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# Effect of elevated temperatures on concrete made with recycled concrete aggregates - an overview

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## Abstract

In the last decades, the use of recycled concrete aggregates (RCA) has proven to be a good solution for making sustainable concrete. Concretes made with RCA show reasonable performance at ambient temperature and has already been used in different real applications. The broader application of concrete with RCA, however, depends on a better understanding of its fire behaviour, a critical factor for building structures. Within this framework, this paper presents a review of previous works on the behaviour of concrete made with RCA at high temperatures. Experimental works on the mechanical and thermal properties are compiled and discussed, to identify the temperature dependency of these properties and the influence of different materials and test parameters. Studies dealing with spalling and the fire behaviour of medium and full-scale concrete elements are also presented. Lastly, the microstructure alterations of heated concrete made with RCA are addressed. The results under review show that the properties of concrete with RCA are affected by the increase of temperature. The influence of the RCA, however, is not well defined. The different theories behind the high temperature behaviour of concrete with RCA are discussed and presented. Lastly, comments are made on the current knowledge gaps and future research needs.

*Keywords:* Recycled concrete aggregates, Fire, High temperature, Mechanical properties, Spalling

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## 1. Introduction

Since the last century, the construction industry is facing a huge problem concerning the depletion of natural resources concomitantly to the massive production of construction and demolition wastes (C&DW). Concrete is the most used construction material in the world [1] and for this reason, it plays an important role in the environmental impact of the construction industry. It is estimated that the construction industry depletes 40 % of raw materials (stone, gravel and sand), 40 % of total energy and 16 % of water [2]. In terms of waste, C&DW represent almost 35 % of all waste in Europe [3] and concrete corresponds to one-third of this value [4]. The most common method of disposal of these materials is still landfilling, which is avoided by public policies in Europe [5, 6].

Aiming to reach sustainable development, it is essential that the construction sector, especially the concrete industry, reduces its environmental impact. One of the possible approaches is the recycling and reusing of C&DW wastes in new construction. During the last decades, the usage of recycled concrete aggregates (RCA) as a replacement for natural aggregates (NA) for producing concrete has shown a great potential to promote ecological efficiency. This solution can reduce the amount of waste produced and sent to landfills, help to solve the depletion of the natural resources, and reduce the impact of production and transportation of aggregates [7, 8].

Employing RCA to produce Recycled Aggregates Concrete (RAC) has gained popularity in research recently. A significant amount of this research focuses on understanding how recycled aggregates influence the mechanical and durability performances of concrete. The main difference between RCA to natural aggregates is that RCA is composed of two different materials: natural aggregate and attached (or adhered) mortar (AM). The concrete made with RCA is a compound of natural aggregate (NA), old natural aggregate, new cement paste and old cement paste. Consequently, three interfacial transition zones (ITZ) are observed: between old aggregate and old cement paste, between new mortar paste and the RCA, and between NA and new cement paste [9].

Recycled aggregates are generally more heterogeneous, porous and less dense than NA. Consequently, RCA presents higher water absorption and lower strength [10, 11]. Hence, these recycled concrete aggregates impact fresh and hardened properties [8]. However, the problems mentioned above have not represented significant drawbacks in the use of RCA into new con-

cretes. RAC may have similar properties to conventional concrete and can reach the desired structural performance, even for high replacement rates [12].

Although significant work has been done in the past years, there are still open issues that prevent the widespread use of RCA [13]. One of these is related to the fire behaviour of concrete made with RCA. This paper aims to provide a comprehensive and updated report about high temperature behaviour of concrete made with recycled concrete aggregates. Firstly, mechanical and thermal properties at elevated temperatures are discussed. Then, spalling, medium and full-scale experiments are presented. Additionally, microstructure related properties are addressed. Lastly, conclusions and research needs are presented.

## **2. Behaviour of concrete made with natural aggregate at elevated temperatures – a brief review**

Before presenting the studies on concrete made with RCA, this section summarizes the main concepts about the high temperature behaviour of concretes made with natural aggregates. When concrete is under heat, several physicochemical changes occur, resulting in the changing of thermo-mechanical properties of the material.

The first reactions that occur are related to the slow capillary water loss associated with a water expansion, from 20 °C to 80 °C [14, 15]. From 80 °C to 100 °C, ettringite dehydrates and decomposes [14]. At this stage, the water physically bonded in aggregates and cement matrix evaporates, increasing capillary porosity and microcracking [15]. From 100 °C to 200 °C, concrete starts losing water and C-S-H (calcium silicate hydrate) of the cement paste starts to dehydrate and decompose, forming  $\alpha\text{C}_2\text{S}$  [14]. Also, between 120 °C and 300 °C, cement gel layers starts to moving closer, increasing van der Waals forces [16, 17]. This may lead to an increase in the strength up to 300 °C. At this temperature, hydration of unhydrated cement grains may also occur, which also may lead to a constant or increase in strength [18]. At 350 °C, water loss becomes more intense and C-S-H continues to decompose, increasing porosity and microcracks [14]. At this point, above 300 °C, concrete starts to have some significant loss of strength and stiffness [18].

After 400 °C and up to 600 °C, CH (portlandite) decomposes, contributing to microcracking in the cement paste [14, 15]. Also, siliceous aggregates containing quartz transform at 573 °C [14, 19]. From 600 °C to 800 °C, a

second phase of the C-S-H decomposition undergoes [15, 19]. At this phase, most of the compressive strength has been lost [18]. From 800 °C to 1200 °C, the dehydrated phases start to melt, with an intense microcracking at 1200 °C [14, 19]. Aggregates also start to melt with temperatures higher than 1000 °C, depending on mineralogical composition [14, 19].

In addition to phase changes and reactions, heating leads to a thermal mismatch between cement paste and aggregates, as the cement paste shrinks, while most of the aggregates used in concrete expand [20, 21]. This differential strain can lead to thermal-induced stresses that might originate microcracks in the ITZ and the cement paste, contributing to the degradation of mechanical properties [22]. Since aggregates occupy 60 % to 80 % of the volume of the concrete, the selection of the aggregate affects the thermal stability of concrete at high temperatures [22, 23]. Razafinjato et al. [23] studied a wide range of petrographic types of siliceous and calcareous aggregates. They concluded that the thermal behaviour of the aggregates depends on their mineralogical and chemical compositions. The petrographic origin of these aggregates also influences the behaviour of heated concrete [24].

Another relevant aspect of the behaviour of concrete at elevated temperatures is spalling due to fire exposure. This phenomenon consists of a sudden detachment of concrete fragments from structures exposed to fire. Spalling can seriously affect the structures' performance, reducing thermal insulation, exposing the steel rebars directly to fire and then reducing the load-bearing capacity [25]. The phenomenon is not yet fully understood, however, previous studies reveal that material, geometry and environmental parameters (such as heating rate and external loading) influence the phenomenon. Among material parameters, transport properties (e.g., permeability, porosity, and water content) appear to affect the mechanism behind spalling [26, 27].

Given the influence of material properties on the high temperature behaviour of concrete, it seems that concrete made with recycled concrete aggregates may behave differently than concrete made with natural aggregates in these extreme conditions. Moreover, the higher porosity, higher water absorption, the different interfacial transition zones and the thermal expansion behaviour of RCA may lead to distinctive behaviour at high temperatures.

### **3. Mechanical properties of concrete made with RCA at elevated temperatures**

The mechanical properties are fundamental parameters for understanding and predicting the behaviour of concrete structures at elevated temperatures. Studies concerning the behaviour of concrete made with RCA evaluated different properties, such as compressive strength, elastic modulus, tensile strength, and stress-strain relationship. Table 1 presents a chronological summary of the works used in this review. A relevant aspect concerning the determination of mechanical properties at high temperatures is the lack of standardized test proceedings, even for concrete made with NA. As pointed out by previous studies [18, 28, 29], the different parameters related to testing conditions, procedures, and mix properties affect the results. The compiled results presented herein come from a wide range of different test parameters and mix properties. The following sections aim to perform an in-depth discussion related to these parameters.

Table 1: Summary of research on the mechanical properties at high temperatures of concrete made with RCA

Author	Replacement Rate		High Temperature Parameters				Experiments
	Coarse Aggregate (%)	Fine Aggregate (%)	Test type	Rate/Curve (°C/min)	Temp. (°C)	Exposure time (h)	
Zega & Di Maio [30]	75	-	Residual	n.s.	500 °C	1; 4	CS; EM; UPV; DME
Zega & Di Maio [31]	75	-	Residual	n.s.	500 °C	1	CS; EM; UPV; DME
Vieira et al. [13]	20; 50; 100	-	Residual	ISO 834	400-800 °C	1	CS; STS; EM
Sarhat & Sherwood [32]	25; 50; 75; 100	-	Residual	n.s.	250-750 °C	1	CS; STS; EM
Xiao et al. [33]	30; 50; 70; 100	-	Residual	ISO 834	200-800 °C	2	CS; FS
Chen et al. [34]	100	-	Residual	2.5	200-600 °C	1	CS; EM; SS
Kou et al. [35]	50; 100	-	Residual	5	300-800 °C	4	CS; STS
Gales et al. [36]	30; 100	-	Hot	2	500-560 °C	2	CS; EM; SS; P
Laneyrie et al. [37]	100	-	Residual	0.5	150-750 °C	2	CS; STS; DME
Liu et al. [38]	30; 50	-	Residual	5	100-800 °C	4	CS; EM; SS
Yang et al. [39]	50; 100	-	Residual	n.s.	200-400 °C	n.s.	SHE
Meng et al. [40]	30; 70; 100	-	Residual	n.s.	200-500 °C	1	TR
Shaikh [41]	50; 100	-	Hot/Residual	8	600-800 °C	1	CS; EM
Xuan et al. [42]	20; 40; 60; 80; 100	-	Residual	10	200-600 °C	2	CS; EM; SS
Yang et al. [39]	30; 50; 70; 100	-	Residual	n.s.	300-500 °C	6	CS; EM; SS
Zhao et al. [43]	25; 50; 75; 100	-	Residual	12	200-800 °C	3	CS; EM; SS
Bui et al. [44]	100	-	Residual	5	500 °C	1	CS; EM; SS; UPV
Chen et al. [45]	30; 50; 70; 100	-	Residual	10	200-800 °C	1	CS; EM; SS
Khaliq [46]	100	-	Hot/Residual	5	100-800 °C	2.50	CS; EM; SS; STS
Xie et al. [47]	100	-	Residual	5	200-800 °C	2	CS; EM; SS
Yang et al. [48]	25; 50; 75; 100	-	Residual	10	200-800 °C	3	CS; STS
Abed et al. [49]	25; 50	-	Residual	ISO 834	100-800 °C	2	CS; FS
Pliya et al. [50]	15; 30	-	Hot	1.5	500 °C	1	CS; DIC, SEM
Salahuddin et al. [51]	30; 60; 100	-	Residual	3	200-600 °C	1	CS; UPV; ML
Wang et al. [52]	100	50; 100	Residual	12	200-800 °C	3	CS; STS
Yang et al. [53]	50; 100	-	Hot	7 - 9	300-800 °C	2	CS; EM; SS
Abed et al. [54]	25; 50	-	Residual	ISO 834	100-800 °C	2	CS; FS
Abed et al. [55]	25; 50	-	Residual	ISO 834	100-800 °C	2	CS; FS; UPV
Deng et al. [22]	50; 100	-	Residual	10	200-400 °C	1	BI
Varona et al. [56]	25; 50; 100	-	Residual	7-7.5	350-850 °C	2	CS
Wang et al. [57]	100	-	Residual	5	200-800 °C	2	TPB
Zhao et al. [58]	100	50; 100	Hot	12	200-800 °C	3	CS; EM; SS
Silva et al. [59]	50; 100	-	Residual	2	150-650 °C	1	CS; EM; SS ; STS
Pliya et al. [60]	30	30	Hot/Residual	2	150-450 °C	2	CS; EM; DIC; SEM

n.s. = not specified

CS = Compressive Strength; EM=Elasticity Modulus; UPV = Ultrasonic Pulse Velocity; DME = Dynamic Modulus of Elasticity;

STS = Splitting Tensile Strength; FS=Flexural Strength; SS=Stress-Strain Curve; P=Poisson; SHE=Shear Strength; TR=Triaxial Loading Test;

BI = Biaxial Loading Test; TPB = Three-Point Bending

### 3.1. Compressive strength

Fig.1 depicts the data collected regarding the compressive strength of RAC at elevated temperatures in terms of relative compressive strength as a function of temperature. The relative compressive strength consists of the ratio between strength at elevated temperatures and strength at ambient temperature ( $f_{cu}^T/f_{cu}$ ). The results depicted in Fig. 1 present no differences regarding mixture proportions nor test conditions. The only differences are related to the testing modality, i.e., hot or residual tests. Further in this section a discussion regarding both types of tests is provided.

Despite the great variability in the results, two different stages can be identified, especially in the residual data. In the first stage, from room temperature up to 300 °C, the compressive strength deviates approximately 20 % from its initial value, with individual data presenting either decrease or increase of strength. The second stage ranges from 300 °C to 800 °C, when the compressive strength starts to decrease prominently. This general trend is very similar to conventional concrete behaviour [18, 29]. The second stage ranges from 300 °C to 800 °C, when the compressive strength decreases prominently. Such a decreasing trend is also observed in the conventional concrete, as pointed out by [18, 29]. The hot dataset presents a more linear decrease trend. However, due to the reduced number of hot tests, one cannot assert whether its variability is lower than the variability obtained from the residual tests.



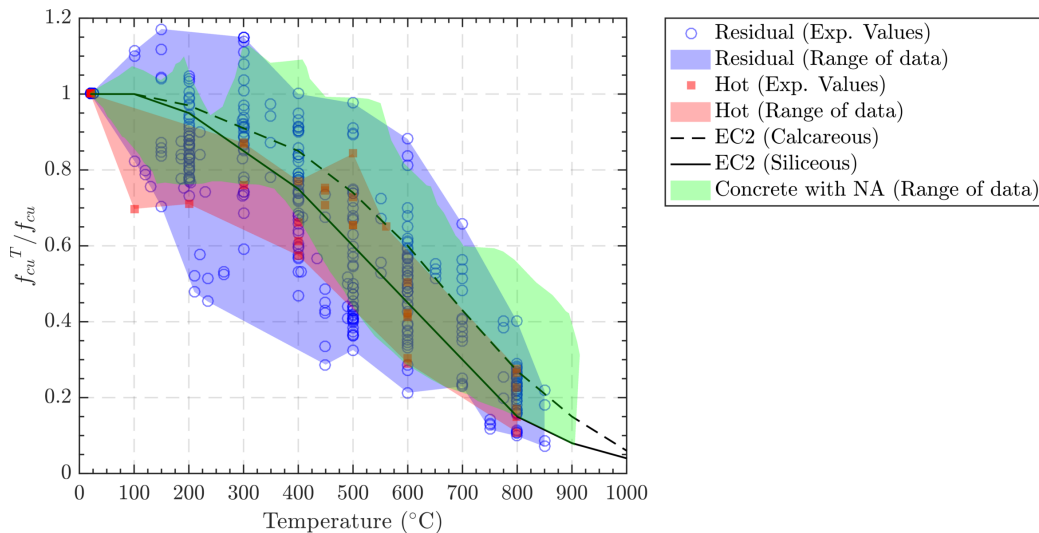


Figure 1: Relative compressive strength of concrete made with RCA at elevated temperatures (residual experimental data from [13, 30–35, 37, 38, 41, 43–48, 51, 52, 56, 58, 59], hot data from [36, 41, 46, 50, 53] and concrete made with NA data from Kodur [28])

Fig. 1 also depicts a comparison between the compiled data and the curves for siliceous and calcareous concrete provided by Eurocode 2 [61]. The curves provided in the Eurocode are the ones used to determine the fire resistance of structures. The high scattering in the experimental results does not allow to draw easily a general conclusion. However, it is noticeable that a significant amount of experimental values are lower than the code provisions. Hence, using the Eurocode 2 [61] for evaluating the fire resistance of structures with RAC may be unreliable. For this reason, particular attention should be paid when using these provisions and complementary curves, adapted for RCA, could be added to Eurocode 2.

The variability in the results is not an exclusivity of concrete with RCA. Different studies [18, 28, 62] point out similar dispersions related to the ordinary and high strength concrete properties at high temperature. This variation in the results can be attributed to different factors, such as testing conditions (e.g., heating rate, hot or residual, sizes, curing, cooling) and material parameters (e.g., moisture, composition, age) [28, 29].

The first material parameter that raises questions is the presence of RCA itself. It is relevant to know how the presence of recycled aggregates affect the mechanical properties when compared to ordinary concrete made with

NA. To depict this difference, the compressive dataset was also compared to results of concrete made with NA. The comparison was made with a set of experimental results (green cloud in Fig.1), extracted from the review paper of Kodur [28]. For higher temperatures (from 700 °C), concretes with NA tend to present higher values. Although no clear conclusion can be drawn from Fig.1, one notices a significant variability in the RAC data, particularly under 500 °C. Such dispersion in data suggests that the design process should be stricter for concrete made with RCA.

From comparing the works available in the literature, it is verified that different authors obtained contradictory results and drew distinctive conclusions. A first group of works [34, 36, 41, 59] stated that concrete made with RCA presented lower relative compressive strength than concrete made with NA after exposure to high temperatures. The authors also reported that the compressive strength reduces as the RCA content increases. Chen et al. [34] attributed the weak behaviour (top right of Fig.2) to the high porosity of RCA. Gales et al. [36] observed similar behaviour in hot tests and asserted that worse performances were associated with three factors: (i) weak ITZ between the old cement paste on the RCA and the new cement paste; (ii) weaker strength at elevated temperatures of the RCA; (iii) possible microcracking in the RCA. Likewise, Shaikh [41] stated that the compressive strength reduction is due to weaker RCA and the greater size of the ITZ's in RCA. Silva et al. [59], on the other hand, attributed this behaviour to the higher total amount of mortar in these mixtures.

A second group of authors [13, 37, 43, 48, 60] reported that the concrete made with RCA presented similar performance of conventional concrete. Fig.2 (bottom left) depicts the results obtained by Zhao et al. [43]. These works [13, 37, 43, 48, 60] did not provide a clear relationship between the compressive strength degradation and the replacement rate. Also, the authors provided no explanations regarding this behaviour.

Finally, a last group of works observed an increase of the relative residual mechanical properties of concrete made with RCA [30–33, 35, 46, 49, 52, 54, 56, 58]. One of the evolution is presented in Fig.2 (top left). The main reason for this improvement, according to different authors [30–32, 35], is better compatibility of the coefficient of thermal expansion between recycled aggregates and the cement paste, which reduces micro and macrocracking in the interface and the cement paste. The compressive strength also increased with the increase of fine RCA (0/5 fraction) quantities, as observed by [52, 58]. The authors also attributed the gains in the behaviour to a better match

between thermal expansions.

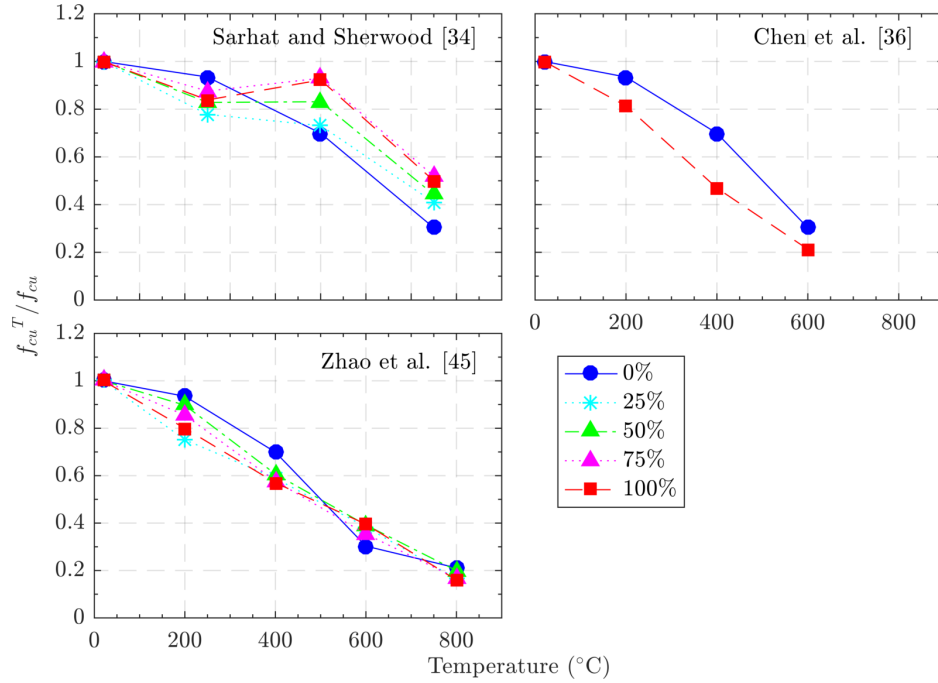


Figure 2: Relative compressive strength of concrete made with RCA for different replacement rates

It is also relevant to disclose that the composition of the recycled aggregates may also affect the compressive strength. Laneyrie et al. [37] studied two different recycled concrete aggregates: one produced in a laboratory with controlled properties and one obtained from an industrial source. The concrete made with RCA from industry presented a more significant decrease in strength. The authors [37] stated that this behaviour was related to the presence of flammable non-cementitious impurities (*e.g.*, bituminous, plastic, wood). As the material burns, additional cracks and pores are created in the matrix.

The water/cement ratio may also influence the compressive strength at high temperatures of concrete. Such influence was first studied by Zega and Di Maio [30, 31]. Both works pointed out that for concrete made with RCA with a low w/c ratio, the reduction of relative residual compressive strength was less significant. The authors [30, 31] attributed this to the fact that the

interface between old mortar and new mortar was better in the case of low w/c; hence, thermal expansion between the materials (new paste and RCA) is closer.

Laneyrie et al. [37] also studied the effects of varying the w/c ratio (0.3 and 0.6) in compressive strength for two different concretes made with RCA (industrial and laboratory-produced aggregates) subjected to high temperatures. Relative residual values were similar for both cases, yet the authors did not comment on this similarity. Likewise, Yang et al. [48] observed that different w/c ratios make insignificant differences in the compressive strength. Lastly, Silva et al. [59] studied concretes with the same RCA content and different strengths (C25 and C65). They observed similar behaviour for both concretes, with an increase of compressive strength at 150 °C, followed by a decrease up to 650 °C. The main difference was a more relevant increase of compressive strength for C25 concrete when compared to C65. The authors did not provide reasons for this behaviour.

Some studies also addressed the effect of mineral additions as partial replacement of cement. For concrete made with NA, previous studies reported that fly ash and slag can improve its resistance at high temperature, while silica fume seems to worsen the performance [18].

Kou et al. [35] evaluated the addition of fly ash and ground granulated blast furnace slag. They reported an improvement in the compressive strength of concrete made with RCA and mineral additions, up to 300 °C. After 500 °C, however, the concrete suffered significant deterioration. Bui et al. [44] evaluated four different mineral additions: fly ash, waste paper sludge ash, silica fume and metakaolin. The results revealed that mineral additions improved the relative residual compressive strength of heated RAC. The use of waste fly ash, cellular concrete powder and perlite powder as replacement for cement in self-compacting concrete with RCA was studied by Abed et al. [49, 54]. The authors state that adoption of 15% of any of the waste materials with 25% of RCA replacement improve concrete performance. Lastly, some studies [34, 41] verified the effects of adding fibres to the concrete with RCA, whereas Xie et al. [47] added fly ash and fibres. Authors reported that fibres improved the residual mechanical properties of heated RCA.

Concerning the testing parameters, two of them stand out: heating rate and type of test. Regarding the heating rate, strong thermal gradients may take place in concrete samples due to their low thermal diffusivity [63]. This kind of thermal gradients induces a structural behaviour in the sample and should be avoided when determining material properties. Moreover, it is

important to guarantee a homogeneous temperature distribution inside the specimen. In that context, RILEM recommendation [64] limits the heating rate up to 4 °C/min, depending on the specimen size. Regardless of the type of mechanical test, hot or residual tests can be carried out. For hot tests, concrete specimens are loaded at elevated temperatures. On the other hand, in residual tests, loads are applied after cooling the samples. The first type of test helps to understand the behaviour of concrete structures during a fire and the second one is more related to the post-fire assessment and repair of concrete structures [65].

Fig.3 presents the influence of the heating rate and the type of mechanical tests in the relative compressive strength of RAC. Fig.3a depicts the relative compressive strengths obtained from low heating rates (up to 5 °C/min), whereas Fig.3b portrays the compressive strengths obtained from high heating rates - including ISO 834-1 [66] fire curve. Additionally, the dataset depicted in Fig.3a was obtained from [34–38, 44, 46, 47, 50, 51], whereas the dataset depicted in Fig.3b was obtained from [13, 30–33, 41, 43, 45, 48, 52, 53, 56, 58]. It is clear that the data distribution varies between both datasets, especially for residual values. Lastly, the dataset obtained from low heating rates presents a two-phase behaviour, with some works showing a slightly increase of strength for temperatures up to 300 °C.

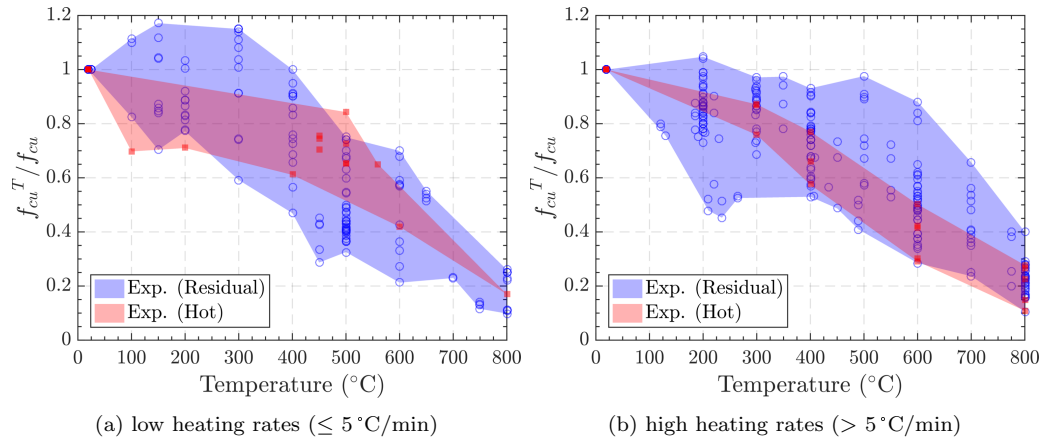


Figure 3: Relative compressive strength of concrete made with RCA at high temperatures

The influences of the type of mechanical test (i.e., hot or residual tests) are also studied by a few authors [41, 43, 46, 53, 60], whose results are plotted in Fig.4. The small amount of works, however, does not allow one to draw

specific conclusions. Some authors [41, 43, 46, 53, 60] studied specifically the influence of the type of testing, and some of their results are plotted in Fig.4. A clear difference in trends is observed, which allows one to assert that the obtained results are contradictory. Shaikh [41] observed that relative compressive strengths from residual tests are higher than hot ones, regardless of the temperature (top left on Fig.4). The author [41] stated that this behaviour is associated with the rehydration of hydration products after cooling, which may reduce porosity.

Khaliq [46], on the other hand, observed a different behaviour. In his study, residual tests values are higher for temperature up to 200 °C. From 200 °C up to 800 °C, the results obtained from residual tests become lower than the results obtained from the hot test (top right on Fig.4). Zhao et al. [43], and Yang et al. [53] reported similar results to Khaliq [46]. Namely, for high temperatures, the relative values obtained from the hot tests outperform the ones obtained from the residual test. Contrarily, for low temperatures, the results obtained from the residual test outperform the ones obtained from hot tests. It is worthwhile mentioning that the results from Zhao et al. [43], and Yang et al. [53] are presented together on the bottom left of Fig.4 as they come from the same research project, having the same test mix and testing conditions. The lower values of hot samples for the lowest temperatures, as observed in Kahliq [46], might be related to a higher internal vapour pressure due to free water evaporation, as stated by Ma et al. [18] for concrete with NA. On the other hand, for high temperatures, lower values of residual tests may be explained by additional mechanical damage due to cooling of concrete [18].

Pliya et al. [60] studied the effect of residual/hot testing and also the effect of different pre-loading (40 % and 70 %) during hot tests. Same rate of 2 °C/min was used in all the tests. Authors stated that hot values, regardless of the pre-load, were always higher than residual ones. They attributed this behaviour to additional thermal stresses due to the cooling phase. The influence of the cooling method was also studied in the works of Yang et al. [48] and Wang et al. [52]. Both studies evaluated the differences between natural and water cooling by spraying cold water for 30 minutes. They concluded that water cooling resulted in a more significant decrease of compressive strength, especially for temperatures below 600 °C. Yang et al. [48] and Wang et al. [52] stated that lower values of normalized compressive strength might be related to the severe thermal shock induced by water cooling.

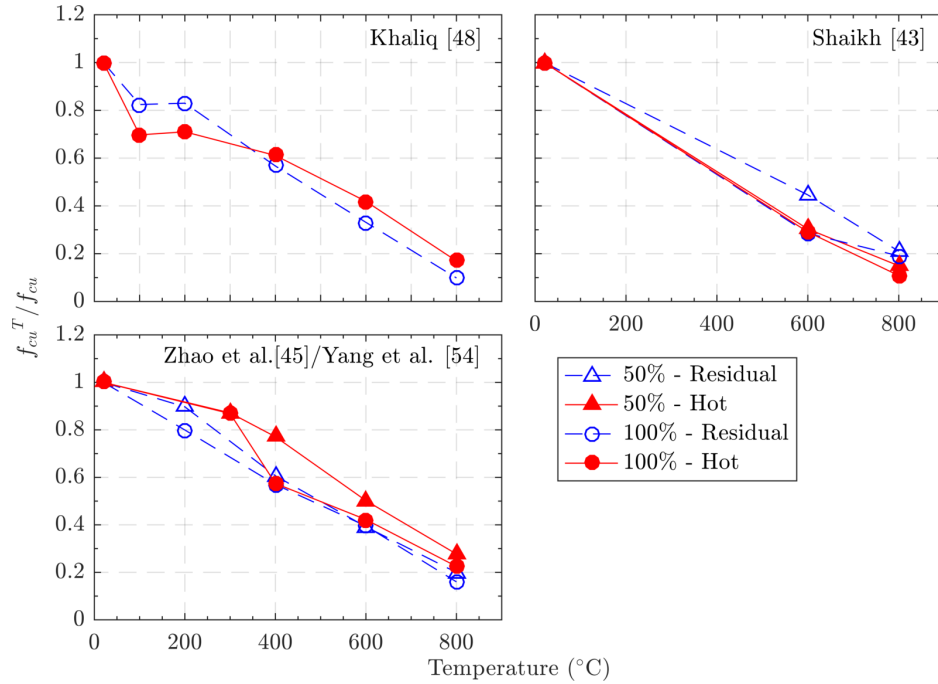


Figure 4: Hot and residual relative compressive strength of concrete made with RCA (percentage refers to the evaluated replacement rate)

### 3.2. Elastic modulus

Fig. 5a depicts the variation of the relative static elastic modulus as a function of the temperature. The relative static elastic modulus consists of the ratio between the elastic modulus at elevated temperatures and the elastic modulus at ambient temperature ( $E_c^T / E_c$ ). No distinction of mixtures was made and results were presented in two groups: residual tests [13, 30–32, 34, 38, 43, 45–47, 59] and hot tests [36, 41, 46, 50, 53]. Similarly to the compressive strength case, the results present a significant scattering of data, especially for residual tests. In general, the elastic modulus decreases almost linearly between room temperatures - and this behaviour is more prominent with hot tests.

The linear decrease of elastic modulus is very similar to those observed in concrete made with NA [18, 28], as observed in Fig.5b. This figure depicts the experimental results obtained by [28] from hot and residual tests for concrete made with NA in the green shaded area. The grey shaded area represents the both hot and residual tests for concrete made with RCA. Remarkably,

the RCA dataset is almost entirely inside the range of concrete with NA. For these reasons, it is possible to assert that the behaviour of both types of concrete is similar. However, the behaviour is not identical as differences can be found between 23 °C and 500 °C, as RAC presents higher relative static elastic modulus. Additionally, [13, 44, 53, 59] highlighted that the decrease of elastic modulus was more significant than in compressive strength. Vieira et al. [13] attributed that to the high level of cracking observed in the heated samples.

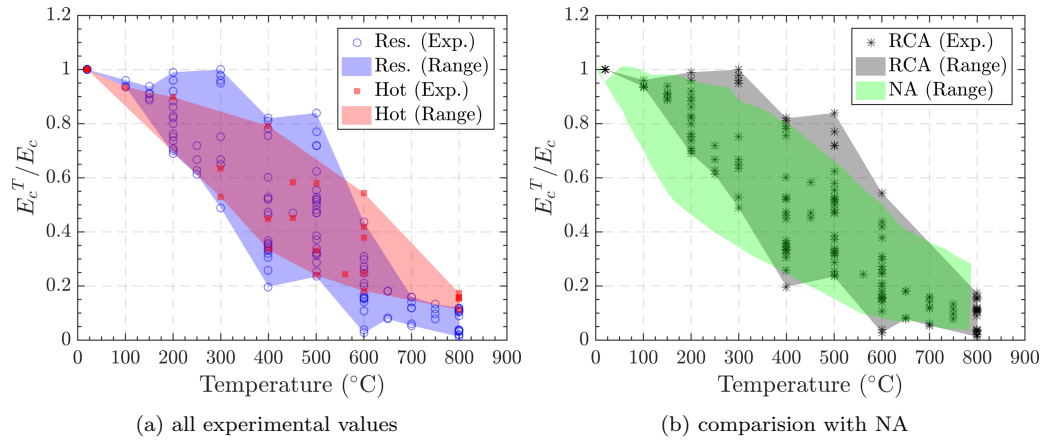


Figure 5: Relative modulus of elasticity of concrete made with RCA at elevated temperatures

In general, the factors that influence elastic modulus are very similar to those affecting compressive strength. Some works [13, 32, 43, 53] stated that the replacement rate makes little difference in the residual elastic modulus. Like the case of compressive strength, however, contradictory conclusions are observed in the literature. Shaikh et al. [41] observed a worse performance of RAC when compared to concrete with NA. They associated these results to the pre-existing microcracks in the RCA. Allegedly, These microcracks induced damages during heating, which reduced the load capacity and increased deformation, resulting in lower elastic modulus. Bui et al. [44] also observed worse behaviour for RAC. They attributed this to the old mortar in the RCA, which had higher deformability than the NA. Lastly, Khaliq [46] reported better elastic modulus retention in high strength RAC samples. The author [46] attributed this behaviour to the lesser deterioration in the microstructure of RA-HSC due to the higher permeability given by the RCA.



The use of fine RCA (0/5 fraction) also showed some increase in the elastic modulus, as observed by Zhao et. al [58]. According to their work, mixes with 50% of fine RCA might improve the residual stiffness after exposure to high temperatures. Similar phenomenon was also observed by Pliya et al. [60] which verified that RAC with 30% of fine RCA presented less damage. Authors attributed these results to the higher porosity of RAC, which might ease the thermal and hydrous transfer and consequently reduce the damage of this material.

### 3.3. Tensile strength

The tensile strength of concrete is significantly lower than compressive strength. For this reason this property is often neglected. At high temperatures, however, such property becomes relevant as the cracking and spalling phenomenons are related to tensile stresses [28]. In the literature, the tensile properties of concrete are usually determined by splitting test. Direct tension tests on concrete made with RCA at elevated temperatures are not reported in the literature. Fig.6a depicts the temperature dependence of the relative splitting tensile strength [13, 32, 35, 37, 46, 48, 52, 59]. The relative splitting tensile strength consists of the ratio between the splitting tensile strength at elevated temperatures and the value at ambient temperature ( $f_t^T/f_t$ ). No distinctions regarding mix proportions and testing procedures were made. The only study giving hot values is highlighted [46]. As the case of the other mechanical properties, wide variability of results is observed.

Fig.6b depicts a comparison with experimental results of concrete made with NA (extracted from Kodur [28]) and Eurocode 2 [61] provisions. Remarkably, the Eurocode 2 [61] provisions are more conservative than the experimental measurements. The analyses regarding the splitting tensile strength must be cautious, as the amount of available data is scarce. Additionally, similarly to the elastic modulus, the deterioration of the tensile strength property is more significant than the decrease in the compressive strength. The main reason for this behaviour is the higher sensitivity of tensile strength to thermal micro and macro-cracks [13, 37, 48, 52]. Comparing the experimental dataset (green and grey clouds in Fig.6b) of concrete made with RCA and NA, a higher variation of RAC results is verified. In general, relative splitting tensile strengths for concrete made with RCA exceeded the results obtained for conventional concrete. Lastly, although the experimental results presented its maximum at 300 °C, Kou et al. [35] did not provide any specific explanation addressing this behaviour.

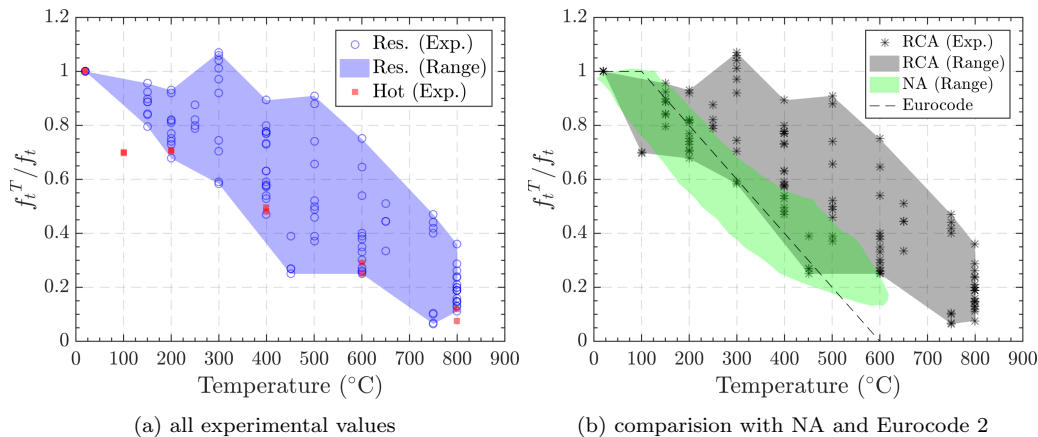


Figure 6: Relative splitting tensile strength of concrete made with RCA at elevated temperatures

However, the general higher tensile strength values for RAC were not always the case in the literature. Similarly to the previous commented concrete properties, contradictory results are reported in the literature. Whereas some works [13, 48, 52] pointed out that the replacement rate did not significantly affect splitting tensile behaviour, other authors [37, 46, 59] related slightly worse behaviour when compared to concrete made with NA. Laneyrie et al. [37] attribute the deterioration in behaviour to the higher number of interfaces, which might increase the development of cracks. According to Silva et al. [59], this behaviour is due to the higher amount of mortar in the concrete made with RCA. Contrarily, Sarhat and Sherwood [32] obtained different results. They observed an increase in the relative splitting tensile strength as the replacement rate increased. They attributed this behaviour to the low performance of the reference concrete with NA obtained from river gravel. Kou et al. [35] also observed some increase in the residual splitting tensile strength. They attributed this to the lower quantity of cracks around RCA (experimentally observed).

Once again, Laneyrie et al. [37] highlighted the influence regarding the quality of the aggregates. Since they used industrial RCA in their concrete, their results presented weak tensile strengths due to the melting and burning of impurities, which left additional voids and cracks. Laneyrie et al. [37] also assessed the strength of concrete and pointed out that high strength concretes (i.e., with low w/c ratio) exhibited lower deterioration of the properties due to a better match between interfaces. Yang et al. [48], however, evaluated

different w/c ratios and concluded that it made no difference in the relative residual splitting tensile strength.

### 3.4. Stress-strain relationship in compression

The stress-strain relationship expresses the mechanical response of concrete under an increasing compression load. The resulting curves are commonly used as an input to mathematical models to determine the fire resistance of concrete structures [28, 62]. Usually, stress-strain curves allow to determine compressive strength, elasticity modulus and peak strain. Many studies [34, 36, 38, 39, 42–47, 53, 58, 59] evaluated the stress-strain relationship of concrete made with RCA at elevated temperatures. In general, the shape and the differences caused by the temperature are very similar for both the RAC and concretes made with NA [18, 28]. As the temperature increase, stress-strain curves flatten, the peak stresses reduce, the slopes decrease and the strains at peak stresses increase. Fig.7 depicts this behaviour by presenting stress-strain curves obtained by Yang et al. [53].

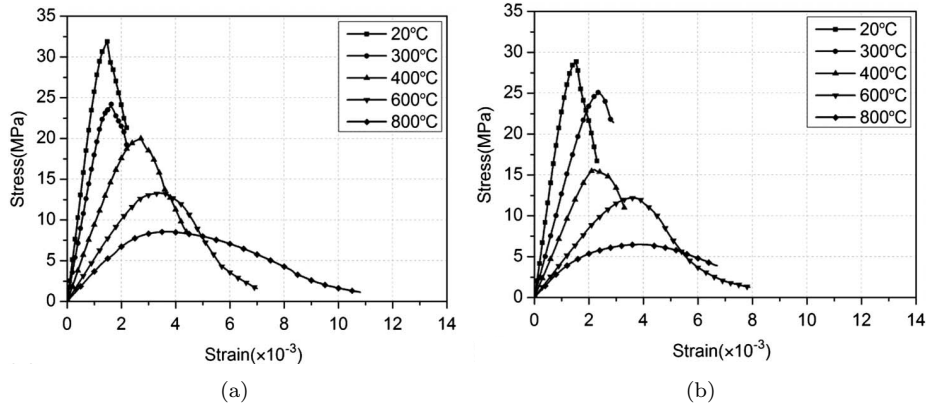


Figure 7: Stress-strain curves of concrete after heating: (a) concrete made with NA (b) concrete made with a 100 % replacement rate (adapted from Yang et al. [53])

Gales et al. [36] were the first ones to present hot stress-strain curves for concrete made with RCA. Strain properties were measured with digital image correlation (DIC), but only the ascending branch was recorded. The temperature dependency of the ascending branch was similar to ordinary concrete. In this study, concrete made with a higher replacement rate presented a lower slope and higher peak strain at elevated temperatures. Khaliq [46] also compared hot and residual stress-strain responses. To measure strains,

LVDTs were attached to compression platens. The author concluded that high strength concrete made with RCA was more ductile than concrete made with NA, notably above 400 °C. Additionally, Khaliq [46] comments that this behaviour is due to the high temperature dilatation and microstructure damage when compared with NA-HSC. Regarding the effect of the type of test, residual test samples presented a more ductile behaviour when compared with hot tests.

Zhao et al. [43] compared normalized (relative) curves and found out that concrete made with RCA registered lower energy absorption capacities when compared with concrete made with NA. Yang et al. [39] tested different replacement rates and did not observe significant differences for the stress-strain curves. Zhao et al. [58] evaluated the influence of fine RCA (0.15-4.75) in the stress-strain response of concrete and stated that the inclusion of fine RCA had an insignificant impact on the behaviour. Lastly, the addition of steel fibres in concrete made with RCA improves the high temperature mechanical behaviour, increasing the energy absorption capacity, as observed by Chen et al. [34], and the stiffness, as reported by Xie et al. [47].

### *3.5. Other mechanical properties*

Different mechanical properties were studied in several works. For instance, Gales et al. [36] determined the Poisson's coefficient at hot state employing digital image correlation (DIC) measurements of transverse and longitudinal strains. According to their research, For ambient temperature, the property is not affected by the presence of RCA. At 500 °C, however, the Poisson's ratio depends on the recycled aggregate content. Compared with ambient temperature, the Poisson's ratio increased for NA and for the mix with 30 % of replacement. For concrete with 100 % of RCA, the Poisson's ratio decreased with temperature. The authors suggested that the Poisson's ratio was dependent on the type of aggregate and the behaviour of the different ITZ inside the concrete.

Pliya et al. [60] also used DIC to measure thermal strains of concrete specimens under transient temperature tests. Different replacement rates (0 % and 30 % of both fine and coarse RCA) were exposed to high temperatures under different sustained pre-loading (40 % and 70 %). The authors [60] stated that the deformation depended on the pre-loading. Besides, it was observed that with 70 % of pre-loading, the transient thermal strains neutralize the effect of free thermal expansion, reversing the total strains

from expansion to contraction. They also verified that thermal strains of concrete with NA were higher than concrete with RCA.

The deformation properties of heated RAC were also evaluated by Zhao et al. [67]. The authors assessed the free thermal strain for different replacement rates. In general, as the temperature increases, the thermal expansion increases. An abrupt increase at 500 °C was verified, related to the quartz transformation of siliceous aggregates. Zhao et al. [67] also observed that beyond 500 °C, thermal expansion significantly increases for concrete made with 50 % of RCA. They attribute this behaviour to the microcracking caused by the non-uniform thermal stresses between the two coarse aggregates (NA and RCA), as it did not for concretes with replacement rates of 0 % and 100 %.

Flexural behaviour of concrete made with RCA was first studied by Xiao et al. [33]. The authors observed that residual flexural strength gradually decreases with the increase of temperature and the effect of the replacement rate is not very significant. The property was also evaluated by Abed et al. [49, 54]. They verified the effect of replacement rate, cement-replacement materials and time in self-compacting concrete with RCA. The authors verified that residual flexural strength increased with the increase of RCA content, due to strong ITZ between aggregates and mortar and also due to the better thermal compatibility. The use of waste material (fly ash and perlite powder) as a replacement to cement also presented a little improvement, depending on the replacement rate.

Meng et al. [40] studied the triaxial compressive properties of concrete made with RCA at high temperatures. The triaxial stress state is usually occurs in concretes during accidental loads (shock, fire, earthquake), in reinforced concrete with spiral hoops or concrete inside steel stubes. When triaxial stress are applied, the residual compressive strength of the material increases due to the limitation of cracks and deformations by the confining stress. The authors [40] stated that, up to 400 °C, the triaxial strength of RAC specimens was not influenced by temperature. From this temperature on, the triaxial strength starts to decline. It is worthwhile mentioning that the deterioration of the triaxial strength is less severe than uniaxial compressive strength. Deng et al. [22] studied the biaxial behaviour. They evaluated different stress ratios, different replacement rates, and different temperatures. The main conclusions were that the biaxial compressive strength decreased as the replacement rate increased. They asserted that this behaviour is associated with initial cracking presented in the RCA.

Shear behaviour of RAC at elevated temperature was evaluated by Yang et al. [68]. Authors evaluated residual shear properties after exposure to temperatures up to 400 °C. Their results revealed that shear modulus and peak secant shear modulus quickly decrease when exposed to high temperatures. Yang et al. [68] also pointed out that the replacement rate had minimal effect on the shear strength, although peak strain slightly increased. Fracture properties of concrete made with RCA, silica fume and fibres were evaluated by Wang et al. [57]. Three-point bending tests were performed on notched beams after heating. Wang et al. [57] concluded that concrete made with only RCA presented worse fracture properties. The addition of silical fume and steel fibres, however, improved this behaviour.

Lastly, some studies [30, 31, 44, 51] made some qualitative evaluations of mechanical properties of concrete made with RCA, such as ultrasonic pulse velocity (UPV). Zega and Di Maio [30, 31] reported that concrete made with RCA presented a lower reduction of UPV values at high temperatures than concrete made with NA. They attributed this behaviour to the better bond in the aggregate-mortar interface. Bui et al. [44] evaluated the effect of adding mineral admixtures and found that it did not affect UPV values. Authors [44] also reported that increase of the cement content improved UPV values of RAC at 500 °C. Abed et al. [55] evaluated the UPV of self-compacting concrete made with RCA with different replacement rates and cement replacement materials. The authors state that the incorporation of both waste materials improved the residual UPV, due to denser ITZ and better bond between mortar-mortar. Correlations with density, flexural strength and compressive strength were also given.

#### **4. Thermal properties**

Thermal properties govern the temperature diffusion inside the concrete; hence, these properties dictate the behaviour of concrete during heating (e.g., during a fire). Usually, thermal properties are defined in terms of thermal conductivity, specific heat and density. Thermal conductivity is the property related to heat conduction and is highly affected by moisture, porosity, and permeability. At room temperature, for concrete made with NA, thermal conductivity ranges between 1.4 and 3.6 W/mK. For concrete made with RCA, two works [37, 67] addressed this behaviour. They observed that thermal conductivity decreases as temperature increases. This decrease is higher

up to 400 °C due to the intense loss of free and pore water in concrete in that range of temperature [67].

Laneyrie et al. [37] evaluated thermal conductivity using the hot disc method and revealed that, up to 900 °C, concrete made with RCA presented less thermal conductivity than concrete made with NA. They also reported that ordinary strength mixes made with RCA had 10 % lower thermal conductivity when compared with the high strength mixes. Zhao et al. [67] used a hot wire method to evaluate thermal conductivity. Fig.8a depicts a comparison between the results from Zhao et al. [67], Laneyrie et al. [37], Eurocode 2 [61] and ASCE models. The results obtained by Zhao et al. [67] are similar to the ones from Laneyrie et al. [37] but are slightly higher than ones obtained from the models values. The authors [67] also showed that increasing RCA content reduces thermal conductivity.

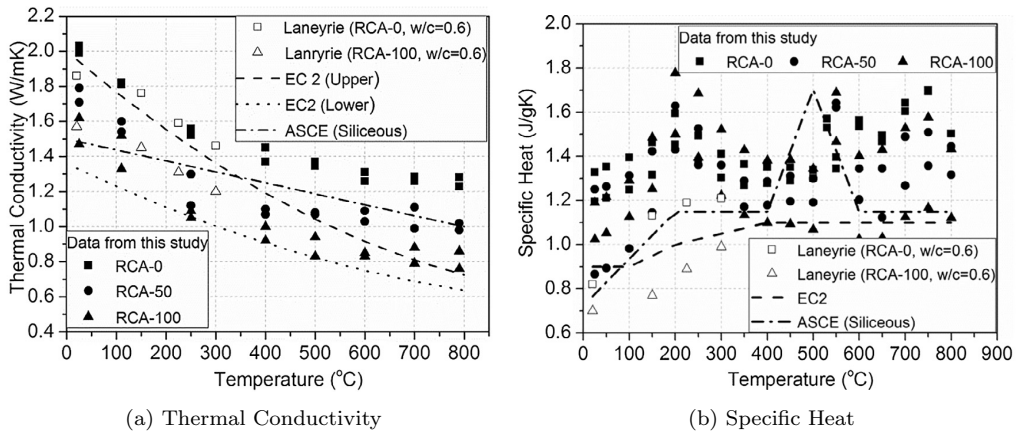


Figure 8: Thermal properties of concrete made with RCA [67]: comparison of experimental results [37, 67] and code models

Aiming to measure the specific heat of concrete made with RCA, Laneyrie et al. [37] employed hot disc method, whereas Zhao et al. [67] opted for the differential scanning calorimeter. The specific heat depends mainly on the physical and chemical transformations that occur in the concrete when heated. Beside, specific heat is highly affected by moisture content and w/b ratio [28, 62]. Laneyrie et al. [37] showed that specific heat of RAC slightly increased as temperature increased. Zhao et al. [67], however, obtained less clear results, revealing relevant discrepancies between different studies, as depicted in Fig.8b. Disparities were also observed while evaluating the influence of the replacement rate. Zhao et al. [67] concluded that coarse

RCA did not significantly influence the specific heat of concrete at elevated temperatures. Additionally, the specific heat of RAC is, in general, higher than the specific heat obtained from EC2 and ASCE models.

Density evolution as function of the temperature was studied by Bui et al. [44], who recorded values at fresh state, 20 °C, 100 °C and 500 °C. At high temperatures, concrete made with RCA presented greater loss of density than concrete made with NA, due to the higher porosity of RCA. Density evolution is mainly driven by the mass loss due to water departure from the material, and mass loss of concrete made with RCA was also evaluated in literature [37, 45–47, 51]. In general, as RCA presents higher water content, concrete made with RCA will also present more significant mass losses than concrete with NA; hence a more significant decrease of density as temperature increases.

## 5. Medium, full-scale and fire spalling tests

Usually, medium and full-scale fire tests consist of evaluating the behaviour of different concrete members subjected to a standard heating curve (e.g., ISO 834-1 [66]). Often called fire resistance tests, these tests aim to check the load bearing capacity, integrity and thermal insulation of concrete members during rapid heating. In addition to fire resistance tests, experiments concerning spalling, bond between RAC and steel rebars, and impact behaviour were observed in the literature.

Dong et al. [69] performed fire tests on columns made from RAC (100 % replacement) and concrete made with NA. The columns were subjected to ISO 834-1 [66] fire curve with a constant axial load. All tested columns failed due to large axial deformations. Dong et al. [69] reported that for the same compressive strength (C30), the fire resistance performance of concrete made with RCA (100 % replacement) was higher (118 min) than columns made of concrete made with NA (78 min). They attributed this to the higher moisture content of concrete made with RCA, which may dissipate heat through water evaporation (lower temperatures in cross-section were measured in concrete with RCA).

Within the French project "Recybeton", Robert et al. [70] carried out fire resistance tests on two RAC reinforced beams. One beam was made with 30 % of coarse aggregates and the other with 30 % of coarse and 30 % fine replacement. Beams were tested under ISO 834-1 [66] standard fire curve for 60 minutes. A comparison between the experimental bending moments and



the bending moments assessed according to Eurocode 2 part 1-2 [61] revealed that experimental bending moments were higher than code previsions.

Robert et al. [70] also tested slabs to verify spalling and thermal diffusion within the thickness of slabs. Similarly to the prior experiments, two reference slabs and two slabs of concrete made with RCA (one with 30 % of coarse aggregates and the other with 30 % of coarse and 30 % fine replacement) were tested. All slabs were subjected to the ISO 834-1 [66] fire curve. As depicted in Fig.9, superficial and localized spalling was observed only in the slabs containing RCA. The authors [70] state that the spalling extent was not detrimental to the stability of the slabs. Additionally, Robert et al. [70] attributed the phenomenon to the high water content of RAC slabs.

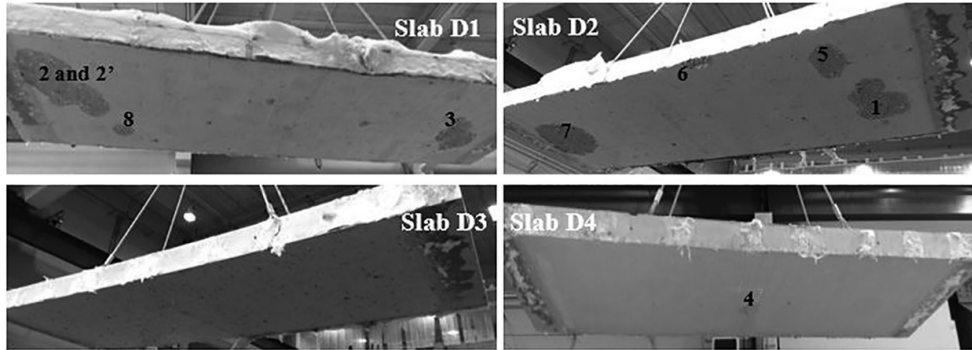


Figure 9: Slabs after ISO 834-1 [66] fire test: D1 and D2 are concrete with RCA; D3 and D4 are concrete with NA (adapted from Robert et al.[70])

Chen et al. [71] evaluated the mechanical behaviour of reinforced concrete and steel-reinforced concrete (i.e., composite) short columns and beams after exposure to elevated temperature. All the studied elements consisted of RAC with different replacement rates. The samples were initially heated inside an electrical furnace, then cooled and subjected to axial and three-point bending tests. The authors [71] verified a significant reduction in the bearing capacity of RAC short columns. They also reported that the shear properties deteriorated more significantly than flexural properties in their experiments. Additionally, Chen et al. [71] observed spalling in all samples heated up to 800 °C.

Pliya et al. [50] tested spalling sensitivity of high strength concrete made with NA and RCA (0 %, 15 % and 30 % replacement rate). To evaluate spalling, authors placed cylinder samples in a furnace and submitted them

to a heating rate of 10 °C/min. The authors [50] reported progressive and explosive spalling, characterized by the sudden disintegration of all samples (i.e., either with or without RCA). It is worth noting that this heating rate is lower than the one expected during a real fire. Pliya et al. [60] reported a similar phenomenon in another study, in which they applied 70 % pre-loading when the surface temperature reached 150 °C.

Another aspect evaluated at elevated temperatures was the bond behaviour between concrete made with RCA and steel rebars. Yang et al. [68] evaluated post-heating bond for different replacement rates (0 % to 100 %) up to 500 °C. Results revealed that increasing RCA replacement increases the relative bond strength after temperature. The authors [68] stated that this increase can be associated with the similar elasticity modulus between RCA and cement paste, the better matching of thermal expansion and the higher moisture content.

The high temperature behaviour of recycled aggregate concrete-filled steel tubes (RACFST) was also studied [72–75]. This use is associated with the fact that RAC presents lower mechanical properties. Hence, confining them with steel tubes might overcome this drawback. Most of the authors [72, 73, 76] observed that RAC specimens presented inferior mechanical properties, such as compressive strength, composite (concrete and steel) elastic modulus, and larger deformations. In general, increasing the replacement rate leads to the degradation of concrete properties. They attribute this behaviour to the lower fire resistance of RAC when compared to NAC [76].

## **6. Microstructure of heated concrete made with RCA**

In addition to mechanical and thermal properties, microstructure properties were also evaluated after heating. The experiments helped to understand the behaviour of concrete during heating and characterize the residual performance of concrete after cooling. The RAC microstructure was studied either by employing optical microscopy [42] or by applying scanning electron microscopy (SEM) [36, 46, 47, 50, 59].

SEM analysis by Gales et al. [36] focused on the ITZ of concretes made with different replacement rates after exposure to high temperature (500 °C/ with a heating rate of 2 °C/min) and mechanical load. The concrete made with 100 % replacement rate presented several microcracks at the interface between RCA and new mortar, which Gales et al. [36] attributed to thermal stresses. To support this affirmation, they studied the microstructure

of samples submitted to mechanical load only (i.e., the samples were not heated) and noticed no cracks in the ITZ. Similarly, the heated specimens of concrete with NA did not showed cracks in the interface, indicating that RAC presented interfaces more prone to cracking. Additionally, Pliya et al. [50] evaluated ITZ of high-strength concrete (HSC) made with RCA with replacements rates of 15 % and 30 %. In both cases, microcracks were observed at the interface and in the new cement paste.

SEM observations made by Xie et al. [47] showed that at 200 °C, the microstructure of concrete made with RCA is almost unchanged. At 400 °C, however, hydration products tend to loosen and at 600 °C, C-S-H morphology starts to transform and CH starts to dehydrate. Finally, at 800 °C, cracks and voids are observed. Similar observations were done by Khaliq [46], who verified a loss of filling compounds due to dehydration.

Silva et al. [59] used SEM images to support their assumption that the decrease of physical properties of concrete (water absorption, mass loss, and density) after exposure to elevated temperature was related to the increase of the total mortar amount (new and attached mortar). Aiming to prove their point, Silva et al. [59] utilized the post-heating SEM observations depicted in Fig.10. As Fig.10 portrays, the higher porosity of RCA and the different interfaces led to bigger crack openings during the heating process.

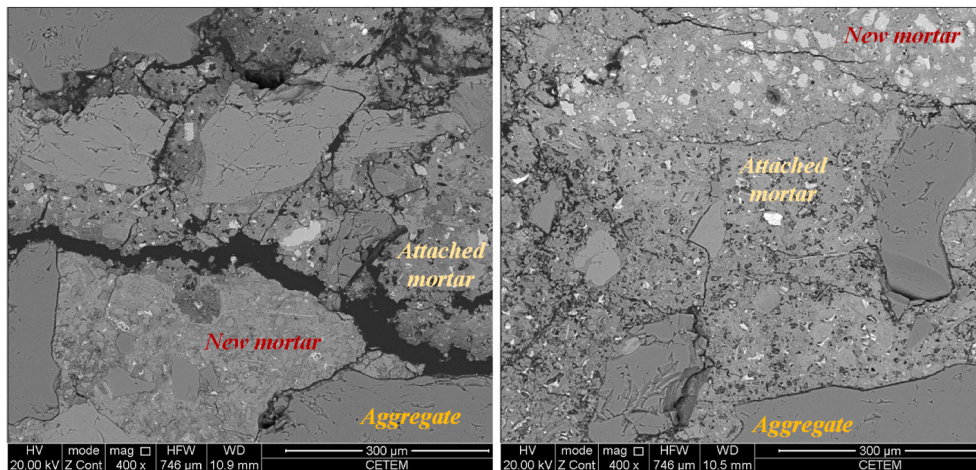


Figure 10: SEM images of concrete made with RCA after exposure to 650 °C: C25 (left) and C65 (right) (adapted from Silva et al.[59])

Xuan et al. [42] used optical microscopy to evaluate mesocracks at the

interfaces and in the mortar of concretes made with NA, RCA, and with carbonated RCA, after a thermal exposure of 600 °C. The idea behind using carbonated RCA relies on the reaction between CO<sub>2</sub> and the hydration products of cement in concrete. Such reactions produces CaCO<sub>3</sub>, which might precipitate in pores and densify the microstructure [77]. The authors [42] observed that by using RCA and carbonated RCA, the mesocracks at the interface aggregate-mortar dissapeared, whereas the width of mesocracks in the mortar after heating decreased. They asserted that the thermal damage of concrete with NA is higher than concrete with RCA after heating up to 600 °C.

The porosity of concrete made with RCA was evaluated by means of water porosimetry [37] and mercury intrusion porosimetry (MIP) [35, 42]. Laneyrie et al. [37] pointed out that water porosity did not change significantly up to 300 °C. From this temperature on, a slight increase was observed. MIP results from Kou et al. [35] revealed that, at room temperature, concrete made with RCA was more porous than concrete made with NA. After heating up to 500 °C and 800 , however, conventional concrete presented increases in porosity and average pore diameter. According to Kou et al. [35], the initial porosity of RAC prevented the build-up of vapour pressure, reduce internal cracks, and improves the thermal compatibility between new mortar and old mortar (attached mortar).On the other hand, Xuan et al. [42] found out that RAC at 600 °C presented more porosity than concrete made with NA and carbonated RCA. They attributed this behaviour to the decomposition of hydration products from the cement mortar in RAC.

Capillary absorption, directly related to porosity, was also studied in previous research. Kou et al. [35] investigated capillary water absorption and found results that agree with MIP, i.e., a relative residual water absorption coefficient that was higher for RAC up to 500 °C. At 800 °C this behaviour shifted, as concrete made with NA presented a higher water absorption.

## 7. Summary and Conclusions

Based on this literature study, some highlights on the behaviour of concrete made with RCA at elevated temperatures can be drawn:

- All the mechanical properties deteriorate as temperature increases, similarly to concrete with NA. Relative residual compressive strength presented different phases - up to 300 °C, some properties remain quite

constant and from this level up to 800 °C, all properties start to decrease significantly. For elastic modulus and splitting tensile strength decrease almost linearly as temperature increases. For stress-strain curves, in general, increasing the temperature causes the curves to flatten.

- The influence of the RCA and the replacement rate on mechanical properties is not well defined. Some works reported a possible increase of the relative residual properties as replacement rate increases. Other results pointed out that the replacement rate makes no significant difference or is even slightly worse. The inferior mechanical behaviour of concrete made with RCA relies upon the peculiar porous microstructure of the RCA and the weaker interfacial transition zones. In contrast, the studies which observed superior behaviour attributed this to the better match of thermal expansion between RCA and cement paste.
- Test conditions, such as heating rate and test modality (residual/hot), influence the measurements of mechanical properties. Additionally, the results found in the literature were also contradictory, as some authors pointed out that residual tests resulted in higher values, whereas others indicated the opposite. Standardized specifications and test protocols are needed to develop reliable outcomes.
- As temperature increases, the thermal conductivity decreases and specific heat presents miscellaneous results. In general, the use of RCA has no significant influence on thermal properties.
- Full-scale tests were performed on slabs, and localized spalling was observed. The authors reported no significant influence on the structural behaviour was noticed. Additionally, full-scale tests were also performed on columns of concrete made with RCA. The results revealed better fire resistance ratings than concrete made with NA. Beams of concrete made with RCA were also tested, and experimental bending moments before collapse were higher than code provisions.
- Microstructural observations pointed out that concrete made with RCA presented ITZs more brittle than concrete made with NA. SEM observations of concrete made with RCA also revealed dehydration of concrete hydrates. Additionally, some works reported that even if RAC

presents high porosity, the increase of relative residual porosity is lower comparing with concrete made with NA. Similar behaviour was observed for the relative residual water absorption.

## 8. Research needs

Based on this literature review, the following research needs and recommendations are proposed:

- Only a limited amount of works measured the mechanical properties at the hot state. Understanding the material behaviour at the hot state is crucial for predicting its performance during an actual fire.
- Deformation properties are another fundamental aspect to understand the concrete behaviour at high temperatures. Moreover, understanding the total strain of concrete made with RCA during heating is crucial to develop realistic computations. The deformation properties comprise the free thermal strain, the elastic strain, and the transient thermal strain.
- The spalling behaviour of concrete made with RCA should be studied more deeply, as it is fundamental for understanding the fire behaviour of concrete structures. Although some works reported spalling in concrete made with RCA (either normal or high-strength), it is yet to be found whether this behaviour is related to the aggregates or other parameters, e.g., the dense microstructure of HSC or water content. The effect of different replacement rates on spalling extent should also be studied.
- More full-scale fire tests are needed. Previous works related a similar behaviour between RAC and concrete made with NA, however, further research with different structural members and testing parameters are needed.
- No numerical modelling of concrete made with RCA at high temperatures was found in the literature. Mesoscale models, including the different phases of concrete made with RCA, should be used for thermo-mechanical simulations.
- Further microstructural observations are needed for an in-depth understanding of the post-fire behaviour of RAC. X-ray diffraction (XRD),

differential thermal analysis (DTA), X-ray computed tomography would improve the knowledge regarding the behaviour and the differences between concrete made with RCA and NA at high temperatures.

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