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Effect of horizontal joints on structural behavior of sustainable self-compacting reinforced concrete beams

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Abstract. This study investigated the effect of horizontal casting joints on the mechanical properties and structural behavior of sustainable self-compacting reinforced concrete beams (SCRCB). The experimental research consisted of two stages. The first stage used four types of concrete mixtures which were produced to indicate the effects of cement replaced with cement waste at 0%, 5%, 10%, and 15% by weight of cement content on fresh concrete properties of self-compacting concrete (SCC) such as, passing ability, filling ability, and segregation resistance. In addition, mechanical properties such as compressive, tensile, and flexural strength were also studied. The second stage selected the best mixture from the first stage and studied the effect of horizontal casting joints on the structural behavior of sustainable SCRCBs. The effect of horizontal casting joints on the mechanical properties and structural behavior were at the 25%, 50%, 75%, and 100% of sample height. Load deflection, failure mode, and theoretical analysis were studied. Results indicated that the incorporation of replacement with cement waste by 5% to 10% led to economic and environmental advantages, and the results were acceptable for fresh and mechanical properties. The results indicated that delaying the time for casting the second layer and increasing the cement waste in concrete mixtures had a great effect on the mechanical properties of SCC. The ultimate load capacity of horizontal casting joints reinforced concrete beams slightly decreased compared with the control beam. The maximum deflection of casting joint beams with 75% of samples height is similar with the control beam. The experimental results of reinforced concrete beams were substantially acceptable with the theoretical results. The failure modes obtained the best forced casting joint on the structural behavior at 50% height of casting in the beam.

Keywords: horizontal casting joints; self-compacting reinforced concrete, mechanical properties, structural behavior

1. Introduction

In recent years, structures of reinforced concrete face increasing demands for new structural design ideas due to the increasing population. Consequently, structural design, strengthening, and reinforcement in concrete structures have become more complex and denser, resistive to concrete flow, and can raise problems of casting and compacting of concrete. (El- Sayed *et al*. 2013, Khalil *et al*. 2018, Yahiaoui *et al*. 2017, Zeyad and Saba 2018, Zeyad and Almalki 2020). Heavily congested steel reinforcement bars have also led to increased blockage due to the bridging of the steel reinforcement. In addition, casting of vibrated concrete involves placement, and subsequent compaction may require prolonged periods, which might result in a loss in workability of concrete and a lack of long-term durability of concrete structures. Self-compacting concrete (SCC) opens the possibility to address many problems related to using vibrated concrete in structures of reinforced concrete because of its intrinsic workability, abilities of filling, and segregation. SCC is a type of concrete which can fill the whole mold completely with a minimum number of defects and which compacts under its own self-weight without vibration. (Kursat and Ehsan 2017, Sheelan and Nahla 2017, Heniegal *et al*. 2017) concluded that the concrete so produced is sufficiently cohesive, flows without segregation or bleeding, and has a reliable quality. A large amount of waste or demolition materials is created by construction each year, increasing the proportions of these materials. (Banfill 2011, Wallevik and Wallevik 2011, Vázquez *et al*. 2014, Ngo *et al*. 2010) recommended that environmentally friendly SCC concrete is gaining ground with awareness and knowledge of the need for sustainability in the field of construction materials. (José 2002, İlker and Selim 2004, Yong *et al*. 2004, Ann *et al*. 2008, Marta and Pilar 2009, Fonseca *et al*. 2011, Djerbi 2012, Silva *et al*. 2014, Zengfeng *et al*. 2015) reported that a method to produce concrete using an extra environmentally friendly material must be found. (Suman and Rajasekaran 2016, Agwa *et al*. 2020, Mohammed *et al*. 2020, Fahmy *et al*. 2012, Heniegal *et al*. 2015, Amin and Abdelsalam 2019, Heniegal *et al*. 2020, Amin *et al*. 2020, Saad *et al*. 2020) reported that the most of the earlier research focused on used to recycle aggregate from demolition waste in concrete. Moreover,

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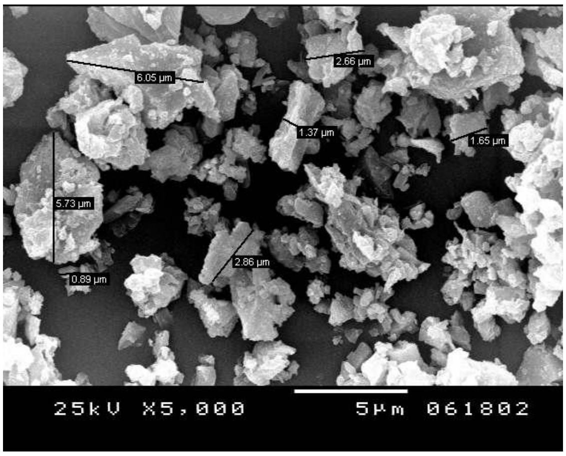

Fig. 1 SEM micro-graphs of CW

SCC is a type of an innovative special concrete and does not require any vibration during its placement in form works. SCC has flowability under the affection of its own weight, enables filling the formworks which are complicated narrow shapes and congested with reinforcement, maintains stability without separation or bleeding, and is the perfect-quality concrete surface. (Nan *et al*. 2011, Mucteba and Kemalettin 2011, Mohammed *et al*. 2013) recommended that SCC mixtures require a material or two of mineral admixtures, superplasticizers (SP), dolomite, and sand. (Shreyas 2016, Zena 2012, Mazaheripour *et al*. 2011) found that the casting of SCC may be quite difficult due to its placement on one time and many specific reasons: Placing large amounts of the concrete, glitch in machines such as the station concreting mixing, concrete pumps, concrete truck, and mixer of concrete in casting site lead to the unexpected occurrence of forced joints. The location of concrete joints is mostly determined by the designer engineer in traditional concrete, but forced casting joint (FCJ) is unlike the known separators such as the settlement joints and expansion joints, which are considered by the designing engineer through the design stages, and their effect on hardened properties of traditional concrete with FCJ. (Maha *et al*. 2010, Torres *et al*. 2016) mentioned a variation between joints in SCC and conventional concrete, where location FCJ in SCC cannot be specified, and the design engineer will not be able to consider this in the design stage for concrete construction. (Nagib *et al*. 2015, Amitha *et al*. 2012) stated that FCJ in conventional concrete at a particular place, whether in the zero moment area or the zero shear area, that difference at SCC which is the horizontally joint because the status of the liquidity is extremely high. (Hassan 2013, Farid *et al*. 2010, Shi *et al*. 2014, Taharb *et al*. 2016, Kou and Poon 2012, Chakradhara *et al*. 2010, Fonseca *et al*. 2011)

Finally, most of the researchers mentioned earlier focused on used to recycle aggregate from demolition waste in concrete. This research focuses on the effect of expired cement waste on concrete mixture and the effect of horizontal casting joints on the mechanical properties and structural behavior of sustainable self-compacting reinforced concrete beams (SCRCB).

Table 1 Chemical composition of OPC, FA, LSP and CW

Compound (%)	SiO_2	CaO	K_2O	Fe_2O_3	Al_2O_3	MgO	SO_3	Na_2O
OPC	22	61.5	0.30	3.5	6.50	4	2.90	0.40
FA	42	26	1.13	4	19	3.5	2.43	0.40
LSP	0.45	52	0.14	0.33	0.65	.33	1.5	0.32
CW	69.33	12	0.4	1.3	1.31	3.2	0.87	0.44

Table 2 Physical composition of OPC, FA, LSP and CW

Property	C	FA	LSP	CW
Specific surface area (cm^2/gm)	3,185	22,372	6,250	-
Specific gravity	3.15	2.15	2.61	3.15
Colour	grey	light grey	carnation	grey

2. Experimental work

2.1 Material

CEM I 42.5 N Ordinary Portland cement (OPC) was produced by the EL-Suez Cement Company, Egypt. Cement tests were performed according to (ASTM C-150). Accordingly, the cement was expected to have a surface area of particles around a range of 3,185 cm^2/gm. The fly ash (FA) used was bought from the Sika Company in Egypt; FA was used as an additional mineral additive. Lime stone powder (LSP) was obtained from the local crusher at Suez Quarries. Testing of LSP proceeded according to (ECP 203-2016). Cement waste (CW) was obtained from expired fresh cement. Fig. 1 shows scanning electron microscopy for cement waste and the shape and size of the cement waste grains. Fig. 2 shows the chemical composition for the CW from x-ray diffraction. Chemical and physical properties of OPC, FA, LSP, and CW are listed in Tables 1 and 2. A high-range naphthalene sulfonate SP was used in all mixes to increase the workability of concrete mixes. SP contents of 2% of the cement weight was used in all the mixes. Dolomite from the Suez quarry in Egypt was used in all the mixes. One size of dolomite was used, denoted as R=10 mm. Physical properties and sand tests were compiled with (ASTM C33/C33M-18). Reinforcement steel deformed high-grade steel bars with a diameter of 10 mm and a yield strength of 540 N/mm^2 were used as longitudinal tension reinforcement. The stirrups used were mild steel bars with a diameter of 6 mm and a yield strength of 320 N/mm^2. Steel bars were tested according to (ESS 76/2001).

2.2 Mix proportion

The proportion of concretes mixes is explained in Table 3, and four mixes of SCC were investigated. Cement was replaced with cement waste at 0%, 5%, 10%, and 15% by weight from cement content when designing mixtures. The ratio of fine to coarse aggregate was 0.45:0.55. The cement content in all the mixtures was 400 kg/m^3, and the w/b ratio was 0.40 from cementitious materials. The FA and LSP ratio was 15% of cement weight, and the SP dosage was 2% by weight from cement weight.

2.3 Mixing procedure

Table 3 Concrete mix proportions for 1 cubic meter

Mixes ID	OPC	CW	Sand	Dolomite	FA	LSP	SP	*W/b**
M-Control	400	0	726	886	60	60	8	208
M-5	380	20	726	886	60	60	8	208
M-10	360	40	726	886	60	60	8	208
M-15	320	80	726	886	60	60	8	208

* *W/b*: water: binder (C + FA + LSP) ratio

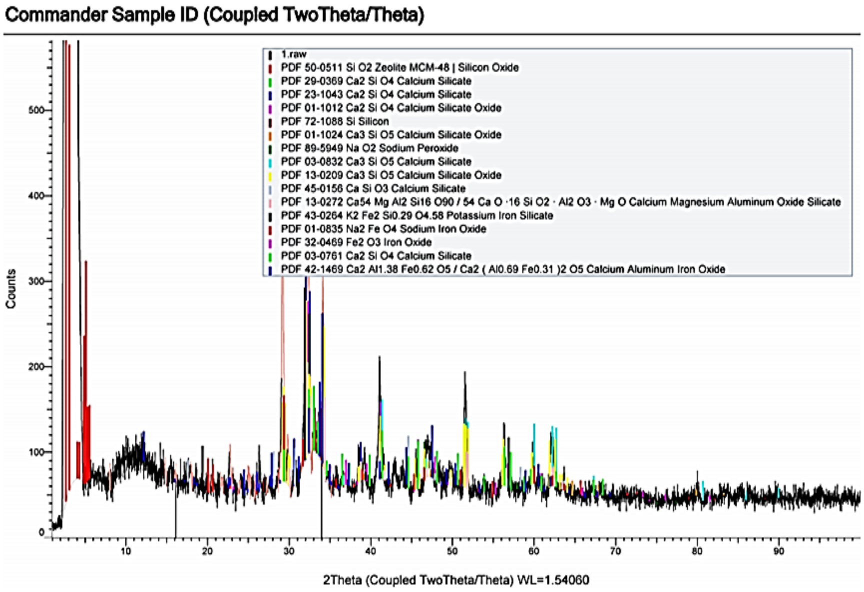

Fig. 2 XRD image of CW (Heniegal *et al*. 2017)

The steps of mixing were as follows: First, the sand was placed progressively in the mixer, followed by dolomite, and mixed for 2 min. Then, OPC, FA, LSP, and CW were added to the mixture and dry mixed for about 1 min. Water and SP were placed in the mixture and mixed for up to 3 min.

2.4 Testing procedure

SCC would appear if the following three requirements are achieved: filling ability, passing ability, and segregation resistance. Basic tests were conducted to fulfil these requirements: S-flow, T50, and V-funnel tests for filling ability, L-box and J-ring for passing ability, and GTM screen-stability test for segregation resistance. All tests were conducted through (EFNARC 2002) methods.

The following tests and specimens were used to determine the hardened concrete properties of SCC: compression test compiled at 28 days on 150 mm cubes, splitting test at 28 days compiled on 150 mm diameter×300 mm height cylinder, and flexural strength test at 28 days compiled for concrete on beam 100 mm width, 100 mm height, and 500 mm length. Achievement was tested according to (ECP 203-2016).

A series of four beams of 1,000 mm length and a rectangular cross-section of 100×200 mm were cast, strengthened, and then subjected to a three-point bending test to study the effectiveness of the FCJ on the structural behavior. The levels of cast in the beams were 25%, 50%, 75%, and 100% of sample height, as shown Figs. 3 and 4. Achievement was tested according to (Maha *et al*. 2010).

Fig. 3 Step casting with FCJ 25, 50, 75 and 100 of samples height

3. Results and discussion

3.1 Fresh concrete properties

Slump flow, T50, and V-funnel test were used to measure the filling ability of the concrete. The measured flowability results slump flow of all mixes are shown in Table 4. The slump flow of all the mixes was in a range of 790-590 mm. The slump flow reduced with the augmentation of CW ratio due to the augmentation in shape

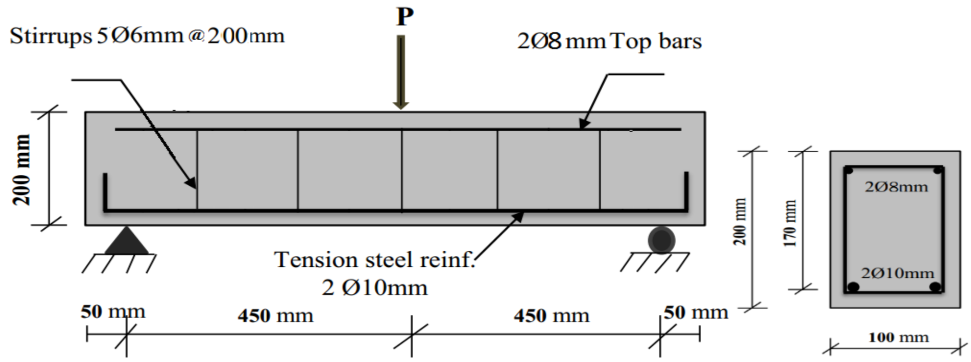

Fig. 4 Sections of beam used

Table 4 Fresh concrete properties

Mixes ID	Slump flow (mm)	Flow time T_{50cm} (sec)	J-ring (mm)	V-funnel T_{0min} (s)	V-funnel $T_{5min.}$ (s)	L-Box ratio(H_2/H_1) (3 rebar's %	Sieve stability %
M-Control	790	2	10	10	13	0.95	7
M-5	700	3	12	10	14	0.90	7
M-10	660	3.5	13	11	15	0.90	8
M-15	590	5	16	12	16	0.85	12

Table 5 Hardened concrete properties

Mix ID	Compressive Strength (N/mm^2) at 28days	Tensile strength (N/mm^2) at 28days	Flexural strength (N/mm^2) at 28days
M-Control	52.89	5.21	7.68
M-5	51.56	5.07	7.48
M-10	50.24	4.94	7.29
M-15	47.60	4.68	6.91

and size of the CW grains. The measured slump flow at T50 cm of all mixtures are shown in Table 4. The slump flow at T50 cm of all mixes was in a range of 2-5 s. The values of flow time (FT10) represent the flowability of concrete out of the funnel. The flow times of all mixes were in a range of 10-12 s for the V-funnel test due to the augmentation in CW ratio. L-box and J-ring were used to determine and measure the passing ability of the SCC, L-box (three rebars) (h2/h1) and J-ring, and the affection of replacement of CW The passing ability decreased by replacement CW of cement increased. As a conclusion of changing cement waste ratio as a replacement by 0.0%-15% of cement content, the L-Box test (blocking ratio) switched from 0.95 to 0.85. The J-ring test varied from 10 mm to 16 mm. GTM screen stability was used to determine and measure the segregation resistance of SCC. As a conclusion of changing cement waste ratio as a replacement by 0.0%-15% of cement content, the segregation ratio changed from 7% to 12%.

3.2 Hardened concrete properties

The compressive strength test results show the decrease in concrete compressive strength by the increase in replacement level of CW content in a range of 52.89-47.60 N/mm^2 with a replacement ratio of 0.0%-15% from cement content. Moreover, the tensile strength reduced by the augmentation in CW content in concrete in a range of 5.21-4.68 N/mm^2 with a replacement ratio of 0.0%-15% of cement content. The flexural strength reduced by the augmentation in CW content in concrete in a range of 7.68-6.91 N/mm^2 with a replacement ratio of 0.0%-15% from cement content, as shown in Table 5. This reduction in the compressive flexural and tensile strength may be related to the chemical and physical changes for CW compared with fresh cement, as shown in Table 1. The results show that the optimal ratio of cement waste in the mixtures is 5% as a replacement of cement weight.

3.3 Structural behavior of self-compacting reinforced concrete beams

From the selected mix containing 5% CW as a replacement from cement weight, the specimens B0-M-5, B1-M-5, B2-M-5, and B3-M-5 prepared at 25%, 50%, 75%, and 100% of sample height casting layer were tested after 28 days of curing in tap water. Table 6 shows that the ultimate load of SCRCB decreased by 13.63%, 4.54%, and 9.09%, respectively, as a result of changing HCJ by 25%, 50%, and 75% of sample height. In addition, as a result of changing HCJ by 25%, 50%, and 75% of sample height, the maximum deflection of SCRCB increased by 47.63%, 21.05%, and 10.52% respectively, compared with 100% of sample height, as displayed in Table 7. by cement content on passing ability. The beam failure at ultimate load is graphically represented in Figs. 5-7. The specimen B0-M-5 (control beam) was without HCJ. The ultimate load of control beam B0-M-5 was 66 KN at 28 days. Failure modes are shown in Fig. 9. The control beam B0-M-5 failed due to the yielding of steel reinforcement, followed by the tension failure in the flexural zone of the concrete at mid-span. The deflection at mid-span and under the points of application of the load were noticed throughout the test.

The specimen beam B1-M-5 at HCJ of 25% sample height failed at the ultimate load, as graphically represented in Fig. 5. The ultimate load of the beam was 57 KN at 28 days with a reduction of 13.63% compared with the control beam due to the increase in the distance between FCJ and the natural axis at 25% sample height. Fig. 10 shows failure modes of B1-M-5 also failed due to the yielding of the steel reinforcement, followed by the tension failure in the flexural zone of concrete at mid-span.

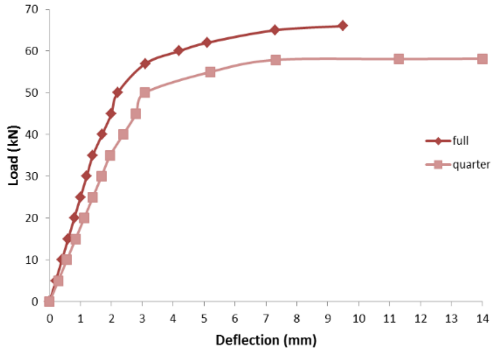

Fig. 5 Load-deflection behavior without and with FCJ at 25% height

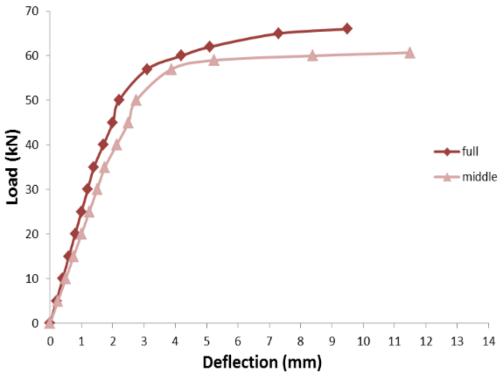

Fig. 6 Load-deflection behavior without and with FCJ at 50% height

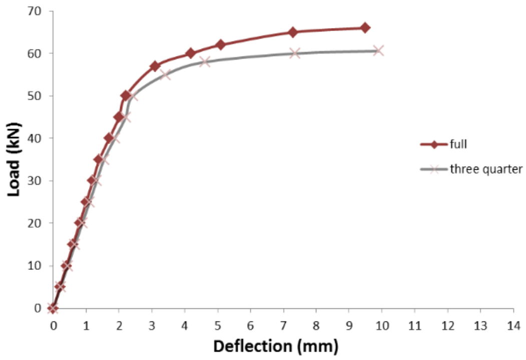

Fig. 7 Load-Deflection behavior without and with FCJ at 75% height

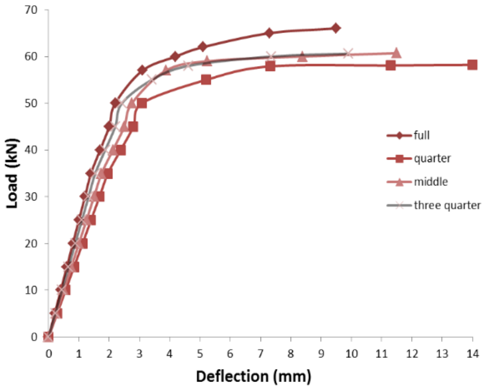

Fig. 8 Comparing load-deflection behavior without and with FCJ at different casting

Fig. 9 Failure mode of beam without FCJ (B0-M-5)

Fig. 10 Failure mode of beam with FCJ at the 0.25 height (B1-M-5)

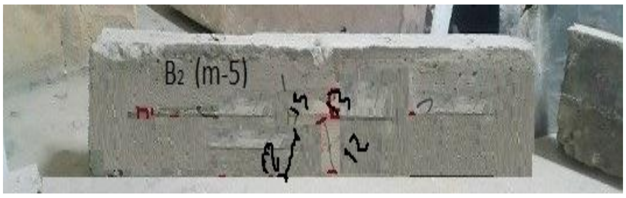

Fig. 11 Failure mode of beam with FCJ at the 0.50 height (B2-M-5)

The specimen beam B2-M-5 at HCJ of 50% sample height failed at the ultimate load, as graphically represented in Fig. 6. The ultimate load decreased by 4.55% compared with the control beam due to the small distance between FCJ and the natural axis at 50% sample height. The ultimate load decreased but was better than 25% sample height because of the close distance between FCJ and the natural axis at 50% sample height. The ultimate load of specimen beam B2-M-5 was 63 KN at 28 days. Failure modes are shown in Fig. 11. The B2-M-5 failed due to the yielding of steel reinforcement, followed by the tension failure in the flexural zone of concrete at mid-span.

Furthermore, the specimen B3-M-5 at HCJ of 75% of sample height. The beams failed at the ultimate load, as graphically represented in Fig. 7. The ultimate load of the beam was 60 KN at 28 d. The ultimate load decreased by 9.09% compared with the control beam due to the small distance between FCJ and the natural axis at 75% sample height zone. The ultimate load decreased but was better than that of 25% sample height and less than that of 50% sample height because of the increase in the distance between FCJ and natural axis at 75% sample height zone. Failure modes are shown in Fig. 12. The B3-M-5 failed due to the yielding of steel reinforcement, followed by the tension failure in the flexural zone of concrete at mid-span. Reinforced concrete beams with FCJ at different locations B0-M-5, B1-M-5, B2-M-5, and B3-M-5 were compared and tested after 28 days. The beams failed at the ultimate load, as graphically represented in Fig. 8. The failure modes obtained the best FCJ on the structural behavior at 50% heights of casting in the beams as shown in Figs. 3, 6, and 11.

Fig. 12 Failure mode of beam with FCJ at the 0.75 height (B3-M-5)

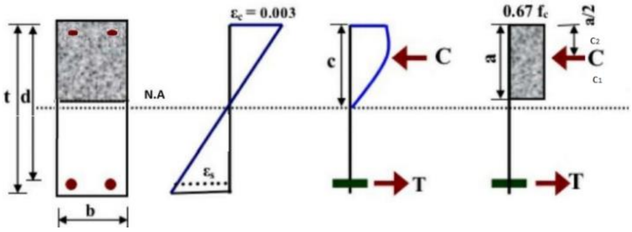

Fig. 13 Stress and strain diagram

3.5 Theoretical analysis

The theoretical analysis of beams was conducted according to (ECP 203-2016). In addition, the theoretical results were compared with the experimental results, as shown in Table 6. The stress and strain on the cross-section of the beam are shown in Fig. 13, where the internal force of the cross-section of the beams was estimated from the following equations

$$C1 = \left(\frac{2}{3} * Fcu * a * b\right) \quad (1)$$

$$C2 = (As * Fy) \quad (2)$$

$$T = As * Fy \quad (3)$$

$$M = \left(\frac{2}{3} * Fcu * a * b\right)\left(c - \frac{a}{2}\right) + (As * Fy)(d - c) \\ +(As * Fy)(d - c) \quad (4)$$

$$P = \frac{M*4}{L} \quad (5)$$

Where:

$C1$: compressive strength of concrete.
$C2$: compressive strength of steel.
T: tensile strength, M: ultimate moment.
b: the width of the concrete cross-section.
f_{cu}: the design compressive strength of concrete.
d: the effective depth of the concrete cross-section.
A_s: the cross sectional area of the tensile reinforcement.
P: ultimate load.

Table 7 shows that the ranges of ultimate load between the experimental and theoretical results were approximately 25.0-37.5 for all the beams. In addition, the percentage of variation factors for beams were control, 25%, 50%, and 75% of sample height for B0-M-5, B1-M-5, B2-M-5, and B3-M-5, respectively.

4. Conclusions

Based on the study reported here, the following conclusions were drawn:

• The replacement of CW by 5%-10% of cement content led to economic and environmental advantages, and the results are acceptable for workability.
• The ultimate load of SCRCB decreased by 13.63%, 4.54%, and 9.09% due to changing the horizontal casting joint by 25%, 50%, and 75% of sample height, respectively.
• The maximum deflection of SCRCB increased by 47.36%, 21.05%, and 10.52% due to changing the horizontal casting joint height by 25%, 50%, and 75%, respectively.
• The maximum deflection of casting joint beams with 0.75 h was similar to that that of the control beam.
• The experimental results of reinforced concrete beams are substantially acceptable with the theoretical results.
• The failure modes obtained the best FCJ on the structural behavior at 50% heights of casting in the beam because of proximity to the natural axis.

Table 6 the experimental and theoretical results of ultimate loads of beams with and without FCJ

Beam ID.		Ultimate Loads (KN)		
		Exp.	Theo.	Exp./Theo.
B0-M-5	Control	66	57.1	1.16
B1-M-5	25% height	57	57.1	1.00
B2-M-5	50% height	63	57.1	1.10
B3-M-5	75% height	60	57.1	1.05

Table 7 Details and specifics of the results

Beam ID.		Ultimate load (kN)	Yield load (kN)	Maximum deflection (mm)	Mode of failure
B0-M-5	Control	66	50	9.5	Tension
B1-M-5	25% height	57	51	14	Tension
B2-M-5	50% height	63	50	11.5	Tension
B3-M-5	75% height	60	49	9.9	Tension

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