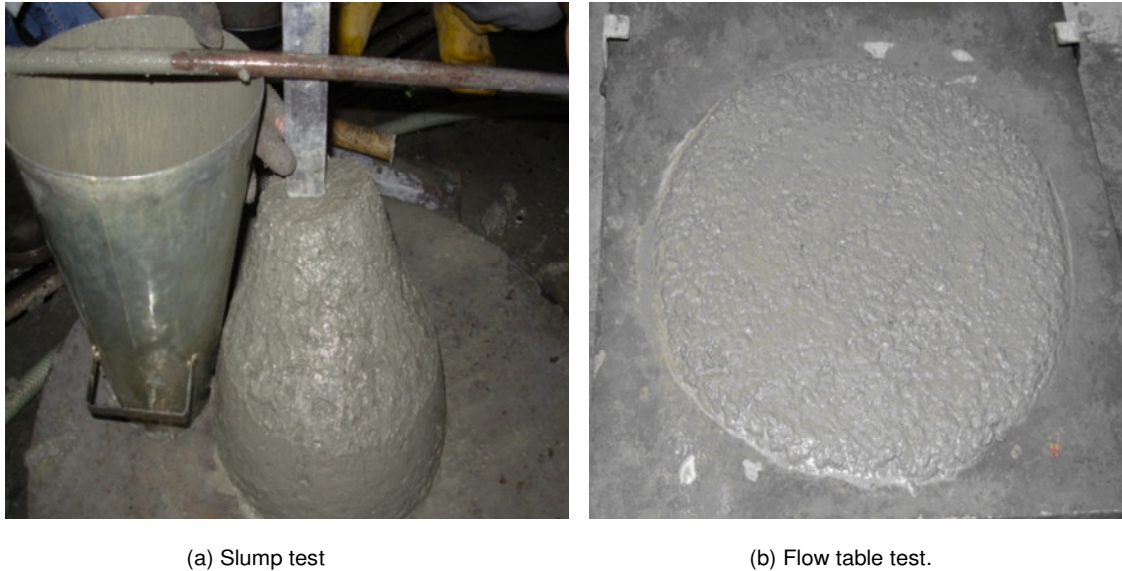
contrast to NWA, the specific gravity of OPKS was only 1.27 and hence it contributed to lower density of OPKSC. In addition, the quantity of sand used in the OPKSC was lower compared to NWC.

### Workability

The measured slump values for the NWC and the OPKSC were 65 and 105 mm, respectively as shown in Table 3. All the measured slumps were true slumps. According to the slump values, NWC produced medium workability while the OPKSC had high workability. It has been found that the silica fume that was added in OPKSC

increased the cohesiveness of the concrete. Thus, to produce the desired workability the addition of SP was mandatory. The spherical particles of fly ash generally contribute to workability. Figure 5 shows workability tests on slump and flow table.

As shown in the Table 2, the SP of about 0.5% on cement weight was added to NWC. However, in the OPKSC, the SP content was 1.0% and this provided fluidity of concrete that produced higher workability. Generally, for LWC concretes, the slump measurements underestimate the workability of concrete and hence flow table test is recommended for concrete in which the cohesion is improved (Clarke, 1993). Thus, the measured flow values were found about 400 mm for OPKSC. This



**Figure 5.** Workability tests. (a) Slump test (b) Flow table test.

result shows that the consistency of the OPKSC is good. Figure 5 (b) shows the flow of concrete measured using a flow table test. Normally, the diameters of flow of concrete in both directions are measured and the mean is reported as flow of concrete.

## Hardened concrete properties

### Cube compressive strength

Table 3 shows the hardened concrete properties at the age of 28 days. At the early stage, strength development in the OPKSC was found higher than the NWC. This could be due to the early strength development on the addition of silica fume. The silica fume reacts with the liberated calcium hydroxide to produce calcium silicate and aluminate hydrates and these both increase the strength (Robert et al., 2003). Thus, silica fume makes the concrete cohesive and influences stress transfer between the OPKS and the matrix. Since only 5% of fly ash was added, its effect on later strength was not established. Figure 6 shows the compressive strength development of both the OPKSC and the NWC up to an age of 90 days. The failure of OPKSC was mainly due to breaking of PKS showed strong bond between the OPKS and the cement matrix. However, the broken specimens showed that the convex surfaces of the OPKS still make the weaker bond between the OPKS and the concrete.

The 28-day compressive strength of about 37 MPa can be compared to the 28-day about 20 MPa for OPS concrete (OPSC) reported by Mannan and Ganapathy (2002). The comparison shows that the addition of silica fume and an increase in cement content in the present

study resulted in 85% increase in strength. However, the cement content used in their investigation was only 420 kg/m<sup>3</sup>. Teo et al. (2006) reported a compressive strength of about 26.3 MPa for OPSC using a cement content of 510 kg/m<sup>3</sup>. A comparison between OPKSC and OPSC (Teo et al. 2006) shows an increase of about 41% for OPKSC with same cement content. Thus, it can be concluded that addition of silica fume has immediate effect on compressive strength.

### Splitting tensile strength

It can be seen from the Table 3 that the average 28-day splitting tensile strength of OPKSC was about 2 MPa. Thus, it is approximately 6% of its compressive strength whereas for NWC concrete, the splitting tensile strength was about 8% of its compressive strength. As mentioned, the weaker bond between aggregate–matrix contributes to the lower tensile strength in OPKSC. In NWC, the rough surface of aggregates increases the bond and thereby increasing tensile strength.

### Modulus of rupture

The average flexural strength of 4.3 MPa of the NWC was about 13% of the 28-day compressive strength. However, the average modulus of rupture of the OPKSC of 3.7 MPa was only 10% of the 28-day strength. The variation in flexural strength between NWC and the OPKSC was mainly due to the strength and stiffness of the aggregates. Granite aggregate is very strong and stiff compared to OPKS, both in compression and in tension.

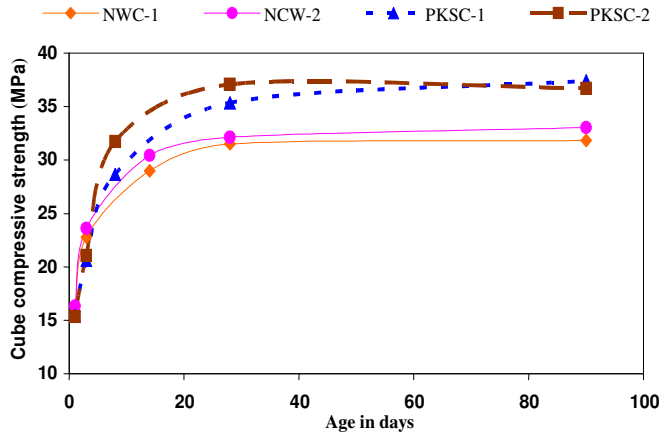


Figure 6. Development of compressive strength.



Figure 7. Pull-out failure of specimen. (a) Before test. (b) OPKSC after failure.

Generally, failure in tension occurs as a result of breakdown of bond between the matrix and the surface of the aggregate or by fracture of the matrix itself, not as a result of fracture of the aggregate. Since gravel stone have rough surface compared to OPKS, it tends to have better bonding with the cement paste. So, NWC showed stronger better flexural strength compared to the OPKSC. In the OPKSC, the broken specimen of the prisms in the modulus of rupture tests showed the failure of OPKS along the path of failure. This proves that weakness of OPKS in tension produced lower flexural strength than NWC.

### Modulus of elasticity or E-value

The modulus of elasticity increases with the compressive

strength and also the density of the concrete. The E-value for NWC concrete was found about  $27.2 \text{ kN/mm}^2$ , while the corresponding value for the OPKSC was only  $10.5 \text{ kN/mm}^2$ . This is only about 40% of the E-value of the NWC. However, it was reported by Mannan and Ganapathy (2003) in their finding that the E-value of the OPSC was only  $7 \text{ kN/mm}^2$ . A comparison between the present research and the OPSC showed that the OPKSC produced nearly 50% higher value than the OPSC. As known, the E-value is influenced by stiffness of coarse aggregate and interfacial zone between aggregate and cement paste.

For a similar cement content of  $510 \text{ kg/m}^3$ , Teo et al. (2006) reported elastic modulus of  $5.28 \text{ kN/mm}^2$  for OPSC. Thus, increase of 98% in elastic modulus of OPKSC with mineral admixtures is very significant. It is evident that the addition of silica fume enhanced overall mechanical properties of PKSC. This was mainly due to the stronger bond between the OPKS and the cement matrix. As silica fume is known for its distribution in the close proximity of coarse aggregates, it had enhanced the bond in the weaker zone of aggregate-paste interface (Neville, 1996).

### Bond behavior

As seen in Figure 7, the failure of pull-out specimens of the OPKSC by splitting of confining concrete showed that there was no pull-out failure. The failure of the OPKSC specimens was also sudden and the slip was not significant during the initial phase of loading. Similar trend in bond stress and slip behaviour was noticed for both the NWC and the OPKSC during the initial phase. Figure 8 shows the specimen after splitting of NWC specimens. As seen in Figure 8, the ends of the reinforcement were provided with an un-bonded length of about 30 mm by means of plastic sheathing.

Three pull-out tests specimens were tested each in OPKSC and the NWC. The average values of bond stress and the unloaded end slip are shown in Figure 9. The bond stress of the OPKSC was found close to the results reported earlier for the OPSC by Teo et al. (2007).

The BS 8110 (BS, 1997) relates the design ultimate bond stress ( $f_{bu}$ ) to the cube compressive strength of concrete. It also restricts the bond coefficient ( $\beta$ ) to 0.5 for type 2 deformed bars, inclusive of a partial safety factor ( $\gamma_m$ ) of 1.4. Thus, in accordance with the BS 8110, the design ultimate anchorage bond stress for the PKSC,

$$f_{bu} = \beta \sqrt{f_{cu}} = 0.5 \sqrt{36} = 3.00 \text{ N/mm}^2$$

The experimental bond stresses of the OPKSC plotted against the slip as shown in Figure 9 showed that the ultimate stresses were nearly  $2\frac{1}{2}$  times higher than the theoretical values calculated based on BS-8110. Thus, the bond stress of the OPKSC showed that it satisfied the

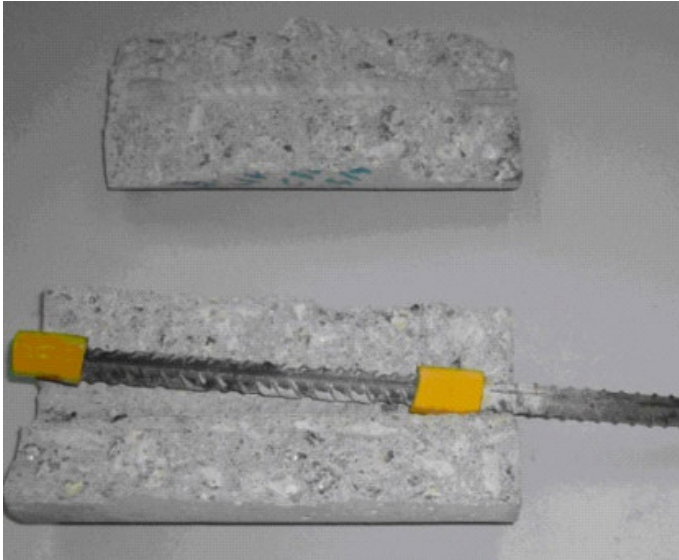


Figure 8. NWC specimen after splitting.

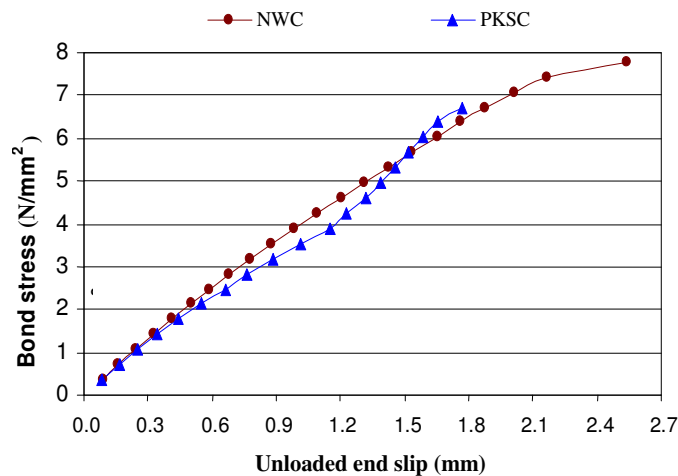


Figure 9. Bond stress and unloaded end slip.

bond criterion as per the code's requirement.

## Conclusions

The following conclusions can be drawn from the investigation: The OPKSC produced a density reduction of about 20% and high workability compared to NWC. The addition of silica fume increased the cohesiveness of OPKSC and hence the use of superplasticizer is mandatory to obtain desired workability. The reaction between silica fume and calcium hydroxide that was liberated due to hydration of cement enhanced the compressive strength. Thus OPKSC produced compressive strength increase of up to 85% compared to previously reported

values. However, in tension, the bond between OPKSC and cement matrix seems to be weaker compared to the bond between crushed granite aggregate and cement matrix. The modulus of elasticity of OPKSC was found between 50 - 98% higher than the previously reported values. Hence, it can be concluded that the addition of 10% silica fume enhanced the overall mechanical properties of the OPKSC. The no slip failure found for OPKSC was an indication that bond between OPKSC and the reinforcement was strong. Though the bond stress of OPKSC was 86% of grade 30 NWC, its ultimate experimental bond stress was found nearly 2½ times higher than the theoretical values calculated based on BS standards.

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