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Rheological, physico-mechanical and durability properties of multi-recycled concrete

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Abstract. The present work looks at the possibilities of recycling more than once demolished concrete as coarse aggregates, to produce new concrete. Different concrete mixes were made with substitutions of 50%, 75% and 100% of recycled concrete aggregates respectively as coarse aggregates. The physico-mechanical characterization tests carried out on the recycled concrete aggregates revealed that they are suitable for use in obtaining a structural concrete. The resulting concrete materials had rheological parameters, compressive strengths and tensile strengths very slightly lower than those of the original concrete even when 100% of two cycles recycled concrete aggregates were used. The durability of the recycled aggregates concrete was assessed through water permeability, water absorption and chemical attacks. The obtained concretes were thought fit for use as structural materials. A linear regression was developed between the strength of the material and the number of cycles of concrete recycling to anticipate the strength of the recycled aggregates concrete. From the results, it appear clear that recycling demolished concrete represents a valuable resource for aggregates supply to the concrete industry and a the same time plays a key role in meeting the challenge for a sustainable development.

Keywords: recycled coarse aggregates; recycled concrete; Rheological parameters; strength; capillary water absorption; water permeability; chemical attacks

1. Introduction

Concrete is the most used construction material throughout the world (Nagaratnam *et al.* 2017). This building material, for which aggregates are the essential ingredient for its formulation since they occupy more than 70% of its volume, has gained this ranking by its fabrication simplicity, its usage flexibility, its ease of concreting and its relatively better durability (Ernst and Markus 2009).

The fabrication of concrete necessitates, thus, huge quantities of aggregates and their ever increasing demand is further accentuated with the evolution of human comfort needs (Sallal *et al.* 2018). Recycling aggregates from demolished concrete and concrete rubbles becomes a viable option since it represents, on one hand, a solution for the protection of the environment from solid waste disposals and, on the other hand, a new supply source of aggregates for making concrete (ACI2011, Kim and Goulias 2015, Esteban *et al.* 2017).

Moreover, rubble materials from demolition of old building sites and from deconstructions in general are in growing quantities and are either land filled or wildly disposed of, causing a serious negative impact on the environment and a drawback for a sustainable development (Hong *et al.* 2017). The protection of our environment leads in no doubt to a sustainable development and goes inevitably through recycling demolished concrete to make aggregates for new concrete. In this sense, building waste accounts for a larger proportion of industrial waste, and demolished concrete debris occupy a large part of such building waste (Hong *et al.* 2017, Rita 2015). Yet, the possibility of completely reusing and recycling the demolished concrete into aggregates for making new concrete has just begun in some places of the world, while it is totally absent in others.

Recycling concrete demolition waste is expected to be even more feasible in the future owing to the rapid depletion of the remaining natural aggregate resources in some regions, which will lead to a lack of such materials and hence increase the prices and create a need for replacements with recycled aggregates (Rolf and Werner 2007). Moreover, new sites for production will be located further and further away from urban areas and hence from construction sites, which will result in costs and environmental problems from increasing transport. Furthermore, the recycling option is helped by the continuing advances in the technology and development for the production and use of recycled materials which will inevitably lead to more cost-efficient demolition methods and recycling plants and a better control of the quality of the recycled product. The lack of space for landfills and the ever-increasing need for land for economic development to

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Table 1 Chemical and mineralogical composition of cement used

Chemical components %									
CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	PAF	RI
61,32	21,93	4,94	3,11	0,66	2,40	0,27	0,60	2,20	0,4
Mineral components %									
C_3S		C_2S			C_3A		C_4AF		
61,50		16			7,25		11,00		

suit human comfort make recycling concrete demolition debris a reliable solution (Amorim *et al.* 2013). With the rareness of quality aggregates in the future and greater awareness of environmental protection, the need to use recycled aggregates more effectively has never been greater. This will, in no doubt, lead to the use of recycled aggregates in new concrete production (Mayuri *et al.* 2018). However, scientific information on using recycled concrete as aggregates to produce a new structural concrete is still insufficient in many regions of the world (El Otaibi and El Houary 2005). Indeed, some contradictory results obtained did not help to stimulate the concrete industry in using such an ingredient for making new concrete (Ridzuan *et al* 2005, Wang and Huang 2003). In Algeria and in third world countries in general, very little is known about the use of recycled aggregate in the manufacture of new concrete (Debieb and Kenai 2008, Azzaz and Chemrouk 2014a). Recycling concrete from structure to structure is necessary and responds to the quest for a life cycle assessment of the built environment in order to fulfil the need for a sustainable development. In this sense, a sustainable construction could be described as a way of designing and constructing buildings that support human health and which are in harmony with nature; buildings which meet the needs for the current generation and which can be transmitted safely to the future generations (Hendriks and Janssen 2004).

The essential aim of the present work is the study of the rheological as well as the physico-mechanical properties of concrete made partially (50% and 75% recycled) or totally (100% recycled) of aggregates recycled from used concrete and of aggregates recycled from reused concrete; that is from two cycles recycled concrete. Water absorption tests, water permeability tests and chemical attack simulation will give some hints as to the durability of concrete made of recycled concrete aggregates. The recycled concrete aggregates considered in this investigation come from the wastes of concrete cylinders, concrete cubes and small blocks of concrete slabs which are crushed in a jaw crusher to produce fractions of aggregates of 15 mm as maximum size.

2. Experimental procedures

2.1 Materials

The cement used in all the mixtures was a Portland cement with additives, locally produced, with a specific surface of 3200 cm^2/g and an average compressive strength

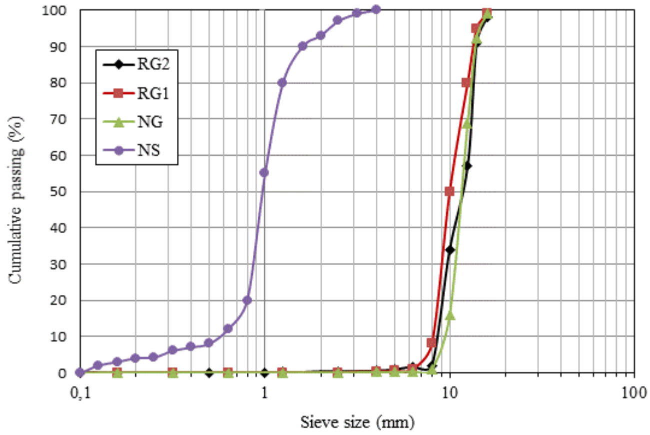


Fig. 1 Grading of natural and recycled aggregates

Fig. 2 Typical compression failure of concrete cylinder, showing non-crushed aggregate particles

of 42.5 MPa. The chemical and mineral compositions of the cement used are presented in Table 1.

The Fine aggregates consisted of a crushed sand coming from a quarry with dimensions varying from 0 to 4 mm. Coarse aggregates consisted of natural limestone aggregates crushed in a quarry into aggregate particles having regular forms and sizes varying from 3 to 15 mm. The coarse aggregates, designated in this work NG (Natural Gravel), are used to make a 30 MPa compressive strength concrete at 90 days (28 MPa at 28 days). The recycled concrete aggregates (RG1) coming from the waste of the tested original concrete were characterized physico-mechanically and used partially and totally for making a new recycled aggregate concrete (RG1C) which had a compressive strength of 27 MPa at 90 days when 100% of recycled aggregates (RG1) were used. This obtained recycled aggregates concrete was in turn crushed and recycled into coarse aggregates designated as RG2. The recycled gravel aggregates (RG2) were in turn characterized physico-mechanically and used partially and totally for making a new recycled aggregates concrete (RG2C) which had a strength of 24 MPa at 90 days when 100% of recycled aggregates (RG2) were used; that is for concrete type RG2C3 (see the notations below). The size distributions of the aggregates used in making the 7 types of concrete considered in this study are shown in Fig. 1.

2.2 Shape and surface texture of recycled aggregate particles

(a) NG aggregate (b) RG1 aggregate (c) RG2 aggregate

Fig. 3 Typical natural and recycled concrete aggregates

(a) NG aggregate (b) RG1 aggregate (c) RG2 aggregate

Fig. 4 Texture of the different types of aggregates

The shape of the aggregate particles of the recycled aggregates is more or less the same as that of the original natural aggregates, since no aggregate crushing was observed during the testing (Fig. 2). This is due to the higher crushing strength of the aggregates by comparison to that of the cement paste.

It is to be noted however that the cement paste bonded to the aggregate particles did create a slight angularity for the recycled aggregates, particularly for those obtained after the second concrete recycling. The texture of the recycled aggregate particles is rougher than that of the original aggregate particles. This rougher surface is due to the cement mortar bonded on the aggregate surface as illustrated in Figs. 3-4. In this sense (Huan *et al.* 2016), a rougher surface is more preferable than a smooth one since it helps to develop a better bond between the hardened cement paste and the aggregate particles, even though it may retain more dust.

2.3 Mix design of natural aggregates and recycled aggregates concretes

The water/cement ratio of all the concrete mixes was kept constant at 0.6. This allowed for observations to be made on the stiffness of the concrete mixes as the proportion of the recycled aggregates increased and as the number of cycles of concrete recycling into aggregates increased. In the absence of any method for designing concrete mixes using recycled demolished concrete as aggregates, recycled aggregates concrete mixes were conceived simply by replacing a part of the proportion of coarse aggregates, or the whole of it, in the natural aggregates concrete mix by a relevant proportion of recycled coarse aggregates in accordance with the Dreux concrete mix design method (Dreux and Fista 1995), using a target strength of 28 MPa at 28 days. Seven concrete mixes, identified below, were prepared in this work as given in Table 2.

Table 2 Mix proportions (kg/m^3) of the natural aggregates and recycled aggregates concretes

Type of concrete	Replacement ratio (%)	Cement (kg/m^3)	Sand (kg/m^3)	Natural Gravel (NG)	Recycled Gravel (RG1)	Recycled Gravel (RG2)
NGC	0	350	544	1286	/	/
RG1C1	50%NG+50%RG1	350	544	643	643	/
RG1C2	25%NG+75%RG1	350	544	321	965	/
RG1C3	100%RG1	350	544	/	1286	/
RG2C1	50%NG+50%RG2	350	544	643	/	643
RG2C2	25%NG+75%RG2	350	544	321	/	965
RG2C3	100%RG2	350	544	/	/	1286

NGC: Natural aggregates (gravel) concrete. **RG1C1**: Recycled aggregates (first recycling) concrete having 50% of natural aggregates and 50% of recycled aggregates. **RG1C2**: Recycled aggregates (first recycling) concrete having 25% of natural aggregates and 75% of recycled aggregates. **RG1C3**: Recycled aggregates (first recycling) concrete having 0% of natural aggregates and 100% of recycled aggregates. **RG2C1**: Recycled aggregates (second recycling) concrete having 50% of natural aggregates and 50% of cycle two recycled aggregates. **RG2C2**: Recycled aggregates (second recycling) concrete having 25% of natural aggregates and 75% of cycle two recycled aggregates. **RG2C3**: Recycled aggregates (second

Fig. 5 Principal parts of the rheometer test (ICAR type Rheometer)

recycling) concrete having 0% of natural aggregates and 100% of cycle two recycled aggregates.

2.4 Testing recycled aggregates concrete

The fresh concrete properties of both the recycled aggregates concrete and the natural aggregates concrete were studied through workability measurements. In this sense, slump tests (NF EN 12350-2 2012) were carried out on samples of fresh concrete made of recycled aggregates, including the two cycles of recycling, RG1 and RG2, and made of natural aggregates NG.

The workability can also be appreciated through the flowability of the fresh concrete. This 'flow' behaviour of a fresh concrete mixture is governed by parameters such as the yield stress of the plastic concrete mixture and the plastic viscosity. Both of the parameters were measured through a rheometer test, shown in Fig. 5.

The characterization of the recycled aggregates concrete at the hardened state is appreciated primarily through the compressive strength measured from the crushing of concrete cubes of 150×150×150 mm, to assess the strength gain with age of recycled aggregates concrete. This compression measurement has covered a whole strength evolution with age, up to 90 days.

The tensile strength is also an important parameter, characterizing concrete at the hardened state. In the present work, the tensile strength of the recycled aggregates concretes was measured at 28 days of age through the splitting test carried out on concrete cubes 150×150×150 mm.

The long term durability of recycled aggregates concrete is appreciated in this study through water absorption tests, water permeability tests and chemical attacks.

Water absorption test consists of measuring the quantity of water absorbed by none-saturated concrete through capillarity. For this test, 100×100×100 mm concrete cubes were oven-dried and made impervious on the lateral faces to prevent the absorbed water from evaporation and to insure a uniaxial absorption of water. The concrete specimens were then immersed partially in water at a depth of 5 mm. At prescribed intervals of time, the immersed concrete specimens were taken out and weighed after wiping away the concrete faces from water drippings and then the specimens were put back in the water recipient.

Permeability tests have also been conducted at 56 days and at 90 days of age, using water as fluid. The concrete cubic specimens 150×150×150 mm were subjected to a permeability test under a specified water pressure (5 bars) for a specified period of time (72 hours). The concrete specimens were then subjected to tensile splitting to allow for measurements of the depth of water penetration as in Fig. 6.

Fig. 6 Measurements of the depth of water penetration inside the different types of concrete

Some chemical agents such as sulphates, chlorides or acids from the environment may react with some concrete constituents, inducing the deterioration of concrete at the longer term and hence affecting its durability. In the present work, chemical attacks of recycled aggregates concrete were simulated through the immersion of concrete cubes 100×100×100 mm into liquid solutions containing sodium chloride (NaCl), magnesium sulphate ($MgSO_4$) and sulphuric acid (H_2SO_4) respectively.

3. Results and discussion

3.1 Properties of recycled aggregates

3.1.1 Density and water absorption of recycled aggregates

Table 3 presents the physical properties of aggregates, including the recycled concrete aggregates, used in making the seven types of concrete identified previously in section 2.3. From Table 3, it can be clearly seen that the absolute density (unit weight) of the aggregates decreases with the number of cycles of concrete recycling into aggregates; decreases of 8% and 15% were recorded for first cycle

Table 3 Physico-Mechanical characteristics of the recycled and natural aggregates

Aggregate	NG	RG1	RG2	NS
Fineness modulus	/	/	/	2.75
Sand equivalent (%)	/	/	/	79.1
Unit weight (kg/m3)	2680	2470	2285	2710
Los Angeles (%)	24	34	38	/

Notation : NG : Natural Granulates; RG1: First cycle Recycled Granulates; RG2: Seconde cycle Recycled Granulates; NS: Natural Sand

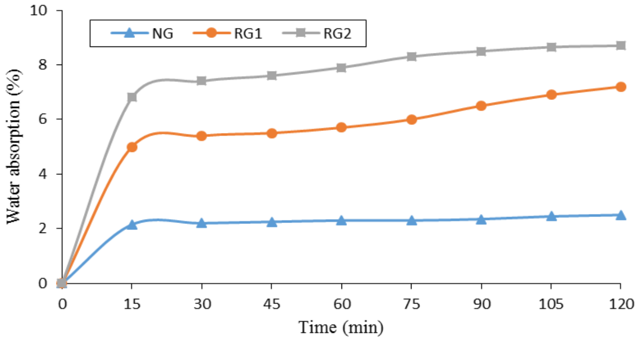


Fig. 7 Water absorption of different types of aggregates

recycled aggregates (RG1) and second cycle recycled aggregates (RG2) respectively. Similar results were reported in the literature (Debieb and Kenai 2008, Kenai *et al.* 2002, Poon and Chan 2006). This decrease is thought to be due to the lower density of the cement mortar bonded to the natural aggregate particles (Cheng-chih *et al.* 2015).

Recycled aggregates have relatively higher water absorption by comparison to the natural ones. This water absorption increases further as the porosity becomes higher with the number of cycles of concrete recycling (Fig. 7). Such trend of increasing water absorption, exhibited by recycled concrete aggregates, applies whatever is the type of the parent concrete (Hearn *et al.* 1994).

Such water absorption is naturally due the porous nature of the hardened cement paste bonded on the aggregates' particles. The more cement paste is bonded to the recycled aggregate particles, the higher the porosity is and consequently the higher the water absorption of the recycled aggregates is (Khoshkenari *et al.* 2014). Obviously, such water absorption should be taken into consideration in any concrete mix design and might be advantageous for the continuation of the cement hydration in the case of premature evaporation of mixing water. It could also be advantageous in offering the necessary moisture against shrinkage of the cement paste on drying.

3.1.2 Mechanical properties of recycled aggregates

The mechanical properties of the aggregates considered in this study were essentially the abrasion and attrition through the Los Angeles test since its results show good correlation not only with the actual wear of aggregates when used in concrete, but also with the strength of concrete made with these recycled aggregates (Azzaz and Chemrouk 2014b). Indeed, it is recommended (NF EN 1097-2 2010) that for obtaining a concrete of 30 to 35 MPa,

Table 4 Properties of the fresh concrete produced

Type of concrete	W/C	Slump (mm)	Entrapped Air
NGC	0.6	115	1.60
RG1C1	0.6	85	1.75
RG1C2	0.6	73	1.95
RG1C3	0.6	65	2.45
RG2C1	0.6	80	2.10
RG2C2	0.6	65	2.30
RG2C3	0.6	55	2.60

the aggregates should have a Los Angeles coefficient less than 40. In the present study, the Los Angeles of the recycled aggregates was well below this limit even after the second cycle of recycling concrete into aggregates; that is for the RG2 aggregates as illustrated in Table 3.

It is to be noted that aggregates having lower values of Los Angeles are more resistant mechanically and hence result in a stronger concrete. In the present investigation, the Los Angeles of the natural aggregates (NG) was 24, that of the aggregates after first recycling of concrete (RG1) was 34 and that of the aggregates after the second recycling (RG2) 38. From the literature, it is reported (Quebaud 1996) that the presence of old mortar on the recycled aggregate particles reduces the resistance to wear and to impact loads and inevitably yields to a relatively lower quality concrete than the original one (Valerie and Aissa 2013). The Los Angeles values recorded in the present tests on natural and recycled aggregates are in line with previous results from the literature, which report values lying between 32 and 38 for recycled concrete aggregates and between 23 and 30 for natural aggregates (Katz 2003).

3.2 Properties of fresh concrete

3.2.1 Workability of recycled aggregates concrete

In general, the slump of fresh concrete, and hence its workability, decreases with the increase in the replacement ratio of recycled aggregates and also with the number of cycles of concrete recycling (Yasser 2016). Table 4 shows the slump test results which decrease when 100% of second cycle recycled aggregates are used (concrete RG2C3) to more than half of that when natural aggregates are used (concrete NGC). Such a loss in the workability is related to the relatively higher water absorption of the recycled aggregates. Such water absorption is mainly due to the porous hardened cement paste bonded to the natural aggregate particles (Salesa *et al.* 2017). However, with the advances in the materials' technology, high efficiency plasticizers are developed for the concrete industry and could be used to compensate for such a loss in workability. This will inevitably add an extra cost to the concrete production, but such an extra cost will certainly be offset by the diverse gains achieved from recycling demolished concrete. The result of Table 4 concerning the slump measurements are plotted against the proportions of recycled aggregates used in the concrete mixes as illustrated in Fig. 8. It can be seen from Fig. 8 that the workability of fresh concrete decreased almost linearly with the proportion

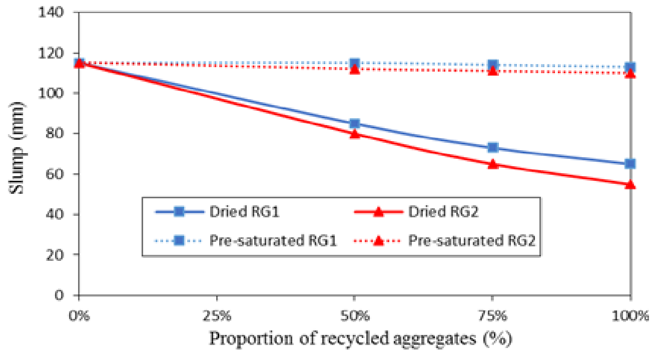


Fig. 8 Variation of the workability of concrete with the rate of substitution of recycled aggregates

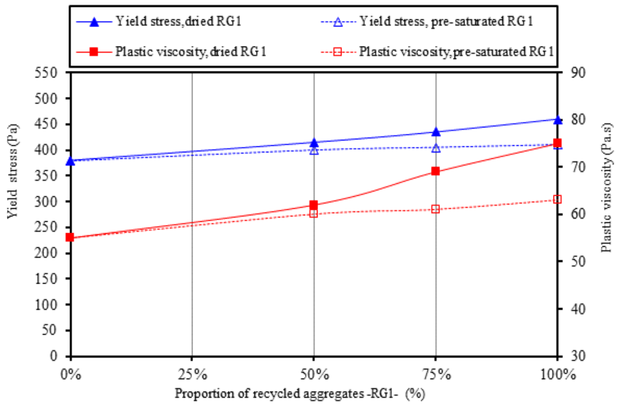
of recycled aggregates used in the mix. It should be pointed out, however, that the decrease in workability remains largely within the specified tolerances (±25 mm) between the recycled aggregates after first cycle of concrete recycling (aggregates RG1) and those after the second cycle of concrete recycling (aggregates RG2).

These results are in conformity with those found by Folino and Xargay (2014) who have reported decreases in the slump values from 180 mm to 55 mm when the replacement rate reaches 100% of recycled aggregates. When the aggregates are pre-saturated before concrete mixing, the loss of slump, and hence of workability, with the proportion of recycled aggregates is almost negligible for the first cycle recycled aggregates (RG1) as well as for the second cycle recycled aggregates (RG2). The saturated pores of the hardened cement paste covering the aggregate particles represent water storages which facilitate the workability of recycled aggregates concrete.

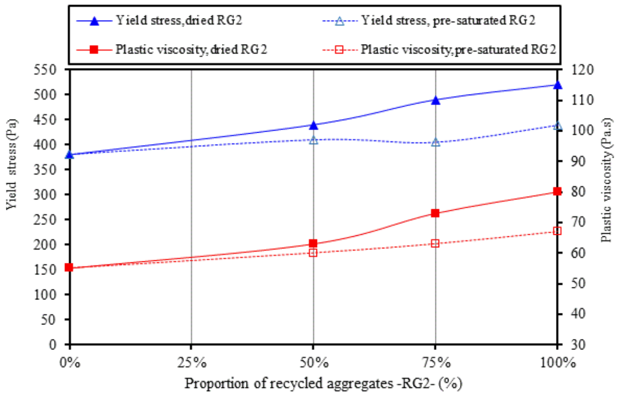
3.2.2 Rheological parameters measurement

Fresh concrete is considered as saturated porous material where hydration, evaporation and absorption are combined together to influence the rheological properties of concrete. The presence of water required to lubricate the aggregates and cement particles and induce the hydration reaction controls the hydro-mechanical behaviour of concrete at early age. When the recycled aggregates are used in the dried state, they lead to a net decrease in the workability of concrete and make its rheological parameters difficult to measure, especially for low w/c ratios (Ait Mohamed *et al.* 2016).

For a w/c ratio of 0.6, the results of the rheological parameters with several replacement rates of RG1and RG2 are illustrated in Fig. 9. When recycled aggregates (RG) are used dry in concrete mixing, the workability is strongly reduced; this loss of workability follows a monotonic increase in the replacement rate of natural aggregates (NG) by recycled aggregates (RG). From Fig. 9, for concrete made solely with recycled aggregates (100% RG), the yield stress of the fresh mix increases by 70% for the first cycle recycled aggregate (RG1) and by 110% for the second cycle recycled aggregates respectively. The viscosity followed also the same trend, making an increase of 60% for the first cycle recycled aggregates (RG1) and 100% for the second cycle recycled aggregates (RG2). This may be due to the



(a) Cycle 1 recycled aggregates



(b) Cycle 2 recycled aggregates

Fig. 9 Variation of rheological parameters of concrete with rate of substitution of recycled aggregate

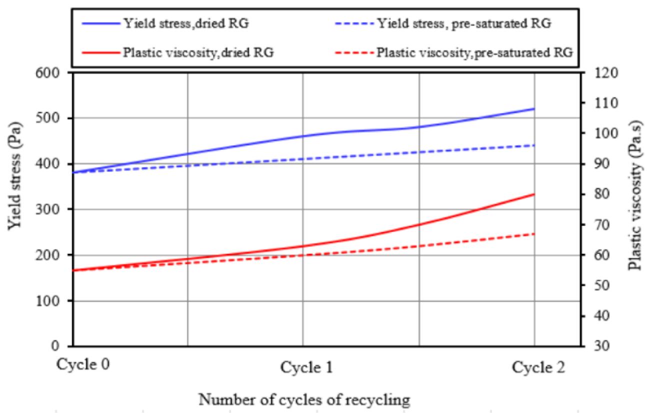


Fig. 10 Relation between the rheological parameters and the number of cycles of concrete recycling

higher water absorption capacity of recycled aggregates (RG) compared to the natural aggregates (NG) as reported by Corinaldesi and Moriconi 2010 who suggested to pre-saturate recycled aggregates (RG) before adding them to the mixture. Indeed, Fig. 9 shows a clear reduction in the increase of the rheological parameters when recycled aggregates are pre-saturated before use. For the same reason, Hansen and Narud (1983) have attributed the loss of workability of recycled aggregate concrete to the rougher surface texture and to the angularity of the recycled

Table 5 Density, compressive strength and tensile strength of fabricated concretes

Type of concrete	Unit weight (kg/m^3)	Compressive strength $\overline{f_c}$ (MPa)									Tensile strength (MPa)
		7 days	28 days			56 days	90 days				
			$\overline{f_c}$	σ	C_V	$\overline{f_c}$	$\overline{f_c}$	σ	C_V		
NGC	2345	22	28	2.1	7.5	29	30	2.3	7.6		2.4
RG1C1	2318	20	27	2.3	8.5	28	28.5	2.4	8.4		2.25
RG1C2	2280	19	25	2.5	10.0	26	27.5	2.7	9.8		2.14
RG1C3	2225	18	24	2.6	10.8	25	27	2.9	10.7		2.10
RG2C1	2290	18	26	2.4	9.2	26.5	28	2.6	9.2		2.25
RG2C2	2245	16.5	24	2.8	11.6	25.5	27	3.1	11.4		1.90
RG2C3	2165	15	21.5	3.0	13.9	22.5	24	3.3	13.7		1.80

With $\overline{f_c}$: Mean compressive strength, σ: Standard deviation, C_V: Variance coefficient

aggregates in addition to the presence of residual mortar on their surface.

The present results are in line with those reported in the literature by Ait Mohamed *et al.* (2016) who argued that incorporating a saturated recycled concrete aggregate has a lesser effect on the rheological parameters and hence on workability. They found that, for concrete made with 60% of pre-saturated recycled aggregates (RG), slump remains practically unaffected while the increase in viscosity is reduced from 170% obtained for concrete made with dried recycled aggregates to 60% and that of the yield stress from 90% to 35% respectively.

The increase in the rheological parameters with the number of cycles of concrete recycling into aggregates, as shown in Fig. 10, is attributed to the increase in the quantity of cement mortar attached to the natural aggregates. This cement mortar fixed to the aggregate particles contains a large volume of pores which promote the absorption of mixing water, leading to the reduction in the lubrication effect of recycled aggregates concrete, as expressed by the rheological parameters of Figs. 9 and 10 and reported in the literature (Adjoudj *et al.* 2014).

3.3 Properties of hardened concrete

3.3.1 Unit weight of recycled aggregates concrete

The values of the densities at 28 days of age for the different concretes fabricated with recycled aggregates and with natural aggregates are presented in Table 5. The variation of the density of concrete with the proportions of recycled aggregates substituting natural aggregates (coarse aggregates) for the two types of recycled aggregates concrete (RG1C and RG2C) is represented in Fig. 11. An almost linear regression is observed for both recycled concretes, with a relatively steeper regression slope for concrete made with aggregates from the second cycle of concrete recycling. A decrease of 10% in the density of concrete is recorded when 100% recycled aggregates from the second cycle of concrete recycling (RG2) were used. This is due to the presence of relatively more voids in the internal structure of the recycled concrete material by comparison to the natural aggregates concrete and also to the presence of pores in the old cement paste bonded to the recycled concrete aggregates. However, this decrease in the density, which might reduce the stiffness of the material and

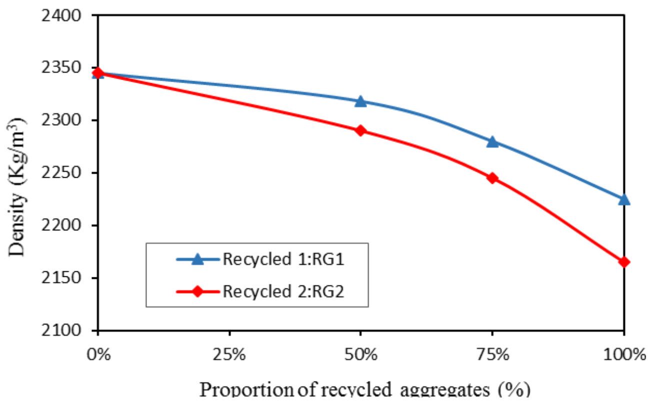
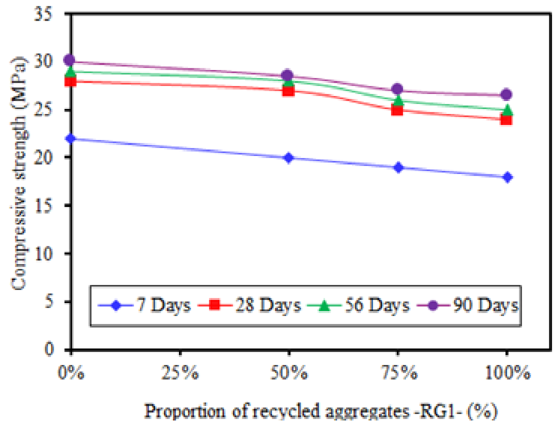


Fig. 11 Variation of density of hardened concrete with rate of substitution of recycled aggregates

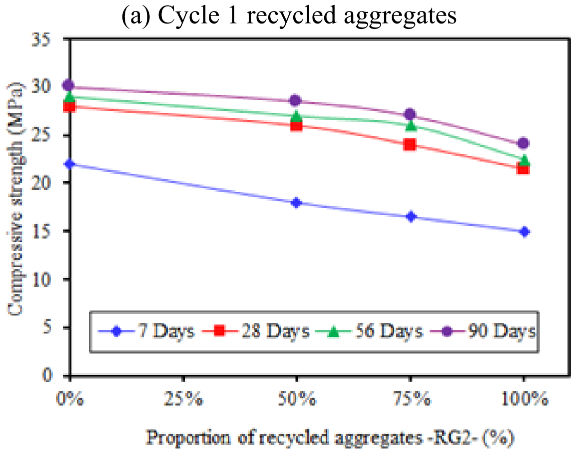
hence its modulus of elasticity, could be indeed considered as negligible in concrete technology, considering the heterogeneous nature of the material in general. For concrete made at 100% of recycled aggregates from the first cycle of concrete recycling, the drop in the density was smaller and did not exceed 7%. This is very satisfactory and is in line with the results reported in the literature (Debieb and Kenai 2008). Furthermore, such a drop in the density of concrete made with recycled aggregates could be overcome by the addition of smaller quantities of mineral fines such as calcareous fines or blast furnace slag fines, to fill-in the extra voids and hence improve the density of recycled concrete. The use of these industrial by-products has an environmental benefit and makes concrete even more friendlier material since it relieves nature from these solid disposal wastes.

3.3.2 Strength in compression of recycled aggregates concrete

The results of the compression strength for the recycled aggregates concretes (RG1C, RG2C) and the natural aggregates concrete (NGC) are presented in Table 5. The variation of the compressive strength of the seven types of concrete fabricated, that is the variations of the compressive strength of concretes with the different substitution rates of recycled aggregates from the first cycle of recycling and from the second cycle of recycling, is illustrated in Figs. 12(a) and (b) respectively. It can be clearly seen from the two Figs. 12(a) and (b) that the compressive strength



(a) Cycle 1 recycled aggregates



(b) Cycle 2 recycled aggregates

Fig. 12 Variation of compressive strength of concrete with rate of substitution of recycled aggregates

decreases with the rate of recycled aggregates substitution at all ages, particularly for concrete made with two cycles recycled concrete aggregates. The decrease in the strength, however, does not seem to be very important, particularly when aggregates from the first cycle of concrete recycling are used in making concrete; that is concrete RG1C. Indeed, the decrease in strength at 28 days of age was in the order of 15% (from 28 to 24 MPa) when 100% recycled aggregates from first cycle of concrete recycling are used in making recycled aggregates concrete (concrete RG1C3). Such strength decrease appears to be linear with the rate of recycled aggregates substitution. For a rate of 50% substitution of natural aggregates by first cycle of recycled concrete aggregates (concrete RG1C1), the strength of concrete decreased by less than 8%. The results obtained for the strength of concrete using recycled concrete as coarse aggregate are comparable with those reported in the literature (Al-Otaibi and El-Hawari 2005, Yaragal *et al.* 2016, Zheng *et al.* 2018) where 20% decrease in strength is reported for a substitution rate of 100% and a slight decrease of about 6% for 50% substitution rate. For recycled aggregates concrete made from the second cycle of concrete recycling into aggregates, the strength decrease reached 22% (from 28 to 21.5 MPa) for a substitution rate of 100 %; that is when concrete was made solely with recycled aggregates from the second cycle of concrete recycling (concrete RG2C3). The strength decrease for this

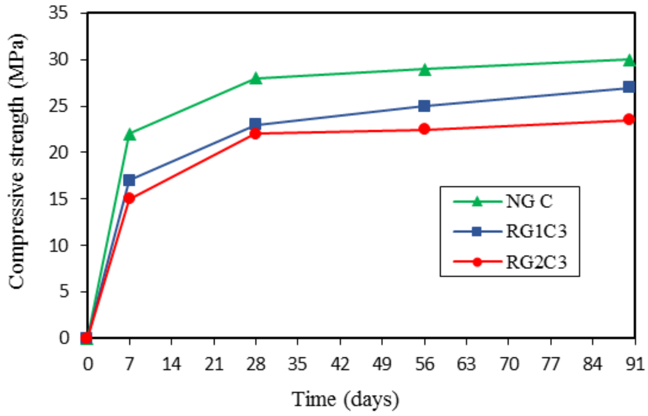


Fig. 13 Evolution of the strength of recycled aggregates concretes with age

second order recycled aggregates concrete seems also to be linear with the substitution rate of recycled aggregates, with a little steeper slope than that of the first order recycled aggregates concrete. It should be noted however, that the strength decrease from concrete made of first cycle recycled concrete aggregates to that made of second cycle recycled concrete aggregates is negligible and there seems to be no appreciable difference between the two recycled concretes in terms of compressive strength (24 MPa for RG1C3 and 21.5 MPa for RG2C3 compared to 28 MPa for NGC). In real practice, strength decreases such as those recorded for the recycled aggregate concretes of the present study could be considered as within the standard deviation limits of the strength for ordinary concrete, a heterogeneous and complex material. Moreover, in third world places, concrete technology has always been considered as a ‘low- tech’ technology and higher differences in strength are obtained from one batch to the other for a concrete having the same mix ingredients and proportions. Strength differences such as those obtained in the present study between natural aggregates concrete and recycled aggregates concrete are quite common in real third world concrete sites. The decrease in the strength of recycled aggregates concrete could be explained by the relatively early rupture of the bond between recycled aggregates and the cement paste; such bond being disturbed by the existing hardened cement paste from the parent concrete.

For a better comprehension of the strength evolution of concrete with time, the strength gain with age for three types of concrete, namely concrete made with natural aggregates (NGC), concrete made with 100% first cycle recycled concrete aggregates (RG1C3) and concrete made with 100% second cycle recycled concrete aggregates (RG2C3) is shown in Fig. 13. It can be seen from Fig. 13 that the strength evolution of the recycled aggregates concretes is similar in all aspects to that of the natural aggregates concrete (Ngoc Kien *et al.* 2017), with a rapid evolution, translating a rapid hydration, within the seven first days. This rapid evolution during the early age calls for an adequate curing to attenuate the heat generated and avoid early evaporation of water which may lead to a premature stoppage of the hydration reaction. After 28 days of age, the compressive strength seems to progress at a very slow rate

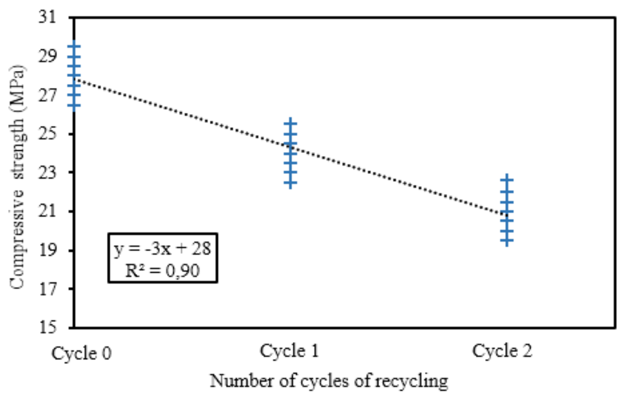


Fig. 14 Relation between compressive strength and number of cycle of concrete recycling, with: Cycle 0= NGC; Cycle 1= RG1C3; Cycle 2: RG2C3

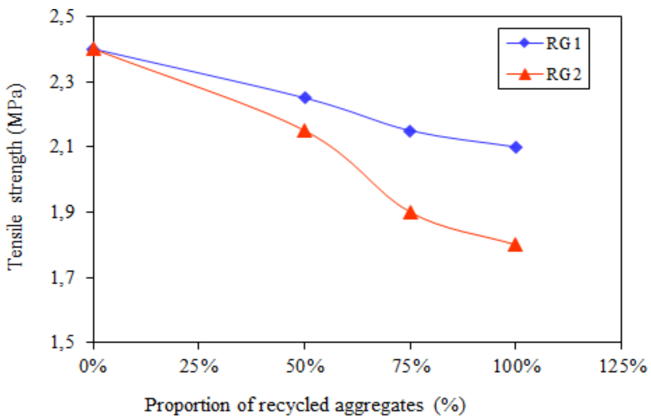


Fig. 15 Variation of tensile strength of concrete with rate of substitution of recycled aggregates

which could be considered as negligible as for natural aggregates concrete.

An attempt is made to relate the decrease in the strength of concrete with the number of cycles of concrete recycling. For the mathematical relation, cycle 0 (n=0) refers to 100% natural aggregates, cycle 1 (n=1) refers to 100% of first cycle recycled concrete aggregates and cycle 2 (n=2) refers to 100% of second cycle recycled concrete aggregates. The variation of the compressive with the number of cycles of concrete recycling is represented in Fig. 14.

From Fig. 14, a linear regression of the compressive strength as a function of the number of cycles of concrete recycling was worked out with a correlation coefficient of 90%. From this, it is tempting to propose the following mathematical model to anticipate the compressive strength of concrete made solely with recycled aggregates consisting of n-cycles of recycled concrete:

$$\mathbf{f_c = -3n + f_0}$$

Where f_0 is the compressive strength of the parent ordinary concrete; that is the compressive strength of the original ordinary concrete, n is the number of cycles of concrete recycling and f_c is the anticipated compressive strength of the recycled aggregates concrete.

3.3.3 Strength in tension of recycled aggregates concrete

In general the tensile strength of concrete is very low by comparison to the compressive strength; it varies between (1/12 to 1/10) of the compressive strength in ordinary concrete (Dreux and Fista 1995, Kong and Evans 1987). An ordinary concrete may be considered as that having a compressive strength between 20 and 40 MPa. For such a concrete, the tensile strength may vary between 1.67 and 4 MPa according to the variation interval above. The tensile strength values obtained for the natural aggregates concrete (NGC), for the first cycle recycled aggregates concretes (RG1C) and for the second cycle recycled aggregates concretes (RG2C) of the present study are presented in Table 5. The tensile strengths measured vary between 1.8 and 2.4 MPa and are within the limits of an ordinary concrete, even for concrete made with two cycles recycled concrete aggregates (RG2C3). However, the results illustrated in Fig. 15 show clearly that the tensile strength reduces with the rate of recycled aggregates substitution.

With the use of 100% recycled concrete aggregates from first cycle, the tensile strength of recycled aggregates concrete was 2.1 MPa, that is a reduction of 13% by comparison to that of the original concrete made with natural aggregates (a reduction from 2.4 to 2.1 MPa). When 100% recycled concrete aggregates from the second cycle were used, the tensile strength dropped to 1.8 MPa, registering a reduction of 25% by comparison to that of the natural aggregates concrete. These results are consistent with those reported in the literature (Marco 2015, Saha and Rajasekaran 2016, Ngoc Kien *et al.* 2017) where 20 to 40% decreases in the 28 days tensile strength were observed. Fig. 15 exhibits an approximate linear decrease of the tensile strength as the substitution rate of the recycled aggregates is increased from 0% to 100%, with a relatively steeper decreasing slope for concrete made with two cycles recycled concrete aggregates. Tensile strength reductions in the same range were also reported earlier (Debieb and Kenai 2008) with crushed bricks recycled as aggregates for concrete. The lower tensile strength values of recycled aggregates concrete imply an early cracking in this type of concrete. In this sense, steel fibers may be used to improve the tensile behaviour of recycled aggregates concrete as was found in previous studies (Boulekbache *et al.* 2015, Chemrouk *et al.* 2013). The tensile strength is very dependent on the bond developed between the aggregates and the hardened cement paste. In the case of recycled concrete aggregates, the cement mortar, which covers partially or totally the surface of the aggregate particles, may disturb the correct bonding between the recycled concrete aggregate and the cement paste of the new recycled aggregates concrete.

3.4 Durability of recycled aggregates concrete

The durability of concrete could be defined as the ability of the material to maintain its physical characteristics and mechanical properties in satisfactory service and security conditions all through the prescribed service life of the structure made with it (Kong and Evans 1987). This refers then to the ability of concrete to resist the forces acting on

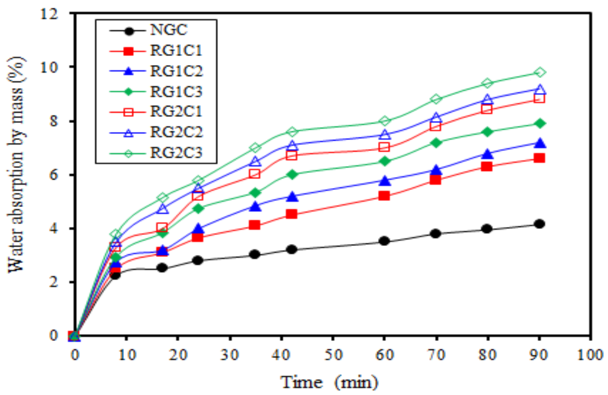


Fig. 16 Water absorption for the different recycled concretes fabricated

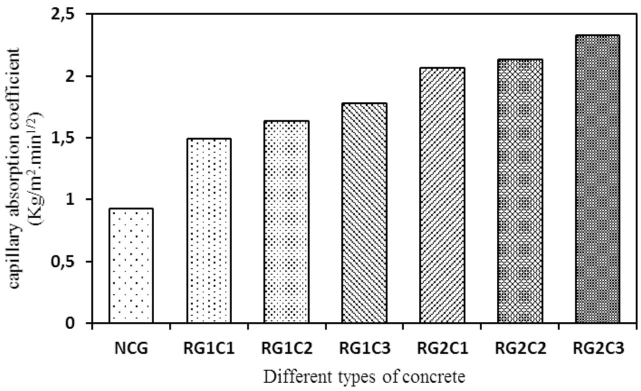


Fig. 17 Absorption coefficient of the different types of concrete

the structure and withstand the environmental conditions to which the structure and hence concrete is exposed. The durability of a material is intimately related to its permeability, which refers to the ease with which a fluid can pass through concrete, including fluids transporting aggressive agents which may, in time, deteriorate concrete and hence affect its durability. Water absorption tests and permeability tests are very important indicators for the appreciation of the durability of concrete.

3.4.1 Water absorption of recycled aggregates concrete

The water absorption results are presented in Fig. 16. It can be seen from Fig. 16 that water absorption increases with the rate of recycled aggregates substitution and with the number of recycling cycles. Following this trend, recycled concrete made with 100% of cycle 2 recycled concrete aggregates (RG2C3) had indeed the highest water absorption (10%) while concrete made with natural aggregates (NGC) had the lowest (4%). These results are consistent with those reported by De Birto and Nabajyoti (2013), Ozbakkaloglu *et al.* (2018) who observed a gradual increase in the water absorption capacity of concrete as the replacement of fine natural aggregate by recycled concrete aggregates increased. This indicates that recycled aggregates concrete is bound to have some absorption problems, the severity of which depends on the rate of recycled aggregates substitution and on the number of cycles of concrete recycling into aggregates. Fig. 16 shows that the water absorption increases with time for all the seven types of concrete and tends to stabilise after a long period; that is after all the existing pores are saturated. This relatively high water absorption of recycled aggregates concretes, particularly that of concrete made with two cycles recycled concrete aggregates (RG2C3), which is more than twice that of natural aggregates concrete (NGC), could be explained by the relatively higher porosity of recycled concrete aggregates due to the recycled cement paste bonded on them. This will make an overall larger mortar volume in recycled aggregates concrete which induces higher water absorption. In this sense, Koenders *et al.* (2017), Guo *et al.* (2018) have reported that recycled concrete aggregates can be considered as a two-phase composite consisting of 'original' natural coarse aggregates and attached mortar (AM) made of sand, hydration products and fractions of un-hydrated cement. The attached mortar is the part which is responsible for the increased absorption capacity of recycled concrete aggregates, due to its relatively higher porosity in comparison with natural aggregates (Koenders *et al.* 2017). Moreover, to appreciate the depth of the existing pores within concrete and how much harm could be done to a concrete material at the longer term, the capillarity absorption coefficients were calculated and are shown in Fig. 17 for the different recycled aggregates concretes.

The capillarity absorption coefficient gives an indication on the inter-connectivity of the pores within concrete and hence translates the ability of conveying aggressive agents inside concrete and how deep these agents can be transported inside the internal structure of the material, and hence how deep will be the deterioration concrete.

The results indicate that this coefficient increases with the rate of substitution of recycled aggregate and with the number of cycles of recycling. The results of Figs. 16 and 17 indicate that durability could be of concern for recycled aggregates concrete unless special care is taken to cater for this porosity such as the addition of mineral fines to densify the internal structure of recycled aggregates concrete. The water absorption test results are in line with the density tests results (Fig. 11) and with the compressive strength results (Table 5, Fig. 12).

3.4.2 Water permeability of recycled aggregates concrete

Fig. 18 illustrates the depth of water penetration as a function of the rate of recycled aggregate substitution. The results of Fig. 18 show that the depth of penetration of water is greater in concrete made with two cycles of recycled concrete aggregates (RG2C3), with values of penetration depth almost twice those of natural aggregate concrete (NGC). This translates the penetration risk of aggressive agents such as the sulphate or chloride chemicals inside concrete, which eventually end up by deteriorating it and inducing durability problems for concrete made with 100% recycled concrete aggregates, particularly for the two cycles recycled concrete aggregates. The same Fig. 18 shows that the depth of water penetration reduces slightly with the maturation of concrete from 56 days to 90 days.

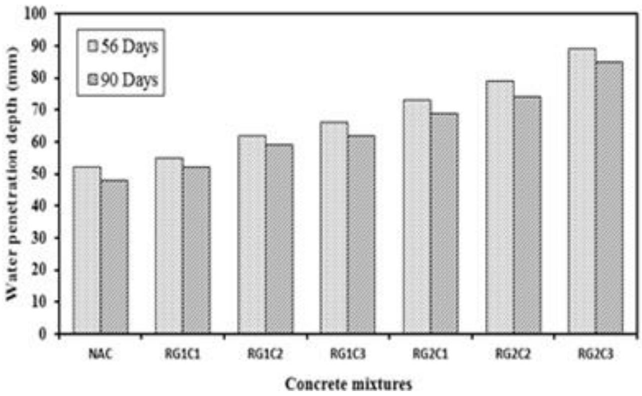


Fig. 18 Water penetration depth inside the different types of recycled aggregates concrete

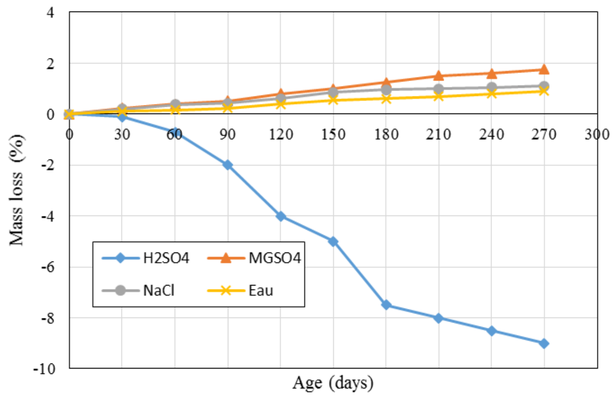


Fig. 19 Mass loss/gain of natural aggregates concrete (NGC) in the different chemical solutions

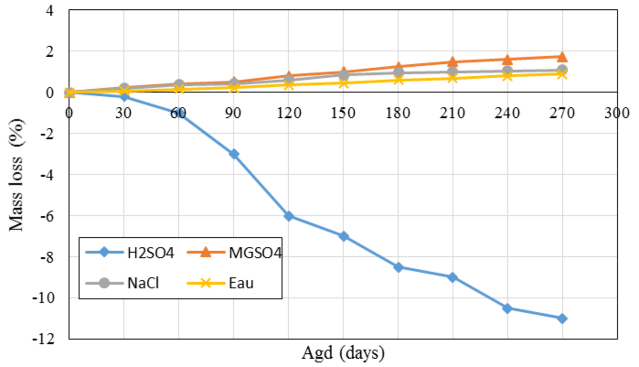


Fig. 20 Mass loss/gain of cycle 1 recycled aggregates concrete (RG1C3) in the different chemical solutions

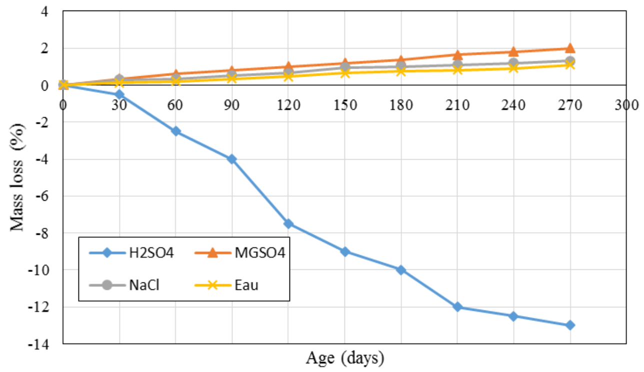


Fig. 21 Mass loss/gain of cycle 2 recycled aggregates concrete (RG2C3) in the different solutions

According to the literature (Ann *et al.* 2008, Kouider *et al.* 2018), recycled aggregates have higher porosity characteristics which lead to higher water penetration into recycled aggregates concrete by comparison to natural aggregates concrete. In this sense, Kenai *et al.* (2002) have found that water permeability has doubled when replacing natural aggregates with recycled aggregates. Therefore for durability concern, precautions should be taken when using recycled aggregates for making concrete.

Water permeability results are consistent with capillary water absorption results as water permeability and capillarity are more related to the size and type of pores (Yahiaoui *et al.* 2017).

3.4.3 Chemical attacks of recycled aggregates concrete

A mass loss can be considered as a good indicator for the resistance of a material to chemical attacks. In this sense, the greater the dissolution of the material, the greater the mass loss and the higher the risk of deterioration of the material is. An excess mass gain may also lead to the deterioration of concrete through cracking after a swelling process. The variations of the masses of the different concretes fabricated in the present study and preserved in different chemical solutions are illustrated in Figs. 19, 20 and 21.

Generally, concrete immersed in water continues to gain weight through a hydration reactivation. The same behavior is recorded for concrete exposed to sodium chloride NaCl and to magnesium sulphate $MgSO_4$ (Figs. 19, 20, 21). In this sense, concrete immersed in magnesium sulphate $MgSO_4$ recorded higher increases in weight than those achieved in other media. This can be explained by the formation of various bulky products such as ettringite and gypsum which can subsequently cause the expansion, leading to the cracking of concrete (Benosman and Mouli 2009). A study by Yildirim and Sumer (2013) showed that the water absorption of cement mortars exposed to magnesium sulphate $MgSO_4$ is higher than the water absorption of mortars exposed to chloride.

In contrast, recycled concretes immersed in sulfuric acid H_2SO_4 lost weight. The loss of mass after 270 days of immersion in an acid solution for the different recycled concretes is 9, 11 and 13% for natural aggregates concrete, for cycle 1 recycled aggregates concrete and for cycle 2 recycled aggregates concrete respectively. Similar results were reported recently by Mohamed and El-gamal (2017).

The action of acids on concrete (Fig. 22) consists of an attack on the components of the hardened cement paste. This action leads to a transformation of all the calcium compounds. As a consequence of the transformation, the bonding capacity of the hardened cement paste is destroyed. The rate of attack depends on the quality and permeability of concrete, and also on the solubility of the salt resulting from calcium (Bakharev *et al.* 2003). The loss of mass is due to the fact that portland cement, after hydration, releases a portion of free calcium hydroxide ($Ca(OH)_2$)

Fig. 22 State of concrete specimens after 270 days of immersion in H_2SO_4 (5%) solution

Fig. 23 State of concrete specimens after 270 days of immersion in $MgSO_4$ (5%) solution

which can be leached outside when subjected to acid attack. For concrete in contact with sulfuric acid (H_2SO_4), calcium hydroxide reacts with sulfuric acid to form calcium sulphate. Then all the components of the cement paste will be broken down and leached.

For the samples of concretes immersed in magnesium sulphate (Fig. 23), a smooth white film is formed on the surface, especially for cycle 1 and 2 recycled concretes. This may be due to the high presence of the old cement paste, which promotes the chemical reaction. However, this bleaching was observed without any flaking or swelling or cracking of the material (Fig. 23). This characteristic whitish appearance is, according to (Neville 2008), a sign of a sulphate attack. The reaction of magnesium sulphate with Portland cement leads to the formation of brucite and gypsum (De Schutter 2012). Other researchers (Sakaropoulou *et al.* 2012) believe that the low solubility of brucite helps to maintain the Portlandite and thus reduce the PH of the medium, making the calcium silicate hydrate C-S-H more susceptible to sulphate attack.

The samples of concretes immersed in sodium chloride NaCl became more opaque with a smoother surface (Fig. 24). White spots are formed all over the surface and a very fine white precipitate is deposited on the walls of the storage tank. No cracking was recorded on the surface of the specimens.

Fig. 24 State of concrete specimens after 270 days of immersion in NaCl (5%) solution

4. Conclusions

From the present experimental work on recycled and multi-recycled aggregates concrete, the following conclusions can be made on the properties and the values of such concrete material:

- The physico-mechanical properties of recycled concrete aggregates are not much different from those of natural aggregates. In this sense, the resistance to wear and abrasion of recycled concrete aggregates, expressed by the Los Angeles coefficient, is found to be within the limits recommended by international codes for concrete making, even after a second round of recycling. Recycled concrete aggregates may be partially or totally enveloped with hardened cement paste, which favours water absorption when used in concrete making. This will inevitably lead to a stiffer fresh concrete as indicated by the slump test and by the rheological parameters investigated in this work.
- The Compressive strength was reduced by 15% and 22% for concrete made with one cycle recycled concrete aggregates and two cycles recycled concrete aggregates respectively, by comparison to that of the parent concrete. Such strength decreases could, however, be considered as within the fluctuations which may occur for different batches of the same concrete mix and is then within the tolerances of a standard deviation for ordinary concrete. The evolution of the compressive strength of recycled aggregates concrete with age is similar in all aspects to that of the natural aggregates concrete, with a high and rapid strength gain at the early age and a very low strength gain after 28 days. From the results, a mathematical model is proposed to anticipate the compressive strength of concrete made completely with recycled aggregates consisting of n-cycles recycled concrete.
- The tensile strength reduction was 13% and 25% respectively for concrete made with one cycle recycled concrete aggregates and two cycles recycled concrete aggregates respectively, by comparison to that of the parent concrete. The tensile strength is found within the expected range of variation of this mechanical property for ordinary concrete ($1/12f_{c28}$ to $1/10f_{c28}$), even for

concrete made with 100% two cycles recycled concrete aggregates (RG2C3).

• The durability of recycled aggregates concrete could be affected when using 100% of recycled concrete aggregates, particularly for concrete made with two cycles recycled concrete aggregates. Concretes made of recycled and multi-recycled aggregates exhibited a relatively more loss of mass in the presence of acids (H_2SO_4) than the natural aggregate concrete. In the presence of chlorides and sulphates (NaCl and $MgSO_4$), a small gain in mass is registered. This excess in mass may lead to expansion and induce cracking at the longer term.

• As a synthesis, recycled concrete aggregates are suitable for making ordinary concrete that could be used in the construction industry as a structural concrete even after two cycles of concrete recycling. Indeed, valuing demolished concrete as aggregates for making a new concrete has a great impact on the environment in a sense that it represents a new source for supplying aggregates. This will also safeguard the ecological equilibrium and relief Nature from building demolition waste disposals as landfills.

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