Flexural Behavior of SCC Beams with Different Shear Span to Effective Depth Ratio

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Abstract Self-compacting concrete (SCC) is a self-consolidating concrete which does not require any compaction. Innovation in SCC adopting waste materials has become one of the research trends worldwide. This study presents experimental results on flexural behavior of SCC beams containing 10% eggshell as partial cement replacement. A total of three reinforced SCC beams with size of 150 × 200 × 1200 mm were tested under four-point bending test. Flexural characteristics such as load–deflection relationship and failure modes of the SCC beams were evaluated considering different shear span to effective depth ratio (*a*/*d*) of 1.0, 1.5 and 2.0. The ultimate flexural strength of the SCC beams was compared with the theoretical values proposed by Eurocode 2. It is found that the beam SCCB1.0 failed in shear whereas SCCB1.5 and SCCB2.0 in shear-flexural mode, respectively. When *a*/*d* ratio increase, the beam failure changed from brittle to ductile manner.

Keywords Self-compacting concrete · Flexural · Eggshell · Shear span

1 Introduction

Self-compacting concrete (SCC) was first introduced in Japan at 1980s. SCC has an excellent flowing characteristic, consolidates under its own weight and achieves full compaction without vibration. Excellent flow ability of SCC makes the concrete completely fills the formwork even in the presence of congested reinforcement. Such concrete could be applied in large structures such as long span bridges and earth retaining systems.

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Many researchers have interests in producing greener and innovative concretes by utilizing waste materials [1, 2]. Innovation in SCC adopting waste materials has become one of the research trends worldwide. Utilization of wastes such as oil palm shell, fly and bottom ash in construction industry reduces allocation of landfill sites. Owing to high calcium, magnesium carbonate (lime) and protein, food wastes particularly eggshells are dried and used as a source of calcium in many countries. Pliya and Cree [3] found that the brown eggshell contains composition of more than 96% calcium carbonate. Following this, the fine-grained powder sieved to the required sizes was also incorporated in concrete at a suitable eggshell to cement ratio. Oh, Lee and Mohd Raizamzamani (2020) reported that the addition of 15% eggshells in SCC mix replacing cement has increased the compressive strength up to 29% as compared to the control mix.

Flexural behavior of green concrete can be obtained experimentally through bending test on large scaled reinforced concrete beam specimens. For instance, Oh et al. [4] compared the structural performance of six high strength concrete beams incorporated with and without recycled concrete aggregates. The flexural characteristics particularly ultimate capacity, load–deflection relationship and failure modes were examined. Rahman et al. [5] investigated foamed concrete beam specimens incorporated with palm oil fuel ash and eggshell powder. The experimental work showed the beam specimens with combination of 20% palm oil fuel ash and 5–10% eggshell powder achieved 13–14% higher ultimate load capacity but more severe cracking compared to control beams (without palm oil fuel ash and eggshell powder). Specifically in the field of SCC, Perumal et al. [6] investigated flexural behavior of SCC beams of 230 × 230 × 1000 mm utilizing coconut husk under both three and four-point bending tests. Slight increment in the ultimate load carrying capacity of the beams was observed when the fly ash was replaced by coconut husk in both bending tests. Ofuyatan et al. [7] studied the properties of SCC developed using 10, 20 and 30% eggshell powder as partial cement replacement. All the mixes with eggshell powder showed comparable compressive strength and flexural strength compared to the control mix (without eggshell powder). Mahmod et al. [8] evaluated the flexural performance of fourteen reinforced SCC beams containing various percentage of steel fiber. The experimental results were compared with ACI 318 code. It was found that the flexural strength in beams increases with increasing concrete compressive strength, longitudinal steel rebar ratio, and fiber amount. Zhang et al. [9] investigated flexural behavior of twelve reinforced SCC beams containing steel fiber, macro polypropylene fiber, micro polypropylene fiber, and their combinations. A calculation method for ultimate bearing capacity of flexural SCC beams considering effect of fibers at room temperature was proposed. Mohammed and Najim [10] determined the compressive strength, flexural strength and modulus of elasticity of series of SCC incorporating recycled coarse aggregate, recycled fine aggregate and superplasticizer at different percentages of replacement. The outstanding four mixes were used in the investigation of flexural behavior of eight 100 × 150 × 1200 mm reinforced concrete beams under four-point bending test. Decrement in hardened properties and the flexural stiffness and toughness after application of recycled concrete aggregate was found.

Many experimental works on reinforced concrete beams containing wastes have been found, however, investigation on the effect of shear span-effective depth ratio on flexural behavior of SCC beams containing eggshell is limited. Khatab et al. [11] determined the effect of shear span-to-depth ratio of 0.8 and 1.7 in eight two-span self-compacting concrete (SCC) deep beams. The predictions using the strut-and-tie model suggested by ACI 318 M-11, EC2 and CSA23.4–04 are conservative results compared to the experimental shear capacities of the beams. Different from Khatab, this paper presents an experimental work on three reinforced SCC beams containing 10% eggshell as partial cement replacement in the mix. The effects of shear-span to effective depth ratio of 1.0, 1.5 and 2.0 on the flexural behavior of the beams were evaluated. The experimental results were further compared with Eurocode 2. The study also presents the fresh properties and compressive strength of the SCC mix incorporating eggshells.

This paper is organized as follows. Section 2 presents the experimental program for investigation of flexural strength of SCC beam containing eggshell. Section 3 presents and discusses the results inclusive the compressive strength of SCC mixes and flexural behavior of the SCC beams loaded with different shear span to effective depth ratio. This section also shows the predicted values of flexural strength from Eurocode 2. Finally, our work for this paper is summarized in the last section.

2 Method

This section presents the experimental program in investigating flexural strength of SCC beam specimens containing eggshell replacing cement. The experimental program is described in three parts: (1) preparation of SCC mix, (2) testing for fresh properties and (3) testing for flexural strength of SCC beam specimens.

2.1 Preparation of SCC Mix

Table 1 shows a mix composition for SCC with eggshell replacing cement. Main materials such as Ordinary Portland Cement, water, fine aggregates, coarse aggregates, eggshell powder and admixture were used in the SCC mix:

Table 1 The material composition of the SCC mix

Cement (kg/m^3)	Water (L/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Eggshell (kg/m^3)	Superplasticizer (L/kg/m^3)
463.5	215	644	966	51.5	5.15

Table 2 Properties of cement and master GLENIUM 8784

Chemical composition (%)		
Compositions	Cement	Eggshell
SiO_2	21.28	16.278
Al_2O_3	5.60	2.917
Fe_2O_3	3.36	4.369
CaO	64.64	71.765
MgO	2.06	NA
SO_3	2.14	2.604
Total alkalis	0.05	0.045
Insoluble residue	0.22	NA
Loss on ignition	0.64	NA
Physical properties of Master GLENIUM 8784		
Relative density	1.10 ± 0.01 at 25 °C	
pH	>6	
Chloride ion content	<0.2%	

Cement. The Ordinary Portland cement confirming Malaysia Standard MS522 was used. The chemical compositions of the cement are shown in Table 2.

Aggregates. Coarse aggregates from gravel of size 6 mm and fine aggregates from local sand of size with range of 0.3–0.8 mm were used. Good combination of aggregate sizes can ensure appropriate workability of SCC and decrease the possibility of segregation in the concrete mix. Fine to coarse aggregate ratio of 0.67 were considered.

Water. In order to provide an optimum strength and stability, water-cement ratio of 0.42 was used.

Eggshells. The eggshell were collected from various local restaurant and street vendors. Eggshells were cleaned and left dried at natural condition under direct sunlight. Then, the eggshells were put in the oven for 24 h for further removal of moisture content. Grinder machine (as shown in Fig. 1) was used to grind the eggshell into fine powder. Eggshell was used at weightage of 10% to partial replacing cement.

Admixture. The superplasticizer Master GLENIUM 8784 certified under ASTM C494 Types G was used. The physical properties of the superplasticizer are shown in Table 2. The amount of superplasticizer added to the mix was 1% from the amount of cement.

Fig. 1 Testing machines (left) grinder (right) compression machine

2.2 Testing for Fresh Properties

Slump flow test, L-Box test and sieve segregation test were conducted in accordance with the European Guidelines for Self-Compacting Concrete, (EFNARC 2005) to assess the fresh properties of SCC mix.

Slump Flow Test

The slump flow test was carried out to assess the flowability of SCC in the absence of obstructions. A truncated cone confirming to EN 12,350–2 was used. The apparatus has height of 300 mm, internal diameter of 200 mm and 100 mm at base and top, respectively. The SCC flowed out from the cone was measured its final diameters in two perpendicular directions. The average of these two measured diameters were calculated as slump flow. Viscosity of ECC was assessed by recording T500 time during the slump flow test, when the diameter of flow reaches 500 mm.

L Box Test

L Box test was conducted to determine the filling and passing ability of SCC. Passing through the apparatus L Box with three bars, the SCC was measured the height at the end of the horizontal box (H1) and the height at the gate side (H2), near the vertical box. The passing ability was measured in ratio of H2/H1. The whole test was performed within 5 min accordance to EFNARC, (2005).

Sieve Segregation Test

The sieve segregation test was performed to assess the resistance of SCC to segregation. With the sieve and receiver on the weighing machine, 5 kg SCC was poured into the sieve. The actual mass of the SCC on the sieve was recorded as Wc in gram. The sieve was removed at least after 2 min, the mass of the receiver and SCC that has passed through the sieve was recorded as Wps in gram. The sieve receiver was weighted and recorded as Wp in gram. The segregated portion SR in percentage was calculated as in the following equation:

$$SR = (Wps - Wp) \times 100/Wc\,\% \tag{1}$$

2.3 Testing for Hardened Properties

A total of six 100 × 100 × 100 mm SCC cubes were cast based on the mix in Table 1 and tested for the compressive strength. The compression test was conducted for the cubes at ages 7 and 28 days based on BS-EN:12,390-3 [12]. At the same time, three beam specimens were cast, to investigate the flexural strength at their age of 28 days. All SCC beam specimens with size of 150 × 200 × 1200 mm were designed with both top and bottom rebars of diameter 10 mm. The effective depth of the beams is 160 mm. The high yield deformed longitudinal rebar has characteristics strength of 460 N/mm^2. The link of 6 mm diameter was provided at 200 mm spacing along the beam, and with characteristics strength of 250 N/mm^2. Both cubes and beams were cured in water curing tank before the testing day.

Figure 2 shows the experimental set up of a four-point bending test and the distance of shear span *a*. The beam specimens were loaded to fail under a load test

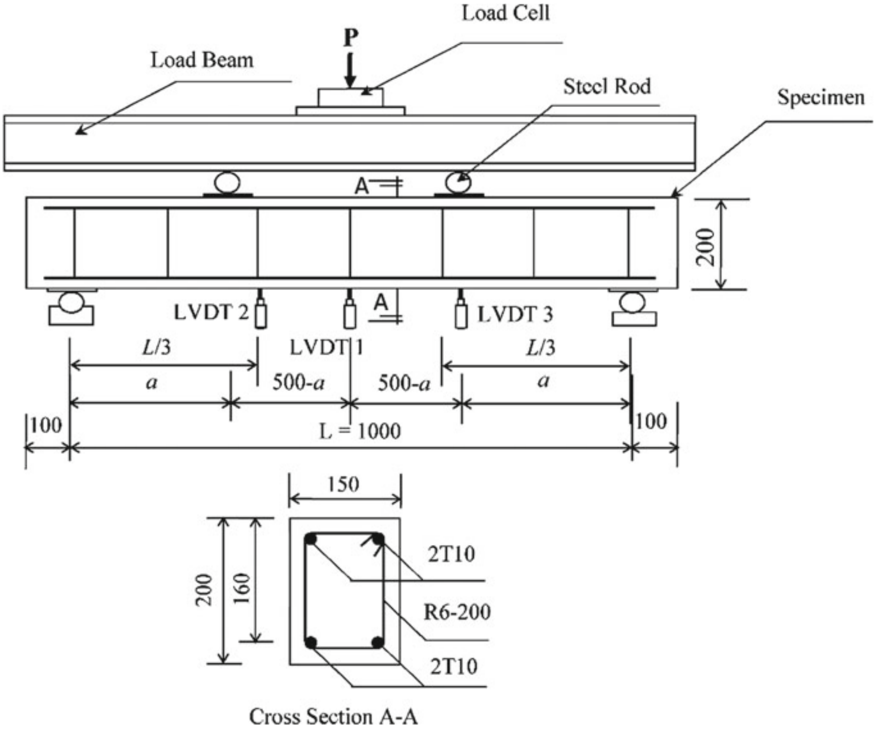

Fig. 2 Experimental set up for four-point bending test (elevation view)

with different shear span to effective depth ratio *a*/*d*. Specifically, beam SCCB1.0, SCCB1.5 and SCCB2.0 denote the beams loaded with shear span *a* of 160 mm and 240 mm and 320 mm, respectively. The linear variable differential transformers LVDT 1, LVDT 2 and LVDT 3 were placed at the bottom of the beams. LVDT 1 was placed at the middle while, LVDT 2 and LVDT 3 at one-third of span length from each support. The load was exerted on the beam with the control criteria using displacement rate of 0.01 mm/s.

3 Results and Discussion

This section presents the fresh properties of SCC, compressive strength for the SCC cubes and flexural strength for the SCC beam specimens containing 10% eggshell as partial cement replacement.

3.1 Fresh Properties

Table 3 shows the results of fresh properties from the slump flow, L-box and sieve segregation tests. All the tests for flexural properties confirmed the mix in the study are within the acceptable limits set by EFNARC. Slump flow and time T500 were recorded as 590 mm and 7 s, respectively. The SCC can be classified as SF1 with the typical applications such as for housing slabs and small diameter piles as recommended by EFNARC. From the viscosity result, classed under VS2, the SCC is generally appropriate for most applications.

For L-Box test, the heights H1 = 110 mm and H2 = 100 mm were recorded. The passing ability measured from L-Box test is 0.91, indicating SCC is type PA2 according to EFNARC. This type of SCC is suitable for civil engineering structures like walls and columns applications. On the other hand, the segregated portion SR was calculated as 14%. EFNARC suggested this type of SCC, category SR2 may be used for tall vertical application with flow distance more than 5 m and confined gap is less than 80 mm. The results of fresh properties of the SCC in this study are comparable to the trend of results in ESP10 (mix incorporated 10% of eggshell) from Ofuyatan et al. [7].

Table 3 Properties of cement and Master GLENIUM 8784

Test	Slump flow		L-Box	Sieve segregation
Unit	D (mm)	T_{500} (s)	$P_l = H_2/H_1$	SR (%)
SCC10	590	7	0.91	14

Table 4 Compressive strength at 7 and 28 days

Specimens	Compressive strength at 7 days (MPa)			Compressive strength at 28 days (MPa)		
	Cube	Mean	Standard deviation	Cube	Mean	Standard deviation
Cube 1	45.93	44.13	1.30	55.54	56.66	3.15
Cube 2	43.56			53.48		
Cube 3	42.90			60.95		

3.2 Compression Strength

The SCC mix was initially designed to achieve the targeted compressive strength 30 MPa at 28 days. Table 4 shows the compressive strength for the SCC mix at ages 7 and 28 days. The mean compressive strength was determined based on the compressive strength of three cubes. It is shown that the mean compressive strength for the SCC mix at 7 days (i.e. 44.13) reached about 78% of the compressive strength at 28 days (i.e. 56.66 MPa). The standard deviations of the compressive strength at 7 days and 28 days are 1.30 and 3.15, respectively. The average compressive strength for the SCC mix at 28 days has achieved compressive strength greater than the targeted.

3.3 Flexural Behavior of SCC Beam Specimens Containing Eggshell

Under four-point bending test, all the beams were loaded gradually until reaching the ultimate load. The results on the flexural behavior of SCC beam specimens containing 10% eggshell as partial cement replacement were presented in terms of load–deflection relationship and failure modes. Effects of shear span to effective ratio on flexural behavior of SCC beams were discussed in this section. Lastly, the experimental flexural strengths were compared with the theoretical values recommended by Eurocode 2.

Load–deflection relationship. Figures 3, 4 and 5 presents the load–deflection curves for SCCB1.0, SCCB1.5 and SCCB2.0 obtained from LVDT 1, LVDT 2, and LVDT 3 respectively. Generally, all the load–deflection curves demonstrate linear elastic pattern at load of range 6–8 kN (the first crack loads) before advancing to plastic manner (i.e. crack development region).

The load–deflection curves for SCCB1.0 demonstrates an increasing nonlinear in the plastic region whereas for SCCB1.5 and SCCB2.0, the curves are almost flat until the beams failed at ultimate load. Beam SCCB1.0 clearly show higher ultimate load (i.e. 20.0 kN) compared to SCCB1.5 (i.e. 10.0 kN) and SCCB2.0 (i.e. 9.0 kN). Maximum deflections at failure loads recorded are 23 mm, 33 mm and 39 mm for SCCB1.0, SCCB1.5 and SCCB2.0, respectively.

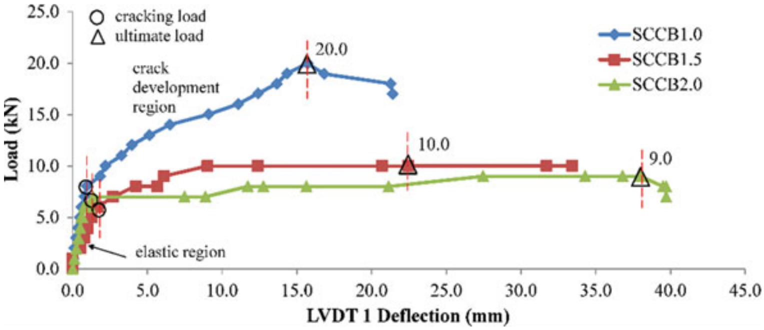

Fig. 3 Load–deflection for LVDT 1

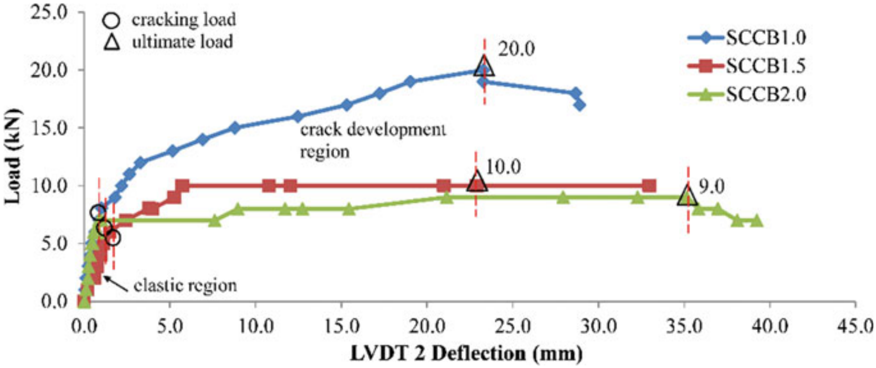

Fig. 4 Load–deflection for LVDT 2

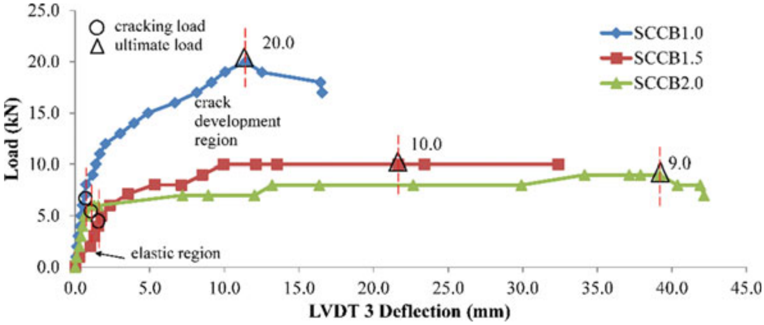

Fig. 5 Load–deflection for LVDT 3

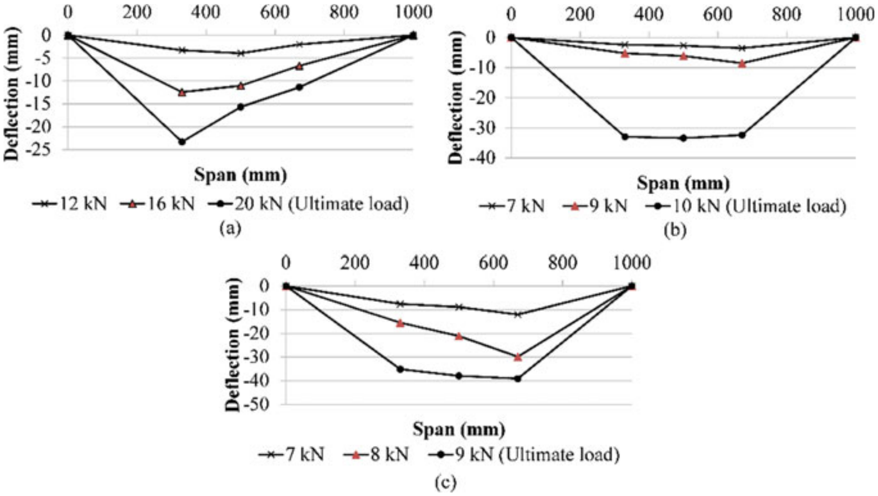

Fig. 6 Deflections along the beam, **a** SCCB1.0, **b** SCCB1.5 and **c** SCCB2.0

Figure 6 shows the deflections along beam specimens SCCB1.0, SCCB1.5 and SCCB2.0 at various load applications. The loads were chosen randomly to illustrate the changes of beam deflections upon loading during the test. It could be seen that the beam SCCB1.0 exhibited obvious deflection at one-third span length from the left support (LVDT2) than mid-span at load insertion of 16 kN onwards. Oppositely, beam SCCB2.0 showed the highest deflection at one-third span length from the right support (LVDT2). On the other hand, the beam SCCB2.0 showed maximum deflection approximately at mid span throughout the test.

From Figs. 3, 4, 5 and 6, it is noted that with lesser *a*/*d* ratio (or when the loads were placed near to supports, i.e. SCCB1.0), beam can sustain greater load with better deflection control. For beam with *a*/*d* of 1.0, the decrease in the maximum deflection at failure was 30.30%, and 41.02% compared to beams with *a*/*d* of 1.5 and 2.0, respectively. In addition, the beam with *a*/*d* of 1.0 resulted in an obvious increase in the ultimate load of 100.00% and 122.22% compared to beams with *a*/*d* of 1.5 and 2.0, respectively. Acting differently, SCCB1.5 and SCCB2.0 obviously show longer strain hardening curve compared to SCCB1.0 (i.e. 40% and 150% longer for SCCB1.5 and SCCB2.0, respectively), indicating better ductile behavior. Beam SCC1.0 (a/d of 1.0) has good agreement with the result from Khatab, Ashour, Sheehan, and Lam (2017) who reported all beams with *a*/*d* ratio of 0.8 and 1.7 failed in brittle manner. To add up the gap, the beams with *a*/*d* 1.5 and 2.0 demonstrated increasing ductility behavior. Generally, when *a*/*d* ratio increase, the beams failure changed from brittle to ductile manner.

3.4 Failure Modes

Figure 7 shows the failure mode of beams SCCB1.0, SCCB1.5 and SCCB2.0. During the exertion of loads, the development of cracks in SCC beams was observed and noted constantly. The first crack was observed at the tension zone near the mid span for both beams. As the load was increased, obvious shear cracks spread from supports of the beam SCCB1.0, moved further upward to the steel rods that inserted point loads.

With further loading penetrations, more shear cracks continued to be developed until the compression area especially under the point load started to crush. Spalling was observed on the beam surfaces as the shear cracks became obvious. The beams SCCB1.5 and SCCB2.0 acted almost the same as SCCB1.0 however demonstrated more flexural cracks at the tension zone near the mid-span of the beam. Besides, the beam SCCB1.0 failed clearly in shear mode whereas SCCB1.5 and SCCB2.0 in

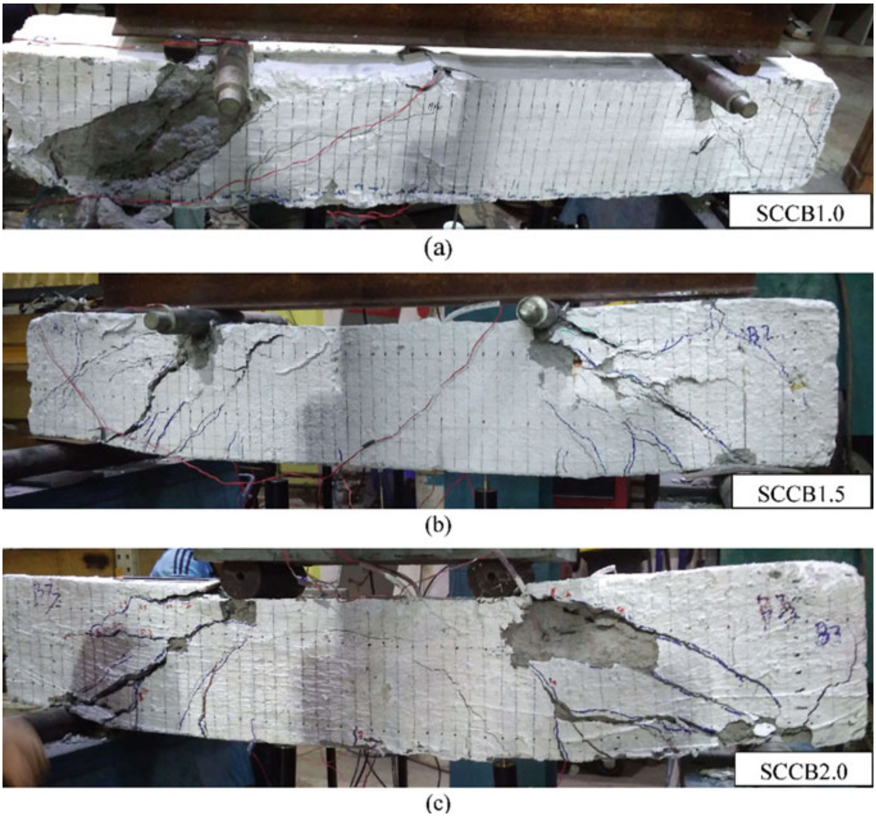

Fig. 7 Failure modes: **a** SCCB1.0, **b** SCCB1.5 and **c** SCCB2.0

Table 5 Prediction of flexural strength from Eurocode 2

Beam	Bending capacity (kNm)		$M_{Exp}/M_{Predict}$
	M_{Exp}	$M_{Predict}$	
SCCB1.0	1.60	11.17	0.14
SCCB1.5	1.20	11.17	0.11
SCCB2.0	1.44	11.17	0.13

shear-flexural mode. This also reveals that when the *a*/*d* increase, the beam behavior change from shear to flexural mode.

3.5 Prediction of Flexural Strength of SCC Beams

The flexural strength of the beam specimens was predicted using Eurocode 2. The stress distribution in the concrete using rectangular-parabolic stress block was chosen and the predicted flexural strength for a singly reinforced section of concrete with grade below C50/60 could be calculated as:

$$M_{\text{Predict}} = A_s f_{yk} d\left[1 - \left(0.513 A_s f_{yk}/bdf_{ck}\right)\right] \tag{2}$$

where f_{ck} is the characteristic cylinder crushing strength of concrete (MPa), f_{yk} is the characteristic strength of rebars (MPa), A_s is the cross-sectional area of steel rebars, b is the width (mm) and d is the depth (mm) of the beam specimens. According to Table 3.1 in EN-1992-1-1 [13], the characteristic cylinder crushing strength of concrete converted from cube strength obtained from the experimental (refer Table 4) for the SCC mix is 46.66 MPa.

Table 5 shows the comparison between the experimental M_{Exp} and predicted flexural strength $M_{Predict}$ in terms of ratio $M_{Exp}/M_{predict}$ for beam SCCB1.0 and SCCB2.0. The ratios $M_{Exp}/M_{Predict}$ for both beams are considered low. This reveals that the Eq. (2) may not predict well the SCC beam containing eggshell in this case.

4 Conclusions

This paper presents results on an experimental work with the main aim to evaluate the flexural behavior of the SCC beams containing 10% eggshell as partial cement replacement. The compressive strengths of SCC cubes at age 7 and 28 days were found greater than the targeted compressive strength. The flexural strength of beam specimens loaded with shear span to effective depth ratio of 1.0, 1.5 and 2.0 were investigated and compared with the predicted value suggested from Eurocode 2. Based on the experimental results, the following conclusions can be drawn:

1. The fresh properties of the proposed mix with 10% eggshell partial replacing cement are within the acceptable limits set by EFNARC, (2005). The recommended specific categories for the flowability, viscosity, passing ability and segregation resistance of SCC (i.e. SF1, VS2, PA2 and SR2) has indicated its potential applications in housing slabs, and vertical applications such as columns, walls, and piles.
2. Beam SCCB1.0 failed in shear whereas SCCB1.5 and SCCB2.0 in shear-flexural mode, respectively. When *a*/*d* ratio increase, the beams failure changed from brittle to ductile manner.
3. When the shear span to effective depth ratio increase, reduction in the ultimate load and flexural strength of beam and increment in maximum deflection were recorded.
4. The ratio experimental and predicted flexural strength, $M_{Exp}/M_{Predict}$ reveals that the Eq. (1) may not effectively predict the flexural strength of SCC beam containing eggshell in this study and required corrections prior to the properties of the new concrete with eggshell.

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