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Relationships between recycled concrete aggregates characteristics and recycled aggregates concretes properties

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HIGHLIGHTS

- Physical and mechanical properties of recycled concrete aggregates.
- The frost resistance of aggregates subjected to freezing/thawing cycles in water.
- Prediction of the properties of aggregates whatever their origins by Voigt's model.
- Establishment of relationship between the properties of concrete and those of gravels.

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ABSTRACT

This research aims to analyze the quality and suitability of recycled concrete aggregates (RCA) produced by crushing concrete blocks provided from building demolition waste by comparison to natural ones in providing concretes for building structures. For each granular type, sieving, water absorption, porosity, Los Angeles and Micro-Deval tests were conducted before and after their exposure to freezing/thawing. Results show that the rules of mixtures (Voigt's model) can be used to predict all the studied properties of granular mixes (natural gravels + recycled gravels) except for the prediction of Micro-Deval index. Relationships are established between physical and mechanical characteristics of aggregates. The analysis of the frost resistance performance show that recycled concrete gravels are less resistant to freeze/thaw than natural one but their degradation, estimated through water absorption, porosity and Micro-Deval index, is not significant. Furthermore, the influence of RCA on mechanical properties of recycled aggregates concretes (RAC) is investigated. It appears that porosity and young's modulus of RAC are significantly affected by the porosity of the granular mixture and consequently of RCA. The compressive strength of RAC is dependent on the Los Angeles coefficient of gravels while tensile splitting strength depends on the porosity of concretes related to that of the granular mixture.

1. Introduction

Development in many sectors has negative environmental effects. In construction sector, there are millions of tonnes of construction and demolition waste (CDW) every year. This CDW has a significant damage on the environment and may endanger its sustainability. To find a conceivable solution for CDW and to preserve the natural resources, particularly the non-renewable ones, worldwide researches on recycled aggregates have been increased in order to investigate their revalorization possibilities in concretes.

The CDW can cover a wide range of materials, which depend on their origins: total or partial demolition of infrastructure, construction of buildings, land leveling excavation, civil works and/or general foundations and road maintenance activities [1]. An estimated 900 millions of tonnes of CDW is generated every year in Europe, USA and Japan as reported by the World Business council for Sustainable Development [2].

The review of selected waste streams by European Environmental Agency [3] presents the annual quantity of CDW produced by European countries and explains the considerable difference between countries in producing waste materials due to some characteristics of industrials and institutional activities. Moreover, it appears clearly that the trends in CDW disposal and recovery in Europe differ from one country to another. France, Germany, United Kingdom and Italy produce 74% of all CDW where France,

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with a ratio of 5.5 tons of waste/person per year, is at the higher level [3–6]. Furthermore, 2.6 million tons of fresh concrete are considered as waste and should be recycled in this country [6,7].

As many developed countries, France also has introduced legislations and strategies to reduce the environmental effects of CDW. Corresponding to problem of CDW, there are two national project called PN-RECYBETON [8] and ANR VBD2012-ECOREB [9] that deal with how to provide concretes for building field using aggregates provided from CDW.

In order to valorise waste materials derived from the demolition of buildings and to preserve consequently the natural resource, a national project, called PN-RECYBETON, was initiated in France in 2012 for 5 years. PN RECYBETON aims to provide recommendations and technical specifications for a possible use of the building demolition wastes as aggregates in building construction projects. The recycled concrete aggregates, RCA, must be widely used to produce new concretes and therefore can be considered as new environmental, economic and technological perspectives.

In parallel to PN RECYBETON another national research project named ECOREB and financed by the national agency of research, ANR was started in 2013 to remove academic and scientific issues which are addressed in PN RECYBETON. ECOREB project is structured around three areas of research: water and recycled materials, mechanical behavior of concrete with recycled concrete aggregates and durability of concretes with RAC. The objectives are to develop methodologies and models to predict the behavior of fresh recycled aggregates concretes (RAC), the plastic shrinkage, the mechanical and fracture behavior of the hardened recycled aggregates concretes (RAC), to develop relationships between the mechanical properties of RCA and RAC and to evaluate the influence of RCA on the performance of concrete durability.

This research is done in the framework of ANR-VBD2012-ECOREB.

Aggregates represent about 70–80% of concrete components. Accordingly, the properties of concretes are directly dependent on the physical and mechanical properties of aggregates. In the literature, most of the researches deal with the influence of the partially or totally substitution of natural gravels by recycled ones on some characteristics of concretes [10–17]. Few of them attempt to propose relations that link the properties of RCA to the strength of RAC [18] or to examine the effect of attached cement mortar content on the properties of recycled aggregates [19].

Hence, this paper presents a detailed research on physical and mechanical properties of natural aggregates, called NA, and recycled concrete ones, designed as RCA produced by crushing concrete blocks provided from building demolition waste. This work aims particularly to

- Check the validity of tests conducted according European standards and those required for the characterization of RAC (water absorption, density, porosity, ...).
- Develop relationships between the water absorption coefficient of aggregates and the others properties independently of the origin and nature of aggregates.
- Ensure that mixture laws allow the prediction of the properties of the granular mixtures (NA + RA).
- Study the frost resistance of recycled and natural gravels and the effect of the old paste on this resistance.
- Develop relationships between the mechanical properties of RCA and mixing parameters and those of RAC.

The proposed relationships are established on the basis of experimental results of this research and data got from the analysis of literature. Hence, proposed models cover a wide range of sources of aggregates.

2. Materials

The NA and RCA were provided by PN-RECYBETON [8]. NA is classified as coarse natural gravels (NG2), fine coarse natural gravels (NG1) and natural sand (NS). The recycled aggregates were produced in a platform of recycling by crushing concrete waste of demolished buildings. They are composed of old paste and natural aggregates and are free of other materials like bitumen. Three granular fractions are considered: coarse recycled gravels (RG2), fine coarse recycled gravels (RG1) and recycled sand (RS) (Table 1). A Portland cement (CEM II/A-L 42.5) and limestone filler (HP-OG) with densities of 3.09 and 2.7 respectively are used. The compressive strength of the cement at 28 days is about 51.8 MPa [8]. To ensure a high workability of all developed mixes, a superplasticizer, MC Power-Flow 3140, was employed.

3. Experimental methods

In order to determine the physical properties of aggregates, all fractions of NA and RCA were separately subjected to sieving, density, water absorption and porosity tests.

To define the size distribution of NA and RCA, the sieving was carried-out according to NF EN 933-1 [20]. It has been observed that, both NG and RG have approximately the similar size distribution (Fig. 1). However, grading curves indicate that RS is containing much fine fraction (<2 mm sieve) than NS. This can be critical for the concrete mix design.

The water absorption (WA) is an important physical property of aggregates. Hence, it was determined by means of three methods. The first one is the pycnometer method according to standard NF EN 1097-6 [21]. The second one is the method of hydrostatic weighing continuously (HWC) used to follow the evolution of mass change of aggregates during their immersion in water. In this method a balance is linked to a computer so that the evolution of the mass is recorded continuously.

The third method obeys to the French standard NF P 18-459 [22]. The gravels are placed in an airtight container and vacuum is created until reaching a pressure of 25 mbar. The vacuum is maintained for 4 h at this pressure. The gravels are, then, weighed (M_w) after being submerged in water at different duration (24 h, 48 h...). After being taken out of container they are weighed (M_{air}) then dried at $105^{\pm 5}$ °C until reaching a constant mass (M_{dry}). The porosity (n) as well as the coefficient of water absorption (WA) are calculated using Eq. (1) and Eq. (2):

$$\text{Coefficient of water absorption}\quad \mathrm{WA}(\%) = \frac{M_{air} - M_{dry}}{M_{dry}} \times 100 \tag{1}$$

$$\text{Porosity}\quad n(\%) = \frac{M_{air} - M_{dry}}{M_{air} - M_w} \times 100 \tag{2}$$

where M_{air} is mass of gravels sample at the saturated surface-dried state, M_{dry} is the mass of gravels sample at oven dried state and M_w is the mass of gravels sample in water.

To assess the mechanical properties of gravels, Los Angeles test is conducted according to NF EN 1097-2 [23] in order to determine their resistance to fragmentation and Micro-Deval test is applied according to NF EN 1097-1 [24] to check their resistance to wear.

The durability of gravels regarding to freezing/thawing cycles is considered according to NF EN 1367-1 [25]. The mass loss (F) of the

Table 1
The fractions of NA and RA.

Aggregates	Codes	Grading (mm)
Natural sand	NS	0–4
Natural gravels	NG1	4–10
	NG2	6.3–20
Recycled sand	RS	0–4
Recycled gravels	RG1	4–10
	RG2	10–20

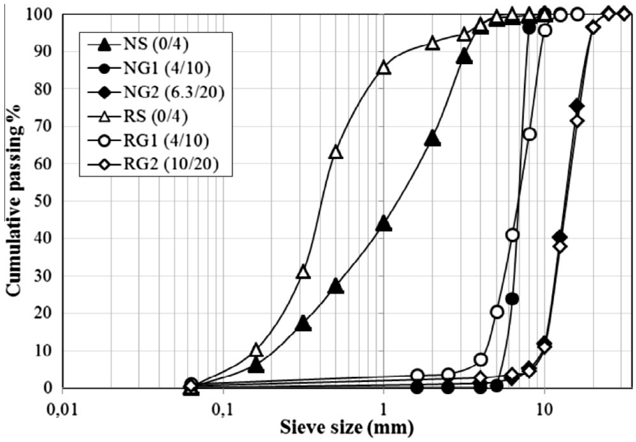


Fig. 1. Granulometric curves of NA and RCA.

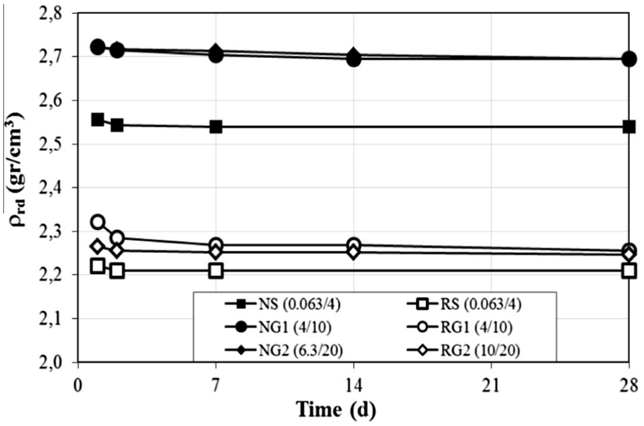


Fig. 2. Evaluation of density versus time.

different fractions of gravels, submitted to freezing/thawing test, was calculated using Eq. (3).

$$F(\%) = \frac{M_1 - M_2}{M_1} \times 100 \tag{3}$$

where, M_1 is the dry mass of sample before test; M_2 is the dry mass of sample retained on the sieve proposed by the mentioned standard.

In order to determine the porosity of concretes, the French standard NF P 18-459 [22] is applied, in which measurements must be done after the specimens' exposure to vacuum for 4 h. After a given period of immersion (44 h) in water, the coefficient of WA and the porosity of concretes are calculated using Eq. (1) and Eq. (2), respectively. The compressive strengths and tensile splitting strength tests on concretes were performed using a servo-hydraulic INSTRON machine with a capacity of 3500 KN with a loading rate of 0.5 and 0.05 MPa/s respectively.

The dynamic modulus of elasticity was measured by E-Meter MK II using the principle of resonant frequency testing method.

For each experimental point the test was repeated at least 3 times.

4. Properties of NA and RCA

4.1. Density

Relative density of NA $\left(\rho_{rd}^{NG\,(or\,NS)}\right)$ and RCA $\left(\rho_{rd}^{RG\,(or\,RS)}\right)$ were determined according to the standard NF EN 1097-6 [21]. The evolution of relative density as a function of the soaking time is illustrated in Fig. 2.

It can be concluded that, the density of RCA is lower than this of natural ones. This is mainly due to the existence of the old cement paste attached to the original virgin aggregate [26]. However, some authors show that low specific gravity of RCA can be more attributed to the quality of the virgin aggregates than to the amount of attached old cement mortar [18,27]. Besides, it can be observed that, the soaking period to determine RCA's relative density should be longer than 24 h (the recommended period by standard). The final soaking time required is about 7 days for RCA and 48 h for the NA. However, we can observe that at 24 h aggregates reach 83%.

The granular skeleton in concretes is composed of a mix of NA and RCA. The granular mixes were prepared with different ratio of substitution of NA by RCA. r_m^A, the ratio of substitution is defined by $r_m^A = M^{RG\,(or\,RS)}/(M^{RG\,(or\,RS)} + M^{NG\,(or\,NS)})$: where $M^{RG\,(or\,RS)}$ are the mass of recycled gravels (RG) or recycled sand (RS) and $M^{NG\,(or\,NS)}$ the mass of natural gravels (NG) or natural sand (NS).

The aggregate mix can be considered as a composite that consists of two materials or phases: natural aggregate "NA" and recycled aggregate "RA". Each phase is characterized by its volume fraction. To predict the effective properties of the composite various mathematical expressions including rules of mixtures (Voigt W. (1887) and Reuss A. (1929)) can be used. Such models involve the identification of the properties of each phase.

Generally, the "rule of mixture" expression for some scalar effective physical property Ψ of a two-phase composite takes the form $\psi = [\xi \times (\psi_i)^\beta + (1-\xi) \times (\psi_m)^\beta]^{\frac{1}{\beta}}$, where (i) and (m) denote inhomogeneities, here natural aggregates and recycled aggregates and ξ the fraction of the phase "i". The exponent β is chosen so as to draw a good fit to the data obtained from experiments.

The Voigt's model (1887) assumes constant strain throughout the composite (iso-strain model) [28] leading to $\beta = 1$ while Reuss (1929) proposed a rule of mixture model where stress is assumed to be constant throughout the composite (iso-stress model) [29] with $\beta = -1$.Voigt's model corresponds to "full strain coupling of the phases (springs in parallel, arithmetic averages)" whereas, the Reuss's model corresponds to "full stress coupling of the phases (springs in series, harmonic averages)". The use of one model than another depends on the micro-topology and material properties of the composite.

In this study Voigt's model is considered to predict the properties of the aggregate mixtures. Hence, the rule mixture will be expressed as:

$$\psi = [\xi \times (\psi_i) + (1-\xi) \times (\psi_m)].$$

Experimental results illustrated in Fig. 3, reveal that the Voigt's model predicts well the relative density of the granular mixes $(\rho_{rd}^A = r_m^A \rho_{rd}^{RCA} + (1 - r_m^A)\rho_{rd}^{NA})$ with correlation coefficients $R^2 = 0.99$.

4.2. Water absorption

Water absorption (WA) is an important parameter that has a key role on concrete's mix design. As mentioned, the WA coefficient of NA and RCA is measured by three methods at different soaking durations longer than 24 h which is recognized by the standard. Results summarized in Table 2 corroborate that 24 h can be used as soaking duration to determine WA coefficient of RCA whatever the used method although a slight increase is observed for recycled sand between 24 and 48 h. Moreover, the WA coefficients obtained using the three methods are close except for the method based on standard NF P 18-459 [22], which leads to

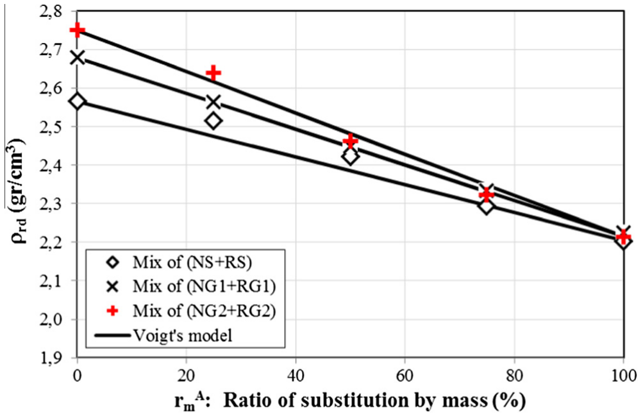


Fig. 3. Density of granular mixtures.

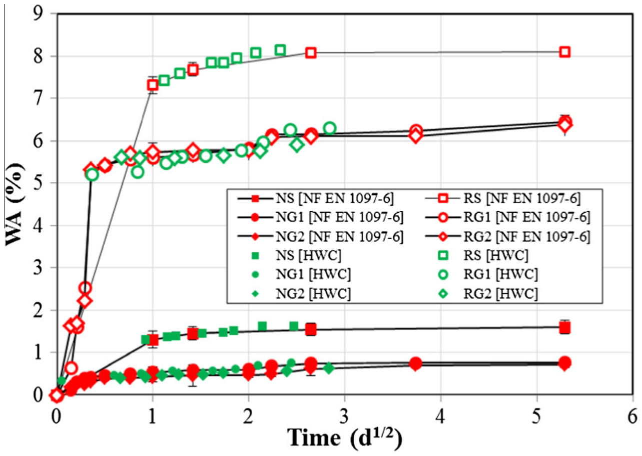


Fig. 4. The evaluation of WA by methods of pycnometer (NF EN 1097-6) and HWC.

higher values of recycled gravels (Table 2). It can be concluded, that compared with NA, RCA are characterized with higher values of WA due to the amount and quality of attached old cement mortar. This corroborates results obtained by others authors who showed that WA_{24h} increases by increasing the mortar content in RCA [10,18,26,27].

The evolution of WA measured according to standard NF EN 1097-6 [21] and using hydrostatic weighing continuously method (HWC) is reported in Fig. 4 as a function of the soaking duration until a period of 7 days.

Both methods lead to the close values and similar evolutions of WA. After 4 days a sudden increase of the WA coefficient is observed.

To check the applicability of the standard to recycled gravels regarding to the determination of the WA coefficient at 24 h, an index of water absorption is calculated by $i_{WA} = WA_{t(h)}/WA_{24h}$: where $WA_{t(h)}$ is the water absorption coefficient determined after a given soaking duration in hours designed by the letter "*t*".

The experimental results indicate that 24 h soaking duration is insufficient to determine the WA coefficient (Fig. 5).

At soaking duration longer than 4 days the index of water absorption increases. This increase is significant for natural gravels and is enhanced for coarse gravels. For RCA the index of water remains almost equal to 1. This emphasizes the importance of the quality of virgin aggregates on their physical properties.

Relationship between relative density and WA_{24h} coefficient is established (Fig. 6) on the basis of the obtained experimental results and those of the literature concerning more than 50 types of NA and RCA from different CDW plants [10–18,27,30–37,44].

It can be concluded that, there is a linear relationship between these two physical properties of aggregates. This relationship can be modeled by Eq. (4) with R^2 exceeding 0.92.

$$\rho_{rd}^{A} = 2.72 - 0.07 \times WA_{24h}(\%) \text{ and } WA_{24} = 0 \quad \text{if } \rho_{rd}^{A} \geqslant 2.72 \tag{4}$$

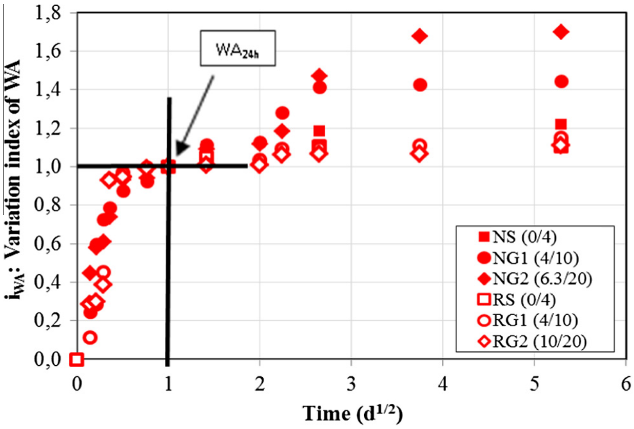


Fig. 5. The variation index of WA by method of pycnometer (NF EN 1097-6).

4.3. Open porosity

The open porosity accessible to water of NA and RCA was measured according to standards NF EN 1097-6 [21] and NF P 18-459 [22]. Obtained results are summarized in Table 2. It is observed that RCA are much porous than natural ones and both methods provide quite similar values. Moreover, it can be pointed out that fine recycled aggregates are characterized by a higher porosity than coarse ones. This can be explained mainly by the higher amount of old cement mortar in fine recycled aggregates. This assumption is in accordance with the literature [26,27].

The open porosity and the WA coefficient of the different aggregates mixes (NA + RCA) are measured and the obtained values are linked to the ratio of substitution as illustrated in Fig. 7. It can be established clearly that, the Voigt's model well predicts the evolu-

Table 2
The experimental results of WA and porosity of aggregates.

Method		RG1		RG2		RS		NG1		NG2		NS	
Soaking duration		24 h	48 h	24 h	48 h	24 h	48 h	24 h	48 h	24 h	48 h	24 h	48 h
Pycnometer [NF EN 1097-6]	WA	$5.6^{\pm0.2}$	$5.7^{\pm0.1}$	$5.7^{\pm0.2}$	$5.8^{\pm0.2}$	$7.3^{\pm0.1}$	$7.7^{\pm0.2}$	$0.5^{\pm0.1}$	$0.6^{\pm0.1}$	$0.4^{\pm0.1}$	$0.5^{\pm0.2}$	$1.3^{\pm0.1}$	$1.5^{\pm0.2}$
	n_p^G	$13.0^{\pm.2}$		$12.7^{\pm0.2}$		$16.1^{\pm0.1}$		$1.4^{\pm0.1}$		$1.1^{\pm0.1}$		$2.2^{\pm0.2}$	
Vacuum [NF P 18-459]	WA	$6.1^{\pm0.1}$	$6.4^{\pm0.1}$	$6.2^{\pm0.1}$	$6.2^{\pm0.1}$	–	–	$0.6^{\pm0.1}$	$0.7^{\pm0.1}$	$0.5^{\pm0.1}$	$0.6^{\pm0.1}$	–	–
	n_v^G	$13.4^{\pm0.2}$		$13.7^{\pm0.2}$		–		$1.6^{\pm0.1}$		$1.2^{\pm0.1}$		–	
HWC	WA^G	$5.4^{\pm0.2}$	$5.7^{\pm0.1}$	$5.6^{\pm0.0}$	$5.6^{\pm0.1}$	$7.3^{\pm0.1}$	$7.8^{\pm0.1}$	$0.5^{\pm0.1}$	$0.6^{\pm0.0}$	$0.4^{\pm0.0}$	$0.5^{\pm0.0}$	$1.3^{\pm0.1}$	$1.4^{\pm0.1}$

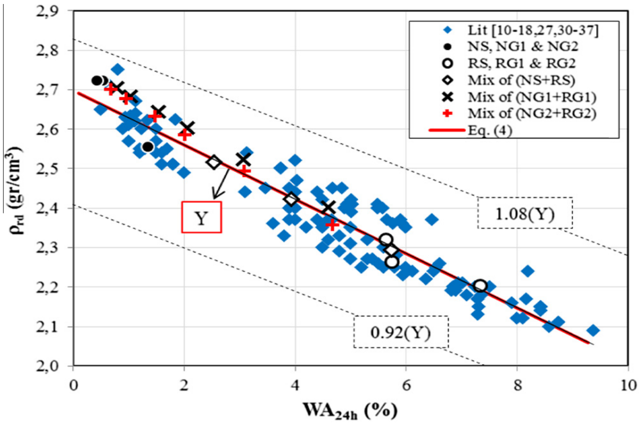


Fig. 6. Relationship between density and WA of aggregates.

tion of the open porosity and the WA coefficient of the aggregates mixes $\left(n_v^A = r_m^A n_v^{RCA} + (1-r_m^A)n_v^{NA} \text{ and } WA_{24} = r_m^A WA_{24}^{RCA} + (1-r_m^A)WA_{24}^{NA}\right)$.

In addition, it is proved that the increase of open porosity of aggregates leads to an increase of WA coefficient determined at 24 h (Fig. 8).

An unequivocal relationship is established between these two properties independently of the granular class and aggregates origin on the basis of the experimental results obtained in this work and those of literature [13,18] (Eq. (5)).

$$n_v^A(\%) = 2.26 \times WA_{24}(\%) \quad \text{with } R^2 = 0.98 \tag{5}$$

4.4. Los Angeles

The test of Los Angeles (LA) was applied according to the standard NF EN 1097-2 [23]. This standard describes that, after 500 tours of machine on 5 kg of gravels (named M1), the gravels are separated into a quantity of material retained the 1.6 mm sieve (mass is designed as M2). In this work, the mass retained on the sieve of 63 µm but passing the sieve 1.6 mm (named M3) and the mass of material passing the 63 µm sieve (named M4), was determined to find out the quantity of fine particles generated by the test.

It appears that RG has a significantly greater LA coefficient than that of NG with $LA_{RG}/LA_{NG} \approx 2$ (Fig. 9a). However these values are acceptable and are in accordance with the requirements of the standards ($LA \leqslant 30$ for NG and $LA \leqslant 40$ for RG if $f_{ck} \geqslant 36$ MPa). It can be observed that M3 and M4 are more important for recycled gravels than for natural ones due probably to the presence of old cement paste in RG which is less resistant to fragmentation (Fig. 9b).

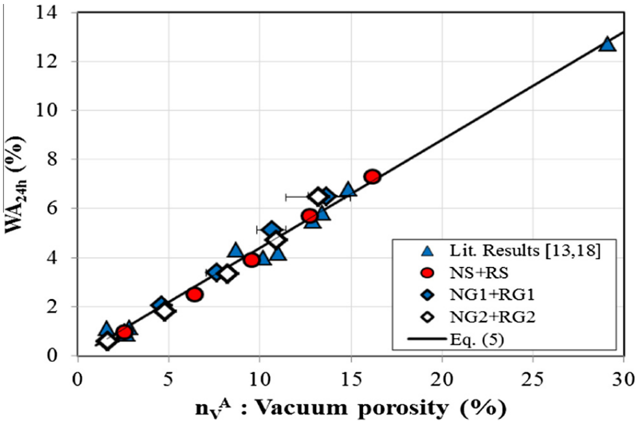


Fig. 8. Aggregates porosity vs WA coefficient.

The LA coefficient of aggregates has relationship with its WA coefficient, the experimental results of this work and those of literature [10,11,18,31,36,37] highlight the effect of WA_{24h} on their abrasion resistance (Fig. 10a). With an increase of WA, we can observe an increase of LA coefficient (Eq. (6)).

$$LA = 2.72WA_{24} + 15.6 \quad \text{with } R^2 = 0.83 \tag{6}$$

LA abrasion test is, also, conducted on the selected granular fractions [4–8 mm] and [10–14 mm] of the gravel mixes (NG + RG). Experimental results show that the Voigt's model $\left(LA(\%) = r_m^G LA_{RG} + (1-r_m^G)LA_{NG}\right)$ well predicts the LA of the gravels mixes (Fig. 10b) where r_m^G is the massic ratio of substitution of NG by RG. Hence, the increase in LA (%) is just proportional to the RCA content.

Furthermore, the evolution of LA as a function of the porosity (Fig. 11a) reveals that gravels with low porosity are characterized by a greater resistance to fragmentation, therefore, The Eq. (6) was verified by the relationship between LA and aggregate porosity (Fig. 11a) using the Eq. (5).

Moreover, as the porosity rises the density decreases leading subsequently to the LA coefficient increase (Fig. 11b). This

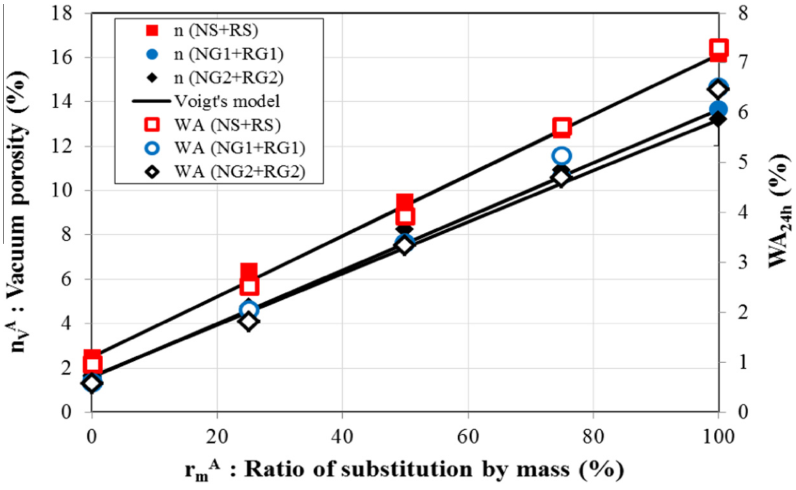
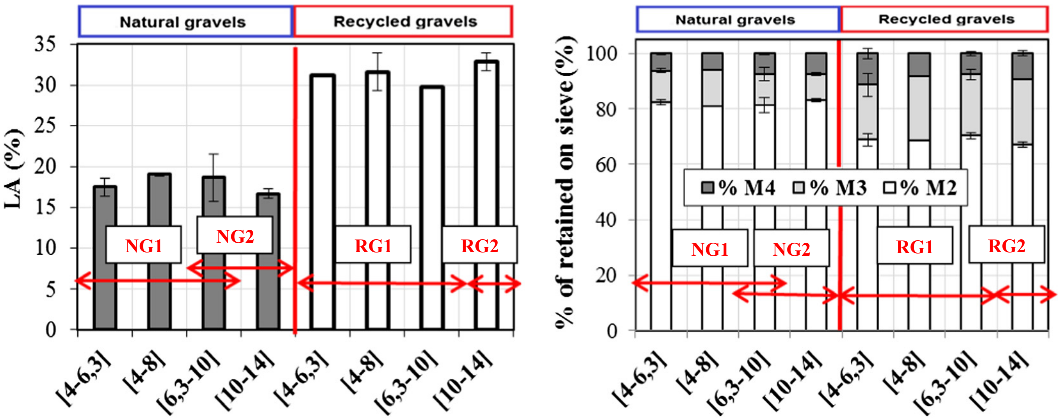


Fig. 7. Porosity and WA vs ratio of substitution.



(a) LA coefficients for NG and RG.

(b) M2 mass retained on 1.6 mm sieve , M3 on 63μm and M4 the mass of fines.

Fig. 9. Results obtained after LA tests conducted on gravels.

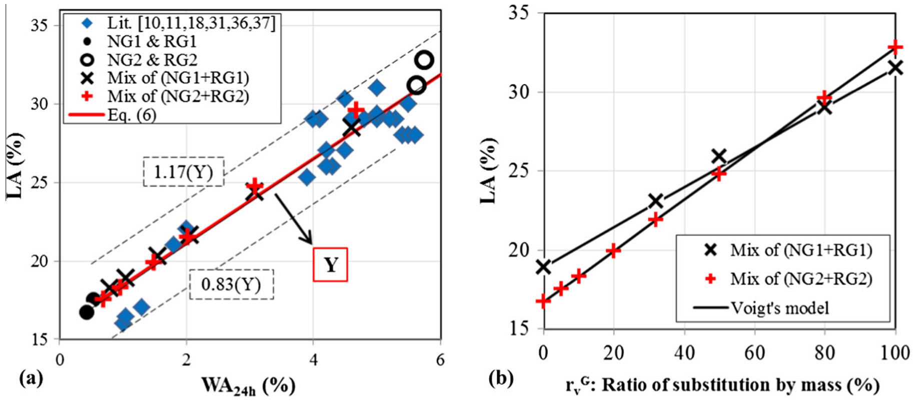


Fig. 10. Effects of WA_{24h} of gravels on their mechanical resistance (LA) (a) and the applicability of Law of mixture for LA test (b).

assumption has been confirmed by means of the experimental results and those of literature [11,18,31,36,37].

4.5. Micro-Deval

The test of Micro-Deval was carried out according to standard NF EN 1097-1 [24] to determine abrasion loss in the presence of water and an abrasive charge of NG and RG. The test has been performed at wet condition (MDE). To find out the quantity of produced fine particles, the gravel masses passing the 63 μm sieve and retained on it (M4 and M3 respectively) and the retained on 1.6 mm sieve (M2) are weighed.

The experimental results (Fig. 12a) reveal that, the MDE coefficient of RG is slightly greater than this of NG ($MDE_{RG}/MDE_{NG} \approx 1.3$ for 10/14 mm size fraction). Testing 4/6 mm and 6.3/10 mm size fractions produce MDE coefficient in accordance with the requirements of the European standard ($MDE \leqslant 20$ for $f_{ck} \geqslant 36$ MPa).

According to experimental results, it is observed that the wear resistance of the NG depends on the tested size fraction of the gravels. A decrease is noticed except for 6.3/10 mm size fraction. Such effects are not observed for recycled ones, probably due to the fact that they are coated by old cement paste having the same wear resistance. Furthermore, the production of fines is more important for RG, phenomenon related to the old paste surrounding natural aggregates which is less resistant to wear than rocky materials (Fig. 12b).

Micro-Deval test was carried out on natural and recycled gravels mixes. It appears clearly that the Voigt's model cannot be used to predict the MDE of the gravel mixes. This can be explained by the fact that wear resistance of gravels is mainly governed by the aggregate mineralogical composition and in a lesser degree by the particle shape.

4.6. Gravels freeze/thaw resistance

The durability of aggregates was measured by means of freezing/thawing cycles in water according to the standard NF EN 1367-1 [25]. The coefficient of mass loss (F) was calculated after 10 cycles as recommended by the standard. Experimental results are given in Table 3. It can be pointed out the effect of fraction size on this parameter which decreases for coarse fraction size of both NG and RG. As expected the durability of RG under freezing/thawing cycles in water is lower than that of NG. The coefficient of WA_{24h} for all fractions of freezing/thawing is summarized in Table 3.

It appears that aggregates with higher WA_{24h} are less frost resistant. In addition, it seems that the source of the gravels as well as their chemical composition play an important role on their frost resistance. Hence for RCA, processed by crushing crushed concretes blocks resulting from the building demolition, it can be expected that the old cement paste contains micro-cracks due to the crushing phenomenon and subsequently the freezing/thawing resistance of RCA is reduced.

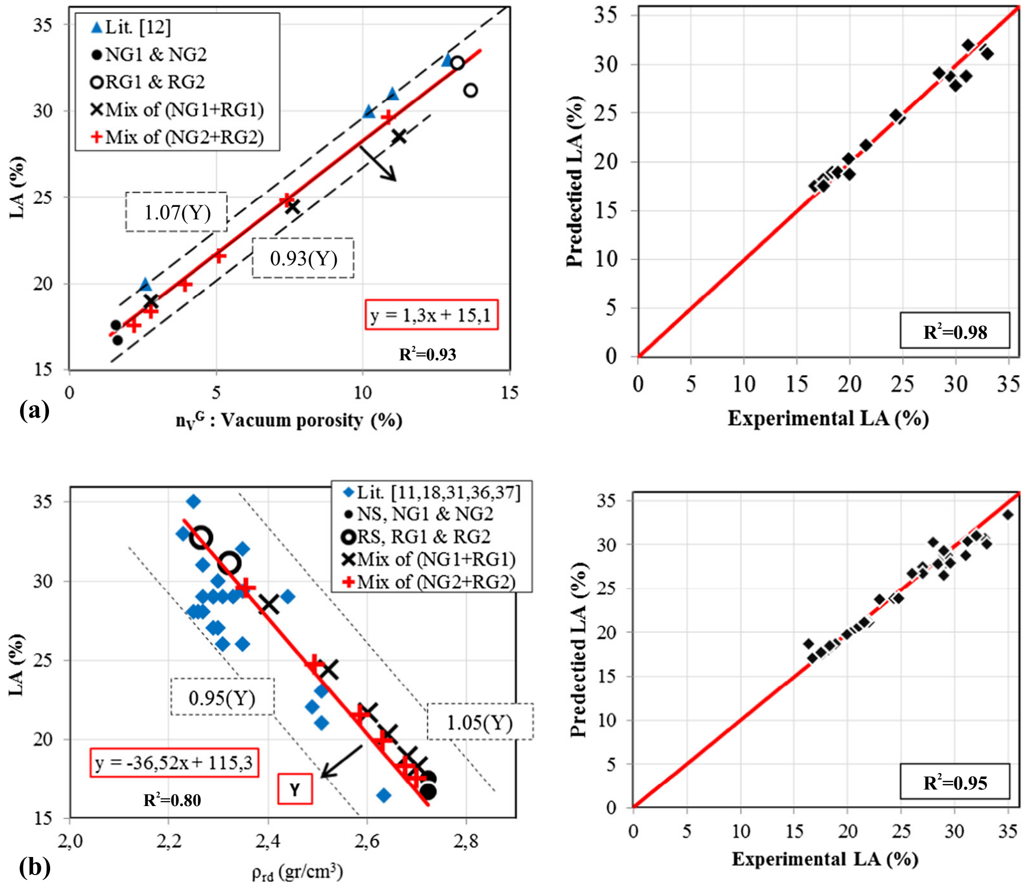
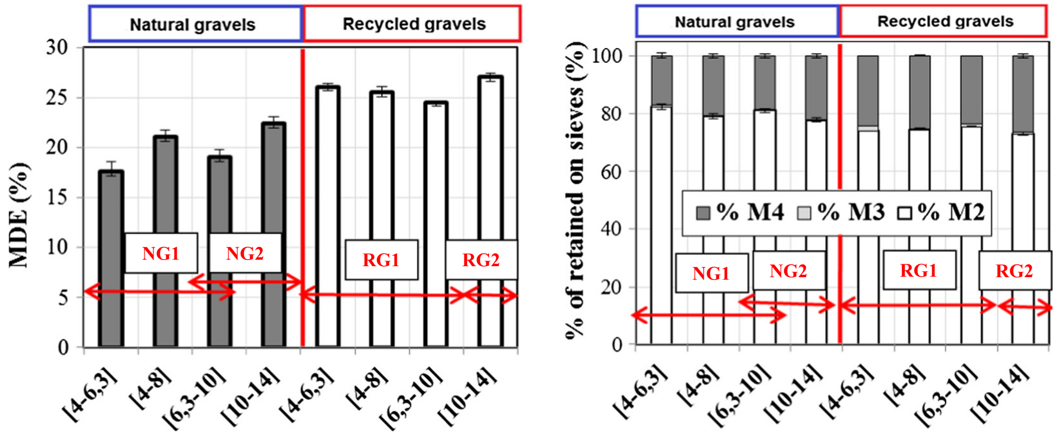


Fig. 11. LA coefficient evolution as a function of the porosity n_v^G (a) and the density of the gravels ρ_{rd} (b).



(a) MDE coefficients for NG and RG.

(b) M2 mass retained on 1.6 mm sieve , M3 on 63µm and M4 the mass of fines.

Fig. 12. Experimental results obtained throughout MDE tests conducted on NG and RG.

The grain size distribution of granular fractions before and after submitting to freezing/thawing cycles is illustrated in Fig. 13.

The curves show that, the granular distribution changes after freezing/thawing cycles for RG while it is almost the same for NG. It means that, freezing/thawing cycles have damaged more severely RG than NG and, subsequently, more fine particles have been produced due to the degradation of the old cement paste surrounding RCA that has been separated from the natural aggregates because of frost. RG collected after frost is the most resistant.

Such degradation can explain that MDE coefficient of RG after freezing/thawing test decreases to reach the value of NG before frost test while it increases for NG (Table 3). For RG, it can be concluded that if the cohesion between the old paste and the natural aggregate is strong, then the old paste protects the natural aggregates against degradations due to frost. This explains the higher resistance to wear of gravels after exposure to freezing thawing cycles. The obtained value is quite similar to this of natural gravels before exposure to freezing thawing cycles.

Table 3
Effects of freezing/thawing cycles on characteristics of the gravels.

	Fraction (mm)	Mass loss	Before freezing/thawing			After freezing/thawing		
		F (%)	WA (%)	n_v^C (%)	MDE (%)	WA (%)	n_v^C (%)	MDE (%)
NG	4/8	$2.7^{\pm 0.4}$	$0.75^{\pm 0.01}$	$2.0^{\pm 0.11}$	–	$0.90^{\pm 0.02}$	$2.4^{\pm 0.11}$	–
	8/16	$2.3^{\pm 0.5}$	$0.55^{\pm 0.01}$	$1.5^{\pm 0.10}$	–	$0.79^{\pm 0.01}$	$2.2^{\pm 0.01}$	–
	16/25	$1.8^{\pm 0.1}$	$0.50^{\pm 0.02}$	$1.4^{\pm 0.13}$	–	$0.76^{\pm 0.01}$	$2.1^{\pm 0.02}$	–
	10/14	–	–	–	$22.4^{\pm 0.7}$	–	–	$26.4^{\pm 0.5}$
RG	4/8	$4.1^{\pm 0.5}$	$6.4^{\pm 0.1}$	$14.2^{\pm 0.3}$	–	$5.9^{\pm 0.1}$	$13.6^{\pm 0.2}$	–
	8/16	$3.5^{\pm 0.4}$	$6.0^{\pm 0.2}$	$13.6^{\pm 0.2}$	–	$5.5^{\pm 0.1}$	$12.7^{\pm 0.2}$	–
	16/25	$3.4^{\pm 0.1}$	$5.9^{\pm 0.2}$	$13,2^{\pm 0.2}$	–	$5.5^{\pm 0.1}$	$12.7^{\pm 0.2}$	–
	10/14	–	–	–	$27.1^{\pm 0.4}$	–	–	$22.9^{\pm 0.2}$

Table 4
Mix proportions and concrete properties in fresh and hardened states.

Constituent (kg/m^3)	C35/45 0R–0R	C35/45 30R–30R	C35/45 0R–100R	C35/45 100R–100R
W_{total}	185	220	238	284
W_{eff}	175	179	185	184
Water used for mixing (RCA in saturated state)	185	183	190	183
CEM II/A-L 42,5 N	299	321	336	381
Limestone filler	58	44	53	70
NS (0/4)	771	491	782	0
RS (0/4)	0	235	0	729
NG1 (4/10)	264	168	0	0
RG1 (4/10)	0	151	168	319
NG2 (6.3/20)	810	542	0	0
RG2 (10/20)	0	175	728	465
Superplasticizer	2.1	1.64	2.18	2.78
W_{eff}/C	0.59	0.56	0.55	0.48
$W_{eff}/(C+F)$	0.49	0.49	0.48	0.41
r_v (%)	0	34	55	100
Slump (cm)	$20^{\pm 0.5}$	$19.5^{\pm 0.3}$	$20^{\pm 0.5}$	$19^{\pm 0.8}$
Air content (%)	$1.8^{\pm 0.1}$	$2.1^{\pm 0.1}$	$2.4^{\pm 0.1}$	$2.9^{\pm 0.1}$
$f_{ctm,sp\text{-}28d}$ (MPa)	$3.59^{\pm 0.2}$	$2.99^{\pm 0.2}$	$2.93^{\pm 0.1}$	$3.01^{\pm 0.1}$
$f_{cm\text{-}28d}$ (MPa)	$40.7^{\pm 0.4}$	$39.5^{\pm 0.9}$	$39.1^{\pm 0.8}$	$38.5^{\pm 0.9}$
$E_{d\text{-}28d}$ (GPa)	$44.8^{\pm 0.5}$	$34.4^{\pm 0.4}$	$32.9^{\pm 0.3}$	$30.1^{\pm 0.2}$

5. Mixture proportions and mixing procedure of RAC

The mix design of concretes under study was proposed by PN-RECYBETON [43].

The mix design has been performed using the software Betonlabpro3 to ensure the target compressive strength and workability classes. This software is based on the maximum packing theory for the optimization of the granular skeleton and on a database of the properties of each component used to elaborate the concrete such as density and compaction. To optimize the paste dosage, the software takes into account the type of cement, the concentration of aggregates, and the use or not of mineralogical additions. In this work 4mixes, coded respectively C35/45 0R–0R, C35/45 30R–30R, C35/45 0R–100R and C35/45 100R–100R, have been manufactured and their properties have been investigated. In the nomenclature C35/45 *x*R–*y*R, *x* represents the replacement percentage by weight of NS by RS and (*y*) the replacement of NG by RG.

In this study the ratio of substitution is defined volumetrically by $r_v = (V_{RS} + V_{RG})/(V_{NA} + V_{RA})$: where V_{RS} is the volume of RS in 1 m^3 of concrete, V_{RG} the volume of RG in 1 m^3 of concrete, V_{NA} and V_{RA} are respectively, the volume of NA and of RCA in 1 m^3 of concrete.

According to equation (r_v), the replacement percentages of NA by RCA, are respectively, 0%, 34%, 55% and 100%. The concrete

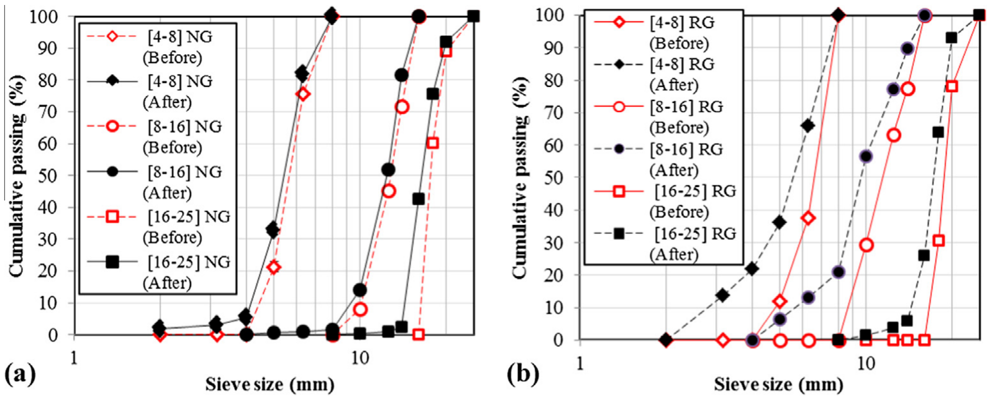


Fig. 13. Particle size distribution of NG and RG before and after freezing/thawing cycles.

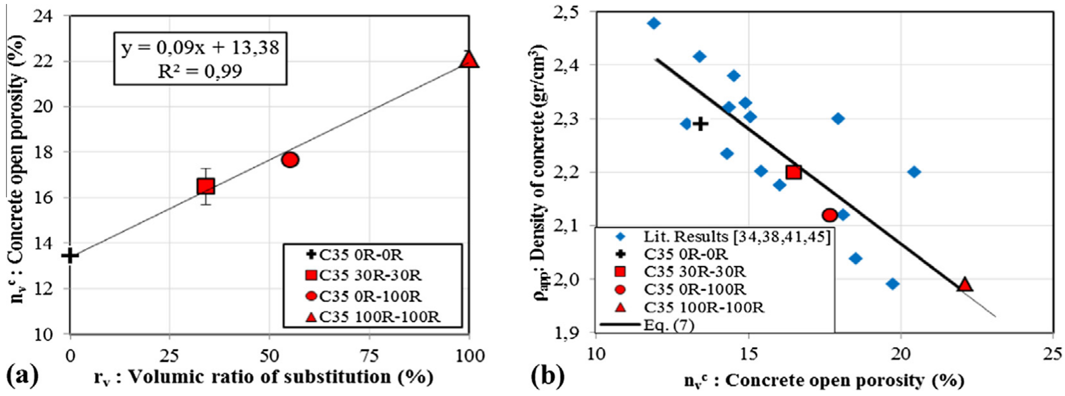


Fig. 14. Concrete porosity versus ratio of substitution (a) and Concretes density versus its porosity (b).

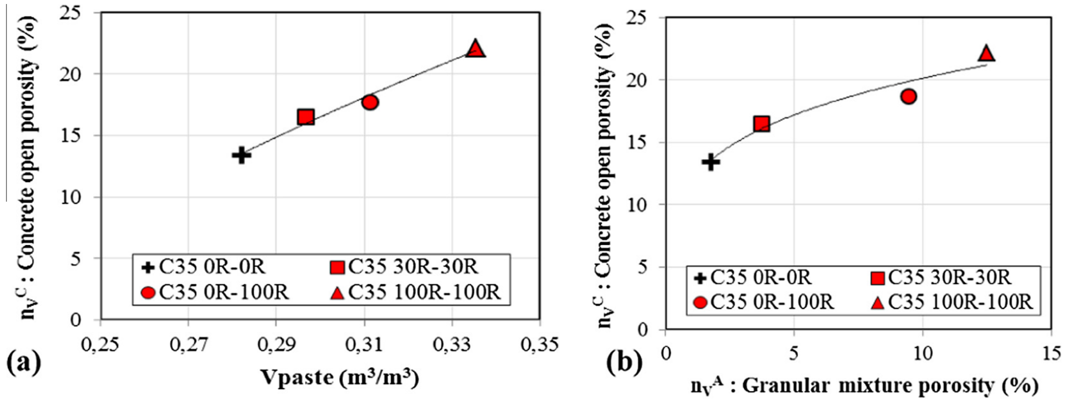


Fig. 15. Effects of paste volume (a) and aggregates porosity (b) on the concretes porosity.

mixes were adjusted in order to achieve the same consistency class of S4 (here equal to $18^{\pm 2}$ cm) and compressive strength class of C35/40 (Table 4).

The RCA were introduced during the mix design at the saturated state.

The components were introduced into the mixer by starting with coarse gravels, followed by fine gravels, sands, fillers, mix of water and superplasticizer. The mixing procedure proposed by PN-RECYBETON [43] is summarized below:

0–1′: Mixing of all dry components and saturated RCA.
1′ to 1′30″: Introduction of water + superplasticizer.
1′30″ to 5′: Mixing of mixes.

The mix proportions of concrete are shown in (Table 4).

6. The properties of the concretes at the hardened state

After 28 days curing in water, the open porosity of concretes was determined under vacuum. A linear increase of the open porosity of concretes, n^C_v, is observed when the substitution ratio of NA by RCA by volume, r_v, is enhanced (Fig. 14a).

Therefore, when the percentage of substitution raises the porosity of concretes increases, leading to a decrease of the density of the concrete (Fig. 14b). The relationship between the density of the concrete and its porosity, described by Eq. (7), is based on experimental results and on those of literature [34,38,41,45].

$$\rho^{C}_{\mathrm{app}}(\mathrm{gr/cm^3}) = 0.034\langle 81 - n^{C}_{v}(\%)\rangle \quad \text{with } R^2 = 0.8 \tag{7}$$

The RAC porosity growth can be attributed to two factors: the increase of the paste volume (Fig. 15a) and the increase of porosity of the aggregates as the substitution ratio raise (Fig. 15b).

Hence a relationship between the concrete porosity and the porosity of aggregates and the volume of the paste can be stablished (Eq. (8)):

$$n^{C}_{v}(\%) = 95(n^{A}_{v})^{0.24}\langle V_{\mathrm{paste}} - 0.202\rangle \tag{8}$$

where n^C_v the concrete porosity in %, n^A_v is the porosity of the granular skeleton composed by all the aggregates: the sand, the fine and coarse gravels. The value of n^A_v in % is calculated using the law of mixture. V_{paste} is the volume of the paste in m^3 by m^3 of concrete: $V_{\mathrm{paste}}(m^3/m^3) = V_{\mathrm{cement}} + V_{\mathrm{water}} + V_{\mathrm{filler}} + V_{\mathrm{air}}$.

The validity of the Eq. (8) is checked by means of other experimental results obtained in the framework of the national project ANR ECOREB [9] by testing a concrete C25/30 manufactured with the same aggregates [46] and those of literature results of Wardeh et al. [34] (Fig. 16).

The compressive tests were carried out on cylindrical specimens of 110 × 220 mm at the age of 28 days. The compressive strengths are given in Table 4. It can be concluded that, the required compressive strength class (C35/40) is achieved for all concretes NAC and RAC. Indeed, it can be observed that the mix proportioning changes from one formulation to another to reach the target resistance as well consistency classes by maintaining almost constant the ratio $W_{\mathrm{eff}}/(C+F) \cong 0.5$ except for C35/45 100R–100R.

The dependency of compressive strengths of concretes made with NA (NAC) and with RCA (RAC) on the LA coefficient of the

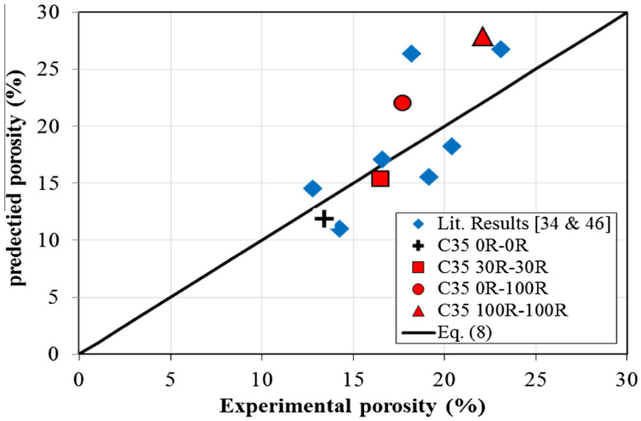


Fig. 16. The verification of purposed model of porosity.

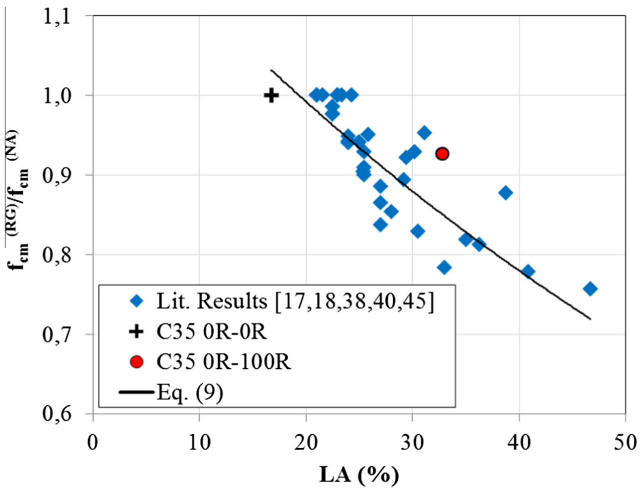


Fig. 17. The compressive strength at 28 days of RAC divided by this of concrete made with natural aggregates versus coefficient of LA.

gravels is investigated on the basis of the experimental results of this research and those of literature. The LA coefficients of the gravels studied in this work are obtained experimentally while those of the literature [17,18,38,40,45] were calculated using Voigt's model. The relationship between the normalized compressive strengths at 28 days and LA (%) is illustrated in Fig. 17.

It can be concluded that, the resistance to fragmentation of gravels influences on the concrete's compressive strength. The relation between the normalized compressive strength at 28 days and LA is described by Eq. (9) and is supported by a strong coefficient of correlation ($R^2 = 0.8$).

$$\frac{(f_{cm-28d})^{RG}}{(f_{cm-28d})^{NG}} = 2.8 \times LA^{-0,34} \quad \text{with } R^2 = 0.8 \tag{9}$$

where LA (%) is calculated using law of mixture.

Subsequently, the concrete's compressive strength depends strongly on the physical and mechanical properties of the used gravels as LA (%) which is related to WA_{24h} (Eq. (6)) and ρ_{rd}^{A} (Fig. 11b). This corroborates the results obtained by Khaleel and Pilakoutas [18], although it is found here that linear model is not the best to predict the compressive strength.

The tensile strength of concretes has been obtained throughout splitting test carried out on cylindrical specimens (110 × 220 mm) at the age of 28 days. The influence of substitution of NA by RCA was analyzed where it was found that, when the LA coefficient of granular mixture increases the tensile splitting strength decreases.

Furthermore, the tensile splitting strength, $f_{ctm,sp}$, related to the open porosity of concrete (Fig. 18) that is linked to the open porosity of the aggregates and the volume of the paste in concrete (Eq. (8)). To check the validity of the proposed relationship (Eq. (10)), experimental results and those of literature [17,30,33–35,42] were examined. It can be seen that, the open porosity of concrete has negative influence on its tensile splitting strength.

$$f_{ctm,sp}\,(\text{MPa}) = f_{ctm,sp\infty} \exp\left[-b \times n_v^C(\%)\right]$$
$$\text{with } f_{ctm,sp\infty} \cong 6\ \text{MPa} \ \&\ b = 0.03 \tag{10}$$

The experimental results of dynamical modulus of elasticity (E_d) are given in Table 4. It can be outlined that, the E_d decreases when RCA is used. This diminution is more pronounceable with a high replacement ratio of NA by RCA. Moreover, it can be assumed that the Young's moduli of concretes are directly linked to its porosity which is related to the quality of aggregates (open porosity) and to the paste volume as illustrated by Eq. (8). In this work elastic moduli are dynamic because their experimental measurement is easier than that of static modulus, E_s, which are necessary for the design of concrete structures. Previous works have shown that the static

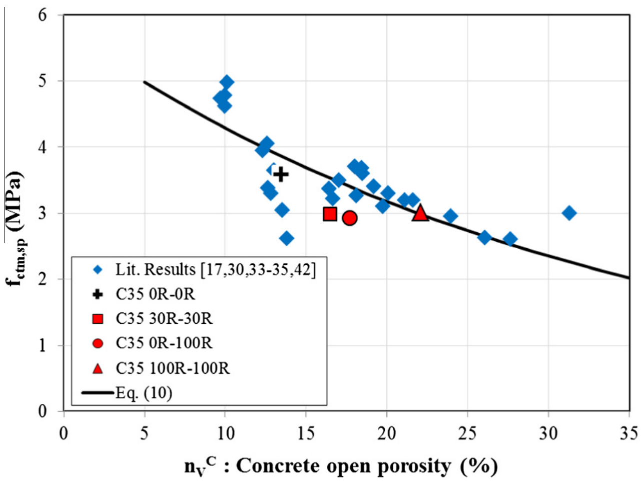


Fig. 18. The tensile splitting strength versus porosity of concretes.

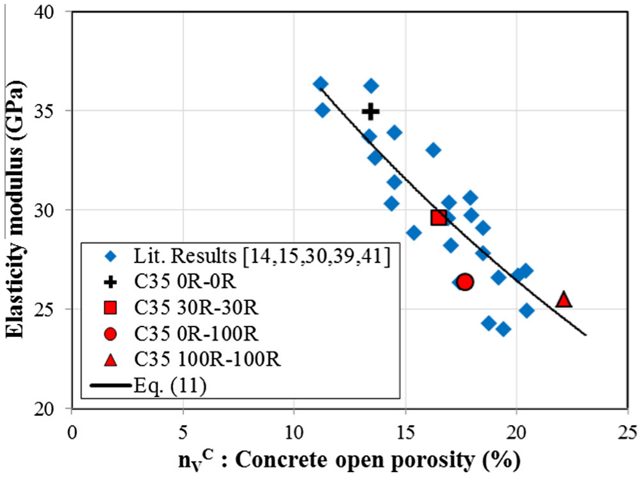


Fig. 19. The evolution of Young's moduli as a function of the open porosity of concrete.

modulus of elasticity is always lower than the dynamic modulus of elasticity, and this difference emphasizes when concrete strength increases [47]. Different attempts have been done to estimate the static elastic modulus using the value of dynamic modulus of elasticity. The model used in this study, is that formulated by Lydon and Balendran [48] $E_s = 0.83E_d$.

The estimated static Young's modulus and those obtained from previous works [14,15,30,39,41] are plotted against the open porosity of concretes. The results, illustrated in Fig. 19, show that the proposed model described by Eq. (11) can be applied.

$$E(\text{GPa}) = E_\infty \exp\left[-b \times n_v^C(\%)\right] \quad \text{with } E_\infty = 54\ \text{GPa and } b = 0.03 \tag{11}$$

where E the static modulus of elasticity.

7. Conclusion

This work is related to the study of some physical and mechanical properties of NA and RCA provided from waste construction materials. These aggregates are used for preparation of concrete for building structure applications. The main objective is to analyze in details the characteristics of the aggregates in order to promote their use in concrete construction applications.

Results point out that, the WA and the porosity of RCA are higher than those of NA, on the other hand, the RCA owning a low density. The resistance to fragmentation of RCA is significantly lower than that of NA. In contrast the MDE is slightly greater for RCA than that of NA as well as the resistance to freezing/thawing cycles.

The old cement paste present in RCA contains micro cracks due to the crushing process of old concrete blocks provided from building demolition waste. It is responsible of porosity's rise then the WA increases and therefore the decrease of density, wear resistance, abrasion resistance and frost resistance independently of RCA's sources. However, it seems that this old cement paste protects natural granular against frost, therefore freezing/thawing cycles affects RG more severely than NG.

In this work, we attest that, the Voigt's model can be used to predict all the studied properties of gravels mixes (NA and RCA) except for MDE.

The relationships between physical and mechanical properties of aggregates were analyzed and the models based on a strong coefficient of correlation are proposed. It can be point out that the WA has linear relationship with its porosity, particle density and strength (LA). The increase of WA and porosity leads a decrease in strength and density of aggregates.

It is worth mentioning that for the concretes, the tests were realized after the concrete being submerged in water for 28 consecutive days.

The concrete porosity was significantly affected by the ratio of substitution, the paste volume and the porosity of their granular mixture, it has to be noted that, the increase of these three phenomena lead an increase in the concrete porosity. Moreover, the compressive strength of concrete has relationship with its gravels' strength (LA).

Arguably, the compressive strength and tensile splitting strength of concrete decrease while, the LA coefficient and porosity of its granular mixture increase.

Through establishing the relationship between the Young's modulus and concrete open porosity, the modulus increases by increasing of concrete porosity.

The models with strong correlation are proposed for these relationships.

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