Visual Abstract

Effects of rubber aggregates on the physical-mechanical, thermal and durability properties of self-compacting sand concrete

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ABSTRACT. The aim of this research was to study the effect of incorporating waste rubber aggregates on the physical-mechanical, thermal and durability performance of Self-Compacting Sand Concrete (SCSC) mixtures. Separately, Rubberized Self-Compacting Sand Concretes (RSCSC) were elaborated with three fractions of rubber grains in which natural aggregates were replaced with powder rubber, sand rubber and gravel rubber and four (5, 10, 15 and 20%) addition ratios as volume rates. The performed fresh properties using slump-flow, spreading, t_{500}, sieve stability and air-entrained content tests proved better results for the RSCSC in comparison with reference concretes. Hardened state characterization of the concretes exhibited decreases in the

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mechanical properties of the RSCSC but the thermal conductivity and the dynamic elastic modulus were improved. Assessment of the concretes' durability was accomplished through determination of apparent porosity, capillary absorption. Experimental outputs revealed that RSCSC may be used in structural elements of dense reinforcement and complex formwork, which allows promising solution to reduce the impact of waste tyres on the environment and fight pollution.

KEYWORDS. Self-compacting sand concrete; Waste rubber; Recycling aggregates; Strength; Thermal conductivity; Durability; Porosity.

INTRODUCTION

The elimination of rubber from Used Tyres (UT) and/or Non-Reusable Used Tyres (N-RUT) became a major environmental concern. Rubber is a non-biodegradable raw material used in tyres manufactures. The accumulation of UT led to serious environmental problems worldwide [1]. Civil engineering sector used these waste tyres for some 30 years in a number of ways. These include the Pneusol technique, which is a combination of used tyres [2] and introduction of their components to reinforce the soil mass [3] as well as construction materials in the form of rubber shreds from UTs, meeting standardized granular classes [4]. For the latter use, several researches were oriented towards the possibilities of using rubber aggregates as a substitute for aggregates in building materials, and their environmental impacts such as asphalt mixtures [2], mortar mixtures [3], vibrated concretes (VC) and Non-Vibrated Concretes (NVC). Many researchers carried out studies related to the use of Rubber Aggregates (RA) in VC and Self-Compacting Concrete (SCC) and in Self-compacting sand concrete (SCSC), usually used in novel concrete constructions. The concretes produced in this way develop high mechanical strengths [4]. Due to their high fluidity, these concretes can flow under their own weight and thus completely fill formworks with complex geometries in presence of dense reinforcement and of course without vibration being necessary [5]. However, up to date studies available in literature still lack knowledge on the use of RA in SCSC. Therefore, it is the purpose of this work to study the effects of the substitution of different sizes RA on the physical-mechanical, thermal and durability properties of SCSC, through experimental analysis and by comparison with other rubberized concretes.

Many researchers undertook studies related to the use of RA in VC and SCC in order to develop a concrete that could be used for a wide range of applications in construction for non-structural components and civil engineering works. Indeed, Khatib and Bayoumi [6] noted through their respective research that the use of RA should not exceed 20% of the total aggregate volume of VC. This choice was conditioned by some of the physical and mechanical characteristics of these concrete such as desiccation shrinkage, fragility and elastic modulus. The durability of concrete seemed to be improved with this replacement rate, which was assumed to be limited to 20% of RA [7]. Issa and Salem [7] concluded that the use of less than 25% of RA as a substitute for crushed sand favors its use in the manufacture of VC. Again, use of RA is still limited, for example, to non-structural elements, clean-up concrete and concrete for curbs and manholes. Despite some negative effects such as a decrease in compressive and tensile strength, the concretes tested in the research by Anh Cuong Ho et al. [8], concerning the effect of incorporating RA on the properties of VC, showed a great improvement in the deformation capacity with a favorable impact on concrete cracking. In their research, they recommended the possibility of using rubber concrete in large areas without joints as in the case of pavements. According to the results reported in the literature the average diameter of the RA seemed to have an influence on the mechanical properties of the concrete that were better in the case of fine RA (0/2 and 0/3) compared to coarse RA (3/8 and 8/15). In the work of Fedroff et al. [9] and Medine et al. [10], the variations in the evolution of mechanical resistance were justified by the low rigidity of fine RA and by a poor interaction between these particles and the cement paste. On the other hand, for SCC, according to Corinaldesi and Moriconi [11], the use of RA contributed to the development of new concretes with the modification of the fresh and hardened properties of SCC. Aslani et al. [12] noted an improvement in the mechanical properties of SCC based on fine RA compared to those based on coarse RA. However, Najim and Hall [13] showed that RA added to SCC components can reduce the spread of the fresh mix and improve thermal and acoustic insulation. Turatsinze and Garros. [14] found that the density of RA-based SCC was inversely proportional to the substitution rates of these aggregates. This result is directly related to the low density of the rubber material present in the concrete as well as the occluded air content created in the same concrete. The study of the effect of RA size on the general durability indicators (porosity and capillary absorption) of concrete was

an important factor in the investigations of Giedrius and Dzigita [15]. The values of porosity and capillary absorption obtained from test results measurements were greater for SCC based on coarse RA than for powder RA-based concretes. Giedrius and Dzigita research [15] showed that with higher rubber content in concrete, the relative pores and capillary wall thicken and the available pore space decreases. To Rahman et al. [16], the use of RA in SCC enabled to increase the value of the dynamic elastic modulus of these concretes compared to those without rubber. The thermal conductivity of rubberized concretes was also reduced [17].
In a previous study, Saleh et al. [21] elaborated an optimal SCSC formulation and showed the effectiveness of such concrete in the field of SCCs. This work was an extension of a research program on the use of SCSCs in concrete constructions. The main objective was to use a similar formulation [21] by adopting a partial replacement of the natural fine and/or coarse aggregates by RA of the same granular class to obtain a rubberized self-compacting sand concrete (RSCSC). This provided several key properties of fresh and hardened SCC. The physical properties of the fresh RSCSC were examined by performing slump-flow tests, spreading tests, t_{500} tests, sieve stability and air-entrained content tests. In the hardened state, the mechanical and thermal properties of these RSCSC were also determined by tests of the bending tensile strengths and compressive strengths, density, the dynamic elastic modulus and thermal conductivity. The validation of the RSCSC elaborated was assessed and porosity and capillary absorption tests were carried out. Besides the contribution of the use of waste rubber to the reduction of environmental pollution, the elaborated concrete was marked both in the fresh state by the inherent suitability for complex reinforcement and formwork geometries used in concrete constructions and in the hardened state, regarding the good mechanical properties.

MATERIALS AND METHOD

Cement

The cement used in the making of the concretes is of the type CEM I 52.5 R, manufactured according to the Algerian standard NA 442-2013 [18]. The Blaine specific surface area and the absolute density of the cement were equal to 368 m^2/kg and 3150 kg/m^3, respectively. Besides, the characteristic compressive strength was equal to 55 MPa at 28 days [19]. The chemical and mineralogical compositions of the cement are presented in Tab. 1.

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	Cl	Insoluble residue	Loss on ignition	C_3S	C_2S	C_3A	C_4AF
63.0	18.9	5.8	4.2	1.1	0.44	0.60	3.5	0.06	0.3	1.2	64	15	8	12.6

Table 1: Chemical and mineralogical composition of cement (%)

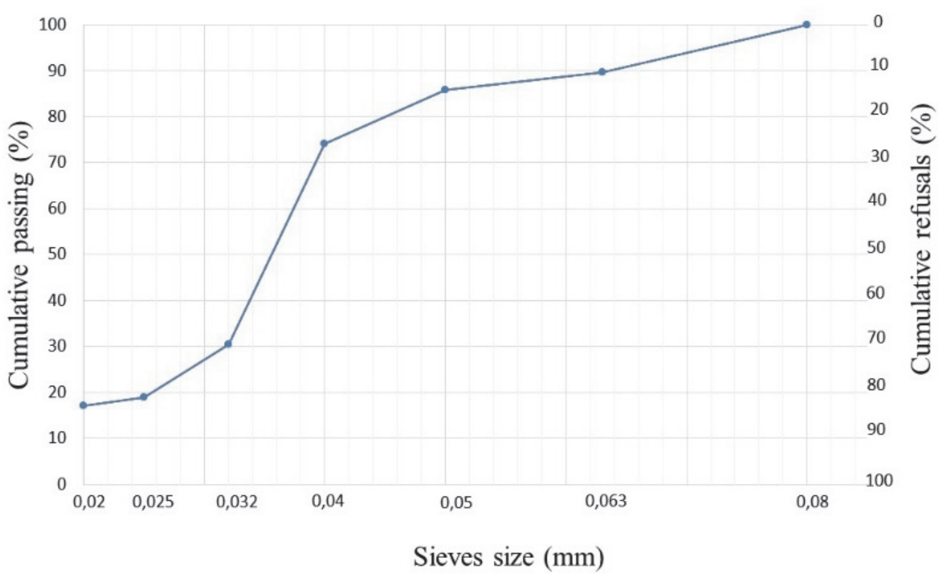


Figure 1: Sedimentometry particle size analysis of limestone fillers (ϕ < 80µm).

Limestone fillers LF

The fillers were extracted from a natural limestone rock of neritic origin, located in the East of Constantine (North-East of Algeria). This rock was selected and then crushed on the deposit site [20]. Only fine limestone with a size of less than 80 µm was selected. The fillers were introduced into the concrete mixtures as an addition whose sedimentometry particle size analysis is given in Fig. 1 and average diameter was 40 µm. The chemical composition of the limestone fines is presented in Tab. 2 and the physical characteristics of the materials used are reported in Tab. 3.

$CaCO_3$	CaO	SiO_2	Na_2O	MgO	AI_2O_3	Fe_2O_3	K_2O	P_2O_5 TiO_2	Loss on ignition	Insoluble residue
98	55.77	0.13	0.01	0.20	0.02	0.04	0.03	0.010	43	1.15

Table 2: Chemical composition of limestone fillers (%).

materials	cement	LF	QS	CS	NG	Rubber	Superplasticizer
Absolute density kg/m^3	3150	2700	2530	2600	2600	980	1.070
Apparent density kg/m^3	1090	980	1880	1640	1690	411	1.057
Sand equivalent SE	-	-	85.0	81.4	-	-	-
Fineness modulus FM	-	-	2.49	3.18	-	-	-

Table 3: Physical characteristics of materials.

Natural Aggregates

Quartz Sand (QS) with a maximum diameter of 2 mm was sourced from the Kristel quarry located in the North-Eastern region of Oran (Algeria). Three grades of crushed calcareous coarse aggregates were used. The first one was limestone Crushed Sand (CS) with (0/3) mm in size and the other two were crushed Natural Gravel (NG) with two sizes, namely (3/8) and (8/15) mm. The crushed sand and gravel was supplied from a quarry located in Sidi-Bel-Abbes (South-West of (Algeria). The physical characteristics of the aggregates are also summarized in Tab. 3 and the grading curves of the aggregates and are shown in Fig. 2.

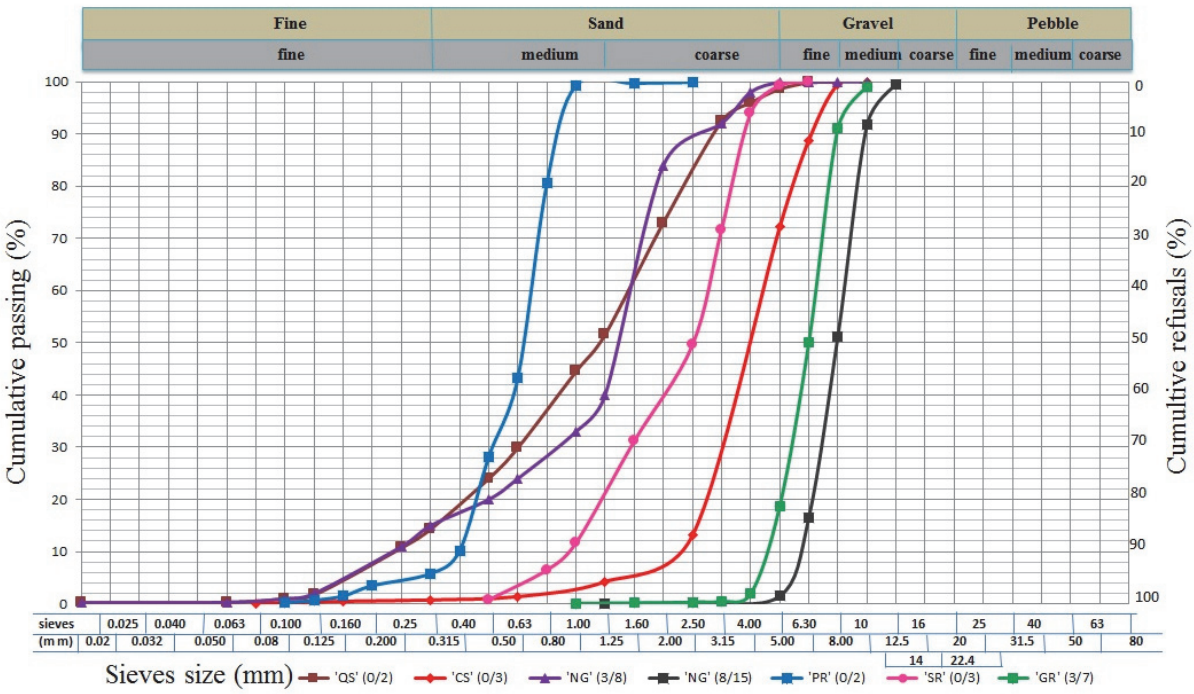


Figure 2: Size analysis of natural and artificial (rubber) aggregates - CS, QS, NG (3/8), NG (8/15), GR (3/7), PR (0/2), SR (0/3)

Artificial Aggregates

Fig. 3 gives an overall composition of tyres used for trucks and cars. The rubber aggregates (RA) were obtained by grinding and shredding used tyres. These aggregates are in the form of coarse rubber grains or Gravel Rubber (GR) (3/7), Powder Rubber (PR) (0/2) and fine rubber grains or Sand Rubber (SR) (0/3). Fig. 4 illustrates the different grain sizes and shapes of the ground and/or shredded rubber used in this study. The shredded grains have a clear angular shape. The aggregates size analysis are also shown in Fig. 2 and the physical characteristics of materials are detailed in Tab. 3.

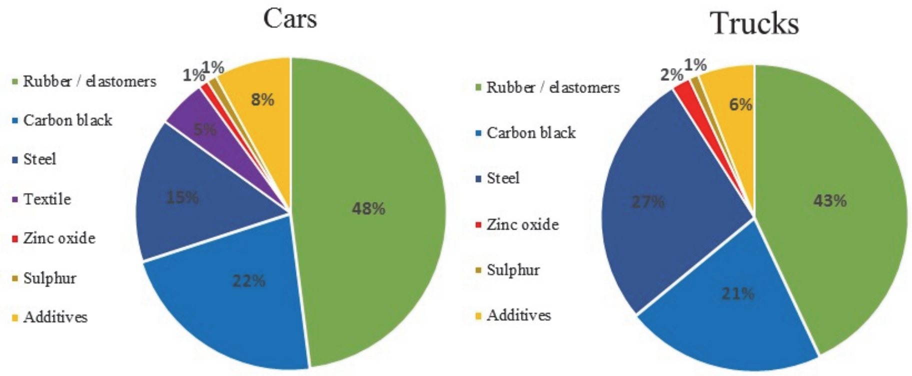
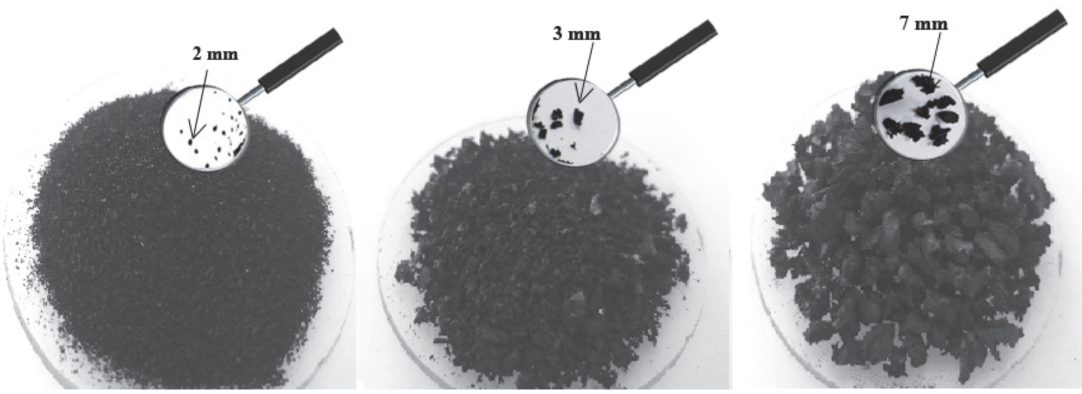


Figure 3: Overall composition of cars and trucks tyres [21]



a) Powder Rubber (PR) (0/2). b) Sand Rubber (SR) (0/3). c) Gravel Rubber (GR) (3/7)

Figure 4: Particle sizes and irregular shape of grain rubber

Admixtures

A high performance third generation Superplasticizer (SP) was used, whose physical properties are exhibited in Tab. 3. According to EN 934-2 standard [21], the superplasticizer is mainly consisting of poly-carboxylate ethers (PCE). This significantly improves the properties of the concrete, reduces the water content without altering the consistency of the concrete. In addition, this agent has no retarding effect on the curing.

Water for mixing

The water used for the manufacture of concrete is tap water supplied by the water and sanitation company (SEOR) of Oran (Algeria). Tab. 4 gives the details of the physical and chemical properties of this water.

Ca mg/l	Cl mg/l	Toughness mg/l	Dry residue mg/l	SO_4 mg/l	NH_4 mg/l	NO_3 mg/l	NO_2 mg/l	Al mg/l	Mg mg/l	Oxidability mg/l	pH at 20°C UPH	Density g/cm^3
56.0	425.6	393	839	11.07	0.56	51	0.24	0.25	43	5.99	8.25	1

Table 4: Physical and chemical properties of the water used

Preparation of the concrete mixtures

Fourteen concrete mixes were selected and elaborated in this study in addition to the ordinary vibrated concrete (VC). Another reference concrete design mix which (a self-compacting sand concrete SCSC developed by Saleh et al. [22]) was also used after being improved, adjusted and adapted to the selected materials in the experimental work herein. For the same cement dosage and W/C ratio as for the SCSC, the twelve other concrete design mixes - made from the SCSC composition described above - were divided into three series. In the first series of concrete mixture composition, quartz sand (QS) (0/2) was replaced by powder rubber (PR) (0/2). In the second series, crushed sand (CS) (0/3) was replaced by the rubber grains noted sand rubber (SR) (0/3). Finally, in the third series, the (NG) (3/8) is replaced by (GR) (3/7). Each set of concrete mixtures consisted of four compositions, each of which was obtained by replacing 5, 10, 15 and 20% by volume of the natural aggregates with recycled rubber aggregates, separately. Tab. 5 shows the different compositions of all concretes.

Mix (kg/m³)	Cement	LF	PR (0/2)	SR (0/3)	GR (3/7)	QS (0/2)	CS (0/3)	NG (3/8)	NG (8/15)	SP	W	$W_{effective}$	G/S	$w_{effective}/C$
VC	350	-	-	-	-	405	608	132	512	-	210	200	0.635	0.57
SCSC	420	200	-	-	-	439	730	292	-	14.5	210	211	0.213	0.5
SCSC PR 5%	420	200	8.5	-	-	417	730	292	-	14.5	210	210	0.215	0.5
SCSC PR 10%	420	200	17	-	-	395.1	730	292	-	14.5	210	211	0.217	0.5
SCSC PR 15%	420	200	25.5	-	-	373.2	730	292	-	14.5	210	211	0.219	0.5
SCSC PR 20%	420	200	34	-	-	351.2	730	292	-	14.5	210	211	0.222	0.5
SCSC SR5%	420	200	-	13.7	-	439	693.5	292	-	14.5	210	211	0.216	0.5
SCSC SR 10%	420	200	-	27.5	-	439	657	292	-	14.5	210	211	0.220	0.5
SCSC SR15%	420	200	-	41.3	-	439	620.5	292	-	14.5	210	211	0.224	0.5
SCSC SR 20%	420	200	-	55	-	439	584	292	-	14.5	210	211	0.228	0.5
SCSC GR 5%	420	200	-	-	5.5	439	730	277.4	-	14.5	210	210	0.201	0.5
SCSC GR 10%	420	200	-	-	11	439	730	262.8	-	14.5	210	211	0.190	0.5
SCSC GR 15%	420	200	-	-	16.5	439	730	248.2	-	14.5	210	211	0.179	0.5
SCSC GR 20%	420	200	-	-	22	439	730	233.6	-	14.5	210	211	0.167	0.5

Table 5: Concrete composition according to rubber grain substitution rates (5, 10, 15 and 20%)

Samples' preparation

378 concrete samples were elaborated for all experimental tests. 42 prismatic (7x7x28 cm³) samples were prepared for the three-point bending tensile strength tests according to European standard EN 12390-5 [54] carried out only at 28 days. 126 cubic (7x7x7 cm³) samples were intended - according to European standard EN 12390-4 [55] - for the determination of compressive strength tests at 7, 28 and 365 days. 84 cubic (7x7x7 cm³) samples were used for the determination of dynamic elastic modulus, according to the American standard ASTM C597-02 [56] at 28 and 365 days. The thermal conductivity tests - carried out according to ASTM D 5334 [57] - also required 84 cubic (7x7x7 cm³) samples at 28 and 365 days. Conversely, the porosity tests that were performed according to ASTM C642 [58] and the capillary absorption tests performed according to AFREM 97 [59] required 42 cubic (7x7x7 cm³) samples for each test performed after 28 and 365 days of humid curing. Arithmetic mean value - obtained on three samples for each test performed on the concrete samples - was established with a standard deviation of less than 8%.

Test methods: Fresh state

The evaluation of the effects of rubber aggregates (RA) on the fresh properties of concrete was investigated by carrying out the apparent spread and viscosity tests according to EN 12350-8 [23], the L-box tests according to EN 12350-10 [24], the sieve stability tests according to EN 12350-11 [25] and the measurement of the occluded air content according to EN 12350-7 [26]. Tab. 6 gives the standard ratings for these tests, as specified in the recommendations of the AFGC [27], EFNARC [28] and EN 206-9 [29].

Test	Spreading Slump-flow (mm)	t_{500} (s)	L–Box (H_1/H_2)	Sieve stability (%)	Air content (%)
EN 206-9 / 2010	660 to 750 SF2 760 to 850 SF3	≥ 2 VS2	≥ 0.8 PL2	≤ 15 SR2	-
AFGC / 2008	660 to 750 SF2 760 to 850 SF3	6	≥ 0.8	≤ 15	-
EFNARC / 2002	650 to 800	2 to 5	0.8 à 1	5	2

Table 6: Limits of fresh test values for SCC according to AFGC [27] , EFNARC [67] and EN 206-9 [29]

Test methods: Hardened state

The physical-mechanical, thermal and durability performances of the concretes at the short and long term were measured by carrying out compressive tests according to EN 12390-4 [30], three-point bending tension tests according to EN 12390-5 [31] and ultrasonic pulse velocity UPV tests according to ASTM C597-02 [32] from which the values of dynamic elastic modulus were determined from the relationship of Krishna Rao et al [33] given by the following equation:

$$E_d = \frac{\rho.(UVP)^2.(1+\mu)}{(1-\mu)} \tag{1}$$

where, E_d is the dynamic elastic modulus in MPa, ρ is the density of the concrete in kg/m^3, UPV is the ultrasonic pulse velocity in Km/s and μ is the Poisson's ratio of the concrete. The thermal conductivity test was carried out according to ASTM D 5334 [34], using the QTM-D3 device with a probe (thermistor) that measures thermal conductivity. The porosity and the capillary absorption tests were carried out according to the recommendations ASTM C642 [35] and AFREM 97 [36], respectively. The two general durability indicators (porosity and capillary absorption) were determined by using the results obtained from these two tests. The capillary absorption coefficient was determined using equation[37]:

$$Ca(t) = \frac{M_t - M_0}{S} = A\sqrt{t} \tag{2}$$

where *Ca(t)* is the capillary absorption in (kg/m^2), M_t is the mass of the sample at time *t* in kg, M_0 is the initial mass of the sample in kg, *S* is the sample area in m^2 and *A* is the absorption coefficient $kg/m^2s^{1/2}$.

RESULTS AND DISCUSSIONS

Fresh state

The properties of the different compositions of fresh concrete are shown in Tab. 7. The results clearly show that the spread values obtained for all the concrete formulations verify the consistency classes (SF2) and (SF3) specific to self-compacting concretes required by the recommendations of the AFGC [27], EFNARC [28] and EN 206-9 [29] prescribed in Tab. 7. The values of the spread values varied between 710 mm (minimum value) and 800 mm (maximum value) for a variation of 11%. These concretes can therefore be classified as self-compacting concretes. Compared to the SCSC reference concrete, the substitution of 5% rubber (5% GR, 5% PR or 5% SR) contributed to a decrease in workability of 2.56, 3.85 and 8.97%, respectively. For the same substitution rate, the concretes workability was inversely proportional to the diameters of the rubber grains. However, this property remained comparable for the two mixtures SCSC and SCSC PR10%. The workability of SCSC SR was improved and reached an increase of 1.28% when compared to that of SCSC. On the other side, it decreased in the case of SCSC GR. For the higher substitution rates (15 and 20%) of rubber, an identical improvement of 2.56% was observed for SCSC PR and SCSC SR. However, SCSC GR contributed to decrease this workability by 7.7% (see Fig. 5). In general, an improvement of the workability of concretes with high rubber grain content was noticed.

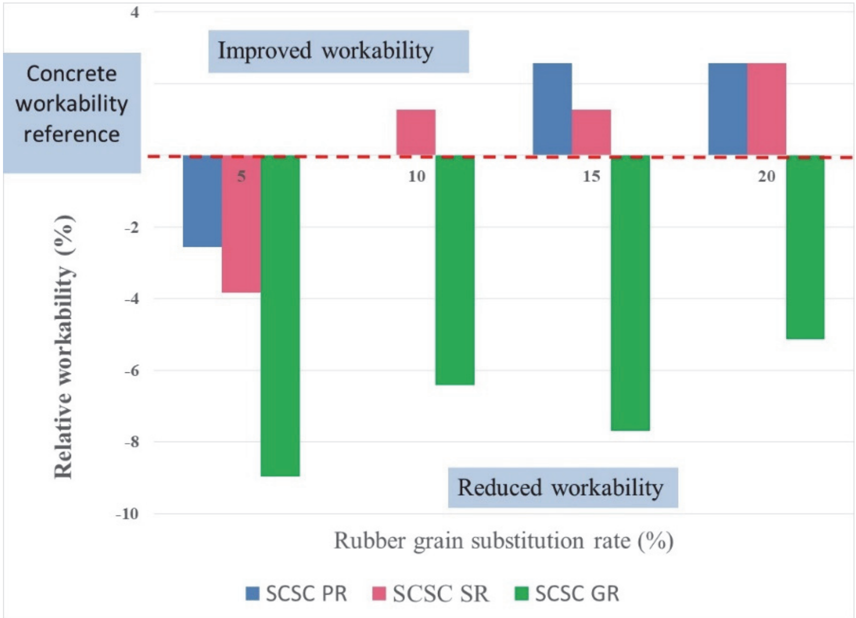


Figure 5: Relative workability (in %) of different concretes mixtures compared to reference concrete SCSC

The apparent viscosity tests - determined by measuring the time t_{500} needed to reach a flow diameter of 500 mm - varied between 3.68 and 4.92 seconds. The lowest t_{500} time was attained for the 15% SCSC PR mixture and the highest t_{500} time was achieved for the 5% SCSC GR mixture. The values of the results were close to the upper limit, specified by the AFGC [27] and EFNARC [28] recommendations. Furthermore, the t_{500} only controled apparent viscosity class VS2, as per EN 206-9 [29]. Fig. 6 shows a sharp overall decrease in viscosity (t_{500}) for all concrete compositions. The decrease in viscosity was more marked when using powder rubber (PR) and/or sand rubber (SR).

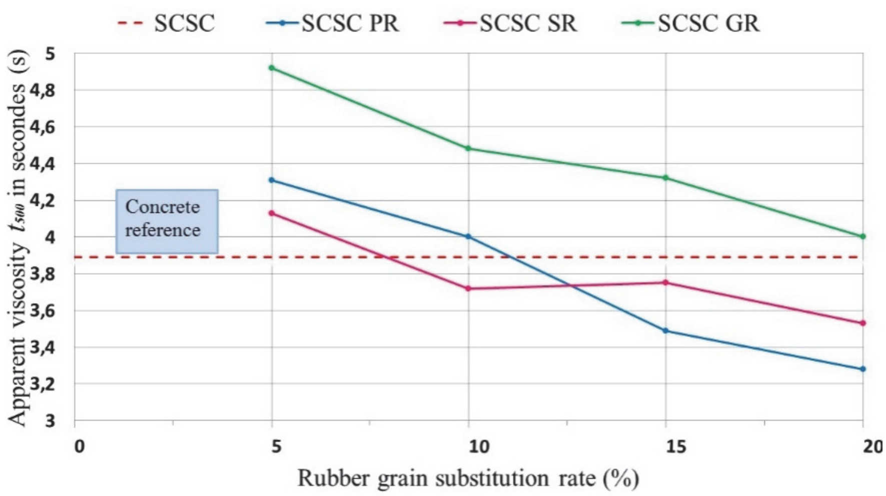


Figure 6: Apparent viscosity evolutions (t_{500}) of SCSC and rubberized concretes (SCSC GR, SCSC PR and SCSC SR) for different substitution rates.

The results were confirmed by the spreading tests results mentioned in the previous paragraph. The values of the concrete L-box fluidity tests - ranging between 0.81 and 1 – complied with the limits prescribed in Tab. 7. Therefore, the concretes were characterized by a fluidity of class PL2, according to EN 206-9 [29]. Also, all concrete compositions were distinguished by a visual absence of segregation.

Mix	Slump flow Spreading (mm)	Classes NF EN 206-9	t_{500} Time (s)	Classes NF EN 206-9	L – Box H_1/H_2	Classes NF EN 206-9	Sieve stability (%)	Classes NF EN 206-9	Air content (%)	density (kg/m³)
VC	110	slump	-	-	-	-	-	-	1.9	2297.88
SCSC	780	SF3	3.89	VS2	1.00	PL2	**0.88**	SR2	1.8	2306.12
SCSC PR5%	760	SF3	4.21	VS2	0.85	PL2	0.92	SR2	1.9	2292.64
SCSC PR10%	780	SF3	4	VS2	0.90	PL2	1.00	SR2	2.1	2279.23
SCSC PR15%	800	SF3	3.68	VS2	1.00	PL2	1.77	SR2	2.3	2265.30
SCSC PR 20%	800	SF3	3.78	VS2	1.00	PL2	1.86	SR2	3.0	2251.92
SCSC SR5%	750	SF2	4.13	VS2	0.81	PL2	1.20	SR2	2.8	2283.10
SCSC SR10%	790	SF3	3.92	VS2	0.89	PL2	1.28	SR2	3.0	2260.13
SCSC SR15%	790	SF3	3.85	VS2	1.00	PL2	1.39	SR2	3.2	2237.17
SCSC SR20%	800	SF3	3.53	VS2	1.00	PL2	1.82	SR2	3.5	2215.34
SCSC GR5%	710	SF2	4.92	VS2	0.89	PL2	**2.34**	SR2	2.5	2297.03
SCSC GR10%	730	SF2	4.48	VS2	0.90	PL2	2.14	SR2	2.9	2287.51
SCSC GR15%	720	SF2	4.62	VS2	1.00	PL2	2.17	SR2	2.8	2278.20
SCSC GR20%	740	SF2	4.51	VS2	1.00	PL2	1.32	SR2	3.0	2269.07

Table 7: Physical properties and Consistency classes of concrete mixtures - VC, SCSC, SCSC GR, SCSC PR and SCSC SR in the fresh state. * Figures in bold correspond to maximum and minimum values.

The results of the segregation and flow resistance, using the sieve stability tests, indicate that all mixtures complied with the limit values recommended in Tab. 7. The values obtained varied between 0.88 and 2.34%. The latter segregation resistance values were always below the limit value of 5%, according to the EFNARC recommendations [28] for the classification of concretes in accordance with EN 206-9 [32]. In the study of Topçu et al. [38], it was generally stated that the fluidity of SCC containing rubber aggregates increased in proportion to the aggregate substitution rates.

The air contents of the concrete mixtures were proportional to the rubber substitution rates. The air content values of the tested concrete mixtures ranged between 1.8 and 3.5%. These values were deemed acceptable, according to EFNARC recommendations [28]. It seemed that this increase depended on the shape and size of the rubber aggregates used. The highest value of occluded air content was recorded for RSCC. This increase is more marked in the case of SCSC SR ($\phi_{caoutchouc}$ $\leq$ 3 mm). This finding was confirmed at separate periods by Fedroff et al. [9] and Medine [39]. They both showed that coarse rubber caused an increase in air content due to the size and rough surface of the macromolecule which may contain air bubbles in the folds of its irregular shape [9] [39]. The irregular and rough shapes of the rubber grains in the present work were confirmed above by the illustrations in Fig. 4.

Hardened state: Flexural strength

The results of the flexural strength tests (f_{tk}) at 28 days are shown in Fig.7. It is worth noting that the flexural strengths evolution (see Fig. 7) was quasi-linear and exhibited negative slopes (downward curves) because the evolution of these strengths was inversely proportional to the substitution rates of the rubber grains. All the values of these strengths remained higher than those of the vibrated concrete (VC). They remained very close to those of SCSC only for the 5% rubber substitution rate. The uncombined use of the three aggregate classes (GR, PR and SR) at substitution rates 5 to 20% revealed that the highest tensile strengths were reached for concrete on powder rubber-based (SCSC PR). On the other hand, and as shown in Fig. 7, the rubber sand concrete SCSC SR developed the lowest strengths compared to other types of rubberized concrete carried out in this study. The flexural strengths decreased by 4.5, 9.3, 11.0 and 12.0% in the case of the replacement of natural sand by rubber sand at rates of 5, 10, 15 and 20%, respectively.

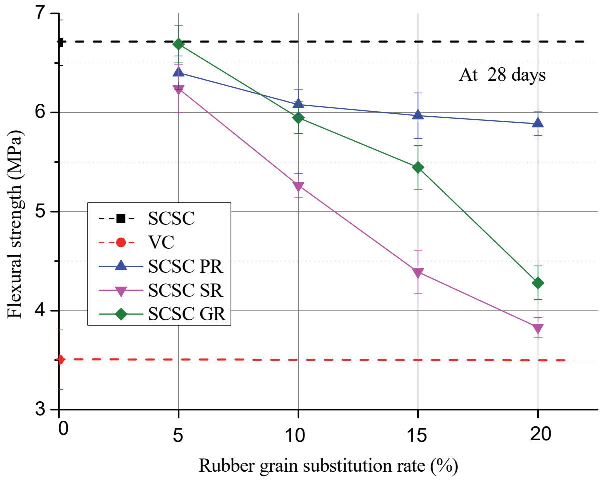
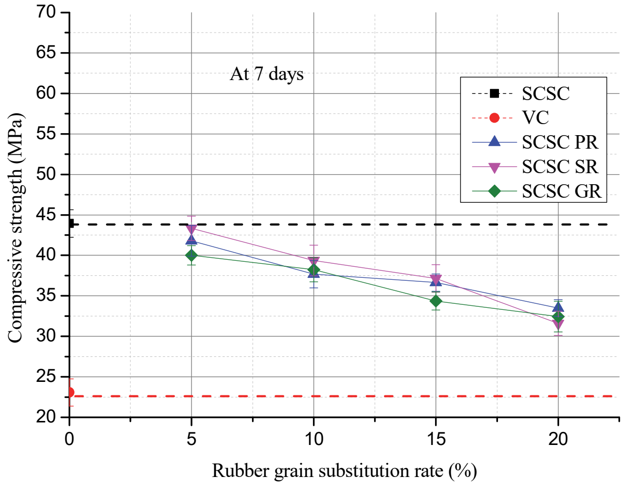
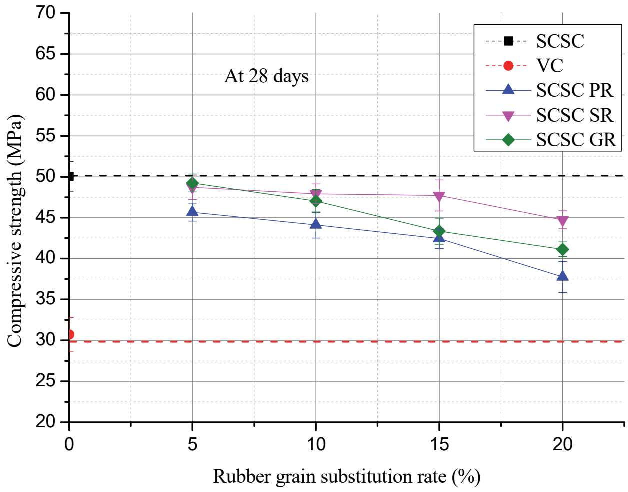


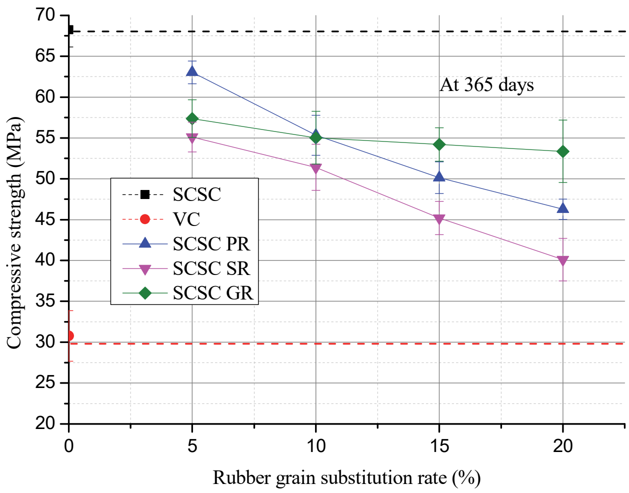
Figure 7: Flexural strength evolution of concrete mixtures (VC, SCSC, SCSC GR, SCSC PR and SCSC SR) vs. rubber substitution rate (in %) after 28 days of curing period.



a) At 7 days.



b) at 28 days.



c) At 365 days.

Figure 8: Compressive strength evolution of concrete vs. rubber substitution rate (in %)

A more significant decrease in this strength was recorded for SCSC SR compared to SCSC PR with the same content rubber. Drops in strengths of 0.1, 11.2, 18.6 and 36.11%, respectively, were recorded for SCSC GR for the same substitution rates rubber, calculated with respect the strengths of the SCSC reference concrete. The changes in flexural strength values obtained in the present experimental work converged with those values reported by Si et al. [40]. The latter found that the modification of concrete compositions by substitution of rubber played a key role in the reduction of the three-point bending tensile strength. In turn, Albano et al. [41] noticed that coarse rubber aggregates showed a negative effect on flexural strength compared to compressive strength. The powder rubber developed lower strength drops than coarse rubber aggregates [38]. In the cases studied herein, and for low rubber content, the flexural strengths were identical. However, for high substitution rates of 20%, a difference (Δf_{tk}) was clearly marked between the tensile strengths of the two (SCSC GR and SCSC PR) concretes and amounted to 1.6 MPa. The strength loss was compensated between SCSC PR and SCSC SR. This was illustrated by a strength gain of almost 2 MPa. All flexural strength values were higher than VC and lower than SCSC. The improvement of the flexural strength of the SCSC GR concretes was mainly due to the sharp irregular form of the grains, which fitted perfectly in the cement matrix. This feature can expand without tearing off in the case of the application of tensile stresses, as it was already confirmed by Segre et al. [42] in their study on the influence of crack propagation and failure in rubber-based concrete.

Hardened state: Compressive strength

The results obtained from the compressive strength tests after 7, 28 and 365 days are illustrated in Fig. 8. Generally, all the compressive strengths of the SCSCs belonged to the same strength class. At 7 days, the strengths varied between 30 MPa and 40 MPa and at 28 days, between 35 MPa and 50 MPa. However, they increased from 45 MPa to 65 MPa, after one year of water curing. All the compressive strengths values were always lower than those of SCSC and higher than VC ones.

The values of the ratios between the compressive strength (f_c) of each concrete at time (t) expressed in days and those of the concrete at 28 days (f_{ck}) are shown in Fig. 9 for the different rubber contents. At the age of 7 days, the results showed a reduction in compressive strength with increasing rubber content in the case of powdered concrete and sand. However, in the case of gravel rubber concrete, this ratio remained constant.

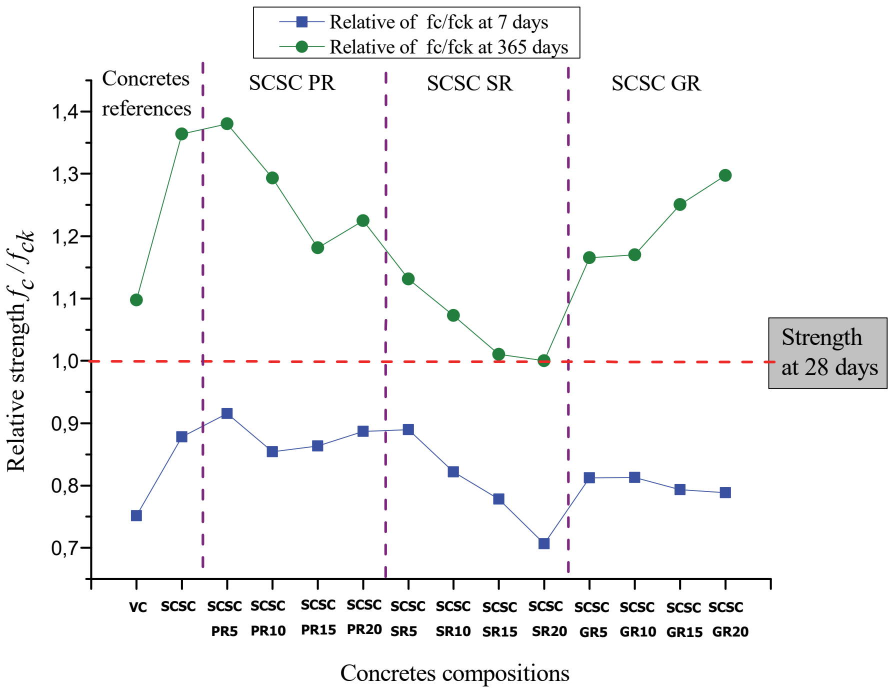


Figure 9: Relatively compressive strengths fc/fck at 7 and 365 days of concrete compositions - VC, SCSC, SCSC GR, SCSC PR and SCSC SR.

For the one-year age, the results showed a clear increase in relative strengths vs. rubber contents introduced into the concrete. However, it should be noted that the reduction in compressive strength of RSCSC was only marked in the case of rubber powder (RP) and sand rubber (SR). However, this trend was reversed in the case of gravel rubber (GR) which confirmed the role and effect of the rubber grain size in the elaborated concretes. It seems that gravel rubber was suitable for the increase of long-term compressive strengths. For instance, the relative compressive strength ratio (f_{c365d}/f_{ck}) for powdered concrete mixtures varied from 1.38 to 1.22 in decreasing order. This order was reversed in the case of GR where these ratios varied from 1.16 to 1.30.

The relative strength at one year gave optimal and equivalent compositions. A rate of 10% PR can be replaced by 20% GR to obtain concretes with the identical efficiency. Other compositions showed the same efficiency coefficients (20% PR can replace 15% GR) and/or (15% PR can replace 5 to 10% GR). This behavior can be attributed to two factors: (i) the rubber particles were tighter (softer) than the cement-based matrix and the inability of the rubber material to withstand stress due to the associated low compressive strength and (ii) because it was considered that the rounded grain shapes of the rubber in the concrete were converted into oval shapes under compression, which caused tension cracks in the cement matrix.

The decrease in compressive strength of rubber-based concretes was strongly related to the increase in content rubber which was in agreement with the available literature results [43] [44] [45] and [13]. Khatib et al. and Aslani et al. [6] [12] found that coarse sizes grains rubber (5 and 10 mm) improved the strengths compared to the other small grains.

It should be emphasized to specify that unlike SR, the compressive strength of SCSC depended on the nature and quantity of sand, which contributed positively contributed in that improvement.

Density

Fig. 10 shows a clear evolution of the density that was inversely proportional to the rubber contents incorporated in the concrete. All the concretes exhibited lower densities than the reference concretes (SCSC and VC). The values of these densities were closer to the upper range of the densities of lightweight concretes. This will allow them to be considered as lightweight concretes. The drop in the density of SCSC PR concrete compositions reached 1.8% between 5 and 20% of the powder rubber. This difference reached 2.4% between SCSC PR20% and the reference concrete SCSC.

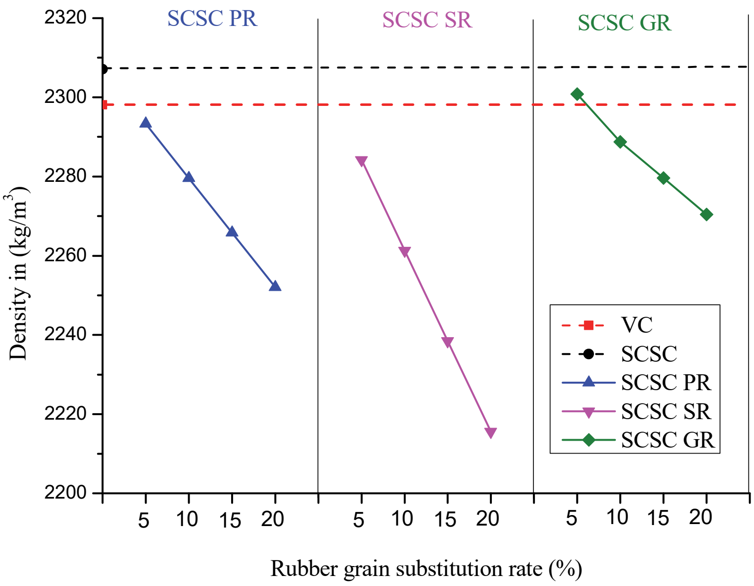


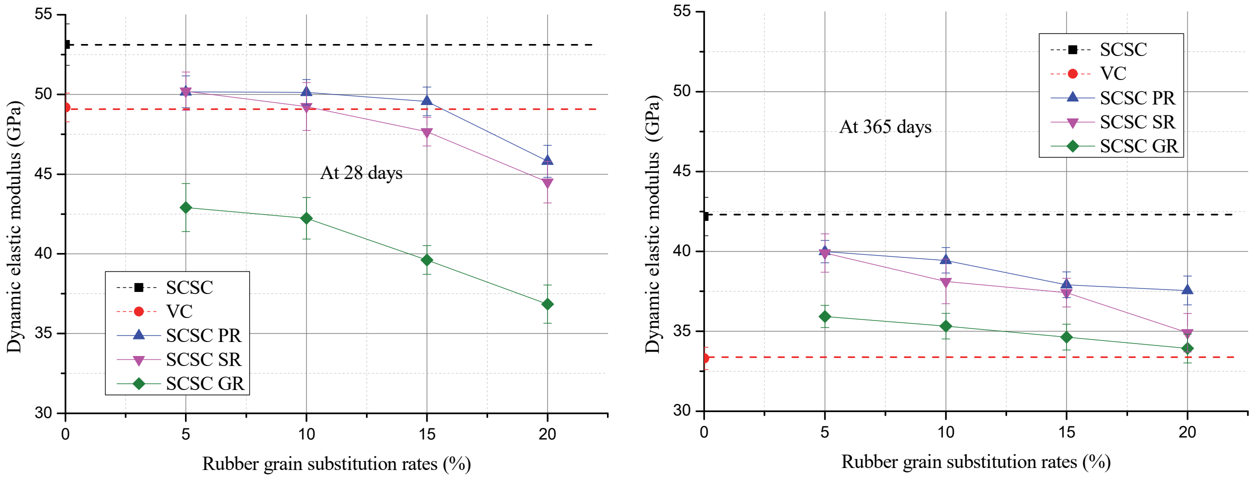
Figure 10: Concretes densities (in kg/m³) evolution vs. rubber substitution rate (in %)

This difference came to 3% in the case of SCSC SR and to 4% between SCSC SR20% and SCSC concretes. Whereas, these differences were narrowing to 1.3% in the case of 1.6% SCSC GR and between 20% of SCSC GR20 and SCSC concretes. Globally, it was observed that the largest kinetics decrease was experienced in the case of SCSC SR compared to other concretes. This was associated with the quantity of quarry sand, which was regarded as the most influencing factor on the weight of SCSCs.

Dynamic elastic modulus

The variation of dynamic elastic modulus values of underwater cured concretes was determined after 28 and 365 days of curing, as shown in Fig. 11. After 28 days of curing, the values of this modulus were inversely proportional to the rubber contents. Relative variations in the dynamic elastic modulus values of the SCSCs were calculated. These values decreased by 5.6, 5.7, 6.7 and 13.8% in the case of SCSC PR concrete mixtures with rubber powder substitution rates of 5, 10, 15 and

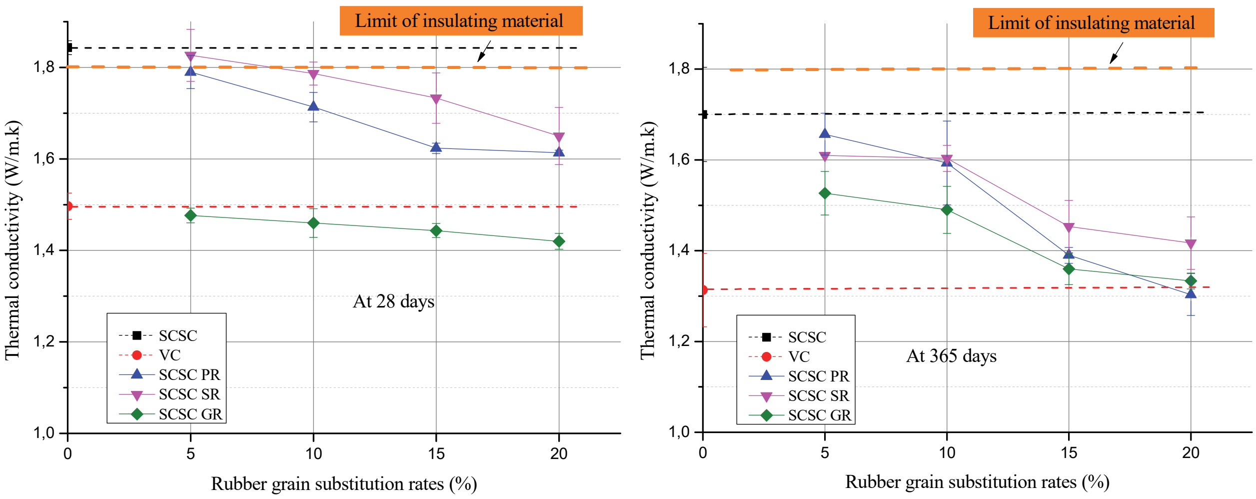
20%, respectively. For the SCSC SR concrete samples, the decreases were similar to those of the SCSC PR ones. They were equal to 5.5, 7.3, 10.3 and 16.2%, respectively. Finally, for the SCSC GR concretes samples, these decreases became larger and more significant. They increased from the initial value and reached percentage values of 19.2, 20.5, 25.4 and 30.6%, respectively. These evaluations confirmed the hypothesis of the influence of the size of the coarse rubber grains on the dynamic elastic modulus.



a) at 28 days of curing period under water. b) at 365 days of curing period under water.

Figure 11: Dynamic elastic modulus variation (in GPa) for concretes samples vs. rubber content.

As a whole, the decreases in the modulus values remained between 13 and 30% for all concrete compositions. These decreases were consistent with the results obtained by Rahman et al. [16] who reported drops in the dynamic elastic modulus between 10 and 20% for rubberized self-compacting concretes. After 365 days of curing, all concrete mixtures showed a net decrease in the values of the dynamic elastic modulus, which reached a difference of 8 to 11 GPa compared to those obtained after 28 days.



a) at 28 days of curing period under water. b) at and 365 days of curing period under water.

Figure 12: Thermal conductivity evolution of concrete samples (VC, SCSC, SCSC GR, SCSC PR and SCSC SR) vs. rubber content

Thermal conductivity

Fig. 12 shows the evolution of the thermal conductivity of the concrete mixtures vs. substitution rates at 28 and 365 days of curing. Regardless of the hydration time of the concretes, the evolution of the conductivity was inversely proportional to the rubber content and the size of the rubber grains. Globally, all thermal conductivity values were between 1.22 and 1.6 W/m.k and remained below the upper range given for the theoretical thermal conductivity values reported in Tab. 8 [46]

[47]. The SCSC GR recorded the lowest thermal conductivity values and the closest ones to those obtained in the VC case. Yet, the obtained values of SCSC PR and SCSC SR remained quite close but were still lower than those obtained for SCSC. For the long-term properties and in comparison with those obtained after 28 days, a decrease in the range of 13% and 18% was recorded for the thermal conductivity value when compared to SCSC PR and SCSC SR with 15 and/or 20% rubber.

Materials	Thermal Conductivity W/(m.k)
lightweight Concrete	0.1 - 0.3 [46]
medium Concrete	0.4 - 0.7 [46]
dense Concrete	1.0- 1.8 [46]
Limestone aggregates	1.26 - 1.33 [46]
Rubber (Belgium)	0.17 [46]
Rubber (Oran-Algeria)	0.16
Quartz Sand	3 [47]

Table 8: Thermal conductivity values of common materials [46] [47].

It seemed reasonable in [46] [47] that the value of the thermal conductivity was higher for concrete incorporating natural aggregates whereas lower thermal conductivity values was obtained for concrete incorporating rubber aggregates. For the sake of comparison, Tab. 8 shows the theoretical values of the thermal conductivities of the usual materials with the exception of the value assigned to rubber from the Oran region of Algeria, which was 0.16 W/(m.k). The lowest value was the thermal conductivity of an insulating rubber material. Partial replacements of quartz sand (QS) (λ = 3), crushed sand (CS) and natural gravel (NG) (λ = 1.3) with rubber led to a decrease in thermal conductivity of 94% for QS and 87% for CS and calcareous NG.

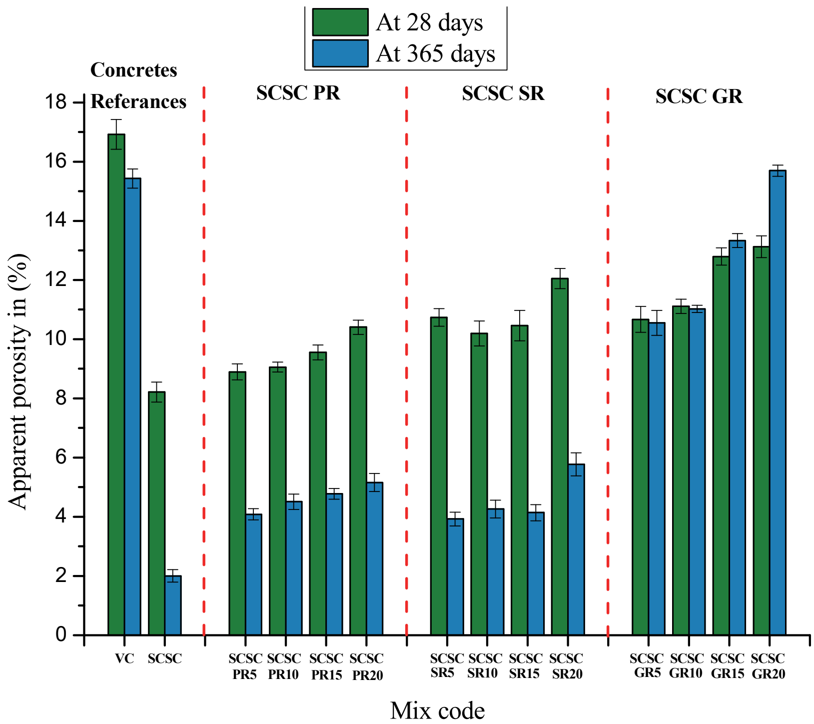
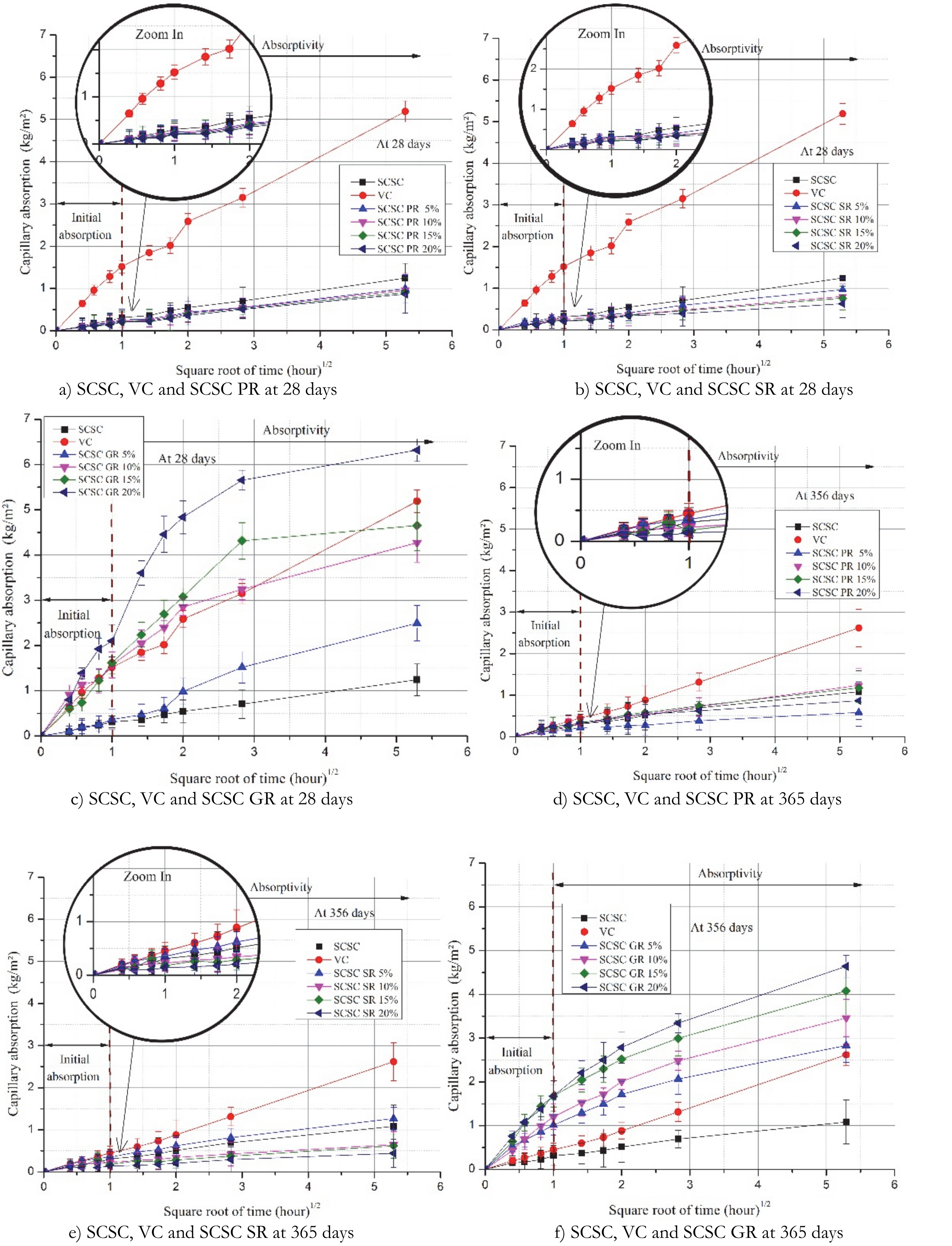


Figure 13: Evolution of the apparent porosity of concrete mixtures at 28 and 365 days of curing period under water



a) SCSC, VC and SCSC PR at 28 days

b) SCSC, VC and SCSC SR at 28 days

c) SCSC, VC and SCSC GR at 28 days

d) SCSC, VC and SCSC PR at 365 days

e) SCSC, VC and SCSC SR at 365 days

f) SCSC, VC and SCSC GR at 365 days

Figure 14: Capillary absorption evolution of concrete vs. square root of the time at 28 and 365 days of curing period under water.

General durability indicators: Apparent porosity

The average apparent porosity values determined at 28 and 365 days for each concrete are presented in Fig. 13. SCSC, SCSC PR and SCSC SR showed the lowest calculated porosity. SCSC developed a low porosity compared to VC. This difference was due to the size and quantity of the grains used in the VC and SCSC mixtures. VC contained significant quantities of 3/8 and 8/15 aggregates. The coarse-to-fine aggregates (Gravel/Sand : G/S) ratio was equal to 0.635 for VC and 0.213 for SCSC. 8/15 crushed aggregates, which were rough and concave in shape, contributed to the formation of additional pores in the cement-based matrix. Besides, the fine grains filled the pores due to their fineness [48]. All concrete compositions prepared with rubber aggregates showed higher porosity values than those of SCSCs because the GR grains contained in the self-compacting concretes increased the porosity compared to the PR and SR grains. The reason for this porosity increase in the cement-based mixes (also observed by Garros [49]) was related to the presence of rubber aggregates in the cement-based matrix. This may further be explained by the weak bonds between the cement-based matrix and the rubber aggregates. Medine [39] also confirmed that the porosity of mixtures containing coarse rubber aggregates was much higher than those containing fine rubber aggregates and reduced voids. In the long term, the porosity values of concrete containing coarse grains were lower than those of the fine grains concretes.

General durability indicators: Capillary absorption

Fig. 14 shows the capillary absorption vs. square root of the time after 28 and 365 days of curing. For the same W/C ratio, all concretes developed similar or even identical capillary absorption (absorption kinetics or sorptivity) values, with coefficients of variation less than 8%. During the first hour, the capillary absorption kinetics of VC increased rapidly compared to that of SCSC. At the end of the test (after 24 hours), the value of the capillarity of the VC was four times higher than that of the SCSC concrete. An improvement in capillary absorption reflected by a decrease in kinetics over time was explained by the generation of hydrates contributing to the densification of the concrete elaborated. Nevertheless, when referring to the results obtained at 28 days, all the concretes maintained the same trend of evolution of the absorption at 365 days. The capillary absorption values of SCSC PR and SCSC SR concretes (Figs. 14-a, 14-b, 14-d and 14-e) remained very close to those of the SCSC (reference concrete) with very negligible differences due to low dispersions in the measurements.

The values obtained for SCSC were the maximum values (upper range) of absorption, whereas those obtained for concrete based on 20% rubber (PR and/or SR) were the minimum values (lower range). During the first hour of SCSC GR concrete, the values of the capillarity (Fig. 14-c, Fig. 14-f)) increased by 1.5 kg/m² for the 10, 15 and 20% substitution rates of in GR compared to those of the reference concrete SCSC. However for the 5% substitution in GR, the capillary absorption demonstrated values identical to those of the SCSC. After one hour (see Fig. 14), the capillary absorption continued to increase until the end of the test (after 24 hours).The capillary absorption evolved proportionally to the substitution rates and reached a minimum value of 2.5 kg/m² (5% GR) and a maximum value of 6.5 kg/m² (20% GR) compared to reference SCSC concrete. The increase in capillary absorption was associated with the evolution and increase in the rate of porosity in SCSC concrete. According to Balayssac et al. [50] and Rabehi [51], the values of the initial capillary absorption during the first hour supported the existence and formation of micro-pores. They also confirmed and explained that the second phase of absorption (1-24 hours) reflected the formation and existence of micro-pores. Beyond one hour, the slope of the absorption curves determined the sorptivity (Sc) of the material [51] [52]. In sum, GR-based concretes developed larger micro-pores and macro-pores than PR- and SR-based concretes. Low thermal conductivity values also confirmed the existence of air in the macro-pores [51] [52].

CONCLUSIONS

The present work covered the effect of incorporating waste rubber aggregates on the physical-mechanical, thermal and durability performance of self-compacting sand concrete (SCSC) mixtures. Also, Laboratory elaborated Rubberized Self-Compacting Sand Concretes (RSCSC) were implemented with three fractions of rubber grains in which natural aggregates were replaced with powder rubber (PR), sand rubber (SR) and gravel rubber (GR) using four (5, 10, 15 and 20%) addition ratios as volume rates. Based on the results obtained in this experimental work, the following conclusions can be drawn:

- The air content of the tested concrete mixtures was between 1.8 % and 3.5%. The values achieved remained acceptable according to EFNARC recommendations. The maximum increase for concrete containing SR 20% was about 80% compared to the reference concrete. The increase in air content with respect to concrete containing rubber grain depended on both the shape and size of the rubber aggregates used. The rough surfaces and the presence of macromolecules in the cement-based matrix enabled to contain and store air bubbles.

- In the fresh state, evolution of the density of concrete was inversely proportional to the substitution rate of rubber. Lighter concretes were obtained for the granular class SR for about 20%. This was regarded as a maximum rate in this study. However, it was possible to rank the concretes from the lightest to the highest density in the following order SCSC SR < SCSC PR < SCSC GR.
- For the three granular classes (GR (3/7), PR (0/2), SR (0/3)), separately introduced in the concrete mixtures, the flexural tensile strength of RSCSC decreased with increasing rubber substitution rate. The flexural tensile strength of the RSCSC was much better when powder grains of PR were incorporated into the SCSC than when GR and/or SR grains were used, whose flexural tensile strengths were lower than those of SCSC GR and SCSC SR.
- The compressive strength was reduced in RSCSC. This was inversely proportional to the substitution rate of rubber grains for the three (GR (3/7), PR (0/2), SR (0/3)) granular classes introduced in the concrete mixtures. The compositions of SCSC GR developed a slightly higher compressive strength than SCSC PR and SCSC SR.
- Thermal conductivity evolution was inversely proportional to the substitution rates and the rubber grains sizes of the cement-based matrix. This type of test highlighted the character of isolation which was more marked for the grains GR than for the other fine grains PR and SR. Test of the thermal conductivity confirmed once again that GR was more insulating than PR and SR and was always the case for the SCSCs.
- Porosity increased proportionally with the substitution rate of the rubber grains in the SCSC as well as with the size of the rubber grains (finest grains to largest ones). Unlikely, porosity was reduced in the long term only for SCSC PR and SCSC SR. However, SCSC GR remained invariant in the long term (365 days) due to the formation of macro-pores in the cement matrix containing GR. The macro-pores contributed to the evolution of capillary absorption. Compared to fine grains (PR and SR), the latter were endowed with micro-pores that showed a low capillarity absorption.
- As for SCSC, using 15% of GR demonstrated good physical-mechanical performance compared to other rubber grain use. This was fully in line with the requirements of extensive applications in the civil engineering sector, including structural elements. Such findings strongly emphasize the use of rubber aggregates of different sizes but not exceeding 15% in SCSC mixtures for future research work.

NOMENCLATURE

SCSC: Self-Compacting Sand Concrete
RSCSC: Rubberized Self-Compacting Sand Concrete.
UT: Used Tyres
N-RUT: Non-Reusable Used Tyres
VC: Vibrated Concretes
NVC.: Non-Vibrated Concretes
RA: Rubber Aggregates
SCC: Self-Compacting Concrete
LF: Limestone Fillers
QS: Quartz Sand
CS: Crushed Sand
NG: Natural Gravel
PR: Powder Rubber
SR: Sand Rubber
GR: Gravel Rubber

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