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SCC mixes with poorly graded aggregate and high volume of limestone filler

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Abstract

Nonpozzolanic fillers are frequently used to optimise the particle packing and flow behaviour of cementitious paste in self-compacting concrete (SCC) mixes. This paper deals with the influence of finely ground limestone and crushed limestone dust on the properties of SCC mixes in the fresh and hardened state. Mixes were prepared using poorly graded crushed limestone aggregate. To compensate the lack of fine material in the crushed sand, a viscosity agent (VA) was added to the mixtures. The results obtained indicate that finer and better-graded limestone dust significantly increases the deformability of the paste. When a high volume of this filler was added to the SCC mix, the required self-compacting properties were achieved at a lower water/(cement + filler) ratio, and it also appeared that the addition of filler improves the 28-day compressive strength of concrete mixes due to the filler effect and improved fine-particle packing.

Keywords: Filler; Self-compacting concrete; Workability; Compressive strength; Tensile properties

1. Introduction

The self-compaction of fresh concrete is described as the ability of such concrete to fill up formwork and encapsulate reinforcing bars through the action of gravity alone, while maintaining adequate homogeneity [1]. This ability is achieved by ensuring suitable rheological properties of fresh concrete: a low yield stress value associated with adequate plastic viscosity. The use of superplasticizers (SP) and optimisation of fine-particle packing and flow behaviour are thus two of the central aspects of self-compacting concrete (SCC) mixture proportioning [2]. Fine particles include both cement and filler materials, either pozzolanic or nonpozzolanic. Among nonpozzolanic fillers, limestone and dolomite fines are the most frequently used to increase the content of fine particles in SCC mixes [3].

The addition of a limestone filler (LF) to Portland cement (PC) has several effects on the properties of fresh and hardened concrete. The LF grains act as nucleation sites for CH and C-S-H reaction products at early hydration ages, and accelerate the hydration of clinker minerals, especially C_3S, resulting in an improvement in early strength [4,5]. Carboaluminates are formed by the reaction between LF and C_3A [6]. Improvement of fine-particle packing can considerably enhance stability and workability of fresh concrete [7–9], as well as increase the density of paste matrix and interfacial transition zone (ITZ) in hardened concrete [10–12]. Due to the refinement and increased tortuosity of the pore system, the addition of LF also modifies the moisture variations in concrete, which control shrinkage and creep strains [13]. Thus, compared to plain concrete with the same W/C ratio and PC type, concrete with a high LF content with suitable particle size distribution (PSD) possesses generally improved strength characteristics [14,15]. On the other hand, the modulus of elasticity as well as the creep and shrinkage strains of concretes with LF admixtures can be higher, the same or lower [16–18], since these characteristics depend not only on LF effects but also on the volume fraction of the paste matrix.

In Slovenia, two types of LFs are available. One type is finely ground LF, and the other is limestone dust, which is produced in quarrying operations. While the price of the first type of LF is approximately half the price of PC, the second type of LF is actually a waste material. Thus, the successful utilization of limestone dust in SCC mixes would not only lower the cost of SCCs, but could also provide a solution regarding the disposal and environmental problems connected with this filler. Concrete mixes produced in Slovenia are mostly made using poorly graded crushed limestone or

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dolomite aggregate. Since the fineness modulus of crushed sand is usually very close to or even exceeds the JUS (former Yugoslav standard) standard upper limit value equal to 3.6, quartzite sand having a fraction of 0–1 mm is traditionally added to compensate the lack of fine material in the crushed sand. Quartzite sand deposits are limited to a few locations, and these supplies are nearly exhausted. The efficient replacement of this sand by an easily available viscosity agent (VA) would thus be very desirable.

The aim of the work reported in this paper was to investigate the influence of two high purity LFs on the fresh properties and strength characteristics of SCC mixes. One was finely ground limestone, and the other was limestone dust. SCC mixes were prepared using poorly graded, crushed limestone aggregate and a VA, and their cement contents ranged from 380 to 390 kg/m^3. Standard tests were carried out according to JUS standards.

2. Materials

PC designated CEM II/A-S 42.5R (EN 197), with a clinker mineralogical composition (Bogue) of $C_3S = 64\%$, $C_2S = 15\%$, $C_3A = 9\%$ and $C_4AF = 9\%$, and with up to 15% of ground-granulated blast furnace slag was used. The cement had a relative density of 3.08 g/cm^3. The finely ground limestone (LF-C) contained 99.6% $CaCO_3$ in the form of calcite and 0.4% quartz (SiO_2), and the limestone dust (LF-L) contained 100% calcite. The texture of the parent rock was predominantly sparitic ($D_{\mathrm{calcite\ grains}} > 10$ μm) for the LF-C, and predominantly micritic (1 μm < $D_{\mathrm{calcite\ grains}}$ < 4 μm) for the LF-L. The two LFs had a relative density of 2.75 g/cm^3.

The PSDs of LF-C, LF-L and PC, obtained by a laser scattering technique (MICROTRAC-FRA9200), are shown in Fig. 1. The parameters of the fitted RRSB distribution were $n = 0.9$ and $x' = 12.7$ μm, $n = 0.88$ and $x' = 6.3$ μm, and $n = 0.99$ and $x' = 19.0$ μm for LF-C, LF-L and PC, respectively. The Blaine specific surface areas of LF-C and PC, and the calculated specific surface areas (CS) of LF-C and LF-L are given in Table 1. As indicated, LFs are finer and better

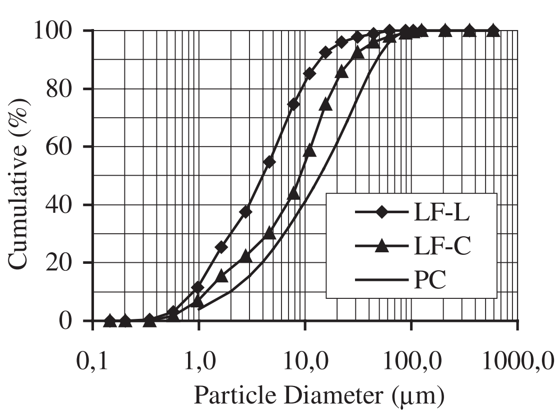

Fig. 1. PSD of fillers and PC.

Table 1
Specific surface area of fillers and PC

	Blaine (m^2/kg)	CS (m^2/cm^3)
PC	373	–
LF-C	372	2.222
LF-L	–[a]	2.705

[a] Inappropriate test method due to the presence of agglomerated particles.

graded than PC, and of the two fillers, LF-L is better graded and much finer than LF-C. However, considering the particle shapes of LFs, the difference does not seem to be significant (Fig. 2).

The used coarse (4–16 mm) and fine (0–4 mm, S1) aggregates consisted of crushed limestone with an average compressive strength of the parent rock of approximately 200 MPa. The coarse aggregate was a combination of 4–8 and 8–16-mm fractions, for which the highest dry rodded bulk density was obtained. For the purposes of comparison, an SCC mix without VA was prepared with sand (S2) that was a combination of 80%$_{\mathrm{vol}}$ of S1 sand and 20%$_{\mathrm{vol}}$ of a natural, 0- to 1-mm quartzite sand. With this combination, optimum dry rodded particle packing was obtained at the lowest quartzite sand content. The grading and physical characteristics of the aggregates are shown in Table 2.

A polycarboxylate-based product with a solid content of 34% was used as an SP. It is produced by a Slovenian company (TKK Srpenica). The VA used was a polysaccharide type admixture with 5% of active ingredient, produced by MAPEI.

3. Test methods and criteria for the fresh concrete mixes

The test methods used for the evaluation of the workability of SCC mixes were selected from those developed by other authors [19]. They were as follows: slump flow test, V-funnel test, CBI L-box test and filling vessel test. The testing procedures and apparatus were those presented by Takada et al. [20], with one exception: for the V-funnel test, a 10-l funnel with the dimensions given by Domone et al. [21] was used. As an additional test, air content was also determined.

The following criteria for satisfactory self-compacting behaviour were adopted on the basis of the author's own experience, as well as recommendations from other authors [21,22]: a slump flow of between 650 and 750 mm, a V-funnel time of between 5 and 15 s, an H2/H1 blocking ratio in the L-box test greater than 0.8, and a filling ratio in the filling vessel test greater than or equal to 90%.

4. Mix design and proportioning

The general method proposed by Okamura and Ozawa [23] was followed for the mix design of SCC mixes. This method generally leads to concrete with a higher paste

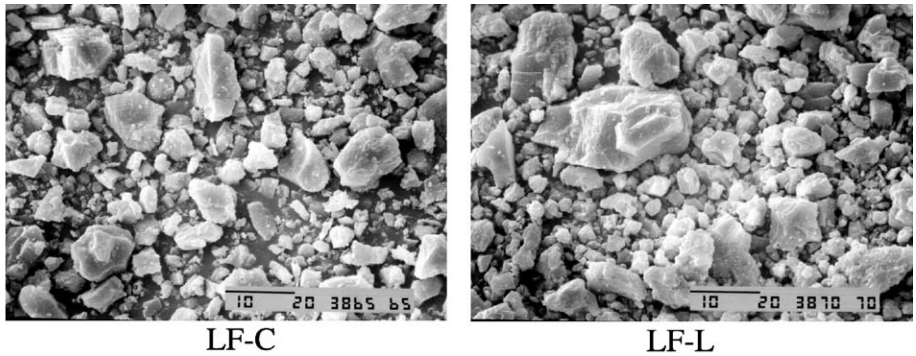

Fig. 2. Shape of LF particles.

volume than required in the optimum mix [24], but ensures more than adequate self-compacting properties for most materials and applications [25,26]. In the first step, a series of flow spread tests according to Domone and Chai [27] were carried out in order to characterize pastes made from PC and LF in volume proportions of 100:0, 75:25 and 50:50. The test results are shown in Fig. 3, and the values of the retained water ratio (β_p) and deformation coefficient (E_p), obtained by regression analysis, are given in Table 3. By increasing the volume fraction of LF-C in the paste, the packing of the cement–filler system in the presence of retained water amount did not change significantly, compared to the cement paste. However, the deformability of the paste was much improved by increasing LF-C fraction from 25% to 50%. On the other hand, with the better-graded and much finer LF-L, the packing of the cement–filler system was improved considerably. Its deformability was better than that of LF-C and was increased by increasing the filler fraction.

Table 2
Grading and physical characteristics of aggregates

	Cumulative passing (%)			
	Coarse crushed	Fine S1 crushed	0–1 mm natural	Fine S2 combination
16 mm	98	100	100	100
8 mm	40	100	100	100
4 mm	1	94	100	95
2 mm		62	100	69
1 mm		38	100	50
0.5 mm		22	93	36
0.25 mm		11	50	19
0.125 mm		6	11	7
Fineness modulus	–	3.68	–	3.24
Relative density (g/cm^3)	2.71	2.71	2.67	–
Dry rodded voids (%)	42	33	39	31
Water absorption (%)	0.3	1.3	0.2	–

Due to the poorly graded coarse aggregate used, the amount of paste obtained in the mix design was approximately 0.42 m^3. Since the cement content in 1.0 m^3 of concrete was set between 380 and 390 kg, a cement–filler mix containing 50%$_{vol}$ of PC and 50%$_{vol}$ of LF was selected in order to comply with the requirements regarding the paste and cement contents. The water/(cement + filler) volume ratio (V_W/V_{C+F}) and the SP dosage were determined by using mortar flow and funnel tests [28]. Both parameters were adjusted until the spread of mortar reached 270 mm, and a flow time of about 10 s was obtained. These proportions were then used as the starting point for the trial concrete mixes. The SP dosage and quantity of water in concrete mixes were further adjusted, and the dosage of VA was determined. The optimum SP dosage thus obtained was 0.6% by mass of cement and filler content. The minimum dosage of VA that compensated the lack of fine material in the crushed sand was 0.3% by mass of mixing water. Five SCC mixes, with the optimum SP dosage and with the proportions summarized in Table 4, were investigated. Two mixes were made using LF-C (C-1 and C-2), and three using LF-L (L-1 to L-3). The mix C-1 was prepared with sand S2 and without the VA, for the purposes of comparison. The other four mixes were prepared using sand S1 and the VA. A

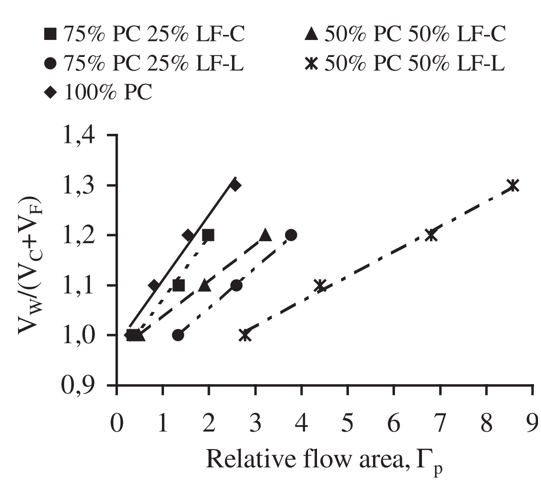

Fig. 3. Results of flow spread test of pastes.

Table 3
Results of regression analysis

PC–LF proportion	β_p	E_p
100% PC	0.98	0.129
75% PC–25% LF-C	0.95	0.120
75% PC–25% LF-L	0.89	0.082
50% PC–50% LF-C	0.96	0.073
50% PC–50% LF-L	0.87	0.050

minimum dosage of VA was added to mixes C-2 and L-1, and in the case of mixes L-2 and L-3, the VA dosage was increased to 0.35% in order to obtain a higher resistance to segregation.

All the concrete mixes were mixed in a laboratory centre-shaft pan mixer, with a capacity of 50 l, and the paste and mortar mixes were mixed in a Hobart paddle mixer in batches of 1.0 and 2.5 l, respectively.

5. Preparation of test specimens and testing

5.1. Fresh concrete mixes

The mixing sequence of a particular SCC mix consisted of first homogenising the coarse and fine aggregates, cement and LF, and then introducing 75% of water and finally, SP and VA, with the remaining water. Concrete was then mixed for 4 min. All the above listed fresh concrete tests were carried out over a period of 15–20 min after the mixing had been completed.

5.2. Hardened concrete test specimens

Five 150 × 150 × 150 mm cubes and three 150 × 300 mm cylinders were cast from each SCC mix. The cubes and cylinders were used to determine the 28-day compressive and splitting tensile strengths, respectively. From each of the mixes L-1 to L-3, three additional cubes were cast for the determination of 1-day compressive strength. Specimens were made by pouring fresh concrete into moulds, removing the excess concrete and levelling the surface, covered with plastic sheets and left in the casting room for 24 h. They were then removed from the moulds and transferred to a tap water bath with a temperature of 20 ± 2 °C, where they were left until testing.

5.3. Reinforced concrete beam

For casting a concrete beam with dimensions of 200 × 300 × 3000 mm (its reinforcement scheme is shown in Fig. 4), mix C-2 was used. Concrete was placed in the formwork using a skip. After filling the formwork with concrete, levelling of the surface by trowelling was carried out. The formwork was removed after 7 days. Until testing, the beam was located in the laboratory at an air temperature of 24 ± 4 °C and a relative humidity of 55 ± 5%. One 150 × 150 × 150 mm cube was cast from each batch of the mix for the determination of compressive strength. The casting and curing of the cubes were performed as described in Section 5.2.

The quality and uniformity of the in situ concrete was assessed by a combination of ultrasonic pulse velocity (UPV) measurements and compressive tests on drilled cores. The UPV measurements were carried out at five locations along the length of the beam (designated I, II, III, IV and V, as shown in Fig. 4), at distances of 150, 750, 1500, 2250 and 2850 mm from the end of the beam. For each location, five measurements were made along the height of the beam, and one 100-mm-diameter horizontal core was taken (see Fig. 4). The tests on the beam and the corresponding cubes were carried out at an age of 56 days.

6. Test results and discussion

6.1. Properties of the fresh concrete

The results of workability tests and air content are given in Table 5. Except for mixes C-1 and L-1, all other SCCs complied with the adopted criteria. For mixes C-1 and L-1, the adopted upper limit of the slump flow value was exceeded, but since the mixes fulfilled all other criteria and did not show a tendency to segregate, they can be declared as SCCs.

A comparison between the properties of mixes C-1 and C-2 revealed that when a VA is used to compensate the lack of fine material in the sand, a higher amount of water is needed to achieve the required filling ability of the concrete with approximately the same volume and composition of the cement–filler mix. By replacing LF-C in mix C-2 by LF-L, mix L-1 with higher deformability and viscosity at a lower

Table 4
Proportions of SCC mixes

Mix	PC (kg/m^3)	LF (kg/m^3)	Water (kg/m^3)	Paste (m^3)	V_W/V_{C+F}	W/C	W/(C+F)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	SP (%$_{fines}$)	VA (%$_{water}$)
C-1	384	343	164	0.413	0.66	0.43	0.23	794	769	0.6	0.00
C-2	380	339	181	0.428	0.74	0.48	0.25	778	745	0.6	0.30
L-1	386	345	174	0.424	0.69	0.45	0.24	791	757	0.6	0.30
L-2	390	348	168	0.421	0.66	0.43	0.23	794	761	0.6	0.35
L-3	380	360	163	0.417	0.64	0.43	0.22	800	766	0.6	0.35

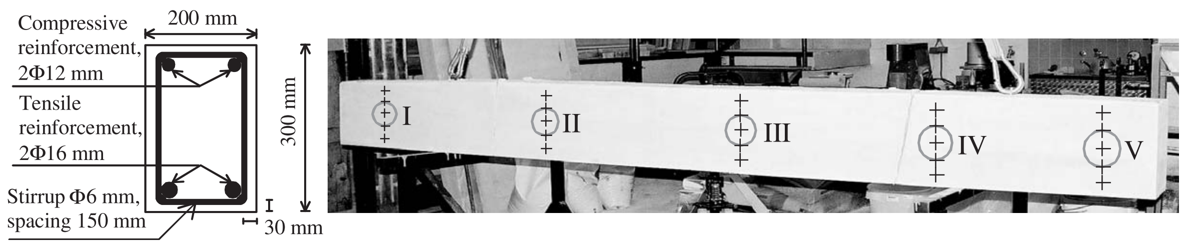

Fig. 4. Reinforcement scheme, configuration and locations of UPV measurements and cores.

V_W/V_{C+F} ratio was obtained. The higher deformability of this mix is probably due to the significantly higher deformability of the constituent paste (see Fig. 3 and Table 3), and the higher viscosity can only be due to the lower V_W/V_{C+F} ratio. Since mix L-1 had the same filling ability as mix C-1, the lower cohesiveness of mix L-1 seems to be the main reason for the significantly higher blocking ratio obtained in the case of this mix. The cohesiveness of the mixes was estimated by visual observation, and was in the case of mix C-1 with sand S2 much higher than for mixes with VA. Mixes L-2 and L-3 exhibited lower deformabilities, as well as blocking and filling ratios, and higher viscosities than mix L-1, not only due to the higher dosage of VA but also due to the lower V_W/V_{C+F} ratio. The improved self-compacting properties of mix L-3 compared with mix L-2 are very likely due to the higher deformability of the paste with increased LF content.

6.2. Properties of the hardened concrete specimens

The compressive and splitting strengths of the different SCCs are shown in Table 6. The SCCs with LF-L developed compressive strengths between 22.4 and 24.5 MPa, and between 63.6 and 67.6 MPa, at 1 and 28 days, respectively. The 28-day compressive strengths of mixes C-1 and C-2 were 57.3 and 50.3 MPa, respectively. The splitting/compressive strength ratio ranged between 0.8 and 0.9 for all the SCCs.

Saje [29] studied the compressive strength of vibrated concrete mixes prepared using 400 kg of the PC CEMII/A-S 42.5R and an aggregate very similar to that used for mix C-1. He obtained 1-day compressive strengths of 21.0, 26.2 and 32.3 MPa, and 28-day compressive strengths of 48.3, 60.3 and 68.9 MPa, at W/C ratios equal to 0.52, 0.44 and 0.40, respectively. By fitting Abrams' law to these strengths, compressive strengths of the vibrated concrete at W/C ratios equal to 0.43, 0.45 and 0.48 were estimated: at an age of 1 day, values of 28, 26 and 24 MPa, respectively, were obtained, and at an age of 28 days, values of 63, 59 and 55 MPa. Compared to the estimated strength of vibrated mixes with the same W/C ratio, mixes L-1 and L-3 developed 3–4 MPa lower 1-day and about 5 MPa higher 28-day compressive strengths, whereas mixes C-1 and C-2 developed about 5 MPa lower 28-day compressive strengths. Mix L-2 is an exception, since its 1- and 28-day compressive strengths were lower than those of mix L-3, with the same W/C ratio, and also than those of mix L-1, with a higher W/C ratio. The poorer self-compacting properties of mix L-2 (Table 5) are probably the reason for the lower compressive strengths obtained.

The addition of LF causes an acceleration in the hydration of the clinker minerals, especially the C_3S [4]. The rate of acceleration is higher when the amount and fineness of the LF is increased. This effect is more pronounced at early ages [5,15]. The addition of the polysaccharide-based VA, on the other hand, can retard the hydration process, and thus considerably delay the onset of the hardening of the cement paste, and also lower its early as well as its 28-day compressive strength. The size of the decrease in compressive strength appears to be related not only to the VA dosage, but also to the dosage and type of SP used [30]. Since the difference in the 28-day compressive strength between mixes C-1 (without VA) and C-2 (with VA) is about the same as in the case of vibrated concrete mixes with W/C ratios of 0.43 and 0.48, the addition of VA does not seem to have had a direct influence on the 28-day compressive strength of the investigated SCC mixes. Its influence is indirect, through the increase in the amount of water required for the selected self-compacting properties of the SCCs. However, the influence of VA on the hydration process at an early age is probably responsible for the lower 1-day compressive strengths of mixes L-1 to L-3, compared

Table 5
Properties of fresh concrete mixes

Mix	V_W/V_{C+F}	Slump flow		V-funnel	L-shaped box			Filling vessel	Air content
		Spread (mm)	T 500 (s)	Flow time (s)	H2/H1	T 200 (s)	T 400 (s)	Filling ratio (%)	%
C-1	0.66	765	3.3	7.5	0.88	1.2	3.0	96	1.9
C-2	0.74	735	2.5	5.8	0.91	0.7	1.6	99	1.3
L-1	0.69	764	3.1	7.5	0.92	1.0	2.3	97	0.9
L-2	0.66	693	4.7	11.7	0.86	1.1	3.7	94	1.4
L-3	0.64	702	4.7	13.4	0.89	0.8	2.8	96	1.6

Table 6
Compressive and splitting strength

Concrete mix	W/C ratio	W/(C+F) ratio	1-day compressive strength		28-day compressive strength		28-day splitting strength		Splitting/compressive strength ratio
			MPa	COV (%)	MPa	COV (%)	MPa	COV (%)	
C-1	0.43	0.23	–	–	57.3	3	4.21	7	0.09
C-2	0.48	0.25	–	–	50.3	3	3.15	14	0.08
L-1	0.45	0.24	23.5	3	64.9	1	4.62	15	0.09
L-2	0.43	0.23	22.4	5	63.6	2	4.53	11	0.09
L-3	0.43	0.22	24.5	6	67.6	1	4.28	13	0.08

to those of vibrated control mixes. It seems that, at this age, the decrease in compressive strength due to VA prevailed over the increase due to LF. The approximately 10 MPa higher 28-day compressive strengths of the SCC mixes with LF-L, compared with those of the mixes with LF-C, can only be due to the influence of the fineness and grading of the fillers on the hydration process of cement and the particle packing of the cementitious system, since there are essentially no differences between the mineralogical compositions of the fillers used. By using the much finer and better-graded LF-L as filler material, a higher degree of cement hydration and improved particle packing of the cementitious system can be expected, compared to the LF-C, leading to the denser paste matrix and the ITZ of mixes L-1 to L-3 at this age. The described processes are also probably responsible for the higher 28-day compressive strengths of mixes L-1 and L-3, compared to those of the vibrated control mixes.

6.3. Properties of the in situ concrete

For casting RC beam, mix C-2 was used, due to the fact that it had the lowest viscosity among the mixes with VA, and thus the highest tendency to segregate. The batches of the mix, however, showed adequate filling and passing ability, with maintained stability during the casting process. After removal of the formwork, a beam with sharp edges and very smooth surfaces of good quality was obtained (Fig. 4). The diameter of the few surface pores did not exceed 2 mm.

The results of in situ UPV measurements and compressive tests on drilled cores are summarized in Table 7. The results of the compressive tests on the cores were calculated and expressed in order to estimate the in situ 150-mm cube strength. The average UPV values for particular locations were between 4862 and 5027 m/s, and the average compressive strength was 55.3 MPa. Bonavetti et al. [5] found that concrete mixes with limestone-blended cements are less sensitive to early interruptions in moist curing, due to the increase in the rate of hydration at an early age. In the case of continuous moist curing, the in situ concrete would thus probably develop only a slightly higher compressive strength (e.g. by a few percent), which would be equal or just a little higher than the average 56-day compressive strength obtained on corresponding cubes (57.5 MPa).

Table 7
Properties of in situ concrete

Location	Distance (mm)	UPV		Compressive strength (MPa)
		m/s	COV (%)	
I	150	5027	1.8	55.3
II	750	4953	1.9	56.2
III	1500	4936	2.1	52.8
IV	2250	4983	1.7	57.3
V	2850	4862	1.7	54.9
Average		4952		55.3
COV (%)		2		3

The statistical analysis tool ANOVA was used to determine whether the differences in concrete homogeneity, estimated by UPV measurements, were statistically significant. It was found that the differences in homogeneity at different locations along the length of the beam and along its height were not statistically significant, even at a significance level of α=.10. In view of these findings, it can be concluded that the in situ concrete of the beam was uniform. They are also in good correlation with the results obtained by Zhu et al. [31], who found that variations of in situ strength and the near-surface qualities along the length of full-scale beams were, in the case of SCC mixes, statistically insignificant.

7. Conclusions

Taking into account the materials and mix design used in this study, the following conclusions can be drawn:

- Around 0.42 m^3 of paste is needed in order to obtain the required self-compacting properties of concrete mixes made from poorly graded, crushed limestone aggregate and VA. In the case of a PC content of between 380 and 390 kg, a volume fraction of LF in the cement–filler blend of around 50% can be expected. By using LF with a fineness and grading that can greatly improve the particle packing and deformability of the cementitious paste, the amount of mixing water can be considerably reduced. In this study, the W/C ratio was reduced from 0.48 to 0.45, by replacing the coarser ground filler with the finer and better-graded limestone dust.
- SCC mixes with a high volume of cement–LF paste can develop higher or lower 28-day compressive

strengths, compared to those of vibrated concrete with the same W/C ratio and cement content, but without a filler. In this study, SCCs prepared using limestone dust and finely ground limestone developed about 5 MPa higher and 5 MPa lower compressive strengths, respectively, than vibrated control mixes. It appears that the strength characteristics of the SCCs are related to the fineness and grading of the LF used. The limestone dust made possible the formation of a denser cementitious matrix and ITZ in the SCCs. The increased rate of the hydration process and improved particle packing are probably responsible for increased density. On the other hand, the finely ground filler did not improve the density of the hardened paste matrix and the ITZ, compared to those of the vibrated control mixes.

- In the investigated SCC mixes, a polysaccharide-based VA was able to effectively replace quartzite sand, which is traditionally used in order to compensate the lack of fine material in crushed sand. However, in order to obtain approximately the same self-compacting properties, the mix with VA needs a considerably larger amount of water, and it appears that VA influences the concrete properties at an early age, probably due to retarded cement hydration. The obtained minimum dosage of VA (0.3% by mass of the mixing water) was sufficient to achieve adequate stability of the SCCs. Even the mix with the lowest viscosity showed adequate filling and passing ability, with maintained stability during the RC beam casting, and generated uniform properties of the in situ concrete along the height and length of the beam.

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