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Study of ASR in concrete with recycled aggregates: Influence of aggregate reactivity potential and cement type

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HIGHLIGHTS

- Alkali-silica reaction was analysed through expansion evolution in concrete mixes.
- Different replacement levels of coarse natural aggregates.
- Reactive and non-reactive coarse recycled aggregates.
- The influence of cement type was also evaluated.

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ABSTRACT

The incorporation of recycled aggregate (RA) in structural concrete requires deep knowledge of this material's potential and limitations by assessing its effect on the concrete properties. Alkali-silica reaction (ASR) is one of the most concerning degradation agents in concrete produced with natural aggregates, and more expectedly in recycled aggregate concrete (RAC), which motivated this study. ASR was analysed through expansion evolution in concrete mixes produced with different replacement levels of coarse natural aggregates (CNA) with reactive and non-reactive coarse recycled aggregates (CRA). In addition, concrete mixes were naturally and artificially aged to simulate the reaction at different ages. The influence of cement type on ASR development in RAC was also evaluated. The results showed that the incorporation of 20% of reactive RA did not affect concrete's expansion behaviour. The highest expansions were obtained when 100% of reactive RA and a higher strength class cement were used.

1. Introduction

Alkali-silica reaction (ASR) occurs between reactive silica constituents present in some aggregates and the alkalis (sodium and potassium) in the cement paste, producing a silica-alkaline gel, which expands in the presence of high humidity and causes various phenomena that condition and change concrete's properties [1–8]. The swelling behaviour of ASR gel causes concrete degradation through various mechanical effects, mainly a reduction of flexural and tensile strength, and modulus of elasticity [5–7]. The reaction may lead to the appearance of cracks, exudations, efflorescence, pop-outs, and expansion of the structure, and consequently, increased permeability and infiltration [3,5,8,9].

Degradation of natural aggregate concrete (NAC) by ASR has become one of the scientific community concerns due to the absence of efficient methods to rehabilitate the affected structures. As a result, through progress in understanding the reaction, methodologies were developed to prevent and mitigate ASR by using non-reactive aggregates, controlling the alkalinity of the concrete (e.g. cements with low alkali contents or using supplementary cementitious materials like fly ash, blast-furnace slag, metakaolin or silica fume), or using lithium-based chemical

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Abbreviations: AMBT, Accelerated mortar bar test; ASR, Alkali-silica reaction; CNA, Coarse natural aggregates; CPT, Concrete prism test; CRA, Coarse recycled aggregates; FNA, Fine natural aggregates; ITZ, Interfacial transition zone; NA, Natural aggregates; NAC, Natural aggregate concrete; RA, Recycled aggregates; RAC, Recycled aggregate concrete; SC, Source concrete; w/c, Water to cement ratio.

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additions [3,5,10–13]. Compared to natural aggregates (NA), the incorporation of recycled aggregates (RA) further raises concerns regarding the ASR issue in concrete. RA comprise fine natural aggregates (FNA), coarse natural aggregates (CNA), interfacial transition zone (ITZ) and adhered mortar. This heterogeneous constitution of RA influences the alkali and reactive silica contents present in the adhered mortar and in NA, respectively, depending on the properties and exposure conditions of source concrete (SC). Assuming that ASR may occur in recycled aggregate concrete (RAC) and that their manifestation may be a consequence of the reactive potential of NA in RAC, it is important to define the circumstances where the partial or total replacement of NA with RA (reactive or non-reactive) becomes detrimental to concrete's properties.

An extensive literature review clarified the lack of knowledge regarding the development of ASR in RAC [14–29]. In fact, research in this field is still very preliminary and there are several doubts on the influence of RA's characteristics on the development of ASR. Previous investigations are often contradictory and generally focused on the ASR's evaluation of demolished concrete structures through accelerated concrete or mortar expansion tests. A few studies [22,25,27] have reported that RAC demands higher amounts of supplementary cementitious materials to reduce the ASR expansion to a level similar to that of NAC. Some investigations [16,21,24] proposed ASR expansion test modifications for RA, to accelerate the reaction and to reduce the expansion dampening effect due to adhered mortar.

Beauchemin et al. [14] evaluated ASR of RAC through concrete prisms test (CPT). Two RA types were tested: one sourced from 15-year old concrete blocks and the other from an overpass bridge. Saturated RA were used, since higher expansion results are obtained under this condition. The CPT results show that higher incorporation levels of RA led to higher expansion values. These researchers also found that the reactivity/expansion of the original concrete of RA influenced the expansion of concrete. RA with high degree of reactivity/expansion/damage can undergo less expansion than concrete with a similar content of unreacted aggregate material of the same origin, due to the consumption of reactive phases of RA and to the fact that RA have adhered mortar that limits the tendency of NA to react. Aggregate crushing also causes the exposure of new fresh aggregate surfaces that may increase reactivity.

Johnson and Shehata [15] investigated ASR of RA through accelerated mortar bar test (AMBT) and the concrete microbar test (CMBT). AMBT was considered effective for the potential alkali-reactivity evaluation as long as well-defined procedures for crushing and water absorption are followed. CMBT had good correlation to the expansion of CPT containing supplementary cementitious materials when an expansion limit of 0.04% at 28 days or 0.10% at 56 days were used.

Calder and Mckenzie [17] studied the susceptibility of RA and NA to ASR's action. Although the petrography indicated the presence of reactive silica forms in some RA and the microscopic analysis showed silica-alkaline gel formation in some specimens, no significant expansions were obtained. Expansion tests rated RA as non-expansive, equivalent to a low reactivity material. The results supported the change in the overall ASR reactivity rating from high to normal RA.

Desmyter and Blockmans [18] studied the properties of RA and some procedures to prevent ASR. For this purpose, a potentially reactive NA, a non-reactive NA and a RA sourced from a demolished bridge affected by ASR were tested. The results confirmed the reactivity and non-reactivity of the first two types of NA, respectively. The results of RA showed an expansive behaviour in the first months, but did not exceed the limit established at 8 months in the French standard AFNOR NF P18-587 [30]. This suggested that the reactive elements present in RA have preserved limited reactivity after years of deleterious reaction in service.

Etxeberria and Vázquez [20] investigated the microstructure and expansion of RAC. The concrete mixes were produced with 25% to 100% of RA affected by ASR and CEM I 52.5R type cement (Na_2O_{eq} > 0.6%). The reactivity study was carried out separately on CRA and adhered mortar, using the ASTM C1260 [31] test. The expansion obtained at 14 days in this test considered FNA present in the adhered mortar as potentially reactive, and the CRA as non-reactive. The microscopic analysis showed that the silica-alkaline gel formation resulted from the increase of alkali content (from new cement), and existence of reactive FNA in the adhered mortar. The cement paste around the fine aggregates, associated with the higher cement fineness (CEM I 52.5R) and aggregate absorption capacity, gave rise to an alkali-rich interface between the new cement paste and RA.

Li [22] and Scott IV [24] analysed the possibility of using RA from ASR-affected concrete in new concrete and evaluated various mitigation and treatment methods in RAC. The results confirmed ASR's mitigation capacity in NAC and RAC by incorporating as cement replacement 25% fly ash, 12% silica fume and 55% blast furnace slag.

Shehata et al. [26] studied the reactivity of RA sourced from primary and secondary crushing of an ASR-effected SC. The results showed that the fine fractions produced from the primary crushing caused lower expansion values than those resulting from the secondary crushing of CRA. The same researchers [27] noted, as previous researchers, a need to incorporate greater amounts of supplementary cementitious materials to mitigate ASR in RAC to the same values as in NAC. The high expansion of RAC was attributed to several factors, including the significant increase in alkali contribution by residual mortar in RA, the expansion of silica-alkaline gel in RA when exposed to high humidity in new concrete, and the exposure of fresh faces of the original reactive NA particles from crushing and processing of RA.

Aside from some known basic principles, ASR's mechanism and the variation of the expansive force intensity are still not well-understood and promote some controversy in the scientific community [4,5,8,32]. To decrease the variability of results found in the literature, an extensive experimental campaign was carried out, covering concrete mixes produced with different replacement levels of CNA with reactive and non-reactive CRA, under natural and artificial aging conditions. In the same mixes, the influence of cement type on ASR development in RAC was also evaluated. For comparison purposes, the difference between the results of RAC and NAC are discussed. The main objective of this study is to create a base on the development of ASR in RAC, parallel to the existing research on NAC.

2. Experimental campaign

2.1. Materials

Two types of Portland cement were used throughout the experimental campaign; CEM I 42.5R and CEM I 52.5R. CEM I 42.5R is recommended by RILEM AAR-3 [33] and ASTM C 1260 [31] for aggregate reactivity tests. Due to logistical difficulties, it was not possible to use the same CEM I 42.5R cement batch in SC and RAC. CEM I 52.5R cement was used to study the influence of high-strength cement on RAC. Table 1 shows the chemical, physical, and mechanical characteristics of each cement batch.

Different types of NA were first characterized in terms of their reactivity (Table 2). According to LNEC E461 [34], aggregates are categorized into three reactivity classes (I, II and III), class I being non-reactive, classes II potentially alkali-reactive, and class III with

Table 1
Characteristics of cements.

Cement type	Chemical analysis		Mechanical strength (MPa)				Physical analysis	
	Tests	Results (%)	Tests	2 d	7 d	28 d	Tests	Results
CEM 42.5R (1) (used for source concrete – SC)	Loss of ignition	2.77	Compression	28	40	50	Density	3.13 g/cm^3
	SiO_2	19.31	Flexion	5.2	6.7	7.6	Expansibility	1.5 g/cm^3
	Al_2O_3	5.43					Initial setting	145 min
	Fe_2O_3	2.99					Residue on sieve 90 μm	1.10%
	CaO total	63.62						
	MgO	1.64						
	SO_3	2.80						
	K_2O	1.11						
	CaO free	1.57						
	Na_2O	0.13						
	Na_2O_{eq}	0.86						
CEM 42.5R (2) (used for recycled aggregate concrete – RAC)	Loss of ignition	1.05	Compression	29	43	54	Density	3.13 g/cm^3
	SiO_2	19.99	Flexion	5.8	7.3	7.8	Initial setting	145 min
	Al_2O_3	6.25					Residue on sieve 90 μm	0.20%
	Fe_2O_3	3.62						
	CaO total	62.48						
	MgO	2.03						
	SO_3	2.55						
	K_2O	1.08						
	CaO free	1.68						
	Na_2O	0.14						
	Na_2O_{eq}	0.85						
CEM 52.5R (used for recycled aggregate concrete – RAC)	Loss of ignition	1.66	Compression	38	48	–	Density	3.10 g/cm^3
	SiO_2	17.68	Flexion	5.9	7.3	–	Expandability	1.0 g/cm^3
	Al_2O_3	5.28					Initial setting	130 min
	Fe_2O_3	3.22						
	CaO total	64.90						
	MgO	2.08						
	SO_3	3.08						
	K_2O	0.93						
	CaO free	2.69						
	Na_2O	0.13						
	Na_2O_{eq}	0.74						

Legend: CEM 42.5R (1): This cement type was used for production of source concrete (SC); CEM 42.5R (2): This cement type was used for production of recycled aggregate concrete – RAC.

Table 2
Characteristics of natural aggregates.

Aggregate types	Performance in service [34]	Origin	Form	Dimension (d_{min}/D_{max}, mm) [34]
CNA-NR2	Non-reactive	Limestone	Crushed	11/22
CNA-NR1	Non-reactive	Limestone	Crushed	6/14
CNA-R2	Reactive	Alluvial siliceous pebble	Crushed	10/16
CNA-R1	Reactive	Alluvial siliceous pebble	Crushed	4/16
FNA-NR	Non-reactive	Alluvial siliceous sand	Round	0/4
FNA-R	Reactive	Alluvial siliceous sand	Round	0/4

Legend: CNA = Coarse natural aggregates; FNA = Fine natural aggregates; NR = Non-reactive aggregates; R = Reactive aggregates.

a higher probability of expansive reactions than class II. In this work, NA were classified as non-reactive (class I) or reactive (class III), as also later confirmed in Section 3.1. The type of NA and RA used in the work in each concrete mix had the same origin regardless of the stage in which it was applied. Thus, the various types of aggregates applied in SC have identical characteristics to the RAC aggregates and are also the basis of RA. In the production of non-reactive source concrete (SC-NR), a limestone (non-reactive coarse natural aggregate – CNA-NR) and an alluvial siliceous sand (non-reactive fine natural aggregate – FNA-NR) were used. For reactive source concrete (SC-R), a crushed alluvial siliceous pebble (reactive coarse natural aggregate – CNA-R) and an alluvial siliceous river sand (reactive fine natural aggregate – FNA-R) were used. CRA were obtained by crushing SC produced with the abovementioned NA and sieving into several particle sizes (see Section 2.2). Two types of CNA were used, CNA1 and CNA2, having different size distributions. Table 2 presents the properties of the different types of natural aggregates.

2.2. Mix design and sample preparation

Fig. 1 presents the sequence of concrete production in this study. Both SC-R and SC-NR were first produced by a concrete company with cement type CEM I 42.5R, consisting of 680 kg/m^3 FNA, 1220 kg/m^3 CNA, 364 kg/m^3 cement, and a w/c ratio of 0.38. Two groups of moulds were used to cast each SC type, one 75 × 75 × 285 mm^3 and the other about 20 × 25 × 250 cm^3. The first set of moulds were used to analyse the susceptibility of the aggregate mixture or SC composition to develop ASR through alkali reactivity test according to RILEM AAR-3 [33].

In the second set of moulds, SC were water cured for 28 days, cut into blocks (20 × 25 × 20 cm^3), stored in boxes for 6 months, and then aged. For aging, each type of SC was divided into two groups to simulate a sample of a few years old concrete and a sample of a more recent concrete. For this purpose, a group of SC-R and SC-NR were kept in natural aging (na) outdoors for a further 6 months, producing a SC-Rna and a SC-NRna, respectively.

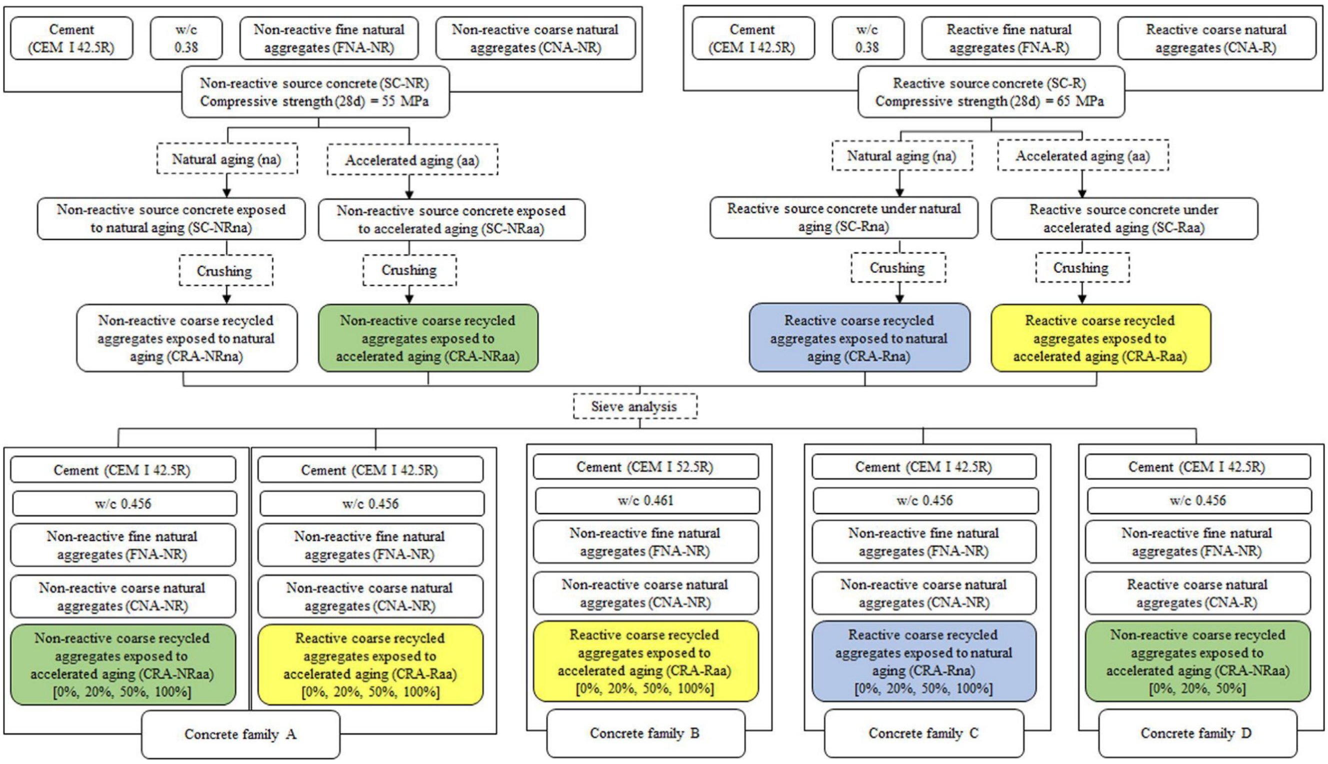

Fig. 1. Summarized sketch showing the production of two source concrete (SC) mixes and the resulting four recycled aggregate concrete (RAC) families.

Another group of SC were exposed to accelerated aging (aa) for 6 months in a chamber with temperature of 38 ± 2 °C and a relative humidity >95%, exposure conditions according to RILEM AAR-3 [33] test conditions, to produce a SC-Raa and a SC-NRaa. After aging, the crushed concrete pieces were stored for another 6 months before crushing. During this period, SC-Raa and SC-NRaa were kept inside the laboratory and SC-Rna and SC-NRna in outdoors at natural exposure environment.

CRA were obtained by crushing SC and sieving into several particle sizes. As a result, four types of CRA were produced; CRA-NRna from SC-NRna, CRA-NRaa from SC-NRaa, CRA-Rna from SC-Rna, and CRA-Raa from SC-Raa (see in Fig. 1 the boxes in line 6). Original particle size distribution of CRA-NRna and CRA-Rna is presented in Fig. 2. For comparison purposes, NA and RA had the same particle size distribution in the new concrete mixes (RAC), which was chosen according to RILEM AAR-3 [33]. The concrete mixes have 46% of coarse aggregate, by volume, at mass proportions of 30% of fine aggregates (0 to 4 mm), 30% of medium-sized aggregates (4–10 mm), and 40% of coarser aggregates (10–20 mm). An intermediate distribution of sizes 4–10 mm and 10–20 mm was taken by following a reference curve (limited by the overall percentages indicated by RILEM AAR-3), using the graph of the Faury reference curves method as a base, with an aperture between sieves equal to the fifth root of the size of the aggregate. CRA were separated by individual sieving in the d_{min}/D_{max} sizes given in Table 2, resulting in a conditioned particle size distribution. The apertures of the sieves were those of the base series plus series 2, provided in EN 12620 [35] as shown in Fig. 3.

Four new concrete families (A, B, C, D) were produced with the obtained CRA with different reactivity levels (reactive – R, non-reactive – NR), exposure type (natural aging – na, accelerated aging – aa), and replacement levels (0%, 20%, 50% and 100%), and also different types of cement (42.5R and 52.5R), as shown in Fig. 1.

In family A, the effect of using reactive CRA on the development of ASR was assessed. Two reference concrete mixes with only CNA-NR or with reactive CNA-R were considered, focusing the analysis

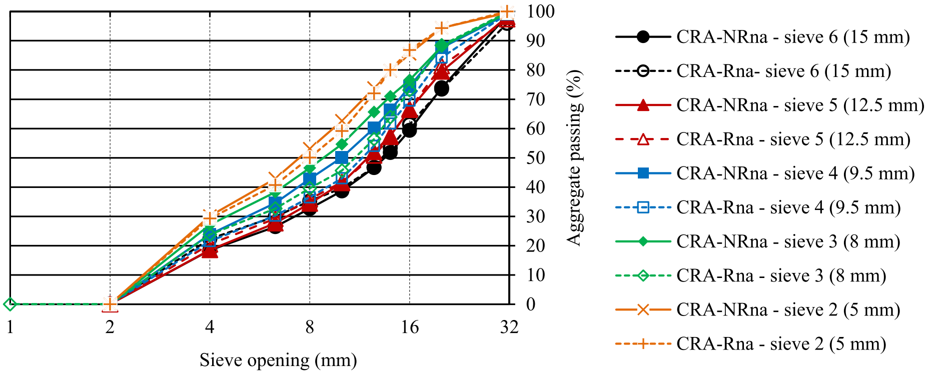

Fig. 2. Particle size distribution of reactive (CRA-Rna) and non-reactive coarse recycled aggregates (CRA-NRna) under natural aging.

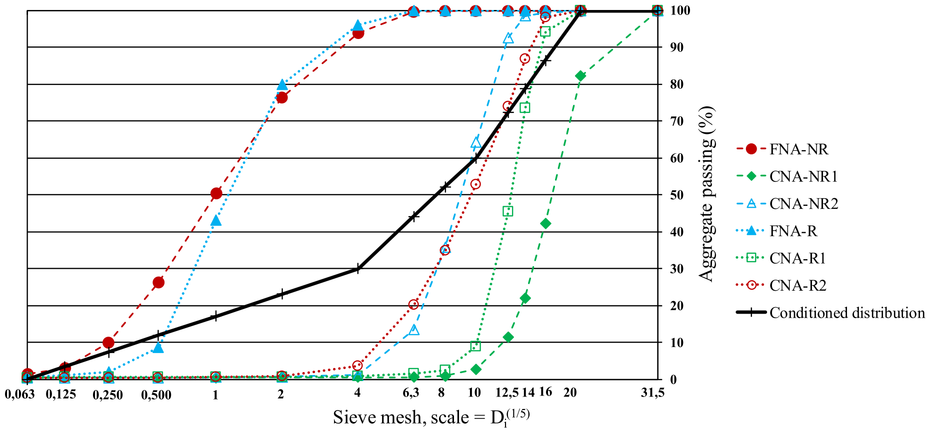

Fig. 3. Original particle size distribution of NA and conditioned particle size distribution used as a reference.

on the best and worse ASR concrete. For each replacement level of CNA-NR with CRA-R, a similar concrete mix using CRA-NR was produced, serving as comparison in the non-reactive concrete with CRA.

Family B was produced with a CEM I 52.5R to evaluate the effect of the physical and microstructural modifications of the cement paste. The amount of Na_2O_{eq} was also adjusted to 5.5 kg/m^3 of concrete. It is intended, with this family, to evaluate the expansion rate in less permeable concrete and with greater mechanical strength, by exclusive effect of the cement type.

Family C was produced to identify differences in the expansion development due to different reactivity of the CRA's. In this family, a concrete with CRA similar to family A but that suffered natural ageing was used, to simulate a waste concrete for example from a precast industry.

Family D is used to find out whether the incorporation of CRA in concrete causes some mitigating effect on the ASR due to the higher porosity of this type of aggregates. Concrete with CRA were mixed with CNA-R and different replacement ratio of CRA-NR.

The concrete mix designs are presented in Table 3. All concrete mixes produced follow RILEM AAR-3 [33] test-method. NaOH was added to the mixing water in order to adjust the alkali content to 1.25% (by cement wt.). The water absorption of NA and CRA were controlled during mixing to keep the effective w/c constant, by taking into account their absorption potential at 5 min, according to Ferreira et al. [36]. The concrete mixing procedure started with adding fine and coarse aggregates (mixing for 1 min), followed by adding 50% of the total water and NaOH (mixing for 1 min), a pause for aggregate water absorbance (1 min), and adding cement and the remaining 50% of water (mixing for 2 min).

2.3. Testing methods

Table 4 presents the carried out experimental tests and the followed corresponding standards. To better understand the evolution of ASR, aggregates were characterized using physical and mechanical analysis. Expansion to alkalis was followed by AMBT and CPT test-methods. AMBT mortar specimens were prepared according ASTM C 1260 test-conditions [31] with crushed fine aggregates (0.15–4.75 mm), cement type CEM 42.5R (cement: sand ratio = 1:2.25), and w/c ratio of 0.47. The specimens were cured for 24 h in a chamber with 23 ± 2 °C and relative humidity higher than 95%. After demoulding, the specimens were immersed in water for 24 h in an 80 °C chamber, and then immersed in a NaOH solution (1 M) for 28 days in the same chamber. The mortar specimens' initial length was registered after removing them from water. The following expansion measurements were performed at regular intervals during 28 days of immersing the specimens in a NaOH solution.

For the CPT method, the concrete specimens, with 75 × 75 × 285 mm^3, were stored at 38 ± 2 °C and relative humidity > 95%, and measurements (weight and length) were performed at regular intervals up to 5 years. The prisms were kept inside closed plastic containers, without wrapped prisms.

3. Results and discussion

3.1. Properties of aggregates and source concrete

The physical and mechanical properties of aggregates are summarized in Table 5. ASR development in the source concrete did not have a marked influence on CRA's properties. It seems that these properties are more dependent on the corresponding characteristics of NA, ITZ, and the adhered mortar than on the ASR level [47]. According to AMBT and the petrographic analysis results presented in Table 6, the non-reactivity of CNA-NR, CRA-NR and FNA-NR and the potential reactivity of CNA-R, CRA-R and FNA-R were confirmed. CPT analysis confirmed ASR potential of SC-R and SC-NR mixes. It is worthy of mention that SC was produced without the alkalis boosting, to obtain Na_2Oeq/m^3 of 5.5 kg in the mix as recommended in the RILEM AAR-3 test [33], which led to an ASR deceleration.

3.2. Expansion evolution of concrete with coarse recycled aggregates

The expansion curve evolution of concrete families A, B, C and D, tested according to RILEM AAR-3 [33], is presented in Figs. 4–9. The evolution of the curves showed some cases of oscillation with shrinkage signs up to 28 days. This may be justified by temperature and humidity variations occurred due to the opening and closing of the climate chamber and the test specimen boxes during measurements.

Up to 1 year of evaluation, using CRA from SC-NR did not lead to significant expansion (Fig. 4). In fact, all the expansion values obtained at 1 year are below the threshold limit defined in RILEM AAR-3 (0.05%). These results were compatible with those obtained using the ASTM C1260 [31] test-method (Table 6). With aging, the expansion values tended to increase with increasing incorporation level of CRA-NRaa from 20% to 100%, relative to those of A-NRref containing only CNA-NR, up to 3 years. In fact, the expansion values of A-NR-20-CRA-NRaa, A-NR-50-CRA-NRaa, and A-NR-100-CRA-NRaa were 12%, 8%, and 27% higher than that of A-NRref, respectively, at 2 years. After 3 years, expansion similarities were

Table 3
Mix compositions per m^3 of concrete.

Analysis	Concrete family	Cement		Coarse aggregates			Concrete type	w/c	Mix design for 1 m^3 of concrete (kg/m^3)								
		Type	Alkali % (Na_2O_{eq})	Source type	Replacement type	Replacement level (%)			CNA-NR	CNA-R	CRA-NR	CRA-R	FNA-NR	CEM I 42.5R	Water	Water ad.	NaOH
CRA type	Family A	CEM I 42.5R	0.85	CNA-NR	–	0	A-NRref	0.456	1242.0	–	–	–	526.0	438.2	200.0	4.9	2.3
					CRA-NRaa	20	A-NR-20-CRA-NRaa	0.456	993.6	–	233.7	–	526.0	438.2	200.0	7.3	2.3
					CRA-NRaa	50	A-NR-50-CRA-NRaa	0.456	621.0	–	584.2	–	526.0	438.2	200.0	11.1	2.3
					CRA-NRaa	100	A-NR-100-CRA-NRaa	0.456	–	–	1168.4	–	526.0	438.2	200.0	17.3	2.3
					CRA-Raa	20	A-NR-20-CRA-Raa	0.456	993.6	–	–	231.8	526	438.2	200	6.9	2.3
					CRA-Raa	50	A-NR-50-CRA-Raa	0.456	621	–	–	579.6	526	438.2	200	9.9	2.3
					CRA-Raa	100	A-NR-100-CRA-Raa	0.456	–	–	–	1159.2	526	438.2	200	15	2.3
				CNA-R	–	0	A-Rref	0.456	–	1214.4	–	–	526.0	438.2	200.0	5.9	2.3
Cement type	Family B	CEM I 52.5R	0.74	CNA-NR	–	0	B-NRref	0.461	1242.0	–	–	–	526.0	434.0	200.0	4.9	2.9
					CRA-Raa	20	B-NR-20-CRA-Raa	0.461	993.6	–	–	231.8	526.0	434.0	200.0	6.9	2.9
						50	B-NR-50-CRA-Raa	0.461	621.0	–	–	579.6	526.0	434.0	200.0	9.9	2.9
						100	B-NR-100-CRA-Raa	0.461	-	–	–	1159.2	526.0	434.0	200.0	15.0	2.9
CRA ageing	Family C	CEM I 42.5R	0.85	CNA-NR	CRA-Rna	20	C-NR-20-CRA-Rna	0.456	993.6	–	–	232.8	526.0	438.2	200.0	7.0	2.3
						50	C-NR-50-CRA-Rna	0.456	621.0	–	–	581.9	526.0	438.2	200.0	10.2	2.3
						100	C-NR-100-CRA-Rna	0.456	–	–	–	1163.8	526.0	438.2	200.0	15.6	2.3
Mitigation	Family D	CEM I 42.5R	0.85	CNA-R	CRA-NRaa	20	D-R-20-CRA-NRaa	0.456	–	971.5	233.7	–	526.0	438.2	200.0	8.2	2.3
						50	D-R-50-CRA-NRaa	0.456	–	607.2	584.2	–	526.0	438.2	200.0	11.6	2.3

Legend: CNA = Coarse natural aggregates; FNA = Fine natural aggregates; CRA = Coarse recycled aggregates; NR = Non-reactive aggregates; R = Reactive aggregates; aa = Aggregates exposed to accelerated aging; na = Aggregates under natural aging; A = Concrete mix from family A; B = Concrete mix from family B; C = Concrete mix from family C; D = Concrete mix from family D.

Table 4
Experimental tests.

Materials	Properties	Standards	Test	Sample size
Aggregates	Geometrical properties	EN 933-1 [37]	Particle size distribution	
		EN 933-3 [38]	Flakiness index	
		EN 933-4 [39]	Shape index	
	Physical properties	EN 1097-3 [40]	Bulk density and voids	
		EN 1097-5 [41]	Moisture content	
		EN 1097-6 [42]	Particle density and water absorption	
	Mechanical properties	EN 1097-2 [43]	Fragmentation resistance	
	Reactivity to alkalis	LNEC E415 [44]	This standard uses petrographic analysis to characterize aggregates' mineralogy, and in the specific case of this work, to detect potentially alkali-reactive constituents. Microscope type Olympus-BX60 was used.	Thin sections 20 × 48 mm^2
		ASTM C1260 [31]	Accelerated mortar bar test (AMBT)	25 × 25 × 285 mm^3
		LNEC E461 [34]	This standard refers to RILEM AAR [33] and RILEM ARP [45,46]. The specimens were not wrapped for this test.	
Concrete	Reactivity to alkalis	RILEM AAR-3 [33]	Concrete prism test (CPT). The specimens were not wrapped.	75 × 75 × 285 mm^3

Table 5
Characterization of coarse and fine natural aggregates and coarse recycled aggregates.

Aggregates		d_{min}/D_{max} (mm)	Density (kg/m^3)				v (%)	Water absorption (%)		W (%)	SI (%)	FI (%)	LA (%)
			ρ_a	ρ_{ssd}	ρ_{rd}	ρ		WA_{24}	WA_{5m}				
NA	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	–	–	–
	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	–
RA	$CRA\text{-}NR_{aa}$	4/20	2680	2540	2460	1320	46.2	3.26	80	1.78	24	13.7	41
	$CRA\text{-}R_{aa}$	4/20	2650	2520	2440	1360	44.4	3.20	80	1.92	16	13.7	31
	$CRA\text{-}NR_{na}$	4/20	2680	2550	2470	–	–	3.10	80	1.70	–	–	36
	$CRA\text{-}R_{na}$	4/20	2660	2530	2450	1350	45.1	3.15	80	1.82	–	–	30

Legend: NA = Natural aggregates; RA = Recycled aggregates; CNA = Coarse natural aggregates; FNA = Fine natural aggregates; CRA = Coarse recycled aggregates; NR = Non-reactive aggregates; R = Reactive aggregates; aa = Aggregates exposed to accelerated aging; na = Aggregates under natural aging; 1 = Smaller aggregates dimensions; 2 = Larger aggregates dimensions; d_{min}/D_{max} = Aggregate sizes from particle size analysis; SI = Shape index; FI = Flakiness index (FI); ρ = Bulk density (ρ); v = Void volume; ρ_a = Apparent density (ρ_a); ρ_{rd} = Oven dry density; ρ_{ssd} = Saturated surface dry density; WA_{24} = Water absorption at 24 h; WA_{5m} = Water absorption of the aggregates with respect to their potential to absorb over 5 min; W = Moisture content before mixing; LA = Fragmentation resistance according Los Angeles method.

Table 6
Expansion results and petrographic analysis of natural aggregates, recycled aggregates, and source concrete.

Materials		Expansion (%)*		Petrographic characteristics	Classification
		AMBT [31] (28 days)	CPT [33] (364 days)		
NA	CNA-NR2	0.00	–	CNA-NR were sedimentary carbonated rocks. Reactive silica and potentially alkali mineral suppliers were not detected.	NR
	CNA-NR1	0.00	–		NR
	CNA-R2	0.37	–	CNA-R were composed of different siliceous rocks (quartzite, gneiss and mylonite). The main components were deformed quartz particles and chert (reactive silica supplier) and biotite, muscovite, chlorite, and plagioclase (alkali suppliers).	R
	CNA-R1	0.51	–		R
	CNA-NR	0.04	–	–	NR
	FNA-R	0.12	–	–	PR
SC	SC-NR	–	0.010	–	NR
	SC-R	–	0.052	–	R
RA	$CRA\text{-}R_{aa}$	0.23	–	–	R
	$CRA\text{-}R_{na}$	0.22	–	–	R

Legend: * = Using AMBT the aggregate is considered reactive if the expansion is higher than 0.20% at 14 days and of doubtful reactivity if the value is lower that 0.20% at 28 days [31]; using CPT at 364 days the aggregate it is considered non-expansive if the expansion result is lower than 0.05% [33]; NA = Natural aggregates; RA = Recycled aggregates; CNA = Coarse natural aggregates; FNA = Fine natural aggregates; CRA = Coarse recycled aggregates; NR = Non-reactive aggregates; R = Reactive aggregates; PR = Potentially reactive; aa = Aggregates exposed to accelerated aging; na = Aggregates under natural aging; 1 = Smaller size aggregates; 2 = Larger size aggregates.

found between A-NR-20-CRA-NRaa and A-NR-100-CRA-NRaa and between A-NRref and A-NR-50-CRA-NRaa.

In the A-NR-CRA-Raa mixes, where CNA-NR is replaced with CRA-Raa, the effect of CRA-Raa's incorporation level on ASR development is only visible after 90 days of testing (Fig. 5). In fact, the expansion values increased with increasing incorporation level of CRA-Raa up to 3.5 years, and stabilized after that. At 1 year, A-Rref (containing only CNA-R), A-NR-50-CRA-Raa (containing 50%

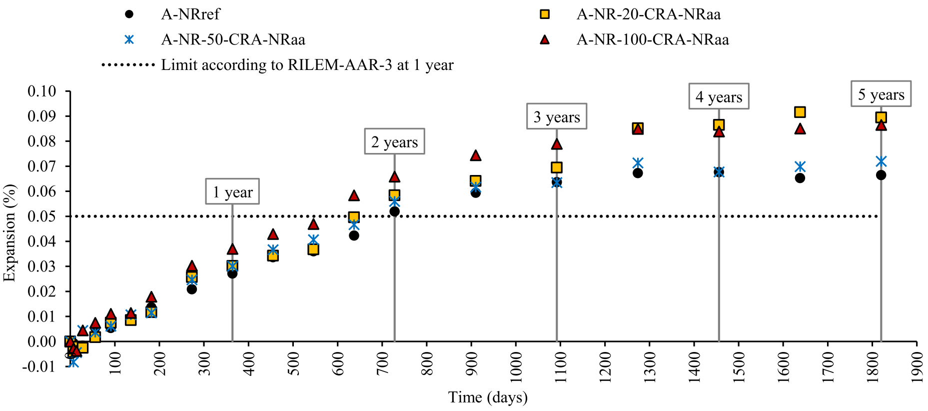

Fig. 4. Expansion evolution of A-NR-CRA-NRaa mixes according to RILEM AAR-3 [33].

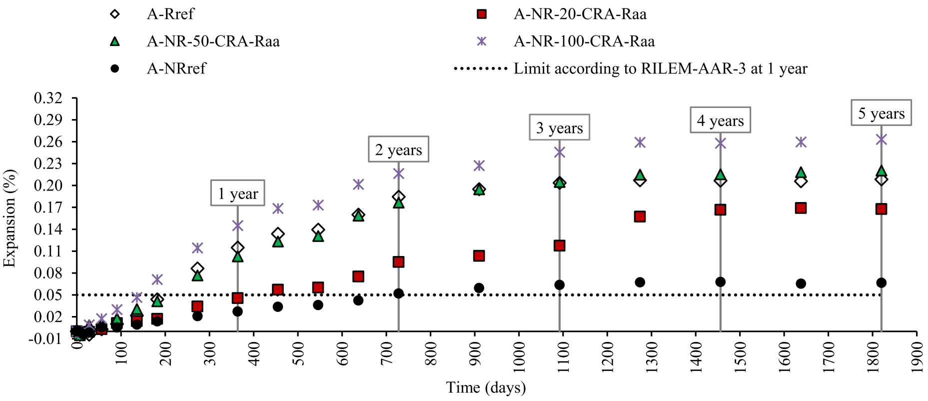

Fig. 5. Expansion evolution of A-NR-CRA-Raa mixes according to RILEM AAR-3 [33].

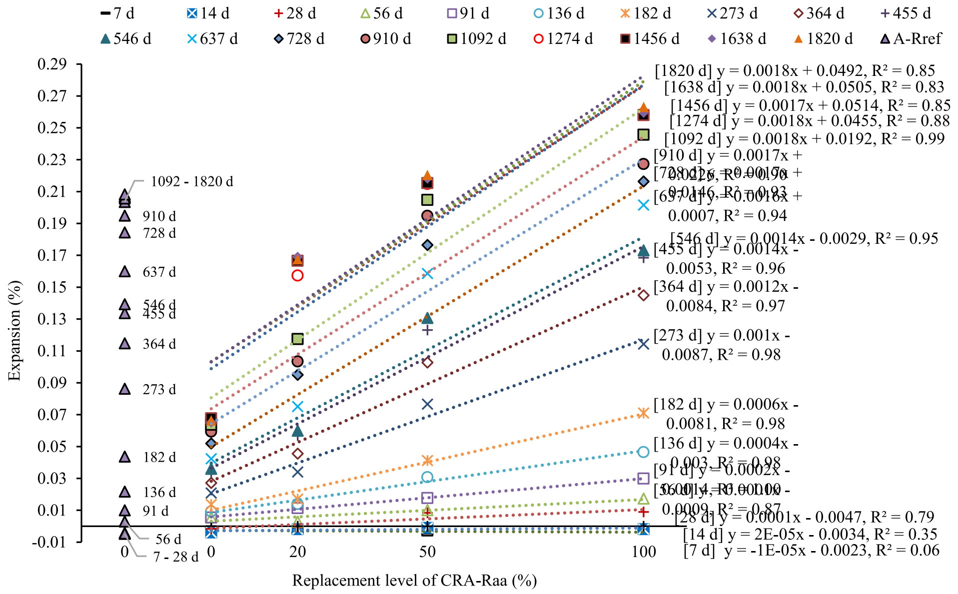

Fig. 6. Relation between expansion of A-NR-CRA-Raa and incorporation level of CRA-Raa.

CRA-Raa) and A-NR-100-CRA-Raa (containing 100% CRA-Raa) exceeded the threshold limit of 0.05%. Although the A-NR-20-CRA-Raa and A-NRref mixes showed an expansion increase along time, they did not exceed the threshold limit. The smaller expansion increase in A-NR-20-CRA-Raa could be attributed to the porosity increase in CR concrete, which could accommodate ASR gel's

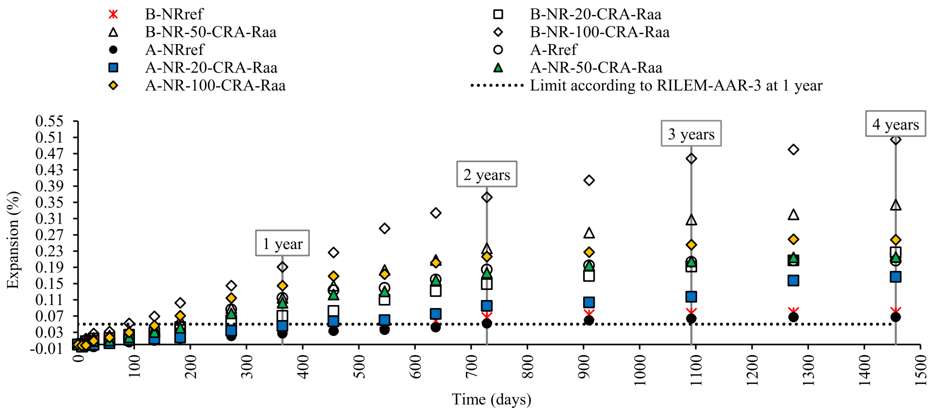

Fig. 7. Expansion evolution of B-NR-CRA-Raa mixes according to RILEM AAR-3 [33].

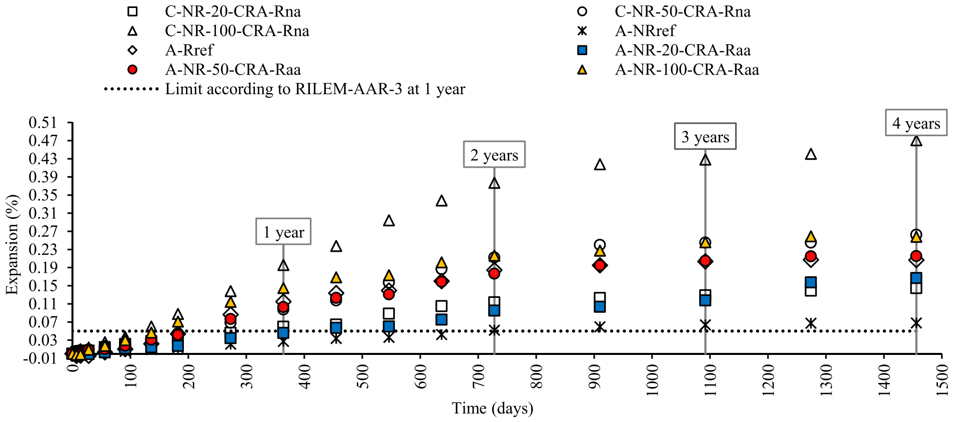

Fig. 8. Expansion evolution of C-NR-CRA-Rna mixes according to RILEM AAR-3 [33].

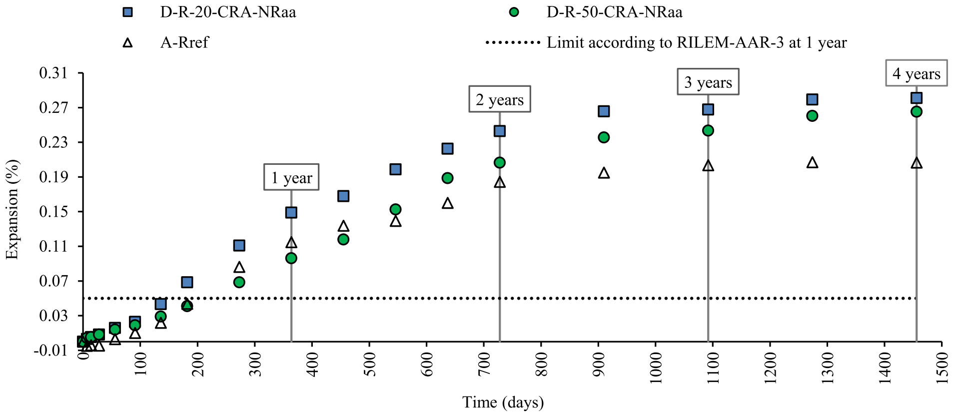

Fig. 9. Expansion evolution of D-R-CRA-NRaa mixes according to RILEM AAR-3 [33].

formation. As the incorporation level of CRA-Raa increased, the porosity increment seems to be insufficient for this accommodation.

Fig. 6 presents the relation between expansion values and incorporation levels of CRA-Raa and testing ages. It shows that the expansion values of all concrete mixes increased with aging and that the correlation between the expansion and CRA-Raa incorporation level improved with aging. After 56 days, the correlation factor (R^2) was higher than 0.80. This trend can be justified with the accessible pore number decrement due to the cement paste consolidation and filling with ASR gel.

The influence of using different types of cement (CEM I 42.5R *versus* CEM I 52.5R) on expansion of concrete made with CRA-Raa is presented in Fig. 7. According to the obtained results, concrete family B containing high strength cement (CEM I 52.5R) reached higher expansion levels than those of concrete family A with CEM I 42.5R, at all ages. In addition, the incorporation of CRA-Raa in concrete family B led to significantly higher expansion increments than in concrete family A, when compared to those of the corresponding reference mixes (B-NRref and A-NRref, respectively). For example, B-NR-100-CRA-Raa exceeded the threshold limit (0.05%) at 91 days, while A-NR-100-CRA-Raa reached this value only after 136 days. The difference between the expansion values of concrete family A and B increased with time.

The expansion curves of concrete family C, where CRA-Rna was used, are presented in Fig. 8. In general and as expected, the expansion of C-NR-CRA-Rna mixes was higher than that of A-NR-CRA-Raa mixes, at all ages. For C-NR-CRA-Rna mixes, the expansion increased with increasing incorporation level of CRA-Rna, up to 4 years. Contrary to that observed in the family A mixes, there is no stabilization of expansion after 3.5 years for concrete family C. It seems that accelerated ageing has diminished the ASR potential.

Fig. 9 shows the expansion evolution of D-R-CRA-NRaa mixes. The D concrete family did not show expansion mitigation due to the higher porosity of CRA or to a decrease in ASR reactivity in CRA-Raa. By the age of 182 days, both mixes in concrete family D exceeded the threshold limit (0.05%). In general, 20% or 50% replacement of CNA-R with CRA-NRaa (respectively, D-R-20-CRA-NRaa and D-R-50-CRA-NRaa mixes) led to higher expansion values than that of A-Rref containing only CNA-R. The expansion values of D-R-20-CRA-NRaa and D-R-50-CRA-NRaa were 32–36% and 12–28% higher than that of A-Rref, respectively, at 2–4 years.

4. Conclusions

From the experimental campaign focused on the expansion evolution of concrete mixes produced with reactive and non-reactive CRA, under natural and accelerated aging, the following conclusions were drawn:

- Concrete mixes with CRA are classified as reactive when 50% or 100% of CRA-R are used. Incorporation levels of 20% CRA-R do not cause a significant increase in the concrete mix's reactivity;
- Incorporating CRA-NR in a concrete mix containing CNA-NR does not affect the expansion behaviour;
- The reactivity of CRA-R is higher than that of CNA-R, which contradicts the mortar results obtained according to ASTM C1260 [31]. This may indicate that SC crushing process is the primary reason for the alkali reactivity increment of these aggregates due to introducing new available silica surfaces for reaction;
- CRA-R produced from SC under accelerated ageing has lower reactivity than that of CRA-R from SC under natural aging. Thus, alkali residual potential of CRA is influenced by the exposure conditions and age of concrete mixes;
- Despite the fact that all studied mixes had the same alkalis content (Na_2O_{eq}), changing the concrete's microstructure by using a high-strength cement (CEM I 52.5R, instead of CEM I 42.5R), has increased the expansion of mixes with CRA;
- Since a good correlation ($R^2 > 0.80$) was obtained between the expansion evolution and CRA incorporation level at longer ages (between 56 and 1820 days), this test under accelerated aging could be used in future research for reduction of CPT [33] method duration.

CRediT authorship contribution statement

Miguel Barreto Santos: Conceptualization, Methodology, Validation, Investigation. **Jorge Brito:** Conceptualization, Resources, Supervision. **António Santos Silva:** Conceptualization, Resources, Supervision. **Hawreen Hasan Ahmed:** .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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