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FIRE SPALLING SENSITIVITY OF CONCRETE MADE WITH RECYCLED CONCRETE AGGREGATES (RCA)

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Abstract.
The fire spalling of concrete is a complex phenomenon, which can affect the integrity of the structures during a fire. This thermal instability is associated with a complex coupled chemo-thermo-hydro-mechanical mechanism and it can be influenced by many factors, related to material (e.g. permeability, porosity and water content), geometry (e.g. shape and size) and environmental parameters (e.g. mechanical load and heating rate). Concrete made with recycled concrete aggregates presents higher porosity, higher water content and different interfaces between aggregates and mortar. All these aspects can lead to a different behaviour under fire exposure, including the spalling risk of these sustainable concretes. The main objective of this paper is to analyse the influence of the use of recycled concrete aggregates on the spalling risk of concrete. In this paper, concrete prisms with different replacement rates of recycled coarse aggregates (0 up to 100%) were exposed to a standard fire curve (ISO 834-1) with a constant uniaxial compression load. After heating, samples surfaces were evaluated by means of digital photogrammetry. Results showed that concrete with RCA is sensitive to explosive spalling. All replacement rates presented higher degree of spalling than concrete made with natural aggregates.

Keywords: Fire, recycled concrete aggregate, spalling.

1. Introduction

In the last decades, the use of recycled concrete aggregates (RCA) has gained popularity due to their potential to make sustainable concrete. As for conventional concretes, the fire behaviour of these concretes, including their spalling sensibility, must be well known to guaranty the safety of the structure in case of a fire. Moreover, fire behaviour is fundamental to enhance the resilience of the buildings for these types of extreme events.

Fire spalling is the detachment of concrete fragments from structures exposed to fire. This phenomenon may affect the integrity of structures, reducing thermal insulation, exposing the steel rebar to fire and reducing the load-bearing capacity [1, 2]. Despite the numerous experimental and numerical studies, there is still a lot of uncertainties about the physical origin of the phenomenon [2]. In general, spalling is associated with a coupled thermo-hygro-chemo-mechanical mechanism.

In general, spalling occurs in different forms, such as aggregate spalling, surface spalling, explosive spalling and corner spalling [3]. Previous studies show that many parameters can influence the occurrence of spalling, and it can be divided into material (e.g. permeability, porosity and water content), geometry (e.g. shape and size) and environmental parameters (e.g. heating rate and mechanical load) [3, 4].

The susceptibility to spalling of concrete made with recycled aggregates (RCA) is barely known. Since RCA aggregates are more porous, the use of this kind of aggregates can contribute to vapour migration, reducing spalling risk [5]. At the same time, these concretes present higher water content and different phase interfaces, which also may affect the spalling risk.

Previous works verified occurrence of this phenomenon. Robert et al. [6] observed superficial and localized spalling in full-scale slabs made with RCA. Authors attributed this behaviour to the high water content of the mix. Pliya et al. [5] observed spalling on some cylinder samples exposed to a rapid heating rate. It is noteworthy that in this case, samples are classified as high strength concrete, which is more prone to spalling due to its denser microstructure.

The aim of this study is then to evaluate the influence of recycled concrete aggregates (RCA) on the spalling behaviour. To this, uniaxial spalling tests were carried out on of ordinary concrete samples containing different RCA (coarse aggregates) replacement rates (0%, 10%, 20%, 40%, 70% and 100%). During fire, spalling events are followed and after fire, the residual sample geometry was evaluated by digital photogrammetry, in terms of volume and spalling depth.

2. Experimental program

2.1. Concrete mixes

Cement CEM II/A-L 42.5 R CE was used. To achieve workability, limestone filler Betocarb HP-SC and SIKA ViscoCrete Tempo-483 superplasticizer were also used in the mixes. Sand used in this study had a fineness modulus of 3.10, density of 2650 kg/m^3 and water absorption of 0.35 %.

Two types of coarse aggregates were used: natural aggregates (NA) and recycled concrete aggregates (RCA). For each type of aggregates, two fractions were used, 4/10 and 10/20. Natural aggregates were made from diorite and have a density of 2820 kg/m^3 (4/10) and 2840 kg/m^3 (10/20), and a water absorption of 0.92 % (4/10) and 0.81 % (10/20). Recycled concrete aggregates were crushed and screened by a recycling company, and have a density of 2570 kg/m^3 (4/10) and 2590 kg/m^3 (10/20), and a water absorption of 5.60 % (4/10) and 4.52 % (10/20). As expected, RCA present higher water absorption values, mainly due to the presence of adhered "old" mortar. RCA aggregates also present some impurities, such as wood, plastic, brick and bituminous materials.

Six different ordinary concrete mixes were prepared and mix proportions are given in Table 1. For concretes made with RCA, NA were directly replaced by RCA in volume, without any changes in the other components. Samples were designed to meet NF EN 206/CN:2014 [7] durability requirements for XD3 exposure class.

To compensate the higher water absorption of RCA and aiming a practical method that can be reproduced in a real concrete plant, all aggregates (sand, NA and RCA) were pre-wetted for one hour using a soaker hose and then covered with plastic sheet for three hours. All mixes have the same water/cement ratio (0.5) and dosage of superplasticizer (0.9 % C). To avoid errors when determining water content in aggregates, the amount of water in the batch is adjusted to obtain approximatively the same slump (180 – 190 mm).

Slump, mechanical and physical properties for all studied mixes are reported in Table 1. For each mix, mechanical properties at 28 days and at fire test age were measured on 11 × 22 cm and 16 × 32 cm cylindrical specimens. For spalling tests, 20 × 20 × 10 cm (height x length x thickness) prisms were casted. Cylindrical samples used to determine 28 days properties were kept submerged in water at 20 řC until test day. Samples for fire tests were first kept submerged for seven days and then placed into sealed plastic bags until fire test age (between 88 and 125 days). This curing induces high water content, thus inducing high probability of spalling for all the mixes. At test age, water content (w_c), was also measured. As expected, higher the replacement rate, higher the water content in the samples, due to higher porosity of RCA. From NA to RCA-100, a variation of 2.11% is observed. The influence of the water content on the different spalling behaviour between concretes made with NA or RCA are discussed in Section 3.

2.2. Spalling Evaluation

Spalling was evaluated by testing concrete prisms subjected to a standard fire (ISO 834-1) and uniaxial loading. Three samples per concrete mix were tested (with exception of RCA-10). Before the tests, the sides of the prisms were sealed with aluminium foil tape (Figure 1a), which was glued using high temperature glue. This was done to avoid moisture loss through the sides of the concrete blocks and provide unidirectional transport condition of heat and moisture.

An intermediate scale furnace, powered by one propane gas burner, was used for the heating process (Figure 1b). Gas flow was controlled during the test in order to follow the ISO 834-1 fire curve. The furnace has an opening of 20 cm x 20 cm and three type K thermocouples were used to measure the heating curve. These thermocouples were placed in the front of the furnace and one centimetre from the heated face of the sample, at three different heights: 4, 10 and 16 cm from the bottom of the furnace opening. More detail can be found in previous works [8, 9].

A hydraulic press was used to apply a uniaxial loading of 5 MPa, in order to be representative of a conventional structure (wall or column for example). The tested specimen was placed between two concrete blocks. The sides of the tested specimen and the support blocks were insulated with rock wool. Figures 1c and 1d presents the full test setup. First, the load was applied and after stabilization, the heating process started. The ISO 834-1 fire curve was applied for 30 minutes and the three thermocouples allowed to follow the temperature of air close to the sample. During tests, each spalling event has been registered, in terms of occurrence time and intensity (small, medium and big noise). After 30 minutes, heating was turned off and after 5 minutes, the sample was discharged.

After heating, post-fire analysis was conducted on all samples with a digital photogrammetry technique. This method allows to construct 3D models from digital photos [10, 11]. The method follows an approach that involves image acquisition and processing, 3D reconstruction, mesh generation and post processing [10].

A digital camera (Panasonic DMC-GX80) was used. Samples were placed in a rotating table, in order to successfully orientate 3D reconstruction. Camera was fixed on a tripod and between each shot, the rotating table was turned around 10ř. A total of 36 images were obtained for each sample. The image processing and 3D reconstruction were done with the Meshroom [12] software and later imported

Material / Property	NA	RCA-10	RCA-20	RCA-40	RCA-70	RCA-100
	Mix					
Cement/Filler/Sand (kg/m^3)	350 / 60 / 804.3					
NA 4/10 (kg/m^3)	331.7	298.5	265.3	199	99.5	-
NA 10/20 (kg/m^3)	711.1	640	568.9	426.7	213.33	-
RCA 4/10 (kg/m^3)	-	30.2	60.5	120.9	211.58	302.3
RCA 10/20 (kg/m^3)	-	64.9	129.7	259.4	453.96	648.5
Water (kg/m^3)	175					
Slump (mm)	194	184	174	176	158	210
f_{c28} (MPa)	44.8 (±0.2)	39.7 (±0.1)	37.4 (±3.5)	39.7 (±3.0)	34.5 (±2.7)	34.6 (±1.1)
j (days)	94	116	88	88	88	125
$f_{c,j}$ (MPa)	46.6 (±1.4)	44.5 (±4.6)	50.8 (±0.5)	49.6 (±0.4)	45.9 (±0.3)	39.1 (±0.3)
$E_{c,j}$ (GPa)	34.5	36.8	34.9	39	30.1	30.5
w_{cj} (%)	4.94 (±0.4)	5.02 (±0.5)	5.10 (±0.2)	5.36 (±0.4)	6.41 (±0.5)	7.05 (±0.3)

TABLE 1. Mix design and properties.

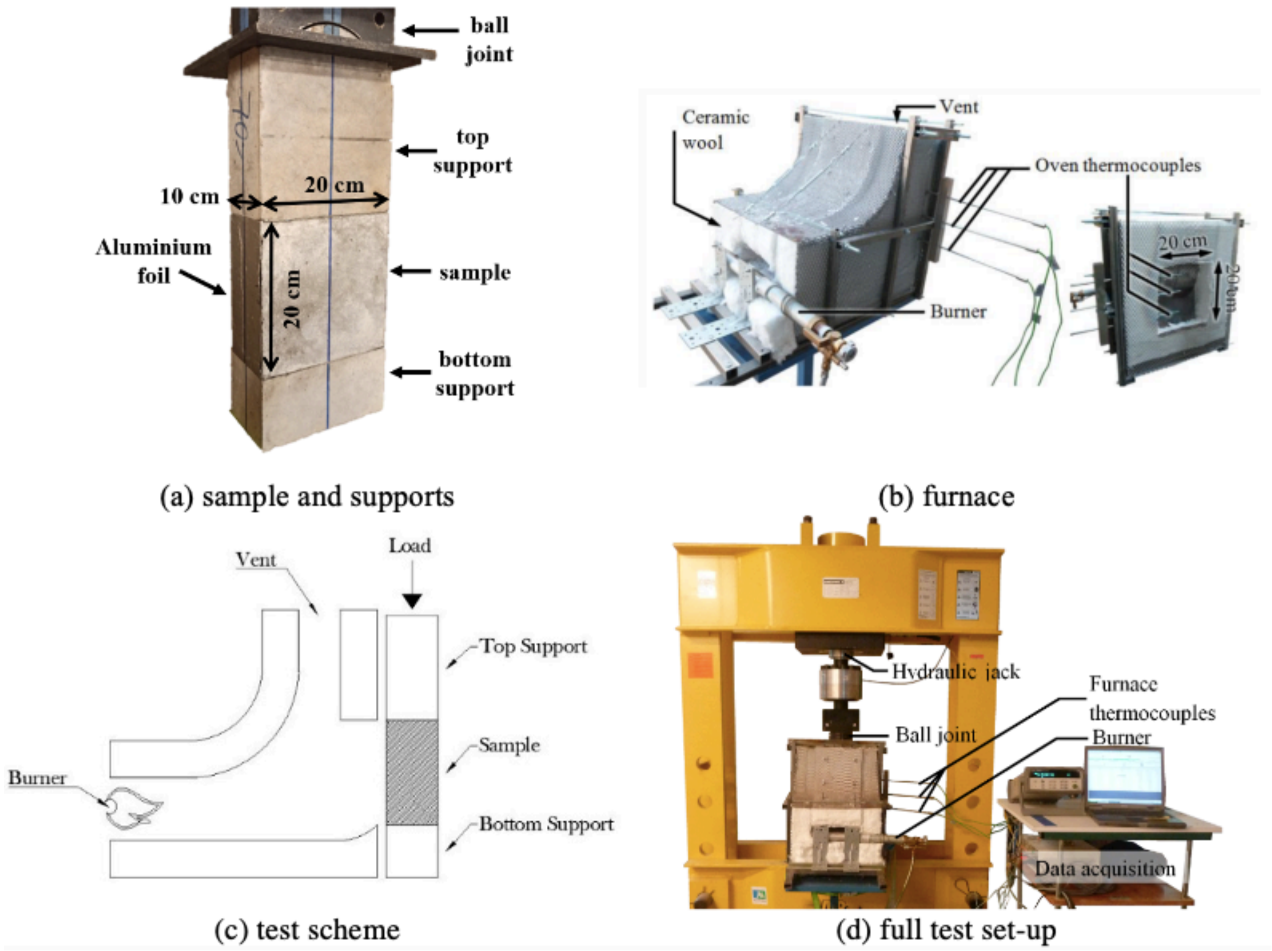

FIGURE 1. Furnace details and test set-up.

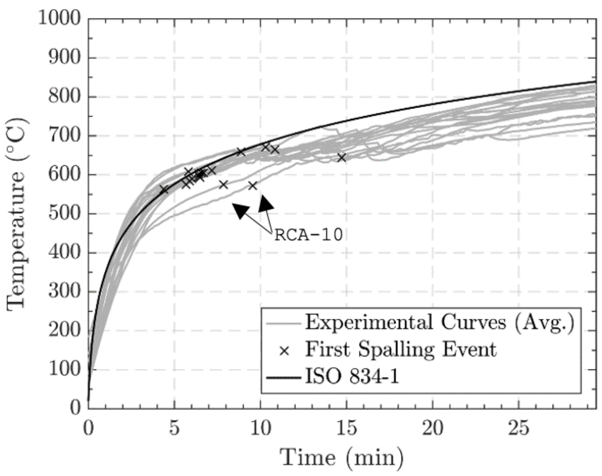

Figure 2. Developed fire curves.

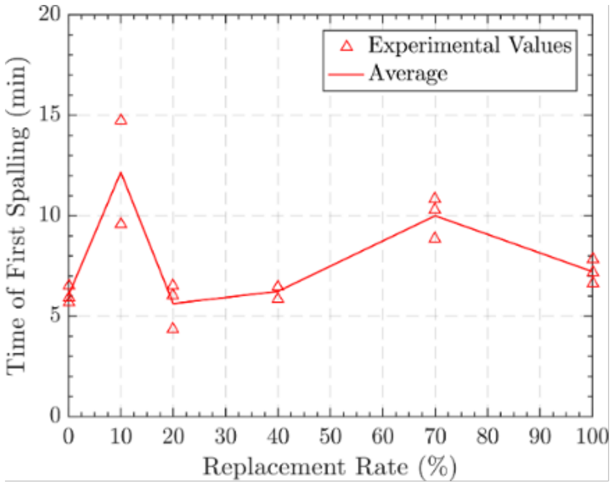

Figure 3. First spalling event.

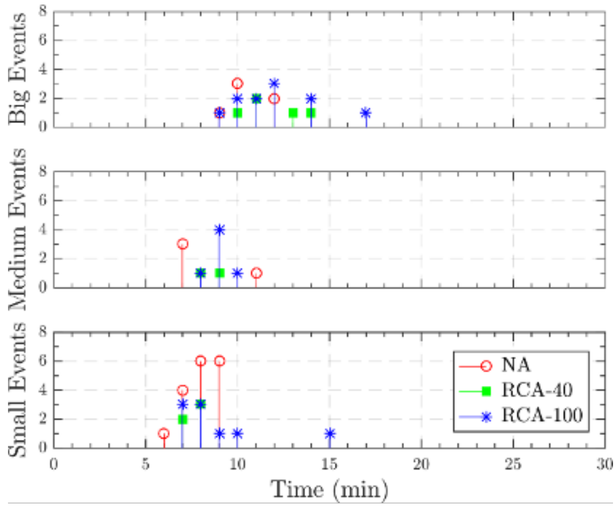

Figure 4. Spalling events.

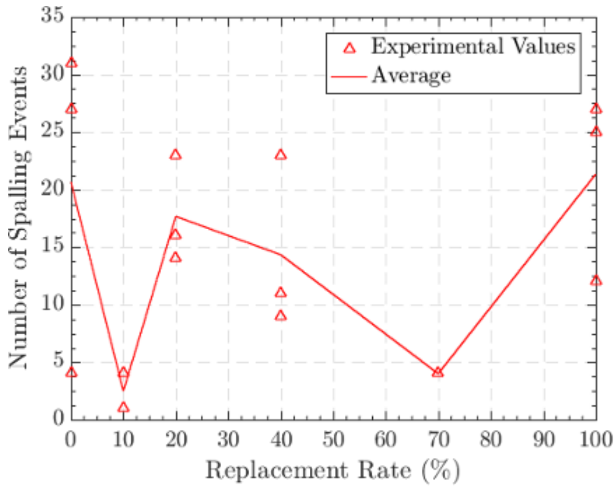

Figure 5. Total number of spalling events.

in CloudCompare [13], where the model was cleaned and scaled. After this processing, a binary mesh was generated and used in a Cast3m [14] algorithm, which post-processed the model to obtain the spalling volume and depths. The error from the methodology applied here is 4.2% (previously determined).

3. Results

3.1. Fire Curves and spalling events

Fire curves developed during fire tests are presented in Figure 2. In grey, the average of the three thermocouples is presented, together with the first registered spalling event. In general, curves follow properly the ISO 834-1 fire curve and the perturbations start after the first spalling event. The oven temperature at the time of the first spalling is usually around 550 °C to 650 °C.

The time of first spalling is also presented in Figure 3, which presents the time of this event in relation to the replacement rate. Except for RCA-10 (indicated in Figure 2), all samples first spalled between 5 and 10 minutes. The perturbations with RCA-10 are related to the fact that the curve in this tests lasted more to reach the temperature that may trigger the spalling.

Besides the first event, each spalling was recorded and categorized in three different qualitative "sound intensity": small, medium and big spalling. In order to have a visualization of these different events along time, Figure 4 is proposed. In this figure, results from three representative samples were plotted. In general, all samples started with small spalling events (pop-up, bottom of the Figure 4), then sound intensity increases with the fire duration. The last events usually had big intensity and happened around 10 – 15 minutes.

Figure 5 presents the total amount of spalling events for each of the tests in relation to the replacement rate. From the Figure 5, we can see it a lot of discrepancies in the spalling events and no direct link with the quantity of recycled aggregates can be observed.

3.2. Inspection after fire spalling test

Different analyses were done after the fire spalling tests. First, a visual inspection was done. Examples

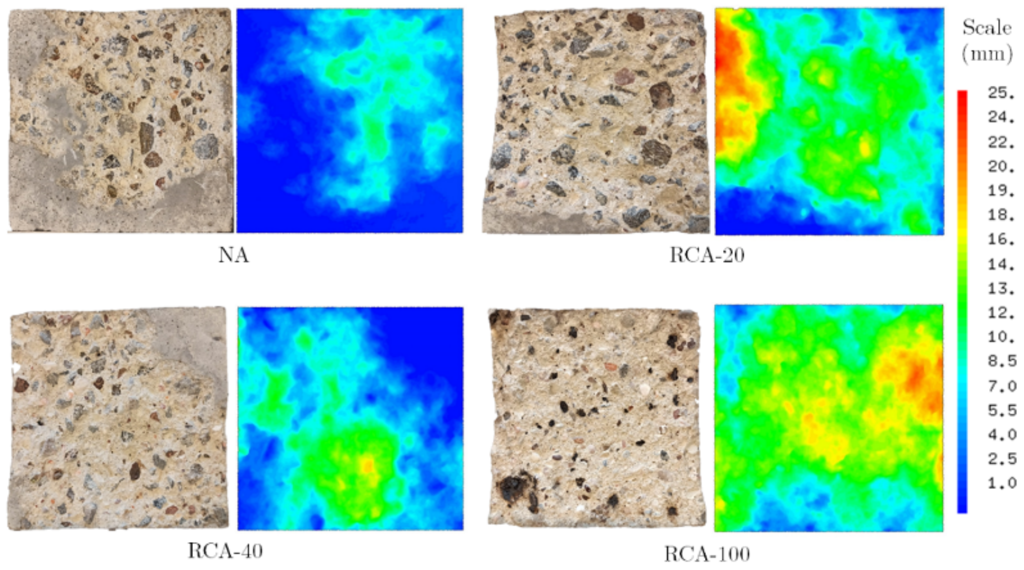

FIGURE 6. Samples after fire: photos and depth colour map.

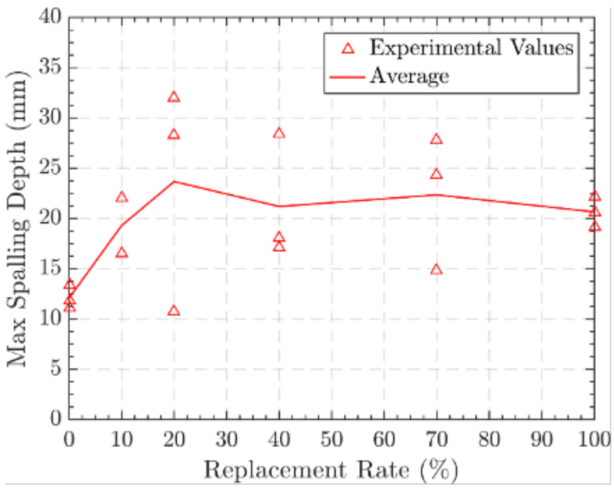

FIGURE 7. Max spalling depth.

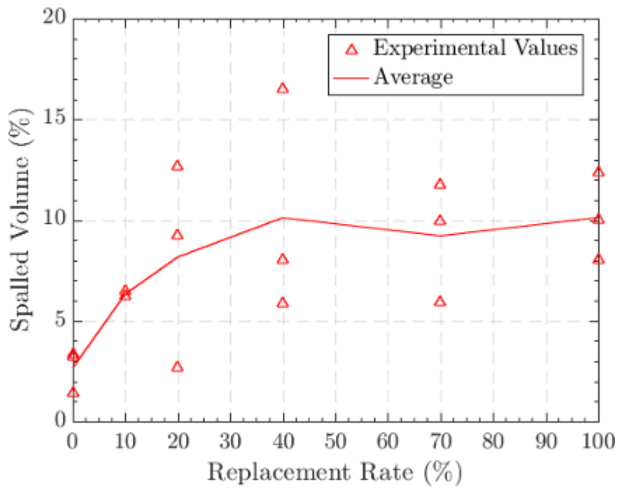

FIGURE 8. Spalled volume.

of samples exposed surface are presented in Figure 6. Visually it is already possible to observe an influence of the type of aggregates on the spalling severity: NA samples present less spalling than mixes made with RCA. The impurities in tested samples are also observed. Especially in RCA 100, the presence of bituminous particles is clearly seen, that burned and melted during the fire test. Its noteworthy that the presence of this impurities reduces the strength of concrete made with RCA at high temperatures, as observed in Laneyrie et al. [15].

Figure 6 also presents the colour maps generated in the photogrammetry process. Max spalling depth and spalled volume were measured with photogrammetry for all the replacement rates (Figures 7 and 8). The first aspect is that concrete made with NA presents lower values of spalling depth and volume than any RCA replacement rate. These graphs confirms some of the tendencies observed in the visual inspection, i.e. concrete made with NA presents lower values of spalling volume and depths.

Another observation is that the evolution of spalling volume and depth with the replacement rate is quite similar. In the first branch, from NA to concrete made with 20% of RCA, an almost linear increase is observed. In the case of the spalled volume, this increase also appears from RCA-20 to RCA-40, but the slope of increase is lower. From 40% to 100%, the average values keep quite constant, with no major changes, independently of the quantity of RCA. A higher variability of results is also noteworthy for concretes made with RCA.

First, the use of RCA results in a higher water content, as seen in Table 1. Usually, higher the water content (or the moisture content), higher is the spalling degree [16]. It seems then logical that the RCA-100, which had the higher water content at the test age (7.05 %), experimented the more severe spalling (volume and depth). However, the influence of water content for the other mixes is not that clear. Indeed, when comparing NA and RCA-20, the increase of spalling volume (5.51 %) is much higher than the increase in water content (0.16 %). Moreover, it can be seen that spalling volume and depth are quite constant from RCA-40 to RCA-100, whereas the water content increases significantly (1.5 %). These factors indicate that the water content may influence the spalling of concrete made with RCA, but is not the only parameter affecting the spalling sensibility.

Another influencing parameter for spalling is the compressive strength. Usually, the higher the strength, the higher will be the spalling probability [16, 17], due to the lower permeability [16] of the mix. This is especially verified with HPC, where the spalling is a real concern [18]. Yet, the influence of compressive strength on spalling is not clearly observed in our study. Indeed, the mix with the lower compressive strength at test age (RCA-100, 39.1 MPa) presents the higher spalled volume. This shows that, in this experimental campaign, the strength was not the main factor affecting spalling sensitivity of concrete made with RCA.

Lastly, internal thermal cracking also may have a contribution to the spalling events. Usually, cracks increase the matrix permeability, allowing pressure release and moisture transport, and then a reduction of the spalling risk [1, 19]. These cracks are mainly due to thermal mismatch between aggregates (that expand) and cement matrix (that shrinks after 100 °C).

The cracking of concrete made with RCA under fire exposure is still not clear. On one hand, increasing the replacement rate of RCA involves, for a fixed volume of new paste, a higher proportion of old mortar / new paste interfaces, and consequently a lower proportion of new paste / aggregates interfaces. This can probably reduce the density of thermal cracking in concretes made with RCA, and then potentially increase the spalling sensibility. On the other hand, the use of RCA also may lead to an excess of water (regarding only the one necessary for cement hydration), especially surrounding the aggregates themselves [5]. This extra water may reduce the bond with the new paste, inducing cracks and a local increase of the permeability [5]. This point will be further analysed by means of microscopic observations of heated samples, permeability measurement and thermal expansion measurements.

4. Conclusions

This paper presented an experimental investigation into the spalling sensitivity of concrete made with RCA. Based on the test results, the following conclusions are drawn:

- Visual inspection showed that concrete made with RCA presents a spalling more significant than concrete made with NA.
- The time of the first spalling event can be a good indicator of the spalling occurrence. Usually, this time is associated with the temperature reached in the material. In this study, no clear influence of the RCA on the time of first spalling was observed, with a high variability of results.
- The evolution of the spalling depth and spalling volume with the RCA replacement rate both present a peculiar behaviour. First, an increase is observed (from NA to RCA-20), then values keep almost constant up to RCA-100. Both indicators showed that concretes made with RCA presents a higher spalling sensibility.
- Different factors may influence the risk of spalling of concrete made with RCA: water content, strength and thermal cracking. In this experimental campaign, compressive strength does not affect the spalling behaviour of concrete with RCA, since concrete mixes with relatively low strength presented a high spalling sensibility. Water content seems to affect the spalling sensibility, since mixes with high water content presented the higher spalling depth and volume. However this is not the main factor, since samples made with RCA and without RCA, and with similar water content, presented big variations of spalling depth and volume. Thermal cracking should be further investigated, along with permeability measurements, microscopic observations and thermal expansion.
- Lastly, it is important to note that all these experimental conclusions are drawn based on a specific thermal and mechanical state, and for a given geometry of samples. To be more representative of real structures, full-scale fire tests on structural concrete elements made with RCA are planned, in order to analyze (i) the spalling sensibility of these concretes in a real situation and (ii) the influence of this spalling extent on the fire resistance of the structure.

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