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Performance of self-compacting concrete with manufactured crushed sand

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Abstract. Self-compacting concretes (SCC) are highly fluid concrete which can flow without any vibration. Their composition requires a large quantity of fines to limit the risk of bleeding and segregation. The use of crushed sand rich in limestone fines could be an adequate solution for both economic and environmental reasons. This paper investigates the influence of quarry limestone fines from manufactured crushed sand on rheological, mechanical and durability properties of SCC. For this purpose, five mixtures of SCC with different limestone fines content as substitution of crushed sand (0, 5, 10, 15 and 20%) were prepared at constant water-to-cement ratio of 0.40 and 490 kg/m^3 of cement content. Fresh SCC mixtures were tested by slump flow test, *V*-funnel flow time test, L-box height ratio, segregation resistance and rheological test using a rheometer. Compressive and flexural strengths of SCC mixtures were evaluated at 28 days. Regarding durability properties, total porosity, capillary water absorption and chloride-ion migration were studied at 180 days. For the two test modes in fresh state, the results indicated compatibility between slump flow/yield stress (τ_0) and *V*-funnel flow time/plastic viscosity (μ). Increasing the substitution level of limestone fines in SCC mixtures, contributes to the decrease of the slump flow and the yield stress. All SCC mixtures investigated achieved adequate filling, adequate passing ability and exhibit no segregation. Moreover, the inclusion of limestone fines as crushed sand substitution reduces the capillary water absorption, chloride-ion migration and consequently enhances the durability performance.

Keywords: crushed sand; limestone fines; self-compacting concrete; rheological properties; mechanical properties; water permeability; chloride-ion migration

1. Introduction

Large quantities of crushed sand with higher limestone fines content is very abundant in many quarries, which lead to enormous disposal waste landfills, and consequently cause potential problems to the environment. Many studies (Felekoglu *et al*. 2007, Kenai *et al*. 1999, Menadi *et al*. 2013) have shown the favorable effect of crushed sand on the fresh and hardened properties of conventional concrete with moderate limestone fines (LF) content. Wang *et al*. (2018) reviewed the effects of limestone fines on cement-based materials and concluded that it is a combination of filler effect, nucleation effect, dilution effect and chemical effect. They concluded that incorporating limestone fines, as cement paste replacement or in the form of fine aggregate, improves the properties of concrete.

The use of crushed manufactured sand in concrete could be considered as an alternative solution to overcome the deficiency in river sand in some countries. She *et al*. (2018) reported that manufactured sand (MS) concrete presented higher strength than river sand concrete and that the strength reaches a peak value when the stone powder content is 7.5%.

In addition, self-compacting concretes (SCC), which are considered to be highly fluid and stable concrete that flows under its own weight without any vibration, require a large quantity of fines to limit the risk of bleeding and segregation (Okamura *et al*. 1999, AFGC 2002). Hence, the use of manufactured crushed sand rich in limestone fines in SCC mixtures can offer economical, technical and environmental benefits.

Regarding the effect of LF on the mechanical properties of mortar, it has been found that the compressive and flexural performance are improved by filler addition, or at least remain equivalent to the reference values. The optimal compressive and flexural strengths seem to be obtained between 0 and 25% filler mass percentage (Benachour *et al*. 2008). Menadi *et al*. (2009), have reported that the substitution of crushed sand by up to 15% of LF does not affect the performance of conventional concrete. Recent studies (Meziane *et al*. 2015) carried on mortar made with crushed sand, showed that LF accelerate the hydration of cement, increase the mechanical properties at early age and enhance the durability of mortar exposed to aggressive

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solutions. The total or partial replacement of natural sand with crushed sand is reported to improve the mechanical properties and reduces the rheological parameters of mortar (Bounedjema *et al*. 2017). Imrose *et al*. (2014) concluded that stone dust can be used as a replacement of sand in mortar mixes with improvement of compressive strength of more than 20% at 35% substitution level. Beixing *et al*. (2009) state that, the incorporation of limestone fines ranging from 10 to 15%, gives a satisfactory concrete workability. Kwan and Mckinley (2014) reported that the addition of LF increases the packing density of the (LF+ cement) mix but increases the paste volume and paste film thickness and hence improves the flow spread and strength of mortar. Silva and de Brito (2013) have found that capillary absorption and resistivity of mixes with LF are comparable to those of fly ash mixes at younger ages but at 182 days, the differences presented were significant. Sunil *et al*. (2017) used tailing material (TM) from mining industry and reported that concrete blend with 35% TM as substitution to river sand and 20% fly ash as substitution OPC, exhibited higher durability characteristics by higher resistance to sulfate, acid and chloride attacks.

The use of LF with appropriate amounts (100 to 130 kg/m^3) in concrete increases compactness and mechanical performance and reduces bleeding without affecting workability or shrinkage (Joudi *et al*. 2012). The shape and texture of crushed sand particles can improve the strength of concrete by increasing its compactness. However, a higher superplasticizer content is required for comparable workability to that of natural sand (Donza *et al*. 2002, Cepuritis *et al*. 2016). Safiddine *et al*. (2017) investigated the influence of limestone fines on the rheological properties of crushed sand based cement mortar of different mineralogical nature (limestone and silica). The results show that spreading/flow diameter decreased as well as the flow time, the yield strength and the viscosity of the mortar increased with the increase of LF content. In addition, the limestone crushed sand mortar exhibits a small loss of rheological properties compared to a crushed siliceous sand mortar.

Crushed sand was also used in the manufacture of self-compacting mortar and concrete. Researchers (Bosiljkov 2003, Benabed *et al*. 2012) have noted that the increase in fines content in self-compacting mortar reduces spreading/flow diameter and changes the flow time in *V*-funnel test. The incorporation of fine limestone powder (0.7 μm and 3 μm) in the cement paste, results in greater resistance to shear stress and viscosity (De Weerdt *et al*. 2011, Okamuara *et al*. 1993). Cepuritis*et al*. (2017) studied the effect of fine particles (<250 μm) on the rheology of the cement paste and showed that the rheological properties depend mainly on the specific surface of these fines.

Generally, mineral additions, especially limestone fines are also used to increase the volume of SCC paste and to act as an accelerator of cement hydration (Nishibayashi *et al*. 1996, Moosberg *et al*. 2004, Ferraris *et al*. 2001, Boukendakdji *et al*. 2009, Sua-iam *et al*. 2016, Ye *et al*. 2007, Vance *et al*. 2013). However, limited research studies have been done so far on the effects of LF from crushed sand on the durability properties of self-compacting concrete.

The aim of the present experimental study is devoted to investigate the effects of quarry limestone fines as crushed sand substitution on the workability, rheological, mechanical and durability properties of self-compacting concrete. In this context, five (05) SCC mixtures with LF content of 0%, 5%, 10%, 15% and 20% were prepared and tested at fresh and hardened states. Fresh state tests were slump flow, slump flow time, L-box height ratio, shear stress and plastic viscosity. For hardened state, compressive strength, flexural strength and durability tests were performed. Durability properties include, total porosity, capillary water absorption and chloride ion migration.

2. Experimental program

2.1 Materials

In the present study, commercial cement Type CEM I/42.5 according to EN 197-1 was used. The specific density and the fineness (Blaine surface) were 3.15 and 300 m²/kg, respectively. The LF was obtained by passing crushed sand in a screen of 80 μm, which consisted of 98% of calcium carbonate ($CaCO_3$) as demonstrated by X-ray diffraction (Fig. 1).

The chemical properties of the cement and limestone fines are given in Table 1. Particle and grain size curves of the cement and limestone fines, using Coulter LS-13320

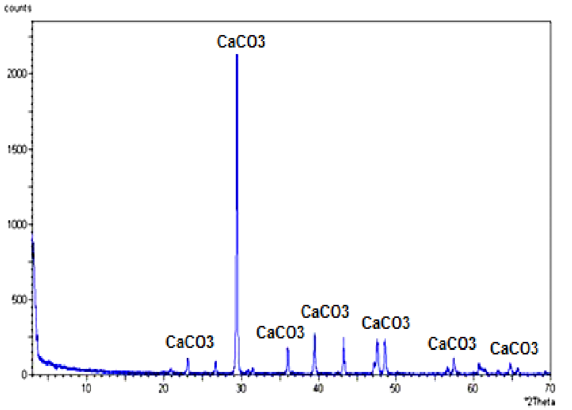

Fig. 1 XRD patterns of crushed limestone fines obtained from crushed sand

Table 1 Chemical composition of cement, crushed sand and limestone fines

Chemical	Cement	Crushedsand	Limestone fines
CaO	64.16	50.68	54.3
SiO_2	22.12	4.51	1.78
Al_2O_3	4.6	1.09	0.79
Fe_2O_3	4.9	0.54	0.34
MgO	0.8	1.01	0.20
SO_3	1.1	-	-
Na_2O	0.12	-	-
K_2O	0.4	-	-
Losson ignition	1.4	41.04	42.5
Insoluble residue	0.4	-	-

Table 2 Physical properties of aggregates

Characteristics	Limestone fines	Crushed Sand (CS 0/5)	Siliceous Sand (SS 0/3)	Coarse aggregates CA 3/8	CA 8/15
Density (kg/m^3)	920	2630	2540	2620	2630
Water absorption (%)	-	0.38	0.20	0.20	0.30
Fineness modulus	-	3.15	0.98	-	-
Sand equivalent (%)	-	70	84	-	-
Fineness (m^2/kg)	365	-	-	-	-

CS: Crushed Sand; SS: Siliceous Sand; CA: Coarse Aggregates.

Table 3 Mix design of SCC mixtures (kg/m^3)

Constituents	SCC0	SCC5	SCC10*	SCC15	SCC20
Cement	490	490	490	490	490
LF	0	30	60	90	120
Crushed sand	600	570	540	510	480
Siliceous sand	323	323	323	323	323
Coarse aggregate (3/8)	443	443	443	443	443
Coarse aggregate (8/15)	295	295	295	295	295
Water	196	196	196	196	196
Superplastiser	6.86	6.86	6.86	6.86	6.86

*SCC 10: Self-compacting concrete with 10% LF as crushed sand replacement

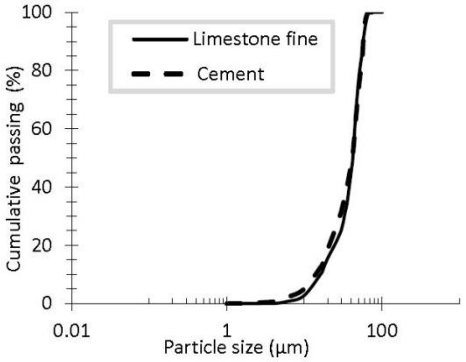

Fig. 2 Cumulative size distribution of cement and crushed limestone fines

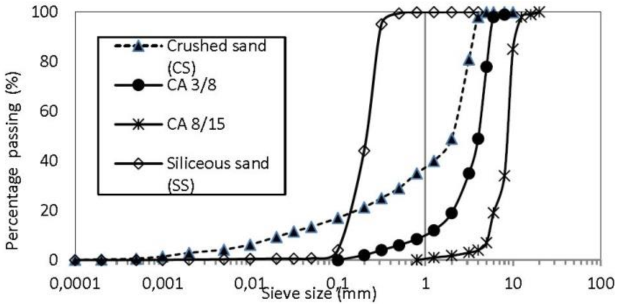

Fig. 3 Particle size distribution of fines and coarse aggregates

laser granulometer are illustrated in Fig. 2.

The physical properties of aggregates used are summarized in Table 2. Two different types of sand were used, siliceous dune sand (SS) and limestone crushed sand (CS) with specific densities and absorption coefficients of 2.54, 2.63 and 0.02%, 0.38%, respectively.

The coarse aggregates were natural crushed limestone, with maximum size of 8 mm and 16 mm, with a density of 2.62 g/cm^3. The grading curves of the aggregates are presented in Fig. 3. A polycarboxylate based superplasticizer (MEDA Flow 145) was used, which had a solid content and specific density of 30% and 1.05, respectively.

2.2 Mix design and procedure

The mix design of all SCC mixtures is based on the Okamura SCC mix design method (Edamatsu *et al*. 2003). Preliminary tests were performed on mortar to optimize the mix. The preliminary tests led to a water to cement ratio (W/C=0.40), sand to mortar ratio (S/M=0.5), aggregate to sand ratio (G/S=0.8) and a constant superplasticizer content of 1.4% by mass of binder material. The sand (S) used in the present study was composed of 65% crushed sand (CS) and 35% siliceous sand (SS) and presented a fineness modulus of 2.39.The proportions of the imestone fines used in the present investigation were 0%, 5%, 10%, 15%, 20% and 25% as substitution of crushed sand by weight. A total of five (05) SCC mixtures have been designed, including control SCC are given in Table 3.

Mixtures of the different self-compacting concretes require mixing at sufficient time to ensure that all components are well mixed (Chopin *et al*. 2004). The mechanism and the mixing sequence are performed as described in Table 4.

2.3 Testing method

2.3.1 Workability

SCC is characterized by three specific characteristics, filling capacity, passing capacity and resistance to segregation. To evaluate these intrinsic properties, the filling ability and deformability of all SCC mixtures were determined with respect to slump flow and the corresponding T500 spread time. The passing ability of SCC mixtures was assessed by *V*-funnel flow time and L-

Table 4 Sequence and mixing procedure

Time (min)	0	0.5	1.5	2.5	7.5	9	9.5
Components	S+C+CA+LF	+2/3 W	+1/3 W +SP				
Mixing method	Dry mixing		Wet mixing		End of mixing	remixing	Start of the test

C: Cement; S: SC+SS; CA: CA3/8+CA8/15; LF: Limestone fines; W: Water; SP: Superplasticizer

Fig. 4 Concrete rheometer test setup

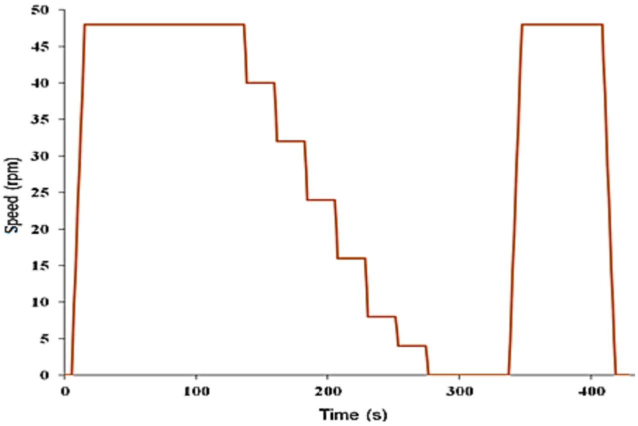

Fig. 5 Profile of imposed rotational speed

box test. The segregation resistance was quantified by sieve test. All tests were performed according to EN and EFNARC guidelines for self-compacting concrete (EN 12350-8, 29EN 12350-9, EN 12350-10, EN 12350-11, EFNARC.2005).

2.3.2 Rheology

The rheological properties of SCC mixtures were measured using a concrete rheometer type Heidolph-RZR 2102 Control Z, composed of an agitator with speed electronic control for recording the torque, a steel vane of 15 cm high and 10 cm in diameter for mixing and a 25 cm cylindrical container of height and 30 cm in diameter as illustrated in Fig. 4.

After each measurement of the above described slump flow property, SCC mixtures samples were transferred directly to the stress-controlled rheometer to evaluate the total torque corresponding to the imposed rotational speed profile (Fig. 5).

Then, the rheological parameters output: plastic viscosity (μ) and the shear stress (τ) were evaluated on the basis of the standard Bingham model described by the following equation

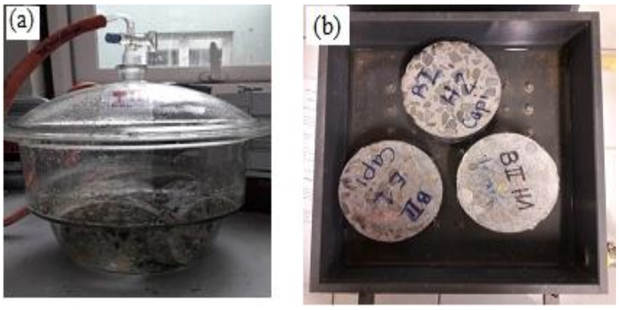

Fig. 6 (a) Vacuum water saturation; (b) capillary water absorption test set-up

$$\tau = \tau_0 + \mu\dot{\gamma} \tag{1}$$

Where: $\tau(Pa)$ is the shear stress, τ_0 (Pa) is the yield stress, μ (Pa.s) is the plastic viscosity and $\dot{\gamma}\left(\frac{1}{s}\right)$ is the shear rate.

2.3.3 Compressive and flexural strength

Cubic 150×150×150 mm specimens were used for compressive strength tests and prismatic 70×70×280 mm specimens were used for the flexural strength tests. The specimens were stored in water under controlled humidity and temperature (20±2°C). Testing was conducted at 3, 7, 14 and 28 days according to NF P 18-406.

2.3.4 Durability

2.3.4.1 Open porosity

The open porosity of all SCC mixtures was determined on the basis of mass water saturation measurements (under vacuum) performed on 100 mm in diameter discs and 50 mm thick, cut from the center of cylindrical samples of 100×200 mm, in accordance with NF EN 18-459.

2.3.4.2 Capillary water absorption

Specimens for water absorption by capillarity of SCC mixtures were oven-dried at 80±2°C until a constant mass and then left to cool in a desiccator (Fig. 6(a)). Specimen sides were then laterally sealed to allow one direction water flows and subjected to contact water at level of 3 mm above the base of the sample (Fig. 6(b)). The amount of absorbed water by specimens was measured at time intervals of 15, 30, 60, 120, 240, 360, 480 and 1440 min. The capillary water absorption coefficient is then determined.

2.3.4.3 Apparent chloride diffusion coefficient

The apparent chloride diffusion coefficient, Dns(mig) for all SCC mixtures was determined using non steady-state migration tests as illustrated in Fig. 7. Dns(mig) can be determined by applying the modified *Nernst-Planck* equation in saturated conditions. It can be calculated by the

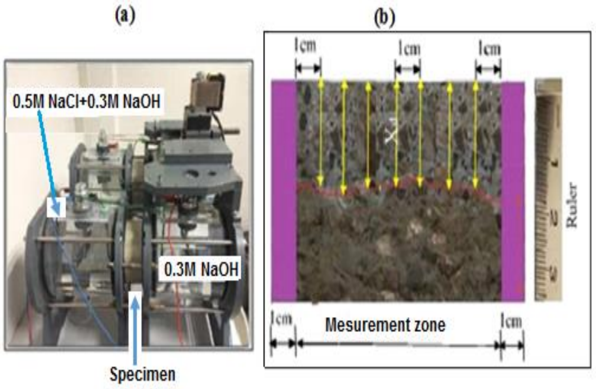

Fig. 7 Apparent chloride diffusion coefficient measurement: (a) Rapid chloride ion migration set-up and (b) measurement of the chloride penetration depth

widely used equation proposed by Tang and Nilsson (1992) (see Eq. (2))

$$Dns(\text{mig}) = \text{R.T.Z.F}'.\text{e}.\Delta\text{E}.xd - \alpha.xdt \qquad (2)$$

where t corresponds to the test duration (s), e the sample thickness (m), Z the valence number of chloride ion (Z=1), F' the Faraday constant (F'= 96.480 J V^{-1} mol^{-1}), ΔE the electrical potential applied between the two sides of the sample (V), R the ideal gas constant (R=8.3144 J mol^{-1} K^{-1}), and T the absolute temperature (K). α is the auxiliary term defined as a function of the test conditions. xd corresponds to the average chloride penetration depth determined by colorimetric test using AgNO_3.

Tests were performed on Discs (100 mm in diameter and 50 mm in height) cut from 100×200 mm cylinders concrete samples after vacuum saturation with a 0.3 M NaOH solution. After that the specimen are placed in the test device and subjected to a 60 V applied DC voltage for 6 h. The chloride penetration profile was obtained by splitting the specimen in two parts (Fig. 7) and applying AgNO_3 spray. The tests were performed on samples after 180 days of water curing.

3. Results and discussion

3.1 Fresh properties

3.1.1 Workability

The results of slump and V-funnel flow time of the five SCC mixtures with and without crushed limestone fines are shown in Fig. 8. Comparing the results of slump and V-funnel flow time of all SCC mixtures investigated with SCC criteria, it can be observed that all SCC mixtures achieved adequate filling ability. The increase in the content of LF as crushed sand substitution from 0 to 20% contributes to the decrease of slump flow from 845 mm to 665 mm and to the increase of the V-funnel flow time from 4.72 to 5.87 seconds. The higher slump flow and the higher V-funnel flow time are noticed for SCC with 15% limestone fines. The decrease of slump flow may be explained by the increase in the water demand of SCC mixtures containing LF. Similar findings are also reported by other researchers (Joudi *et al*. 2012, Bosiljkov 2003, Benabed *et al*. 2012).

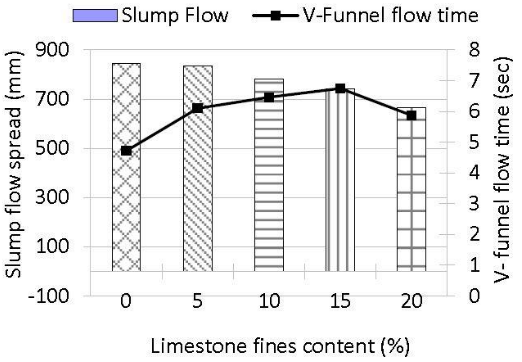

Fig. 8 Slump flow, *V*-funnel flow time as a function of limestone fines content

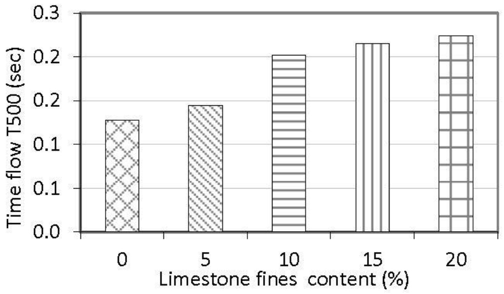

Fig. 9 T500 flow time vs. limestone fines content

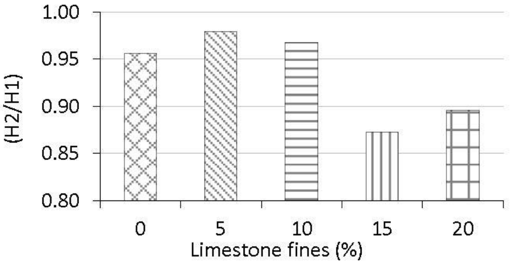

Fig. 10 Blocking ratio (H2 /H1) as a function of limestone fines content

In order to evaluate the flow velocity of SCC mixtures, the 500-mm slump flow time T500 was also conducted in this investigation.

Fig. 9 shows the results of the effect of LF content on T500. It can be observed that slump flow time T500 of all SCC mixtures with and without LF fall within the limits required for SCC. The increase of the limestone fines as crushed sand replacement decreases the flow time T_{500}. SCC mixture with 20% LF presents a lower viscosity.

The mobility of SCC mixtures in heavily reinforced area is strongly related to the quantity of fines. This requirement is examined by the determination of the filling rate using the *L*-box test (De Weerdt *et al*. 2011).The results of SCC mixtures with and without limestone fines are illustrated in Fig. 10. It can be seen from this figure that increasing the LF content from 0 to 10%, causes an increase in the H_2/H_1 ratio from 0.96 to 0.97 compared to SCC control. SCC gives the highest value of H2/H1 with 5% LF. A reduction of the passing ability is observed with the increase of the LF beyond a 10% LF replacement level. The lower value of

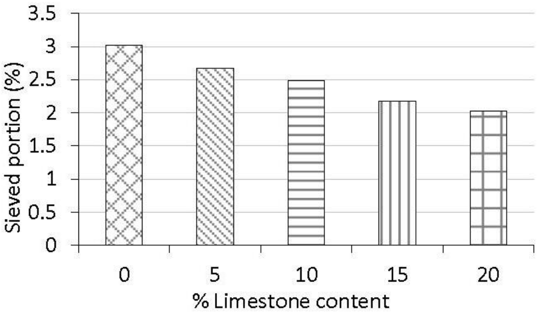

Fig. 11 Sieve stability of the different SCC mixtures

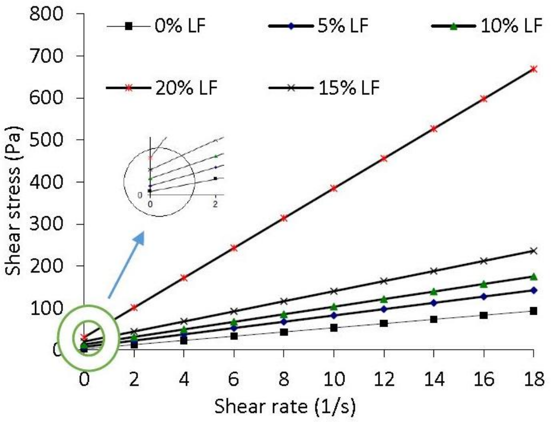

Fig. 12 Variation of shear stress as a function of shear rate

H_2/H_1 ratio is noticed for SCC with 15% of LF. It can be concluded that all SCC mixes with and without LF present no risk of blocking according to EFNARC guidelines (EFNARC 2005).

The results of the resistance to segregation of SCC mixtures with and without LF are illustrated in Fig. 11. It can be seen from this figure, that the resistance to segregation of all SCC mixtures decreases with increasing LF content. It can be observed that the lower resistance to segregation is given by SCC mixture with higher LF content. The results revealed that all SCC mixes with and without LF possess adequate segregation resistance as specified by NF EN 12350-11.

3.1.2 Rheology

Fig. 12 shows the flow curves of the shear stress with shear rate of all SCC mixtures containing different LF content as crushed sand replacement. The law of behavior of the SCC mixtures is obtained according to the linear Eq. 2. The results indicate that all the SCC mixtures exhibit Binghamian viscoplastic behavior in accordance with different investigations (NF P18-459, XP P18-462, Hamza *et al.* 2014). From these flow curves, the rheological properties of each type of SCC mixtures were determined, in which the shear stress, $\tau(Pa)$ is the intersection point of the descending curves with the ordinate axis (y) and the plastic viscosity is the tangent of the curves.

The relationship between the shear stress and slump flow as a function of the content of LF, is given in Fig. 13. From this figure, an inverse relationship between the spreading and the yield stress can be noticed.

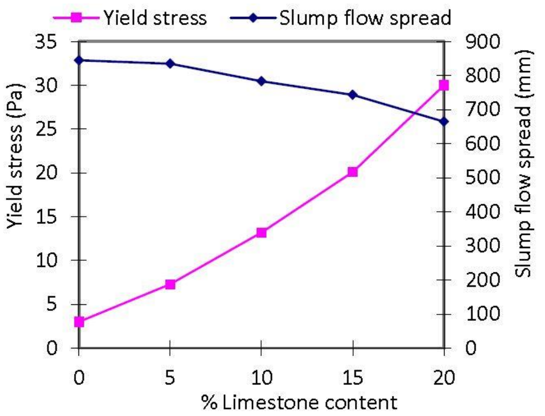

Fig. 13 Relationship between yield stress, slump flow and limestone fines content

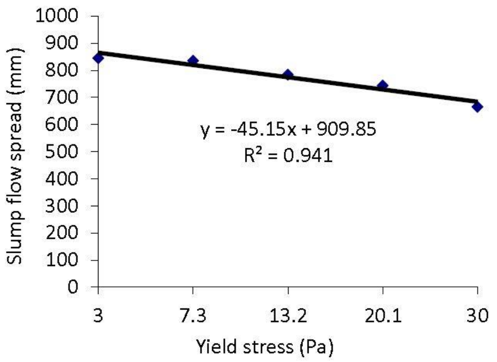

Fig. 14 Slump flow spread as a function of yield stress

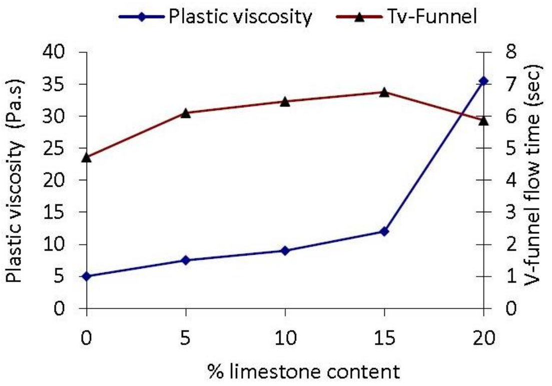

Fig. 15 Relationship between Plastic viscosity, *V*-funnel flow time and limestone fines content

The partial replacement of LF in crushed sand from 0% to 20% decreases the spread flow from 845 mm to 665 mm, and increases the yield stress from 3 Pa to 30.5 Pa. This increase can be explained by high fineness of LF which favors a higher water demand and by the increase of the intergranular friction between the particles, and consequently the increase of the yield stress of the SCC mixtures. These findings have been confirmed by other researchers (Grünewald*et al.* 2003, Nielsson *et al.* 2003). Results plotted in Fig. 14 shows the decrease of the measured slump flow with an increase of the yield stress of SCC mixtures with and without LF. A good regression coefficient (R^2=0.94) was found to predict the shear stress

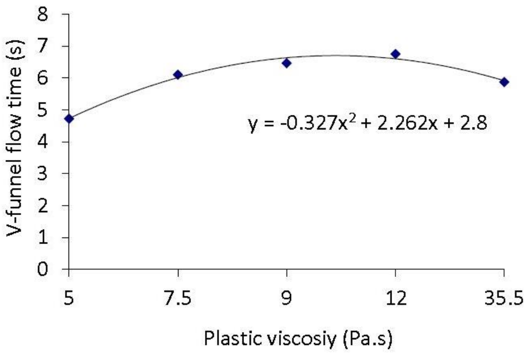

Fig. 16 V-funnel flow time as a function of the plastic viscosity

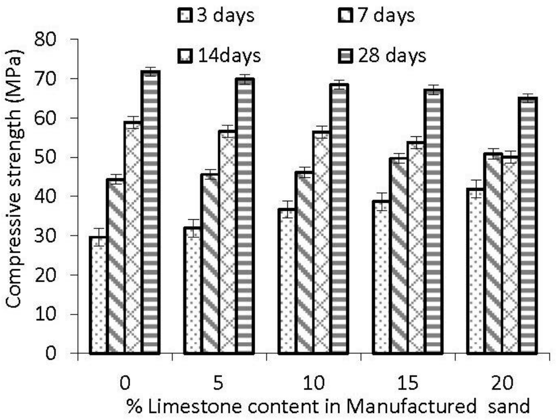

Fig. 17 Compressive strength of SCC mixtures

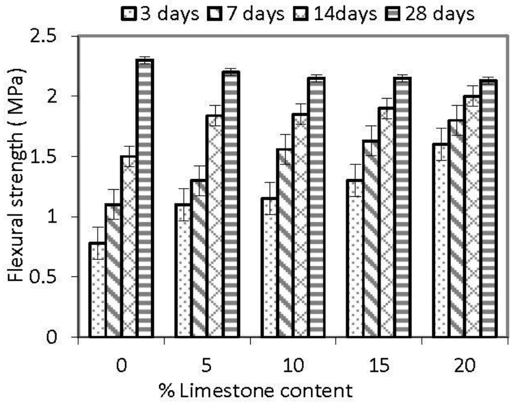

Fig. 18 Flexural strength of SCC mixtures

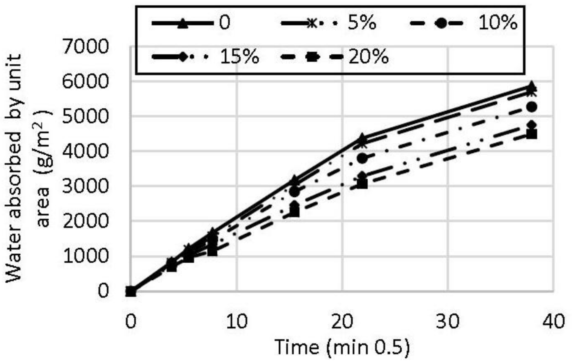

Fig. 19 Water absorbed by capillary action for all SCC mixtures at 180 days

from the slump flow.

Fig. 15, gives the relationship between plastic viscosity (μ) and flow time (*Tv*-funnel). It could be seen that plastic viscosity increases with increasing LF content up to 15%. A slow increase of the plastic viscosity was observed between 5 Pa.s and 12 Pa.s for LF content between 0% and 15% and then a significant increase of 35.5 Pa.s for 20% of fines, was observed.

The increase in plastic viscosity could be attributed to the substitution of crushed sand by LF, which are finer and require more water in order to wet the fine particles and hence increase internal friction causing an alteration of the flow properties and consequently the increase in viscosity (Geiker*et al.* 2003). This figure shows also that increasing of the LF from 0 to 15% induces an increase in *V*-funnel flow time from 4.72 s to 6.75 s, and a plastic viscosity of 5 Pa.s to 12 Pa.s. A variation of 15% to 20% of LF gives an increase in plastic viscosity at 35.5 Pa.s, and a decrease in *V*-funnel flow time to 5.87 s. A good correlation (R^2=0.97) between viscosity and V-funnel flow time was found (Fig. 16).

3.2 Properties of hardened SCC

3.2.1 Strength

Fig. 17 shows the compressive strength results of SCC mixtures with and without LF content at different ages.

Compressive strength of SCC mixtures ranged from 65 MPa to 72 MPa at the age of 28 days. Mixtures with LF exhibit a lower compressive strength compared to control concrete at the age of 28 days. However, an increase of compressive strength is observed for SCC mixtures with LF at the ages of 3 and 7 days compared to control mixture. This increase may be attributed on the one hand to the increase of the hydration of cement grains due to the nucleation sites created by the limestone fines and on the another hand to the filler effect. These results are in agreement with those reported by other authors (Celik *et al.* 1996, Bonavetti *et al.* 1994, Bonavetti *et al.* 1993).

The results of the flexural strength at 3, 7, 14 and 28 days of all SCC mixtures investigated are illustrated in Fig. 18. The substitution of crushed sand by LF, generally reduces the flexural strength of all mixtures at the age of 28 days. However, and similarly to compressive strength, the flexural strength at early age (3 and 7 days) is increased. Similar findings has also been also reported by other researchers in the case of vibrated concretes and mortars (Menadi *et al.* 2009, Celik *et al.* 1996).

3.2.2 Durability of self-compacting concrete mixtures

3.2.2.1 Water capillary absorption

Fig. 19 shows the capillary water absorption of all the SCC mixtures investigated in the present study. The water absorption of different mixes is easily differentiated after about one hour of testing.

Increasing LF content in crushed sand decreases the capillary water absorption of SCC mixtures. SCC control, which corresponds to concrete that includes large pores,

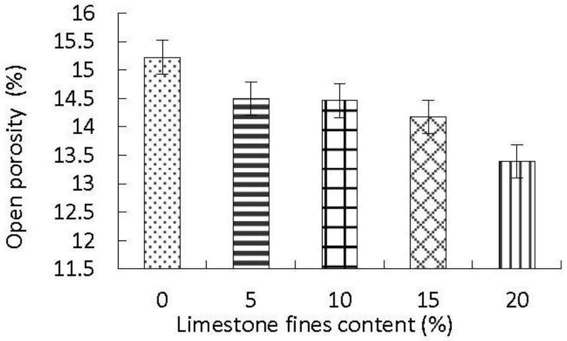

Fig. 20 Effect of limestone fines on the open porosity at 180 days

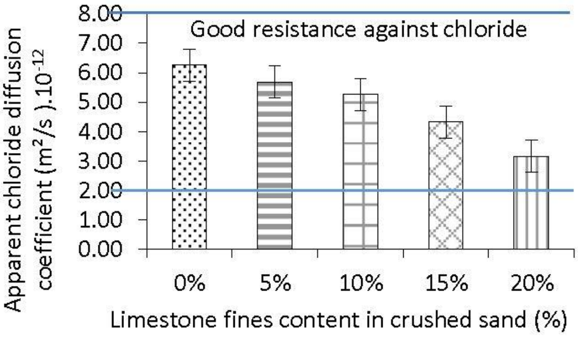

Fig. 21 Apparent chloride diffusion coefficient in SCC mixtures at 180 days

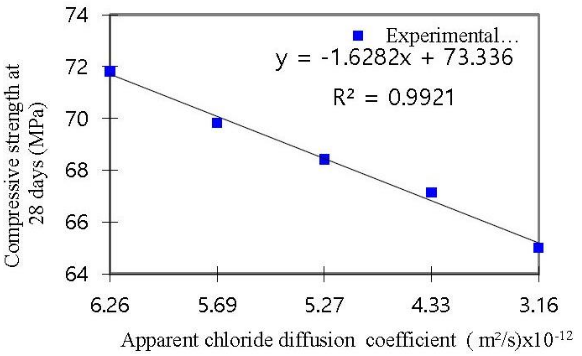

Fig. 22 Relationship between the compressive strength and the apparentchloride diffusion coefficient Dns(mig)

presents higher capillary water absorption coefficient of 5.89×10^3 g/cm^2 compared to SCC mixtures with LF content. Increasing LF content from 0% to 20% decreases the coefficient from 5.89×10^3 g/cm^2 to 4.75×10^3 g/cm^2, respectively. The lower water absorption coefficient is given by SCC mixtures with 20% LF. This decrease could be explained by the filling of the pores by the limestone fines leading to a decrease in the porosity of the paste of the mixtures and consequently a decrease in the capillary absorption.

3.2.2.2 Total porosity

The results of the total porosity tests at 180 days of the SCC mixtures with and without LF are given in Fig. 20. It can be seen from this figure a reduction of the total porosity of SCC mixtures with an increase of LF content. It is observed that SCC mixture with 20% LF content gave a lower porosity value of 13.4% compared to SCC control mixture value of 15.20%. This behavior may be explained by the positive influence of the limestone fines on the compactness and the decrease of the voids of the SCC mixtures.

3.2.2.3 Apparent chloride diffusion coefficient of SCC mixtures

Apparent chloride diffusion coefficient results of all the SCC mixtures at 180 days are shown in Fig. 21. The chloride migration ions coefficient values are in the range of (3.16-6.26) 10-12 m^2/s. The lowest value is given by SCC with the highest level content of LF (20%). The positive effect of incorporation of LF in the mixture results in reduction of the chloride migration coefficient of up to 49.5% for high LF content. The reduction in the apparent chloride diffusion coefficient is mainly due to the compactness of the mixes with LF where the voids are filled. Similar results are reported for vibrated concrete containing crushed limestone fines (Menadi *et al*. 2009). Apparent chloride diffusion coefficient values between 2 and 8 m^2/s indicate good resistance to chloride ions migration. According to tests results, all the SCC mixtures with and without limestone fines had a good resistance against chloride ingress.

A relationship between the compressive strength at 28 days and the diffusion coefficient of chloride ions is shown in Fig. 22. A linear equation linking the diffusion coefficient resistance of chloride ions gives a high coefficient of determination (R^2=0.99).

4. Conclusions

Based on the experimental results of this investigation, the following conclusions could be drawn:

1. Increasing the level of quarry LF as substitution of crushed sand decreases the flowability of SCC mixtures, but remains in the target as per EFNARC.
2. The use of quarry LF as crushed sand replacement provides good stability and resistance to segregation for all SCC mixtures.
3. The increase in the level of LF induces an increase in the yield stress and the plastic viscosity for all the SCC mixtures. A good relationship was found to predict yield stress from slump flowand V-funnel flow time from plastic viscosity.
4. Partial replacement of manufactured crushed sand by LF in SCC slightly decrease the compressive and flexural strengths at 28 days. However, an improvement of compressive strength was noticed at early ages. Similar trend was obtained for flexural strength.
5. The capillary water absorption and chloride-ion migration of all SCC mixtures were considerably improved with increasing LF substitution compared to SCC control mixture. SCC mixture with higher inclusion of LF of 20% (SCC20) exhibits higher resistance against chloride ingress and water penetration.

6. Limestone fines could be used as crushed sand replacement up to 20% to produce self-compacting concrete mixtures.

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