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Study of permeability and mechanical properties of concrete made with substitutions of recycled coarse aggregate: Sustainable alternative

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Abstract — The use of recycled aggregates for the production of concrete is increasingly frequent, contributing to the preservation of the environment by reducing the consumption of natural aggregates. Unfortunately, the properties of concrete manufactured with recycled aggregate differ from those of conventional concrete, being the entrance of water and aggressive ions a determining factor in the durability of structures, thus making it important the study of their mechanical and permeable properties. In this work the resistance to compression and the permeability properties of concrete manufactured with the replacement of natural coarse aggregate. Therefore, adding 25% recycled coarse aggregate guarantees a performance similar to conventional concrete without compromising the durability of civil works, making the concrete manufactured with recycled coarse aggregate a viable alternative as a sustainable material to use in the construction industry.

Keywords — Sustainability, reuse, total Porosity, effective Porosity, absorption, Sortivity, useful life.

Resumen — El uso de agregados reciclados para la producción de concretos es cada vez más frecuente, contribuyendo a la preservación del medio ambiente al reducir el consumo de agregados naturales. Lamentablemente, las propiedades del concreto fabricado con agregados reciclados difieren de las del concreto convencional, siendo la entrada de agua e iones agresivos un factor determinante en la durabilidad de las estructuras, por lo que es importante el estudio de sus propiedades mecánicas y permeables. En este trabajo la resistencia a la compresión y las propiedades de permeabilidad del concreto fabricado con la sustitución del agregado grueso natural. Por tanto, la sustitución del agregado grueso natural por un 25% de agregado grueso reciclado garantiza un comportamiento similar al concreto convencional sin comprometer la durabilidad de la obra civil, haciendo del concreto fabricado con agregado grueso reciclado una alternativa viable como material sostenible para utilizar en la industria de la construcción.

Palabras Claves — Sostenibilidad, reutilización, Porosidad total, Porosidad efectiva, Absorción, Sortividad, vida útil.

I. INTRODUCTION

The useful life of concrete structures is reduced due to various factors: failures in the design, quality control and construction; being it necessary to make repairs, substitutions and/or demolitions of the works, where again the use of construction materials is required to carry them out. Unfortunately, the concrete industry causes a severe environmental impact due to the nature of its manufacturing process, destroying natural resources due to the consumption of raw materials and of the waste that result from demolition discarded in landfills. This situation causes increases in the extraction of natural resources and consequently affects the environment [1]. In order to help solve the problem of natural resource extraction, the concrete product of demolition has been reused to manufacture Recycled Coarse Aggregate (RCA) by crushing, replacing Natural Coarse Aggregate

(NCA) in the construction of new civil works , contributing to the sustainability of the concrete industry [2–4]. Regarding the durability of concrete works, water is a determining factor in its degradation, as it is the means of transporting harmful substances and being part of the pore solution of the concrete matrix. In addition, *permeability*, *water absorption and capillary absorption* of concrete define its physical and chemical deterioration in aggressive environments, controlling the penetration of water, chlorides and other ions [5–7]. As strategies to counteract this situation, it has been projected to improve the durability of concrete and the use of recycled materials; however, the use of RCA in a 100% replacement of NCA is risky because it causes deterioration of the structures and demerits in its durability. These properties have been studied in isolation in various investigations [8–10], emerging the need to be evaluated quantitatively together as a measure of durability of the concrete manufactured with RCA in replacement of NCA. The use of RCA in concrete offers new alternatives for the reuse of materials in the construction industry, being directed towards a sustainable development. The recycling of construction waste, has been studied since the 50s, countries like Japan and Korea have remarkable progress in this regard, being able even to construct structures exclusively with RCA [11–13]. There are also regulations worldwide regarding the issue of recycled concrete such as: BS 8500-2: 2002 [14] y RILEM [15,16], among others; nevertheless, in Mexico and in many other third world countries, there are no regulations on the use of RCA. In addition, several researchers have made recommendations and studies regarding the production, preparation and implementation of RCA [17–19]; however, they are isolated studies where they have used materials of different properties between investigations where it is not possible to make correlations between mechanical and permeable properties.

In the present work, the properties of resistance to compression and permeability in specimens with the same properties were evaluated, proposing from the results a maximum percentage of RCA replacing NCA for the manufacture of structural concrete, without significantly altering its performance in resistance and durability, guaranteeing a performance similar to conventional concrete and contributing to the sustainability of the concrete industry.

II. METHODOLOGY

2.1 Materials

In tests and manufacture of specimens we used: NCA of crushed limestone with a maximum size of 1" and natural river silica sand. These materials were obtained from a local sieve in the community of Charay, El Fuerte, Mexico. The concrete cylinders were used from waste obtained from the laboratory. of Construction of the Bachelor of Civil Engineering in Los Mochis, Sinaloa, Mexico, which were designed with a compressive strength of 25 MPa, distilled water and Portland cement composed of 30R brand Cemex® were also used. Sulfur was used for capping the specimens, and silicone, epoxy resin, and high-vacuum lubricant were used for permeability analyses. For the chlorine ion penetration study, a 0.3 N NaOH aqueous solution and a 3% NaCl aqueous solution were used.

2.2 Equipment

It was used in tests and manufacture of specimens: Jaw crusher model: JS-0804, set of granulometric meshes, digital precision scale: 0.1 gr., Concrete disc cutter, electric oven, scanning electron microscope with EDAX brand: JEOL model: JSM-5800LV, vacuum chamber, drill with bit for extraction of concrete hearts, axial compression press, chloride penetrator standard: ASTM C1202, desiccator, oven, gloves for industrial use, trays, plastic containers, cylindrical metal molds, shovel, wheelbarrow, digital vernier, metal hammer, specimen pitch base and metal basket.

2.3 Manufacture of RCA.

The waste concrete was obtained from a quality control laboratory, Figure 1 shows the raw material used for the manufacture of the RCA, after a mechanical crushing process with a jaw crusher.

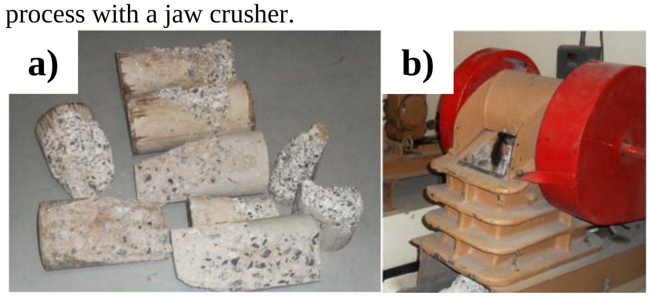

Fig. 1. a) Recycled specimens and b) jaw crusher.

2.4 Physical Properties of Aggregates

Physical properties of the aggregates are shown in Table 1. The relative RCA specific mass was 16% lower than NCA, while the humidity and absorption of RCA outperformed NCA, situations attributed to the effect of the paste adhered in the natural aggregates of the RCA, product of its previous use.

Table 1. Properties of natural and recycled aggregates.

Aggregate Type	Property	Value
NCA	Relative Specific Mass	2.50
	Compact dry volumetric mass (kg/m^3)	1614.58
	Humidity (%)	0.28
	Absorption (%)	0.52
RCA	Relative Specific Mass	2.10
	Compact dry volumetric mass (kg/m^3)	1383.27
	Humidity (%)	1.26
	Absorption (%)	6.25

Natural Fine (Sand)	Relative Specific Mass	2.43
	Compact dry volumetric mass (kg/m^3)	1609.09
	Humidity (%)	6.15
	Absorption (%)	4.08

2.5 Granulometry of aggregates.

The granulometry of NCA, RCA and natural sand is shown in Figure 2 according to ASTM C33, being the fineness modules of 2.49, 2.46 and 3.04, respectively. Figure 3 shows the graduated RCA used for the manufacture of concrete.

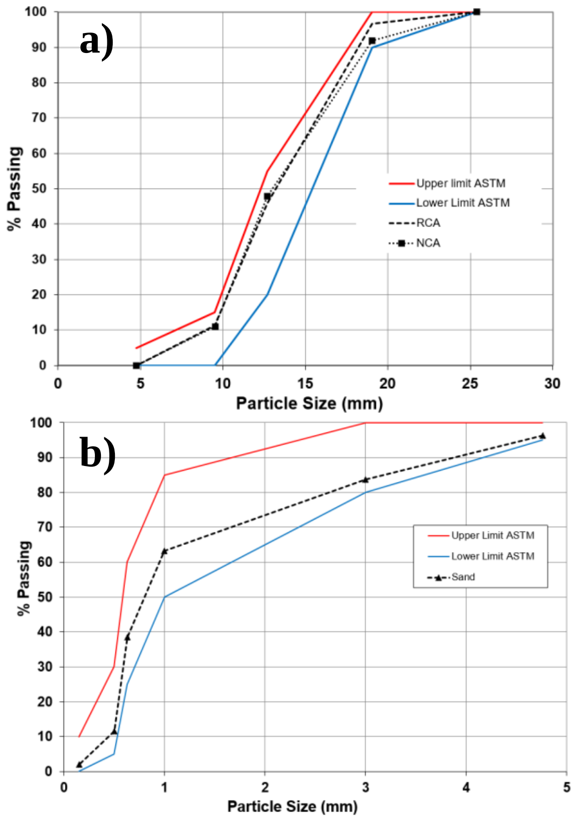

Fig. 2. Granulometry of aggregates according to ASTM C33. a) RCA and NCA and b) Sand

Fig. 3. Graduated recycled coarse aggregate.

2.6 Dosage of concrete mixtures.

The replacement factor (r) represents the weight percentage of NCA substituted by RCA in the preparation of the mixtures. Specimens were manufactured with different r: 0.00, 0.25, 0.50, 0.75 and 1.00, performing the dosage by using the method of the absolute volumes of the Portland Cement Association, design resistance of 280 kg/cm^2, maximum size of aggregate of 1" thick, river sand with 3.0 fineness modulus, 75 to 100 mm of shrinkage and 0.50 water/cement ratio. The water requirement for the case of concrete manufactured with RCA is 23.5% higher than that manufactured with NCA, gradually increasing with the substitution of RCA 5.9% for every 0.25 of increment of "r", as shown in Table 2.

Table 2. Dosage of mixtures (kg).

Material	Replacement factor (r)					Total
	0.00	**0.25**	**0.50**	**0.75**	**1.00**	
Water	2.52	2.67	2.81	2.96	3.11	14.07
Cement	5.34	5.34	5.34	5.34	5.34	26.68
Natural Gravel	14.55	10.91	7.27	3.64	0.00	36.37
Recycled Gravel	0.00	3.15	6.29	9.44	12.59	31.46
Sand	9.44	9.36	9.29	9.21	9.14	46.44

2.7 Tests performed and specimen dimensions.

The tests performed, the standards that were followed, and the dimensions of the sample are shown in Table 3.

Table 3. Specimen dimensions and test regulations.

Test	Normativity	Dimensions Diameter x height (cm x cm)
Mechanical compression and unit mass tests	ASTM C30 y C33	10 x 20
Absorption by immersion and total porosity	ASTM C642	10 x 5
Rapid Chloride Penetration	ASTM C1202	10 x 5
Capillary Absorption and Effective Porosity	ASTM C1585	10 x 3

2.8 Monitoring of interfacial transition zone in hardened concrete.

The specimen to observe the Interface Transition Zone (ITZ) by electronic scanning microscopy was performed by embedded in resin, polished to obtain a mirror surface with carbon coating in a vacuum chamber, placing the interface areas between the AN, AR and paste of cement, with the intention of identifying the different existing ITZs. Figure 4 shows specimen and equipment.

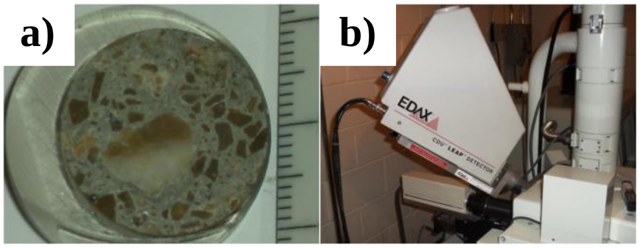

Fig. 4. Specimen and equipment to obtain micrographs. a) Concrete sample and b) Equipment.

III. RESULTS AND DISCUSSION

3.1 Interfacial transition zone

The different ITZs existing between the RCA, NCA and the new mortar are shown in Figure 5, with cracks generated in the crushing process. In the first, the fissure was generated in the old NCA and in the second it is in the old mortar, both present in the RCA, the new NCA does not present damage. There are 3 different ITZs in the concrete: new NCA - new mortar, old NCA - old mortar and old mortar - new mortar [20], generated due to the superficial absorption of the aggregate water, which absorbs the water present in the mortar during the process of manufacturing, generating an area with poor hydration and giving rise to the ITZ [21], this has a marked influence on the different properties of water flow and ions in the mass of the concrete by having permeability properties superior to the rest of the mass of the concrete.

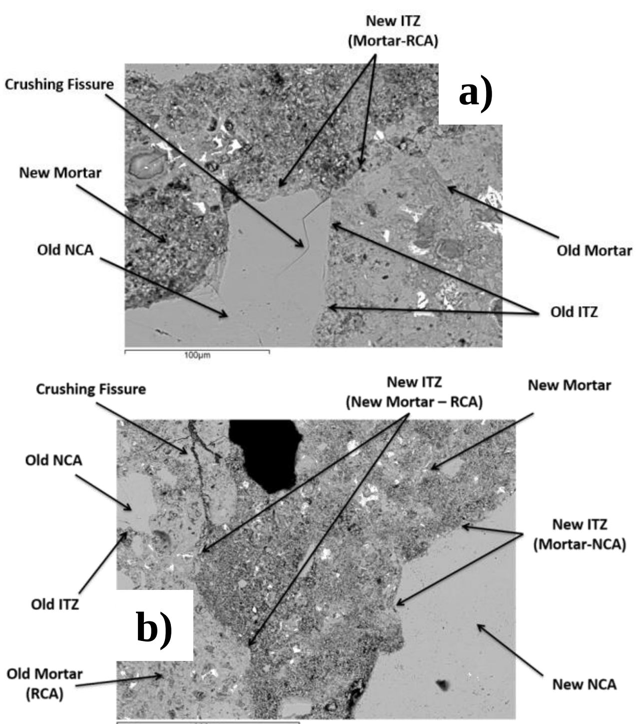

Fig. 5. ITZ of recycled aggregate (a) and new mortar (b).

3.2 Resistance to simple compression and unit mass.

Resistance to compression and its reduction with increments of r is shown in Figure 6, being an inverse linear relation. The maximum resistance to compression was in r of 0.0 with 29.7 MPa, while the minimum was in r of 1.0 with 24.4 MPa. For r of 0.25 the decrease in resistance is low with 3.37%, attributed to the fact that most of the mass of the concrete is still NCA and the RCA is scattered in isolation throughout the mass of concrete, favoring low reductions in resistance. Additionally, the unit mass in hardened state is shown in Figure 7, being 3.43, 4.72, 5.58 and 6.01% the unit mass decreases for r of 0.25, 0.50, 0.75 and 1.00, respectively. This is attributed to the fact that the recycled aggregate has already had a life cycle, it contains cracks caused by its previous application and others caused by the crushing process. This leads to it not supporting internal stresses as efficiently as the natural aggregate [22].

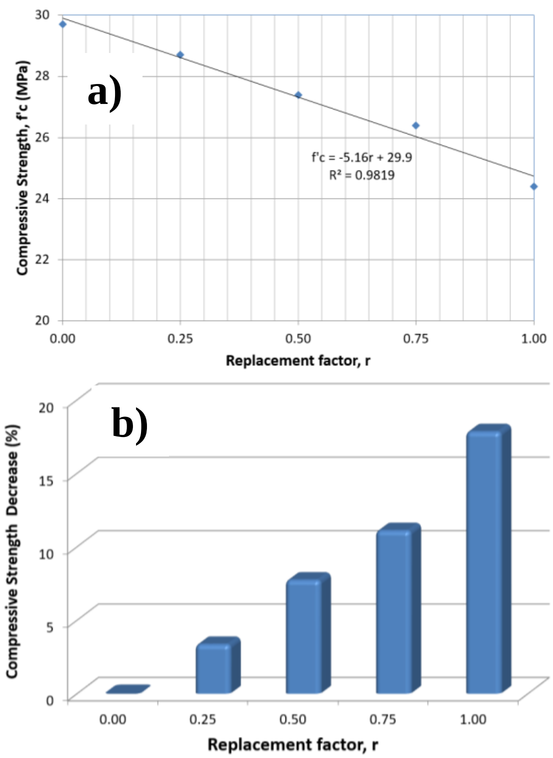

Fig. 6. a) Resistance to compression (MPa) and b) Decrease.

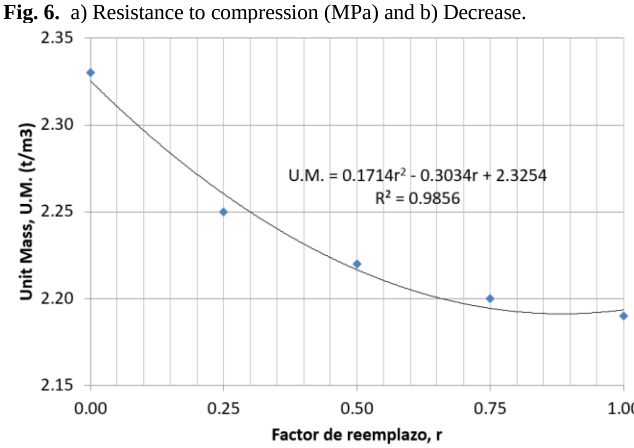

Fig. 7. Unit mass in hardened state.

3.3 Permeability properties

3.3.1 Total Porosity.

Total porosity and its increase with increments of r is shown in Figure 8, being a direct linear relationship. The minimum total porosity corresponds to r of 0.0 with 15.26% and the maximum to r of 1.0 with 22.36%. The total porosity considers the connected and unconnected pores of the cementitious matrix, its increment is due to the increase in the volume of the paste in the concrete and the pore network, whether in new or old concrete paste [23,24]. In addition to this, it presents the generation of an ITZ additional to the old ITZ of the RCA, with porosity properties greater than NCA and RCA. The increase in porosity for r of 0.25 is, in proportion, smaller than the rest of the replacements, showing up increases above 40% for r of 1.00. Whence, the increase in total porosity is attributed to the greater amount of cement paste and the increase in ITZ regions.

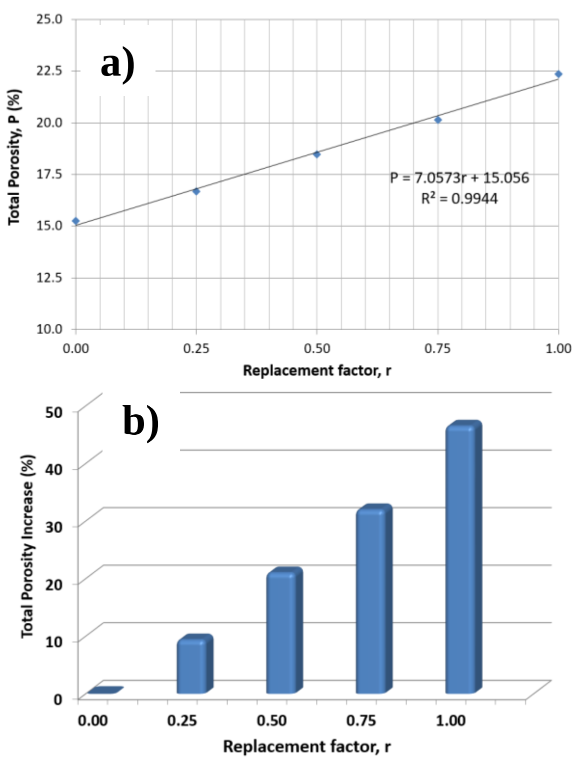

Fig. 8. a) Total porosity and b) increase.

3.3.2 Absorption by immersion.

The absorption by immersion and its increase with increment of r is shown in Figure 9, being a direct linear relationship. The minimum absorption by immersion corresponds to r of 0.0 with 6.95%, while the maximum at r of 1.0 with 10.96%. Absorption by immersion refers to the total water absorbed in the pores connected in the network formed within the mass of the concrete [25,26], the fact of presenting an increase with increments of r, is due to the parallel increment in the volume of the cement paste. Similar to the total porosity, the increment in absorption by immersion for r of 0.25 is, in proportion, smaller than the rest of the replacements, with increases above 40% for r of 1.00. Therefore, the increment in the absorption by immersion is also attributed to the greater amount of cement paste and the increase in the ITZ regions, in similarity with the total porosity [27].

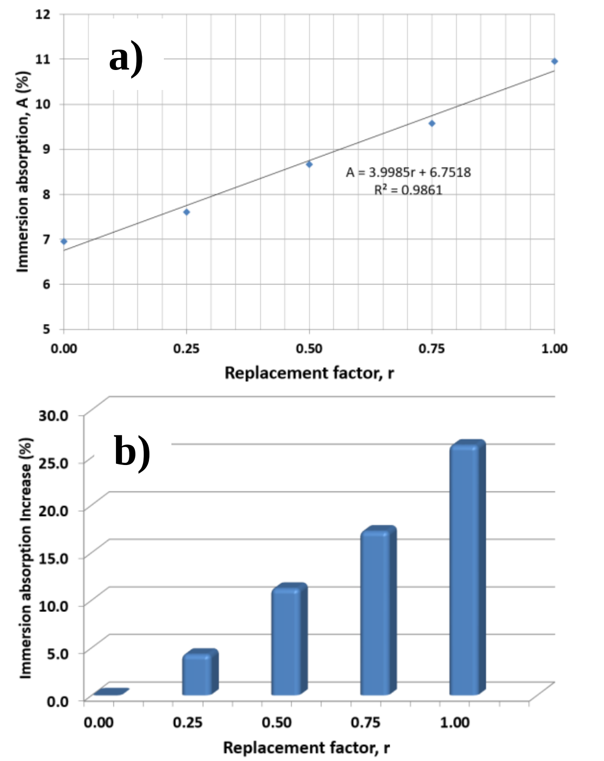

Fig. 9. a) Absorption by immersion and b) Increase.

3.3.3 Rapid Chloride Permeability Test

The determined total past load according to ASTM C1202 is a useful parameter for classifying concrete according to its chloride ion permeability. The past load and its increase with increment of r is shown in Figure 10, being a direct nonlinear relation. The minimum past load corresponds to r of 0.0 with 708 Coulombs and the maximum to r of 1.0 with 1215 Coulombs, increasing above 20% for r of 0.25 and 60% for r of 1.00. The increase in the past load, or the chloride permeability, is attributed to the presence of 3 different ITZs, shown in Figure 5, of which the new ITZ formed on the surface of old mortar - new mortar has permeability properties far superior to the other two, due to its particular characteristics acquired by the poor hydration of that area [28]. Situation that promotes an increase in the effective porosity of the concrete mass and possible conductive routes for ionic movement, generating a favorable medium for electro-migration of chlorides [29].

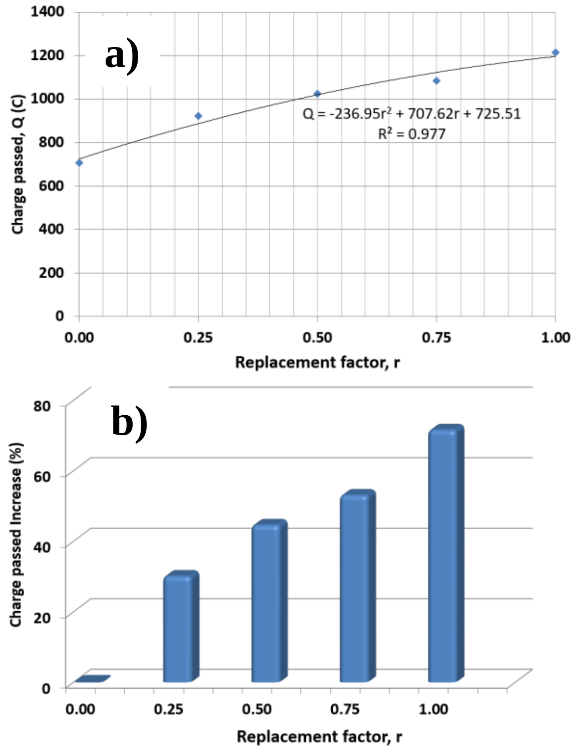

Fig. 10. a) Total past load and b) Charge passed increase.

3.3.4 Capillary absorption and effective porosity test (ASTM C-1585).

Capillary absorption and its increase with increment of r is shown in Figure 11 and the sortivity in Figure 12. Both sortivity increase with the increment of r, in the first 6 hours there is a higher absorption rate, decreasing significantly after that period. For r of 0.25 the initial sortivity shows an increment of 1.3%, interesting from the point of view of the decision making of a value of feasible r to be applied in the construction industry. The increase in the sortivities is attributed to the refinement in the distribution of pores presented in the cement matrix due to the presence of the different ITZs shown in Figure 6, reaching smaller pore sizes but in greater quantity and allowing a capillary absorption of greater ratio of change [30].

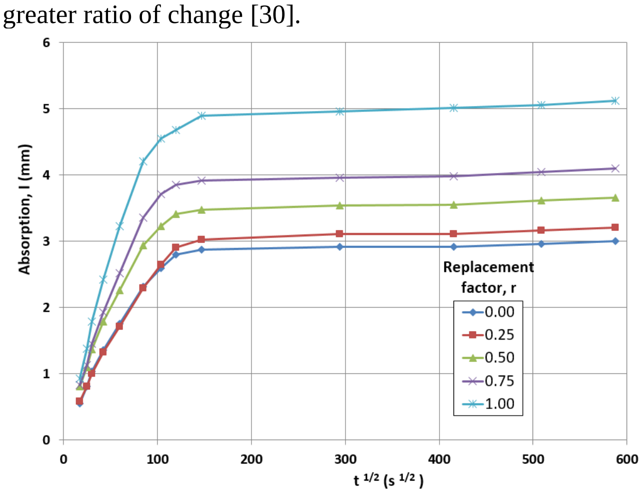

Fig. 11. Capillary Absorption.

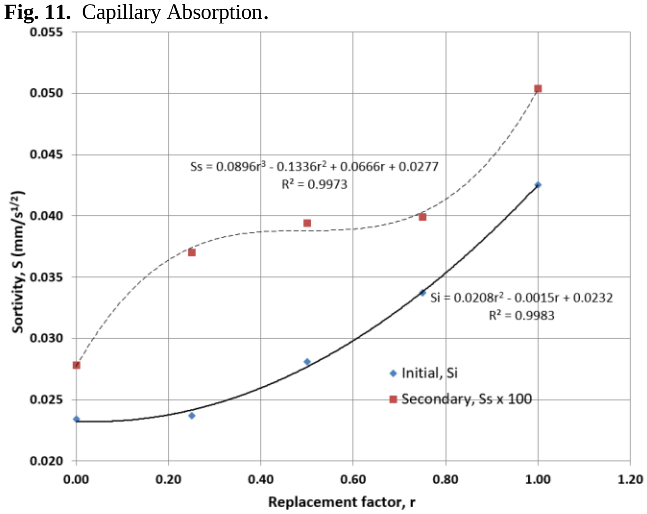

Fig. 12. Initial and secondary sortivity.

The coefficient of capillary absorption and its increase with increment of r is shown in Figure 13. The minimum coefficient of capillary absorption corresponds to r of 0.0 with 0.0327 $mm/s^{1/2}$, while the maximum in r of 1.0 with 0.0564 $mm/s^{1/2}$. The increase in the coefficient of capillary absorption for r of 0.25 of 0.23% is considered insignificant, reflecting the similarity between the properties of capillary absorption for r of 0.00 and 0.25. Opposite case, for r of 1.00 the increment in its coefficient of capillary absorption of 72.4%, being the increment in the coefficient of capillary absorption attributed to the increase of interconnected pores in the mass of the concrete.

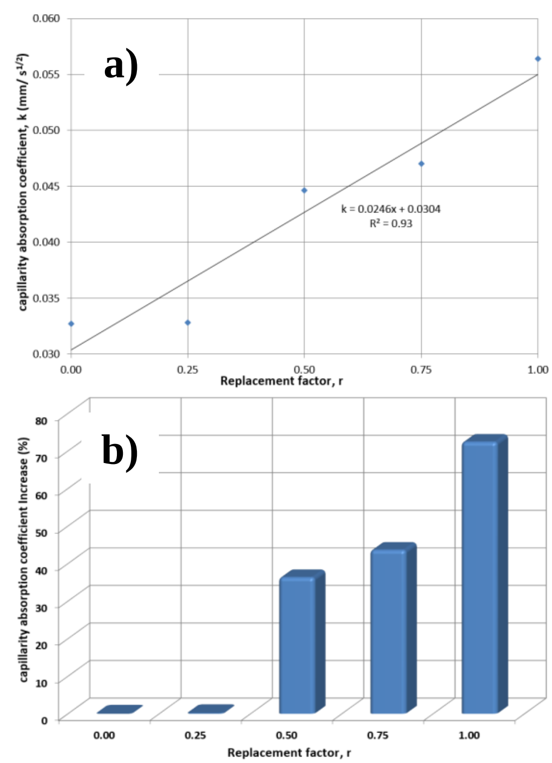

Fig. 13. a) Coefficient of capillary absorption and b) increase.

3.3.5 Effective porosity

The effective porosity indicates the percentage of interconnected pores of the total contained in the mass of the concrete. The effective porosity and its increase are shown in Figure 14, there was the minimum effective porosity in r of 0.0 with 9.48%, while the maximum in r of 1.0 with 13.81%. For r of 0.25 there was an increase of 7.6%, smaller in proportion to the rest of the substitutions tested. The increment in the effective porosity is attributed to the increment in the ITZs caused by the increase in the cement paste for greater substitutions of r, causing greater interconnections between the pores of the cementitious network [31].

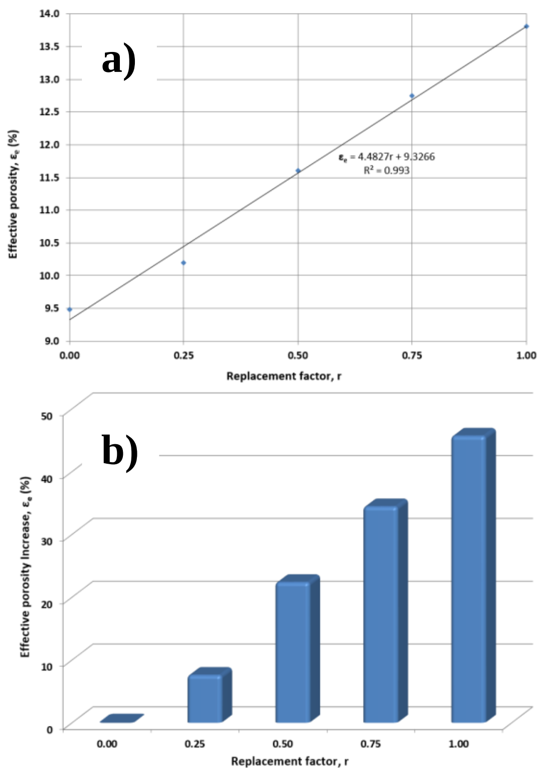

Fig. 14. a) Effective porosity and b) increase.

3.4 Correlation of properties

This correlation was made with respect to the effective porosity, considered the most important permeability property for the flow of liquids and ions in the concrete mass. There are investigations where total porosity with resistance to compression properties and Young's modulus of elasticity are correlated [12]. However, it was considered more convenient to carry out this interrelation with the effective porosity, as it is the property responsible for the ionic transport. The correlation with the different properties is shown in Table 4, its behavior is attributed to several factors: reduction of the unit mass of the concrete, the gradual total increment of paste with the increment of r, the greater amount of ITZ in the mass of the concrete, to the greater number of pores present due to the increase in the mortar paste, the refinement in the pore size caused by the greater presence of ITZ in the mortar paste and the presence of greater interconnection between the pores of the paste, causing increment in the ionic transport routes. The correlation between the properties presents the effective porosity as a determining parameter in the flow of liquids and ions. When the increment of this property occurs, the mechanical properties decrease, while the properties related to the transport of fluids in the mass of the concrete, are incremented, to a lesser or greater degree.

Table 4. Type of correlation with effective Porosity

Property	Correlation	
	Type	**Attributed to**
Resistance to compression	Inverse non-linear	Unitary Mass Reduction
Total porosity	Direct linear	Mortar Paste Increment
Absorption by immersion	Direct non-linear	Increment of mortar paste
Capillary absorption	Direct linear	Increment in amount of ITZ
Sortivity	Direct non-linear	Refinement in pore size
Passed load, Chloride Permeability	Direct non-linear	Greater amount of interconnection between the pores of the paste

IV. CONCLUSION

The use of RCA as substitute for NCA of concrete, causes a decrease in the performance of the mechanical properties and an increase in the permeability properties. The resistance to compression decreased to 17.85% for a 100% of replacement of NCA by RCA, while the properties of total porosity, absorption by immersion, chloride penetration, capillary absorption and effective porosity increased to 46.50%, 26.28%, 71.6 %, 81.6% and 45.7%, respectively.

Resistance to compression, porosity, water absorption and chloride penetration of the concrete manufactured with a maximum of 25% of RCA does not differ significantly with respect to the properties of the concrete without substitutions. Therefore, the replacement of NCA by 25% of RCA guarantees a performance similar to conventional concrete without compromising the durability of civil works, making the manufactured concrete with RCA a viable alternative as a sustainable material to be used in the construction industry.

V. ACKNOWLEDGMENT

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