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STRUCTURAL BEHAVIOUR OF OIL PALM SHELL CONCRETE BEAMS

Mohd Zamin Jumaat[1], Hilmi Mahmud[1] and U.Johnson Alengaram[2]
[1]Department of Civil Engineering, Faculty of Engineering, University of Malaya, Malaysia
[2]Faculty of Engineering & Built Environment, SEGi University College, Selangor, Malaysia

ABSTRACT

In Malaysia the abundant availability of waste oil palm shell (OPS) had given rise to a number of researches on the use of OPS as lightweight aggregates (LWA) to produce lightweight concrete (LWC). This paper presents the experimental results on mechanical properties and structural behaviour of OPS concrete (OPSC). The behaviour of grade 30 OPSC was compared with that of similar grade normal weight concrete (NWC). Ten percent of silica fume and five percent of fly ash were added as mineral admixtures in the OPSC. An in-depth mix design programme was conducted to obtain the appropriate mix design for the OPSC. Mechanical properties investigated include compressive strength, modulus of rupture, splitting tensile strength and Young's Modulus. To study the flexural behaviour of OPSC, four reinforced OPSC and NWC beams of size 150 mm x 250 mm x 2600 mm were prepared. Each beam was tested under four point loading until failure. The experimental results were also compared with theoretical values and numerical analysis. The results show that the OPSC produced a density reduction of about 22% compared to NWC. However, the modulus of elasticity of OPSC was found to be about 46% of NWC. Similarly, OPSC produced 15% lower modulus of rupture compared to NWC. The flexural behaviour of OPSC beams shows superior performance compared to that of NWC. The experimental moment capacities of OPSC beams were found higher than the theoretical ultimate moment capacities obtained from the theoretical values and numerical analysis. The experimental ultimate moment capacity of OPSC beam was also found close to that of NWC beams. Though the lower modulus of rupture of OPSC resulted in early cracks, the OPSC beams exhibited a lot of cracking that resulted in smaller crack-spacing and crack widths compared to NWC beams. The crack widths of OPSC beams were also found within the serviceable limit state. The ductility ratio of OPSC beams was found to be twice that of the NWC beams.

***Keywords**: Oil palm shell; lightweight concrete; mechanical properties; flexural behaviour*

INTRODUCTION

Lightweight aggregate concrete (LWAC) using lightweight aggregates (LWA) gained a right place in concrete industry in 1920s in the USA and later during 1950s in Europe [1]. The main requirement for using lightweight aggregate is that it should have a crushing strength sufficient to have reasonable resistance to fragmentation[2]. While concrete using LWA can be produced with density of 2000 kg/m^3 or below, its density could be further reduced where the desired compressive strength is lower. RILEM classifies lightweight concrete (LWC) with compressive strength of 15 N/mm^2 or more as structural grade concrete-class-I, and strength between 3.5 and 15 N/mm^2 as structural and insulating concrete-class-II [3].

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. However, in many developing and underdeveloped countries in Asia and Africa, utilization of industrial wastes is in the preliminary research stage and hence manufactured LWA are not available. This may be attributed to various reasons, such as a general lack of understanding of the production techniques of LWA, towering production costs, and non-availability of raw materials and resources. In addition, there is insufficient information on the structural performance of LWC. Malaysia, Indonesia, Thailand and Nigeria produce significant quantities of palm oil and in that process large industrial wastes are dumped in the factory yards. During the last 20 years, there has been awareness in Malaysia, Thailand and Nigeria on the utilization of agricultural and industrial wastes into potential construction materials. The most notable one is the ongoing research on the use of industrial waste, known as oil palm shells (OPS) as LWA [4, 5, 6, 7].

Malaysia is the second largest palm oil producing country in the world and it produces more than half of world's palm oil. The requirement of vegetable oil is constantly increasing and more cultivation of palm oil is forecast in the near future [8]. At the same time, the production of palm oil result in by products such as empty fruit

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bunches (EFB), oil palm shells (OPS), pericap and palm oil mill effluent (POME). These are waste materials and stockpiling such wastes have caused storage problem in the vicinity of the factories as large quantities of these wastes are produced every day. Also, these wastes are stockpiled in open fields and thus it had negative impact on environment. One of the ways of disposing these wastes would be utilization of some of these into constructive building materials. This will also help to prevent the depletion of natural resources and to maintain ecological balance. OPS are hard stony endocarps that surround the kernel and the shells come in different shapes and sizes. They are light and naturally sized; they are ideal for substituting aggregates in LWC construction. Being hard and of organic origin, they will not contaminate or leach to produce toxic substances once they are bound in concrete matrix.

MATERIALS, SPECIMEN PREPARATION AND INSTRUMENTATION

Materials

Ordinary Portland cement (OPC) conforming to MS 522; Part-1:2003 with specific gravity and surface area of 3.10 and 335 m^2 / kg respectively was used for all mixes. Five percent of Class F fly ash (FA) and ten percent of silica fume (SF) both by weight of cement were used as cement replacement and additional cementitious materials respectively. The SiO_2 content and specific gravity of class F fly ash (FA) used in this investigation were 65% and 2.10 respectively. Silica fume (SF) in undensified form with specific gravity of 2.10 was used. No cementitious material was used in NWC.

Table 1: Properties of aggregates

Properties	Granite aggregate	OPS aggregate
Thickness (mm)	20	0.7 – 5.00
Bulk density (kg/m^3)	1510	620
Specific gravity (saturated surface dry)	2.67	1.37
Fineness modulus	6.57	6.24
Water absorption – 1 hour (%)	<1	10-12
Water absorption – 24 hr (%)	<1	24.5
Aggregate impact value (%)	16.78	3.91

Mining sand was used as fine aggregates with specific gravity of 2.7. It was dried and sieved to a particle size range between 0.15 and 2.36 mm. OPS used as coarse aggregates were obtained from local crude palm oil producing mill. Fig 1 shows the OPS in dried condition. Crushed granite aggregates were used as coarse aggregates for NWC. The comparison of properties of OPS and granite aggregates are shown in Table 1.

Figure 1: Oil Palm shells (OPS)

Preparation of Concrete, Beams and Instrumentation

The mix design of OPSC was based on relative densities of materials, FA as cement replacement, SF as additional cementitious material and proportion of the constituent materials. Table 2 shows the mix proportioning of the OPSC and NWC. The water to binder ratio (w/c) and aggregate to cement ratio (a/c) were kept constant for all mixes at 0.35 and 0.8 respectively for OPSC mixes. All the materials were weight batched. For NWC, the method recommended by the Department of Environment (DOE) was used to obtain grade 30 concrete.

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The mixing of materials for the preparation of OPSC was done in the following order: Firstly one-half of coarse aggregate and sand were mixed in the mixer. This was followed by addition of one-half of cement, fly ash and silica fume; part of water with superplasticizer was then added; on complete mixing, the remaining portion of materials were added in appropriate order. For NWC the order of mixing was similar to the OPSC, except for cementitious materials.

The specimens, 100 mm cube, 150 mm diameter and 300 mm height cylinders and 100 x 100 x 500 mm prism moulds were cast and covered with plastic sheeting in the uncontrolled laboratory condition for 24 hours and then demoulded. The fresh, as cured and oven dry densities of OPSC were measured. Workability tests by slump and flow measurements were done in accordance with British Standards. The mechanical properties investigated include compressive strengths, splitting tensile, modulus of rupture and modulus of elasticity at the age of 90 days.

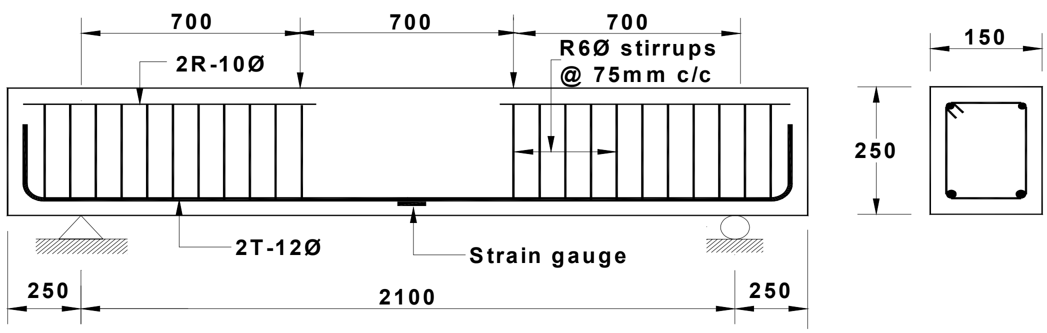
The reinforcement details of beams are shown in Fig.2 along with the sectional view of shear portion. It can be seen from the sketch that there was no holding bar provided in the pure moment zone. This was done to obtain typical flexural failure. Table 3 shows the beam and reinforcement details. A total of four beams two each on NWC and OPSC were cast.

All beams were designed as under-reinforced using BS 8110-Part 1:1997 [9] and cast in steel moulds. They were vibrated using internal vibrator and covered with jute clothes for 28 days and cured. Afterwards the beams were kept under laboratory condition till the day of testing at the age of 90 days. The testing arrangement of the beams is shown in Fig.3.

Table 2: Details of mix proportion of concrete

Mix proportions of OPSC and NWC								
Mix details	Target density (kg/m^3)	Ratio			Percentage			Cement content (kg/m^3)
		w/b	s/c	a/c	Silica fume[a]	Fly ash[a]	SP[a]	
OPSC	1870	0.35	1.20	0.80	10	5	0.5	500
NWC	2400	0.65	3.30	2.60	NA	NA	0.7	315

[a] by weight of cement



Note: All dimensions in mm
Clear Cover: 30 mm (all beams)

Figure 2: Reinforcement details of test beams

Table 3: Details of beam and reinforcement

Beam designation	Beam size (mm)	Bar size (mm)	Yield strength, f_y (N/mm^2)	Steel ratio ρ = As/bd (%)
NWC-B1	148 x 253	2T-12	500	0.36
NWC-B2	149 x 254	2T-12		0.36
OPSC-B1	152 x 253	2T-12		0.36
OPSC-B2	152 x 253	2T-12		0.36

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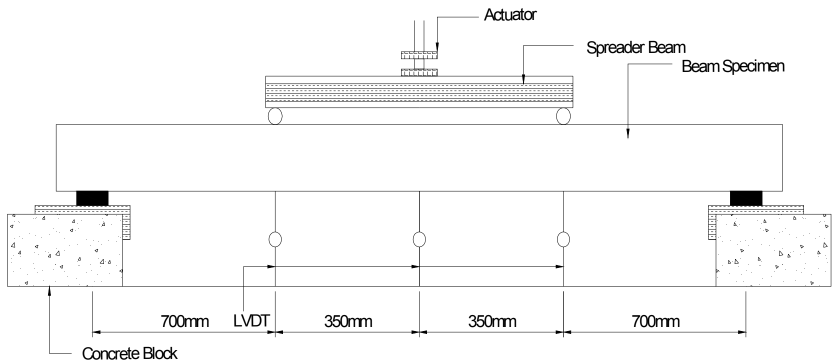


Figure 3: Testing arrangement for beams

The tensile and compressive strains of both reinforcement and concrete were measured through electrical resistance gauges. All the strains were recorded using data logger. In addition, the strain distribution on the vertical face of the beams in the flexural zone was determined using de-mountable digital extensometer with a sensitivity of 0.001 mm. Three linear voltage displacement transducers (LVDT) were placed, one at centre of beams, the other two under load points, to measure the deflections at centre and under load points. The crack widths at the level of tensile reinforcement were measured using hand held microscope with sensitivity of 0.02 mm. All the beams were loaded under two-point loads that were kept at 700 mm apart on a span of 2100 mm. All strain, crack width and deflection measurements were measured at every load increment of 5 kN.

TEST RESULTS AND DISCUSSIONS

Comparison of Mechanical properties

The mechanical properties at the age of 90-days of both NWC and OPSC are given in Table 4. The development of compressive strength is shown in Fig.4. The decrease in density in PKSC was about 24% as compared to NWC. The NWC designed for grade 30 produced 90-day cube compressive strength of little over 30 MPa. Thus, the comparison of 90-day cube strength of OPSC shows that an average increase in compressive strength of about 14% compared to NWC. Thus, it can be concluded that OPSC has advantage in both strength and density. However, OPSC contained SF of about 10% as additional cementitious material.

Table 4: Properties of fresh and hardened concrete

Concrete designation	As-cured density (kg/m^3)	Slump (mm)	Compressive strength (MPa)	Modulus of rupture (MPa)	Splitting tensile strength (MPa)	Young's modulus (kN/mm^2)
NWC-B1	2335	65	31.83	4.21	2.81	30.71
NWC-B2			33.04	4.42	2.85	31.08
OPSC-B1	1888	105	37.41	3.83	2.40	14.45
OPSC-B2			36.70	3.50	2.34	14.02

OPSC generally possess lower modulus of rupture compared to NWC. It can be seen from results given in Table 4 that an average 15% reduction of flexural strength in OPSC. Similarly the splitting tensile strength of NWC was 16% higher than the OPSC. The modulus of elasticity of OPSC is only about 46% as that of NWC. The broken specimen of the cubes, prisms and cylinders tested for mechanical properties shows bond failure along the convex surface of the OPS. In addition, the failure was also caused due to failure of OPS along the failure surface. Thus, it is evident that both the failure of OPS and the bond failure contribute to the lower mechanical properties compared to NWC. Lower modulus of elasticity of the OPSC is mainly attributed to lower stiffness of OPS and it will have effect on deflection of OPSC beams.

Mode of Failure

The flexural failure mode was observed for the both NWC and OPSC beams; thus the yielding of steel took place and this was followed by crushing of concrete in the compression zone. Since all the beams were designed as under-reinforced, the failure started by yielding of the tension steel bar before the compression failure of concrete as expected. As can be seen from Fig.2, in order to ensure typical flexural failure, the shear and compression reinforcements were not provided in the pure bending region. Also, the stirrup spacing was kept at 75 mm centres in the shear zone and thus all beams failed in typical flexural mode.

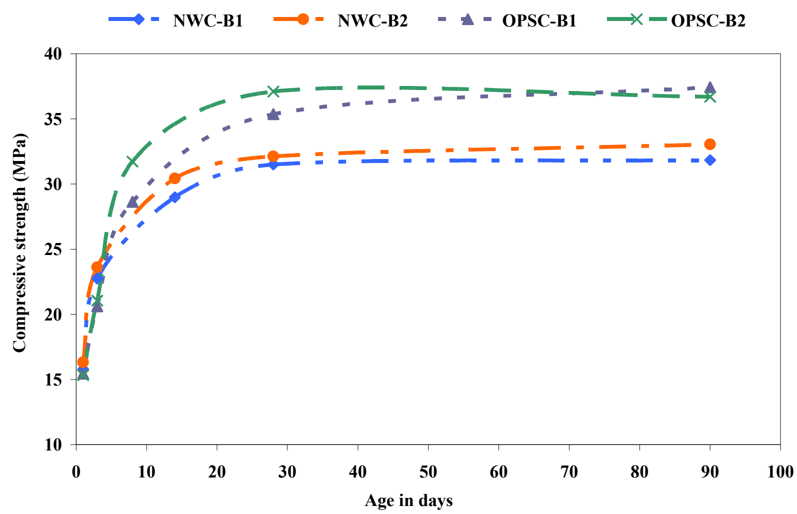
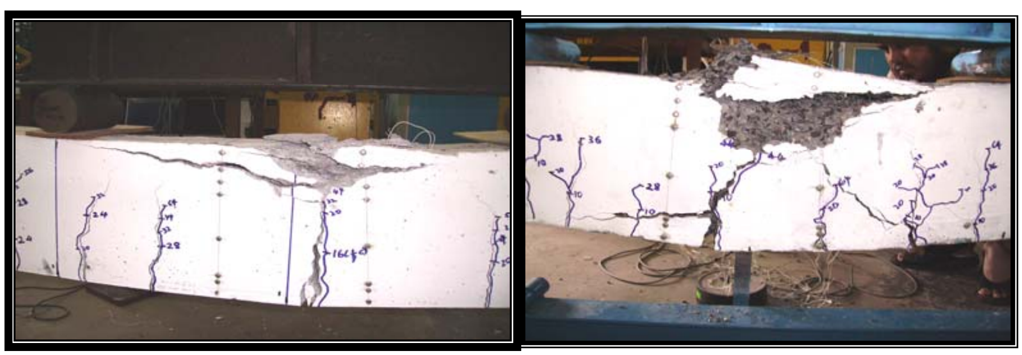


Figure 4: Development of compressive strength of NWC and OPSC

For both types of concrete, failure started with flexural crack and extended to the neutral axis. The first flexural crack, after reaching the neutral axis, started to incline to form compression failure zone. And the crushing of concrete took place in that zone during failure. NWC concrete exhibited brittle failure; the prolonged deflection at maximum load of OPSC beam has given sufficient warning before final failure and thus the beam failed in ductile manner. However, the failure zone of OPSC was larger than NWC beams as seen from Fig.5.



a) NWC beam *b) OPSC beam*

Figure 5: Failure mode of NWC beam

Table 5. Ultimate load, deflection and crack characteristics of NWC and OPSC beams

Beam designation	Ultimate load (kN)	First cracking load (kN)	First crack width (mm)	Maximum deflection (mm)	Theoretical ultimate moment (kNm)		Experimental ultimate moment M_e (kNm)	$M_e/M_{t,BS}$
					BS 8110, $M_{t,BS}$	Numerical analysis, $M_{t,FEA}$		
NWC-B1	76.01	16	0.06	42	24.91	26.95	26.10	1.05
NWC-B1	78.00	16	0.06	51	25.08	27.30	26.81	1.07
OPSC-B1	77.47	10	0.06	104	25.62	25.20	26.72	1.04
OPSC-B2	81.09	8	0.02	93	25.54	24.85	28.99	1.09

Deflection

Fig.6 shows the deflections at mid-span for all the four beams tested. As expected, OPSC beams have shown higher deflections. This may be attributed to their lower stiffness of OPSC compared to that of NWC. Table 4

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shows that the modulus of elasticity of PKSC is less that half that of NWC. Thus, the OPSC beams had undergone large deflections. It can also be seen that at early loads both NWC and OPSC beams behave linearly. At service moment, the actual deflections of OPSC beams were less than 10 mm and NWC beams also exhibit similar deflections under service loads. Though the modulus of elasticity of OPSC is only 46% as that of NWC, at service loads, the deflections of both NWC and OPSC beams are much closer.

The maximum deflections of NWC beams were found to be between 40 to 50 mm. However, OPSC beams exhibited higher deflections than NWC beams. The large deflections at near maximum load of OPSC beams exhibited ductile behaviour that gave ample warning before total collapse. The NWC beams failed in brittle manner as expected. The ratio of maximum deflection near collapse to deflection at first crack for OPSC beams is about 100 and this shows that OPSC beams are highly ductile compared to NWC beams.

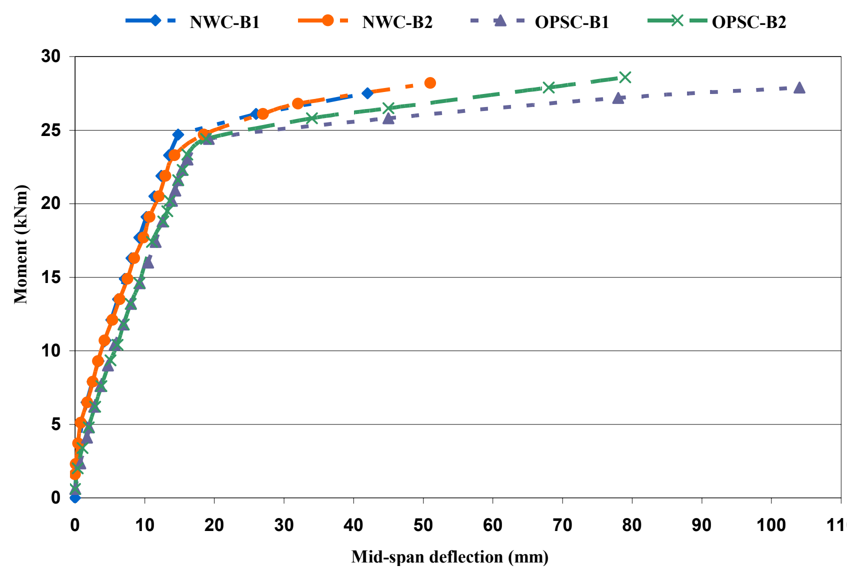


Figure 6: Deflection of NWC and OPSC beams

Crack Width

Fig. 7 shows the relationship between load applied and the crack width. Generally, in beams cracks occur when the stress in the tensile zone reaches the modulus of rupture of the concrete beam. Table 5 shows the summarized values of first crack load, and first crack width. For all four beams, the first crack appeared at the centre of the beam. Fig. 8 shows the crack pattern for the OPSC and NWC beams for one-half of portion. The vertical pattern of cracks indicates that they were flexural cracks. The average spacing of crack width for NWC is 150 mm while it was closely spaced at 70 mm for OPS concrete beams. Generally, closed spaced cracks or more number of cracks is an indication of smaller crack width. In one of the OPSC beams, referred to here as OPSC: B1, the crack width was slightly smaller compared to other OPSC: B2. OPSC beams had more number of cracks of about 25 to 30 compared to average number of cracks of 12 for NWC. Thus, OPSC beams had lesser crack width and bore highest failure load compared to other beams tested.

Under service load condition, the crack width of OPSC beams did not exceed the value of 0.3 mm, as stipulated by BS 8110. Whereas, the crack widths of NWC beams are close to the allowable crack width of 0.3 mm at the service loads. Thus, OPSC beams fulfilled BS Code specification on crack. Table 5 shows that the first crack load for OPSC is quite low compared to NWC beam. This is because of the lower modulus of rupture for OPSC than NWC. The crack widths and spacing are subject to wide scatter; however for the beams tested in this experiment, the test readings show consistency.

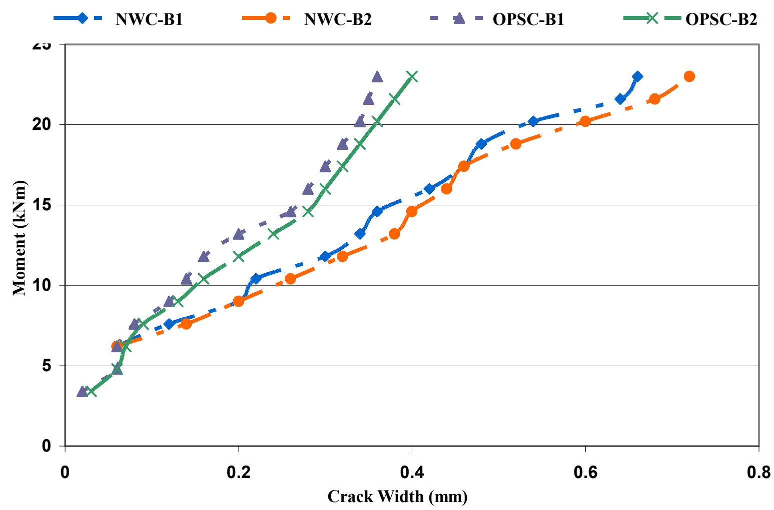
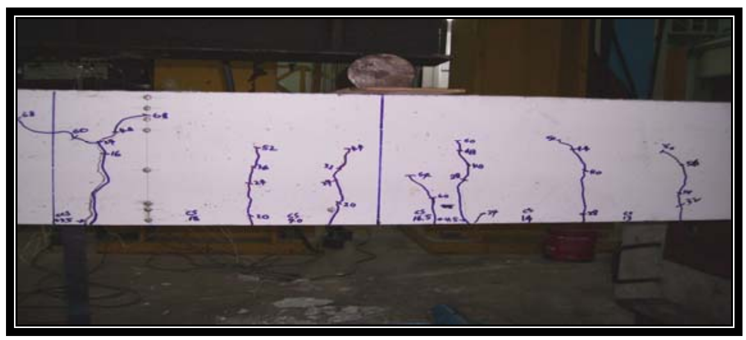
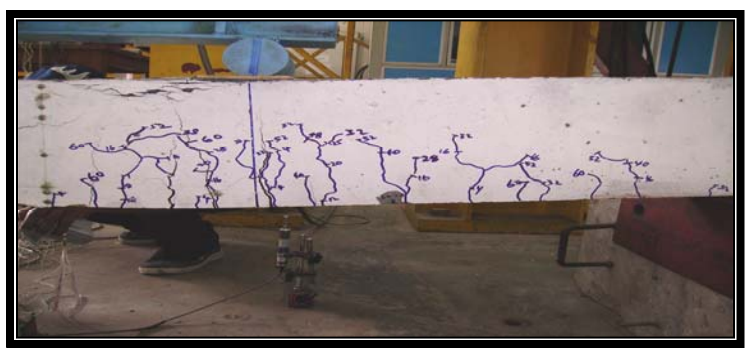


Figure 7: Crack widths of NWC and OPSC beams



a) NWC beam



b) OPSC beam

Figure 8:. Cracking pattern of NWC and OPSC beams

Steel and Concrete Strain

The tensile and compressive strains of reinforcement and concrete were measured at every load increment. The strain measurements against the loads for both NWC and OPSC beams are shown in Fig.9. The maximum tensile and compressive strain in OPSC beams reached 10,000 x 10^{-6} m/m and 4400 x 10^{-6} m/m, respectively in OPSC: B2 before failure; in NWC beams, the maximum strains recorded were 3900 x 10^{-6} m/m and 3700 x 10 ^{6}m/m in steel and concrete respectively. The higher strains in OPSC beams may be attributed to higher deflection due to low modulus of elasticity. The strains were linear in both NWC and OPSC beams until yielding of steel and then rapidly increased before failure. The higher strains in OPSC concrete beams also show

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that good bond between steel and concrete existed till the yielding of steel. The strains, before final failure may have been higher than the strains mentioned here. The compressive strains in concrete at service loads varied between 800 x 10^{-6} to 1200 x 10^{-6} m/m in NWC beams; however the OPSC beams recorded slightly higher strains between 1200 x 10^{-6} to 1600 x 10^{-6} m/m.

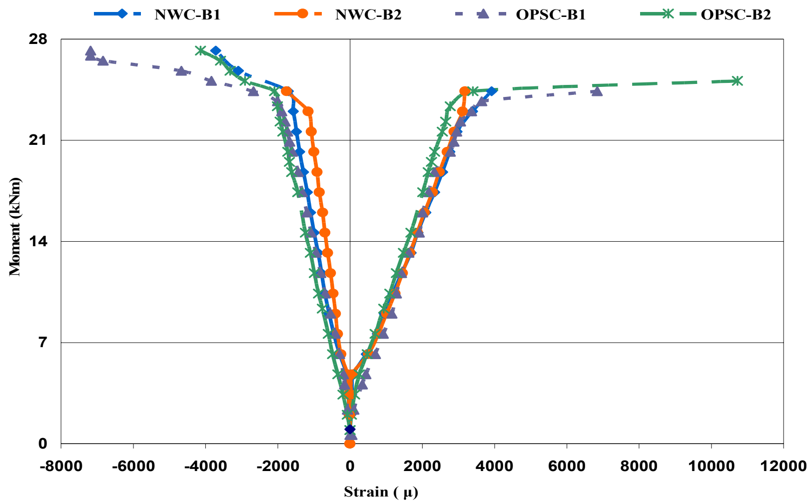
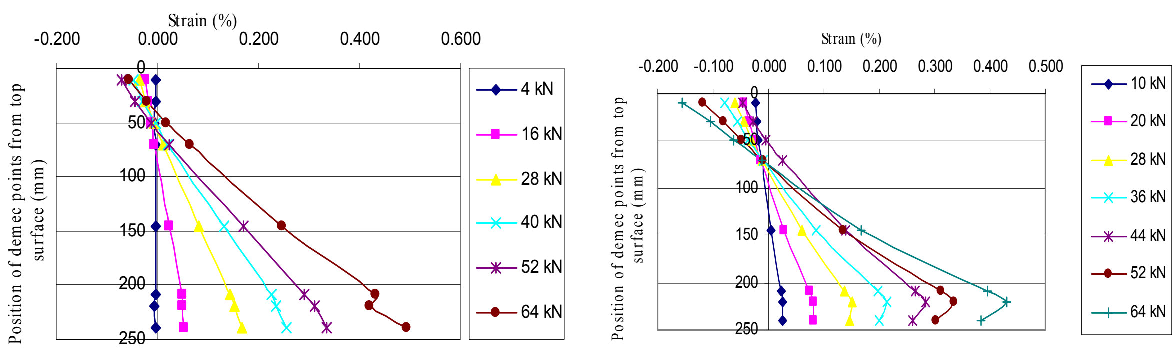


Figure 9. Cracking pattern of NWC and OPSC beams

Strain Distribution

The strain distributions on the vertical face of the beams that were measured for each load increment in NWC and OPSC beams are shown in Fig.10. The neutral axis depths could be observed from these data show that the strains were distributed approximately linearly above the neutral axis, while the strains below neutral axis became non-linear after cracks have occurred. As seen from the Fig.10, the depth of neutral axis of OPSC beam was found nearly 1.7 times higher than NWC beam. Owing to lower modulus of rupture of OPSC than NWC, the cracks in OPSC beams have occurred earlier than NWC beams, and this led to non-linear variation in strain distribution from the beginning in OPSC beams. Similar findings for LWAC beams have been reported by Swamy et al.[10].



a) NWC b) OPSC

Figure 10. Strain distribution and neutral axis depth

CONCLUSIONS

The conclusions that can be drawn from this study include the followings,

i. OPSC produced a density reduction of about 24% compared to NWC of similar mix design,
ii. the modulus of elasticity of OPSC was found to be about 46% as that of the NWC,
iii. the flexural strength of OPSC was about 15% lower than that of the NWC,
iv. lower modulus of rupture of OPSC resulted in early cracks in OPSC beam. However, the close spacing and large number of cracks in OPSC beams resulted in lesser crack widths than NWC beams,

v. the ultimate moments predicted by the theoretical values and numerical analysis showed close agreement with that of the experimental values.

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