Rheology and strength of concrete made with recycled concrete aggregates as replacement of natural aggregates

Újrahasznosított beton adalékanyag hatása a beton szilárdságára és reológiai tulajdonságaira

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Abstract

This paper presents the results of an experimental study carried out to evaluate the influence of the nature and the content of the recycled fine and coarse aggregates from concrete construction and demolition wastes on the rheological and strength properties of concrete. For this purpose, concretes mixtures were made with different percentages (15, 30, 50, 70 and 100%) of recycled sand and recycled gravel. Three different cement / admixture ratios were used. At fresh state, tests applied include slump, yield stress, plastic viscosity, air content and fresh density. Moreover, in order to follow the evolution of these properties over time, the tests were carried out at different times: directly after mixing, 30 minutes, 60 minutes and 90 minutes after completion of the mixing). At hardened state, compressive strength was determined at age of 7 and 28 days. The results show that, the properties of the concretes made with recycled aggregates depend up on the cement / admixture ratio and the substitution level of recycled aggregates. This means that there is indeed an influence of the recycled aggregates on the compatibility (physicochemical equilibrium) of the cement / admixture ratio. This influence is more noticeable on the sand than on the gravel. The results also show that, increasing the percentage of substitution of recycled aggregates in concrete mixture increases the yield stress and the plastic viscosity of fresh concrete. However, a decrease in the compressive strength was found with increasing the content of recycled aggregate.

Keywords: concrete, admixture, recycled aggregates, yield stress, rheology, mechanical strength
Kulcsszavak: beton, adalékszer, újrahasznosított adalékanyag, folyáshatár, reológia, szilárdság

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1. Introduction

Given the strong demand and supply for material resources and the need to preserve the environment in a sustainable development vision, it has become essential to investigate all possibilities for the reuse and recycling of wastes and industrial by-products in the field of civil engineering [1,2]. Indeed, concrete is the most widely used construction material in the field of civil engineering, despite its high environmental impact. The cement is made from limestone and requires a very high-temperature heating of 1450°C, engendering high CO_2 emissions. So, about 8% of the worldwide emissions are stemming from the manufacturing of cement. As an example, the production of a ton of Portland cement generates 930 kg of CO_2. The manufacturing of the cement establishes then an important source of greenhouse gas. The extraction of aggregates participates in the high carbon assessment of the concrete as well.

Every year, 3 billion tons of waste are produced in Europe, among which approximately 900 million by the construction industry, is more than 25% of all produced waste [3]. Indeed, the demolition of damaged or obsolete structures generate a huge quantity of concrete waste which creates serious ecological and environmental problems [4]. One way to minimize this impact is the use of recycled concrete aggregates [5–11]. Actually, the incorporation of recycled aggregates from construction waste or demolition significantly improves the ecological footprint of concrete. The concrete mixtures have rheological properties that are characterized by the parameters of Bingham material model (the yield stress and the plastic viscosity). The constituents' properties and mixtures composition affect commonly these parameters [12–15].

Slump is the most practical and widely accepted measure of the rheological behavior of concrete. Slump is not only an index of flow behavior, which includes the workability and implementation of fresh concrete, but is also used to quantify the consistency of mixtures. Variations of slump in concrete may be caused by factors related to concrete mix-design, particularly the quantity of water, as well as aggregate properties such as granular distribution, shape, and water absorption. In the field of construction, with the development of new concretes and new installation techniques such as pumping and projection, the control of the rheological behavior of fresh concrete becomes principal factor to facilitate its implementation [16]. It is also necessary to define the basic parameters that are used in the rheological behavior of a material as well as the most common behavioral models. Several rheological behaviors which are divided into two major families: Newtonian fluids and non-Newtonian fluids [8,17]. In the case of fresh concrete, workability is studied. The first, consistency, is an index of the mobility (ability to flow) of fresh concrete. The second is an indication of stability (ability to prevent segregation). For only a few decades, more characterizations that are precise have appeared to determine quantities related to the Bingham parameters.

The rheological test is essential for the execution of a construction project. During the mix-design of concrete in the laboratory to the test, the workability of concrete can be predicted on site. At the time of the construction of the structure, it is used for quality control, thus making it possible to take the necessary precautions before placing the concrete in case of an accident that can occur during manufacturing. The test therefore, avoids or minimizes economic loss. Many tests essentially empirical have been developed to evaluate the workability of concrete [18]. However, the complexity of the concrete mixture makes it difficult to study the rheology of this material. Some authors, then, propose a simplification that considers the fresh concrete as a two-phase material (cement paste and aggregates). Nevertheless, the interaction between these two phases does not consist in a simple lubrication between paste and aggregates, but in a complicated combination of the viscous effect of the paste and the mass of the aggregates. Therefore, it is useful to understand the rheology of cement paste, which has much in common with that of concrete. Some factors influencing the rheology of fresh concrete are related to the nature of the materials and water absorption capacity, which is higher for recycled aggregates than natural aggregates [1,19]. Other factors are related to the composition of the concrete itself. These factors are determining its rheology then concern the formulation of the concretes (water / cement (W/C), gravel / sand (G/S), paste volume, additions). The time factor is an important in the evaluation of the rheology of concrete, since it is not intrinsically part of the composition of the concrete. The duration of the period during which the fresh concrete remains sufficiently workable is limited due to the hydration process. When this limit is exceeded, the concrete loses its workability and its rheological behavior is changed.

In this context, the main objective of this research is to study the effect of recycled aggregate concrete (RAC) with different substitution percentages of 15, 30, 50, 70, and 100% of coarse and/or fine natural aggregate (NA) by recycled aggregate (RA), and the cement / admixture combination on the rheological behavior of concretes. Three different times T0, T30 and T90 were considered corresponding to 0 min, 30 min and 90 min after completion of mixing.

2. Materials

2.1 Cement

Three types of cement, CEM I 52.5R CE CP2 (C1), CEM I 52.5R CE (C2) and CEM I 52.5N CE CP2 ES (C3) from LAFARGE in France were used. The chemical and physical properties of these cements are summarized in *Table 1*. From *Table 1*, cement C1 has a higher C_3A and a lower C_3S than those of cement C2 and C3.

Cement	C1	C2	C3
Nomination	CEM I 52.5R CE CP2	CEM I 52.5R CE	CEM I 52.5N CE CP2 ES
Blaine Fineness (cm²/g)	4520	3250	4110
Median diameter (µm)	9.7	16.5	12.3
Water demand (%)	27.2	26.0	26.5
Initial setting time (min)	120	165	140
Hydration heat at 41h (j/g)	328	300	320
S_iO_2	19.54	20.19	20.1
Al_2O_3	5.70	3.81	5.5
Fe_2O_3	3.06	2.99	4.8
CaO	60.10	61.50	59.70
SO_3	3.71	3.31	2.31
MgO	1.85	1.96	3.26
K_2O	0.86	0.81	1.81
Na_2O	0.19	0.17	0.22
Cl^-	0.07	0.02	0.06
Loss on ignition	0.33	0.68	0.78
Clinker (%)	99	98	99
Alite (C_3S) (%)	53.4	67.0	46.4
Belite (C_2S) (%)	15.8	7.4	22.7
Aluminate (C_3A) (%)	9.9	5.0	6.5
Ferrite (C_4AF) (%)	9.2	9.1	14.6

Table 1 Chemical analysis and physical properties of cements used
1. táblázat Az alkalmazott cementek kémiai összetétele és fizikai tulajdonságai

2.2 Fine aggregates

Natural sand (NS) (0/4 mm) from limestone quarries and recycled concrete sand (RS) from concrete construction and demolition wastes (0/4 mm) from a recycling plant were used. Steps used to prepare recycled aggregates (RA) are detailed in [1]. The grain size distribution and morphological appearance of recycled and natural aggregates are presented in [1]. Water absorption and density are given in *Table 2*. The fineness modulus of RS (3.27) is significantly higher than that of NS (2.25).

Type of aggregate	Water absorption (%)	Density (%)
NS (0/4 mm)	0.9	2.59
RS (0/4 mm)	10.0	2.71
NG (4/10 mm)	0.5	2.71
RG (4/10 mm)	5.1	2.17
NG (10/20 mm)	0.4	2.31
RG (10/20 mm)	5.7	2.29

Table 2 Water absorption and density of aggregates used
2. táblázat Az alkalmazott adalékanyagok vízfelvétele és sűrűsége

2.3 Coarse aggregates

Two natural limestone gravels (NG) of fractions (4/10 mm and 10/20 mm), and two recycled gravels (RG) of fractions (4/10 mm and 10/20 mm) concrete construction and demolition wastes are used in this study. The grain size distribution of recycled and natural aggregates is presented in [1]. Density and water absorption are given in *Table 2*. Recycled aggregate (RA) shows relatively higher water absorption compared to NA.

2.4 Admixtures

Three admixtures (A1, A2 and A3) are used. Their physical properties and chemical analysis are summarized in *Table 3*.

Admixtures	A1	A2	A3
Chemical Type	Polycarboxylate	Ether polycarboxylique	Polycarboxylate
Type	High water reducing	Water reducing	Water reducing
Solids content	22.5%	22.5%	20%
Shape	liquid	liquid	liquid
Colour	light yellow	light brown	light yellow
pH	4 up to 6	6 up to 8	4.5 ± 1.0
Recommended Dosage	0.1% up to 3.0%	0.2% up to 1.9%	0.1% up to 3.0%
Content Na_2O Eq.	≤ 1%	≤ 1%	≤ 0.5%
Content ions Cl^-	≤ 0.1%	≤ 0.1%	≤ 0.1%

Table 3 Chemical analysis and physical properties of used admixtures
3. táblázat Az alkalmazott adalékszerek kémiai összetétele és fizikai tulajdonságai

3. Experimental program

3.1 Mixture proportioning

Three concretes (with cement C1, Cement C2 and Cement C3) and 36 different concrete mix proportions have been used, keeping the same quantity of cement and the same granular selection. Either coarse aggregates or natural sand were partially replaced by RA with percentages of replacement of 15, 30, 50, 70 and 100% respectively to the amount of aggregate. All the mixtures proportions of concretes are summarized in *Table 4*.

3.2 Casting and testing

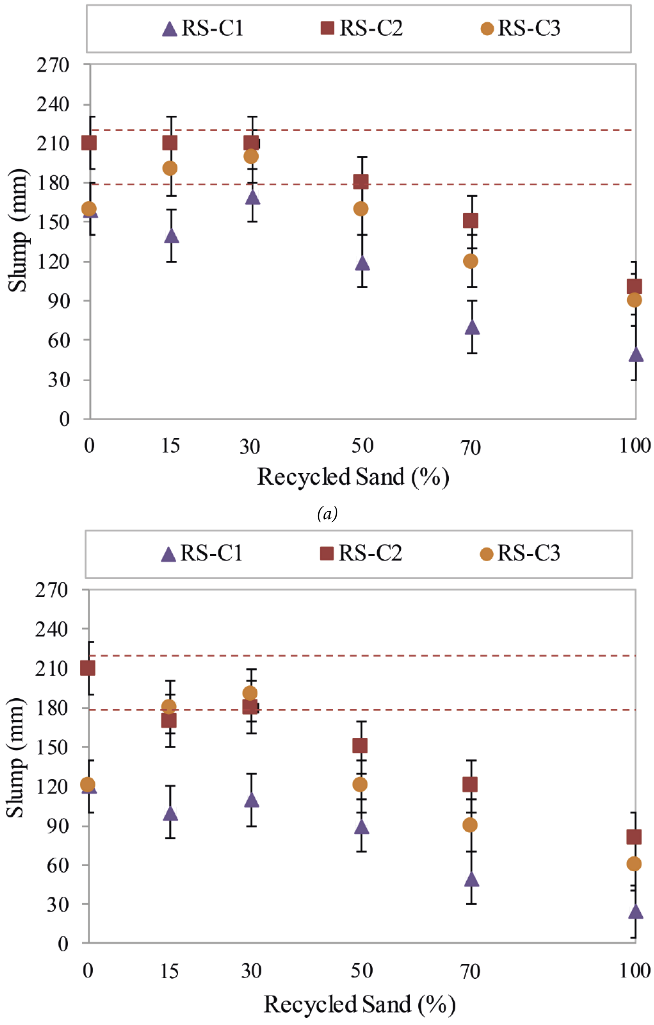
The recycled aggregates were used in a saturated state, and steps used to prepare recycled aggregates are detailed in [1]. The rheological behavior of concretes made with recycled sand is studied using a concrete rheometer developed by Soualhi et al [21]. The principle consists in rotating a blade in a cylindrical sample of fresh concrete at different speed stages. The torques applied to rotate the blade at different speed levels are measured. The rheological parameters (the yield stress and the plastic viscosity) are then calculated.

The compressive strength was measured at the ages of 7 and 28 days according to NF P 18-455 [20].

4. Results and discussion

4.1 Workability

In all concrete mixes, constant slump of 200 +/- 20 mm is used, in order to limit the number of mixes. Slump results of concrete mixes with recycled sand is shown in *Fig. 1*. It is evident that slump is almost constant for mixes with 30% of RS, but beyond this percentage, the slump is reduced with 55% to 65% when RS content increases. This is due to the particle packing and surface roughness of the particles of RS. these results are similar to those reported by [21,22]. On the other hand, regardless of the cement / admixture ratio, low rheology is with 100% recycled sand. This is due to particle packing of recycled sand and surface roughness. It is observed that, irrespective of RS used, concrete made with cement C2 prove higher slump than that with cement C3 and C1. This can be explained by the lower amount of C_3A in cement C2. So, the degree of hydration of the cement is delayed and the workability of the mixture is increased [23]fillers and superplasticisers are typically added to the binder system. It is clear that cement, filler and admixture interact, and influence concrete properties. By means of an experimental programme on concrete with different types of Portland cement, with and without partial cement replacement by silica fume, and considering a naphthalene sulphonate superplasticiser, the interaction between C3A, silica fume and naphthalene sulphonate superplasticiser has been investigated. A higher C3A content of the Portland cement leads to a higher required dosage of superplasticiser. Partial cement replacement by silica fume leads to an acceleration of the second hydration peak (hydration of C3S.



(a)

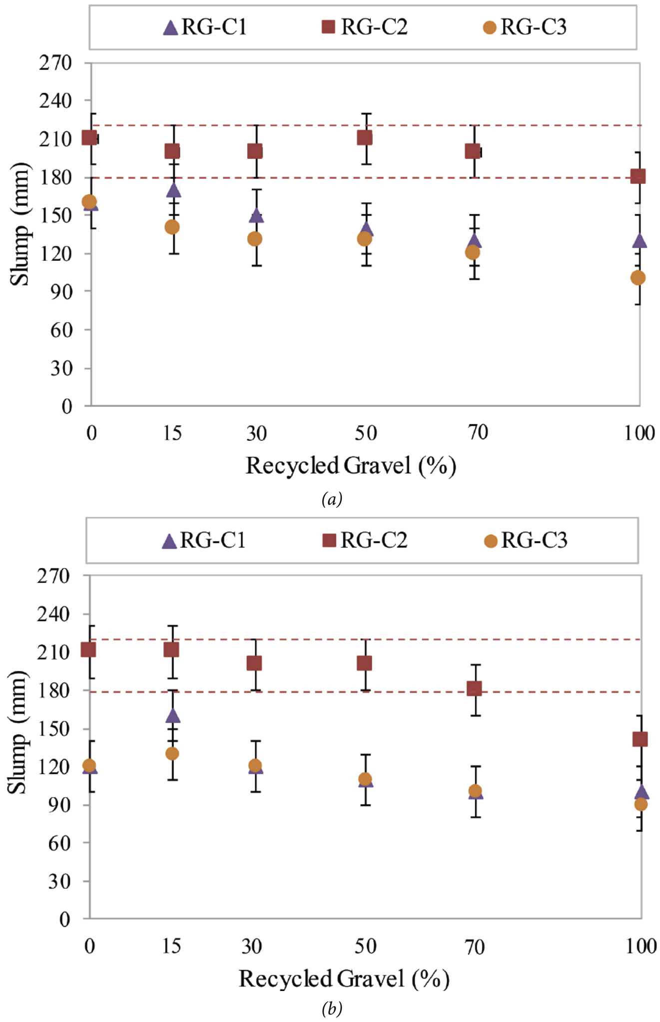
(b)

Fig. 1 Variation of slump with percentage of substitution in RS: (a) T30; (b) T90
1. ábra A roskadás változékonysága az újrahasznosított homok (RS) mennyiségének függvényeként: (a) T30; (b) T90

Cement (C)	Mixture	C	NS	RS	NG (4/10)	NG (10/20)	RG (4/10)	RG (10/20)	SP (%)	Water (kg/m^3)	w/c
		(kg/m^3)									
C1	0RS0RG	320	852	0	325	696	0	0	0.40	188	0.59
	15RS0RG		724	105					0.40	196	0.61
	30RS0RG		596	211					0.40	206	0.64
	50RS0RG		426	350					0.40	218	0.68
	70RS0RG		256	492					0.40	231	0.72
	100RS0RG		0	702					0.30	250	0.78
	0RS0RG		852	0	325	696	0	0	0.40	188	0.59
	0RS15RG				276	592	42	87	0.40	193	0.60
	0RS30RG				228	487	84	173	0.58	200	0.63
	0RS50RG				163	348	140	288	0.65	205	0.64
	0RS70RG				98	209	195	404	0.78	217	0.68
	0RS100RG				0	0	279	578	0.78	200	0.63
C2	0RS0RG	320	852	0	325	696	0	0	0.20	176	0.55
	15RS0RG		724	105					0.40	185	0.58
	30RS0RG		596	211					0.40	195	0.61
	50RS0RG		426	350					0.40	205	0.64
	70RS0RG		256	492					0.40	220	0.69
	100RS0RG		0	702					0.40	238	0.74
	0RS0RG		852	0	325	696	0	0	0.20	176	0.55
	0RS15RG				276	592	42	87	0.67	182	0.57
	0RS30RG				228	487	84	173	0.51	189	0.59
	0RS50RG				163	348	140	288	0.50	200	0.63
	0RS70RG				98	209	195	404	0.48	206	0.64
	0RS100RG				0	0	279	578	0.42	218	0.68
C3	0RS0RG	320	852	0	325	696	0	0	0.30	180	0.56
	15RS0RG		724	105					0.40	195	0.61
	30RS0RG		596	211					0.40	203	0.63
	50RS0RG		426	350					0.40	215	0.67
	70RS0RG		256	492					0.40	230	0.72
	100RS0RG		0	702					0.40	245	0.77
	0RS0RG		852	0	325	696	0	0	0.30	180	0.56
	0RS15RG				276	592	42	87	0.50	188	0.59
	0RS30RG				228	487	84	173	0.50	190	0.59
	0RS50RG				163	348	140	288	0.45	200	0.63
	0RS70RG				98	209	195	404	0.45	220	0.69
	0RS100RG				0	0	279	578	0.42	228	0.71

Table 4 Mixtures proportions of concrete
4. táblázat Beton keverékek összetétele

Fig. 2 shows slump of concrete mixes with RG. It can be seen that regardless of cement / admixture ratio, slump decreases slightly with increasing of the percentage of RG. The slump of concrete with cement C2 is higher than that of concrete with cement C3 and C1. It can be seen also that (i) workability of RAC with cement C2 is better; (ii) workability reduces with higher percentage of recycled aggregates. Up to 30% recycled sand, slump values are similar. However, beyond 30% recycled sand, reduction was significant; 80% for 100% of recycled sand, (iii) reduction in workability of RAC with RS is higher than with RG, and this is due to the interaction between C_3A and superplasticizer [23,24]fillers and superplasticisers are typically added to the binder system. It is clear that cement, filler and admixture interact, and influence concrete properties. By means of an experimental programme on concrete with different types of Portland cement, with and without partial cement replacement by silica fume, and considering a naphthalene sulphonate superplasticiser, the interaction between C3A, silica fume and naphthalene sulphonate superplasticiser has been investigated. A higher C3A content of the Portland cement leads to a higher required dosage of superplasticiser. Partial cement replacement by silica fume leads to an acceleration of the second hydration peak (hydration of C3S.



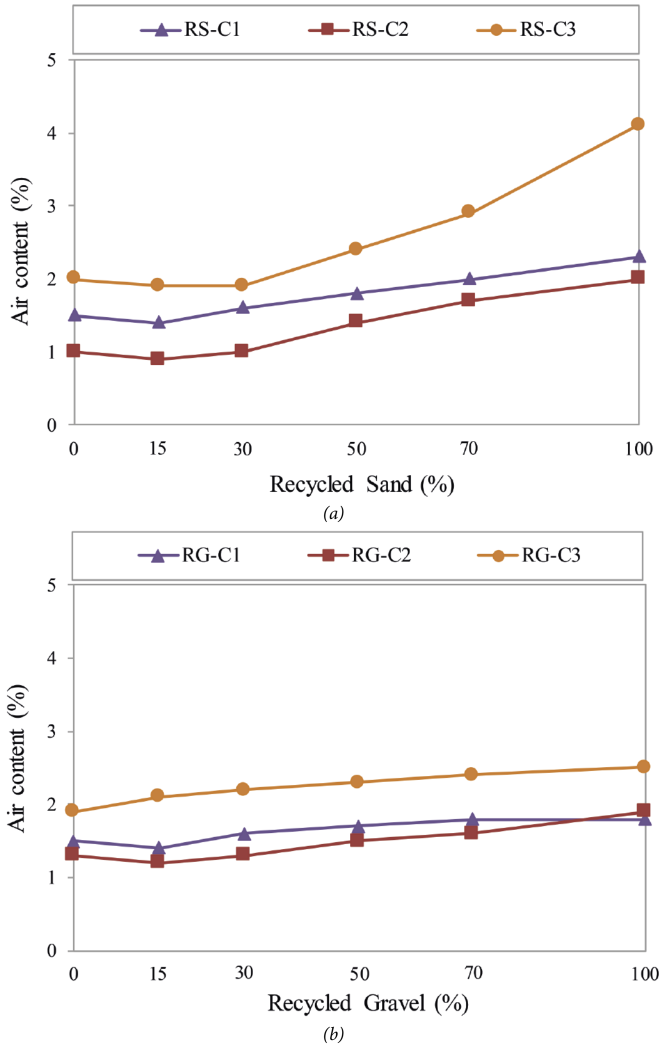
(a)

(b)

Fig. 2 Variation of slump with percentage of substitution in RG: (a) T30; (b) T90
2. ábra A roskadás változékonysága az újrahasznosított durva adalékanyag (RG) mennyiségének függvényeként: (a) T30; (b) T90

4.2 Air content and density

Air content and density results of concrete are shown in *Fig. 3* and *4*. It can be seen that beyond 30% of RS, and whatever the type of cement used in mixtures, the air content is higher than mixture with 0% of RS. Effectively, because of the roughness and shape of the recycled sand and the formation and immobility of air bubbles during vibration of concrete, since the recycled sand has a higher porosity than natural sand [25]. The results also show that the air content of RAC are affected by cement / admixture ratio. Concretes with the cement C3 and C2 have lower air content than those made with cement C1. Similarly, the figures indicate that with an increase in recycled gravels, the air content increases. However, this increase is slightly less than that the one observed with RS. This result indicates that the fine portion of RA influences negatively the behavior of RAC.



(a)

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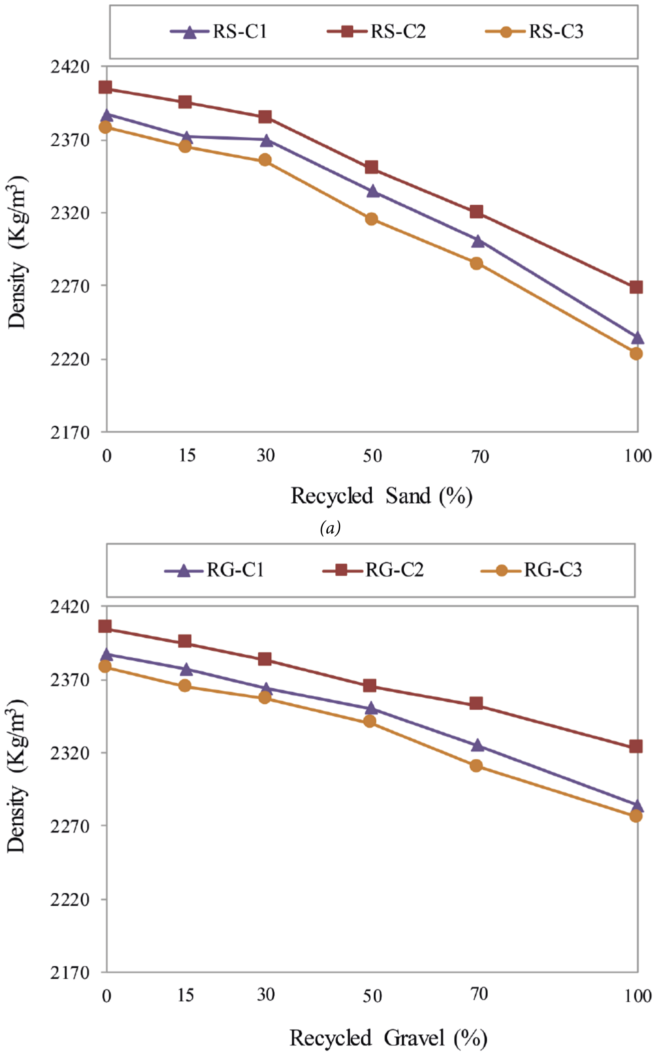
Fig. 3 Variation of air content with percentage of substitution of RA: (a) RS; (b) RG
3. ábra A levegőtartalom változása az újrahasznosított adalékanyag (RA) mennyiségének függvényeként: (a) RS; (b) RG

Fig. 4 indicates that densities of NAC (reference concrete) are higher than those of RAC. Up of 30% of substitution, the density of RAC with RS decreases and then remains constant. This is because of adhered old mortar included in RA surrounding the NA. The figures also indicate that with RG content, density decreases slightly. This is due to the more porous nature and lightweight of adhered old cement mortar to the RA. The density of sand aggregate reduction is within 6% and 4% of the gravel aggregate. This means that where lightweight concrete is needed, the RA can be used. Therefore, for using the RA of low density and with adequate strength, 30% RS can be used in concrete mixtures.



(a)

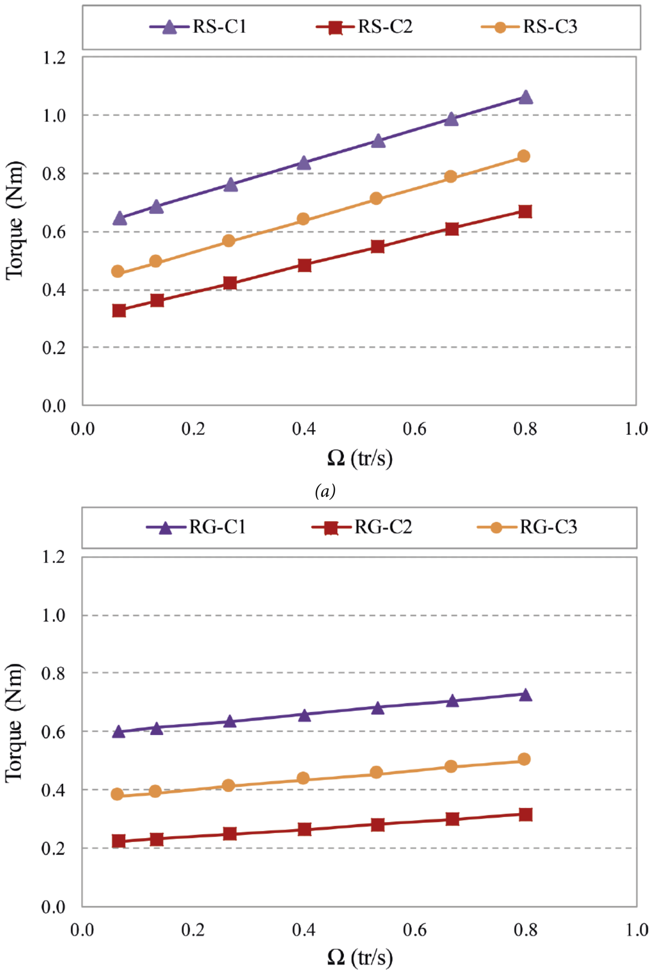
(b)

Fig. 4 *Variation of density with percentage of substitution of RA: (a) RS; (b) RG*
4. ábra *A sűrűség változása az újrahasznosított adalékanyag (RA) mennyiségének függvényeként: (a) RS; (b) RG*

4.3 Rheology

4.3.1 Effect of recycled fine aggregate

Fig. 5 show the evolution of torque as a function of the rotational speed at T0 for the several of cement / admixture ratios for concrete with recycled fine aggregates. The results show, firstly, that torques are increasing linearly with speed. On the other hand, these results show a distinction between different cement / admixture ratio. It can be said that, the rheological behavior of recycled sand concrete exhibits a Bingham fluid. Indeed, the graphs are linear and do not pass through the origin. These results are explained by the low amount of C_3A in the cements C2 of the RS-C2 couple, thus delaying the setting of concrete, and then conferring good fluidity at the fresh state. A high percentage of C_3A for cements C1 of the RS-C1 couple accelerates the setting of the concrete and reduces its fluidity. The cements C3 of the RS-C3 couple present an average quantity of C_3A.



(a)

(b)

Fig. 5 *Variation of torques with speed of RA: (a) RS; (b) RG*
5. ábra *A forgatónyomaték változása az újrahasznosított adalékanyag (RA) mennyiségének függvényeként: (a) RS; (b) RG*

(a) Rheometer *(b) Cylindrical sample* *(c) Blade*

Fig. 6 *The configuration of the rheometer used and its constituents [21]*
6. ábra *Az alkalmazott reométer mérési összeállítása és alkotóelemei [21]*

a. Development of the yield stress τ_0

This part of the study is devoted to the analysis of the evolution of the yield stress at T0 (just after completion of the mixing) and at T90 (after 90 minutes), as a function of the percentage of substitution for the three cement / admixture ratio. *Fig. 7* shows the evolution of the yield stress as a function of the percentage of recycled sand for the three cement / admixture ratio. According to *Fig. 7*, it should be noted that:

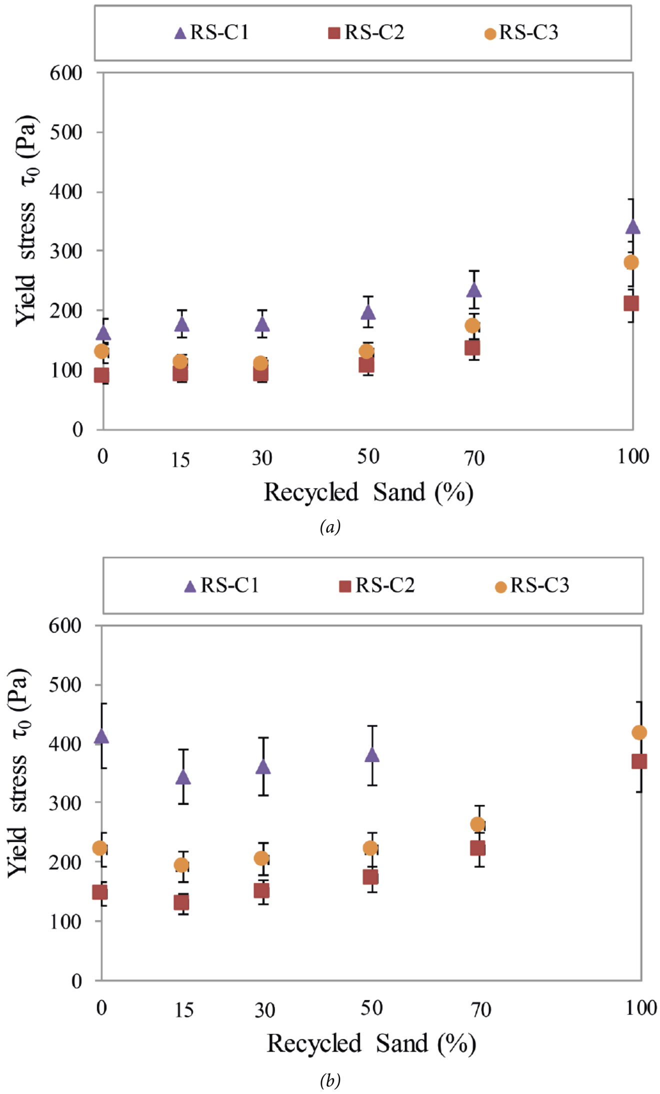


Fig. 7 Variation of yield stress with percentage of substitution in RS: (a) T0; (b) T90
7. ábra A folyási feszültség változása az újrahasznosított homok (RS) mennyiségének függvényeként: (a) T0; (b) T90

At a percentage less than 30% of substitution, the yield stress is nearly constant at T0 and at T90. Beyond this, the yield stress increases quasi-linearly, whatever the cement / admixture couple at T0 and T90. The "yield stress-substitution percentage" graphs present clearly the three torques versus time (T0, T90). The first torque has low yield stress (RS-C2 concretes). The second one has higher yield stress (RS-C1 concretes) and the third one has average yield stress (RS-C3 concretes). Finally, whatever the torque and the percentage of substitution, the yield stress at T90 is always higher than that at T0. These differences in results between torques of different mixes can be explained by the fact that the yield stress varies significantly according to slump [26–30]. RS-C2, concretes have higher slump than RS-C1 and RS-C3 concretes, regardless of the substitution percentage.

b. Development of the plastic viscosity μ

The purpose of this section is to study the evolution of the plastic viscosity at the outlet of the mixer and after 90 minutes according to the percentage of substitution of natural sand by recycled sand for three ratios of cement / admixture. *Fig. 9* shows the evolution of the plastic viscosity as a function of the percentage of recycled sand for the three cement / admixture ratio. *Fig. 9* shows an increase in the plastic viscosity with increasing of the percentage of substitution of recycled sand. This increase in the plastic viscosity can be explained by the increase in the ratio (∅/∅^*) of concrete when adding recycled sand due to the action of two mechanisms. On the one hand, increase in the volume concentration of sand (natural sand + recycled sand) (∅), and on the other hand, the reduction in the compactness of the granular mixture (natural sand + recycled sand + natural gravel) (∅ *) when the substitution content of natural sand by recycled sand in the concrete increases. The plastic viscosity of concrete is proportional to this ratio (∅ / ∅ ^ *) according to the literature [15,31,32]. The increase in the ratio (∅ / ∅ ^ *) therefore leads to an increase in the plastic viscosity of the concretes. In addition, the same type of rheometer should be used to measure, and then compare the rheological parameters of the concretes (yield stress and plastic viscosity). Indeed, each type of rheometer gives results that differ significantly according to its configuration.

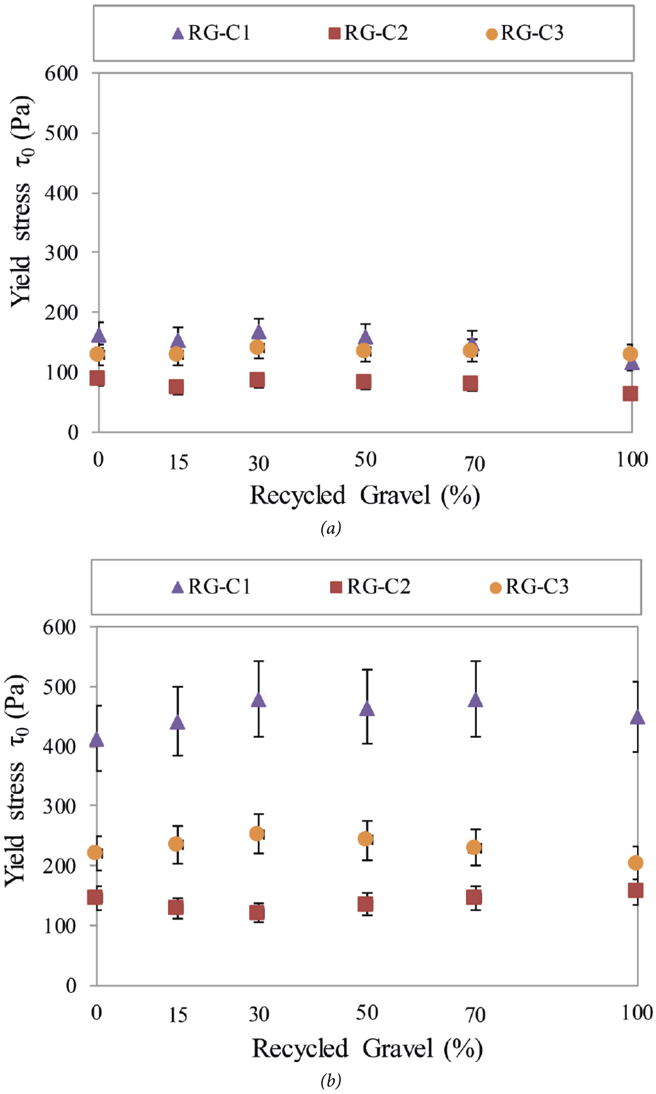
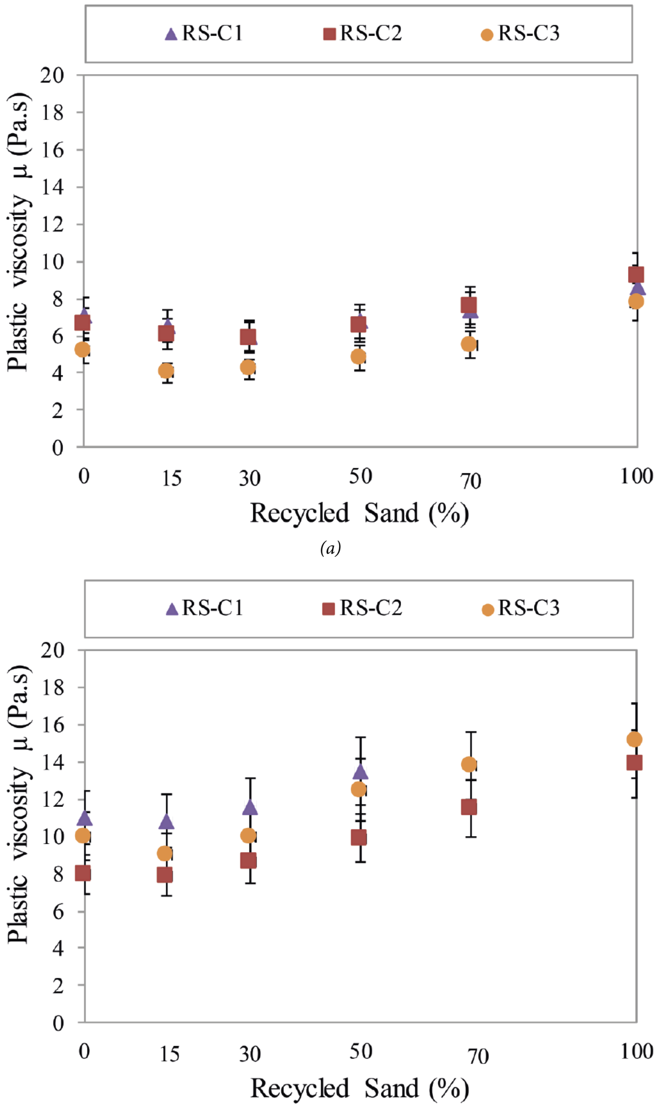


Fig. 8 Variation of yield stress with percentage of substitution in RG: (a) T0; (b) T90
8. ábra A folyási feszültség változása az újrahasznosított durva adalékanyag (RG) mennyiségének függvényeként: (a) T0; (b) T90



(a)

(b)

Fig. 9 Variation of plastic viscosity with percentage of substitution in RS: (a) T0; (b) T90

9. ábra A plasztikus viszkozitás változása az újrahasznosított homok (RS) mennyiségének függvényeként: (a) T0; (b) T90

c. Discussion

The following conclusions can be drawn from the assessment of the rheological parameters of concrete made from recycled sand:

- For substitution content less than or equal to 30%: Recycled sand has little influence on the amount of admixture to be introduced into the concrete mixtures (for a slump of 200 ± 20 mm). The slump is maintained constant at T30 and T90 for the different ratio, except for RS-C1. Regardless of the cement / admixture couple, the slump decreases slightly as a function of time compared to the reference concrete. The air content and densities of concrete mixtures are almost constant. The yield stress is practically constant at T0 and T90.
- For substitute content more than 30%: The demand for admixture increases to reach the desired workability. Regardless of the time and the cement / admixture couple, the slump decreases. The slump loss for RS-C1 mixtures with 100% recycled sand is up to 70% compared to natural concrete. Regardless of the cement / admixture couple, air content increases and densities decrease.
- Regardless of the cement / admixture couple at T0 and T90, the yield stress increases linearly.
- Independently of the substitution percentage, the slump decreases with time for each cement / admixture couple. Concretes made with low C_3A cements have a higher reduction and better maintenance of slump as a function of time compared to those made with higher C_3A cements. Therefore, the yield stress of concretes made with C_3A of RS-C3 cements is lower.
- Regardless of the cement / admixture couple, the yield stress at T90 is always higher than at T0. Whatever the time (T0 or T90), the plastic viscosity increases steadily and the total replacement of the natural sand by the recycled sand increases double the value of the plastic viscosity. The cement / admixture couple influences the yield stress and the viscosity of the concrete with recycled sand.

4.3.2 Effect of recycled coarse aggregate

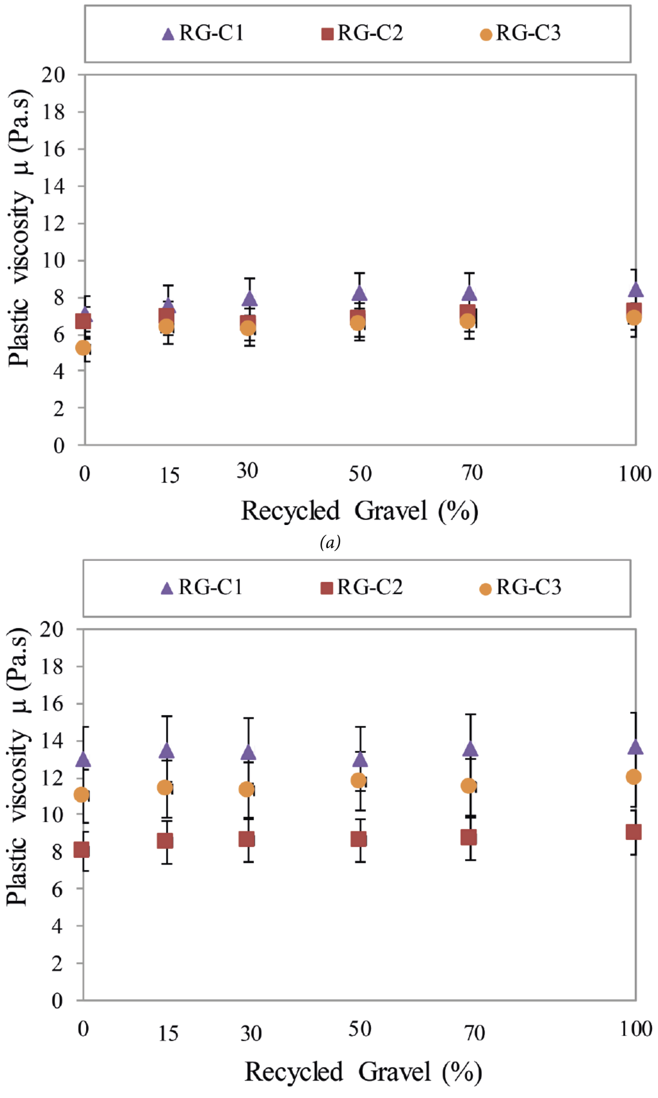
Fig. 5b shows the torque evolution at different rotational speed at T0 for concretes made with recycled gravel and natural sand. The results show that the torques increase slightly in a linear way as a function of speed. Moreover, the torque-speed curves are distinguished from the cement / admixture ratio.

a. *Development of the yield stress* τ_0

The yield stress of concrete made with recycled gravels is measured by a Couette rheometer (*Fig. 6a*). The measurement of this parameter was performed on the three cement / admixture ratio at times T0 and T90. *Fig. 8* shows the development of the yield stress as a function of the percentage of recycled gravels in concrete mixtures. As seen from *Fig. 8*, whatever the percentage of substitution at T0 and T90, the yield stress increases slightly as compared to concrete made with natural gravel. Three ratio of concrete are used in this test. The first one has a low yield stress (RG-C2 concretes), up to 60 Pa at T0 and 100 Pa at T90. The second one has a higher yield stress (RG-C1 concretes), up to 210 Pa at T0 and 500 Pa at T90 for 100% recycled gravels. The third one has an average yield stress (RG-C3 concretes). The difference in results between these three ratios can be explained by same logic as those invoked for concretes made with recycled sand, specifically that the yield stress is a function of the slump. Indeed, it has been found that the RG-C2 ratio has a good hold with respect to the other ratio (RG-C3 and RG-C1). The evolution of the yield stress for each substitution percentage is due to its significant variation as a function of slump [26–30].

b. Development of the plastic viscosity μ

This part presents the evolution of the plastic viscosity (μ) of the concretes manufactured with recycled gravels as a percentage of substitution, for various cement / admixture ratio at T0 and T90. *Fig. 10* shows the obtained graphs. According to the results, the plastic viscosity of the concretes based on recycled aggregates increases slightly in comparison with concretes manufactured with natural aggregates, regardless of the percentage of substitution. In addition, the concrete mixture C1 has the highest plastic viscosity and it reaches a value of 14 Pa.s at T0 and 19 Pa.s at T90. This is due to a significant amount of C_3A in this cement, which accelerates the setting and thus makes the concrete more viscous and less workable. On the other hand, the pair of concrete C2 that has a small amount of C_3A is characterized by lower plastic viscosity (5 Pa.s at T0 and 3 Pa.s at T90). The cements C3 of the RS-C3 couple present a medium quantity of C_3A.



(a)

(b)

Fig. 10 *Variation of plastic viscosity with percentage of substitution in RG: (a) T0; (b) T90*

10. ábra *A plasztikus viszkozitás változása az újrahasznosított durva adalékanyag (RG) mennyiségének függvényeként: (a) T0; (b) T90*

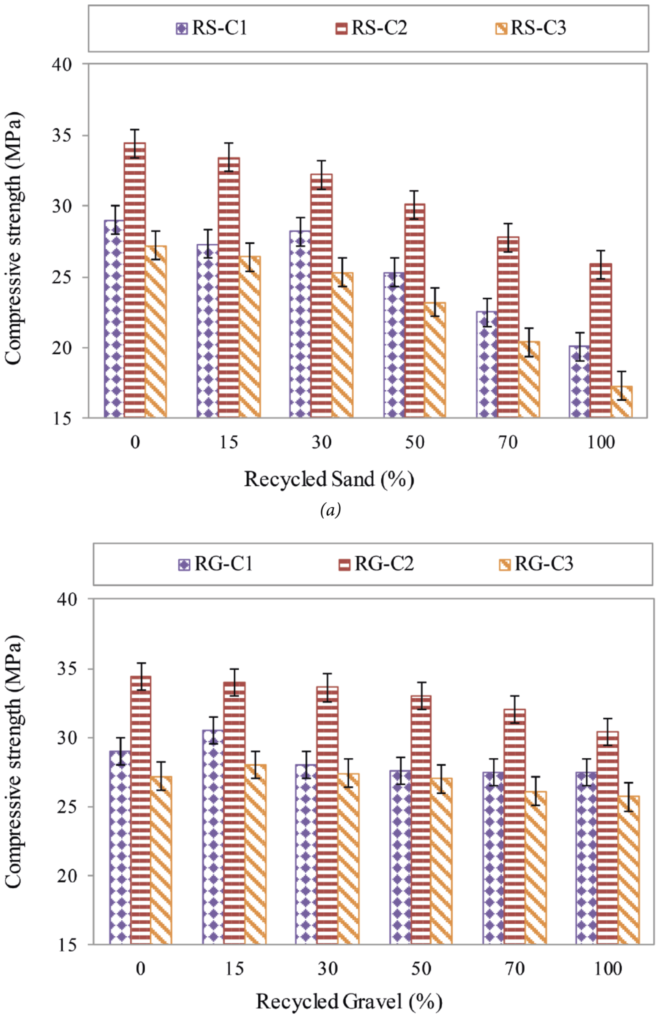
c. Discussion

Following the assessment of the rheological properties of concretes made with recycled gravel, the following conclusions can be made:

- To maintain a slump of 200 ± 20 mm, the amount of admixture increases gradually in the concrete when the percentage of substitution of the recycled gravel increases.
- At T30 the slump is maintained for the different torques except for the RG-C1 concretes. In addition, 100% maintenance loss of concrete made with recycled gravels (up to 55% for RG-C1 concretes) should be noted.
- A gradual decline in subsidence for the three ratio was noted up to T90.
- Between the measurement at the mixer outlet (T0), and the measurement after 90 minutes (T90), for reference concrete (0% substitution), a loss of workability of up to 25% is recorded. For concretes with 100% recycled gravels, a loss of workability of 40% is retained, except for RG-C1 concrete, which has a loss of workability of 70%.
- Whatever the cement / admixture couple, the slump of the concretes decreases slightly as a function of time. This decrease is less remarkable in the case of concretes made from recycled sand.
- The time-dependence of the concretes based on recycled gravel depends on the cement / admixture ratio.
- The air content increases slightly as the percentage of recycled gravels increases. This increase follows a lower slope than concretes made with recycled sand concretes, regardless of the cement / admixture couple.
- The air content measured at T90 increases more pronouncedly as a function of the percentage of recycled gravels than that measured at T0.
- The cement / admixture couple influences the yield stress and the plastic viscosity, whatever the measurement time (T0 or T90) and the percentage of substitution.
- Whatever the percentage of substitution and whatever the measurement time (at T0 and T90), the yield stress increases slightly compared to that of the concrete made with natural gravel.

4.4 Compressive strength

Fig. 11 and *12* present the results of the compressive strength for concrete mixes with cement C1, C2 and C3. It can be seen that compressive strength of RAC decreases with the increase in RA content. Two reasons are possible for this state: the first one is that the strength loss due to the recycled sand adhered paste contains un-hydrated cement [5]; and the second one is the increasing porosity is due to the increased paste of the RS. On the other hand, when the RG percentage increases, compressive strength of RAC decreases slightly because air content and density of concrete have a slight variation when the content of RG increases. Further, the small amount of the old cement stuck in the RG weakened the structure of concrete with RS [33]. It should be noted that, the type of cement affects compressive strength [34,35]. Thus, the combinations C1 and C3, in which the C_3S dosage is lower than of C2, presents weak early strength, however, concrete with 100% recycled sand exhibits a reduction in compressive strength of 45%. This is because of concrete with RS, which has a low air content and density. Further, the structure of the mixture is weakened by cement mortar content in RS. From *Fig. 11*, it is evident that the combination cement / admixture at 7 days regardless of the percentage of RA affects the compressive strength. The RAC with cement C2 achieved higher compressive strength at 7 days than that with cement C3 and C1. However, from *Fig. 12*, 28 days compressive strength is not significantly affected by the cement / admixture ratio.



(a)

(b)

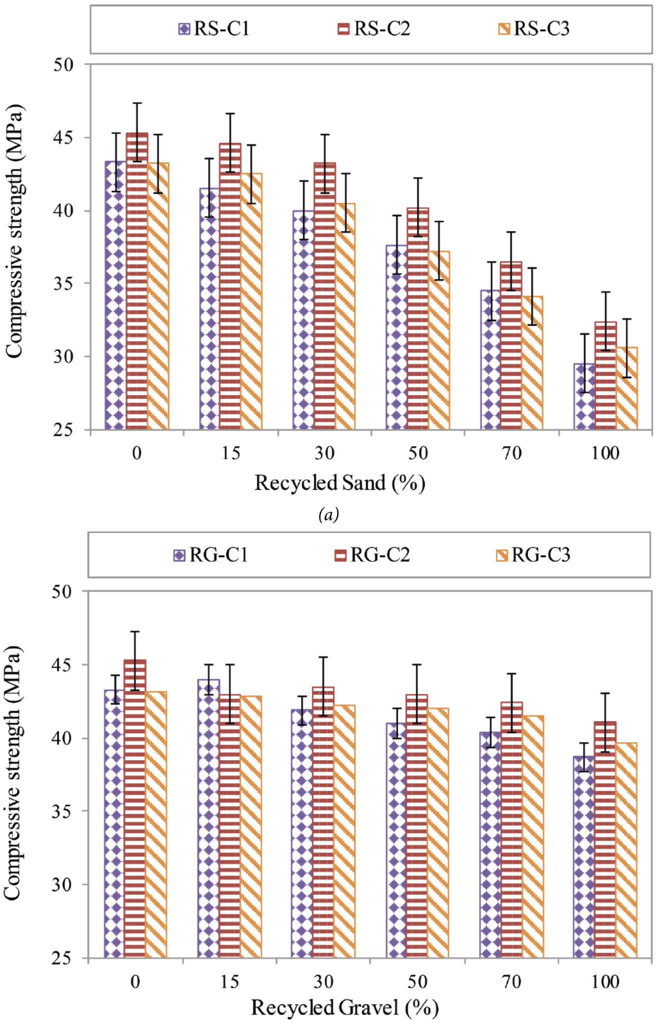
Fig. 11 *Compressive strength evolution of RAC with three cement / admixture and with RA substitution rate at 7 days: (a) RS; (b) RG*

11. ábra *Újrahasznosított adalékanyag tartalmú beton nyomószilárdsága (3 különböző cement/adalékszer típus esetén) az adalékanyag helyettesítési mennyiségének függvényében 7 napos korban: (a) RS; (b) RG*

5. Conclusions

The aim of this paper is the comparison of the fresh behavior of concrete made from recycled sand and recycled gravel. The results lead to the following conclusions:

- Slump of the concretes produced with recycled gravels decreases slightly as a function of time, regardless of the cement / admixture couple tested. This decrease is less pronounced in the case of recycled sand concretes. Recycled gravels therefore affect less than recycled sand on maintaining the workability of concrete.
- The air content increases slightly as the percentage of recycled gravels increases. The slope that represents this increase is less than that of concretes made with recycled sand. This observation is evident whatever the cement / admixture pair used.
- For both types of aggregate substitution, whatever the dosages, the cement / admixture ratios at T0 and T90 influence the yield stress and the plastic viscosity. These parameters increase in both substitution cases but more significantly for recycled sand (this increase is slight in the case of substitution by recycled gravel).
- Recycled gravel concretes have workability, air content and density that develop slightly as a function of the percentage of substitution. Concretes based on recycled sand exhibit the same behavior when the substitution percentage is less than or equal to 30%. Beyond this dosage, the behavior is not well determined.



(a)

(b)

Fig. 12 *Compressive strength evolution of RAC with three cement / admixture and with RA substitution rate at 28 days: (a) RS; (b) RG*

12. ábra *Újrahasznosított adalékanyag tartalmú beton nyomószilárdsága (3 különböző cement/adalékszer típus esetén) az adalékanyag helyettesítési mennyiségének függvényében 28 napos korban: (a) RS; (b) RG*

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References

[1] Z. Tahar, T.-T. Ngo, E.H. Kadri, A. Bouvet, F. Debieb, S. Aggoun, Effect of cement and admixture on the utilization of recycled aggregates in concrete, Constr. Build. Mater. 149 (2017) 91–102. https://doi.org/10.1016/j.conbuildmat.2017.04.152.

[2] I.B. Topçu, N.F. Günçan, Using waste concrete as aggregate, Cem. Concr. Res. 25 (1995) 1385–1390. doi:10.1016/0008-8846(95)00131-U.

[3] Eurostat, Eurostat, environment and energy, 2010. Generation and Treatment of Waste. (last accessed in 18.05.14.), (2010). http://ec.europa.eu/eurostat/.

[4] E. Wirquin, R.H.F. Buyle-bodin, Utilisation de l'absorption d'eau des bétons comme critéres de leur durabilité - Application aux bétons de granulats recyclés, 33 (2000) 403–408.

[5] L. Evangelista, J. de Brito, Mechanical behaviour of concrete made with fine recycled concrete aggregates, Cem. Concr. Compos. 29 (2007) 397–401. https://doi.org/10.1016/j.cemconcomp.2006.12.004.

[6] D.A. Khalaf FM, Recycling of demolished masonry rubble as coarse aggregate in Concrete: review, ASCE J Mater Civ. Eng. (2004) 331–340. https://doi.org/10.1017/CBO9781107415324.004.

[7] J.M. Khatib, Properties of concrete incorporating fine recycled aggregate, Cem. Concr. Res. 35 (2005) 763–769. https://doi.org/10.1016/j.cemconres.2004.06.017.

[8] Z. Tahar, E.H. Kadri, T.-T. Ngo, A. Bouvet, A. Kaci, Influence of recycled sand and gravel on the rheological and mechanical characteristic of concrete, J. Adhes. Sci. Technol. 30 (2016) 392–411. https://doi.org/10.1080/01694243.2015.1101185.

[9] B. Benabed, (2018) Effect of combined use of crushed sand and Algerian desert dune sand on fresh properties and strength of SCC. Epitoanyag-Journal of Silicate Based & Composite Materials. 70(5), 2018, pp. 155-166. https://doi.org/10.14382/epitoanyag-jsbcm.2018.29

[10] Younes Ouldkhaoua, Benchaa Benabed, Rajab Abousnina, El-Hadj Kadri (2019) Rheological properties of blended metakaolin self-compacting concrete containing recycled CRT funnel glass aggregate. Epitoanyag-Journal of Silicate Based & Composite Materials. 71(154-161), 2019, pp. 18-23. https://doi.org/10.14382/epitoanyag-jsbcm.2019.27

[11] Mohammed Abed, Rita Nemes (2019) Fresh properties of the self-compacting high performance concrete using recycled concrete aggregate. Epitoanyag-Journal of Silicate Based & Composite Materials. 71(1), 2019, pp. 18-23. https://doi.org/10.14382/epitoanyag-jsbcm.2019.4

[12] C. Hu, F. De Larrard, The rheology of fresh high-performance concrete, Cem. Concr. Res. 26 (1996) 283–294. https://doi.org/10.1016/0008-8846(95)00213-8.

[13] C. Hu, F. de Larrard, T. Sedran, C. Boulay, F. Bosc, F. Deflorenne, Validation of BTRHEOM, the new rheometer for soft-to-fluid concrete, Mater. Struct. 29 (1996) 620–631. https://doi.org/10.1007/BF02485970.

[14] T. Bouziani, A. Benmounah, Z. Makhloufi, M. Bédérina, M. Queneudec T'kint, Properties of flowable sand concretes reinforced by polypropylene fibers, J. Adhes. Sci. Technol. 28 (2014) 1–12. https://doi.org/10.1080/01694243.2014.924176.

[15] H. Soualhi, E.-H. Kadri, T.-T. Ngo, A. Bouvet, F. Cussigh, B. Benabed, Rheology of ordinary and low-impact environmental concretes, J. Adhes. Sci. Technol. 29 (2015) 2160–2175. https://doi.org/10.1080/01694243.2015.1059641.

[16] T.-T. Ngo, Influence de la composition des bétons sur les paramètres de pompage et validation d'un modèle de prévision de la constante visqueuse, Universite de Cergy-Pontoise, 2009.

[17] T.T. Ngo, E.H. Kadri, R. Bennacer, F. Cussigh, Use of tribometer to estimate interface friction and concrete boundary layer composition during the fluid concrete pumping, Constr. Build. Mater. 24 (2010) 1253–1261. https://doi.org/10.1016/j.conbuildmat.2009.12.010.

[18] C. Hu, Rhéologie des bétons fluides, Ecole Nationale des Ponts et Chaussées, 1995. https://pastel.archives-ouvertes.fr/tel-00523283.

[19] C. Laneyrie, A.L. Beaucour, M.F. Green, R.L. Hebert, B. Ledesert, A. Noumowe, Influence of recycled coarse aggregates on normal and high performance concrete subjected to elevated temperatures, Constr. Build. Mater. 111 (2016) 368–378. https://doi.org/10.1016/j.conbuildmat.2016.02.056.

[20] NF P 18-455 Concrete-Test for hardened concrete, 2010

[21] H. Soualhi, E.H. Kadri, T. Ngo, A. Bouvet, F. Cussigh, S. Kenai, A Vane Rheometer for Fresh Mortar : Development and Validation, Applied rheology 24 (2014) 1–7. https://doi.org/10.3933/APPLRHEOL-24-22594.

[22] M. Chakradhara Rao, S.K. Bhattacharyya, S. V. Barai, Influence of field recycled coarse aggregate on properties of concrete, Mater. Struct. 44 (2010) 205–220. https://doi.org/10.1617/s11527-010-9620-x.

[23] A. Djerbi Tegguer, Determining the water absorption of recycled aggregates utilizing hydrostatic weighing approach, Constr. Build. Mater. 27 (2012) 112–116.https://doi.org/10.1016/j.conbuildmat.2011.08.018.

[24] E.-H. Kadri, S. Aggoun, G. De Schutter, Interaction between C3A, silica fume and naphthalene sulphonate superplasticiser in high performance concrete, Constr. Build. Mater. 23 (2009) 3124–3128. https://doi.org/10.1016/j.conbuildmat.2009.06.026.

[25] W. Prince, M. Edwards-Lajnef, P.-C. Aïtcin, Interaction between ettringite and a polynaphthalene sulfonate superplasticizer in a cementitious paste, Cem. Concr. Res. 32 (2002) 79–85. https://doi.org/10.1016/S0008-8846(01)00632-9.

[26] İ.B. Topçu, S. Şengel, Properties of concretes produced with waste concrete aggregate, Cem. Concr. Res. 34 (2004) 1307–1312. https://doi.org/10.1016/j.cemconres.2003.12.019.

[27] C. Ferraris, F. De Larrard, Testing and Modelling of Fresh Concrete Rheology, Natl. Inst. Stand. Technol. (1998) 59.

[28] J. Hu, K. Wang, Effect of coarse aggregate characteristics on concrete rheology, Constr. Build. Mater. 25 (2011) 1196–1204. https://doi.org/10.1016/j.conbuildmat.2010.09.035.

[29] J. Wallevik, Relationship between the Bingham parameters and slump, Cem. Concr. Res. 36 (2006) 1214–1221.

[30] J. Murata, H. Kukokawa, Viscosity Equations for Fresh Concrete, ACI Mater. J. 89 (1992) 230–237.

[31] N. Roussel, Correlation between yield stress and slump: comparison between numerical simulations and concrete rheometers results, Mater. Struct. 39 (2006) 501–509.

[32] F. De Larrard, Structures granulaires et formulation des bétons, 2000. http://www.concretonline.com/pdf/00hormigon/art_tec/docu_ref01.pdf.

[33] T. Sedran, D.E.L. F, RENÉ-LCPC: un logiciel pour optimiser la granularité des matériaux de génie civil, (1994) 1–10.

[34] M. Etxeberria, E. Vázquez, A. Marí, M. Barra, Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cem. Concr. Res. 37 (2007) 735–742. https://doi.org/10.1016/j.cemconres.2007.02.002.

[35] K.K. Sagoe-Crentsil, T. Brown, A.H. Taylor, Performance of concrete made with commercially produced coarse recycled concrete aggregate, Cem. Concr. Res. 31 (2001) 707–712. https://doi.org/10.1016/S0008-8846(00)00476-2.

[36] J. Sim, C. Park, Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate., Waste Manag. 31 (2011) 2352–60. https://doi.org/10.1016/j.wasman.2011.06.014.

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