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Alkali–silica reaction in mortars and concretes incorporating natural rice husk ash

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HIGHLIGHTS

- ▶ Mortars and concretes with residual rice-husk ash (RHA) as nature were prepared.
- ▶ Alkali–silica reaction (ASR) in concretes with natural and ground RHA was studied.
- ▶ Concretes with RHA, under field conditions, were evaluated up to three years.
- ▶ The RHA can inhibit or promote ASR depending on their particle size.
- ▶ RHA as nature requires a proper selection of the cement to avoid ASR.

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ABSTRACT

Rice-husk ash (RHA) is a supplementary cementing material of great interest in many developing countries. Before using in concrete the rice husk needs to be burnt at a controlled temperature. In other conditions a residual RHA is obtained with a lower quality, but it can be improved by grinding (GRHA). As a way to simplify RHA processing and amplify its use nearby where it is produced, it was demonstrated that it is possible to produce structural concretes incorporating residual RHA "as nature" (NRHA), adapting the mixing process to optimize the ash particle size by grinding it in the mixer together with the coarse aggregate. Nevertheless as RHA has siliceous vitreous minerals and cristobalite, deleterious reactions with Portland cement can take place when alkalis and certain environmental conditions are present. This paper studies the development of alkali–silica reaction (ASR) in mortars and concretes prepared with NRHA and GRHA. Accelerated and long term expansion tests, mechanical characterization, microscopic observations and studies on prototypes are included. The RHA can inhibit or promote ASR depending on its particle size. Furthermore, the risks of cracking and the selection criteria for the best binders when using NRHA are shown.

1. Introduction

Nowadays the use of mineral additions in the construction industry is constantly increasing mainly due to their environmental and sustainability implications. In addition to the traditional mineral additions (blast furnace slag, calcareous filler, fly ash or natural pozzolan), many other supplementary materials are being considered. Among them, rice-husk ash (RHA) appears as a specific option for the area of the State of Rio Grande do Sul (Brazil), Uruguay and the Mesopotamia of Argentina, as its use represents a solution for the disposition of this residue, generated in large quantities (approximately 500,000 t/year).

It is well known that RHA can contain non-crystalline silica and that a highly reactive pozzolan is obtained when the rice-husk is burnt under controlled conditions [1–3]. In other conditions a "residual RHA" is produced with a lower quality, usually presenting residual carbon (which increases the water demand) and part of the silica in crystalline state. However, the residual RHA can be improved by grinding it to an appropriated particle size, although this process comes with a considerable cost, as expected [4,5]. Both processes imply energy costs and strategies for selection and disposition.

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Recently, a joint project[1] was developed with the aim of analyzing the viability of the use of residual RHA "as nature", without previous grinding, adopting an appropriate sequence for the incorporation of component materials during the mixing process of concrete. An adequate RHA particle size was obtained mixing RHA together with the coarse aggregates during a convenient period of time (near 8 min) [6]. This paper concludes that Natural Rice-Husk Ash (NRHA) is a residue apt to be incorporated into cement based materials, reducing the cement contents with a consequent positive environmental impact. It was possible to improve the ash's particle size by adapting the mixing process; however, the results are highly dependent on the equipment and mixing cycle adopted. Both the control concrete without ash and the concrete with 15% of the cement replaced by NRHA achieved similar mechanical and durability properties, but they were lower than those obtained in concretes prepared with previously grinded RHA (GRHA). Regarding other properties, it was shown that matrix/aggregate bond strength improved when GRHA or NRHA were incorporated. No significant effects on the stress–strain behavior in compression or in the residual properties after high temperature exposure were found. Creep and shrinkage were similar in both the reference concrete without ash and concretes that replaced cement by GRHA or NRHA. Other studies of the same project performed on concretes with 28-day compressive strengths ranging from 20 to 40 MPa and where 15% of cement weight was replaced by NRHA included measurements of the carbonation depth, the permeability to oxygen, and the capillary suction capacity show the viability of using NRHA.

In order to perform a complete analysis on the durability of concretes incorporating NRHA, it is important to note that RHA has some siliceous minerals that could lead to deleterious reactions in Portland cement based materials. X-ray diffraction analysis confirmed significant amounts of vitreous material and cristobalite. In the presence of alkalis and some environmental conditions, depending on the size of the particles, the incorporation of RHA can produce inhibition effects or promote the alkali–silica reaction. It was found that ASR expansions in concrete can be reduced by the use of optimized RHA burnt under controlled conditions [7]. However, this is not necessarily the case when using NRHA as their mineralogical and physical characteristics considerably differ. This paper studies the development of alkali - silica reaction in mortars and concretes with natural and ground RHA.

2. Experiences

2.1. Materials

A residual rice husk ash (generated by uncontrolled burning conditions), from Rio Grande do Sul State, Brazil, was used "as nature" without previous grinding. As explained in a previous paper [6] the weak burnt particles of the natural rice husk ash (NRHA) can be ground during concrete production by adopting an adequate sequence during the mixing process, where the RHA and the coarse aggregates are mixed together during a certain time before the rest of the component materials are incorporated. Details about the chemical analysis and how the ashes were obtained are presented in [6].

Table 1 presents the identification and physical characteristics of the ashes. After the burning process, the NRHA is only dried, homogenized, and packed to ease transport to the laboratory. N*RHA is this same ash after 10 min mixing together with the coarse aggregates in a concrete mixer. It represents the grinding the particles undergo when incorporated in concrete. Ground rice husk ash (GRHA) was obtained after grinding this same ash for one hour the ash in a ball mill for optimization. It can be clearly seen that the amount of particles between #50, #100, and #200 sieves was significantly modified due to the grinding effect produced during mixing. The Blaine specific surface area of the GRHA was 750 m^2/kg and the particles' mean size ranged between 4 and 6 μm, but a few particles were as large as 100 μm. To complete the study, a finer G#RHA (950 m^2/kg) was also used for accelerated mortar tests. Since the coarse aggregates are not present when preparing mortars, N*RHA was prepared separately and used instead of NRHA.

Fig. 1 shows the X-ray diffraction (XRD) analysis of GRHA and NRHA. A clear peak of cristobalite, abundant amorphous siliceous material and quartz (between 2θ angles 15° and 30°) can be seen.

Different types of cements from Brazil and Argentina including ordinary Portland cement (OPC), Portland cement incorporating calcareous filler (FPC) and pozzolanic Portland cement (PPC) were used. Their main properties related to the ASR performance are summarized in Table 2; the country of origin is indicated as a reference. The cement OPC3 (0.71% Na_2O_{eq}) made in Argentina was also combined with 30% of a natural pozzolan. This pozzolan is a volcanic tuff with glass content higher than 93%, ground to 600 m^2/kg and has shown a high effectiveness in ASR inhibition.

Reactive and nonreactive coarse and fine aggregates, from Buenos Aires Province, Argentina, were selected.

The non-reactive coarse aggregate (g), 19 mm maximum size, was a granitic crushed stone that when tested in accordance with ASTM C 1293 [8] gave expansions of 0.006% at 52 weeks. The structures in which it has been used show excellent performance both in strength and durability. The reactive coarse aggregate (r), 19 mm maximum size, was a siliceous metaquartzite with quartz grains with recristalized borders that enhance the dissolution of the silica in the presence of alkalis. When tested in accordance with ASTM C 1293, this aggregate presented expansions of 0.044% at 52 weeks, indicating a moderate reactivity grade.

The non-reactive fine aggregate was a siliceous natural sand obtained from the east coast of the La Plata River (fineness modulus 2.36, density 2.63). It has rounded particles composed of quartz (>70%), lithic granitic fragments, feldspars (plagioclase), pyroxenes and a very small amount (0.5%) of chalcedony. Expansion tests according to ASTM C 1293 and ASTM C 1260 [9] indicate expansions of 0.038% at 1 year and 0.080% at 16 days, respectively. The reactive sand (rs) was obtained by crushing the coarse aggregate r.

Regarding the rest of the component materials, potable water and in some cases a high range polycarboxilic based water reduction admixture were used. The superplasticizer was incorporated to compensate the differences in the water demand, especially in the case of NRHA.

2.2. Experimental program

Three experimental studies were developed in order to analyze the performance of concretes incorporating NRHA.

The first study (Program 1) evaluates the use of RHA for the mitigation of ASR. Mixtures incorporating different contents of NRHA and GRHA (the same ash optimized by grinding) as cement replacement combined with reactive and non-reactive aggregates were studied. Accelerated expansion tests on mortars and concretes were made and the mechanical properties of the concretes were evaluated.

As Program 1 showed an expansive behavior in mixtures incorporating NRHA even with non-reactive aggregates, a second study (Program 2) was developed with the aim of analyzing the criteria for the cement selection to avoid ASR. Accelerated expansion tests on mortars prepared with different types of cements from Brazil and Argentina combined with NRHA and GRHA were performed. Complementarily, mechanical tests and microscopic observations were done.

The third step (Program 3) included studies on the performance of small slabs in field conditions during three years with the aim of analyzing the influence of the use of NRHA or GRHA with and without alkali addition. The crack patterns and length variations of the slabs plus the expansions and the mechanical properties measured on prisms and cylinders stored by the slabs were evaluated. In addition, other groups of prisms and cylinders were stored at 38 °C in accordance with ASTM C 1293.

2.3. Experimental details

2.3.1. Mortar tests

Accelerated expansion tests on mortars in accordance with ASTM C 1260 [9] were done in Programs 1 and 2. A cement:aggregate ratio equal to 1:2.25 and water/binder ratio 0.47 were used.

In Program 2, to observe the effects of the damage process into the material structure, the mortar residual mechanical properties were also evaluated. After expansion tests, the bars were sawn and three-point bending tests were implemented over a span of 100 mm. A 5 mm notch was cut using a diamond saw; displacement rate of 0.1 mm/min and a clip gage for measuring the crack mouth opening displacement (CMOD) were used. In addition, mortar residual compressive strength was measured on sawn square prisms with 25 mm sides and 50 mm high.

Finally, optical and microscopic observations on mortar slices were performed.

[1] The Project "Produção de concreto estrutural com cinza de casca de arroz "in natura", sem beneficiamento" (production of structural concrete with natural rice husk ash without optimization process), was performed by the Centro de Tecnología, Departamento de Estruturas e Construção Civil (GEPECON/UFSM Universidade Federal de Santa Maria, Brazil), the Universidad de la República (UDELAR, Montevideo, Uruguay) and the LEMIT-CIC, La Plata, Argentina. The project supported by the Programa Sul-Americano de Apoio às Atividades de Cooperação em Ciência e Tecnología – PROSUL-CNPq (South-American Support Program to Cooperation Acctivities in Science and Technology), was developed with the general objective of analyzing the feasibility and economical advantages for the use of natural residual RHA (without burnt control and grinding optimization) in concrete and other cement based materials.

Table 1
Physical properties of RHA.

Identification		NRHA	N*RHA	GRHA	G#RHA
Fineness		Original	After 10 min mixing together with coarse aggregates	Previously grinded in a ball mill	
Pass (%)	#50	47	81	100	100
	#100	23	39	100	100
	#200	18	15	95	95
Density		1.45–1.60		2.05	1.97
Blaine specific surface (m^2/kg)				750	950

2.3.2. Concrete tests

Accelerated expansion tests were performed in accordance with ASTM C 1293 [8] using prisms of 75 × 75 × 300 mm, stored at 38 ± 2 °C. The length changes were measured using a mechanical length comparator with a precision of 0.0025 mm. In Program 3, the same measurements were also made on prisms stored by the slabs; in addition, the strains on the surface of the slabs were measured with a mechanical deformation device (0.0025 mm).

The stress–strain behavior under uniaxial compression was evaluated on standard cylinders of 100 × 200 mm and also on 100 mm diameter cores drilled from the slabs. Loading–unloading cycles up to 40% of the maximum stress were applied to determine the modulus of elasticity, after which the load was increased monotonically up to failure. A controlled closed loop system was used, with the axial deformation as the control signal, in order to obtain the complete stress–strain curves. Different curing conditions were adopted considering the objectives of each study. In Program 1 the cylinders were cured in saturated conditions at 38 °C. In Program 3 standard cylinders placed by the slabs and cores extracted from the slabs were also tested. (Tests and procedures were performed following the general guidelines of ASTM C 31, ASTM C 42, ASTM C 39 and ASTM C 469 standards).

3. Results and discussion

3.1. Program 1: use of RHA in concretes with reactive aggregates

As it is well known, pozzolanic materials may contribute to controlling ASR. However, as the particle size of NRHA is quite coarser than GRHA, both its pozzolanic activity and the effectiveness for ASR control can substantially decrease.

With the aim of evaluating the use of NRHA for the mitigation of ASR, mixtures incorporating different contents of NRHA and GRHA as cement replacement combined with the reactive aggregates were studied, including mortars and concretes.

Five mortars were prepared incorporating the reactive sand (rs) and cement OPC1 with total alkalis (Na_2O_{eq}) 0.66%: a reference mortar without ash and four mortars replacing 15% or 25% of cement weight by GRHA or N*RHA. They are identified as control, G15, G25, N15 and N25, respectively.

Fig. 2 shows the results of the expansion tests performed in accordance with ASTM C 1260. The control mortar achieves the limit of 0.100% expansion before 16 days. At the same age, mortars G15 and G25 show expansions of 0.069% and 0.187%, respectively; the expansions drastically increase in mortars incorporating N*RHA, with values of 0.370% and 0.513% for N15 and N25.

Based on the fact that significant expansions were found in the mortars, and considering that concrete tests are more reliable than accelerated mortar bar tests, concretes incorporating reactive (*r*) or non-reactive (*g*) coarse aggregates, non-reactive sand, replacing 15% or 25% of cement OPC1 by GRHA and NRHA were prepared. Mixture proportions were adopted as indicated by ASTM C 1293: water/binder ratio 0.44, fine:coarse aggregate ratio 40:60, binder content of 420 kg/m^3 and alkali content (Na_2O_{eq}) of 5.25 kg/m^3. Prisms of 75 × 75 × 300 mm and cylinders of 100 × 200 mm were cast. All of them were compacted by external vibration and kept protected after casting to avoid water evaporation. After 24 h they were covered with a cotton sheet and placed inside plastic bags, including 5 ml of water. These bags were stored at 38 ± 2 °C. Concretes were identified in accordance with the type and percentage of ash, including the sub index *r* in mixtures prepared with reactive coarse aggregates (G15, G25, G15-*r*, G25-*r*; N15, N25, N15-*r*, N25-*r*).

Fig. 3 shows the evolution of linear expansions up to 52 weeks. When incorporating GRHA the expansions are higher in concretes with reactive aggregates as expected, however, all values remain below the limit of 0.040%. On the contrary, all concretes with NRHA

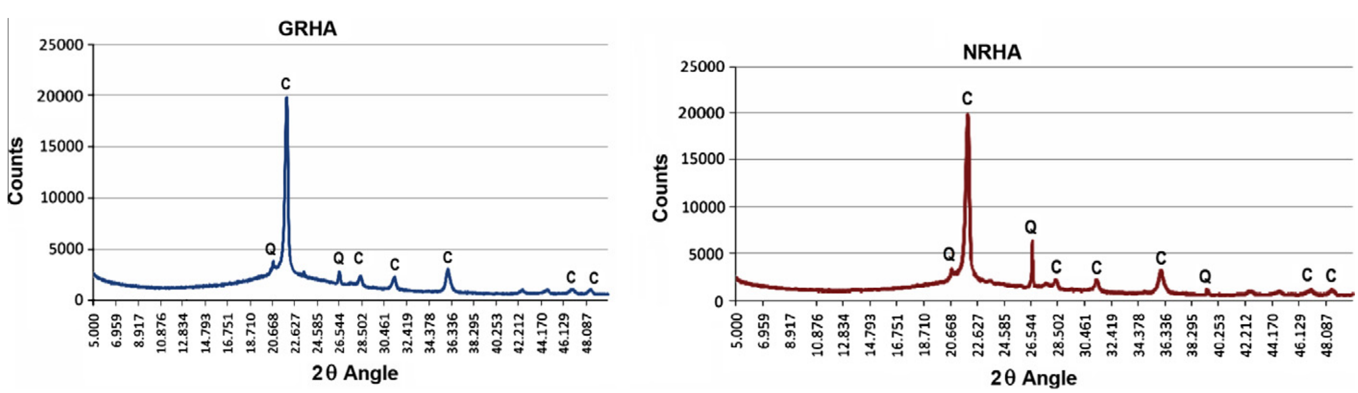

Fig. 1. XRD analysis of GRHA. C: cristobalite; Q: quartz.

Table 2
Chemical and physical properties of used cements.

Identification	OPC1	OPC2	OPC3	FPC1	OPC4	FPC2	PPC
From	Argentina				Brazil		
Loss on ignition (%)	1.5	1.2	2.0	7.2	3.0	5.6	4.8
Insoluble residue (%)	0.41	0.64	0.60	1.5	0.34	8.2	35.1
Na_2O_{eq} (%)	0.66	0.80	0.71	0.66	0.44	0.74	0.57
Blaine specific surface (m^2/kg)	358		295	354	343	510	467
Pass #75 μm (%)	96.6	97.7	98.6	97.4	99.3	99.2	99.8
OPC	Ordinary Portland cement						
FPC	Portland cement incorporating calcareous filler						
PPC	Pozzolanic Portland cement						

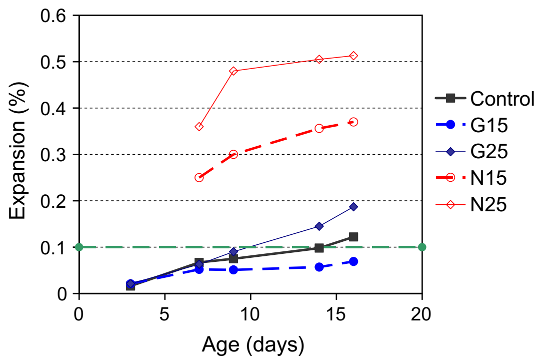

Fig. 2. Expansion tests in mortars with reactive sand.

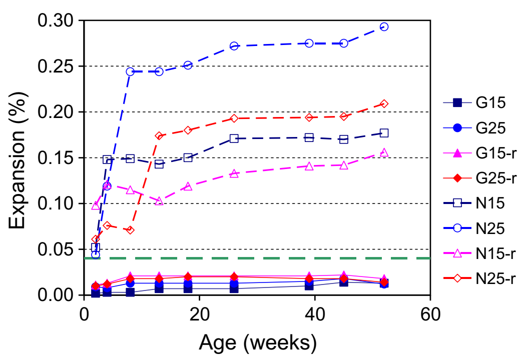

Fig. 3. Expansion tests up to 52 weeks in concretes of Series G and N.

show significant expansions, even those incorporating non-reactive aggregates. It is clearly seen that the expansions increase as the NRHA content increases, making evident that the presence of NRHA is responsible for this behavior.

Fig. 4 shows the stress–axial strain curves obtained at 28 days for each concrete. Table 3 summarizes the values of compressive strength ($f'c$) and modulus of elasticity (E); the results are the mean of three tests with coefficients of variation lower than 6%. The mechanical properties improved with the GRHA content, which can be attributed to the pozzolanic activity of this ash and is coherent with previous studies [6]. On the contrary, concretes incorporating NRHA show clear reductions in strength and especially in stiffness, significant increases in residual axial deformations after the first loading–unloading cycles up to 40% $f'c$, and

Table 3
Program 1: mechanical properties of concretes at 28 days.

Concrete	$f'c$ (MPa)	E (GPa)
G15	30.6	32.3
G25	35.0	33.6
G15-r	32.4	30.0
G25-r	34.1	33.2
N15	28.2	21.1
N25	22.4	13.7
N15-r	25.8	12.1
N25-r	19.7	9.5

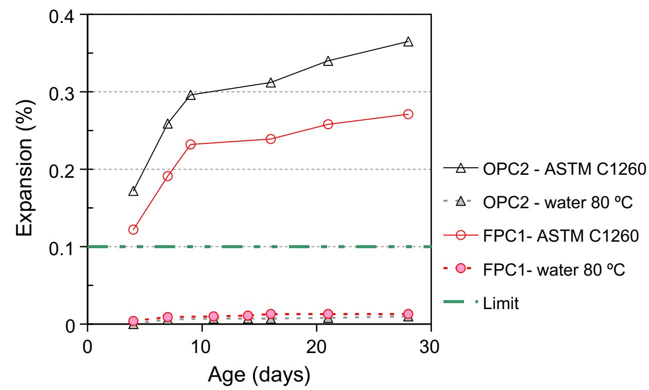

Fig. 5. Expansion tests in mortars with natural sand, NRHA and different cements, exposed at 80 °C with and without alkalis.

drastic increments in the deformation corresponding to the peak load (>3000 μm/m), both with reactive or non-reactive coarse aggregates. The mentioned work [6] indicated that concretes replacing 15% of cement weight by NRHA achieved 90% of the strength of concretes with 15% GRHA. In this case when alkalis were incorporated, the specimens prepared with NRHA showed the typical residual behavior of concretes damaged by ASR reactions [10,11].

It must be noted that although significant expansions were measured, the typical signs usually observed in concretes affected by ASR, like the presence of gels or cracks, were not found. Thus, a new set of mortars was prepared with the nonreactive sand. It includes two mortars replacing 15% of N*RHA by cement weight prepared with cements OPC2 and FPC1 with total alkalis (Na_2O_{eq}) 0.80% and 0.66%, respectively. Mortar bars were divided in two groups. The first was stored in a 1N solution of NaOH at 80 °C as indicated by ASTM C 1260, and the second was stored at the same temperature, but in water without alkalis. Fig. 5 shows the

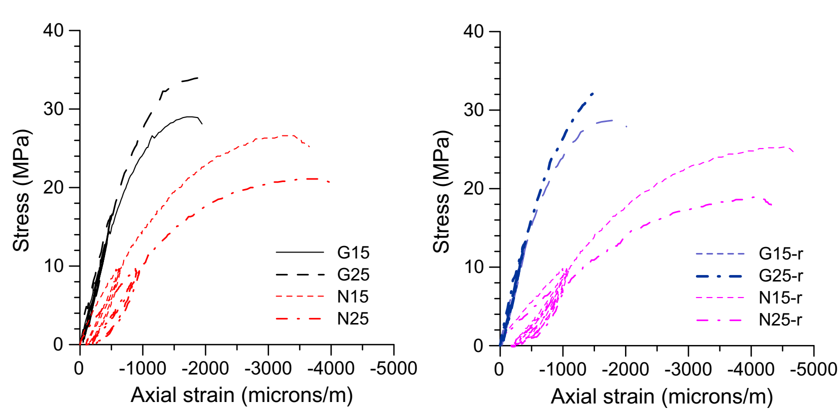

Fig. 4. Stress–strain curves in compression obtained at 28 days in concrete prepared with reactive and non-reactive coarse aggregates.

expansions measured up to 28 days. Mortars incorporating NRHA that were not in contact with alkalis did not show expansions. It can be clearly seen that the NRHA is responsible for the expansions, but they only take place when a high content of alkalis is present.

The obtained results show that:

- Considering mortar accelerated tests, in the presence of alkalis NRHA increases the expansions while GRHA can lead to inhibition or exacerbation of the ASR, depending on the percentage used.
- Concretes incorporating GRHA showed expansions (ASTM C 1293) below the limit of 0.040%, while drastic expansions were found in concretes with NRHA, both with reactive and non-reactive coarse aggregates. A typical residual mechanical behavior of concretes damaged by ASR was observed in the last case. Nevertheless, no typical signs of ASR were found.

The potential reactivity of NRHA with alkalis makes it necessary to explore alternatives to mitigate this problem. It is also important to evaluate the responses of the cements usually employed in the region, as well as the combination of NRHA with other mineral additions.

3.2. Program 2: mortars incorporating RHA prepared with different cements

Based on previous observations, a specific program of accelerated expansion tests on mortars following the general guidelines of ASTM C 1260 was developed.

Four Series of mortars with the non-reactive sand and different cements were made. Series 1 includes a reference mortar without RHA and mortars replacing 15%, 30% or 45% of OPC4 in weight by GRHA or N*RHA. Series 2–4 include a reference mortar and mortars replacing 15% of GRHA and N*RHA. Cements FPC2 and PPC from Brazil and cement OPC3 from Argentina combined with 30% of the natural pozzolan were used. Finally mortars incorporating 15% of G#RHA were also included in Series 1 and 2. Table 4 summarizes the studied mortars and their identifications.

Fig. 6 shows the length variations measured up to 28 days. Important expansions were found in mortars with N*RHA of Series 1, with the case of 1-N15 being the highest. The control mortar (1-0) showed expansions at 28 days near 0.1%, and lower values were found in mortars with GRHA and G#RHA. In all mortars of Series 2 (CPF2) important expansions over the limit of 0.1% were found. For example in 2–15N, values higher than 0.80% were measured,

Table 4
Program 2: mortars prepared with different types of cements and RHA.

Series		Cement	GRHA (%)	G#RHA (%)	N*RHA (%)
1	1-0	Ordinary (Brazil) Na_2O_{eq}: 0.44%			
	1-15G		15		
	1-30G		30		
	1-45G		45		
	1-15N				15
	1-30N				30
	1-45N				45
	1-15G#			15	
2	2-0	Fillerized (Brazil) Na_2O_{eq}: 0.74%			
	2-15G		15		
	2-15N				15
	2-15G#			15	
3	3-0	Pozzolanic (Brazil) Na_2O_{eq}: 0.57%			
	3-15G		15		
	3-15N				15
4	4-0	70% CPN40 (Argentina) Na_2O_{eq}: 0.71 + 30% pozzolan			
	4-15G		15		
	4-15N				15

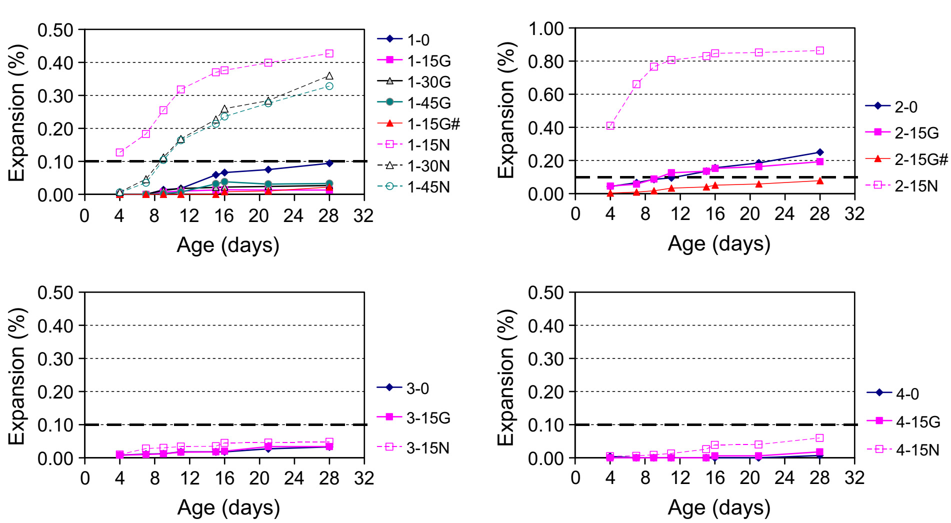

Fig. 6. Expansions in mortars of Series 1–4, prepared with different types of cements and contents of RHA.

presenting the bars big and numerous cracks. In Series 3 (CPP) and Series 4 (OPC3 + 30% pozzolan) the expansions were always below the limit.

After expansion tests, stereo-zoom and polarizing microscope observations were performed on slices obtained from the mortar bars. Typical signs of ASR in concrete, such as the presence of gels, did not appear even in very cracked specimens. A more dense and homogenous paste was observed in mortars without ash or with GRHA, when compared with those that had N*RHA. Fig. 7 shows the aspect of mortars 1–0, 1–15G and 1–15N.

Finally Table 5, gives the results of bending and compressive tests and Fig. 8 shows the stress–CMOD curves. In Series 1 a decrease in strength can be seen as the GRHA content increases, which can be attributed to a dilution effect, but no changes in the responses appear that would indicate the presence of internal damage. On the contrary, in mortars with N*RHA, the ascending branch of the curves became non-linear and the softening branch clearly showed the existence of microcracking inside the material. Differences between mortars with GRHA and NRHA can also be observed in Series 2. In Series 3 and 4, where no expansions appear, all mortars have similar load-CMOD responses.

As a synthesis Fig. 9 shows the variation of the mortar expansions and the flexural strength with the RHA content in Series 1. Fig. 10 shows the effect on expansion and strength of incorporating 15% of NRHA or GRHA for Series 1–4.

The accelerated mortar tests show that:

- The use of NRHA implies risks of expansion and mechanical degradation by reactions with alkalis with damage levels strongly varying in accordance with the cement used, as expected.
- Regarding the ash content, there seems to be a pessimum, probably associated to the presence of cristobalite.
- The use of pozzolans can minimize the risk of reaction when NRHA is incorporated.
- The damage process is strongly associated with the particle size of RHA.
- Clear effects on the mechanical properties were found that indicate the presence of internal damage.
- The typical signs of ASR observed when using reactive aggregates, were not found even in mortars that achieve significant expansions.

Based on these observations, it became interesting to evaluate the performance of concretes incorporating NRHA in field conditions.

3.3. Program 3: field performance of small slabs incorporating RHA

Results of Programs 1 and 2 indicate high reactivity in mortars and concretes incorporating NRHA in accelerated conditions. With the aim of evaluating the performance of NRHA in concrete located outdoors, two Series of small prototypes were performed. Non-reactive aggregates, siliceous natural sand and granitic crushed stone, were used.

Table 5
Program 2: properties of mortars.

Series	Mortar	Flexural strength (MPa)	Compressive strength (MPa)	Expansion at 16 days (%)	Expansion at 28 days (%)
1	1-0	6.6	46.5	0.066	0.094
	1-15G	6.8	46.3	0.014	0.013
	1-30G	4.7	31.9	0.022	0.027
	1-45G	4.1	28.7	0.038	0.033
	1-15N	3.9	29.4	0.376	0.427
	1-30N	2.4	13.1	0.260	0.360
	1-45N	1.3	9.4	0.236	0.328
	1-15G#	6.2	42.7	0.008	0.022
2	2-0	4.3	35.7	0.156	0.250
	2-15G	4.4	32.3	0.152	0.193
	2-15N	2.0	20.4	0.847	0.864
	2-15G#	Not measured	Not measured	0.051	0.078
3	3-0	4.2	29.4	0.018	0.033
	3-15G	4.6	28.5	0.020	0.034
	3-15N	4.4	28.1	0.045	0.048
4	4-0	5.7	41.5	−0.001	0.007
	4-15G	5.5	32.9	0.006	0.018
	4-15N	4.5	30.4	0.039	0.060

Series A included three $0.80 \times 0.60 \times 0.20$ m slabs prepared with a reference concrete (A1) and two concretes replacing 15% of cement in weight by GRHA (A2) and NRHA (A3). In all cases, following the general guidelines of ASTM C1293, NaOH was added to achieve 5.25 kg/m^3 of total alkalis (NaO_{eq}). Cement OPC1 was used, having a total cementitious content of 420 kg/m^3.

The slabs were located within the urban area of La Plata, Buenos Aires Province, Argentina. Meteorological characteristics are given in Table 6. From each concrete, 100×200 mm cylinders and $75 \times 75 \times 300$ mm prisms were cast. The cylinders were cured for 7 days in a moist room, and then placed by the slabs. The prisms were divided in two sets, one placed by the slabs and the other stored according to ASTM C1293 (38 °C in saturated conditions inside plastic bags). At the age of four months, three cores of 100 mm diameter were extracted from each slab.

The expansions of the prisms, the length variations on the slab surfaces and the mechanical properties of the cylinders were measured over the course of three years. In addition, compression tests on cores drilled from the slabs were made.

As concrete with NRHA showed an important degradation, a second group of prototypes (Series B), including three slabs of $0.50 \times 0.50 \times 0.10$ m, was later studied. In this case all concretes replaced 15% of cement in weight by NRHA, varying the cementitious material and the alkali contents. Cement OPC2 was used. The first concrete (B1) incorporated 5.25 kg/m^3 of total alkalis (NaO_{eq}) and 420 kg/m^3 of total cementitious material, the second

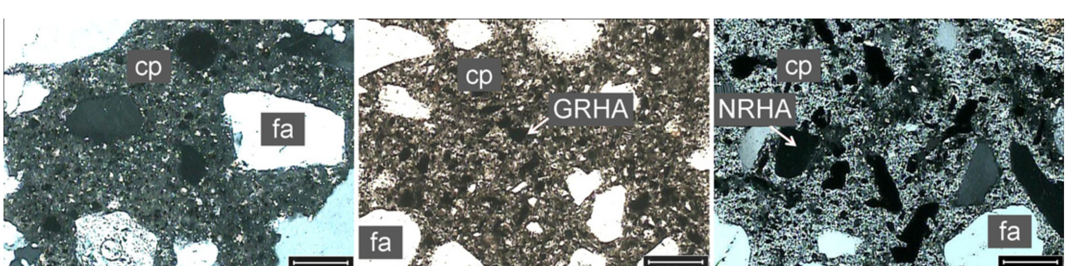

Fig. 7. Left: mortar without ashes, fine aggregates (fa) immersed in the cement paste (cp), bright points correspond to CH. Centre: mortar with GRHA, black particles of ash immersed in a homogeneous and dense structure. Right: mortar with NRHA, coarser particles of ash immersed in a more porous cement paste.

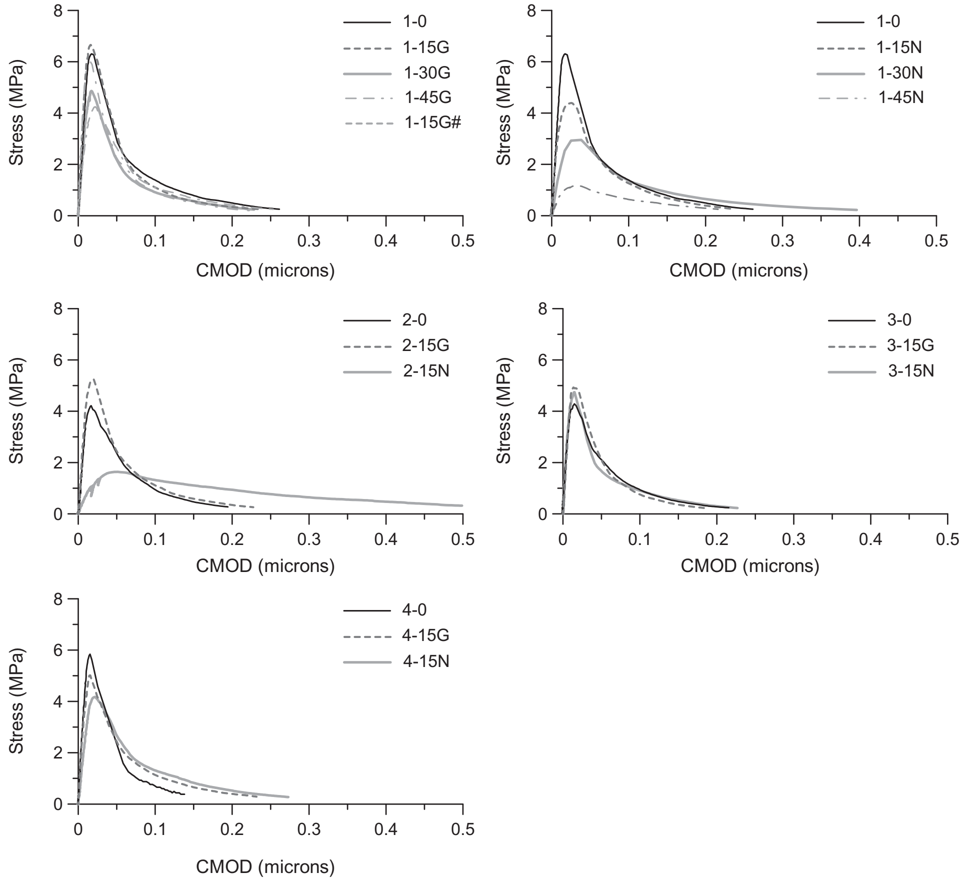

Fig. 8. Stress–CMOD curves in bending obtained from mortar bars after expansion tests.

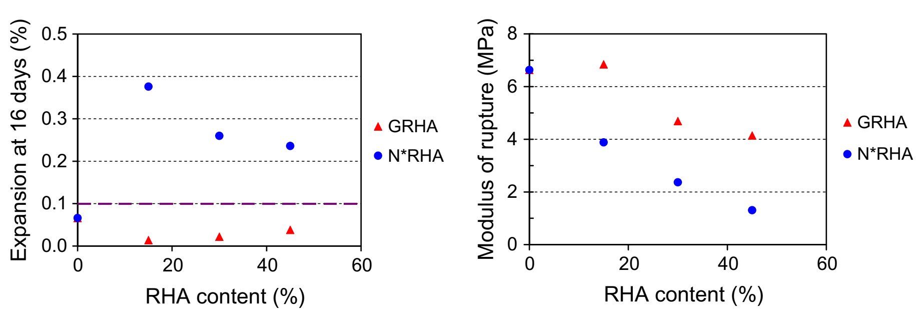

Fig. 9. Variation of the mortar expansions and the flexural strength with the RHA content in Series 1.

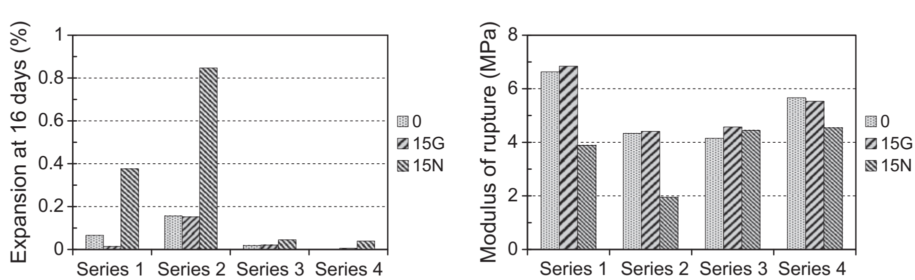

Fig. 10. Effect on expansion and strength of incorporating 15% of NRHA or GRHA in Series 1–4.

(B2) used the same binder content but without the addition of alkalis. The third (B3) was also prepared without addition of alkalis, but the total cementitious content was reduced to 330 kg/m^3 (280 kg/m^3 of OPC2 and 50 kg/m^3 of NRHA). With this last mixture proportion, compressive strengths of 30 MPa at 28 days were previously obtained [6].

The slabs were placed in the same conditions as Series A. Prisms and cylinders were cast and the same types of evaluations were

Table 6
Meteorological parameters of La Plata region. Annual means of the last ten years, with minimum and maximum means.

Parameter	Annual mean	Minimum	Maximum
Temperature (°C)	16.6	12.4	21.3
Relative humidity (%)	78.0	55.8	95.2
Rainfall (mm)	1065	–	–

Table 7
Program 3: characteristics of concretes.

Concrete	Series A			Series B		
	A1	A2	A3	B1	B2	B3
OPC1 (kg/m^3)	420	357	357			
OPC2 (kg/m^3)				357	357	280
NRHA (kg/m^3)			63	63	63	50
GRHA (kg/m^3)		63				
Na_2O_{eq} (kg/m^3)		5.25		5.25	2.86[a]	2.24[a]
w/c+RHA		0.44		0.44	0.44	0.56
Slump (mm)		180 ± 10			80 ± 5	
Slab dimensions	0.80 × 0.60 × 0.20 m			0.50 × 0.50 × 0.10 m		

[a] Supplied by the cement.

performed. The prisms were divided in two groups, one placed by the slabs and the other stored at 38 °C in saturated conditions inside plastic bags (according to ASTM C1293). The cylinders were cured two days in a moist room and then placed by the slabs. In addition a group of cylinders was cured at 38 °C in saturated conditions. Test results up to 1 year are presented in this paper. Table 7 summarizes the main characteristics of Series A and B.

Fig. 11 shows the appearance of the slabs and the specimens of Series A after four months. Significant cracking, both in the cylinders and the slab of A3, can clearly be seen when NRHA was incorporated. The cracks in the slab were larger and more numerous than those observed in the cylinders.

The stress–strain behavior under uniaxial compression was evaluated on standard cylinders and also on cores drilled from the slabs. Loading–unloading cycles up to 40% of the maximum stress were applied to determine the modulus of elasticity, after which the load was increased monotonically up to failure. A controlled closed loop system was used with the axial deformation as control signal. In this way it was possible to obtain the softening branch of the stress–strain curves to improve the analysis of the internal damage and its effects on the mechanical behavior.

Table 8 presents the compressive strength and the modulus of elasticity of Series A. The standard specimens were tested at the ages of 1, 4 and 36 months and the cores at 4 months. The ratios between the core/standard cylinder results are also indicated. Fig. 12 compares the stress–strain curves in compression of concretes A1, A2 and A3 at 4 months.

In concretes A1 and A2 the compressive strength continuously increases, achieving values higher than 56 MPa at 36 months. On the contrary, concrete A3 shows a decrease in strength between 1 and 4 months and then it gains strength until 3 years achieving only 36 MPa. Regarding the modulus of elasticity, there is an important decrease in stiffness in A3; when comparing A3 with

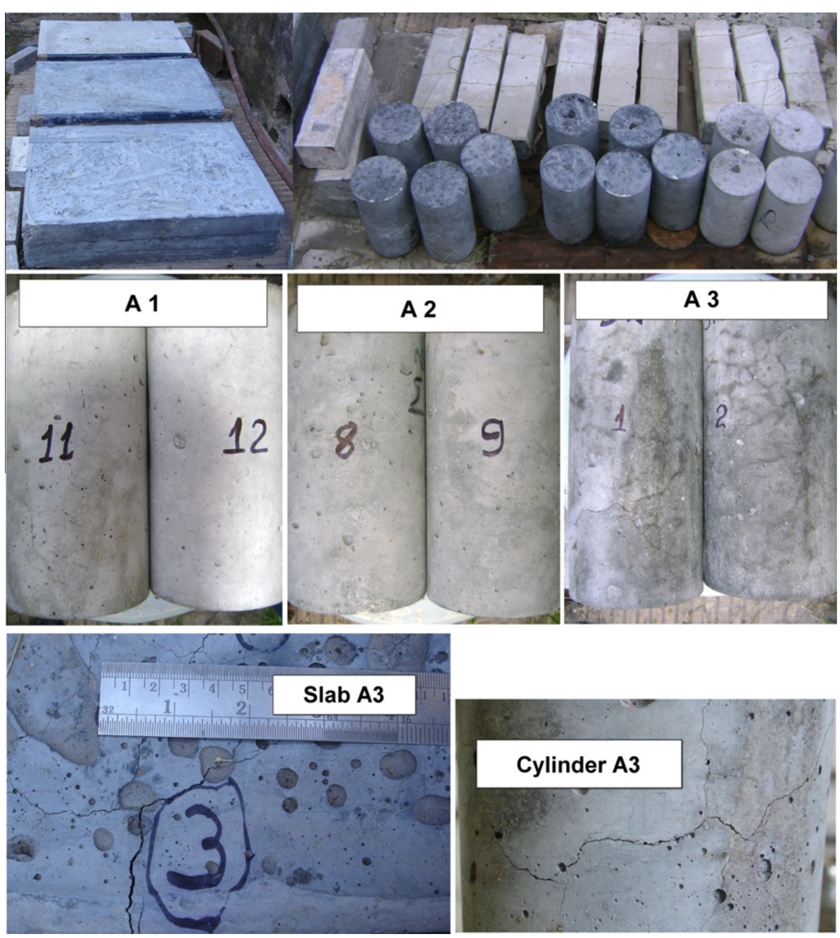

Fig. 11. Concretes A1, A2, and A3. View of the slabs, prisms and cylinders after 4 months.

Table 8
Program 3: mechanical properties of concretes of Series A.

	Compressive strength (MPa)					Relative values (%)			
	Standard specimens			Cores	Cores/specimens	Standard specimens			Cores
Months	1	4	36	4		1	4	36	4
A1	31.6	34.5	56.1	42.2	1.22	100			
A2	31.0	36.6	56.3	42.3	1.16	98	106	100	100
A3	32.7	22.7	36.2	26.0	1.15	104	66	64	62
Modulus of elasticity (GPa)						Relative values (%)			
A1	32.2	32.6	35.4	38.5	1.18	100			
A2	30.8	33.5	32.0	31.7	0.95	96	102	90	82
A3	26.6	8.7	10.6	8.3	0.95	82	27	30	22

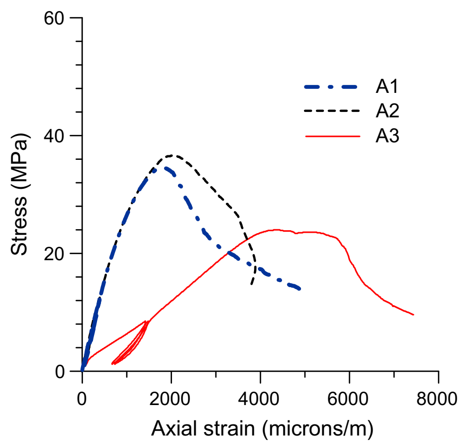

Fig. 12. Stress–strain curves in compression of concretes A1, A2 and A3 at 4 months.

A1 it can be seen that the reductions in stiffness (>70%) are quite greater than those in strength (near 35%). The results obtained in cores and in standard specimens show a small increment in the slab's strength that can be attributed to a better availability of water for hydration. The decrease in strength and modulus of elasticity in A3 is clearly justified by the extensive cracking. The effects of the internal damage, produced by the reaction of NRHA in the presence of alkalis, are evident in the shape of the stress–strain curves. There is an important residual strain after the first cycle of loading and the strain corresponding to the peak load increases from usual values near 2000 microstrains to values higher than 5000 microstrains.

The process of damage is reflected in the values of expansion measured on the slabs surfaces and on the different groups of prisms, as shown in Fig. 13. There are drastic increases in the expansion of concrete A3, while in A1 and A2 the linear variations are always below the limit of 0.04%. In A3 a more extended induction period was observed in the slabs and in the prisms kept close to the slabs.

Fig. 14 shows the aspect of the specimens of Series B after 10 months and Fig. 15 presents the expansions measured on prisms and on the slab surfaces. The mixture proportions of concrete B1 are similar to A3, varying the cement used (OPC2 instead OPC1, respectively). Again, drastic expansions take place in B1 prepared with 420 kg/m^3 of total cementitious content and 5.25 kg/m^3 of Na_2O_{eq}, with the induction period being strongly reduced in the prisms exposed at 38 °C in saturated conditions (ASTM C 1293). In the prisms and the slabs placed outdoors, the expansions increased up to values higher than 0.2%; with extensive cracking also appearing. The situation differs in B2 and B3 where the alkali contents

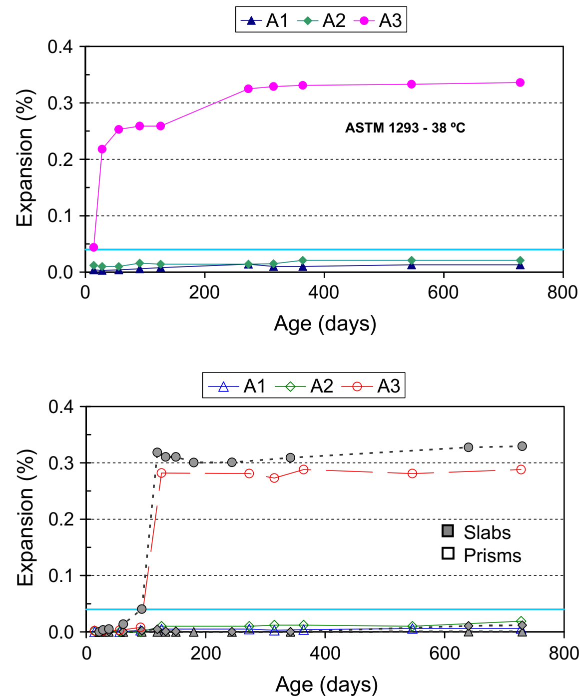

Fig. 13. Expansions measured on slabs surfaces and on the different group of prisms of Series A.

correspond to those introduced by the cement. The linear length variations were below the limit and, as expected, were smaller in B3, which has the lowest total cementitious content. Although the expansions were lower than 0.04%, a few small cracks were seen in the slab cast with B2 at the age of 1 year.

Fig. 16 shows the stress–strain curves in compression obtained on standard cylinders of Series B at the age of 1 year. Table 9 presents the values of compressive strength and elastic modulus of specimens kept by the slabs at 1, 3 and 12 months. The same values measured, at the age of 3 months, in cylinders stored at 38 °C and the relationship between them and the cylinders placed outdoors are also indicated. Both concretes B2 and B3 show evolutions in strength from 1 to 12 months with differences in accordance with the water/binder ratios used. It is verified that B1 repeats the behavior of A3 and it has mechanical properties lower than B2 even at 1 month. The strength and especially the stiffness of B1 decrease at 3 months indicating the development of internal damage. At this moment its mechanical properties were lower than those of B3. At later ages there is an increase in strength, reflecting the formation of hydration products as in Series A.

Regarding the cylinders stored at 38 °C, their compressive strength is always lower than that of the cylinders stored by the slabs. Concrete B1 had the greatest loss of strength due to the development of the reaction. Considering the modulus of elasticity, no variations were found in B2 and B3, while a decrease of nearly 50% was found in B1.

Finally the effects of the reaction in B1 are again reflected in the shape of the stress–strain curves. Great strains at the maximum load, residual deformations after unloading and a more gradual descending branch in the curves were found.

Summarizing:

- The use of NRHA gives rise to a process of damage (generalized cracking) with significant decrease in strength and stiffness when there is high alkali availability (Na_2O_e: 5.25 kg/m^3) and the temperature and humidity conditions are proper for the development of ASR.

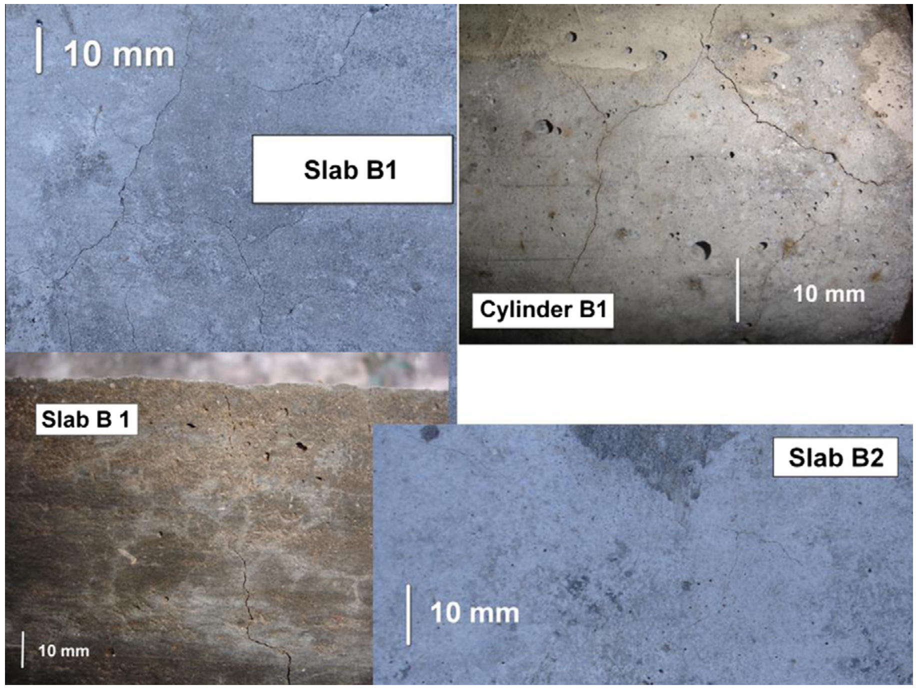

Fig. 14. Slabs and specimens of Series B after 12 months.

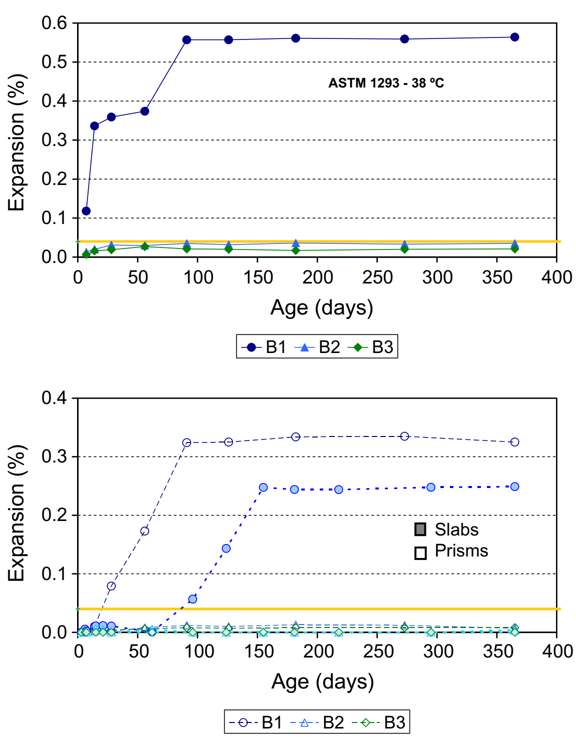

Fig. 15. Expansions measured on slabs surfaces and on the different group of prisms of Series B.

- For the same conditions, this does not happen in the mixes with GRHA, where the mechanical properties even improved.
- With NRHA and for the alkali contents provided by the cement (Na_2O_e: 2.86 and 2.24 kg/m^3) no expansions or degradation were observed after 12 months. Only few and small cracks were observed on the slabs with the highest content of cement. However, no effects on the strength and only some minor effects on the stiffness were found.

4. Conclusions

Natural Rice-Husk Ash (NRHA) can be used in concrete when the ash particle size is reduced by adapting the mixing process; however, the presence of a significant amount of vitreous material and cristobalite makes it necessary to study the development of damaging processes that occur in the presence of alkalis. The performed study shows that:

- The incorporation of RHA in concrete implies risks of expansions and mechanical degradation by reactions with alkalis, with the damage process strongly associated with the particle size of RHA.
- Accelerated tests (ASTM C 1260) in mortars show that NRHA increases expansion, while previously ground ash (GRHA) can lead to inhibition or exacerbation of the alkali–silica reaction (ASR), depending on the percentage used.
- The damage levels strongly depend on the cement used, so when using NRHA the cement must be carefully selected, since some of them can enhance the risk of ASR. The presence of pozzolans can minimize the risk of reaction when NRHA is incorporated.
- Concretes incorporating GRHA showed expansions (ASTM C 1293) below the limit of 0.040%, while drastic expansions were found in concretes with NRHA. Although the use of NRHA leads to a residual mechanical behavior characteristic of damaged concretes, no typical signs of ASR as the presence of gels were found.
- In field conditions, when external alkalis were added, the performance of concretes incorporating NRHA was in accordance with the behaviour expected from mortar and concrete prisms results. When alkalis were supplied only by the cement, prisms tests and field measurements indicated admitted grades of

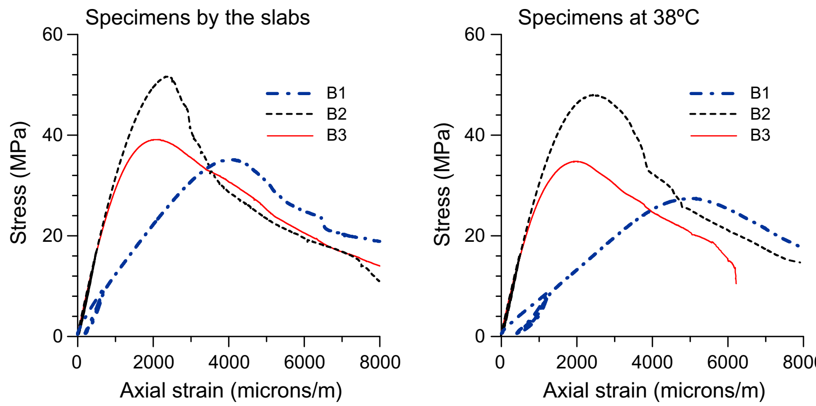

Fig. 16. Stress–strain curves in compression obtained on standard cylinders of Series B at the age of 12 months.

Table 9
Program 3: mechanical properties of concretes of Series B.

Compressive strength (MPa)						Relative values (%)			
	Outdoors by the slabs			38 °C	38 °C/ Outdoors	Outdoors by the slabs			38 °C
Months	1	3	12	3		1	3	12	3
B1	26.4	19.7	35.1	26.7	0.76	89	53	68	56
B2	29.5	36.9	51.5	47.5	0.92	100			
B3	21.2	23.1	39.5	35.4	0.90	72	62	77	74
Modulus of elasticity (GPa)						Relative values (%)			
B1	23.2	9.8	13.2	7.4	0.56	86	27	40	22
B2	26.9	36.1	32.7	33.6	1.03	100			
B3	26.4	34.2	31.7	31.0	0.98	98	95	97	92

expansions, nevertheless a few small fissures were observed on the slab with higher content of cement (Na_2O_{eq} equal to 2.86 kg/m^3).

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