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Use of recycled fine aggregate in concretes with durable requirements

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A B S T R A C T

The use of construction waste materials as aggregates for concrete production is highly attractive compared to the use of non-renewable natural resources, promoting environmental protection and allowing the development of a new raw material. Several countries have recommendations for the use of recycled coarse aggregate in structural concrete, whereas the use of the fine fraction is limited because it may produce significant changes in some properties of concrete. However, during the last decade the use of recycled fine aggregates (RFA) has achieved a great international interest, mainly because of economic implications related to the shortage of natural sands suitable for the production of concrete, besides to allow an integral use of this type of waste. In this study, the durable behaviour of structural concretes made with different percentage of RFA (0%, 20%, and 30%) is evaluated. Different properties related to the durability of concretes such as absorption, sorptivity, water penetration under pressure, and carbonation are determined. In addition, the results of compressive strength, static modulus of elasticity and drying shrinkage are presented. The obtained results indicate that the recycled concretes have a suitable resistant and durable behaviour, according to the limits indicated by different international codes for structural concrete.

1. Introduction

The recycling of construction waste materials is highly attractive compared to the use of non-renewable natural resources, promoting environmental protection and allowing the development of a new raw material. The use of these wastes as aggregates for the concrete production, especially those obtained from the crushing of old concrete, is one of the most important issues in the world today.

Different studies on the evaluation of recycled aggregate properties have been done from different perspectives, related to the quality and the source of the waste concrete. However, most of them evaluate the coarse fraction, and the results obtained respect to the characteristics and properties of these aggregates are very similar to each other (Hansen and Narud, 1983; Tavakoli and Soroushian, 1996; Buyle-Bodin and Hadjieva-Zaharieva, 2002; Padmini et al., 2009; Sánchez de Juan and Alaejos Gutiérrez, 2009; Zega et al., 2010). Several countries have recommendations for the use of recycled coarse aggregates in structural concretes, but the recycled fine aggregates (RFA) are discarded because they may produce modifications on the fresh and hardened concrete properties (Hansen, 1986; RILEM, 1994; Grübl and Rühl, 1998; EHE, 2008).

However, during the last decade, the use of RFA has become more important in concrete production because of economic implications related to the shortage of natural sands suitable for that, and the need for a comprehensive utilization of such wastes, since the fine fraction remains when the recycled coarse aggregates are used, which storage and control is complex.

Respect to the use of RFA in structural concrete, in the literature some studies related to the resistant behaviour of concretes made with different content of RFA can be found. Khatib (2005) informs that concretes made with 25% and 100% of RFA present reductions of 15% and 30% in the compressive strength. On the other hand, Evangelista and de Brito (2007) conclude that the compressive strength is not affected by the utilization of RFA up to 30%, although the splitting tensile strength and static modulus decrease as the recycled aggregate content increases. The most important changes produced on the behaviour of concretes with RFA are related to higher drying shrinkage and less durability, respect to those made with natural fine aggregates (Sri Ravindrarajah et al., 1987; ACI 555, 2002; Evangelista and de Brito, 2004).

Previous studies made on the use of RFA in concrete (Zega and Di Maio, 2006), showed that the use of RFA over 50% produce significant decreases on the slump of the mixes at the fresh state, similar to those produced in concretes made with natural crushed sand.

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The main objective of this study is to evaluate the durable behaviour of recycled concretes, made with variable content of RFA (0%, 20%, and 30%), respect to those of similar characteristics made with natural fine aggregates. Different properties related to the concretes durability such as water absorption by immersion, sorptivity, and water penetration under pressure are evaluated. Besides, the carbonation depth of samples exposed to urban-industrial atmosphere is determined. Complementary, the results of compressive strength, static modulus of elasticity and drying shrinkage of the studied concretes are presented.

2. Experiences

2.1. Materials and mixtures

Blended Portland cement (type I (SM) ASTM or CEM II-M), river siliceous sand, and granitic crushed stone (nominal size 6–20 mm) were used to make the concretes. For recycled concretes, recycled fine aggregate (RFA) obtained from crushed waste concretes of different qualities, and made with granitic stone, were used by replacing different contents (0%, 20%, and 30% by volume) of natural sand. In all concretes, a water-reducing admixture was used. The physical properties determined on coarse and fine aggregates, such as fineness modulus, specific gravity (saturated and surface dry – SG_{ssd}), water absorption, and material finer than 75 μm are presented in Table 1.

Different regulations specify a maximum water/cement ratio (w/c) in concretes with durable requirements. The Spanish Code (EHE, 2008) and the American Code (ACI 318, 2008) indicates maximum w/c ratios 0.45 and 0.40, respectively, while in the case of Argentinean Regulation (CIRSOC 201, 2005) the maximum w/c ratio is 0.45. Respect to the use of natural crushed sand in concrete production, the CIRSOC 201 imposes a limit of 30%. Thereby, in accordance with these guidelines, a conventional concrete (CC) made with 100% of river siliceous sand and w/c ratio 0.45 were used as reference concrete. The recycled concretes were made keeping constant the mixture proportions of CC concrete and the natural river sand was replaced by 20% and 30% of RFA (RC20 and RC30). The mixture proportions of the different concretes are presented in Table 2.

Regarding to the mixing procedure, the materials were incorporated to the mixer in the following order: coarse aggregate, fine aggregate (natural and recycled), cement, and the water with the admixture was added after a brief mixing of dry materials. The aggregates were used in air-dry state. The RFA had an initial water content of 2.39% in terms of weight, so the effective water/cement ratio of RC concretes is lower than that of CC concrete.

The water-reducing admixture was used in minimal dose (0.3% of cement weight) in the CC concrete, which was increased in 0.05% in RC20 and in 0.1% in RC30, due to the higher water absorption and material finer than 75 μm of the recycled fine aggregate respect to the river siliceous sand. Different specimens were cast with each mixture and placed in a fog room (T: 23 ± 2 °C; RH: 95%) until the test age.

Table 1
Properties of aggregates.

Properties	Coarse aggregate	River sand	RFA
Fineness modulus	6.72	2.49	3.15
SG_{ssd}	2.72	2.63	2.56
Water absorption (%)	0.3	0.9	8.5
Material finer than 75 μm (%)	0.6	0.2	4.0

Table 2
Mixtures proportions.

Materials (kg/m^3)	CC	RC20	RC30
Water	170	170	170
Cement	375	375	375
River siliceous sand	850	680	590
Recycled fine aggregate	-	165	250
Granitic crushed stone	1000	1000	1000
Water-reducing admixture	1.13	1.31	1.50
Effective water/cement	0.45	0.43	0.41

3. Results and analysis

3.1. Fresh state properties

The fresh state properties determined to the different concretes such as slump, unit weight, and natural entrained air, are presented in Table 3. The consistency of RC20 concrete was similar to that of CC concrete (slump: 80 ± 10 mm), while the slump of RC30 was significantly lower, although the admixture dose was increased. The use of RFA in air-dry state allowed that part of the mixing water be absorbed together with the admixture. In the case of the RC30 concrete, this effect is more important on fresh state properties of concrete, as a consequence of the increase of the RFA content.

3.2. Mechanical properties

In order to know the mechanical behaviour of concretes under study, different properties were evaluated. The results of compressive strength, splitting tensile strength and static modulus of elasticity, determined on cylindrical specimens (100 × 200 mm), are presented in Table 4. In each case the indicated value represents the average of three tests.

At the evaluated ages (28 and 84 days), the compressive strengths of recycled concretes are similar to those of CC concrete, with a maximum decrease of 5% for the RC30 concrete at 28 days. The similar compressive strengths achieved in all concretes can be attributed to the lower effective water/cement ratio of RC concretes respect to CC, because the same content of water is used in all concretes, and the water absorption capacity of RFA is much higher than natural sand. Consequently part of the added water is absorbed by RFA. At the age of 84 days, all concretes present compressive strengths 16% higher than those obtained at 28 days.

Respect to the splitting tensile strength, the RC30 concrete shows a slight decrease (7%) compared with the other concretes. Moreover this concrete present a static modulus of elasticity 7%

Table 3
Fresh state properties.

Properties at fresh state	CC	RC20	RC30
Slump (mm)	85	70	35
Unit weight (kg/m^3)	2390	2380	2385
Natural entrained air (%)	3.1	3.0	2.5

Table 4
Mechanical properties.

Mechanical properties	Age (days)	CC	RC20	RC30
Compressive strength (MPa)	28	43.6	42.7	41.4
	84	50.2	49.4	48.6
Splitting tensile strength (MPa)	28	4.3	4.4	4.0
Static modulus of elasticity (GPa)	28	35.4	34.8	32.9

lower than the CC concrete modulus. This fact can be attributed to the lower compressive strength of RC30 concrete.

3.3. Water absorption

A quick way to assess the possible durable behaviour of concrete is by determining the water absorption. In the concretes under study, this test was carried out according to the guidelines specified in ASTM C 642 (1990). The results obtained for each concrete, as average of five tests, are presented in Fig. 1, indicating also the standard deviation.

The water absorptions of RC concretes are 15% higher than that of CC concrete, although there are no differences between concretes made with different RFA content. The higher water absorption capacity of recycled concretes is attributed to the higher water absorption of RFA compared with natural river sand, because of the original mortar present on the recycled aggregate particles. The RC30 has an effective water/cement ratio less than the RC20; this fact would explain the similar water absorption of both recycled concretes. On the other hand, recycled concretes present standard deviations similar to that of CC concrete.

3.4. Sorptivity

The capillary absorption test allows the characterization of the porous structure and is an indicator of the concrete durability. The test technique consists of recording, at fixed intervals, the mass increment by capillary suction of a specimen with one face in contact with water, up to constant weight (difference between two consecutive weighings less than 0.1%). The test of capillary suction was carried out according to IRAM 1871 (2004), on cylindrical specimens of 100×50 mm sawing from cylindrical specimens of 100×200 mm (Fig. 2).

The quantification of capillary absorption is made by determining the sorptivity (S), which represents the capillary rise velocity at which the liquid ascends through the concrete porous structure. It is calculated as the slope of the straight line obtained by linear regression, which defines the absorption per unit area versus square root of time. Another parameter obtained from the capillary test is the capillary absorption capacity (C), which is the maximum value of absorption obtained up to constant weight. Individual value of S and C of each tested sample was in the range ± 15% of the average.

For each evaluated concretes, the limit curves obtained from consideration ± 15% of the average curve are presented in Fig. 3. It can be seen that the intervals for RC concretes are overlapping each other, and both are also largely overlapped with the intervals of CC concrete, being possible to indicate that both types of concretes (RC and CC) present a similar performance. This behaviour of the recycled concretes can be attributed to the lower effective water/cement ratio of RC concretes, in RC30 lower than in RC20, and possibly to the better interface transition zone (ITZ) of RFA compared with the natural sand.

Fig. 4 shows the capillary absorption curves obtained for the different concretes studied, being each curve the average of five tests. The recycled concretes present a similar behaviour, and the respective curves are slightly above of CC concrete curve. This fact is attributed to the higher absorption of RFA respect to natural sand. The described behaviour is reflected in the obtained values of sorptivity and capacity in each concrete. The sorptivity of CC concrete was 3.1 $g/m^2/s^{1/2}$ while for RC concretes was 3.5 $g/m^2/s^{1/2}$. The capillary absorption capacity of RC concretes was 2725 g/m^2, which is 13% higher than that of CC concrete (2410 g/m^2).

From the obtained results, it must be indicated that the RC concretes satisfy the requirements specified by the Argentinean Regulation respect to the capillary test (sorptivity values lower than 4 $g/m^2/s^{1/2}$).

3.5. Water penetration under pressure

The water penetration test provides information about the permeability of concrete, which is a durable parameter determined usually on concretes exposed to aggressive environments. This test

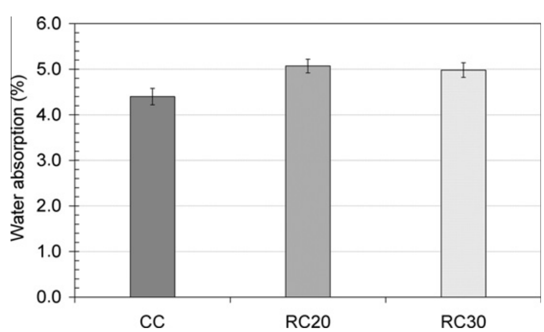

Fig. 1. Water absorption.

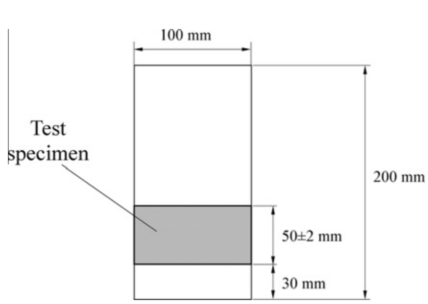

Fig. 2. Specimen for capillary absorption test.

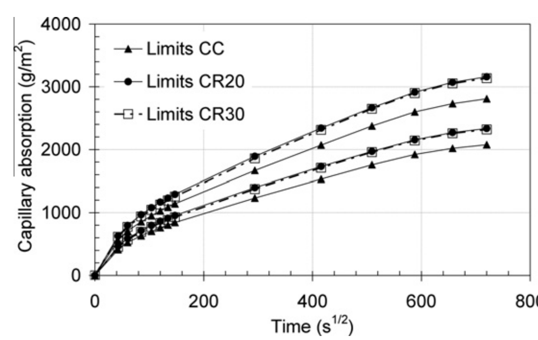

Fig. 3. Limit curves for the interval of ±15%.

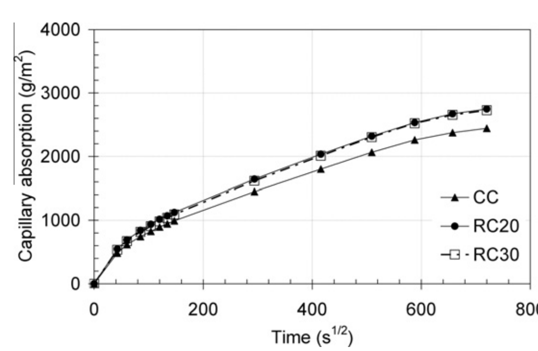

Fig. 4. Capillary absorption curves.

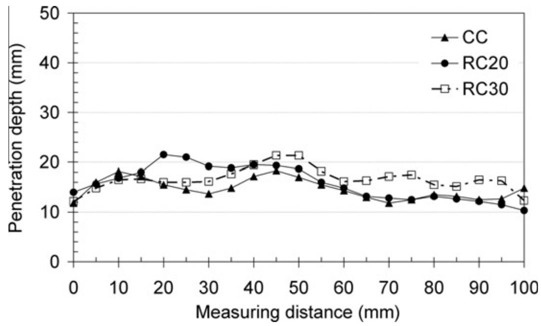

Fig. 5. Water penetration profiles.

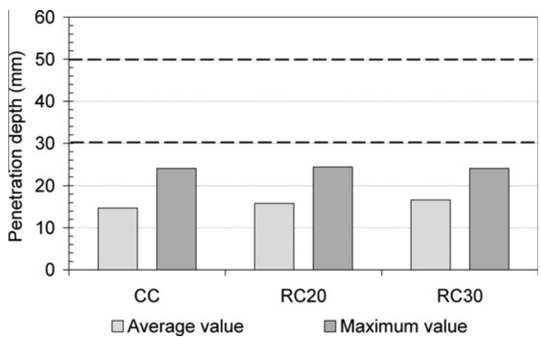

Fig. 6. Water penetration depths of concretes.

was carried out according to IRAM 1554 (1983) on 200 mm cubic specimens. The concrete specimens are placed under a variable water pressure for a period of 96 h (48 h at 0.1 MPa, 24 h at 3 MPa, and 24 h at 7 MPa). After this time, a splitting tensile test is performed with the purpose of demarcate the water penetration profiles on both halves generated. Then, the average and the maximum water penetrations are obtained.

In Fig. 5, the profiles obtained for each concrete under study are presented, as average of three tests. The RC20 and RC30 concretes present penetration profiles similar to that of CC concrete. This behaviour is reflected in the obtained values of water penetration, which are presented in Fig. 6.

The values of water penetration of RC concretes are similar to that of CC concrete. The average values were 15, 16, and 17 mm for CC, RC20, and RC30 concretes, respectively, while the maximum value was 24 mm for all concretes. This behaviour is attributed to the lower effective water/cement ratio of RC concretes respect to CC concrete, as mentioned above.

As in the capillary suction test, the obtained water penetration depths are lower than the limits indicated by Argentinean Regulation (CIRSOC 201, 2005), similar to those indicated by the Spanish Code (EHE, 2008), as a necessary requirement for durable concretes. These limits are 30 and 50 mm for the average and maximum values, respectively.

In the water absorption and sorptivity tests, the respective parameters of the recycled concretes are 15% and 13% higher than those corresponding to the CC concrete, while for the water penetration test all concretes present a similar behaviour. This fact is related to the different transport mechanisms involved in each case.

3.6. Carbonation

Respect to the carbonation effect on concretes with different characteristics, several studies conclude that the carbonated thickness measured on recycled concrete (made with coarse and fine recycled aggregate) is higher than the one obtained in conventional concretes. In these cases, the concretes were exposed to accelerated carbonation processes, although under different conditions of temperature, humidity and carbon dioxide concentration (CO_2). This fact generates that the differences obtained between conventional and recycled concretes are greater when the CO_2 concentration increases (Hansen, 1986); Buyle-Bodin and Hadjieva-Zaharieva, 2002; Katz, 2003; Otsuki et al., 2003).

In this study the carbonation assessment was performed on prismatic specimens (75 × 75 × 300 mm) exposed to an urban-industrial natural environment. The place is located on the outskirts of La Plata city, Argentina, with a precipitation regime of 1000 mm/year, an average relative humidity of 78%, and average minimum and maximum temperatures of 5 °C and 30 °C, respectively.

The evaluation of carbonation depth was performed by the dyeing technique with phenolphthalein on the sawn surface, taking the measurements at 310 and 620 days of exposure. The obtained carbonation depths are presented in Table 5.

Table 5
Carbonation depths.

Exposure time(days)	Carbonation depths (mm)		
	CC	RC20	RC30
310	2.0	2.0	1.5
620	2.0	2.0	2.0

While the exposure time to produce carbonation could be considered relatively short, taking into account the low water/cement ratio of the studied concretes, it can be observed that all concretes present a similar behaviour, for both evaluation ages, which is very similar to those found in the absorption and water penetration tests. In this case, the observed behaviour is attributed to the lower effective water/cement ratio of RC concretes because of the high water absorption capacity of RFA. A lower w/c ratio certainly influences porosity (by reducing it) and it is able to compensate the use of a more porous aggregate (Corinaldesi and Moriconi, 2009).

3.7. Drying shrinkage

Other parameter evaluated on the different concretes under study is the drying shrinkage, which may present significant variations considering the characteristics of recycled fine aggregates respect to the natural fine aggregates. The evaluation of the drying shrinkage of concretes was carried out on prismatic specimens (75 × 100 × 430 mm). They were kept in the fog room for 28 days, after that they were placed in a room with controlled temperature and humidity (T: 20 ± 2 °C; RH: 55%), keeping them in these

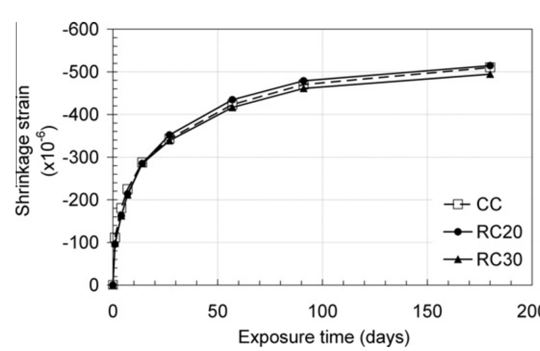

Fig. 7. Drying shrinkage strain.

conditions during the measurement period. Initial reading was performed at the time of placing the specimens in the room, and then they were measured at the ages of 1, 4, 7, 14, 28, 56, 90, and 180 days. For each concrete, three samples were evaluated. The curves of drying shrinkage strain versus time, recorded for CC, RC20 and RC30 concretes are presented in Fig. 7.

It can be observed that, until the age evaluated (180 days), the drying shrinkage of recycled concrete RC20 is similar to that of CC concrete, whereas the RC30 presents a slightly lower drying shrinkage, due to the lower effective w/c ratio of this last concrete.

Concretes with equal w/c ratio and aggregate volume have similar drying shrinkage (Newman and Choo, 2003). In the present study, all concretes have the same aggregate volume (69%) and the w/c ratios are very close, so it is expected that the drying shrinkage are too similar.

4. Conclusions

From the results obtained in this study on concretes made with recycled fine aggregate (RFA) replacing different percentages (0%, 20% and 30%) of natural river sand, and taking into account the resistance and durable requirements indicated by the Argentinean Regulation, it can be concluded:

- The compressive strengths of concretes made with 20% and 30% of recycled fine aggregate are similar to those of concrete made with 100% of natural fine aggregates. This fact can be attributed to the lower effective water/cement ratio of RC concretes respect to the CC concrete.
- Because of the same mixing water content used in all concretes, the drying shrinkage at the age of 180 days of CC and RC20 concretes are similar, but the RC30 has a slightly lower drying shrinkage strain due to the lower w/c ratio.
- The durable behaviour of recycled concretes is as good as that of conventional concrete, with sorptivity and water penetration's values lower than the limits indicated in the Argentinean Regulation. This fact is due to the lower effective water/cement ratio of recycled concretes respect to CC concrete, and probably because the interface transition zone (ITZ) of RFA are better than that of natural sand.
- At the ages of 310 and 620 days, the carbonation depths determined on recycled concretes are similar to those of conventional concrete, because of the lower effective water/cement ratio of RC concretes. The low values obtained for all concretes (about 2 mm) are related to the medium-level aggression of the natural environment, and the low water/cement ratio of concretes.
- As a general conclusion of these studies, it is possible to indicate that concretes made with up to 30% of recycled fine aggregate present an adequate mechanical and especially durable behaviour, because they verify the requirements imposed by different codes for structural concretes. Similar mechanical and durable behaviour of RC concretes respect to CC concrete were obtained by reducing the w/c ratio by using plasticizer admixture.

References

ACI 318S, 2008. Requisitos de Reglamento para Concreto Estructural. American Concrete Institute, P.O. Box 9094, Farmington Hills, Michigan 48333-9094, USA.

ACI Committee 555R-01, 2002. Removal and reuse of hardened concrete. Mater. J., ACI, 99-M31, 300–323.

ASTM C 642, 1990. Standard Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete. Annual Book of ASTM Standards, vol. 04.02, ASTM International, West Conshonocken, PA.

Buyle-Bodin, F., Hadjieva-Zaharieva, R., 2002. Influence of industrially produced recycled aggregates on flow properties of concrete. Mater. Struct. 35 (252), 504–509.

CIRSOC 201, 2005. Proyecto de Reglamento Argentino de Estructuras de Hormigón. Instituto Nacional de Tecnología Industrial. (En trámite de aprobación).

Corinaldesi, V., Moriconi, G., 2009. Influence of mineral additions on the performance of 100% recycled aggregate concrete. Constr. Build. Mater. 23 (8), 2869–2876.

EHE, 2008. Instrucción de Hormigón Estructural. Comisión Permanente del Hormigón, Ministerio de Fomento, España. Anejo 15, Recomendaciones para la utilización de hormigones reciclados. (www.fomento.es).

Evangelista, L.R., de Brito, J.C., 2004. Criteria for the use of fine recycled concrete aggregates in concrete production. In: Vázquez, E., Hendriks, Ch.F., Jansen, G.M.T. (Eds.), Proc. Int. RILEM Conference: The Use of Recycled Materials in Building and Structures, RILEM, 503-510. November 8–11, Barcelona, Spain..

Evangelista, L., de Brito, J., 2007. Mechanical behaviour of concrete made with fine recycled concrete aggregates. Cem. Concr. Compos. 29 (5), 397–401.

Grübl, P., Rühl, M., 1998. German Committee for Reinforced Concrete (DafStb) – Code: Concrete with Recycled Aggregates. Proc. Int. Symposium Sustainable Construction: Use of Recycled Concrete Aggregates. University of Dundee, London. (www.b-i-m.de).

Hansen, T.C., 1986. Recycled aggregates and recycled aggregate concrete. Second State-of-the-art. Report developments 1945–1985. RILEM Technical Committee-37-DRC, Demolition and Recycling of Concrete. Mater. Struct. 19 (111), 201–246.

Hansen, T.C., Narud, H., 1983. Strength of recycled concrete made from crushed concrete coarse aggregate. Concr. Int. 5 (1), 79–83.

IRAM 1554, 1983. Hormigón de cemento Pórtland. Método de determinación de la penetración de agua a presión en el hormigón endurecido. Instituto Argentino de Normalización y Certificación, Argentina.

IRAM 1871, 2004. Concrete. Test method for determination the water capacity and the capillary suction speed of the hardened concrete. Instituto Argentino de Normalización y Certificación, Argentina.

Katz, A., 2003. Properties of concrete made with recycled aggregate from partially hydrated old concrete. Cem. Concr. Res. 33 (5), 703–711.

Khatib, J.M., 2005. Properties of concrete incorporating fine recycled aggregate. Cem. Concr. Res. 35 (4), 763–769.

Newman, J., Choo, B.S., 2003. Advanced Concrete Technology. Concrete Properties. Elsevier. Linacre House, Jordan Hill, Oxford OX2 8DP, 200 Wheeler Road, Burlington MA 01803. ISBN 0750651040.

Otsuki, N., Miyazato, S., Yodsudjai, W., 2003. Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete. J. Mater. Civ. Eng., ASCE. 15 (5), 443–451.

Padmini, A.K., Ramamurthy, K., Mathews, M.S., 2009. Influence of parent concrete on the properties of recycled aggregate concrete. Constr. Build. Mater. 23 (2), 829–836.

RILEM, 1994. Recommendation 121-DRG, Guidance for demolition and reuse of concrete and masonry. Specifications for concrete with recycled aggregates. Mater. Struct. 27, 557–559.

Sánchez de Juan, M., Alaejos Gutiérrez, P., 2009. Study on the influence of attached mortar content on the properties of recycled concrete aggregate. Constr. Build. Mater. 23 (2), 872–877.

Sri Ravindrarajah, R., Loo, Y.H., Tam, C.T., 1987. Recycled concrete as fine and coarse aggregates in concrete. Mag. Concr. Res. 39 (141), 214–220.

Tavakoli, M., Soroushian, P., 1996. Strengths of recycled aggregate concrete made using field-demolished concrete as aggregate. Mater. J., ACI, 182–190.

Zega, C.J., Di Maio, A.A., 2006. Comportamiento de Hormigones Elaborados con Agregado Fino Reciclado. Proc. 16° Reunión Técnica de la AATH, Mendoza, Argeninta, 47–54.

Zega, C.J., Villagrán-Zaccardi, Y.A., Di Maio, A.A., 2010. Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates. Mater. Struct. 43 (1–2), 195–202.