Original Scientific Article • DOI: 10.2478/rmzmag-2023-0004

Received: January 29, 2023
Accepted: May 19, 2023

Recycling of foundry sand wastes in self-compacting concretes: Use as cementitious materials and fine aggregates

Recikliranje odpadnega livarskega peska v samozgoščevalnih betonih: Uporaba kot cementni materiali in drobni agregati

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Abstract

This paper discusses waste recycling as a compound in building materials. Foundry sand-based self-compacting concretes (SCC) were investigated to see the possibility of recycling foundry sand wastes (FSW). FSW was used as a cementitious addition (by partial cement replacement: 10%, 20% and 30% wt. cement), then as a fine aggregate (by partial sand substitution: 10%, 30% and 50% wt. sand). For this, an experimental study was carried out to evaluate physical and mechanical properties of SCC at fresh and hardened states. The results show that the FSW also played the role of a filling material, which slightly improved the compactness of the concrete while saving part of the cement. According to the results of the non-destructive tests by ultrasonic tests, all concretes gave a dynamic modulus of elasticity that was almost identical and which was greater than 36 GPa. Compressive strength value slightly reduced with the cement substitution by the crushed foundry sand waste. However, up to 30% FSW, the compressive strength recorded after 28 days was around 30 MPa. A slight decrease in the fluidity of concrete at 10% substitution of natural sand by FSW was observed. After up to 30% replacement of sand by foundry sand wastes, the fluidity of the concrete was improved. The improvement in the fluidity of the concretes was perhaps due to the fineness of the natural sand and that of the foundry sand. When used as up to 50% of sand substitution, FSW can be used as a fine aggregate for concretes without affecting the essential proprieties of concretes.

Keywords: foundry sand wastes, cement, self-compacting concrete, slump test, compressive and flexural strength, dynamic elastic modulus

Povzetek

Članek obravnava recikliranje odpadnega livarskega peska za ponovno uporabo v gradbenih materialih. Za ugotavljanje možnosti recikliranja odpadnega livarskega peska (FSW) so bili raziskani samozgoščevalni betoni na osnovi livarskega peska (SCC). FSW se uporablja kot cementni dodatek (z delno zamenjavo cementa: 10 %, 20 % in 30 % mas. % cementa) in kot drobni agregat (z delno zamenjavo peska: 10 %, 30 % in 50 % mas. % peska). V ta namen je bila izvedena preiskava za oceno fizikalnih in mehanskih lastnosti SCC v svežem in strjenem stanju. Iz rezultatov je razvidno, da ima FSW tudi vlogo polnila, ki nekoliko izboljša kompaktnost betona, hkrati pa prihrani del cementa. Po rezultatih neporušnih preiskav z ultrazvokom so vsi betoni izkazovali skoraj enak dinamični modul elastičnosti, ki je večji od 36 GPa. Vrednost tlačne trdnosti se je z zamenjavo cementa z zdrobljenim livarskim peskom nekoliko zmanjšala. Vrednost tlačne trdnosti do 30 % FSW po 28 dneh je bila okoli 30 MPa. Opaženo je rahlo zmanjšanje fluidnosti betona pri 10 % zamenjavi naravnega peska s FSW. Vrednosti do 30% zamenjava peska z odpadki livarskega peska izkazujejo boljšo fluidnost betona. Izboljšanje fluidnosti betona je morda posledica finosti naravnega peska in livarskega peska. Z uporabo do 50 % nadomestitve peska se FSW lahko uporablja kot fin agregat za betone, ne da bi to vplivalo na bistvene lastnosti betonov.

Ključne besede: odpadni livarski pesek, cement, samozgoščevalni beton, preiskava s posedom, tlačna in upogibna trdnost, dinamični elastični modul

Introduction

Several researchers have studied the use of foundry sand wastes (FSW) in various civil applications. Billie et al. [1] reported the reuse of foundry sand in agriculture, mixed with topsoil for landscaping, or reclamation, and as a rooting area for sports turf. Naik et al. [2] reported that sinkable mud with desirable physical properties can be made using foundry sand as a replacement for fly ash up to 85%. Sen and Mishra [3] reported the use of FSW in village road construction. Petavratzi and Wilson [4] reported the possibility of using foundry sand in facing bricks as filler at low substitution rates (substitution of primary sand at 2.5 to 5%). Alberta and Gardner [5] studied the use of industrial by-products in urban road infrastructure. Koff et al. [6] studied the improvement of physical strength in foundry greensand waste for reuse as a soil amendment. Lin et al. [7] reported using recycled foundry sand waste as a raw material for cement additives. Dungan et al. [8] investigated the characterization and composition of bacterial communities in soils mixed with spent foundry sand. Sayeed Javed [9] studied the use of foundry sand in road construction. Mgangira [10] evaluated the influence of the proportion of foundry sand waste on the geotechnical engineering properties of clay soils. Lee et al. [11] performed their test on a retaining wall model with foundry sand waste mixed with backfill. Little work has been reported on the use of foundry sand wastes (FSW) in concrete and concrete-derived products. Some researchers have reported works relating to the different applications and methods used for the testing of concrete made with FSW, namely Naik et al. [12], who conducted a study to evaluate the performance of foundry by-products in concrete and masonry products. Based on their test results, they concluded that the addition of foundry sand resulted in a decrease in the workability of the concrete. Also, compressive strength of concrete decreased slightly due to replacement of regular coarse aggregates with foundry slag. However, the compressive strength observed for the 50% and 100% slag blends was adequate for structural uses. The modulus of elasticity of the 100% slag mixture was the highest of the three mixtures evaluated. They also found that all masonry blocks made with 35% new/used foundry sand meet ASTM requirements for compressive strength, absorption and bulk density. Khatib et al. [13] and Monosi et al. [14] studied the properties of mortars and concretes containing different dosages of spent foundry sand (FSW) by partial substitution of sand in both fresh and hardened states. From the test results obtained, they concluded that FSW reduces workability when added as a natural sand substitute (at the same W/C ratio). Bhardwaj et al. [15], Bradshaw et al. [16], Mavroulidou et al. [17], and other researchers performed many tests on concrete comprising FSW as a partial replacement of sand at ambient temperatures [18–22]. Since the elevated temperature is a catastrophic phenomenon, Hazrat et al. have evaluated the behavior of FSW concrete under elevated temperatures [23]. Recently Sebki et al. [24] studied the possibility of recycling FSW in a fluid mortar such as self-compacting mortar (SCM) by partial and total substitution of fine aggregate on the one hand, and by partial substitution of cement on the other. This study showed that it is possible to substitute cement by FSW up to 30% by weight of the cement without affecting the properties of SCM in the fresh state and in the hardened state, with a compressive strength of 50MPa after 28 days of curing. Concerning the substitution of fine sand by FSW, we find that it is possible to save up to 50% of the natural sand while preserving the physical and mechanical properties of the SCM. The main objective of the current research is to evaluate the properties of self-compacting concrete with its fine aggregates partially replaced by FSW and using it as a cementitious addition. For proper utilization of FSW in the building and construction industry, experimentation was conducted to evaluate the properties of fresh and hardened concrete with different amounts of foundry sand wastes. Compressive strength and flexural tensile strength were evaluated at different ages (3, 7, and 28 days) of all concrete mixtures. The modulus of elasticity was also part of this investigation.

Figure 1: *Foundry sand wastes used in this work: (a) rejected zone, (b) FSW as sand.*

Table 1: *Chemical analysis of foundry sand wastes.*

Compounds	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Na_2O	K_2O	MgO	P_2O_5
(%)	6.328	60.762	11.688	9.642	1.851	0.010	1.281	2.195	0.010

Experimental study

Materials used

The materials used in this study were Portland cement (CEM II 42, 5), limestone filler, Polycarboxylate based superplasticizer (from SIKA, Tempo 12 type), Natural sand (0/5mm), and foundry sand waste (FSW).

The foundry sand waste used (Figure 1) in our work is recycling waste from an Algerian foundry. This waste was characterized. It is remarkable that the FSW contained essentially silica (Table 1). Therefore, the characteristics of this sand are determined either at the natural state or the crushed state. The physical properties of natural sand (NS) and foundry sand waste (FSW) are given in Table 2. From this table, it was noted that FSW is finer than natural sand according to the obtained fineness modulus of the used sands. The foundry sand wastes were also subjected to microstructural analysis using a scanning electron microscope (SEM). The SEM images obtained are shown in Figure 2. According to these pictures, the morphology of foundry sand is rounded in shape with different sizes.

Figure 3 shows the particle size distribution of the used FSW and natural sand. According to the figure, natural sand contains fine particles.

Table 2: *Physical properties of natural sand and foundry sand wastes.*

	Natural Sand NS	Foundry Sand Wastes FSW
Apparent density (kg/m^3)	3150	1240
Specific gravity (kg/m^3)	2760	2400
Fineness modulus	2	2.47

It is also noted that FSW has round shape granulometry.

In order to check the fineness of the finely ground foundry sand, we proceeded to the laser particle size analysis of the cement and ground foundry sand. The results are given in the form of a curve, which represents the volume fraction in a percentage as a function of the size of the particles in μm (Figure 4). It is remarkable that cement is thinner than the FSW. In fact, the latter contains grains with a diameter of 100μm more than cement. Besides, cement has particles with a diameter of 10 μm, exceeding 50% relative to the ground foundry sand (Figure 5).

The study of the pozzolanic activity of ground foundry sand waste, or its pozzolanicity, is the ability of certain materials lacking their own hydraulic properties to fix calcium hydroxide

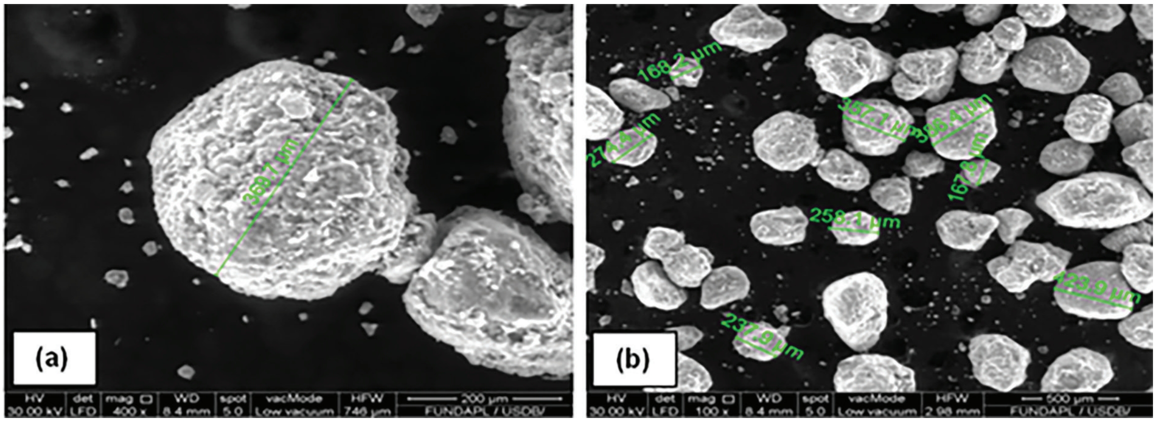

Figure 2: *SEM images of used foundry sand waste: (a) at 400x magnitude, (b) at 100x magnitude.*

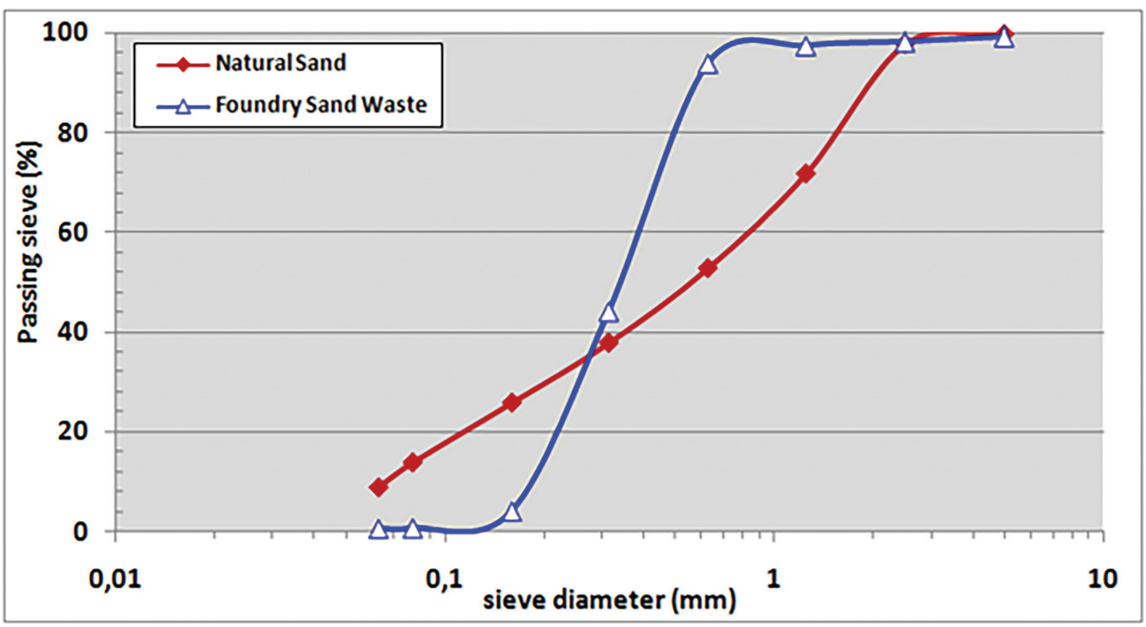

Figure 3: *Particle size distribution of natural sand and foundry sand wastes.*

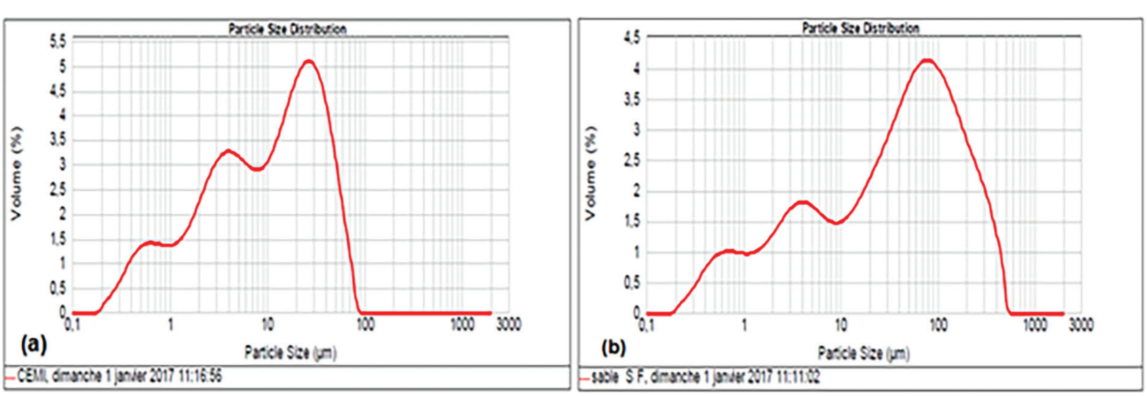

Figure 4: *Particle size distribution of cement and crushed foundry sand in volume fraction obtained by Laser Granulometry: (a) cement, (b) crushed foundry sand waste.*

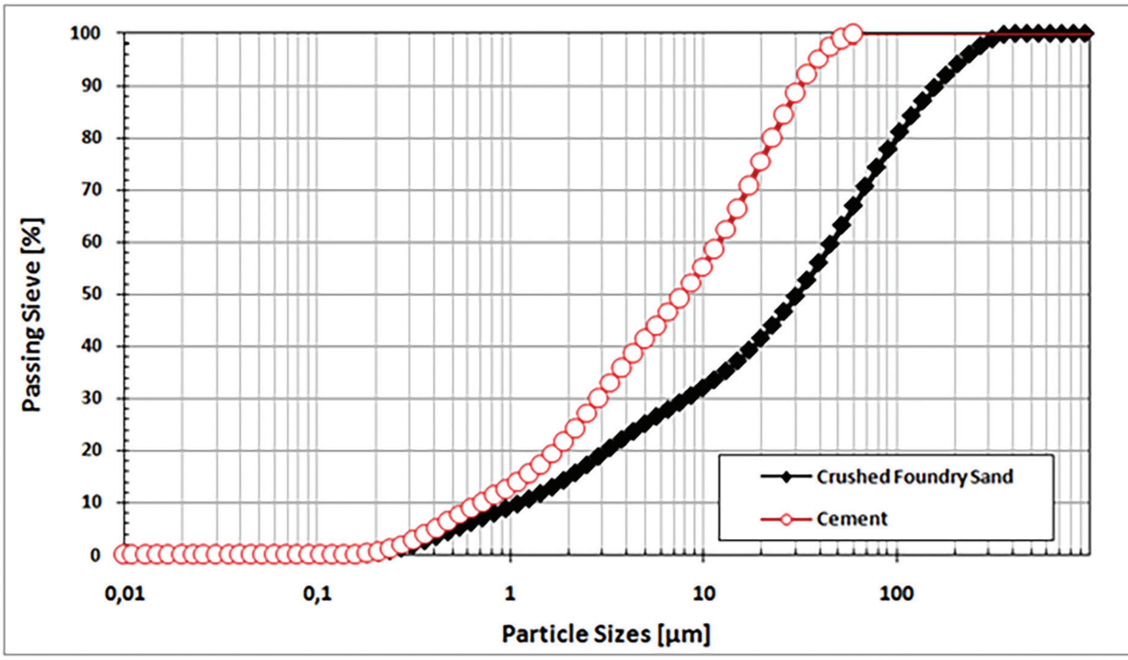

Figure 5: *Particle size distribution of cement and crushed foundry sand waste.*

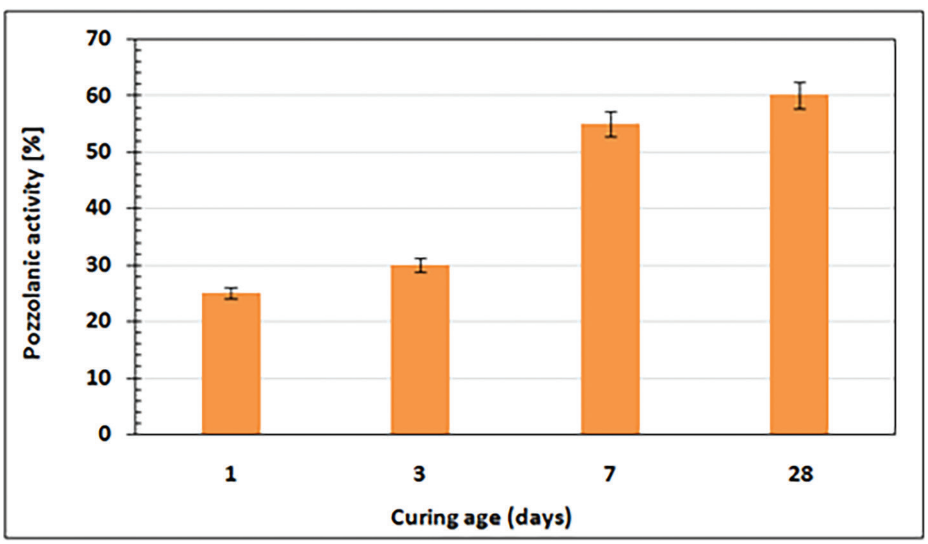

Figure 6: *Pozzolanic activity of FSW obtained by the saturated lime test.*

in the presence of water to give hydrates similar to those of Portland cement. In order to highlight a possible consumption of lime by the foundry sand waste used, we chose the method known as the saturated lime test [25–26].

According to the values of the saturated lime test given in Figure 6, the foundry sand waste has an average pozzolanic activity of 55% at 7 days and 60% at 28 days. Lime consumption increases with steaming time.

Coarse aggregates (3/8 and 8/16 gravel) are traditional aggregates commonly used in concrete. Gravel 3/8 is a gravel of minimum diameter 3mm and maximum diameter 8mm. Gravel 8/16 has a minimum diameter of 8 mm and a maximum diameter of 16mm. In this work we used 8/16 gravel. From the physical gravel testing, we confirmed that the absolute density (1.57 g/cm^3) for 3/8 and 8/16 gravel was the same because they were of the same nature.

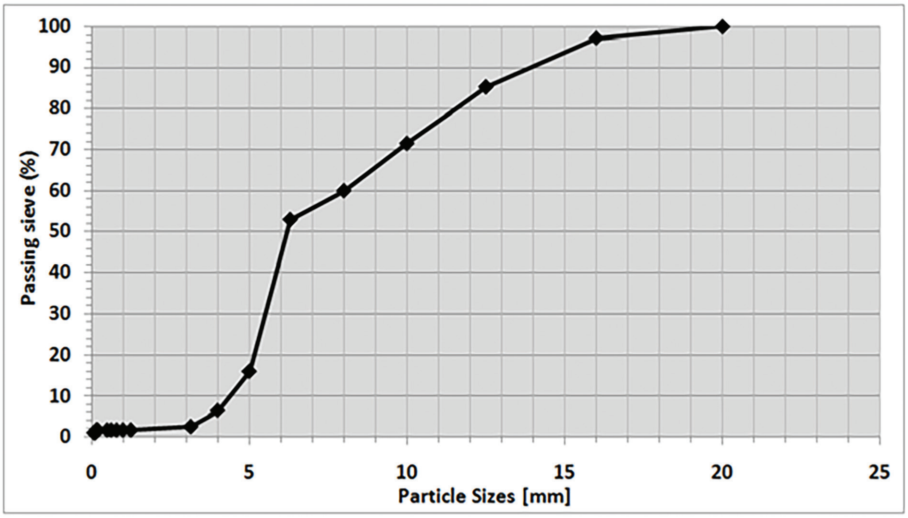

Figure 7: *Particle size analysis by sieving of gravel 8/16.*

It is clear that this gravel contains grains of sizes between 3 mm and 8 mm, as well as grains of sizes between 8 mm and 16 mm. For this, we will only use class 8/16 gravel, which contains both types of gravel: 3/8, as well as 8/16 (see Figure 7).

Mix proportions of studied concretes

In the literature, there is a large number of formulation approaches and methods for self-compacting concretes (SCC). We have retained for our formulation a purely experimental method called "Japanese" proposed by Okamura et al. [27]. Table 3 shows the mix details of control concrete (SCC0) and other variants, which were obtained by using FSW as sand substitution at various dosages (10, 30, and 50% wt. of sand). Table 4 gives all the concrete mixtures of this case. Table 5 gives the concrete mixtures of the case with cement substitution by crushed foundry sand (10, 20, 30 and 50% wt. of cement). The studied concrete formulations were prepared using a concrete mixer according (Figure 8a). The ratio F/C = 0.10 was kept constant. The mixing protocol was kept constant for all mixtures.

Mix Notation

- Cement substitution: SCC0, SCC10, SCC20 and SCC30
- Sand substitution: CFS0, CFS10, CFS30 and CFS50

Table 3: *Mixture details of self-compacting concrete (SCC).*

Component [Kg/m3]	SCC
Cement *	500
Limestone fillers	118.1
Natural sand**	843.7
Water	216
Superplasticizer	7.5
Gravel 8/16	742.8

SCC0: concrete control (without FSW);
* Cement is substituted by FSW (finely crushed) at dosages (0%, 10%, 20% and 30% wt.)
** Sand is substituted by FSW at dosages (0%, 10%, 30%, and 50% wt.)

Preparation, curing and test methods

Fresh properties

After each preparation, all the concrete mixtures studied were characterized with the spreading test, L-box test, and sieve stability test according to ASTM C143/143M [28].

Hardened Properties

According to ASTM C192/C192M [29], for the compressive strengths, cubic self-compacting concrete specimens of 150×150×150 mm were made for each mixture (Figures 8b and 8c). While 150×150×500 mm prismatic specimens were casting, we sought to find the bending tensile strengths. One day after casting, samples were stored in water under 21±1°C. Three-point bending and uniaxial compression tests were carried out after 3 and 28 days of

Table 4: *Mixture details of self-compacting concrete (SCC): Cement substitution case.*

Component [Kg/m3]	SCC0	SCC10	SCC20	SCC30
Cement *	500	450	400	350
Crushed FSW	0	50	100	150
Limestone fillers	118.1	118.1	118.1	118.1
Natural sand	844	844	844	844
Water	216	216	216	216
Superplasticizer	7.5	7.5	7.5	7.5
Gravel 8/16	742.8	742.8	742.8	742.8

Table 5: *Mixture details of self-compacting concrete (CFS): Sand substitution case.*

Component [Kg/m3]	CFS0	CFS10	CFS30	CFS50
Cement	500	500	500	500
Limestone fillers	118.1	118.1	118.1	118.1
Natural sand**	844	844	844	844
Foundry sand waste	0	84.4	168.8	253
Water	216	216	216	216
Superplasticizer	7.5	7.5	7.5	7.5
Gravel 8/16	742.8	742.8	742.8	742.8

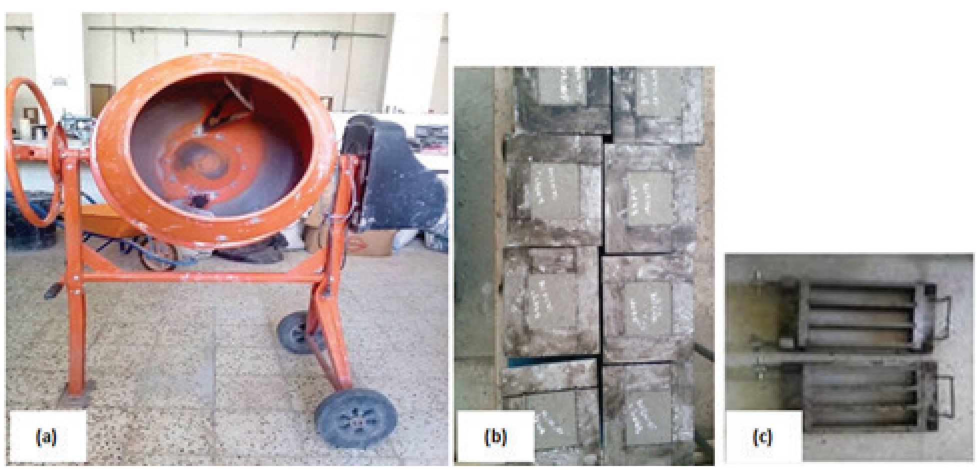

Figure 8: *Mixer and molds used for self-compacting concrete: (a) concrete mixer, (b) cubic samples (150x150x150 mm3), (c) prismatic samples (70x70x280 mm3).*

hardening (Figures 9a and 9b). Other various tests and measurements were also carried out.

Results and discussion

Sand Substitution

a) Fluidity of Concretes

The fluidity of the studied concretes was estimated by the Abrams cone-spreading test. The results are shown in Figure 10. According to the results, we notice a slight decrease in the fluidity of the concrete at 10% substitution of natural sand by foundry sand. Then, beyond 10% substitution, the concrete becomes more fluid. At 30% replacement of sand by foundry sand, the fluidity of the concrete has been improved. The improvement in the fluidity of the concrete is perhaps due to the natural sand's fineness compared to that of foundry sand. The latter is less fine than natural sand,

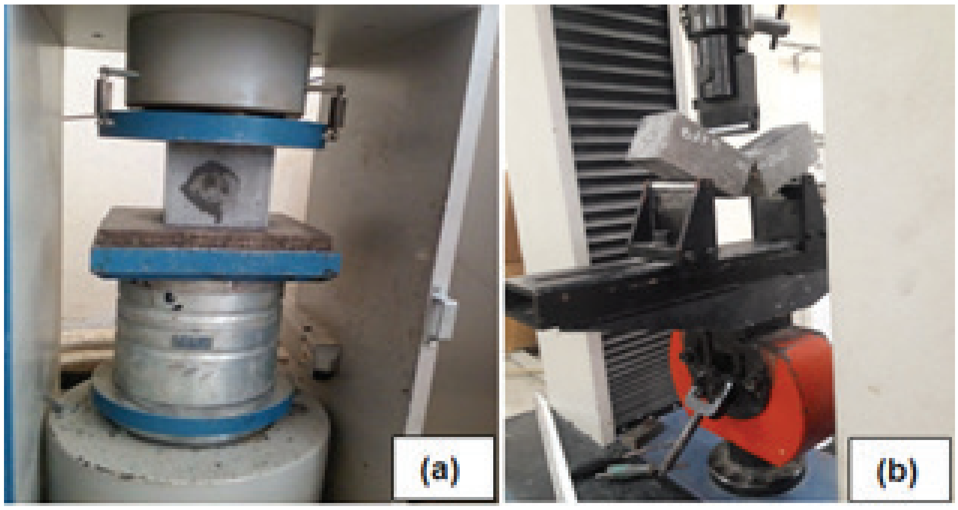

Figure 9: *Mechanical tests: (a) compressive, (b) flexural strength.*

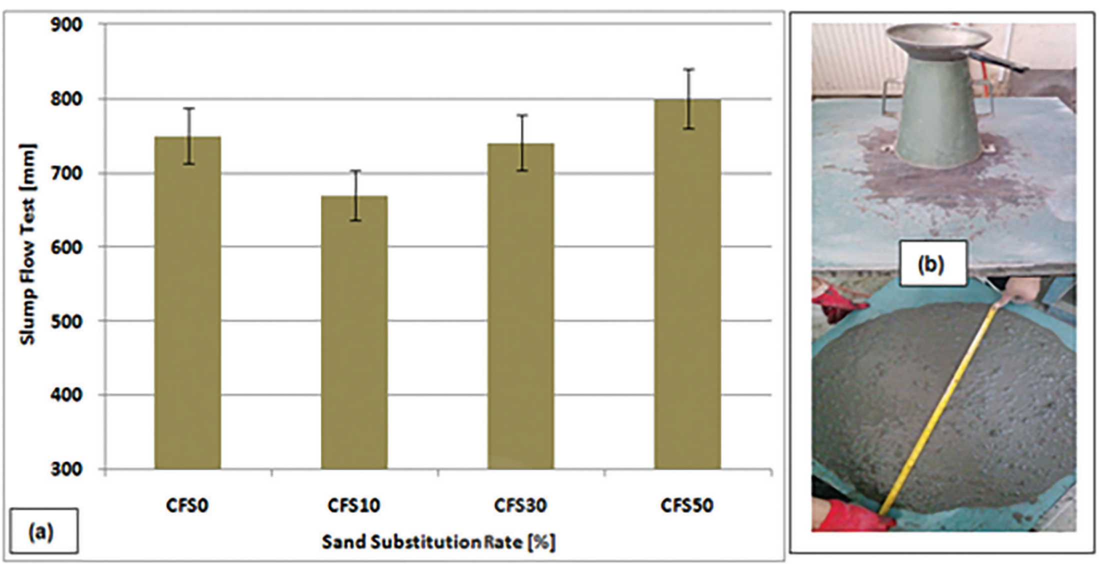

Figure 10: *Fluidity concretes studied by sand substitution: (a) obtained result, (b) practical flow test of concrete.*

which has a fineness modulus 2 lower than that of foundry sand (at 2.47).

b) Filling capacity (L box test)
The L-box test (Figure 11) was performed for self-compacting concrete only. It is used to assess the risk of blockage and the filling capacity of concrete in a confined environment.

The results of this test are given in Figure 11. According to the figure, we can see that the more the rate of substitution of sand by foundry sand increases, the more the implementation of the concretes improves, and the easier the concretes become to put in place. This improvement in emplacement is also explained by the fineness of the sands. Indeed, foundry sand is less fine than sand, which promotes the flowability of concrete.

c) Concrete stability
The sieve stability test is used to qualify self-compacting concrete with respect to the risk of segregation. The percentage by weight of laitance is measured in relation to the weight of the sample passing through a sieve with an opening of 5 mm. The results in Figure 12 clearly show that the more the sand substitution rate by the foundry sand waste increases, the more the passers-by at the sieve increase. Up to 30% substitution,

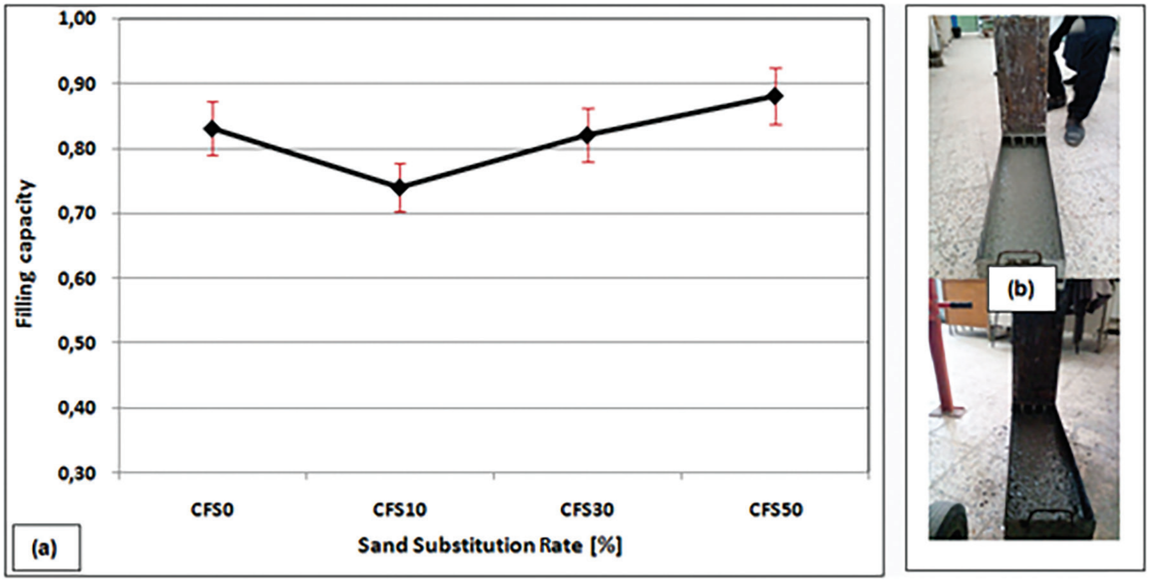

Figure 11: *Filling capacity of the concretes studied according to the rate of substitution of sand by FSW: (a) filling capacity of the concretes, (b) practical L-box test of self-compacting concrete.*

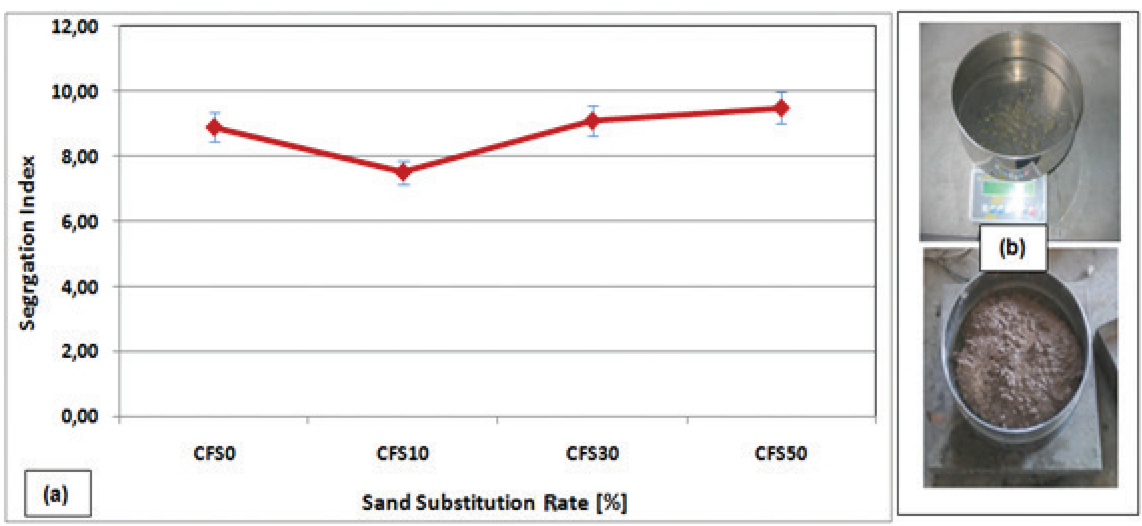

Figure 12: *Segregation index of the concretes studied according to the substitution rate of sand by FSW: (a) segregation index of the concretes, (b) segregation test of self-compacting concretes.*

more or less acceptable concrete laitance was recorded.

d) Compressive and flexural strength

The evolution of the compressive and flexural strength of the concretes studied has been represented in the form of histograms in Figure 13. According to the results obtained, it is remarkable that for all the concretes, the mechanical strength of the concretes increases according to the age of hardening (measured at 3, 7 and 28 d). This is explained by the hydration of the clinker minerals contained in the cement, which produces the calcium silicate hydrate (CSH) gel improving the strength of the concrete. The strength of the concrete with 10% foundry sand is the same as that of the control concrete. This is reflected by the presence of foundry sand which has favored the implementation of the concrete, which increases the compactness of the concrete. However, a slight decrease of 10% in strength was observed for concretes with 30% and 50% substitution of natural sand by foundry sand waste.

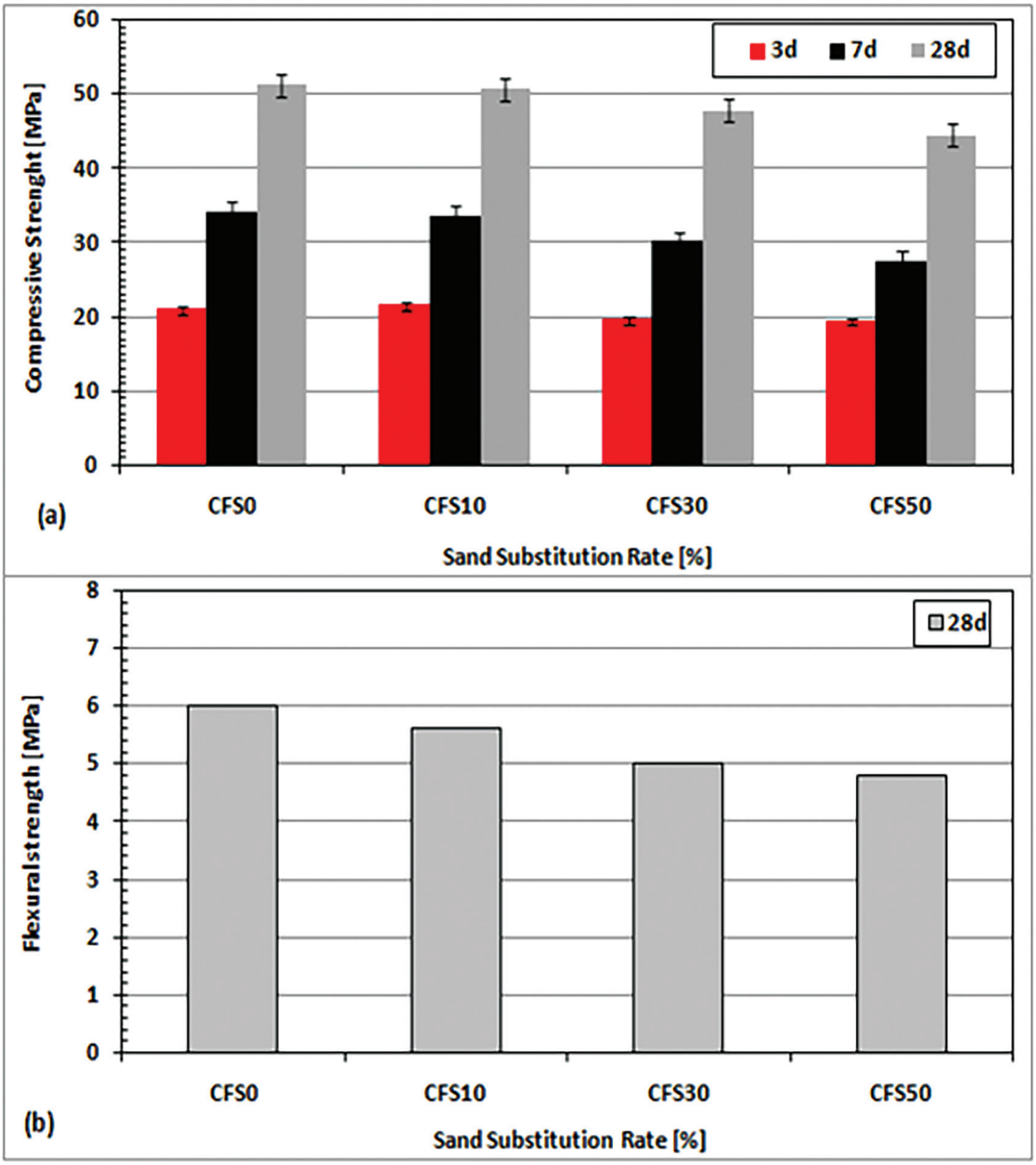

Figure 13: *Mechanical strength development of studied self-compacting concretes: (a) compressive strength, (b) flexural strength tested at 28d.*

e) Ultrasound (Ultrasonic Pulse Velocity Test)
This test is a method for determining the propagation velocity of longitudinal ultrasonic waves in hardened concrete. It consists of measuring the propagation time between two designated points on the surface of the object to be tested.

$$E_d = \rho v^2$$

v: The speed of ultrasound in km/s
ρ: density in kg/m^3.
E_d: Modulus of dynamic elasticity

In order to verify the effect of the addition of foundry sand on the compactness of the self-compacting concretes studied, ultrasonic tests were carried out on the prismatic to measure the speed of sound propagation through the concrete after 28 hardening days. After measuring the speed and the densities, we calculated the values of the dynamic modulus of elasticity of each concrete. The results of this test are shown in Figure 14. It is remarkable that all the concretes have a modulus of elasticity exceeding 40 GPa and which can be classified

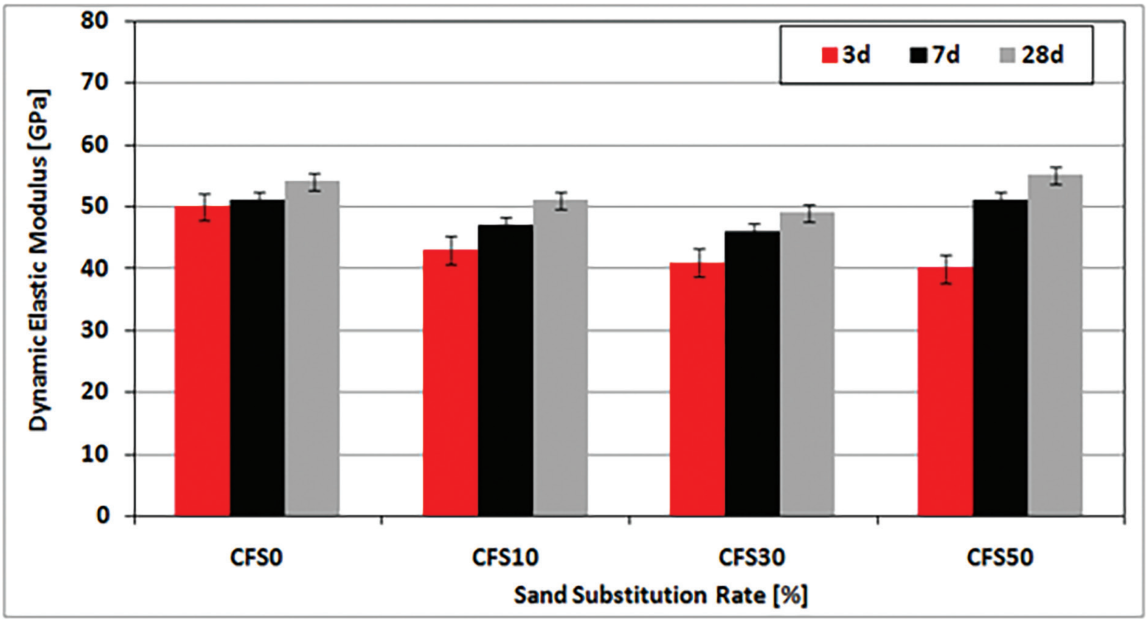

Figure 14: *Evolution of the dynamic elasticity coefficient of concretes according to the substitution rate of sand by FSW.*

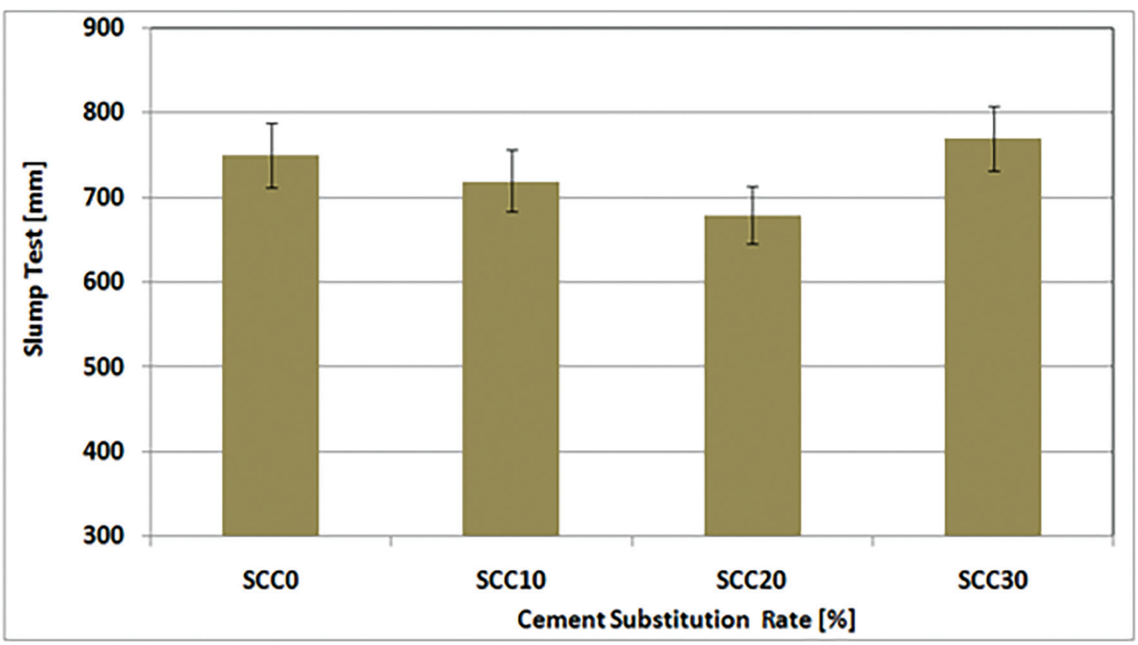

Figure 15: *Fluidity of concretes studied by cement substitution.*

as quality concretes according to the standards in force. This proves that foundry sand waste can be used as sand (0/3 mm) without affecting the compactness and strength of concrete while saving up to 50% of natural sand. Indeed, up to 50% substitution of natural sand by foundry sand can give a self-compacting concrete of acceptable compactness.

Cement substitution

In this part, we will study the possibility of recycling foundry sand waste in self-compacting concrete, while saving part of the cement. For this, we will manufacture SCCs based on foundry sand, by partial substitution of cement (use as a cement addition) at percentages of (10, 20 and 30% by weight of cement).

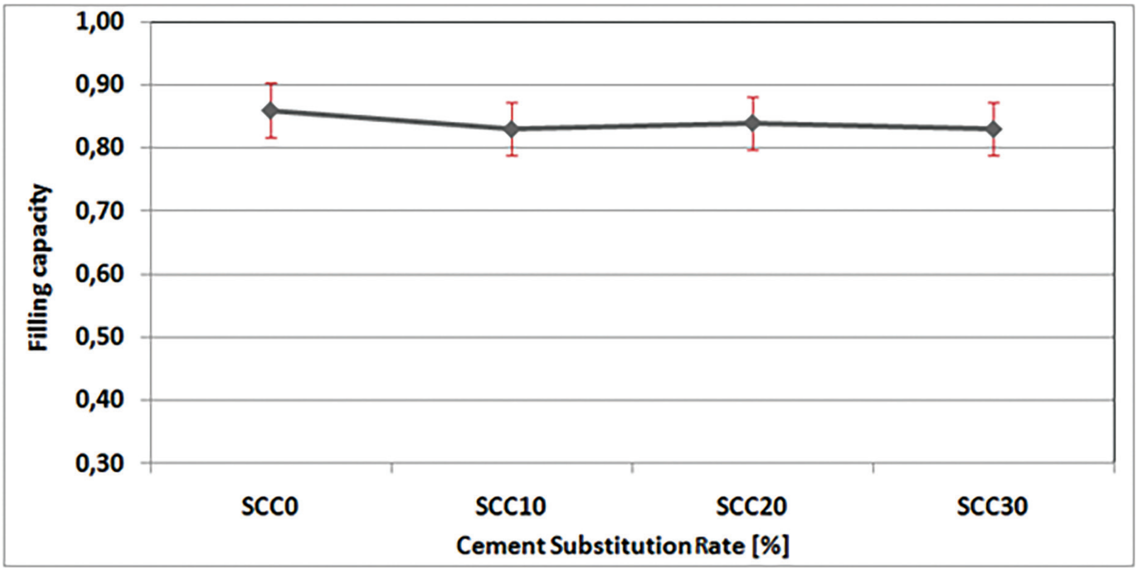

Figure 16: *Filling capacity of the concretes studied according to the substitution rate of cement by foundry sand waste.*

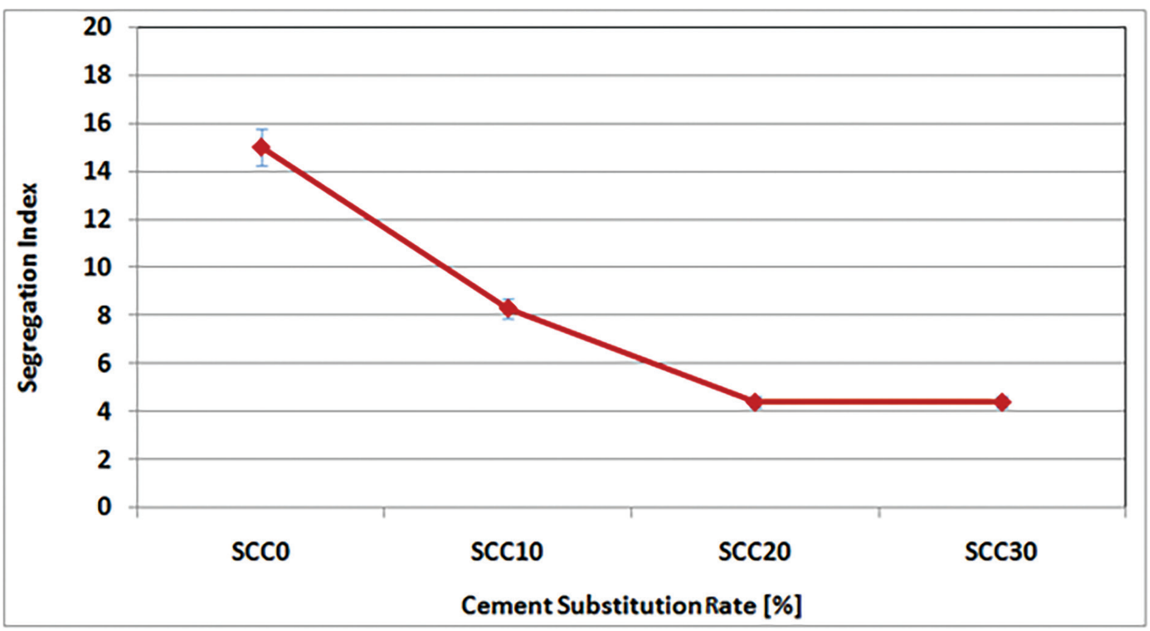

Figure 17: *Stability of concretes studied.*

a) Fluidity of concretes:

All the concrete mixes studied were prepared with a spread varying between 650 and 800 mm. Figure 15 represents the fluidity of the concretes studied as a function of the rate of substitution of cement by finely ground foundry sand waste. According to the results of the spreading tests, we notice a slight decrease in the fluidity of the concretes with the increase in the rate of substitution of cement by foundry sand waste. Indeed, up to 20% substitution, the reduction is not significant enough because the concrete always remains self-compacting. The fluidity of the concrete at 30% cement substitution by FSW was 640 mm; this fluidity was caught up by adjusting the dosage of superplasticizer to reach a value of 770 mm.

b) Filling capacity (L box)

To qualify self-compacting concrete as flowable concrete, there must be good workability

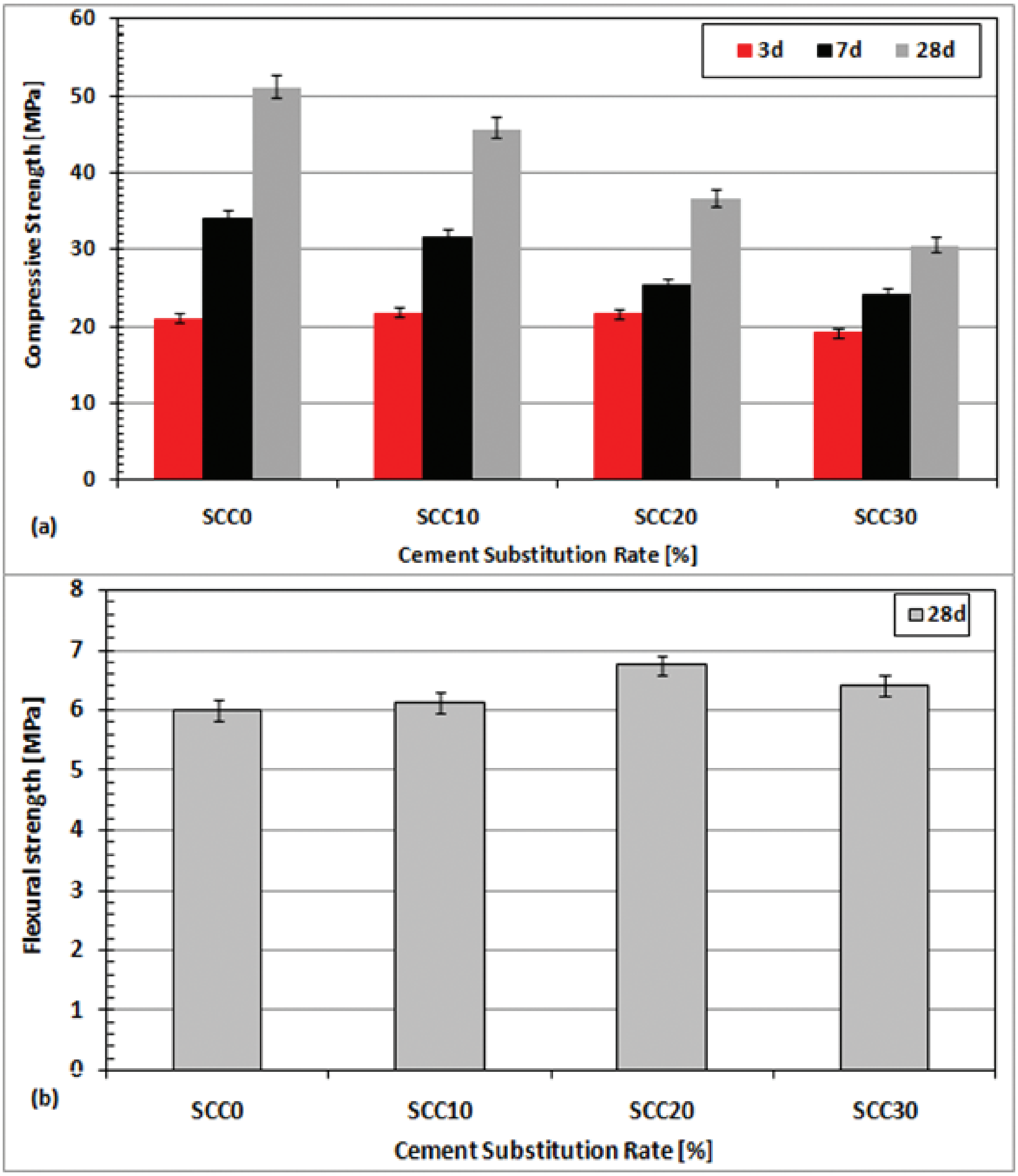

Figure 18: *Evolution of the mechanical strength of the concretes studied: (a) compressive strength, (b) flexural strength tested at 28d.*

through the reinforcement into a structure during pouring. The implementation of the concretes studied was determined by the L-box test. According to the results represented in Figure 16, it is observed that the implementation of the concretes is not influenced by the presence of foundry sand waste, and that a slight disturbance of the filling capacity was also observed.

c) Concrete Stability (Screen Stability)

The stability of the studied concretes was evaluated by measuring the refusal on the screen of the fresh concrete. Figure 17 shows the variation in sieve stability of the self-compacting concretes studied as a function of the rate of substitution of cement by finely ground FSW. According to this figure, there is a decrease in the stability of SCC up to 30% substitution.

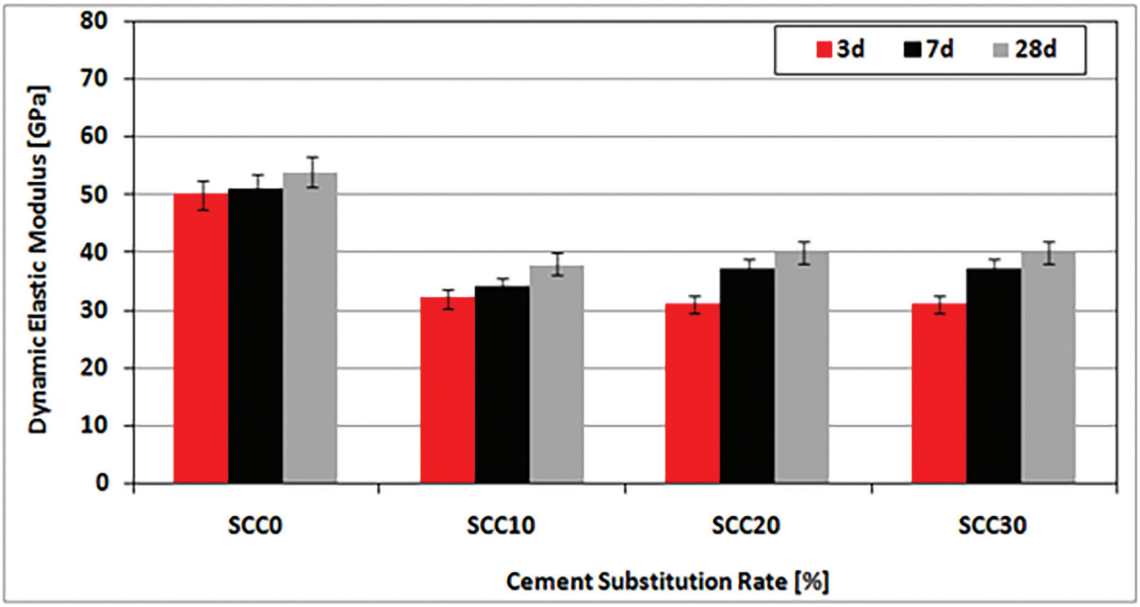

Figure 19: *Dynamic elastic modulus of the concretes studied.*

This may be due to the mineralogical and physical nature of the cementitious addition, which is the FSW. Indeed, the activity vis-à-vis mineral addition water (such as foundry sand) can decrease the stability of a concrete while increasing the need for water.

d) Compressive and flexural strength

The results of the mechanical tests, namely the compressive strength of the concretes studied, are presented in Figure 18. It can be seen that the value of the resistance of the concretes decreases with the substitution of cement by foundry sand waste. However, at 30% foundry sand waste, the compressive strength recorded after 28 days is approximately 30 MPa. The tensile strength by bending increases slightly with the substitution of cement by foundry sand waste compared to the control concrete. However, the flexural strength increased slightly for the concretes, with 10 and 20% substitution, then a slight decrease in strength for the SCC 30% substitution. The flexural tensile strength of the SCCs with substitution of cement by the FSW is higher than that of the control concrete; this is explained by the fact that the finely ground DSF has a pozzolanic activity.

e) Ultrasound (Ultrasonic Pulse Velocity Test)

By using the parameters, which are the density and the speed of sound, after having carried out non-destructive tests, we determined the dynamic modulus of elasticity of the concretes studied. Figure 19 represents the evolution of the dynamic modulus of elasticity of the concretes studied. According to Figure 19, we noticed that all the concretes have the almost identical dynamic modulus of elasticity and which is greater than 36 GPa. The results show that the foundry sand also played the role of a filling material, which slightly improved the compactness of the concrete while saving part of the cement. Indeed, up to 30% substitution of cement by finely ground foundry sand can give a self-compacting concrete having a dynamic modulus of elasticity exceeding 40 GPa, which is an acceptable value.

Conclusion

In this study, the self-compacting concretes based on foundry sand wastes (FSW) have been elaborated in order to recycle foundry sand waste as a cementitious additive and fine aggregate. Through the experimental study we carried out, it can be concluded that up to 50% replacement of natural sand by foundry sand wastes can lead to a self-compacting concrete with acceptable fresh characteristics and having a compressive strength at 28-days exceeding 40 MPa. However, a 20% reduction in cement consumption translates into concrete with acceptable characteristics for construction. Moreover, the results show that the FSW also played the role of a filling material, which slightly improves the compactness of the concrete while saving a part of cement. Indeed, up to 30% of cement substitution by finely ground FSW can give a self-compacting concrete with a dynamic modulus of elasticity exceeding 40 GPa, which is an acceptable value.

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