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Potentially alkali-reactive recycled aggregates - Their effect on concrete's mechanical characteristics

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Abstract

One of the proposed actions to promote sustainable construction is the use of recycled aggregates (RA) as a construction material. The alkali reactivity level of RA raises the alkali-silica reaction (ASR) issue. Due to RA's composition, well-known changes on concrete properties occur but there are some doubts about its behaviour regarding ASR.

In order to contribute to solve this problem, an experimental program was conducted to know the effect of natural aggregate's replacement with reactive RA on concrete's performance. Controlled RA were prepared with aggregates of known alkali reactivity and with non-reactive aggregates, which were artificially aged to obtain two RA with different residual reactivity. Concrete mix formulations were produced with those RA under the conditions of RILEM AAR-3 concrete prism test, with 0, 20, 50 and 100% of coarse reactive RA incorporation ratio.

The results obtained after one year show that the mechanical behaviour of concrete with reactive RA generally remains close to that of concrete with non-reactive RA. As observed in concrete mixes with natural aggregates, the modulus of elasticity is the property where ASR's effects are more evident, probably due to the lower stiffness of the adhered mortar and to some fracture of the interstitial transition zone (ITZ) due to ASR's gel expansion.

Keywords: *alkali-silica reaction; concrete degradation; durability; reactivity; recycled aggregate.*

1. INTRODUCTION

One of the main chemical causes of concrete degradation is alkali-silica reaction (ASR). After its identification by Stanton in 1940 [1], ASR has been identified worldwide. This harmful reaction occurs between some silica forms present in the aggregates and the alkalis that, in the presence of a given moisture content, produce a silica-alkaline gel, which expands and causes concrete properties' degradation. One of the main sources of alkalis is the cementitious binder, although any other internal or external source of sodium or potassium ions can be mobilized for the development of the reaction.

One of ASR effects is the mechanical depreciation of concrete properties, like flexural and tensile capacity and the reduction of the modulus of elasticity. Compressive strength is less affected than the precedent ones. ASR also causes cracking of the concrete surface, increasing the ingress of harmful external agents that decrease the durability of concrete structures.

Larive [2] did not detect major changes in the volumetric deformation in concrete with ASR in which longitudinal compressive stresses up to 10 MPa were applied. The author submitted concrete with ASR to longitudinal compressive stresses of 0, 5, 10 and 20 MPa. It was observed that the expansion involves an anisotropy induced by stresses that is characterized by the inhibition of cracking in the direction of application of the stresses, with the development of cracks in the direction parallel to loading. The author also observed that cracking increased with concrete age.

According to Hobbs [3], the decrease in compressive strength caused by ASR can differ up to 30%, depending on the expansion level, i.e. depending on the reactivity of the aggregates. Ben Haha [4] states that, according to Clark [5], the compressive strength decreases with the increase of damage caused by ASR. The compressive strength can reach 40% reduction when large expansions occur.

Andrade et al. [6] also considered that the compressive strength of concrete is slightly affected by the expansive reaction, relative to tensile strength and modulus of elasticity. The study was carried out on the ASR-affected foundations of a building and a negative influence of the expansive reaction on the splitting tensile strength was observed.

The modulus of elasticity is the property in which the influence of the ASR damage is more noticeable. For expansions between 1 and 3 mm/m, the loss in modulus of elasticity is about 20 to 50% respectively [4]. According to Andrade et al. [6], the decrease in the mechanical properties is justified by the weakening of the paste/aggregate interface and the micro-cracking state of the concrete.

ASR cracking opens a way for water, air, and other harmful species to be transported into reinforced concrete, reaching the steel and creating internal stresses and expansion fractures.

Hydraulic structures are particularly affected by this expansive reaction, with degradation effects as [7] [8]: decreased resistance by internal micro-cracking; superficial cracking as a result of non-uniform expansion; loss of tightness; increased permeability and consequent increase in infiltrations; variation in size due to expansions; transfer of charges on adjacent structural elements; problems with moving elements.

Currently, one of the challenges of 21st century construction is its sustainability, minimizing the demand and exploitation of natural resources and improving the reuse of construction and demolition waste. The use of recycled aggregates (RA), from concrete structures on a new concrete mix is pointed out as a contribution measure to close the materials’ life cycle. However, the alkali reactivity level of coarse RA (CRA) raises the ASR issue. Due to RA’s composition, well-known changes on concrete properties occur but there are some doubts about its behaviour regarding future ASR development.

CRA are composed of coarse natural aggregates (CNA) and fine natural aggregates (FNA), an interstitial transition zone (ITZ), and a portion of mortar adhered to them. CRA’s quality is mainly conditioned by the source concrete’s properties. In general, CRA presents higher porosity and higher water absorption than those of CNA of similar origin [9] [10] [11]. Relatively to CNA, CRA also shows a lower density, and crushing and abrasion resistance, usually depending on the content and quality of the adhered mortar [12] [13] [14].

The different characteristics between natural aggregates (NA) and RA produce expected changes in the mechanical properties of concrete with CRA due to the level of substitution of CNA by CRA. According to Juan & Gutiérrez [15], the main causes of CRA’s quality loss are the amount of adhered mortar to the aggregate and the compressive strength of the source concrete. Duan & Poon [14] state that good quality CRA (with low content of adhered mortar and low water absorption) can be used to replace CNA and produce concrete with similar mechanical properties to natural aggregate concrete.

The porosity of CRA negatively influences the compressive strength, the modulus of elasticity and the tensile strength, among others properties [9]. For Ann et al. [16], the existence of a porous network also simplifies the access of oxygen and water, which increases the ASR effects. Butler et al. [17] realized that, with small changes in the proportions of the mix (in the amount of cement and in the water-to-cement ratio), it is possible to produce concrete with the same slump and compressive strength as concrete with natural aggregates. However, differences in modulus of elasticity, tensile strength and fracture energy were observed, which indicate that they were more affected by the properties of the coarse aggregate than by the composition of the mix.

If no measures are taken in mix design, the differences in compressive strength between concrete with CNA or CRA are most noticeable when the strength class of the new concrete and the replacement ratio are higher [10] [18] [19] [20]. Kwan et al. [21] stated that the compressive strength reduction can be also related to the crushing process of CRA that created areas of fragility in aggregate. Using admixtures, Barbudo et al. [22] and Soares et al. [23] found that it is possible to incorporate up to 100% of CRA without affecting the concrete’s compressive strength.

There is no clear trend in tensile splitting strength with the replacement ratio of CNA with CRA. Researchers pointed new and old ITZ’s quality as the main reason for changes in this property [13] [20] [22] [23]. The modulus of elasticity of concrete with CRA is usually inferior and more dependent of the stiffness of the adhered mortar of CRA. For instance, Soares et al. [23] obtained a maximum reduction of 11% when using concrete with 100% of CRA, due to higher deformability of the adhered mortar. The small reduction in the modulus of elasticity was justified by the high quality of the CRA.

Brito & Alves [24] stated that it should be considered that the performance of a concrete with CRA is, in most cases, inferior to that of an equivalent concrete with CNA, but that the variability of its properties is similar. The decrease in performance can be predicted with knowledge of the properties of the aggregates and of the replacement ratio.

A state-of-the-art paper on ASR in concrete with recycled aggregates was recently presented [25]. It was observed that ASR can continue in RAC and that the ASR potential is influenced by the RA’s age, exposure conditions, type of crushing, alkalis and reactive silica content of RA, and incorporation ratio.

This research campaign is trying to know the effect of natural aggregate's replacement with reactive RA on concrete's mechanical performance, and understand whether the results are different from those obtained on conventional concrete, when ASR issue is a problem.

2. MATERIALS AND METHODS

2.1 Materials

Two controlled source concrete (SC), with and without reactive aggregates, were produced using the same mix design and the same cement CEM I 42.5R, without alkalis boosting. Non-reactive source concrete (SC-NR) was produced with a non-reactive coarse limestone gravel (CNA-NR), of size 6/14 (CNA-NR1) and 11/22 (CNA-NR2) and a non-reactive siliceous sand (FNA-NR). Reactive source concrete (SC-R) was produced with a reactive coarse siliceous aggregate (CNA-R), of size 4/16 (CNA-R1) and 10/16 (CNA-R2) and a reactive siliceous sand (FNA-R). The alkali-reactivity of the used aggregates is known from field concrete performance and petrographic results, and was also confirmed by the accelerated mortar-bar test (AMBT) according to ASTM C1260 [26] (Figure 2.1).

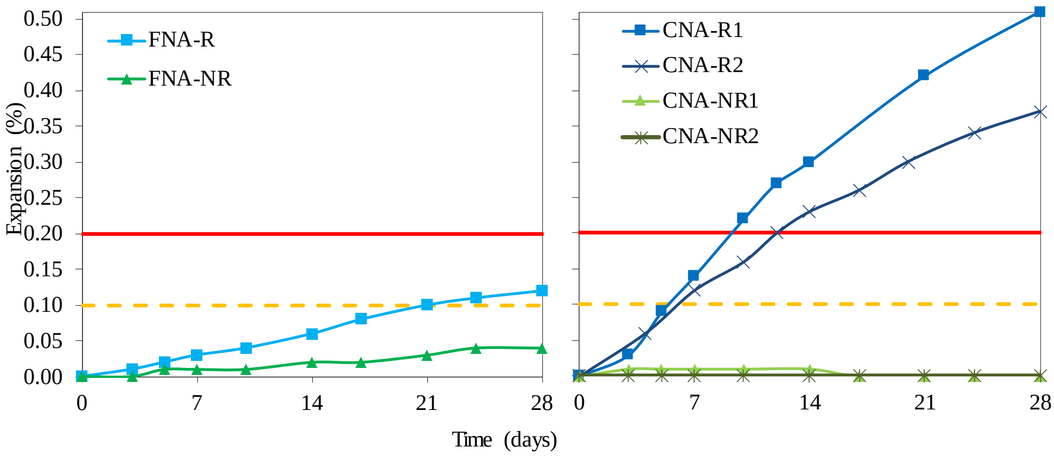

Figure 2.1: Expansion test results FNA and CNA according to ASTM C 1260 [26]

Aggregates' reactivity was also evaluated using the concrete prism test (CPT) as per the RILEM AAR-3 [27] test-method. The observation at SEM/EDS confirms ASR gels in the reactive source concrete.

Figure 2.2 illustrates the average compressive strength at 28 days of both SC. The 10 MPa difference in compressive strength was attributed to the different types of natural aggregates used.

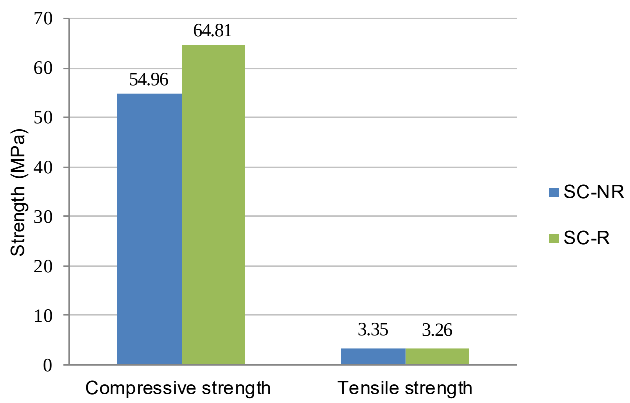

Figure 2.2: Compressive and tensile strength of the source concrete

To increase ASR development and simulate concrete with some years, both source concrete mixes suffered an accelerated aging in a climatic chamber at 38 ± 2 °C and relative humidity higher than 95% for 6 months (similar to the RILEM AAR-3 test conditions). After this period, the SC experienced additional 6 months in a natural exposure environment, inside the laboratory, being afterwards crushed in a jaw crusher and the resulting coarse recycled aggregate (CRA) separated in the size fractions 4-10 mm and 10-20 mm (limited by the overall percentages indicated by RILEM), using the Faury [28] reference curve method as a base. All non-reactive CNA and CRA (CNA-NR, CRA-NR) and reactive CRA (CRA-R) were separated by individual sieving in the conditioned particle size distribution used to comply with RILEM AAR-3's concrete composition. Table 2.1 shows the aggregates' properties and Figure 2.3 present the particle size distribution of CRA-R and of CRA-NR.

Table 2.1: Characteristics of FNA, CNA and CRA

Aggregates		d/D (mm)	Density (kg/m^3)				v (%)	Water absorption (%)		W (%)	SI (%)	FI (%)	LA (%)
			ρ_a	ρ_{ssd}	ρ_{rd}	ρ		WA_{24}	WA_{5m}				
Original particle size distribution	CNA-NR2	11/22	2720	2700	2680	1460	45.4	0.46	75	0.03	-	-	27
	CNA-NR1	6/14	2720	2700	2680	1490	44.4	0.48	75	0.02	-	-	28
	CNA-R2	10/16	2680	2650	2630	1410	45.8	0.62	75	0.07	-	-	19
	CNA-R1	4/16	2670	2630	2610	1400	46.6	0.76	75	0.07	-	-	24
	FNA-NR	0/4	2640	2630	2620	1450	44.7	0.26	50	0.02	-	-	-
	FNA-R	0/4	2650	2640	2630	1430	45.8	0.26	50	0.02	-	-	-
Conditioned particle size distribution	CNA-NR	4/20	2720	2700	2680	1510	43.6	0.50	75	0.03	17	13.5	-
	CNA-R	4/20	2670	2640	2620	1440	44.9	0.63	75	0.03	21	13.4	-
	CRA-NR	4/20	2680	2540	2460	1320	46.2	3.26	80	1.78	24	13.7	41
	CRA-R	4/20	2650	2520	2440	1360	44.4	3.20	80	1.92	16	13.7	31

Legend: 1 = Smaller aggregates dimensions; 2 = Larger aggregates dimensions; d/D = Aggregate sizes from particle size analysis; SI = Shape index; FI = Flakiness index; ρ = Bulk density; v = Void volume; ρa = Apparent density; ρ_{rd} = Oven dry density; ρ_{ssd} = Saturated surface dry density; WA_{24} = Water absorption at 24 hours; WA_{5m} = Water absorption of the aggregates with respect to their potential to absorb over 5 minutes; W = Moisture content before mixing; LA = Fragmentation resistance according Los Angeles method.

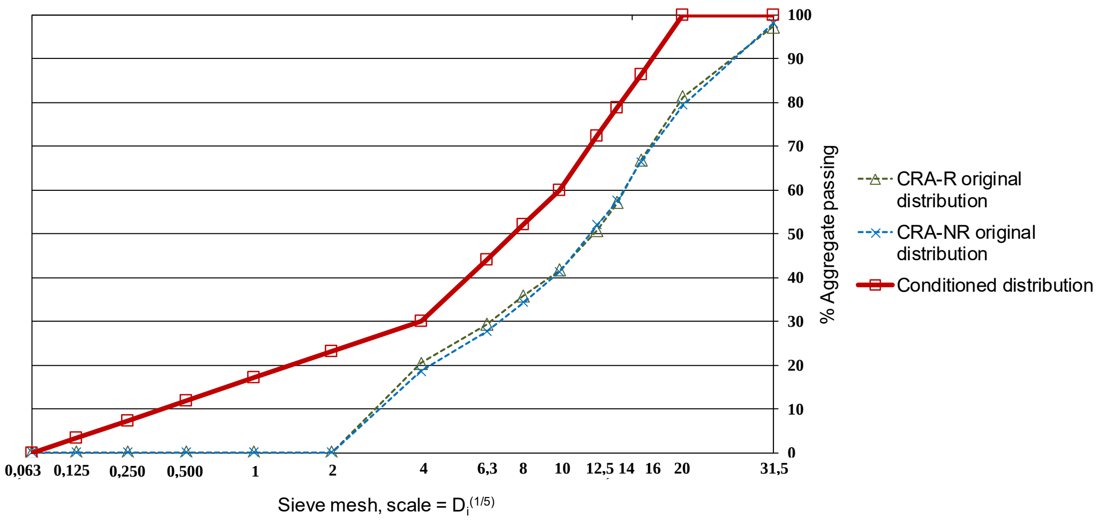

Figure 2.3: Original particle size distribution of CRA-R, CRA-NR and conditioned particle size distribution used as a reference

2.2 Mix design

To evaluate the effect of alkali-reactive recycled aggregates on concrete's mechanical characteristics, two types of recycled aggregate concrete (RAC) and two types of natural aggregate concrete (NAC) were produced with the same composition. Replacement levels of 0%, 20%, 50% and 100% of CNA-NR with

CRA-NR or CRA-R were studied. In order to designate the concrete mixes, the following order was assigned in the nomenclature: NAC or RAC - Type of concrete; 20, 50, 100 - replacement ratio; NR or R - CRA reactivity type. CNA-NR and FNA-NR were used as reference concrete for comparison purposes.

The concrete mixes were produced according to the oldest version of RILEM AAR-3 [29], following proportions by volume: 14% of cement; 20% of water; 46% of coarse aggregate; 20% of fine aggregate. The proportions by weight of the aggregates are presented in Table 2.2. The alkali content (Na_2O_{eq}) of the mix was adjusted to 1.25% of the cement weight, by addition of sodium hydroxide in the mixing water. Table 2.2 shows the mix design of the mixes tested.

In order to promote ASR development, the concrete specimens were placed in a climatic chamber (38 °C and HR > 95%), closed in plastic bags to minimize alkali leaching, as well as to uniform humidity. The procedure followed the RILEM AAR-3 [27] method.

Table 2.2: Concrete mix compositions tested

Mix	CNA-NR *(kg/m³)*	CNA-R *(kg/m³)*	CRA-NR *(kg/m³)*	CRA-R *(kg/m³)*	FNA-NR *(kg/m³)*	Cement *(kg/m³)*	Water *(kg/m³)*	Water ad. *(kg/m³)*	NaOH *(kg/m³)*	W/C
NAC-NR	1242.0	-	-	-	526.0	438.2	200.0	4.9	2.3	0.46
RAC-20-NR	993.6	-	233.7	-	526.0	438.2	200.0	7.3	2.3	0.46
RAC-50-NR	621.0	-	584.2	-	526.0	438.2	200.0	11.1	2.3	0.46
RAC-100-NR	-	-	1168.4	-	526.0	438.2	200.0	17.3	2.3	0.46
RAC-20-R	993.6	-	-	231.8	526.0	438.2	200.0	7.0	2.3	0.46
RAC-50-R	621.0	-	-	579.6	526.0	438.2	200.0	9.9	2.3	0.46
RAC-100-R	-	-	-	1159.2	526.0	438.2	200.0	15.0	2.3	0.46
NAC-R	-	1214.4	-	-	526.0	438.2	200.0	5.9	2.3	0.46

2.3 Test-methods and analysis

The concrete mixes were characterized by the following tests in the fresh state: slump, according to NP EN 12350-2 [30]; air content, according to NP EN 12350-7 [31]; and density, according to NP EN 12350-6 [32]. The concrete mixes were characterized by the following tests in the hardened state: compressive strength, according to NP EN 12390-3 [33]; modulus of elasticity, according to LNEC E397 [34]; and tensile splitting strength, according to NP EN 12390-6 [35].

3. RESULTS AND DISCUSSION

3.1 Concrete fresh properties

The effective water-to-cement (w/c) ratio was kept constant. For this purpose, a maximum ratio between the theoretical and the real density in the range of 1.000 ± 0.010 was considered, based on recommendations of the newest RILEM AAR-3 protocol [27]. This option overlapped the maintenance of workability (normally used to compare RAC), since it was important to keep the content of cement alkalis constant and with no influence on the reactive potential to alkalis of concrete. The results showed a maximum ratio of 0.992 between the theoretical and the real density of all mixes.

RAC's density showed a linear decrease with the increase of replacement ratio (Figure 3.1). The correlation reach values of 0.9959 and 0.9938 in RAC-NR and RAC-R, respectively. The density in RAC is consistent with the density of CRA, which is also smaller in CRA-R compared to CRA-NR. This difference also exists in CNA, with the density of CNA-R being less than that of CNA-NR.

The air content of fresh concrete was steady, with values of 1.3 ± 0.1%. A slight growing trend with the increase of CRA replacement ratio was observed for both types of concrete, RAC-NR and RAC-R.

Fresh concrete slump shows a decrease with the increase of the replacement ratio of CNA with CRA. The slump was kept in the range of 60 ± 20 mm (Figure 3.2), within the tolerance of ± 20 mm indicated by NP EN 206-1 [36] for concrete with slump values between 50 and 90 mm. Thus, it can be considered that the workability of the studied concrete mixes was maintained, although this was not a pre-defined condition. Tabsh & Abdelfatah [12] stated that RAC requires more water in the mix than NAC to maintain a constant slump, without the use of admixtures, which may affect the performance of concrete.

A maximum reduction of 40% (30 mm) was observed between NAC-NR and RAC-100-NR and 47% (35 mm) between NAC-NR and RAC-100-R. The difference between the slump of RAC types is constant, with the RAC-R type having a slightly lower slump (2 to 5 mm). The difference in slump between NAC-NR and NAC-R is 40%, while between recycled concrete RAC-NR and RAC-R it is never higher than 11%, regardless of the ratio of replacement.

The results obtained in slump are consistent with the increase in roughness and shape of the aggregates in the mix. The high volume of coarse aggregates in the mix (70%) compared to fine aggregates (30%) increased the friction between coarse particles. The mix design used may have reduced the slump of concrete, which was more evident when CRA was used. However, this difference was not observed in concrete's visual aspect or touch, which remained constant.

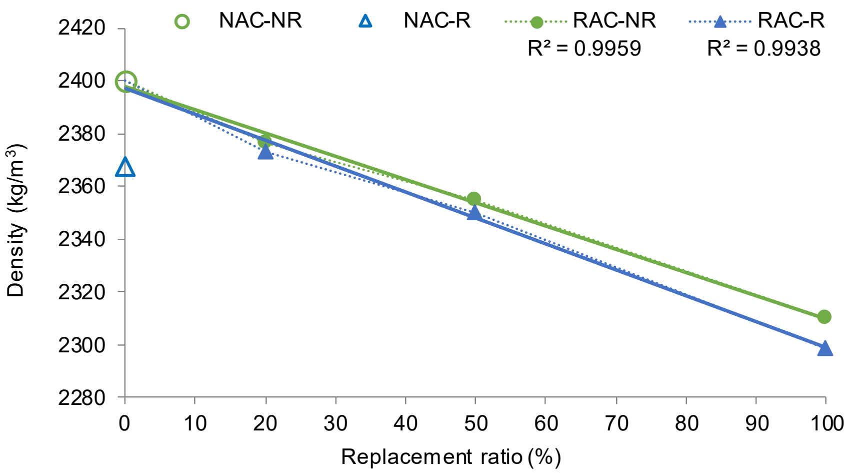

Figure 3.1: Density range with the replacement ratio of CNA with CRA

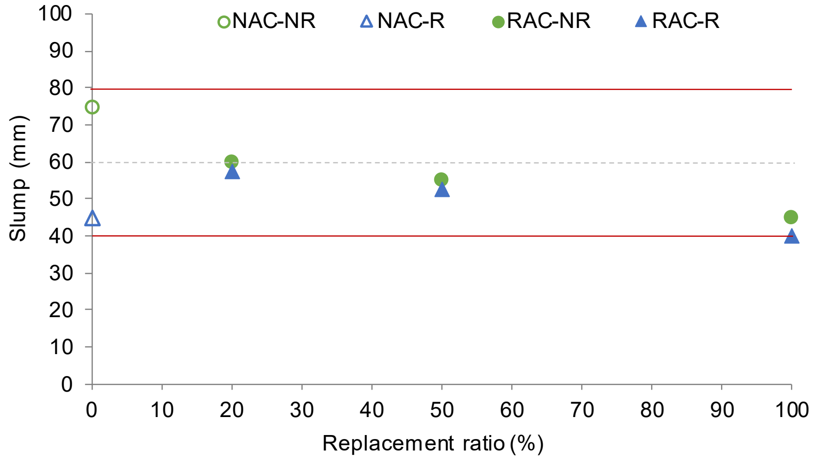

Figure 3.2: Slump range with the replacement ratio of CNA with CRA

3.2 Concrete mechanical hardened properties

3.2.1 Compressive strength

The results of the evolution with age of the compressive strength of the concrete specimens exposed to ASR accelerated test conditions are shown in Figure 3.3 for RAC-NR, and Figure 3.4 with for RAC-R. The expansion results of CPT test according to RILEM AAR-3 [27] are also indicated. There were no noticeable differences in results or any exact trend in concrete behaviour. All concrete mixes reached at 28 days, in accelerated reaction environment, an average strength in the range of 37.7 to 40.9 MPa, with a maximum variation in relation to the reference concrete (NAC-NR) of 7.8%. This value decreased to 6.1% at 364 days. The results between specimens showed low dispersion, with a maximum coefficient of variation of 3.1%.

Strength increased, on average, by about 22% from 28 to 182 days and about 30% from 28 to 364 days due to continued hydration reactions. At this age, there is no decrease in compressive strength associated with ASR, although some important expansions have already been recorded in RILEM AAR-3 test. This could mean that, at this age, the increase in compressive strength due to continued hydration still compensates the loss of compressive strength due to ASR. However, from 182 days to one year an important reduction in compressive strength growth is observed.

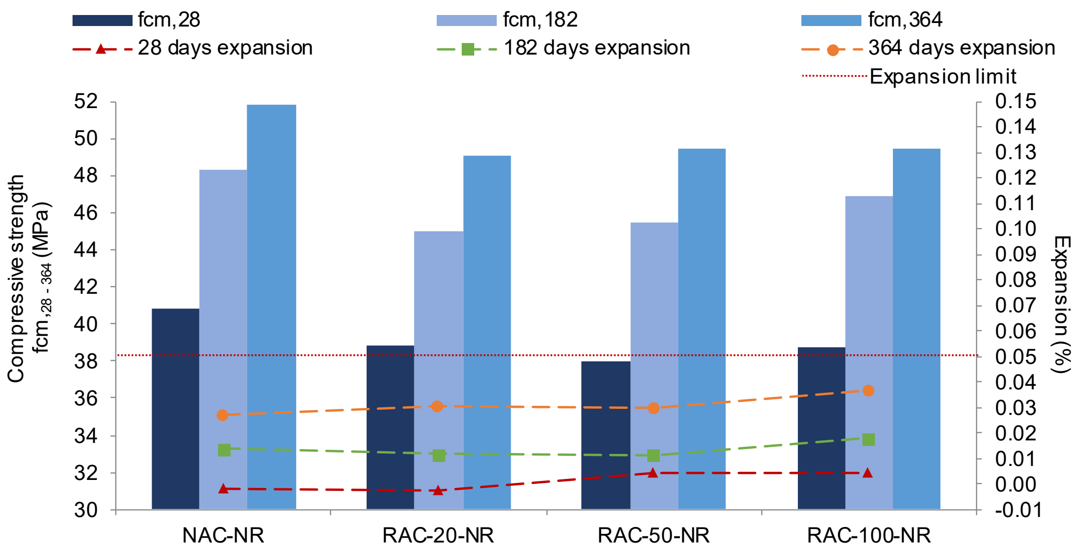

Figure 3.3: Evolution of compressive strength for NAC-NR and RAC-NR mixes; specimens were tested after storage in a climatic chamber at 38 °C and HR > 95%

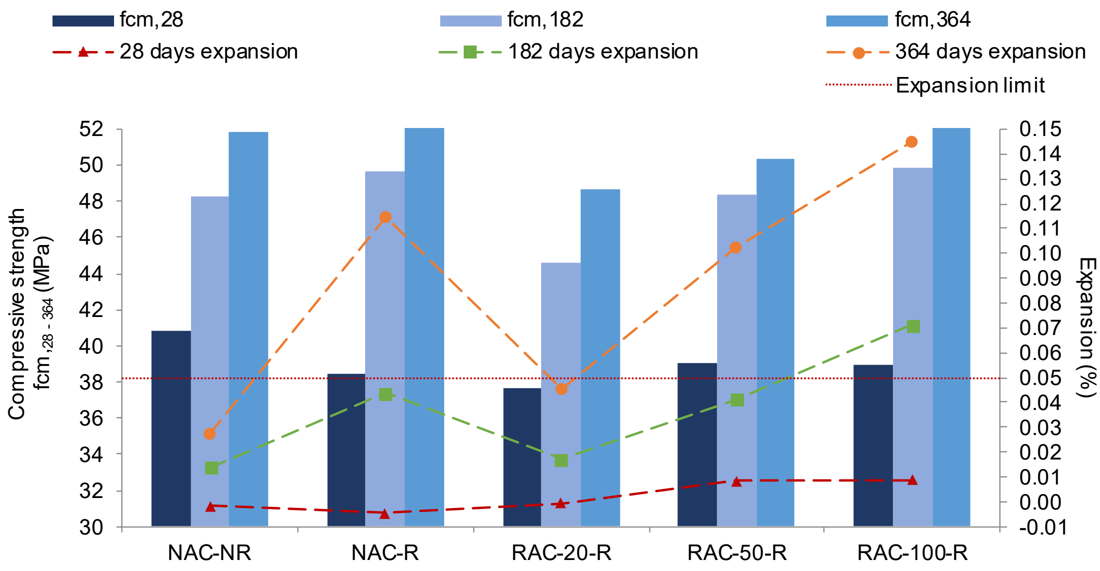

Figure 3.4: Evolution of compressive strength for NAC-NR, NAC-R and RAC-R mixes: specimens kept in a climatic chamber at 38 °C and HR > 95%

According to Hobbs [3], the reduction in compressive strength can differ up to 30%, depending on the reactivity of the aggregates and the expansion obtained. Larive [2] and Andrade et al. [6] observed that the compressive strength is not affected by ASR, even in concrete with very high expansions. Santos Silva [37] confirmed that the compressive strength of concrete with ASR continued to increase over time. The author concluded that the compressive strength is not an adequate parameter to evaluate the development of ASR in concrete with reactive aggregates.

The evolution of compressive strength was higher than that predicted in Eurocode 2 (EC2) [38] for concrete with CNA and CEM I 42.5R cement, with a hardening coefficient of 1.13 (Figure 3.5). The evolution of compressive strength over time was higher with the increase of CRA in concrete, with the exception of RAC-20-NR. Notice that RAC-R followed the increase in compressive strength of the NAC with CNA-R (original aggregate of the CRA-R), showing a dependence between the strength of the RAC, the original CNA and the CRA.

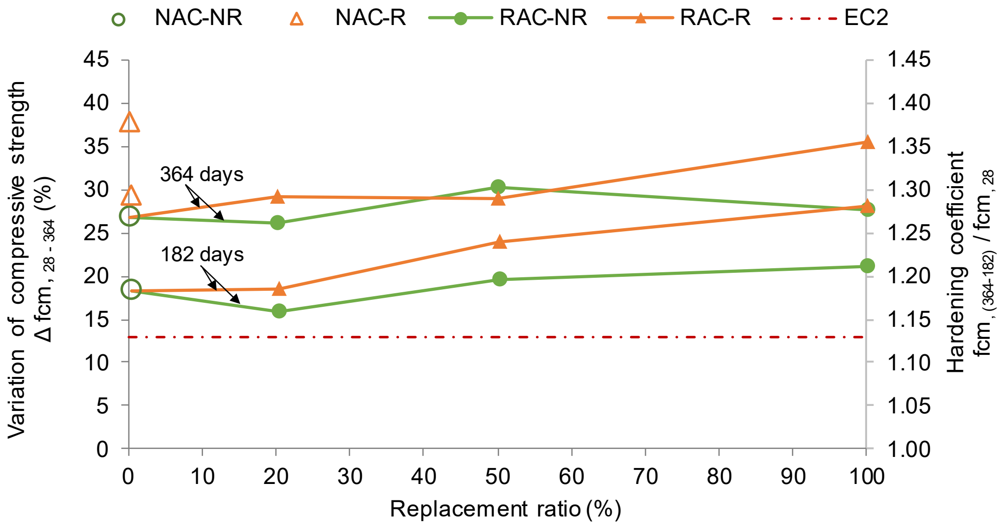

Figure 3.5: Variation of the compressive strength and hardening coefficient between concrete with 28 and 364 days in a climatic chamber (38 ° C and HR > 95%), depending on the replacement ratio.

3.2.2 Modulus of elasticity

Figure 3.6 illustrates the variation of the modulus of elasticity between 182 and 364 days of concrete under aggressive environment, at 38 ºC. The results between specimens showed low dispersion, with a maximum coefficient of variation of 3.2%.

As expected, the modulus of elasticity decreases with the replacement ratio of CNA with CRA. The compressive strength of the SC of the CRA does not appear to directly affect the modulus of elasticity. The compressive strength of SC-R is about 10 MPa higher than that of SC-NR, which was not reflected in the RAC. The modulus of elasticity of RAC decreases with the increase in the replacement ratio and the extent of reduction depends on the CNA type used in the SC.

There is a reasonable correlation between the values of the modulus of elasticity and the ratio of substitution of CNA with CRA, with values greater than 0.95, except for RAC-R at 365 days.

The results of the mix placed in a climatic chamber (at 38 °C and RH > 95%) for 364 days show the negative effect of ASR on the modulus of elasticity, as seen in Figure 3.7 and Figure 3.8. An indicative value at 28 days of the modulus of elasticity of concrete under conventional temperature and humidity is presented.

The modulus of elasticity decreased with age, but mainly from 182 to 364 days in all RAC-R mixes with substitution of CNA-NR with CRA-R. RAC-100-R presents the greatest expansion at 364 days (0.145%), which is also followed by a greater reduction in the modulus of elasticity (25.4%). This trend is contrary to the evolution of the elasticity module in NAC and RAC in a conventional temperature and humidity conditions. In a detailed literature review, Silva et al. [39] showed the increasing evolution of RAC's modulus of elasticity over time, with values generally compliant with NAC standards.

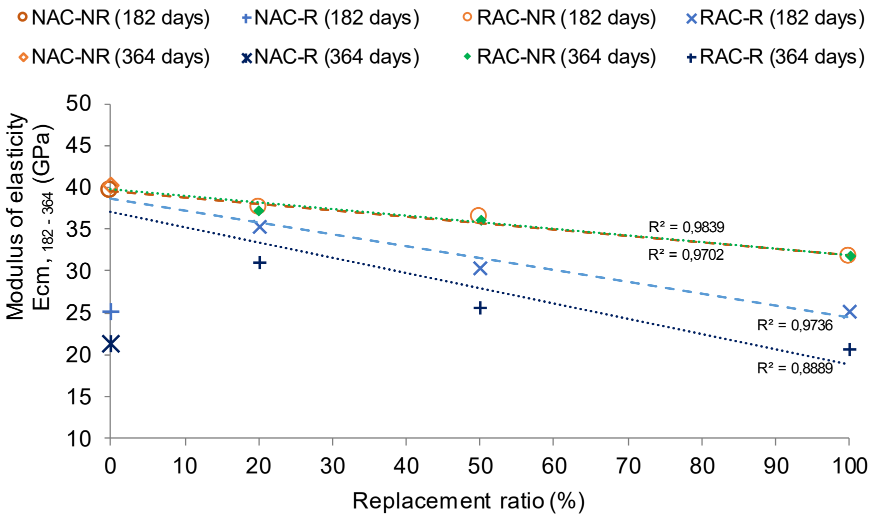

Figure 3.6: Variation of the modulus of elasticity with the replacement ratio, between 182 and 364 days, for NAC-NR, NAC-R, RAC-NR and RAC-R mixes.

According to Santos Silva [37], the modulus of elasticity is important in monitoring the development of ASR, as it allows estimating the state of micro-cracking in concrete. The author, in the reactive reference concrete of his experimental campaign, registered an increase in the modulus of elasticity up to 90 days and a slight decrease from that age onwards, which he attributed to ASR. According to Hobbs [3], this reduction can reach values above 50%, depending on the level of expansion. The relationship between the micro-cracking of concrete due to expansion and the decrease in the modulus of elasticity may explain the results, as referred also by Andrade et al. [6].

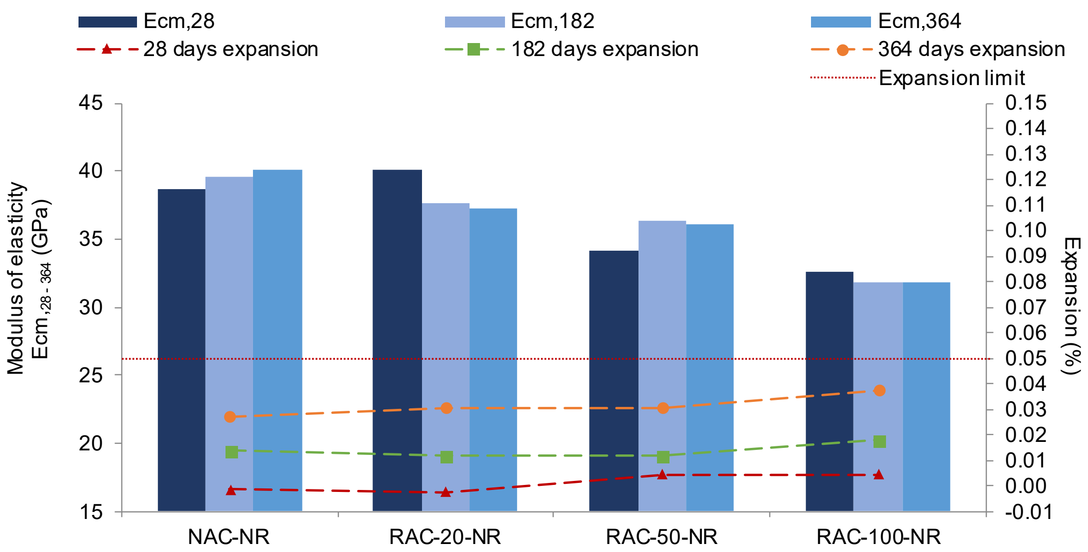

Figure 3.7: Effect of NR substitution on the evolution of the modulus of elasticity for the NAC and RAC mixes.

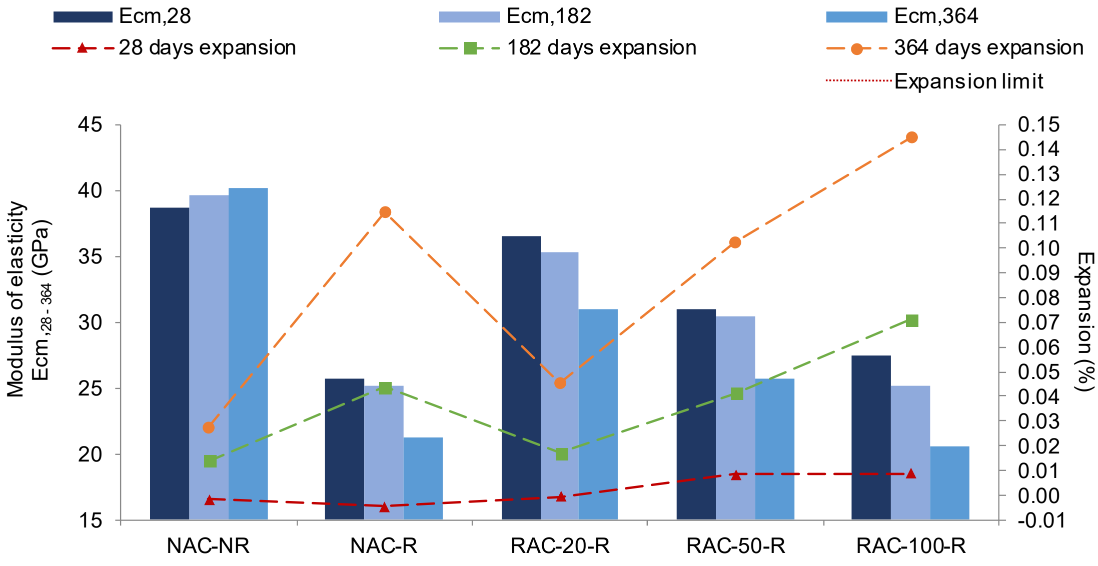

Figure 3.8: Effect of R substitution on the evolution of the modulus of elasticity for the NAC and RAC mixes.

3.2.3 Tensile splitting strength

The results of the evolution of the tensile splitting strength between 182 and 364 days of concrete under aggressive environment, at 38 ºC, are shown in Figure 3.9, for RAC-NR, and Figure 3.10 for RAC-R. The reference concrete (NAC-NR) and the expansion results of CPT test according to RILEM AAR-3 are also indicated. An indicative value of the tensile splitting strength of concrete at 28 days under conventional temperature and humidity is also presented.

All concrete mixes increased their tensile strength between 28 days and 182 days. The increments in strength at 182 days are higher in concrete with 0 or 100% CRA, with values 15% to 20% higher than those at 28 days. Mixes with intermediate replacement ratios had more restrained increases. The results between specimens showed low dispersion, with a maximum coefficient of variation of 3.2%.

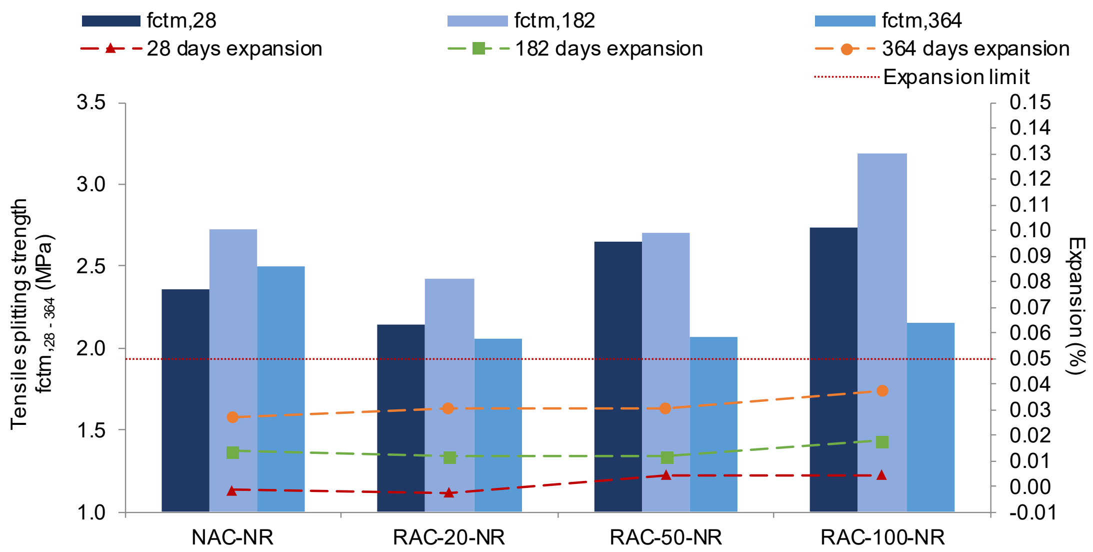

Figure 3.9: Effect of NR substitution on the evolution of the tensile splitting strength of the NAC and NR mixes.

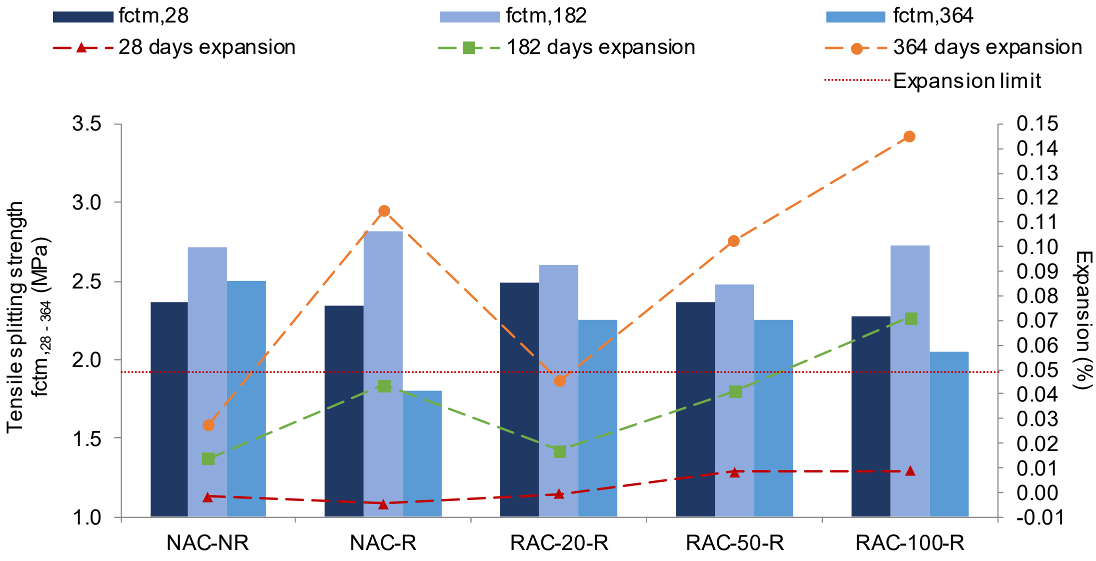

Figure 3.10: Effect of R substitution on the evolution of the tensile splitting strength of the NAC and RAC mixes.

In concrete with 182 days, it was not possible to see any effect of ASR expansion on the tensile strength. From 182 days until one year, all mixes were severely affected and a high decrease in tensile strength was observed. Maximum reductions of 32.5% for RAC-100-NR and 36.1% for NAC-R, from 182 to 364 days, were observed.

Aggressive conditioning (38 ºC, HR > 95%) could influence the ITZ's microstructure. According to Coutinho [40], through concrete hardening, the supply of heat speeds up the reaction between the cement components and water. The heating of concrete, without hydration water loss by evaporation, produces concrete with higher tensile strength in a shorter period and the increase in strength over time is affected. As the crystallization is faster, the hydrated cement crystals do not develop well, and the concrete ages faster.

Evangelista [41] also states that the results of tensile splitting strength test are highly dependent on the material quality in a narrow area of the specimen and on the heterogeneity of the failure plan. This can explain the higher coefficient of variation between specimens in this test, that achieved a maximum coefficient of variation of 12.6% at 182 days and 7.5% at 364 days. With conventional temperature and humidity aging conditions, Silva et al. [42] observed in a literature review that the trend of RAC is identical to that of NAC.

4. CONCLUSIONS

The main conclusions of the analysis of results obtained at 1 year of testing are the following:

- The compressive strength of the SC of the CRA does not appear to directly affect the compressive strength or modulus of elasticity of the RAC.
- Although there is a residual expansion due to ASR in SC, a similar behaviour of the compressive strength evolution of RAC and NAC was observed. However, from 182 days to one year, an important reduction in compressive strength growth is observed in all mixes; the effect of ASR on RAC due to the replacement ratio is not evident;
- It is confirmed that modulus of elasticity is more sensitive to ASR development than compressive strength. A reduction of the modulus of elasticity was observed in alkali-reactive mixes with CRA, which is attributed to the lower stiffness of the mortar adhered and to some failure in the ITZ of the CRA due to ASR expansion;
- The observed variations in the results of tensile strength did not allow observing any trend of this property with the increment in the replacement ratio of CNA with CRA. The test is very dependent on the quality and heterogeneity of the material in the area of the failure plan, which is intensified by the use of CRA.

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