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Uniformity of in situ properties of self-compacting concrete in full-scale structural elements

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Abstract

Inadequate homogeneity of the cast concrete due to poor compaction or segregation may dramatically lower the performance of mature concrete in situ. To ensure adequate compaction and facilitate placement of concrete in structures with congested reinforcement and in restricted areas, self-compacting concrete (SCC) has been developed. Considering the highly flowable and self-levelling nature of the SCC, there are general concerns that segregation and settlement may occur during its transport and placing. This study was designed to provide information on uniformity of in situ properties of SCC mixes in practical structural columns and beams and to compare results with those of properly compacted conventional concrete. The in situ concrete properties were assessed by testing cores for in situ strength, pull-out of pre-embedded inserts and rebound hammer number for near-surface properties. The results indicated that there were not significant differences in uniformity of in situ properties between the SCC mixes and the corresponding well compacted conventional mixes. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Self-compacting concrete; In situ properties; Uniformity; Structural elements

1. Introduction

Self-compacting concrete (SCC), first developed in Japan 10 years ago, and adopted in Europe and the rest of the world more recently, represents one of the most significant advances in concrete technology for decades. It can flow and compact in a mould or formwork under its own weight without the need for vibration. Use of SCC offers substantial benefits in enhancing construction productivity, reducing overall cost, improving working environment and in sustainability [1–4]. Considering the highly flowable and self-levelling nature of the SCC, however, there are general concerns that segregation and settlement may occur during its transport and placing. Standard, separately cast specimens that are easy to compact cannot reliably indicate substandard, poorly compacted concrete placed in situ, so it is essential to verify that SCC cast in situ can provide similar uniformity in key properties to that obtained with traditional vibrated concrete.

Work carried out by Khayat et al. [5,6] has shown that variations of in situ strength along the height of experimental walls and columns were similar for the SCC and conventional non-SCC mixtures. However, structural elements used in their investigation were relatively small, i.e., $950 \times 200 \times 1500$ mm^3 for the experimental walls and $235 \times 235 \times 1400$ mm^3 for the columns. The aim of the current research was to investigate the uniformity of in situ strength and near-surface properties of SCC and corresponding reference conventional concrete mixes in full-scale 3-m columns and 3.8-m beams. The work reported here was carried out as part of the Brite EuRam research project: "Rational production and improved working environment through using SCC" [7]. The main goals of the project were:

- Development and optimisation of SCC mixes, and verification of their fresh, hardened and in situ properties;
- Development of production, transport and casting methods suitable for SCC.

The University of Paisley was responsible for Task 4 of this research programme: "properties of hardened concrete", and a major part of this task was the investigation of in situ properties and their variations in practical structural elements.

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The LOK pull-out and rebound hammer tests, and concrete cores were used to evaluate the uniformity of in situ concrete strength and near surface properties. Tests on separately cast standard specimens and other properties, such as shrinkage, freeze/thaw resistance, modulus of elasticity, bond, surface absorption and durability, were considered, but have been dealt with elsewhere [8–10].

2. Structural elements used

Structural elements of a realistic size, i.e., $300\times 300\times 3000$ mm^3 columns and $200\times 300\times 3800$ mm^3 beams, were adopted for this study. Two types of reinforcement configurations, one for housing application and one for civil engineering application were designed for the column and the beam, and details of the reinforcements for the columns and the beams are given in Figs. 1 and 2, respectively. Extremely congested reinforcement configuration was adopted deliberately for the civil engineering application to verify that good compaction could be achieved using SCC without vibration. The structural columns and beams were designed to comply with the requirement of Eurocode 2 by NCC of Sweden, partner of the SCC project. The design loads were 2000 and 4000 kN, respectively for the housing and civil engineering columns, while the design loads generating bending moments of 45 and 120 kNm were used for the housing and civil engineering beams, respectively.

3. Materials and mix designs

Two classes of concrete were examined: a concrete for housing application with a characteristic cube strength of 35 MPa (C35) and a concrete for civil engineering application with a characteristic cube strength of 60 MPa (C60). For each of these classes a SCC, and a reference mix (REF) compacted conventionally by vibration were produced. Thus the notation C35-SCC in this paper stands for the SCC mix with 35 MPa designed strength. A steel fibre reinforced self-compacting concrete mix (SFR-SCC) was also tested due to the potential technical and economical benefits in using fibre reinforced concrete in structural floor slabs and beams to control cracking and replace partially the steel bars. Restricted by a cutback in costs, the SFR-SCC mix was used for the housing beam, thus replacing the C35-SCC beam.

SCC mixes often contains a large quantity of powder materials which is required to maintain sufficient yield value and viscosity of the fresh mix, hence reducing bleeding, segregation, and settlement [4,5]. Since the use of a large quantity of cement increases cost and results in greater temperature rise, other powder materials such as limestone powder, granulated ground blastfurnace slag (GGBS) and fly ash are usually used instead in various SCC mixes.

The SCC design used in this study was determined by trial mixes and on the basis of general advice from the SCC Brite EuRam project partners. The reference C35 and C60 concrete mix designs were those of a commercial concrete supplier, the only specifications given being for a target slump of 75 mm and for the characteristic strength. Details of the concrete mixes used are given in Table 1. Standard 42.5N grade Portland cement and the GGBS were provided by Blue Circle and Castle Cement, respectively. The fine limestone powder, with 98% <45 μm and 25% <5 μm, was obtained from Longcliffe Quarries, England. It is of interest to note that the use of fine limestone powder in concrete is very rare in Britain, but widely used in France and Sweden by the project partners. Based on advice from the project partners in Europe and extensive laboratory trials a specialist SCC admixture, provided by Sika was used for the SCC mixes. A common type of superplasticizer, also produced by Sika, was used for the reference C60 mix. The coarse and fine aggregates were from local quarries with grading curves shown in Fig. 3. Due to the highly congested reinforcement configuration of the civil engi-

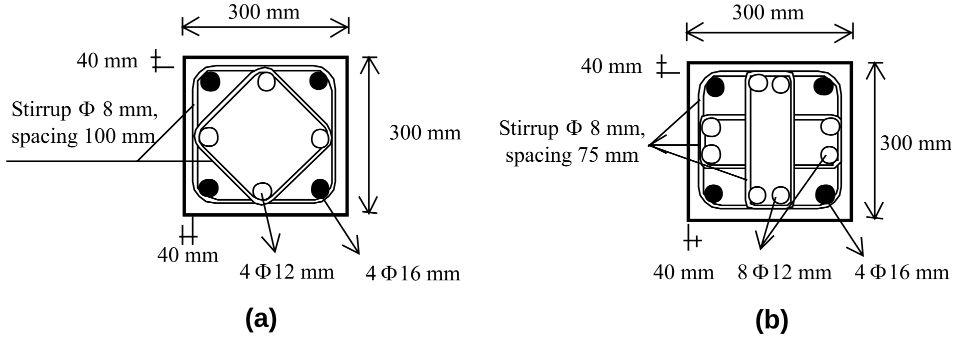


Fig. 1. Details of reinforcement configuration for the 300 × 300 × 3000 column: (a) for housing application; (b) for civil engineering application.

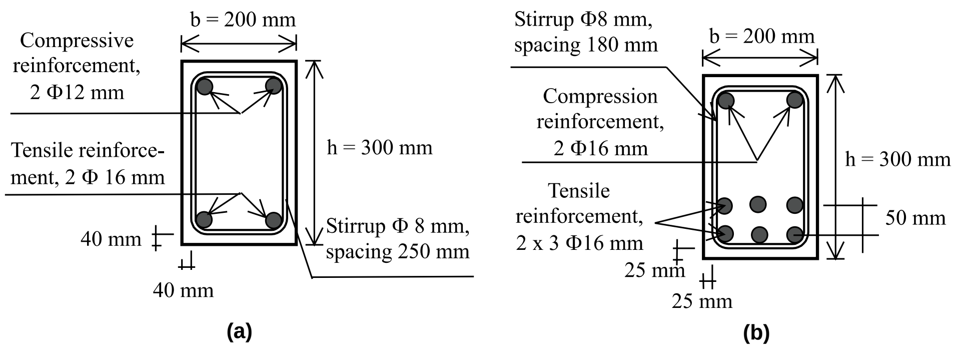


Fig. 2. Details of reinforcement configuration for the 200 × 300 × 3800 mm^3 beam: (a) for housing application; (b) for civil engineering application.

Table 1
Mix design and basic properties of concrete used

Mix details	Mix proportions (kg/m^3)				
	Housing		Civil engineering		Fibre mix
	C35-REF	C35-SCC	C60-REF	C60-SCC	SFR-SCC
Portland cement 42.5	295	280	515	330	285
Limestone powder (fine)	–	245	–	–	270
GGBS (ground slag)	–	–	–	200	–
Steel fibre (Dramix SF: RC65/35BN)	–	–	–	–	30
Free water	200	190	220	192	160
Sand (40% < 600 μm)	840	865	655	870	940
Crushed agg. (5–20 mm)	970	750	–	–	715
Crushed agg. (5–10 mm)	–	–	930	750	–
Specialist SCC admixture	–	4.2	–	5.3	4.4
Superplasticizer	–	–	6.4	–	–
	Basic concrete properties				
Slump (mm)	65	–	70	–	–
Slump flow spread (mm)	–	650	–	690	665
Standard 28d compressive strength (cube) (MPa)	37.0	47.0	61.5	79.5	63.0

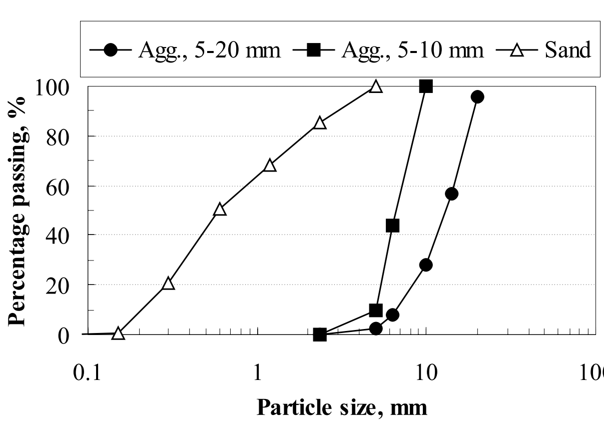


Fig. 3. Grading curves of the aggregates used.

neering columns and beams, 10 mm maximum size aggregate, instead of the normal 20 mm aggregate was used for the C60-SCC and C60-REF mixes.

The 2.5 m^3 loads of SCC and reference concretes were pre-mixed at the supplier's plant and delivered in truck mixers. The mixing procedure for the SCC was the same as for the reference mixes of traditional vibrated concrete, except that the mixing time for the SCC was 30 s longer after the addition of the special admixture. The limestone and GGBS were added to the mixer together with the aggregates at the beginning and the admixtures were added near the end of the mixing time which took between 2.5 to 3 min. The fine limestone powder was considered as an inert filler and used in the C35-SCC and SFR-SCC mixes, where its contribution to 28-day strength was not required. The GGBS was considered as an active binder material with a capacity to contribute significantly to the strength at 28 days and beyond. It was thus used in the higher strength C60-SCC mix. The results of standard compressive strength tested at 28 days for all the mixes are given in Table 1. It was unfortunate, for the purposes of comparison, that the SCC strengths were at the upper end of the normal range for the characteristic strengths, while the reference mixes were at the lower end.

A set of three identical full scale columns or beams were cast each time, one for load testing to destruction, one for in situ cores and LOK pull-out tests, and one for future assessment of durability in an outdoor exposure site. The traditional concrete was cast and compacted conventionally for the reference mixes. External vibrators attached to the formwork were used for the columns cast in-doors and hand-held poker vibrators for the beams cast out-doors. In the case of the SCC mixes, the columns were cast and "self-compacted" by directly pouring the concrete from the top using a skip, no external vibration being applied. Thus, the SCC mix was allowed to free-fall through the formwork with reinforcement from a height of 3 m. For the beams, the SCC mixes were poured into the formwork at one end (denoted as end A) and allowed to flow to the other end (end B). The formwork was filled over the 3.8-m length without any vibration. All the columns and beams were stripped after 6 days and then immediately sprayed with a curing compound.

4. Test arrangement

The quality of the in situ concrete in the 3-m high columns and 3.8-m long beams was assessed in three ways:

- Core test – for assessing in situ compressive strength.
- Rebound (Schmidt) hammer test – for assessing surface hardness and uniformity.
- LOK pull-out test – for assessing near-surface quality and uniformity.

Tests were carried out at the top, bottom and middle section for the columns, and both ends and the middle section for the beams, to examine if SCC mixes achieve adequate compaction, and similar uniformity in properties within the element to those obtained with proper compacted reference concrete mixes. A diagram showing the test layout for the columns is given in Fig. 4.

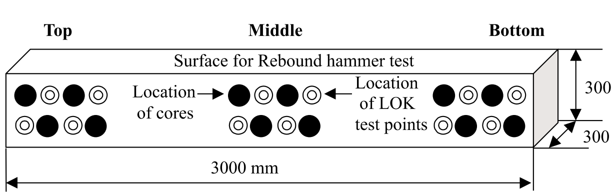


Fig. 4. Schematic diagram showing the in situ test locations on a typical column.

4.1. Core test

Tests were carried out according to procedures described in British Standard [11]. Three 100-mm diameter horizontal cores were taken at each test location within selected columns and beams. The cores were then cut to the required length and their ends capped. The prepared concrete cores were tested at the age of approximately 3 months, and the results were calculated and expressed as estimated in situ cube strength.

4.2. Rebound (Schmidt) hammer test

The test principle and procedures are described in Draft European standard [12]. A digitised apparatus, namely Digi Schmidt hammer which automatically records the rebound number for each testing was used in this study. Testing was carried out at the ages of 7 and 28 days, and a minimum of 40 readings was taken at each location along the height of columns and along the length of beams. The rebound number obtained provides an indication of hardness of the surface concrete.

4.3. LOK pull-out test

LOK pull-out testing has attracted special attention over recent years because of the excellent correlation obtained between pullout force and standard compressive strength. The system is flexible and produces only a minimal destruction to the structure. The LOK test was selected in this study to provide direct information on the quality of cover concrete and its uniformity.The test method has been described in draft European standard [13]. In this study, four cast-in inserts were used in each

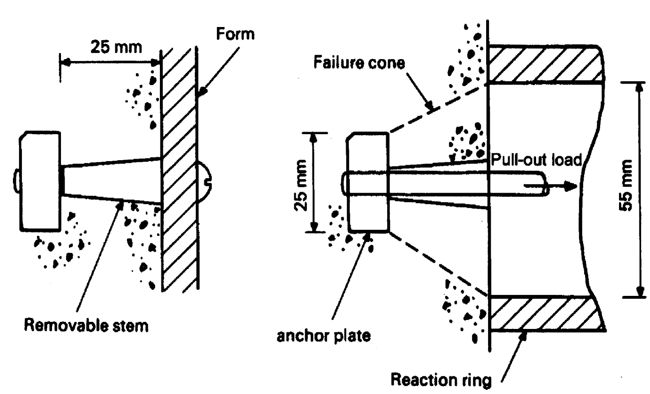


Fig. 5. Illustration of the LOK test inserts and pull-out arrangement used.

test location (i.e., top, middle, bottom section of a column, and end A, middle, end B section of a beam). Two of the four inserts at each location were pulled out at 7 days and the other at 28 days, and the pull-out force determined. A diagram illustrating the LOK test inserts and the pull-out arrangement is given in Fig. 5.

5. Results and discussions

The core test results were expressed as estimated in situ cube strengths in accordance with British Standard practice to allow for difference in core dimensions, the presence of steel bars and the direction of drilling. The results of the core test for the selected columns and the selected beams are plotted in Figs. 6 and 7, respectively.

For the strength variation in columns, diagrams shown in Fig. 6 demonstrate that the bottom parts of the columns were stronger than the top parts, as can be expected [14]. The general profile of the distribution of in situ strength was similar in all the cases, with an exception in the C60-REF mix which showed a considerably lower result in the middle section. Compared to the strength variations along the height of the columns, the strength variation along the length of beams was much smaller, as shown by the test results given in Fig. 7. For example, a difference of strength between top and bottom section was up to 15% for the columns, while the maximum strength difference in beams was 7%. The general profile and relative variation of the results for beams were similar for all the mixes studied.

To assess the reliability of the results and determine if the differences of results within the columns or beams were statistically significant, all the individual test data were analysed statistically. The average results of in situ cube strength obtained from nine cores for each selected column or beam and their variations in the columns and beams for all the SCC and reference concrete used were calculated and presented in Table 2. The statistical analysis tool – analysis of variance ANOVA was also used to determine if the differences of results along the height of column and along the length of beam were statistically significant. It was found that at a significance level (related to probability) $\alpha = 5\%$ the differences of in situ compressive strength at different sections of the column and beam were not statistically significant. At $\alpha = 10\%$, however, the difference of in situ strength along the height of column (i.e., top, middle and bottom sections) became statistically significant for the C35-REF, C35-SCC and C60-REF mixes, while the differences for the C60-SCC column and all the beams remained statistically insignificant.

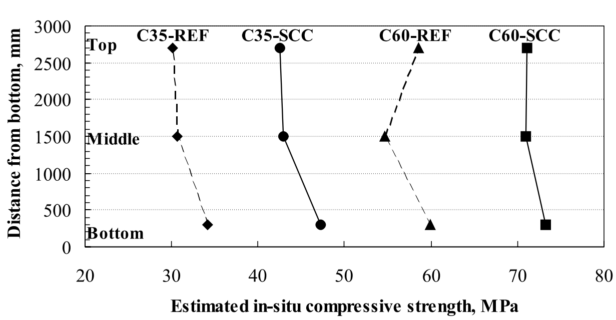
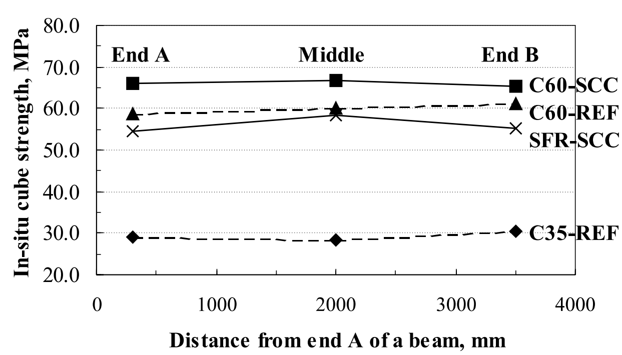


Fig. 6. Variation of in situ compressive strength along height of column.



(End A being casting point for SCC mixes)

Fig. 7. Variation of in situ compressive strength along length of beam.

Table 2
Statistical variation of in situ compressive strength for columns and beams

In situ cube strength (MPa)	Results for column			Results for beam		
	Mean	STD[a]	COV (%) [b]	Mean	STD	COV (%)
C35-REF	31.35	3.02	9.6	29.28	1.94	6.6
C35-SCC	44.60	2.96	6.6	N/A	N/A	N/A
C60-REF	57.65	3.25	5.6	60.00	3.40	5.7
C60-SCC	71.82	4.50	6.3	66.04	5.83	8.8
SFR-SCC	N/A	N/A	N/A	56.13	3.24	5.8

[a] STD – sample S.D.
[b] COV – coefficient of variation.

Similar analysis was also applied to the results of rebound hammer test. 40 readings were taken at each location along the height of columns or along the length of beams. Testing was carried out on two columns and two beams for each concrete mix, and all the data points (a total of 80–160 points) were taken for the analysis. The mean values and the variations of rebound number along the height of columns and along the length of beams for all the SCC and reference concrete used are calculated and presented in Table 3. It was found that the differences of rebound number along the height of column were statistically very significant (at $\alpha = 1\%$ in most cases) for all the SCC and reference mixes. For the variation along the length of beams, however, the differences were found to be not statistically significant, even at $\alpha = 10\%$. This appeared to support the findings for the significance of in situ strength variations in the columns and beams for all the mixes.

In view of the ANOVA findings, direct comparisons of uniformity of in situ properties in columns between different concrete mixes were made by expressing the in situ test results as percentage of the top section of the columns, as shown in Fig. 8.

Results in Fig. 8 indicated that the three in situ properties determined, namely the strength, the LOK pullout load and the Schmidt hammer rebound number, had a similar pattern of variation in columns for all the mixes examined. The results clearly showed that the difference between top and bottom of the columns was more pronounced in the housing mixes (i.e., C35) than in the civil engineering mixes (i.e., C60). The variations of in situ strengths along the height of column were found to be 10–15% and 3–7% for the C35 and C60 mixes, respectively, which were much lower than the average value of 25–30% reported previously for such elements [14]. Furthermore, differences between the uniformity of the properties of SCC and the corresponding reference mixes were not statistically significant; if anything, the uniformity for the SCC mixes seemed to be marginally greater. Test results of LOK pull-out [15] and rebound number also confirmed that the concrete properties were less variable along the length of beams than along the height of columns, particularly for the housing mixes.

Comparisons of the in situ strength results to the corresponding 28-day standard cube strengths were made by plotting the relative results as presented in Figs. 9 and 10 for columns and beams, respectively. Results in Fig. 9 indicated that the in situ strength achieved in the columns varied between 80–100% of the standard 28-day strength for all the mixes, which was well above the average value of 65% reported for such elements [16]. It was also noted that the in situ strength of the C35-SCC mix was much higher and closer to the 28-day cube strength than that of the corresponding reference mix C35-REF in the C35 grade. In the C60 grade, however, the ratio of in situ strength to the standard 28-day strength was similar or slightly lower for the SCC than for the reference mix. Such a difference could be explained by the difference in curing between standard

Table 3
Statistical variation of rebound number for columns and beams at 28 days

In situ rebound number		Results for column			Results for beam		
		Mean	COV (%)	Number of test points	Mean	COV (%)	Number of test points
C35-REF	Top, A[a]	34.8	7.8	160	33.3	9.7	80
	Middle	37.3	11.0	160	33.7	8.5	80
	Bottom, B[b]	40.8	15.0	160	33.6	8.4	80
C35-SCC	Top	35.7	7.1	160			
	Middle	35.7	7.7	160	N/A	N/A	N/A
	Bottom	40.8	11.3	160			
C60-REF	Top, A	44.1	6.9	160	41.4	6.0	80
	Middle	46.5	6.9	160	42.3	4.4	80
	Bottom, B	46.6	5.5	160	42.4	6.7	80
C60-SCC	Top, A	45.0	5.2	120	39.8	7.6	80
	Middle	46.0	4.7	120	40.5	8.6	80
	Bottom, B	46.3	4.6	120	40.2	5.6	80
SFR-SCC	End A				42.9	7.5	80
	Middle	N/A	N/A	N/A	43.3	7.5	80
	End B				42.3	5.7	80

[a] Top, A – indicating location of test points were either near the top for the columns or near the end A (i.e., the casting end for SCC mixes) for the beams.
[b] Top, B – indicating location of test points were either near the bottom for the columns or near the end B for the beams.

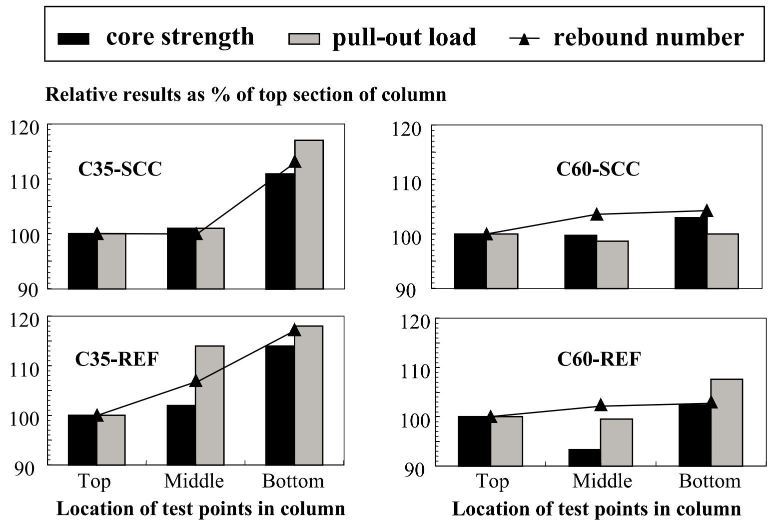


Fig. 8. Uniformity of in situ properties of SCC and reference mixes in column.

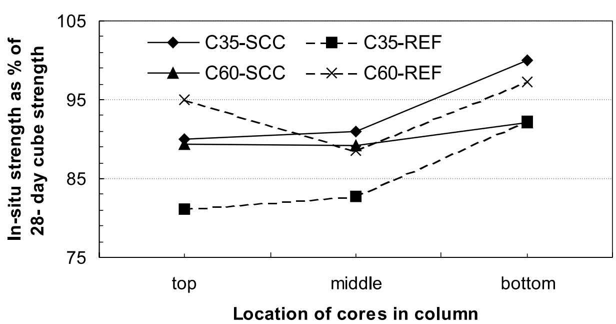


Fig. 9. In situ compressive strength in columns in relation to standard 28-day strength.

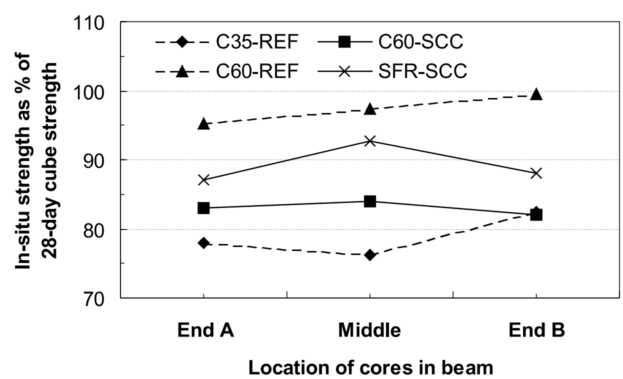


Fig. 10. In situ compressive strength in beams in relation to standard 28-day strength.

samples (in water) and in situ elements (in air), and in rates of strength development for the SCC and the reference mixes. It was shown [8] that the C35-SCC mix containing fine limestone filler was less sensitive to air curing than the C35-REF mix, possibly due to its enhanced water retentivity and accelerated early strength development induced by the fine limestone powder, as discussed by Pera et al. [17]. On the other hand, it is known that concrete containing GGBS as a replacement of Portland cement is more vulnerable to poor curing than the Portland cement concrete mix due to its initial low rate of hydration [18,19].

Results in Fig. 10, show a different picture from that in Fig. 9. For C35-REF and C60-SCC mixes, the in situ strength in beams relative to the 28-day cube strength was significantly lower than in columns. The different temperatures of the environment during casting of the individual elements can explain such a difference in performance. All the columns were cast inside the laboratory building with a relatively constant temperature of around 20°C all year round to simulate a precast concrete production condition. The beams were cast outdoors, with a wide range of temperatures depending on the month of the year to simulate open, in situ production. The casting of C35-REF and C60-SCC mixes was carried out in January and March, respectively, with an average air temperature of 5–10°C, while the C60-REF and SFR-SCC mixes were cast in June and July with temperatures sometimes exceeding 20° in daytime. Taking the different casting temperatures into account, the results for the beams appear to be reasonable and generally in agreement with the results for the columns. The average relative strength value previously reported for such elements was 75% [16].

6. Conclusions

The quality of the in situ concrete properties in the columns and beams was assessed by testing cores for in situ strength, pull-out of pre-embedded inserts and rebound hammer number for uniformity in near-surface properties. From the overall test results and analysis, the following general conclusions have been drawn.

- The variations of in situ strength and near surface qualities of the concrete along the length of full-scale beams were not statistically significant for either the SCC or the reference mixes.
- The differences along the height of columns were statistically significant for all the mixes. The in situ concrete properties, such as compressive strength, increased from top to bottom of the column, the difference between the top and bottom being greater for the C35 housing mixes than for the C60 civil engineering mixes.
- In terms of the variation of in situ properties in columns and beams overall, the results from SCC mixes were similar to those of the corresponding traditional, vibrated reference concretes, although the properties of the SCC mixes were marginally more uniform. It was thus confirmed that SCC cast in situ could provide similar (or even better) uniformity in key properties compared to those obtained with properly compacted traditional concrete.

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