Mix proportioning and performance of a crushed limestone sand-concrete

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Abstract. Satisfying the ever-growing demand of concrete aggregates poses a problem in many parts of the world due to shortage of natural sand. Moreover, to conserve natural resources and protect civil engineering infrastructures, there is a need to find alternative materials. Crushed stone sand has been identified as a potential substitute material for natural sand in making good quality concrete. The main objective of the present investigation is to determine an adequate mix design method and evaluate engineering properties of crushed limestone sand concrete mixtures in both the fresh and hardened sates. More than thirty concrete mixtures were examined. The results indicate that water demand and cement paste content in crushed sand concrete are generally higher than that used in similar conventional concrete. Good mechanical properties were obtained for concrete using crushed limestone sand as fine aggregates with a superplasticizer. However, a higher than normally used dosage of superplasticizer is required in these concrete mixtures and the optimum dosage of the superplasticizer needs to be determined for each cement and sand content.

Key words: Crushed stone, fine aggregate, limestone, mix proportioning, fresh concrete, performance, mechanical properties.

1. Introduction

A guaranteed continuous supply of sand to produce the ever-growing amount of concrete needed for economic development poses a problem in many parts of the world due to the shortage of natural river sand. Therefore, to preserve natural resources and to maintain a sustainable construction, alternative resources are needed. In Algeria where the amount of sand needed annually is estimated at more than 25 Million Tons, crushed rock sand may constitute a viable substitute to natural river sand. Crushed sand, with particle size less than 5 mm, is a by-product obtained in the process of rock crushing to manufacture gravel or coarse aggregates. Thus, many of the sand properties (chemical and mineralogical compositions …etc.) are related to the source rock. However, crushed rock sand differs from the usual river sand in particle shape, grading, surface texture, and particularly in the content of fines or dust. Fines are defined as the part of sand passing a determined test sieve. The standards BSI (1992), ASTM (1996), AFNOR (1997) and CEN (2002) recommend respectively the sieves 75μm, 80μm and 63μm for determining fine content. The BSI standard allows a dust content of 16% by mass of sand for crushed rock fine aggregate whereas the corresponding limit in the ASTM (1996) standard is only 7%. However, in the NFP18-540 standard (AFNOR, 1997), the maximum amount of allowed fines is set to 12%. These restrictions are aimed at limiting the adverse effects on the properties of fresh and hardened concrete that the dust is thought to have. In fresh concrete, high percentage of dust increases the fineness and the total surface area of aggregates, and thus leads to an increase in the amount of water needed to obtain a suitable workability (Celik, 1996; Ahmed, 1989). Obviously, this higher demand of water will adversely affect the strength and shrinkage properties of hardened concrete (Neville, 1995). Durability properties may also be affected by the presence of dust as it acts on the nature of the paste-aggregate interface by coating the aggregate surface (Ahmed, 1989; Makhloufi, 2012a; Makhloufi, 2012b). Moreover, the use of crushed sand may be an alternative source of filler, which help to achieve an adequate workability (Donza, 2002). The research results reported by Celik and Marar (1996) and Ahmed and Elkourd (1989) seems to suggest that the optimum amount of dust may lie between 5 and 10% of the quantity of crushed sand. This perceived risk associated with crushed sand together with the lack of data has contributed to skepticism and the reluctance to use crushed sand. It also led some aggregates manufacturers to invest on costly processing equipment to screen off or remove the fines (Benabed, 2012; Gschaider, 2001).

The shape of crushed sand together with the mineralogical properties of the dust associated with it depends on the nature and the degree of stratification of rock deposit. Moreover, the quality of fresh and hardened concrete is greatly influenced by the properties of crushed sand such as shape, size of particle and the surface texture (Donza, 2002; Taylor, 1996). The amount of additional paste content needed in the case of crushed sand depends also on the shape, texture and grading of the sand (Donza, 2002). On the other hand, water demand seems to be primarily dependent on the particle shape of the sand (Nichols, 1982; Bharatkumar, 2001). Nevertheless, crushed sand with no or a relatively small percentage of dust content (less than 3%) is reported to be an adequate substitute material for natural silica sand in producing good quality concrete and is more suitable for the production of high strength concrete than natural sand (Nichols, 1982; Lecomte, 1995; Celik, 1996; Taylor, 1996; CEN, 1997; Donza, 2002; Park, 2012).

While it is important to control the dust content in the aggregate, it may be more objective that limits are set on the basis of the source and mineralogical properties of the dust. Higher limits can be set when the dust is clean and is essentially a by-product of the fracture of rocks. In contrast tighter limits are set when this dust contains a considerable amount of deleterious substances such as clay or shale (Lecomte, 1995; Nichols, 1982). This seems to be the reason that the CEN standard (CEN, 2002) was reluctant in fixing precise limits on the amount of fines allowed in crushed sands. Furthermore, a considerable enhancement in the properties of fresh and hardened concrete could be achieved by adding clean and properly graded fines to the concrete mix. These fines act as filler and help to reduce the total voids content in concrete which in turn decreases water permeability and improves the quality of concrete (Celik, 1996). They also contribute in cement hydration during the early age by acting as a nucleation sites for the hydration products (Donza, 2002; Bosiljkov, 2003; Pipilikaki, 2009b). Furthermore, the packing of fine particles is improved by the addition of fillers. As a result the stability and workability of fresh concrete are enhanced and the concrete density is increased (Bosiljkov, 2003). Improvement in concrete strength is also obtained due to better aggregate-paste interface (Donza,. 2002; Bosiljkov, 2003).

The main objective of this paper is the proportioning and the evaluation of the performances of a crushed limestone sand-concrete with and without superplasticizer. The experimental program reported herein was carried out to document and evaluate engineering properties of crushed limestone sand-concrete mixtures in both fresh and hardened states. These properties were then compared to traditional concrete mixtures made with natural silica sand to expand the beneficial use of crushed limestone concrete and underline its potential applications. Two series of concrete mixtures using crushed limestone sand have been investigated during this study; the first mixture (series A) did not contain any admixtures while in the second one (series B) a superplasticizer (SP) was incorporated into the concrete mixtures.

2. Mixture design approach

All the aggregates used in this research were quarried from a Turonian limestone rock deposit of the Mesozoic era in the region of Laghouat (south Algeria). Three granular fractions were considered in the concrete mixtures. The first fraction (0/5mm) was a crushed sand while the two other fractions (5/15 and 15/25mm) were combined to make the mixture coarse aggregate. The main physical characteristics of these aggregates are summarized in Table 1 while Figure 1 shows their particle size distributions. The surface texture of the sand was rough and its gradation fell within the limits prescribed by both the BS and AFNOR standards. The content of fines in the sand is higher than the limit proposed by the ASTM standard (ASTM, 1996), but is lower than that proposed by the BSI and the AFNOR standards (BSI, 1992; AFNOR, 1997). Figure 2 shows the X-ray diffraction of fine crushed sand content, where it is noted that the main components of the fines is $CaCO_3$ in the form of Calcite. Therefore, most of the fine material contained in the sand can be considered as clean limestone filler. The particle size distribution of this filler, obtained by using the sedimentation test method, is shown in Figure 3. The shape of the coarse aggregates was mainly angular with a rough surface texture.

Table 1: Physical characteristic of crushed sand and gravels.

Characteristics	Symbol	Unit	Sand 0/5	Gravel 5/15 - 15/25
Absolute density	ρ_S	Kg/m^3	2700	2680
Apparent density	ρ	Kg/m^3	1530	1270
Real density	ρ_r	Kg/m^3	2610	2590
Absorption	Abs	%	2.5	1.42
Porosity	η	%	3.33	3.36

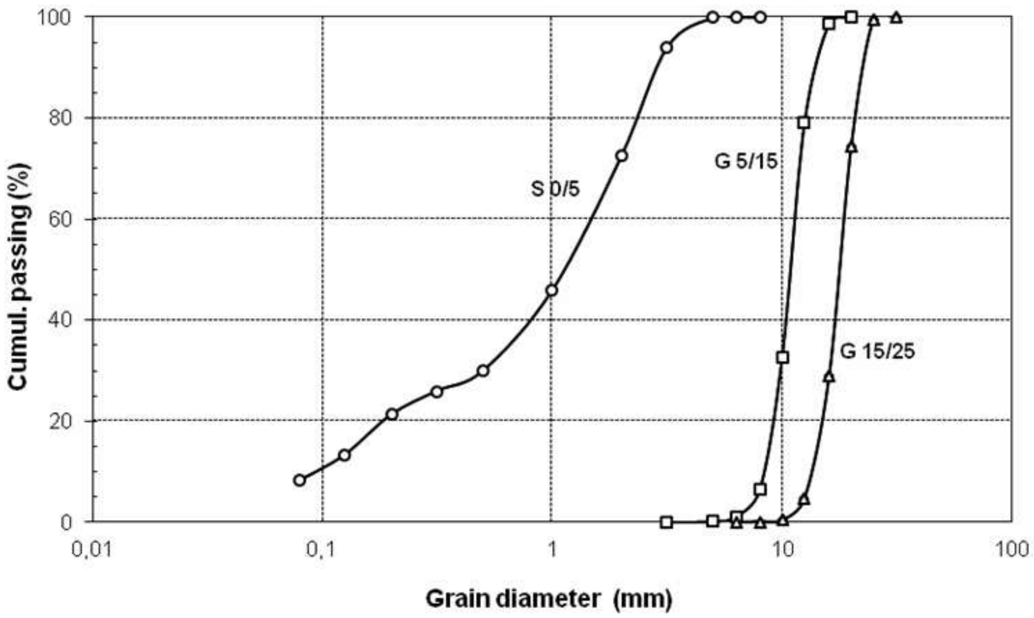

Fig 1: Particle size distribution curves of the limestone sand and gravel

A Portland composite cement designated CEM II 32.5N, which properties are shown in Table 2, was used in this investigation. A sulphonated naphthalene superplasticizer type (SP) in aqueous form was incorporated in the second series of the mixes. The solid content and the pH values of used SP are respectively 33.5% and 6.5.

As stated before, the present investigation was intended to assess the effect of various controlling parameters on the performance of crushed limestone concrete. To achieve such objective, more than 30 concrete mixtures were made and both workability and strength were determined. All the concrete mixtures were carried out in a tilting drum type mixer machine. The mixing sequence of concrete without SP consisted of homogenizing at first the aggregates with cement, and then water was added. For concrete with SP, after the homogenizing phase, water and a third of the SP were first added and mixed and then the rest of SP was added to achieve the required workability. The overall mixing time was about two and a half minutes.

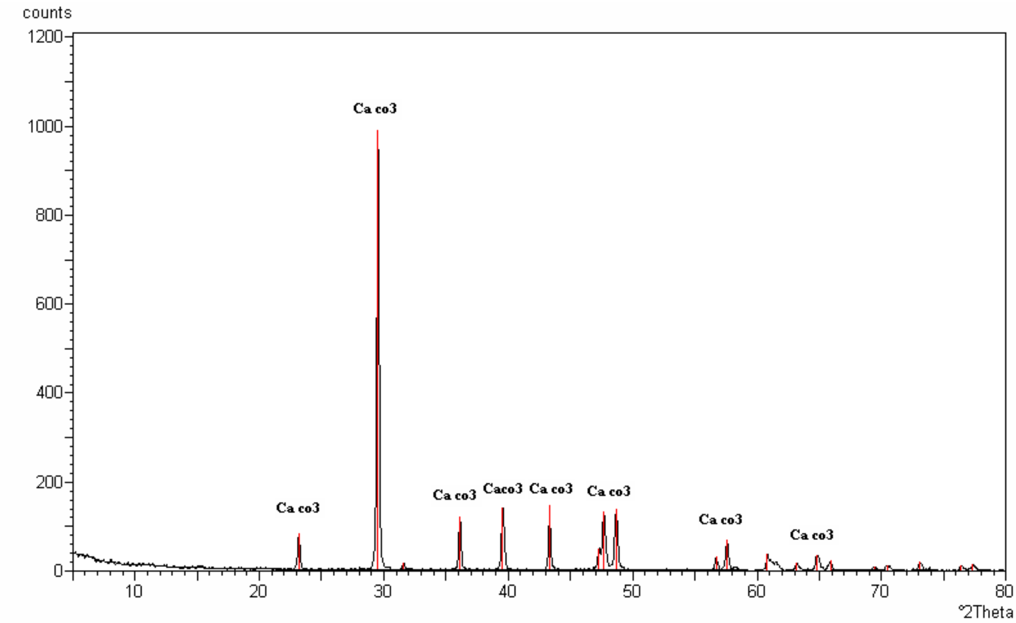

Fig 2: X-Ray diffraction of the fine crushed sand content.

Table 2: Chemical composition and physical properties of cement.

Chemical composition	
Oxides	%
SiO_2	21.04
Al_2O_3	4.97
Fe_2O_3	3.91
CaO	63.80
MgO	1.08
K_2O	0.62
Na_2O	0.08
SO_3	0.96
Physical properties	
Loss on ignition	0.57
Absolute density	3 g/cm^3
Blaine Specific Surface	3678 cm^2/g
Cement class (σ_{28})	37.10 ± 0.62 MPa

Two workability-control tests were considered during this study; the slump test and the LCL test (AFNOR, 1998). Standard procedures were followed in performing both tests. The LCL apparatus, like the remoulding test, determines the time it takes for concrete to flow into a new form. Immediately after measuring the workability, the test specimens were made. No significant loss in workability was noted over this time. Six cylinders of 160x320mm were cast from each concrete mixture. The steel moulds were filled in three layers and compacted using a small internal vibrator. The specimens were kept in their moulds and covered with plastic to prevent water evaporation until the following day when they were demoulded and putted in water at 24°C for approximately one week. After this period, the specimens were left to cure in the laboratory. The compressive strength of prepared concrete mixtures made was determined by testing three cylinders at 28 days. The remaining ones were used to determine the splitting tensile strength of concrete at the same age.

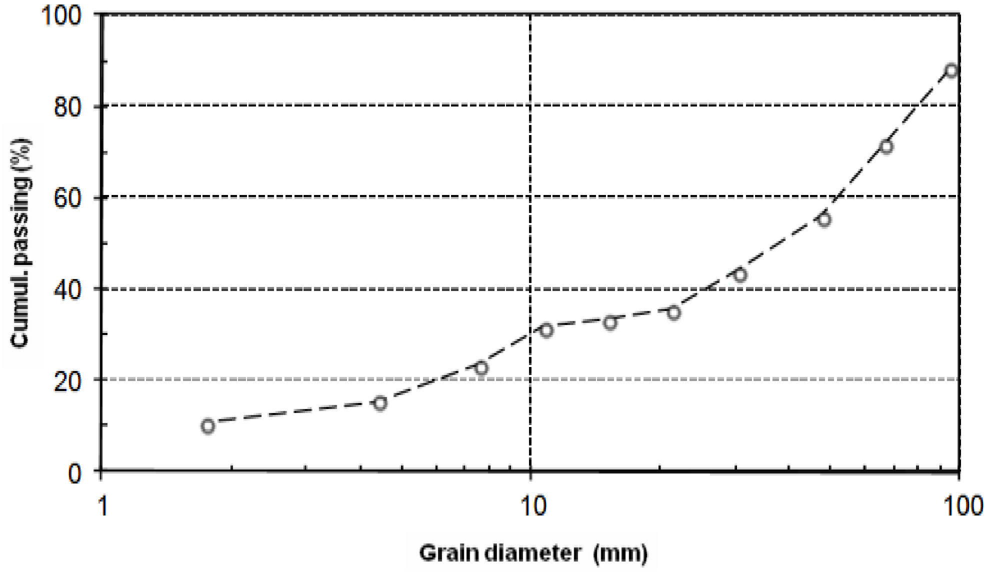

Fig 3: The particle size distribution of limestone filler

3. Mixture proportions

The mix proportioning of concrete is rather a complicated task (Neville, 1995; Al-Ghahtani, 1998; Sriravindrarajah, 2012) as it involves many parameters such as the properties of the ingredients and the specifications of the construction job which are usually given in term of workability, strength and durability. Once most of these parameters are specified, the procedure consists then of finding for a particular gradation of aggregates, a first approximations of mix proportions; water to cement ratio (W/C), total aggregate to cement ratio ((S+G)/C) or fine to coarse aggregate ratio (S/G). This first approximation is further adjusted until it meets the initial specifications. A number of mix proportioning methods exist and, despite various attempts to develop computer or manual methods aimed at determining the exact mix proportions; these have invariably been adjusted empirically. Since Dreux mix proportioning method (Dreux, 1998) is widely used in Algeria and is reported to yield the required workability for the ingredients presently available there, it was adopted in the present study to get the first approximation of the concrete mixture proportions. The Dreux method makes use of Bolomey equation to estimate the strength of concrete at 28 days (Bolomey, 1935):

$$R_{c28} = G\,\sigma_{c28}\left(C/W - 0.5\right) \quad (1)$$

Where:

R_{c28} = average or nominal compressive cylinder strength of concrete at 28 days.

G = empirical constant used to take into account the aggregate nature and gradation.

σ_{c28} = cement class (Table 2).

C/W = cement to water ratio.

Methods based on the Bolomey equation are reported to be adequate for conventional concrete and provided that the particle size distribution of the concrete mixture follows closely a reference curve which is thought to give a higher concrete compactness (Lecomte, 2001). For a targeted characteristic strength of concrete (R_{c28}=25MPa) with a medium workability (slump=60mm), the Dreux method yielded a W/C of 0.5, the cement content was 400 kg/m^3 and the total volume aggregates (V_{agg}) was 658.67 l. The volume of aggregates comprised the volume of sand (V_s=41.4%) and the volume of coarse aggregates (V_G=58.6%) with a sand to coarse aggregate ratio (S/G) of 0.71. The coarse aggregate volume was a combination of 5/15mm (V_{G1}=39%V_G) and 15/25mm (V_{G2}=61%V_G).

The water quantity (W=200 l) is the effective or free water (W_e), which is necessary to achieve the required workability and ensure the hydration of cement (Neville, 1995). The aggregates are therefore supposed to be in a saturated and surface-dry area condition when they are introduced into the mix, and adjustment to the mixing water (W_m), needs to take into account the actual moisture content and the absorption of the aggregates. The mixing water, W_m, together with the total water in the mix (W_t) are given by the following relation (Lecomte, 1995):

$$W_m = W_e + W_{abs} + W_c \quad (2)$$

$$W_t = W_m + W_c \quad (3)$$

Where:

$$W_{abs} = K_S M_S + K_G M_G$$

$$W_c = \omega_S M_S + \omega_G M_G$$

M, K, and ω are respectively weight, absorption, and water content of the aggregate. The subscripts (S) and (G) refer to the sand and the coarse aggregate respectively.

The computed mixing water, W_m, was 15.5% higher than the effective water W_e, which confirms the findings of other researchers (Ahmed, 1989; Celik, 1996; Donza, 2002) that crushed sand concrete mixtures tend to require more water than conventional concretes.

In order to reduce the number of variables affecting the concrete mix, a preliminary investigation was carried out to determine the optimum S/G ratio, and subsequently the optimum aggregate packing (Al-Ghahtani, 1998; Lecomte, 2001). To achieve this, the Baron-Lesage method was used (Baron, 1976). For constant volumes of paste and aggregates, the method consists of varying the proportions of sand and coarse aggregate to find the optimum S/G ratio that gives the lowest concrete flow time, measured by the LCL apparatus and hence the optimum workability. This optimum workability corresponds to the best apparent viscosity of the mix and to the highest packing of the aggregate in the mix (Lecomte, 2001).

Only a slight increase in water demand (W/C=0.52) was needed to get the initially specified workability (slump=60mm) thus validating the approach used in estimating the mixing water (Eq. 2). Thereafter, seven different concrete mixtures were investigated to identify the optimum S/G ratio. The results of this phase are presented in Figure 4, whereby the optimum S/G was found to be 0.68 (close to 0.71 establish by Dreux) and the weights of the aggregates needed to achieve this are given in Table 3.

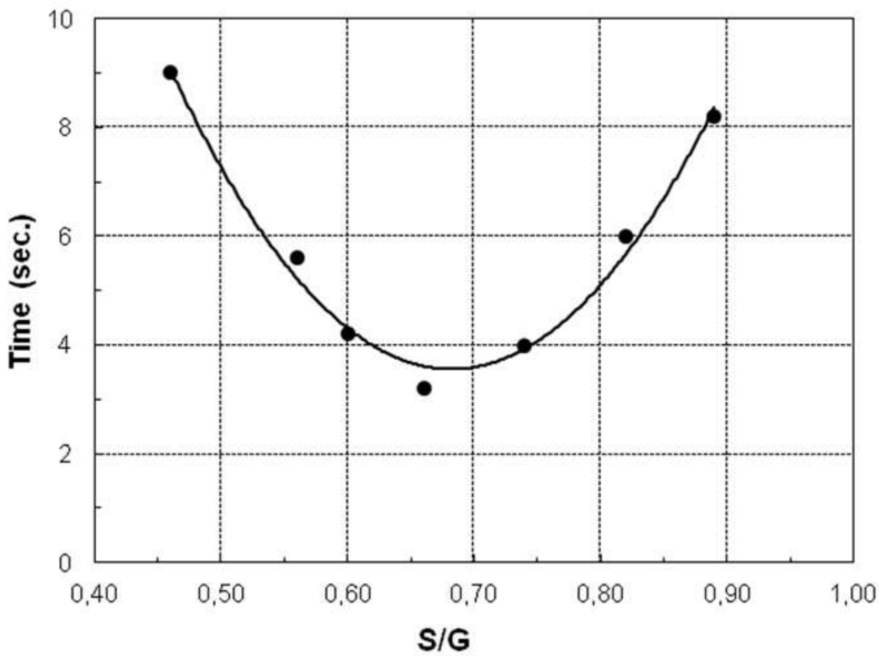

Fig 4: Variation of LCL-flow time according to S/G ratio.

Table 3: Weights of aggregates according different cement contents and We/C ratios.

Cement (kg/m^3)	We/C	Sand dry	G1 dry	G2 dry
		(kg)		
250	0.66	791	452	726
	0.71	779	445	716
	0.73	773	441	710
	0.81	753	430	692
	0.89	731	417	671
350	0.50	745	425	684
	0.51	741	423	681
	0.57	720	411	661
	0.66	690	394	634
	0.71	670	382	615
450	0.41	700	400	643
	0.43	690	394	634
	0.46	680	388	625
	0.49	666	380	612
	0.54	639	365	587

Once the optimum S/G was found, the following step was to investigate the performance of crushed limestone sand-concrete with a fixed granular matrix. This means that the weights of the aggregates with a ratio S/G=0.68 (Table 3) were kept constant and only the cement and the water contents were varied during this investigation. Three cement contents, 250, 350 and 450 kg/m^3 were considered. For each dosage of cement, five concrete mixtures were carried out with different W/C ratios to achieve a range of chosen workability.

As stated before, the performance of crushed limestone sand-concrete with SP was also investigated in this research. The concrete mixtures used were the same as those used above: the weights of aggregates are shown in Table 3 (with S/G=0.68), three cement contents 250, 350 and 450 kg/m^3 were considered, and five W/C ratios were surveyed for each dosage of cement. Prior to this, a preliminary study was undertaken to identify the optimum dosage of the SP. The testing procedure consisted of making several concrete mixtures that incorporate increasing proportions of the SP and measuring the slump for each mixture (Baalbaki, 1990; Kismi, 2012). Self-evidently, in the calculation of the mixing water, due allowance was made for the volume of the liquid SP content. The results of this investigation are shown in Figure 5 and the optimum SP dosages in terms of cement content are shown in Table 4. The determined dosages are higher than those proposed by the manufacturer (1.5% in liquid form), and seem to depend on the cement content. Moreover, the determined dosages appear to confirm results reported elsewhere by Donza *et al.* (2002), which indicate that a high dosage of SP is needed in concretes made with crushed and for each type of sand and cement content the optimum dosage need to be studied. However, high dosage of SP aimed at reducing the water content to a very low value is undesirable as the effectiveness of the SP depends on temperature, cement chemistry and fineness (Bharatkumar, 2001).

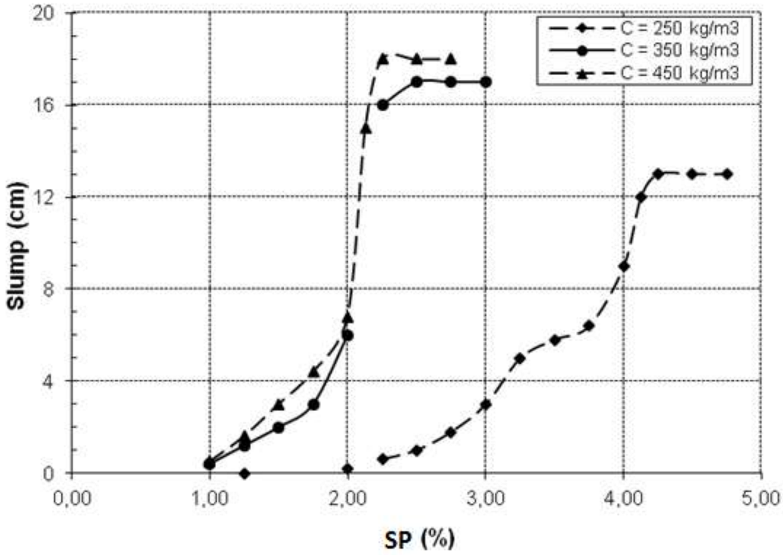

Fig 5: Variation of slump as function of SP dosage, according different cement contents.

Table 4: Optimum SP dosages in terms of cement content.

Cement (kg)	Saturation dosage	Dry extract (%)
250	4.25	1.42
350	2.50	0.84
450	2.25	0.75

4. Results and discussion

4.1.Fresh concrete properties

Results of the workability tests together with details of the concrete mixes considered during the investigation are given in Figure 6. As expected, this figure shows that for any value of the cement content, the slump increases almost linearly with the increase in W_e/C. For a given slump, the W_e/C required is higher for leaner mixes. However, water demand (quantity of W_e) in the concrete mixtures tends to be higher for richer mixes. Therefore, for mixes with high cement content, both the relatively high amount of water and the increase in cement paste contribute in enhancing the workability of the concrete mixture. Fresh concrete density decreases upon an increase in either the We/C ratio or the slump. This may be ascribable to the fact that voids in concrete that are initially packed with filler become progressively filled with water (substance lighter than filler) as the slump or water in the mixtures increases. Consequently, for a given We/C ratio, the richer concrete mixtures tend to have the lowest fresh density due to the greater amount of water present in them.

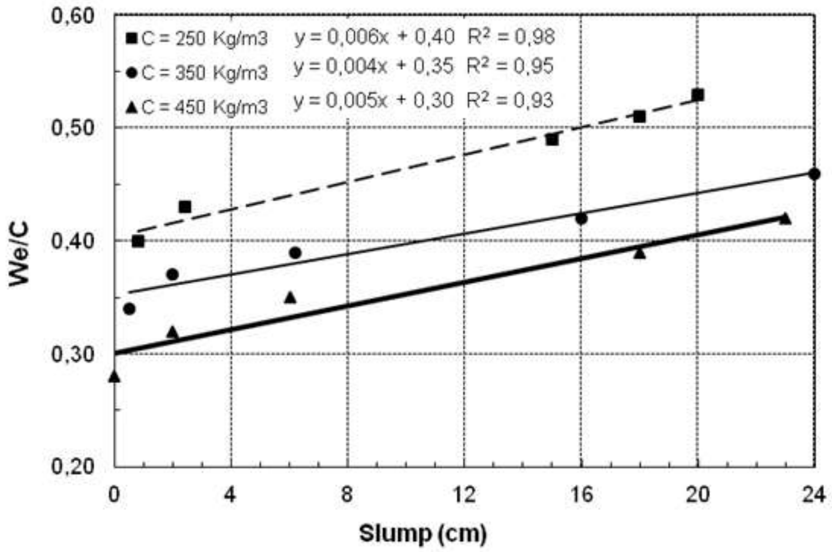

Fig 6: Variation of the needed We/C ratio according to slump.

The inclusion of the SP into concrete mixtures resulted in both a reduction of water quantity and an improvement of the workability. The deflocculation of cement particles by the SP produces a much more efficient binder which leads to better workability, hydration, and strength (Neville, 1995; Pipilikaki, 2009a; Menadi, 2009; Aquino, 2010). The average reduction of water in the mixes was 30% which is much higher than the 15% stated by the manufacturer for conventional concretes. Moreover, the workability as well as the deformability of fresh concrete was enhanced by the incorporation of the SP. For a given We/C, workability improves from low in the case of series A mixtures to medium in the case of series B mixtures. The use of SP increased also the density of fresh concrete, thus denoting an enhancement in the packing of concrete. However, as reported by researchers (Donza, 2002), all series B mixtures displayed a considerable loss in workability after 20min.

4.2.Hardened concrete properties

The compressive as well as the tensile strengths of concrete for various mixes are presented in Table 5. The obtained 28-day compressive strengths varied from 6 to 33MPa for series A mixtures whereas series B strengths are ranged from 29 to 54MPa. The corresponding tensile strength ranged from 1.6 to 3.8 MPa for series A and from 3.0 to 5.0 MPa.

The failure of the majority of series A test specimens occurred at the aggregate-paste interface. However, in series B specimens, the excellent aggregate-paste bond resulted in a predominance of fractured particles. Since the ratio We/C is the principal factor in concrete mixture proportioning for strength and durability (Neville, 1995; Al-Ghahtani, 1998), the variation of the concrete compressive strength with C/We (Bolomey equation) is shown in Figure 7. The best fits for series A and series B as shown in Figure 7, are respectively given by the following relations:

$$R_{C28} = 16.69 \frac{C}{W_e} - 12.24 \quad (4)$$

$$R_{C28} = 15.63 \frac{C}{W_e} - 0.75 \quad (5)$$

The relation between compressive and tensile strengths is depicted in Figure 8 for the considered series.

Table 5: Compressive and tensile strengths results (MPa)

Cement (kg)	Series A				Series B			
	We/C	Rc_{28}	Rt_{28}	Rc_{28}/Rt_{28}	We/C	Rc_{28}	Rt_{28}	Rc_{28}/Rt_{28}
250	0.56	12.91	2.38	5.42	0.40	33.89	3.60	9.41
	0.66	11.29	2.24	5.04	0.43	33.21	3.53	9.41
	0.71	10.50	2.18	4.82	0.49	28.64	3.11	9.21
	0.73	8.42	2.00	4.21	0.51	27.72	3.03	9.15
	0.81	6.43	1.84	3.49	0.53	27.15	2.97	9.14
350	0.89	20.82	3.04	6.85	0.34	42.33	4.28	9.89
	0.50	20.18	2.99	6.75	0.37	41.52	4.20	9.89
	0.51	16.85	2.71	6.22	0.39	39.41	3.99	9.88
	0.57	13.22	2.41	5.49	0.42	35.22	3.59	9.81
	0.66	11.26	2.24	5.03	0.46	32.39	3.34	9.70
450	0.71	28.04	3.65	7.68	0.28	49.25	4.85	10.15
	0.41	26.15	3.49	7.49	0.32	47.99	4.72	10.17
	0.43	24.31	3.34	7.28	0.35	45.65	4.48	10.19
	0.46	22.12	3.15	7.02	0.39	39.81	3.92	10.16
	0.49	18.44	2.84	6.49	0.42	37.78	3.73	10.13

The inclusion of the SP in concrete mixtures increases the strength by enhancing both the compactness of concrete through a reduction of water, air and the paste-aggregate interface bond. The gain in strength seems to be more significant (44 to 130%) for leaner mixes or mixes with excess of water (We/C ≥ 0.5). For concrete mixture with low We/C (≤0.5) the increase is relatively moderate (20 to 44%). However, the addition of SP did not alter with the same proportions the tensile strength of concrete.

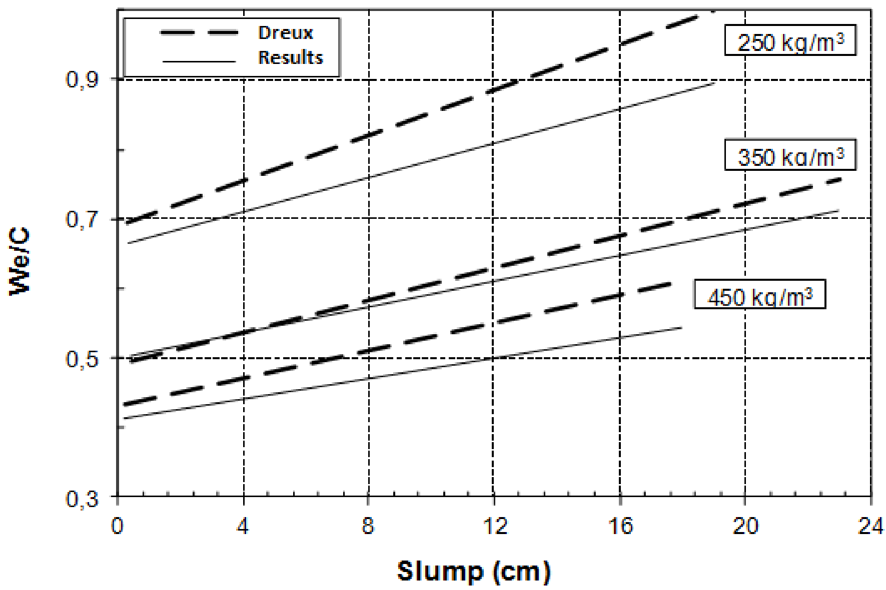

Fig 7: Evolution of the compressive strength according to the C/We ratio

The relation between R_{C28} and R_{T28} for the two series is similar to those found for conventional concretes. However, the tensile strengths of series A seem to be higher than what is traditionally found in concrete with the same R_{C28} as clearly indicated in Table 5 (ratio R_{C28}/R_{T28}) and Figure 8. This may be attributed to the contribution of the limestone filler contained in the sand to the hydration of cement (CEN, 2002; Makhloufi, 2012a) by acting as a nucleation site.

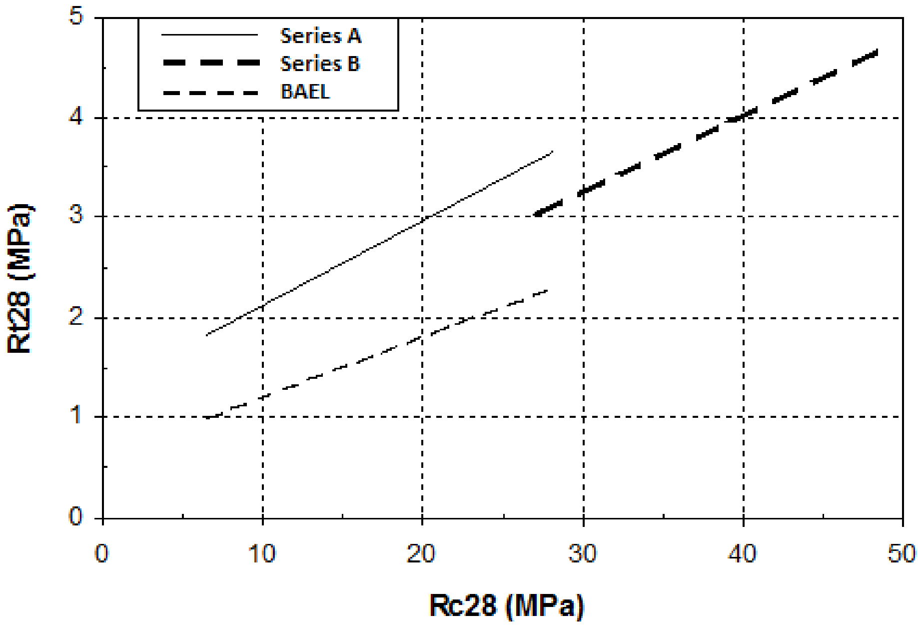

Fig. 8 Relation between compressive and tensile strengths for series A and B mixtures.

4.3 Comparison with conventional concrete

In order to identify the potential use of the concrete studied herein, a comparison between its properties (series A) and those of conventional silica sand-concretes was attempted. The conventional concrete results used in this comparison were obtained from the literature (Dreux, 1998). Comparison of the fresh behaviour of the concretes is captured in Figure 8, whereby it can be observed that the two concretes have similar trend of behaviour; an increase in slump increases We/C. For a given workability and in the case of low workability or in leaner mixes (<450kg/m^3), the We/C required for crushed limestone sand is lower than the corresponding value for conventional concrete. Consequently crushed sand appears to have a better fresh concrete behaviour than conventional concrete in this range. This may be due to the lubricant action of the filler particles (particles size ≤ 150μm) present in the crushed sand (Neville, 1995). In richer mixes, the high amount of cement present in the mix tend to provide sufficient particles of the size indicated above to lubricate the concrete mix, and the fines of sand become less required. Moreover, for a given water content and a chosen slump, crushed sand-concrete requires therefore more cement than conventional concrete (lower We/C).

If Eq. (1) is applied to natural sand-concrete made with the same coarse aggregates and cement as the crushed sand concrete studied herein, it will yield:

- Natural sand $R_{C28} = 18.5\dfrac{C}{W_e} - 9.25 \quad \Rightarrow \quad \dfrac{C}{W_e} = \dfrac{R_{C28} + 9.25}{18.5}$
- Crushed Sand $R_{C28} = 16.7\dfrac{C}{W_e} - 12.24 \quad \Rightarrow \quad \dfrac{C}{W_e} = \dfrac{R_{C28} + 12.24}{16.7}$

It can be clearly seen from the above relations that for a given strength of concrete, crushed sand-concrete (series A) needs a higher C/We (lower We/C) ratio. This can only be realistically achieved with an increase in the amount of the paste.

5. Conclusions

The following conclusions can be drawn from this study:

- Mixture proportioning of concrete elaborated with crushed limestone sand can be adequately determined using standard mixing methods provided that the mixing water is properly estimated.
- It appears that higher limits on the quantity of fines content in the crushed sand could be allowed for provided that the fines are clean and properly graded.
- Crushed limestone concrete required more mixing water than conventional silica sand concrete to achieve a specified fresh behaviour. A higher amount of paste is also needed for crushed sand concrete to acquire medium range strength.
- Similar or better mechanical strength than conventional natural sand concrete can be produced using crushed limestone sand as fine aggregate with a SP. However, to overcome the adverse effect of crushed sand such as texture and shape, a higher than normally used dosage of SP is required. The optimum dosage of SP needs to be determined for each cement and sand content. The inclusion of SP reduces the water content which in turn reduces the cement content for a specified W/C. Consequently the saving of cement can compensate the extra cost of the SP.

6. References

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