ANALYSIS OF THE VARIABLES THAT AFFECT THE STRENGTH OF CONCRETE WITH RECYCLED AGGREGATES FROM PREFABRICATED PIPES

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ABSTRACT

The influence of several parameters in the compressive and flexural strength of concrete with recycled aggregates is analyzed. The concretes are dosed for a compressive strength of 30MPa. The recycled aggregates are obtained from debris of prefabricated concrete pipes with a compressive strength of 20MPa. Four variables are considered in this analysis: the percentage of natural course aggregates that are replaced by recycled ones; the amount of mortar adhered to the surface of the aggregates, that will be reduced applying mechanical abrasion processes instead of the chemical traditional ones; the maximum size of the replaced aggregates and the percentage of cement addition specified in the dosing. Taguchi's statistical method is used considering three levels for each of the four parameters to determine their effects on the material behavior, minimizing the number of the experimental tests required. The tests are performed after curing the samples during 28 and 90 days. The three levels for each parameter are stablished after former studies and/or previous experimental tests. The results are quantified through the analysis of variance methodology (ANOVA), to determine which of the variables has higher effects in the final strengths. The results show that materials with equivalent compressive strengths to those of a control concrete can be obtained restricting the percentage of replaced aggregates to 30% and reducing the amount of adhered mortar through abrasion processes, when the samples have been cured for 28 days. The effect of the size of the recycled aggregates gains significance after 90 days of curing, while the amount of cement addition controls the flexural strength. These results indicate that materials with equivalent mechanical properties to those of a control concrete can be obtained by controlling several parameters, allowing the reuse of debris and reducing the amount of natural course aggregates needed significantly.

Keywords: Recycled aggregates; Recycled concrete; Concrete mechanical properties; Compressive strength.

1.- Introduction

Sustainable management is becoming an obligation in construction engineering and in other areas, due to a strong social demand. As a part of this global process, the reuse of concrete obtained from demolished constructions not only concerns to industrialized regions but responds to a worldwide need.

Usually, there is almost a 5% rate of loss of product in the precast concrete industry due to defective materials or production faults. This material is rejected and considered a residual in the production plants. Nevertheless, the absence of foreign bodies such as ceramic material, lime, paint traces or rebar makes it a perfect candidate for recycling. Considering its reuse within the same production plant would save costs, not only in raw material but in residual disposure.

Previous works on concretes that use recycled aggregates (0,0,0,0,0), show a significant difference in the mechanical behavior of these concretes when compared to conventional ones.

One of the main causes of this loss of strength is the old mortar adhered to the surface of the recycled aggregates. Two interfaces have to be considered instead of one when using recycled aggregates; the usual one (old interface), between the old mortar and the aggregates, and a new one (new interface), between the aggregates, with the old adhered mortar, and the new cement matrix (0,0,0). Consequently, the quality and quantity of the adhered mortar will strongly influence the mechanical behavior of the recycled concrete, particularly, its mechanical strength (0,0).

Alternatives to control the loss of strength have been analyzed lately. The first and most considered one is to limit the amount of the recycled aggregates. Authors (0,0,0, 0,0,0,0,0,0) prove that concrete properties are not significantly modified when the use of these aggregates is restricted to relatively low percentages. Therefore, nowadays, several European technic regulations allow the use of up to 30% of recycled aggregates in the production of structural concrete.

Other ways to obtain a desirable strength have been studied. Adjusting the water/cement rate increasing the amount of cement would reduce the effect of the aggregates and, consequently, limit the loss of compressive strength (0,0,0).

The size of the recycled aggregates is also involved in the new material strength. Fine recycled aggregates are not recommended because the smaller the size of the recycled aggregates the bigger the surface (old and new interfaces) involved, increasing the amount of old adhered mortar in the cement mix and the concrete production. Its characterization is complex, making it highly unpredictable, producing unexpected modifications in the properties of fresh and hardened concrete 0.

The main issue in the use of recycled aggregates relays in the old adhered mortar. Studies have been performed to reduce de amount of mortar on the recycled aggregates. Ismail & Ramli 0 use different acids to minimize o even eliminate the loose mortar particles adhered to the aggregates surface. The physical properties of the concrete significantly improved, a reduction in the mortar improves the quality of the contact surface between the new cement matrix and the aggregates, increasing the mechanical strength of the concrete.

Considering these precedents, in this study the optimum limits of the mentioned variables (recycled aggregates percentage, cement addition percentage, size of aggregates and amount of mortar) are evaluated, in aim to obtain similar strengths to the ones of the control concrete.

2.- Problem description

2.1.- Materials

The coarse aggregates used in this investigation were obtained from precast concrete debris, specifically, from cylindrical tubes with an average load capacity of

20MPa after 28 days of curing, provided by a local company (*Prefabricados Burzios*, Temuco, Chile). The debris were grinded in a jaw crusher, obtaining aggregates with a maximum size of 30mm, that were later separated using mechanical sieving to use only the fraction between 6.3 and 19.3mm.
Previous works reduce the amount of mortar by mainly applying chemicals dissolving adhered materials. Instead, a mechanical process is used here. A mechanical Los Angeles abrasion machine was used to reduce the adhered mortar through erosion. It will be quantified through the revolutions applied by the abrasion machine to the aggregates. The procedure is illustrated in Fig. 1.

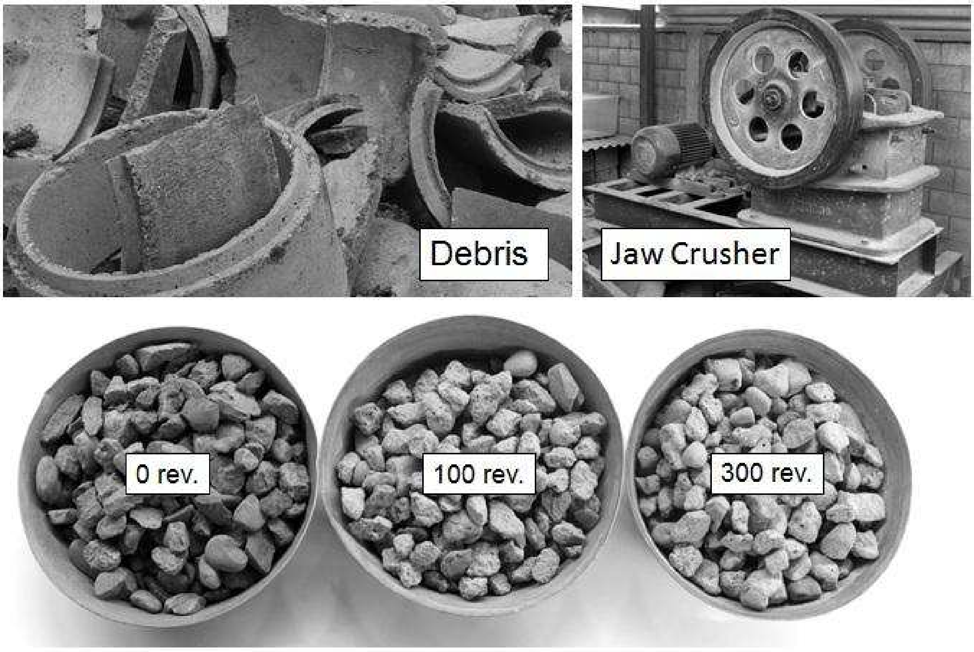

Fig. 1 **"**The debris is grinded in a jaw crusher. Example of the aggregates with no abrasion (0rev), 100rev and 300rev mechanical abrasion processes are applied".

In Table 1 real density and absorption values of these aggregates are shown. The natural aggregates have higher dry density values (Gn) than the recycled ones (Gr), because of the presence of adhered mortar in recycled aggregates. Therefore, density will increase when the amount of mortar is reduced.

	Sand	**G_N**	**G_R**	**G_{R100R}**	**G_{R300R}**
Dry density (Kg/m^3)	2630	2666	2300	2330	2420
Water absorption (%)	1,4	1,7	6,2	5,3	4,0

Table 1 **"**Aggregates densities and absorption". Gn Natural gravel; Gr: Recycled gravel without erosion; Gr100r: recycled gravel with erosion applying 100rev; Gr300r: recycled gravel with erosion applying 300rev.

Sideways, the water absorption of recycled aggregates is almost 3.6 times bigger than the one of natural aggregates. Nevertheless, when the abrasion level increases, the absorption decreases to values around 3.1 and 2.4 times the one of the natural aggregates when 100rev and 300rev abrasion is applied respectively.
The characteristics of pozzolanic cement, that was used to make the concretes, are shown in Table 2.

		Values	NCh 148 Of. 68 Requirements
Physical and mechanical Characteristics			
Specific gravity (g/cm3)		2,8	
Autoclave Expansion (%)		0,1	1,0 max
Initial setting time (hh:mm)		02:40	01:00 min
Final setting time (hh:mm)		03:40	12:00 max
Compressive strength (kg/cm2)			
	3 days	280	
	7 days	320	180 min
	28 days	410	250 min
Chemical Characteristics			
Loss on ignition (%)		4,0	5,0 max
S03 (%)		3,5	4,0 max

Table 2 “Characteristics of pozzolanic cement”.

2.2.- Experimental method

Experimental phase consisted in analyzing the differences in the compressive and tensile strength between concrete made with recycled aggregates and a control concrete made with natural aggregates. Several tests are performed to identify the most significant variables involved in the properties of concrete with recycled aggregates from prefabricated debris.

According to the results obtained by previous authors and to the ranges stablished by different technic regulations, different values were set to be considered for each variable:

- Recycled aggregates percentage: 20%, 30% and 40%. The choice was made considering different technic regulations that nowadays allow the use of recycled aggregates.
- Cement mix percentage: 0%, 5% and 10%. Based on previous authors (0,0,0), but using national -Chilean- product.
- Recycled aggregates size: 6.3-9.5mm, 9.5-12.5mm and 12.5-19.3mm.
- Amount of mortar: 0rev, 100rev, and 300rev abrasion levels. The use of mechanical abrasion to reduce the old adhered mortar is new. The abrasion levels were chosen in base to experimental tests performed prior to the analysis.

To analyze all the possible scenarios and figure out the influence of each variable all the combinations should be tested. This factorial design would imply developing 3^4 experimental tests. To reduce this number Taguchi 0 experimental method was used. Using a set of so called orthogonal arrays the number of different dosages required can be minimized while giving full information. In this case we consider 4 different independent variables with 3 level values each, so L9 orthogonal array is used, limiting the number of needed experimental tests to 9. The method assumes that the variables do not interact, meaning that the effect of the variation in one variable does not depend on the level settings of the other independent variables. The orthogonal arrays considered here are displayed in Table 3. The results will be analyzed applying ANOVA.

	Recycled agg size (mm)	Cement mix rate (%)	Recyc agg (%)	Abrasionlevel (rev)
H1	6,3-9,5	0	20	0
H2	6,3-9,5	5	30	100
H3	6,3-9,5	10	40	300
H4	9,5-12,5	0	20	0
H5	9,5-12,5	5	30	100
H6	9,5-12,5	10	40	300
H7	12,5-19,3	0	20	0
H8	12,5-19,3	5	30	100
H9	12,5-19,3	10	40	300

Table 3 “Values of the parameters applied in each test for each of the 4 variables”.

Worth to mention that all of the concretes are made using natural sand, only the natural course aggregates will be partially replaced by recycled coarse aggregates.
The properties, slump, apparent density and air content of the fresh concretes are measured. Mechanical properties are evaluated through compression and flexural tests. Compression tests are performed following the NCh1037 and the NCh1017 regulations, using three cubic 15x15x15cm test specimens that will be cured during 28 and 90 days. Flexural ones are performed following the NCh1038, using three prismatic 15x15x50cm test specimens cured during 28 days.

3.- Methodology

Different mixtures were designed using Faury 0 method calibrated for compressive strength of 30MPa after curing the sample during 28 days. A water/cement ratio of 0.42 was considered for control concrete and concrete without cement aggregates. When concretes with cement addition are considered this ratio will decrease between 5 and 10%.
To calculate the final amount of water used in each mixture the recycled aggregates underwent a pre-saturation process reaching 80%. Based on previous works, this pre-saturation process helps sealing the pores in the recycled aggregates, what limits water exchange plus avoids problems on the workability of fresh concrete and the water/cement ratio (0,0).
The values used in the dosage of the concretes, considering the pre stablished levels given by Taguchi’s method 0, and the results obtained when applying Abrams cone and air content are shown in Table 4.
All the samples were elaborated in laboratory conditions and unmolded after 24 $\pm$ 2 hours after the mixture. Then, they were completely immersed in water with lime at 23 $\pm$ 3ºC during the curing time required (28 or 90 days).

	Sand (Kg/m3)	Gn 2,36-19,3 mm	Gr 6,3-19,3 (mm)	Cement (Kg/m3)	Water (Kg/m3)	Slump (cm)	Air content (%)
HCN	781,8	1024,2	-	382,3	162,6	2,5	1,1
H1R	781,8	819,3	204,8	382,3	162,6	1,5	1,5
H2R	781,8	717,0	307,3	401,4	162,6	1,5	1,3
H3R	781,8	614,6	409,6	420,5	162,6	1,3	1,3
H4R	781,8	819,3	204,8	382,3	162,6	4,4	1,7
H5R	781,8	717,0	307,3	401,4	162,6	3,0	1,6
H6R	781,8	614,6	409,6	420,5	162,6	3,2	1,1
H7R	781,8	819,3	204,8	382,3	162,6	3,8	1,0
H8R	781,8	717,0	307,3	401,4	162,6	5,5	1,4
H9R	781,8	614,6	409,6	420,5	162,6	3,0	1,8

Table 4 **“**Tests in control concrete (N) and recycled (R) ones with each dosage”.

Compression tests according to Chilean Standards NCh1037.Of2009 were carried out on each of the cubic specimens, which were tested at right angles to the position of casting.
Splitting tension tests were carried out on prismatic specimens tested at right angles to the position of casting, in conformance with Chilean Standards NCh1038. Of2009.
Three specimens are tested for each case and dosage, considering the mean value as the final result.

4.- Results and discussion

The results for compressive and flexural strength obtained for each of the samples are shown in Table 5.

	Compressive strength (MPa)		Flexural strength (MPa)
Sample	**28 days**	**90 days**	**28 days**
HC	34,8	40,2	5,3
H1	25,5	34,8	4,2
H2	30,5	39,2	5,0
H3	29,6	36,5	5,1
H4	29,7	35,1	4,9
H5	35,9	36,2	4,4
H6	25,0	32,4	4,6
H7	28,7	38,4	4,0
H8	35,7	43,1	4,2
H9	26,1	36,9	5,5

Table 5 “Results obtained for each specimen”

4.1.- Compressive strength

In Fig. 2 the results for compressive strength after curing the samples for 28 days are displayed. Only two of the concrete samples with recycled aggregates, H5 and H8, reaching values of 35.9 and 35.7MPa respectively, equal or exceed the compressive strength of the control sample (34.8MPa). Both of them use 30% of recycled aggregates that suffered 100rev abrasion, and 5% cement addition. Despite all the concrete samples were designed to reach a minimum resistance of 30MPa, only 3 of them, H2, H5 and H8, did exceed this value, the three of them containing 30% of recycled aggregates.

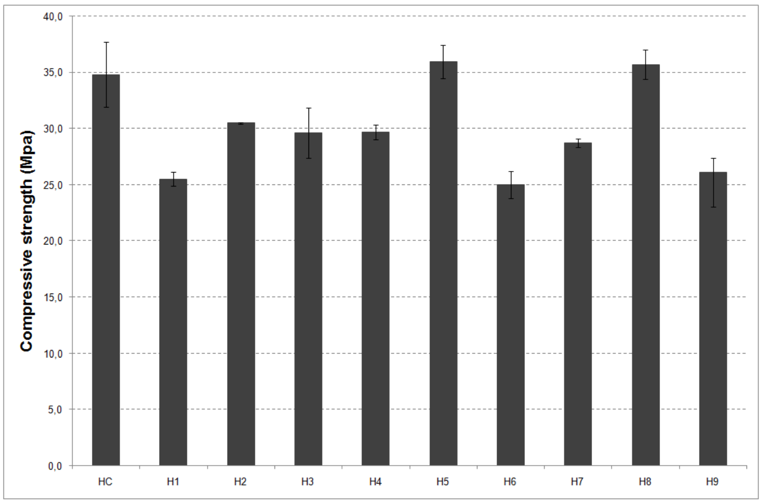

Fig. 2 “Compressive strength after 28 days”.

The minimum values of compressive strength were obtained for samples H1, H6 and H9, presenting a decay of between 25% and 28% of the value obtained for the control concrete. For these three samples a 40% of non-abrasion recycled aggregates was used with no cement addition. The other three samples (H3, H4 and H7) presented a decay of compressive strength of between 15% and 17% of the value obtained for the control sample.
Fig. 3 shows the results for compressive strength after curing the samples for 90 days. After a long curing time all of the samples satisfy the design strength. Either ways, only H8 sample equals the compressive strength obtained by the control sample. H6 presents the minimum value, 19% lower than the control, and all of the others are between 5% and 13% lower than the control sample.

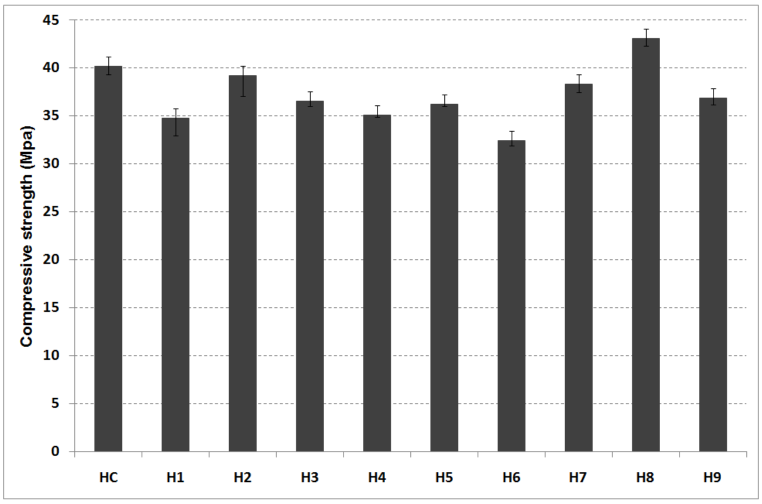

Fig. 3 “Compressive strength after 90 days”

These results reveal that concretes with recycled aggregates have a higher gaining rate after 90 days rather than after 28 (Fig. 4). This conclusion agrees with previous analysis (0,0) where the compressive strength was attributed to a stronger union in the interface between the cement and the coarse aggregates. Yu & Shui 0 postulates that during the cement hydration process some of the particles won’t react. When using recycled aggregates these particles are present in the surface adhered mortar, so, when a new hydration process is performed the particles may be able to reactivate, producing a higher gaining compressive strength rate in the long term. Furthermore, considering that the hydrating and hardening processes are significantly slower when recycled aggregates are used (0,0,0) stronger bonds may be created between the cement and the coarse recycled aggregates, what may be able to compensate, up to certain degree, the negative effects of weaker aggregates when a long term curing is considered.

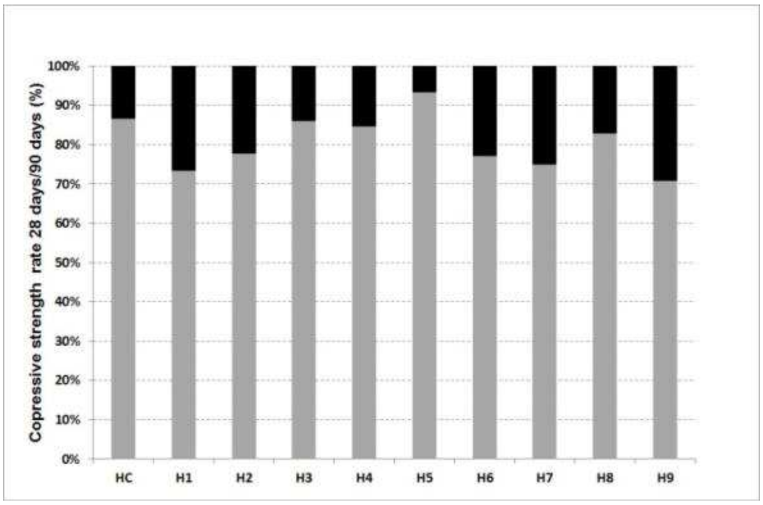

Fig. 4 “Relative compressive strength after 28 days/ after 90 days”.

4.2.- Influence of studied parameters

In this section the results obtained using Taguchi optimization method 0 are discussed to understand the influence of each parameter in the compressive strength after 28 and 90 days.

Fig. 5 shows the influence of two parameters, the abrasion level and the percentage of cement added, in the final compressive strength. Both values evolve similarly, increasing their levels leads to bigger compressive strength values. The effect is more significant when the sample is cured during 28 days. An increase of cement addition from 0% to 10% results in an 8% more resistant sample, and an increase of abrasion from 0rev to 300rev results in a 14% more resistant material. After 90 days the cement addition has almost no more influence (about 1% increased compressive strength), what could be due to the original mechanical properties of the concrete controlling the maximum values that can be achieved in a new one with recycled aggregates 0.

After 90 days the compressive strength increases a 6% when 300rev are applied. This behavior agrees with observations from Matias et al 0, where the use of angular plane particles is studied. They consider that this kind of particles may present layer stratification, what would limit the durability and compressive strength of the concrete. These effects may be controlled using rounder aggregates. When recycled aggregates are used, abrasion provokes a change in their shape, softening corners and ending with more rounded material. Furthermore, Ismael and Ramli [4] conclude that one of the main factors in low compressive strength in concrete with recycled aggregates is the mortar adhered to the aggregates; and Gonzalez & Etxeberria 0 point out that the use of recycled aggregates with higher absorption level affects the final properties of the concrete. The abrasion process, as shown in Table 1, leads to a decrease in these absorption levels because of the decrease of the adhered mortar to the recycled aggregates.

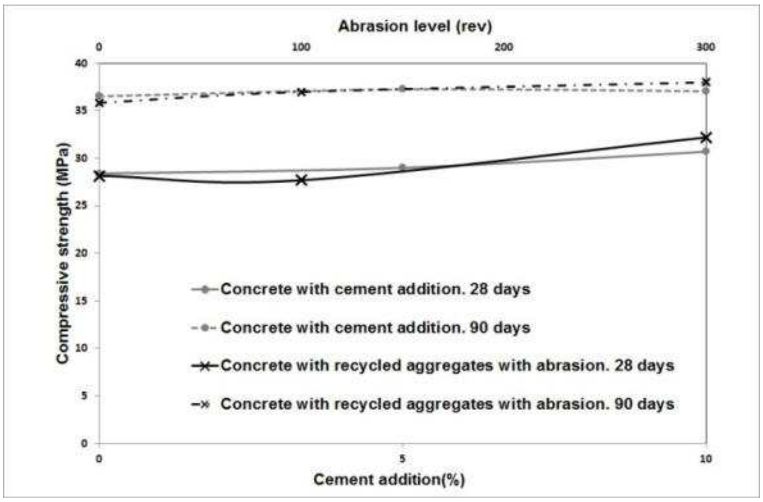

Fig. 5 “Compressive strength variation with abrasion level and cement addition after 28 and 90 days”.

The effect of the amount of recycled aggregates and their minimum size is analyzed in Fig. 6. When the maximum size of the aggregates grows from 9.5mm to 19.3mm the compressive strength increases 8% when cured during 28 days and 7% for 90 days. The use of bigger recycled aggregates reduces the amount of old mortar in the mixture (interfaces), what reduces the weakened zones 0. When the amount of recycled aggregates is 40%, the compressive strength decays a 14% and a 12% of the values obtained for 30% of aggregates, after 28 and 90 days respectively. Kwan et al. 0 and Gonzalez & Etxeberria 0 conclude that this decay obeys to the low quality of the adhered mortar.

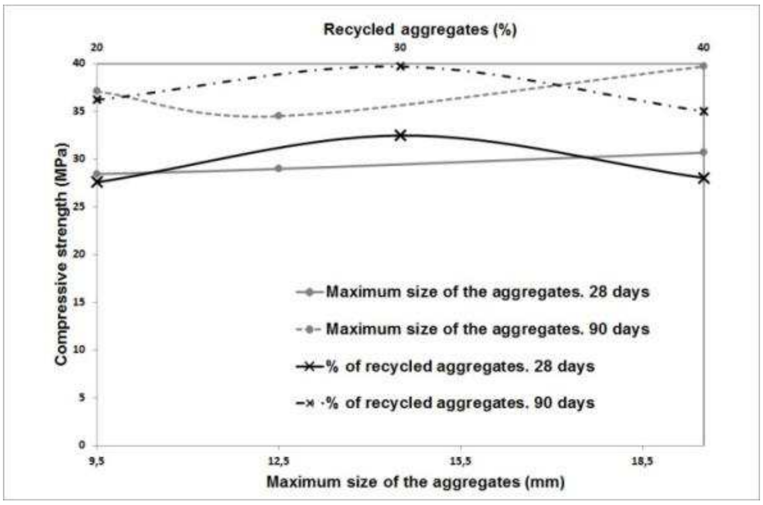

Fig. 6 “Compressive strength variation with amount and size of recycled aggregates after 28 and 90 days”.

Table 6 shows the results of the ANOVA obtained using Taguchi method.

Variable	Deg Fr	Square Sum		Variance (V)		Participation rate(%)	
		28d	90d	28d	90d	28d	90d
% Agg.	2	88.8	48.7	44.4	24.3	69.0	35.9
Ab.	2	20.4	11.4	10.2	5.7	15.9	7.9
C. Add.	2	14.1	0.9	7.0	0.5	10.9	0.2
Max S	2	5.4	69.4	2.7	34.7	4.23	51.4

Table 6 “Summary of the compressive strength results of the ANOVA analysis”

The participation rate varies with the curing days. After 28 days, the most significant parameters (the ones with bigger participation rate values) were the amount of recycled aggregates and the abrasion level, while after 90 days the size of the aggregates gains significance and the abrasion is slightly involved.

4.3.- Flexural strength

The results of the flexural strength are presented in Fig. 7. They are all between 4MPa and 5.5MPa, presenting very small differences between them. Several authors (0,0,0) conclude that the flexural strength is not as influenced by the amount or quality of the recycled aggregates as the compressive strength is.

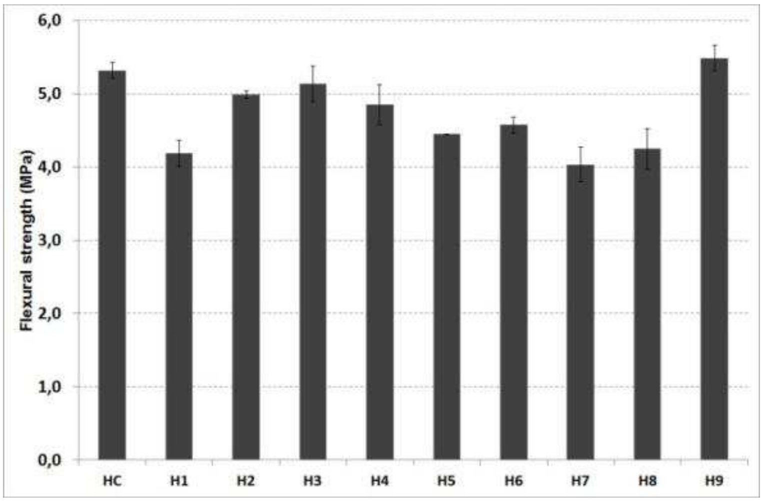

Fig. 7 “Flexural strength after 28 days”.

Higher values are obtained for H3, H4, H5 and H9 samples; three of them use more than 30% of recycled aggregates and more than 5% cement addition. On the other hand, the samples that present lower values are H1, H7 and H8; their percentage of recycled aggregates is equal o lower than 30% and two of them use no cement addition. Fig. 8 shows the individual results for each variable. The flexural strength slightly increases with the amount of recycled aggregates used. This effect may be due to the texture of these aggregates. As the mortar is adhered to their surface, they are rougher than natural aggregates what would generate more resistance when flexural tension is applied. The 5% cement addition samples are the ones that present more flexural strength. These results agree with those obtained with ANOVA (Table 7), where it can be observed that the variables that affect more significantly to the flexural strength are the percentage of the recycled aggregates and the cement addition.

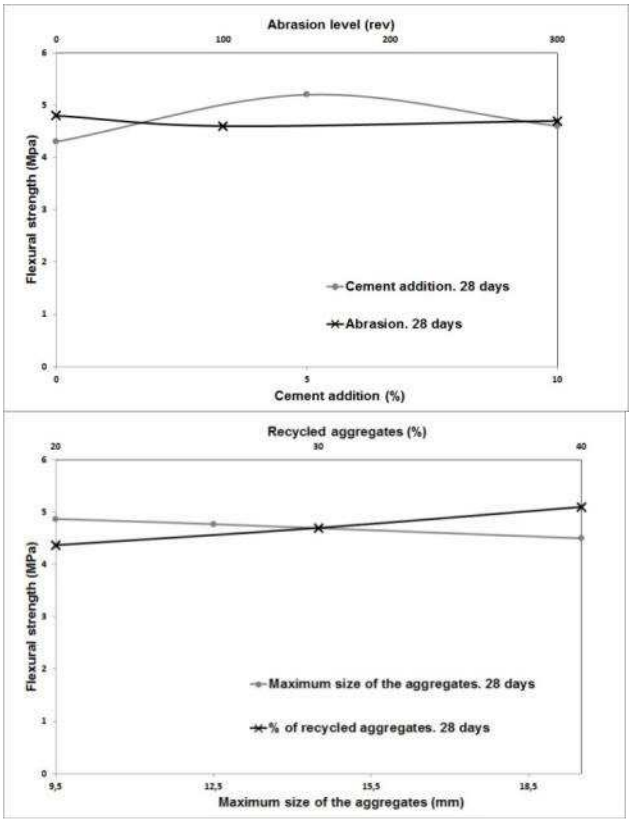

Fig. 8 A) “Flexural strength variation with abrasion and cement addition after 28 days”. B) “Flexural strength variation with amount and size of recycled aggregates after 28 days”.

Varaible	Deg Fr	Square Sum	Variance (V)	Participation rate(%)
% Agg.	2	0.735	0.367	30.0
Ab.	2	0.068	0.034	2.8
C. Add.	2	1.428	0.714	58.3
Max S	2	0.215	0.107	8.8

Table 7 “Summary of the flexural strength results of ANOVA”.

ACI 318-11 0 proposes eq. 1 to calculate the ultimate tensile strength or flexural strength.

$$f_r = 0{,}62\sqrt{f_c'} \quad (1)$$

Where f_r is the ultimate flexural strength (MPa) and f_c' the cylindrical compressive strength (MPa)

The experimental results and those obtained using eq. 1 for the studied samples are shown in Fig. 9. All the samples show higher values than the ones specified by ACI 318 0. As the values stablished by ACI 318 0 are quite conservative it is possible to conclude that concretes with recycled aggregates exceed expected resistances.

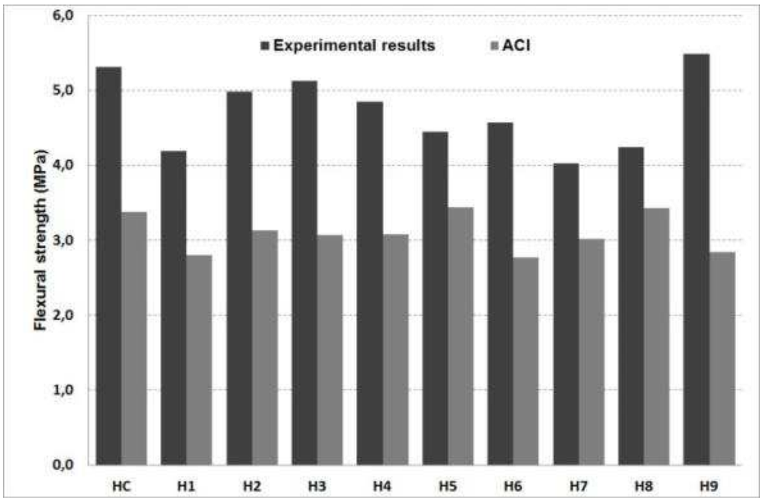

Fig. 9 “Flexural strengths obtained experimentally and following ACI 0 equation (1)”

5. - Conclusions

One of the main problems when using recycled aggregates in concrete is the mortar adhered to their surfaces. This mortar generates a double weak interface and an increase in the water absorption values. The water absorption registered for the recycled aggregate used is 3.6 times the one of the natural aggregate. A new method has been applied to reduce this mortar through mechanical processes. When 100rev and 300rev are applied to the reused aggregates, the mortar decreases to 3.1 and 2.4 times the value obtained for the natural one respectively. Therefore, the abrasion process is effective eliminating the adhered mortar to reduce the absorption values of the recycled aggregate.

Taguchi analysis proves that the more influential parameters in the strength of the concrete studied, after 28 days, are the amount of recycled aggregates and the level of abrasion applied. On the other hand, the maximum size of the recycled aggregates and the cement addition don’t seem to have a significant influence in the compression strength.

We can conclude that using up to a 30% of recycled aggregates in the concrete maintains the compressive strength values of the material similar to the ones of a traditional concrete.

Reducing the amount of mortar, measured directly through the abrasion level applied, increases the compressive strength up to a 14% after 28 days and 6% after 90. To establish further conclusions on this parameter a deeper analysis is needed to study the effect of a higher level of abrasion applying more revolutions to the material.

The compressive strength of concretes with recycled aggregates can be increased by mainly controlling the percentage of recycled aggregates used and the amount of the mortar adhered to the surface of the aggregates.

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