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Use of limestone sands and fillers in concrete without superplasticizer

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ABSTRACT

This paper deals with the effects of the amount of limestone fillers with respect to the rheological, mechanical, and dimensional properties of concretes without superplasticizer. These concretes were made with two limestone coarse aggregates and one limestone sand from the same quarry, in order to avoid any artifact. Five sand containing fillers rate between 1.8% and 24% – representative rates of the categories defined in the EN 12260 norm for aggregates for concretes – were produced by mixture of original sand with its fine fraction or its grained fraction extracted beforehand by washing. The concretes were mix designed with the BetonlabPro2 software, whose algorithms take into account the presence of the limestone fillers. The experimental results show that the concretes containing from 100 to 150 kg/m^3 limestone fillers often present optimal properties, with equal consistency. But, higher quantities of fillers do not deteriorate significantly the properties of the concretes, even if their packing density decreases. This behavior is explained not only by the binding effect allotted to the limestone fillers, but also by an improvement of the paste-aggregates bond.

1. Introduction

The presence of limestone fillers in concrete has been a subject of increasing interest in the literature. Studies generally consist of carrying out tests on mortars in which part of the sand or cement was replaced by limestone fillers. The purpose is generally to define the amount of filler can be allowed in cement [1] or in the crushed sand [2,3]. However, the extrapolation of the results to the concretes is difficult, since the coarse aggregates present in concrete significantly modify the properties of the composite. Other works were carried out on concretes, generally based on quarry sands of various origins, with varying levels of limestone fillers [4,5]. In these cases, making generalized observations based on the results obtained from these mixtures may raise certain difficulties, due to the variability of aggregate properties according to their origin.

These studies made it possible to show that the limestone fillers had an accelerating effect at early ages, as well as a certain binding effect over the long term [6]. They also improve the degree of hydration of the clinker [7] and the packing density of the mineral skeleton, at least if the used quantities were adapted. European standards used some of these results to specify the characteristics of the materials intended for the concretes, especially the fine aggregate sands. For example, the EN 12620 "aggregates for concrete" standard [8] defines five categories of content of filler in sands. Article 10 of the French equivalent standard NF XP P 18-545 [9] distinguishes four codes (A, B, C, D) corresponding to four categories (levels of quality). The specifications for sands are presented in Table 1 (f_A–f_D for the fillers content). Concrete aggregates are chosen from these categories (see Table 2). For example, for concretes placed in aggressive environments, only the aggregates of A category are allowed (sand fillers content $\leqslant$10%). For ordinary concretes, materials of C category can be used (sand fillers content $\leqslant$16%).

The EN 206-1 standard of the concretes admits, in the French application [10], that the 'active' limestone filler declared [11] can be considered an admixture. In this case, in the presence of a mass C of cement CEM I 42,5 or 52,5 N or R, these fillers can be counted in the equivalent binder L by assigning to the quantity A taking into account an activity coefficient equal to 0.25. The formula is $L = C + 0.25 \cdot A$. The maximum ratio of filler being able to be taken into account in the equivalent binder $A/(A + C)$ depends on the class of exposure of the concrete. For example, the equivalent binder of a concrete placed in an environment without risk of reinforcements attack or corrosion (X0[1]) can include up to 25% limestone filler. In systems exposed to sea water (XS1, 2, 3) or to freezing with salt (XF4), the maximum filler content decreases to 5%. No limestone filler is allowed in concretes subject to chemical attacks (XA1, 2, 3).

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[1] Exposition classes according to EN 206-1.

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Table 1
Specifications of sands for concrete.

Dimensions	EN 12620 – NT 21.30				NF XP P 18-545 – Article 10					
	Granularity		Fillers content		Granularity Gr		Fillers content f		Property	
	<D	Category	<63 μm	Category	<D	Code	<63 μm	Code	MB[a]	Code
D = 4 mm and d = 0	85 to 99	G_F85	⩽3 ⩽10 ⩽16 ⩽22 ⩾22	f_3 f_{10} f_{16} f_{22} f_{Dec}	85–99	Gr_A–Gr_D	⩽10 ⩽16 ⩽22	f_A f_B and f_C f_D	⩽1.5	P_A–P_D

[a] Blue value on the fraction 0/2.

Table 2
Choice of concretes aggregates, according to NF XP P 18-545 norm.

Use	Code of aggregates			
	A	B	C	D
Agressif Environnements (XF4, XA3[a])	Yes	Yes, if Ab_A	No	
Concrete Building fc_{cyl} > 35 MPa	Yes	Yes, for certains characteristics	Maximum 2 characteristics with C or D code if study or reference	
Ordinary Concretes	Yes			Maximum 2 characteristics with code D

[a] NF EN 206-1: XF4 freezing in presence of water with agent of de-icing or sea water; XA3 environment at high chemical aggressivity.

This review shows that there is today a normative framework allowing the use of filler-rich sands in concretes. However, these specifications eliminate various interesting local resources, unless specific studies validate this possibility [10].

More generally, specific studies are required also in countries where the normative framework is less used, in order to obtain a foundation of relevant examples. Most studies are carried out on priority limestones which are an important alternative mineral resource when other sources of aggregate are exhausted. In Tunisia, for example, limestone formations are the only aggregate sources available near the centers of concrete production [4]. The concerned limestones generally display properties sufficient to be included as quality coarse aggregates, but the crushed sands that are available have been dismissed until now due to their high concentration of fine particles. On the scientific level, predicting the rheological properties and the strength of concretes including limestone fillers was studied in various works [6]. It is thus important also to refer to these studies, to confirm their relevance by complementary data. Finally, some concrete, such as Self Compacting Concrete (SCC), require a quantity of fine quite higher than the normative limits, to ensure the stability of the suspension.

This work has these different objectives. It has consisted of studying the role of the amount of limestone fillers in the rheological, mechanical and dimensional behavior of five concretes produced with two coarse aggregates and one sand. These materials came from the same quarry located near Tunis. As the materials have the same mineralogical nature, any artifact in the data due to compositional discrepancies is thus avoided. The sand was separated into two lots. One was preserved while the other was split by wash on sieve of 80 μm into a fine fraction (<80 μm) and a fraction without fine particles (>80 μm). Five sands corresponding to the categories of the EN 12620 standard or the similar Tunisian standard NT 21.30 [9] (f_3–f_{Dec}, Table 1) could be thus manufactured by combination of the original sand with one or other two separated lots washed. The mix design of the different concrete was carried out with BetonlabPro2 software [13] based on the Compressible Packing Model (CPM). This software takes into account the role of limestone fillers.[2] All concretes contain originally 350 kg of cement CEM I 42.5 N and varying amounts of water to reach three different slumps (~7, 15 and 23 cm). The same types of concrete were mix designed with superplasticizer. The corresponding results are not presented here. This study is justified by the fact that most of ordinary concretes are casting without superplasticizer. Its results must be also compared with those of concrete with superplasticizer and having the same fillers amounts.

The paper presents the properties of the materials, their preparation and the mix design carried out. The results are then analyzed and compared to the predictions made by models of BetonlabPro2. An appendix reminds the equations of these models to which references are made in the text.

2. Origin, preparation, properties of materials

On the basis of previous results [4], limestone aggregates from the quarry of Jbel Ressas, located about thirty kilometers from Tunis, were obtained for this study. The quarry provided three aggregates from the same production run: two coarse aggregates (G4/8 and G10/20) and one fine aggregate sand (S0/4) containing 16% limestone filler.

Part of the S0/4 sand was washed on 80 μm sieves. The washing water was completely preserved in vats and the fine fraction was recovered without loss after decantation and siphoning of the clear water. The obtained limestone fillers (*LF*) were homogenized and preserved at the wet ground state in a hermetic container until use. Their water content was taken into account in the calculation of the mixtures. The activity of these fillers was checked according to the French standard NF P18-508 [11]. Five sands of same mineralogical nature, but of different grain size distributions (filler rate) could be thus manufactured in sufficient quantities to formulate the desired concretes. These five sands include:

- a sand (f_3) deprived of fines (1.8%), made up of the only grained fraction of washed sand;
- two sands (f_{10} and f_{16}) containing 7.1% and 12.5% fines, respectively, produced by mixing washed sand and the original sand;
- two sands (f_{22} and f_{Dec}) containing 18% and 24% fines, respectively, produced by mixing the original sand and *LF*.

Aggregate particle size analysis was carried out by wet process sieving. That of the *LF* was done by laser granulometry. The

[2] It should be noted that since this work, the BetonlabPro3, version 3 of this software has been published [14].

Table 3
Grading (% passing) and packing density of materials.

Size (mm)	CEM I	LF	f_3	f_{10}	f_{16}	S0/4	f_{22}	f_{Dec}	G4/8	G10/20
0.000315	1.6	1.3		0.1	0.2	0.2	0.2	0.3		
0.00040	3.2	2.7	0.0	0.2	0.3	0.4	0.5	0.6		
0.00050	4.7	4	0.1	0.3	0.5	0.6	0.7	1.0		
0.00063	7.7	5	0.1	0.4	0.6	0.8	0.9	1.2		
0.0008	10.7	6.1	0.1	0.4	0.8	1.0	1.1	1.5		
0.001	13.6	7.1	0.1	0.5	0.9	1.1	1.3	1.7		
0.00125	16.4	9.1	0.2	0.6	1.1	1.5	1.6	2.2		
0.0016	19.6	11.3	0.2	0.8	1.4	1.8	2.0	2.7		
0.002	22.5	13.3	0.2	0.9	1.7	2.1	2.4	3.2		
0.0025	26.8	16	0.3	1.1	2.0	2.6	2.9	3.8		
0.00315	30.8	18.8	0.3	1.3	2.3	3.0	3.4	4.5		
0.004	35.5	21.7	0.4	1.5	2.7	3.5	3.9	5.2		
0.005	40.4	25	0.5	1.8	3.1	4.0	4.5	6.0		
0.0063	44.7	28.9	0.5	2.1	3.6	4.6	5.2	6.9		
0.008	52	32.8	0.6	2.3	4.1	5.2	5.9	7.9		
0.01	58.2	36.9	0.7	2.6	4.6	5.9	6.6	8.9		
0.0125	64.6	41.8	0.8	3.0	5.2	6.7	7.5	10.0		
0.016	71.7	47.2	0.8	3.4	5.9	7.6	8.5	11.3		
0.02	79.5	52.1	0.9	3.7	6.5	8.3	9.4	12.5		
0.025	85.2	58.3	1.0	4.2	7.3	9.3	10.5	14.0		
0.0315	88.6	65.8	1.2	4.7	8.2	10.5	11.8	15.8		
0.04	92.2	73.6	1.3	5.2	9.2	11.8	13.2	17.7		
0.05	95.5	80.9	1.5	5.8	10.1	12.9	14.6	19.4		
0.063	99	88.5	1.6	6.3	11.0	14.2	15.9	21.2		
0.08	100	100	1.8	7.1	12.5	16.0	18.0	24.0	1.5	1.2
0.1			2.3	7.9	13.5	17.2	19.1	25.0		
0.125			2.7	8.6	14.4	18.3	20.2	26.0		
0.16			4.2	10.0	15.8	19.6	21.5	27.2		
0.20			7.6	13.2	18.7	22.4	24.2	29.7		
0.25			10.9	16.3	21.6	25.2	26.9	32.3		
0.315			14.3	19.4	24.6	28.0	29.7	34.9		
0.4			19.6	24.4	29.3	32.5	34.1	38.9		
0.5			24.6	29.1	33.7	36.7	38.2	42.7		
0.63			29.6	33.9	38.2	41.1	42.5	46.7		
0.8			38.5	42.2	45.9	48.3	49.6	53.3		
1			46.5	49.7	53.0	55.1	56.1	59.4		
1.25			54.6	57.3	60.0	61.8	62.8	65.5		
1.6			63.5	65.7	67.9	69.3	70.1	72.3		
2			71.6	73.3	74.9	76.0	76.7	78.4		
2.5			80.5	81.7	82.8	83.6	84.0	85.2	2.2	
3.15			89.7	90.3	91.0	91.4	91.6	92.2	2.5	
4			94.7	95.0	95.3	95.5	95.6	96.0	3.1	
5			98.5	98.6	98.7	98.7	98.8	98.6	11.7	
6.3			100	100	100	100	100	100	55.2	
8									96.9	1.7
10									99.3	4.7
12.5									100	30.5
16										79.2
20										99
Φ	0.574	0.600	0.699						0.624	0.593
Φ^*	0.644	0.691								
β_i	0.483	0.512	0.604						0.684	0.669
β_i^*	0.558	0.613								

spectrum obtained was reduced and combined with the percentage of filler present in each sand. The complete grain size distribution of these materials, based on the standardized series of sieves, is given in Table 3. It is noted that the coarse aggregates G4/8 and G10/20 contain 1.5 and 1.2% *LF*. This has been accounted for in the mix design calculations.

The real density (*RD*), water absorption (*Ab*) and blue value (*MB*) were measured according to Tunisian standards (Table 4). The aggregates conform to Tunisian standard NT 21.30 [12]. In addition, Blaine specific surface area (S_{FI}) of the limestone filler was estimated using granularity and density by assimilating the grains to spheres. The obtained values (added to Table 4) were used to calculate the compressive strength of the binder matrix (Eq. (A2)).

The concretes were made with Tunisian CEM I 42.5 N cement, the grain size of which was measured by laser granularity (Table 3). Its mineralogical composition and its properties were provided by the cement plant and its real class was checked by tests at 1, 3, 7 and 28 days (Table 5). They made it possible to calculate the parameter $d(7)$ necessary for Eq. (A2). The value of $d(7)$ is added to Table 5. This cement contains 1.6% limestone filler, also recorded in the calcareous fine fraction. The real class measured at 28 days was chosen for the calculation of fc_{m28} (Eq. (A2)).

Other properties specific to the use of the CPM (Eq. (A10)) were measured on materials. They are in particular virtual packing densities β_i of the elementary classes of the various materials.

Virtual packing densities are calculated with the CPM starting from the packing density Φ of a grain-packing setup according to a given protocol. For the grading higher than 80 µm, the measurement is carried out at dry state [6]: a representative sample of dry mass *Ms*. and real density *RD* is placed in a metal cylinder of diameter *D* fixed on a vibrating table and closed by a piston exerting a pressure of 10 kPa. The set is subjected to a vibration of 50 Hz for

Table 4
Physical properties of materials.

	CEM I 42.5 N	LF	f_3	f_{10}	f_{16}	S0/4	f_{22}	f_{Dec}	G4/8	G10/20
Content in LF (%)	3	100	1.8	7.1	12.5	16	18	14	1.5	1.2
RD (kg/m^3)	3110				2690				2687	2685
S_{Fl} (m^2/kg)	320	310								
Ab (%)						0.3				
MB (g/100 g 0/2)						1.03				

Table 5
Properties of cement CEM I 42.5 N.

Composition (%)				Other properties		Real class (MPa)		
Cement		Clinker				Day	Announced	Verified
Clinker	95.4	C_3S	73	Setting start (mn)	224	1	8.1	8.1
Limestone Fillers	1.6	C_2S	6.3	Mixing water (%)	23.4	3	24.8	21.7
Gypsum	3	C_3A	2.2	Na_2O_{eq} (%)	0.35	7	41.9	34.2
		C_4AF	13.5	d(7)	−0.0184	14		45.2
						28	59.1	52.8

1 min. The final height h of the compacted sample is then measured. The associated packing index with this process is $K = 9$. The packing density Φ is given by the following relation:

$$\Phi = \frac{4 \cdot M_s}{RD \cdot \pi \cdot D^2 \cdot h} \quad (1)$$

Knowing the granularity of the materials, Φ and K, virtual packing densities β_i (not confined) are found with the CPM, by taking into account the wall effect produced by the metal cylinder. The values of Φ and β_i are added to Table 3.

For the cement, a water/cement ratio (W/C) is searched which produces a paste of normal consistency, as measured by Vicat probe. The packing index characterizing this process is $K = 4.8$ [15]. The packing density Φ is calculated according to Eq. (2).

$$\Phi = \frac{1}{1 + \rho_C \frac{e}{c}} \quad (2)$$

For the limestone filler, two measurements of Φ were made in the presence of 10% and 20% cement. The packing density of the filler alone is then extrapolated. The values of Φ and β_i for cement and limestone filler are added to Table 4.

3. Formulation and manufacture of the concretes

The concretes have been designed with BetonlabPro2 software [13], by optimizing first the granular skeleton according to the Baron–Lesage approach [16] using coarse aggregates G4/8 and G10/20 and alternatively one of the five reconstituted sands. Then, the effective water is adjusted to reach slump values equal to 7, 15 and 23 cm, respectively. The amount of cement was fixed at 350 kg/m^3. Thus, for each type of sand, three concretes of various consistencies were designed, a total of 15 mixtures.

The aggregates were delivered and preserved in big-bags. The cement used come from a single batch. For the manufacture of the mixtures, the quantities of materials necessary for each batch (40 or 65 L) were taken two days in advance, were homogenized and preserved in closed containers. Their water content was measured the day before manufacture and taken into account in the calculation of effective water. The mixtures were carried out by introducing first aggregate and cement into the mixer, followed by 1 min of mixing. Water was then introduced gradually and mixed for another 2 min. For the mixtures requiring the addition of filler, these products were put in suspension in part of the mixing water to ensure a good dispersion.

Slump values were measured as soon as the concrete was mixed (two measurements). If it was lower than that sought, minor amounts of water were added to reach the desired consistency, checked after 1 min of mixing by new slump measurements. The concrete was poured in five cylindrical PVC 16 × 32 cm molds, vibrated, and cleaned. Their filling and their slapping did not pose any particular problem, even for the concretes containing high values of filler. These molds were then immediately weighed. After 1 h, the bleeding water was delicately eliminated with a sponge and the molds were weighed once again. The specimens were unmolded after 24 h of curing and weighed before being placed under water at 20 °C for 28 days.

For the five concretes of 15 cm slump, six additional cylinder specimens (71 × 640 mm) were vertically cast in PVC tubes (Fig. 1). These molds included a metal bottom cap that supported in its center a pin intended for shrinkage/expansion measurement. The molds were closed, after filling and vibrating in successive stages, by a circular plate placed on the concrete, being able to

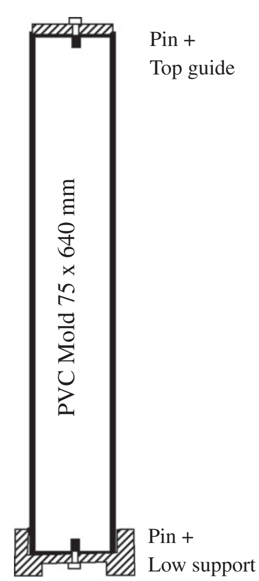

Fig. 1. Schematic of the molds built for the dimensional variation measurements.

move freely in case of plastic shrinkage and/or bleeding. This plate contained another pin in its center. After 24 h, the plates were removed. The ends of two specimens were closed with aluminum adhesive and kept in a room at 20 °C and 65% relative humidity. After 28 days, they were demolded. The four other specimens were demolded after 24 h and were cured either in water at 20 °C, or in ambient laboratory conditions. The initial length L_0 of the specimens was noted at 24 h. Their mass and their dimensional variations measured during the following year, by measurements brought closer at first, then increasingly spaced.

The various weighings carried out made it possible to calculate the density of the freshly-mixed concretes, their bleeding at 1 h and their hydration evolution. The comparison of the real density measured at a fresh state, RD_{fr}, and of their theoretical density (without air) RD_{th} gives a good estimate of the trapped air a (in L) in a unit volume, according to Eq. (3).

$$A = 1000\left(1 - \frac{RD_{fr}}{RD_{th}}\right) \tag{3}$$

The theoretical density of the concretes was deduced from the initially calculated density $RD_{th\text{-}init}$ by taking into account the water correction Δ_e added eventually to the batch of volume Vg according to:

$$RD_{th} = \frac{RD_{th\text{-}init} + \Delta_e/Vg}{1 + \Delta_e/Vg} \tag{4}$$

The final compositions of the concretes resulting from these corrections were calculated (Table 4). The total mass of fillers and the packing density Φ for each mixture are also given Table 4. These compositions were reintroduced in the BetonlabPro2 software in order to simulate the properties of the various concretes carried out (Table 7). This Table gives also the measured properties: compressive strength (average of 3 measurements); traction (average of 2 measurements); shrinkage at 365 days (average of 2 measurements).

4. Properties of the concretes

4.1. Fresh state

In the fresh state, the predicted slump values given by BétonlabPro2 (Table 7) were generally higher than the obtained measurements (Table 6), but the difference is acceptable since it is only of a few centimeters. Logically, the deviations of firm concretes are lower. The most relevant predictions are given for the concretes containing f_{16}. For the entrained air, the differences between measurements and predictions are a few liters, though the concretes containing f_{22} and $f_{Déc}$ performed slightly better. The algorithms of the software thus seem to be well adapted to predict the properties of these fresh limestone concretes, including those with filler-rich sands. The parameters of Eq. (A8) intended for the calculation of the yield stress are therefore appropriate for these materials. Slump (Eq. (A7)) and air content (Eq. (A9)) are particularly important in the calculation of yield stress [6].

The quantity of filler also influences bleeding (Fig. 2a), in terms of the water that appeared on the surface of the specimens after 1 h (L/m^3). In practice, the quantity of cement also influences bleeding, but it is constant here. When the filler quantity increases, the bleeding speed decreases in all three slumps. This is similar to the use of fine particles (cement, limestone filler) to stabilize suspensions, as in SCC. Finally, the fillers control also the packing density of the concrete which passes by a maximum for the three consistencies (Fig. 2b), for a contribution of 100–120 kg of filler per m^3. With lower amounts, the intergranular voids are less well filled. With higher quantities, the suspension is uncompacted by excess the grains of the same sizes (filler, cement), which generates a stronger water demand, as shown in Fig. 3 where the evolution of the ratio (W/C_{eq}) is compared with the quantity of fillers.

4.2. Compressive strength, tensile strength

For the theoretical compressive strength, the strength of the matrix (fc_{m28}) was at first calculated according to Eq. (A2), after

Table 6
Composition of concretes (kg for 1000 L of concretes).

	Sand	f_3			f_{10}			f_{16}			f_{22}			f_{Dec}		
Slump (cm)	Aimed	7	15	23	7	15	23	7	15	23	7	15	23	7	15	23
	Without water correction	4	6	14.5	2.6	12.2	18.9	6.1	14.9	16	6.6	8.8	19	7	8.6	15.1
	With water correction	8	12.5	20	7	13.6	21.3	7.6	14.9	21.4	6.6	13.1	20.4	7	13	20.2
Composition and effective density of concretes	Washed sand	818	810	786	514	505	491	196	193	187	0	0	0	0	0	0
	Complete sand (S0/4)	0	0	0	308	303	295	588	580	562	815	802	781	723	710	690
	Fillers brought	0	0	0	0	0	0	0	0	0	20	19.6	19.1	76.3	75	72.9
	Coarse aggregates 4/8	55.7	55.2	53.6	74.6	73.3	71.4	56	55.1	53.5	68.9	67.8	66	120	118	115
	Coarse aggregates 10/20	983	974	946	969	952	927	1025	1010	980	934	919	895	913	898	873
	Effective water	184	198	221	185	194	221	186	196	222	189	204	226	194	208	234
	Cement CEM I 42.5 N	350	351	350	352	350	351	351	351	350	351	350	351	351	350	350
	Density (without air)	2427	2405	2365	2428	2412	2368	2426	2411	2365	2420	2394	2358	2414	2387	2343
	Measured density	2395	2390	2358	2406	2382	2364	2407	2391	2368	2385	2365	2342	2383	2361	2335
	Air calculated (L)	13.5	6.2	3	9.1	12.6	3.1	8.1	8.5	3.1	15	12.3	7.2	12.9	10.9	3.7
	Total mass of fillers	33.1	32.9	32.1	77.1	75.8	74	117	115	112	168	166	161	210	207	201
	A/(A + C)	0.09			0.17			0.25			0.32			0.37		
	Concrete packing density Φ	802	796	776	806	793	776	806	796	775	795	784	766	793	781	762

Table 7
Computed and measured properties of concrete.

	Sand		f_3			f_{10}			f_{16}			f_{22}			f_{Dec}	
Model parameters for compressive strength	D_{max}	16														
	G	0.681	0.675	0.655	0.668	0.656	0.639	0.653	0.644	0.624	0.624	0.613	0.597	0.606	0.595	0.579
	g^*	0.805	0.805	0.805	0.812	0.812	0.812	0.815	0.815	0.815	0.814	0.814	0.814	0.815	0.815	0.815
	MPT (mm)	0.92	0.97	1.14	1.08	1.18	1.33	1.22	1.31	1.49	1.48	1.58	1.74	1.66	1.77	1.94
	C_{eq}(kg/m^3)	357	358	357	359	357	358	359	358	358	358	357	358	358	357	357
	fc_m (Mpa)	40.6	38.3	31.4	42	36.6	31.3	41.7	37.6	30.9	37.3	33.3	28.7	36.5	32.5	27.8
	fi/g	0.018			0.043			0.066			0.099			0.128		
	p^*–q–kt	1.137–0.002–0.36														
Computed properties (BétonlabPro2)	fc_{28} (MPa)	42.8	40.5	33.6	44.8	39.4	34	45.4	41.3	34.4	43	38.7	33.7	44.4	39.8	34.3
	ft_{28} (MPa)	3.1	2.9	2.6	3.2	3.1	2.7	3.3	3.2	2.8	3.3	3.1	2.8	3.3	3.2	2.8
	Total shrinkage (10^{-6})	547	604	735	625	665	819	682	728	902	818	887	1030	903	977	1154
	Slump (cm)	9.2	16.9	24	9.4	15.2	23.9	8.7	15	23.6	6.9	16	23.2	7.2	16.2	24
	Air (L)	16	12	9	16	13	9	15	12	8	18	13	10	16	12	9
Measured properties	fc_{28} (MPa)	38.6	36.2	21.3[a]	48.3	40.1	33.1	44.7	42.2	34.5	43	40.8	33.5	43.8	39.8	29.8
	ft_{28} (MPa)	4.3	3.2	2.8	3.7	2.7	2.3	3.2	3.2	2.7	2.8	3	2.2	2.9	2.9	2.5
	Shrinkage 365 days ($\times 10^{-6}$)		387			443			392			347			360	

[a] Average of two measurements. Deleted values.

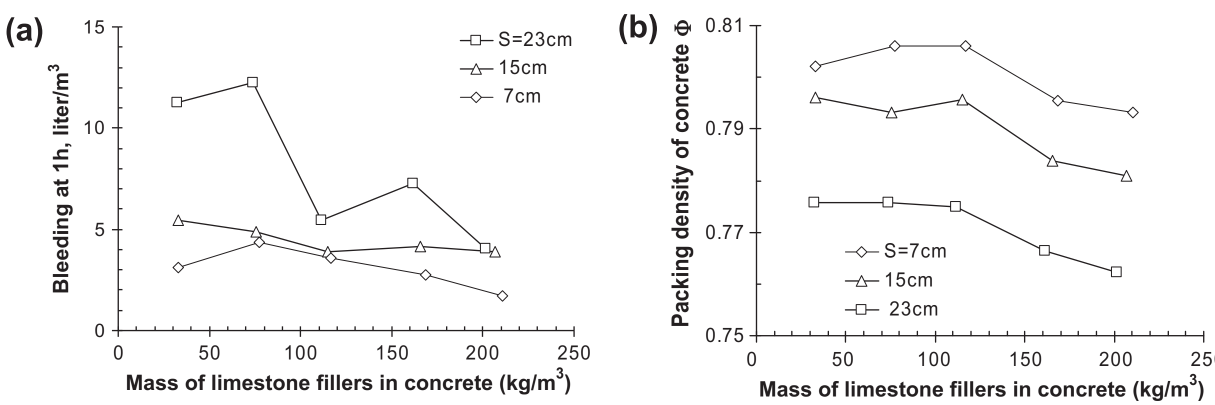

Fig. 2. (a) Bleeding after 1 h.; (b) packing density of the concretes vs. the quantity of fillers.

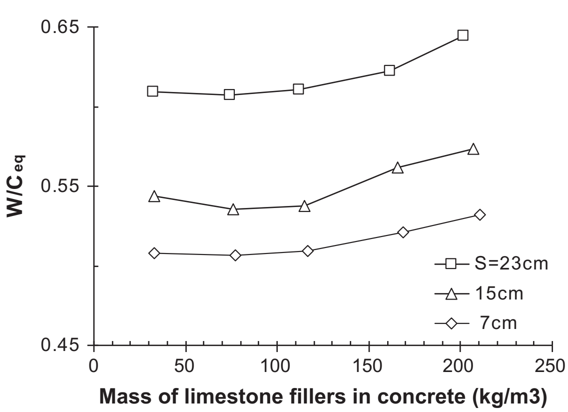

Fig. 3. W/C_{eq} ratio vs. quantity of fillers.

having calculated the *MPT* and the quantity of equivalent binder (C_{eq}) according to Eqs. (A4) and (A5). The corresponding values for each concrete are given in Table 7. The bond effect p and the ceiling effect q of the aggregates were then given by comparing the measured strength fc_{28} to the strength of the matrix fc_{m28}. Only those having a mass filler/aggregates ratio (fi/g) less than or equal to 0.1 were considered because beyond this threshold, according to [17], the parameter p increases with fi/g to take into account the improvement of paste/aggregate adherence. In this case, it is the parameter p^*, specific to the aggregate[3], which is determined. The relation between p and p^* is given in [17]:

$$p = p * (1 + 9(fi/g)^2) \quad (5)$$

The ceiling effect q, which depends on the strength of material, was preserved equal to that previously given for these aggregates with another cement [17], i.e. $q = 0.002$. The parameter p^* was found by minimizing the absolute deviation between measured and calculated strengths. Its value is $p^* = 1.137$. The corresponding curve is presented in Fig. 4. It should be noted that the obtained values of p^* and q indicate a good paste/aggregate adherence and an aggregate with a low ceiling effect (good intrinsic properties).

Predicted strengths were then calculated according to Eqs. (A1) and (5). They are added to Table 7, where the values of fi/g, p^* and q are also given. The comparison between predictions and

[3] The cement nature has (probably also) an impact on this propriety.

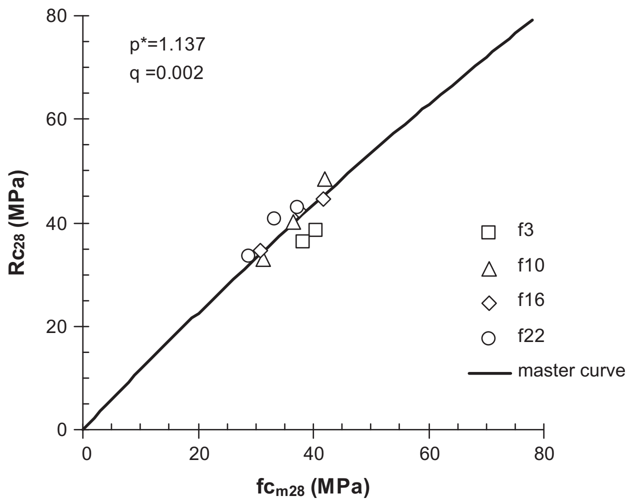

Fig. 4. Determination of the parameters p* and q of the aggregates.

measurements shows a variation of more than 4 MPa for the concretes low in filler (sand f_3). This difference is lower for the concretes richer in filler, with an absolute deviation of only 1.2 MPa, thus confirming the relevance of the tool and the extensions made for the concretes rich in fillers.

Experimental strengths are shown in Fig. 5a, according to the quantity of fillers. At the same slump, the strengths reach maximum values for a contribution from 100 to 130 kg/m^3, quantity which also leads to the maximum of packing density. For a lower quantity, strengths are appreciably lower, in particular for the concretes lowest in fillers, whereas their packing density is rather high (Fig. 2b). Beyond this quantity, strengths practically do not decrease, although packing density drops. In both cases, this behavior is due to the strength of the paste/aggregate interface and the rigidity of the binding phase which increases with the quantity of filler. The binding effect of the filler is quickly reached with a small quantity of product (sand f_3) and then remains constant (see C_{eq}, Table 7). When this quantity increases, the mechanical behavior of the paste approaches that of the aggregate, and the composite becomes mechanically more homogeneous, leading to better performance. In this scheme, significant amounts of fillers (~200 kg/m^3 or $A/(A+C) \sim 0.4$) used in the limestone concretes (without superplasticizer) do not constitute a handicap with respect to the compressive strength. It should be noted that BetonlabPro2 software, which does not integrate the concepts associated with Eq. (5), predicted for the concretes rich in fillers a lower resistance (not communicated here).

The tensile strengths predicted by BetonlabPro2 software (Table 7) were calculated after having the coefficient *kt* (Eq. (A6)) adjusted at value of 0.36 (Table 7), characteristic of a semi-hard limestone [6]. They are overall rather close to the measured strengths (Fig. 5b). Although these results are the average of only two measurements, it is noted that strengths are appreciably constant (~3 MPa) whatever the quantity of filler, except for the firm concretes (slump = 7 cm) rich in fillers, for which the performances

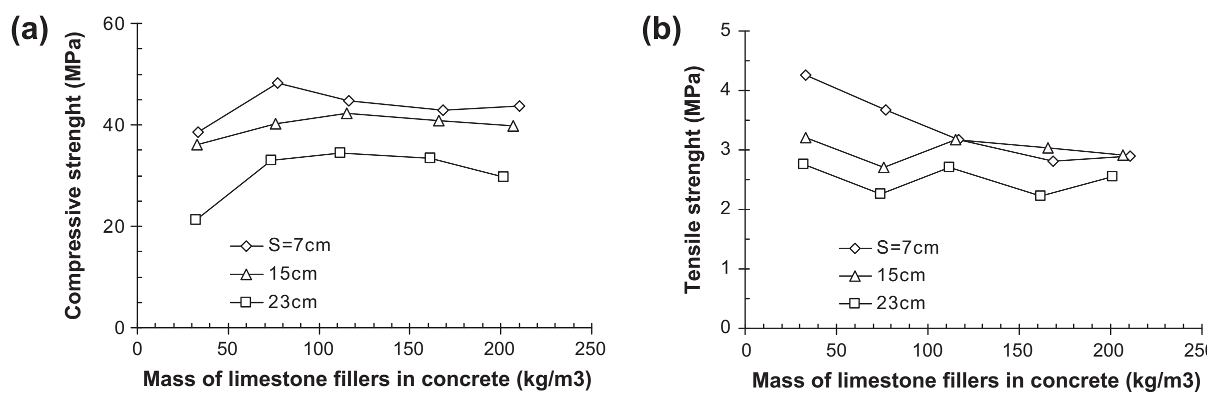

Fig. 5. (a) Experimental compressive strengths, (b) tensile strength vs. quantity of fillers.

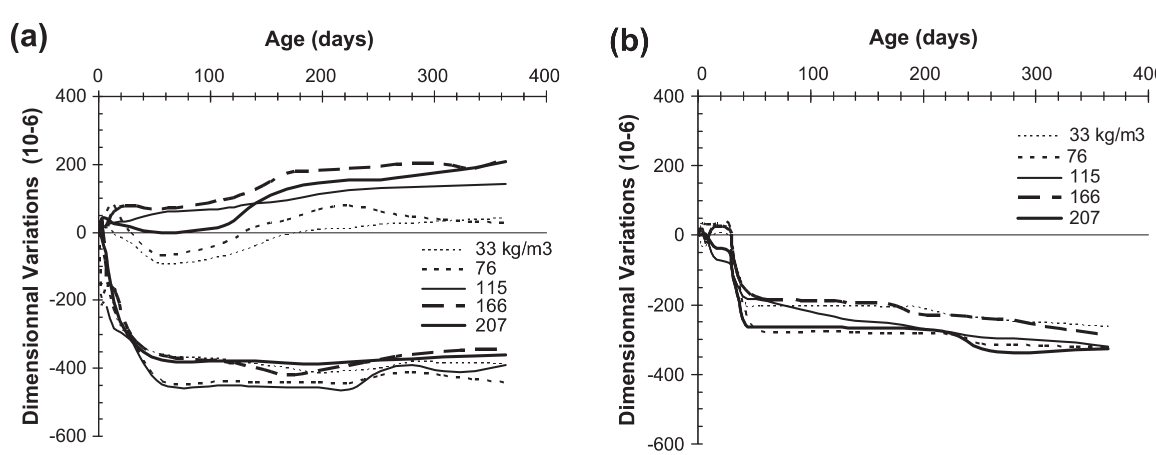

Fig. 6. Dimensional variation of the concretes; (a) shrinkage in the air and expansion in water; (b) endogenous shrinkage and desiccation shrinkage in the air starting 28 days. For each concrete, the total quantity of limestone filler is given in kg/m3.

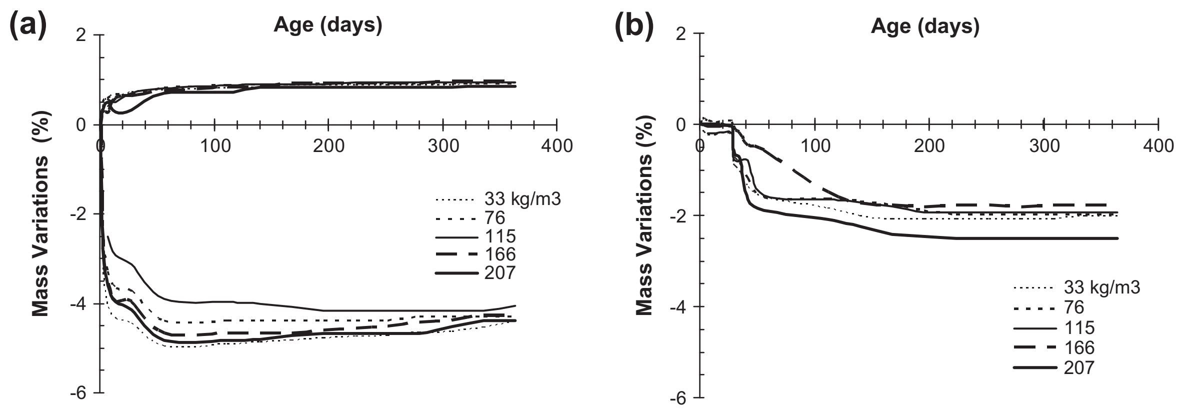

Fig. 7. Mass variations of the concretes; (a) in the air and in water; (b) protected during 28 days then in air. For each concrete, the total quantity of limestone filler is given in kg/m3.

are lower than expected. Aside from these values, significant quantities of limestone filler do not decrease the tensile strength, as already noted in preceding work [18].

4.3. Dimensional variations

Measurements of dimensional variation were carried out over 1 year on the concretes with intermediate slump (15 cm) cast in test-tubes with an appropriate support equipped with a digital comparator. This specimen geometry was selected out of concern for combining precision measurements with feasibility. The results of specimens stored in ambient conditions (shrinkage) and in water at 20 °C (expansion) are presented (Fig. 6a; average of two measurements at each term) along with measurements of mass variation (Fig. 7a).

In terms of shrinkage, it should be noted that there are no net distinctions depending on the amount of fillers. The majority of the shrinkage is reached after only 2 months of exposure, with a value of about 400×10^{-6} which remains quasi-constant thereafter. The mass losses are faster and seem to be connected to the quantity of fillers and packing density, but they converge in the long run. The shrinkage is thus not directly due to desiccation. The BétonlabPro2 software predicts a much higher final shrinkage (Table 7) depending on the quantity of fillers. This difference is likely due to the different contexts investigated: specimens of diameter = 160 mm, relative humidity of 50% and long term final shrinkage for BétonlabPro2 [6], and specimens of diameter = 71 mm, average relative moisture of 70%, varying from 56% to 76% [19]. for the actual experimental specimens. The low average radius (section/perimeter ratio) of the specimens explains also this behavior which results from a hydrous balance reached at the same time, regardless of the quantity of filler and/or the packing density of the concretes.

For the specimens preserved in water, depending on the concrete and the amount of filler, stagnation, even shrinkage was observed at early ages. Afterwards, the expansion progressed slowly for all concretes. Over the long term, it is apparent that the concretes rich in fillers will reach an expansion higher than 200×10^{-6}. For the concretes with the least filler, it will likely be less. All the specimens present an increase in mass after immersion (Fig. 7a), without real distinction between the amount of filler. Here again, there is no relation between the two phenomena.

For the specimens protected initially from any hydration during 28 days (Figs. 6b and 7b), it is difficult to distinguish from the reliable differences in endogenous shrinkage between the concretes. This shrinkage does not exceed 50×10^{-6}. After exposure to air, the concretes undergo a fast shrinkage during the first 15 days, whereas the loss of mass is slower. It is however half ($\sim 200 \times 10^{-6}$) than that of the concretes exposed directly to the air at one day. It then slowly progresses to join in the long term shrinkage of the specimens exposed to air from the beginning. As for these latter specimens, it appears difficult to be able to distinguish differences according to the quantity of fillers, because of the similar behavior.

5. Conclusion

This study performed on concretes without superplasticizer confirms that the limestone filler is beneficial to the properties of both fresh and hardened concrete. With the amount of cement employed, a quantity of filler from 100 to 130 kg/m^3 makes it possible to increase packing density and mechanical performance, and to reduce bleeding, without harming the workability or shrinkage. Higher amounts reaching 200 kg/m^3 lead to a low increase in the W/C ratio and to a concomitant drop of packing density, but the mechanical properties are not affected. In these proportions, the limestone filler improve the mechanical behavior of the paste and aggregate, make the composite more homogeneous and improve the paste-aggregate bond. The adverse effect of additional water is thus compensated.

In their great majority, these fillers are introduced by crushed sand. These results show that all the normative categories of sand concrete (f_3–f_{22}) can be used *a priori* in the ordinary concretes, provided that they satisfy the requirements of the exposure classes. The f_{10} categories and f_{16} are most interesting and allow optimization of the properties of the concretes (packing density, W/C ratio, compressive strength). The f_{Dec} category is not excluded (no significant changes of the properties). It can be considered for use in SCC to bring whole or part of the significant amount of fillers generally encountered in these products. The concretes carried out with superplasticizers, not presented here, bring answers in this direction.

This work allowed also comparison of the predictions of the models associated with BétonlabPro2 software, integrating the presence of the limestone fillers, with the measured properties of these concretes. Generally, the model and the experiments provide similar results, except for the mixtures rich in filler for which strengths are underestimated.

Finally, in practical terms, these works show the feasibility of limestone concrete in Tunisia. They have also contributed to the drafting of the first technical manual on the use of limestone resources in this country [21].

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Appendix A. LCPC models of concrete including limestone fillers

A.1. Models of compressive and tensile strength

In the paste-aggregate model proposed by the LCPC [6], the 28-day compressive strength fc_{28} of a concrete containing limestone fillers is related to the strength of the paste, also called matrix, fc_{m28}, by the following hyperbolic relationship:

$$fc_{28} = \frac{pfc_{m28}}{1 + qfc_{m28}} \tag{A1}$$

with p and q two coefficients describing the contribution of the paste/aggregate bond and the ceiling effect of the aggregate, respectively.

The strength of the matrix, which takes into account the accelerating effect of the limestone filler, is given by:

$$fc_{m28} = 13,4\sigma'_{c28}\left[-B\frac{d(7)}{28}\cdot\frac{\sum S_{FI}fi}{c} + \left(1 + \rho_c\frac{e+a}{c_{eq}}\right)^{-2,85}\right]MPT^{-0,13} \tag{A2}$$

with:
- σ'_{c28}: the cement real class at 28 days measured on mortar specimens.

- e and a: the air and water volume in a unit volume of fresh concrete, in liters.
- c: the cement mass (clinker) in a unit volume of fresh concrete, in kg
- c_{eq} and ρ_c: the mass (kg) and the density (kg/L) of the equivalent cement.
- $d(7)$: a term kinetic cement for the development of the compressive strength at 7 days, calculated according to the following relationship:

$$d(7) = 0.0522\left(\frac{\sigma'_{c7}}{\sigma'_{c28}} - 1\right) \tag{A3}$$

- σ'_{c7}: the cement real class at 7 days.

- fi and S_{FI}: mass and specific surface of the limestone fillers present in a unit volume of fresh concrete.
- B: a parameter taking into account the accelerating effect of the limestone fillers.
- MPT: the Maximum Paste Thickness, given by the relation:

$$MPT = D_{\max}\left(\sqrt[3]{\frac{g^*}{g}} - 1\right) \tag{A4}$$

with:
- $D_{\max}$: the maximum size of aggregate.
- g and g^*: real and maximum packing density of the granular fraction higher than 80 μm. This last property can be measured directly according to a particular protocol (see § 2) or calculated with the CPM [6].

The mass of equivalent cement, which takes into account the binding effect of the limestone filler, is given by:

$$c_{eq} = c\left[1 + \Psi'\max\cdot t_{C3A}\left(1 - \exp\left(K_{FI}\frac{\sum fi}{t_{C3A}\cdot c}\right)\right)\right] \tag{A5}$$

with:
- $\Psi'_{\max}$ and K_{FI}: two parameters taking into account the binding effect of limestone fillers.
- t_{C3A}: the C_3A content of the cement.

The values of the coefficients B, $\Psi'_{\max}$ and K_{FI} were calibrated based on the results of a study carried out on mortars with a variety of limestone fillers [20]. The suggested values [6] are B = 0,0023, $\Psi'_{\max}$ = 0017, K_{FI} = 79.

For tensile strength, the suggested model is written as:

$$ft_{28} = kt\cdot fc_{28}^{0.57} \tag{A6}$$

where kt is a tensile coefficient.

A.2. Rheological models

The slump S (mm) is estimated starting from the yield stress τ 0 (Pa) of the concrete and of its density ρ (kg/m^3), according to the relation:

$$S = 300 - 347\frac{(\tau_0 - 212)}{\rho} \tag{A7}$$

The yield stress is predicted by a parametric model presented as the following:

$$\tau_0 = \exp\left[2.537 + \sum_{\text{aggregates}} a_iK_i + [0.224 + 0.910(1 - Sp/Sp^*)^3]K'c\right] \tag{A8}$$

where
- $K'c$ and K_i: the packing index relating to cement and fillers and to the granular sections i of the aggregates. These parameters are calculated with the CPM [13].
- a_i: parameter determined for each granular section of average diameter di, according to the relation: $a_i = 0.736 - 0.216\log(d_i)$.

At last, the trapped air (L/m^3) is estimated starting from the relation below, where CA and FA are the masses of coarse aggregates and sands in kg/m^3, S the slump in mm and Sp the amount of superplasticizer:

$$a = (1 + 0.0683Sp - 0.00222S)(-0.000988CA + 0.00368FA) \tag{A9}$$

A.3. Compressible Packing Model (CPM)

This model [6] calculates the packing density Φ of an granular mixture starting from its granularity yi, the virtual packing density β_i of the elementary sections which constitute, the virtual packing density γ_i when class i is considered dominant, and of the packing index K associated with the placed mode. These various terms are connected between them by the following implicit relation:

$$K = \sum_{i=1}^{n}\frac{yi/\beta i}{\frac{1}{\Phi} - \frac{1}{\gamma i}} \tag{A10}$$

The CPM is used to characterize the granular structure in its entirety and its details. In addition to packing density Φ, it makes it possible to calculate for example the parameters g^*, $K'c$ and Ki referred to above.

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