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Sustainable Use of Construction Waste: Fire Resistance and Strength Characteristics of Recycled Aggregate Concrete for Sustainable Concrete

Zubair Yousuf[1]*, Viktor Hlavička[1]

[1] Department of Construction Materials and Technology, Faculty of Civil Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary
* Corresponding author, e-mail: zubair.yousuf@edu.bme.hu

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Abstract

The pursuance of sustainability in construction has propelled the adoption of innovative materials, with recycled aggregate concrete (RAC) emerging as a pivotal solution to address the environmental challenges posed by traditional concrete. Sustainability in construction has become a global priority, driven by the need to reduce environmental impacts and conserve natural resources. The increasing use of green building certifications like LEED and BREEAM highlights the push towards innovative materials, including RAC. With construction and demolition (C&D) waste accounts for 31% of Europe's total annual waste and global consumption of natural aggregates (NAs) projected to double in the coming decades, recycling concrete waste into recycled concrete aggregates (RCA) has emerged as a sustainable alternative. Studies show that RCA use can reduce greenhouse gas emissions by 65% and non-renewable energy consumption by 58%. Despite advancements in RAC research, challenges remain, particularly regarding its performance under extreme conditions like fire. This study investigates the mechanical and durability properties and potential of using recycled aggregate(RA) in conventional concrete as a replacement in varying percentages of recycled fine and coarse aggregates (0%, 25%, 50%, 75%, and 100%) after exposure to different elevated treatment temperatures (20, 100, 200, 300, 400, 500, 600, and 800 °C). The findings aim to address gaps in understanding the thermal behavior of RAC and promote its adoption as an environmentally friendly construction material.

Keywords

recycled aggregate, residual properties, elevated temperature, integrated temperature endurance

1 Introduction

Sustainability is now a global movement influencing the materials used in many famous structures. The use of green and innovative building materials is being facilitated by international certification organizations such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM). Because of its high embodied energy demand, concrete can make it difficult to meet these certifications. To help obtain green certification, a specific sustainable and innovative concrete mix has been employed in a variety of structures for at least the past ten years. Recycled concrete aggregates (RCA) were used to create this concrete blend in place of traditional natural coarse aggregates (NCAs). Recycled concrete waste can be used to source and grade RCA [1]. Approximately 850 million tons of construction and demolition (C&D) waste are generated annually in Europe, accounting for 31% of the total waste produced [2]. In recent years, the common practice for managing C&D waste involved disposing of it in landfill sites. This approach has resulted in massive accumulations of C&D waste, consuming valuable land and posing significant environmental challenges [3]. In 2015, global consumption of natural aggregates (NAs) reached approximately 48.3 billion tons, with an estimated growth rate exceeding 5% every five years. Projections indicate that, at the current rate of increase, the demand for NAs is expected to double within the next two to three decades Table 1 [4–6]. In the US, from 2013 to 2023, the annual consumption of crushed stone, sand and gravel increased at cumulative average growth rates of 2.5% and 1.0%, respectively, rising from a combined total of 2.2 billion tons in 2013 to 2.8 billion tons in 2023 [7]. Considering environmental concerns, the depletion of natural resources, and the growing demand for concrete construction, the

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Table 1 Global consumption of NAs [4–6]

Region	Year				Annual growth (2010–2015)	Annual growth (2015–2023)
	2005	2010	2015	2005–2010		
???	27300	37400	48300	6.5	5.2	–
North America	3280	3010	3710	−1.7	4.3	2.5
Western Europe	2920	2630	3050	−2.1	3.0	1.8
Asia/Pacific	16000	24750	32600	9.1	5.7	4
Others	5100	7010	8940	6.6	5.0	2.2

significance of recycling C&D waste is increasingly emphasized. Recycling concrete to produce recycled coarse aggregate (R-CoA) has emerged as a prominent strategy for promoting sustainability in the construction industry. The use of recycled aggregate concrete (RAC) is widely advocated as a sustainable solution that conserves natural resources, reduces landfill accumulation, and fosters environmentally friendly construction practices. Extensive research has been conducted on RAC to optimize the utilization of aggregates derived from recycled concrete, focusing on various parameters in both fresh and hardened states. Key properties studied include replacement ratios, thermal and mechanical performance, shrinkage, creep, cracking resistance, rheology, permeability, and fire resistance, primarily under ambient conditions [8]. Another study reveals that a life cycle assessment conducted in Hong Kong on the environmental impact of recycled aggregates (RAs) showed that R-CoAs from C&D waste (CDW) can lead to a 65% reduction in greenhouse gas emissions and a 58% decrease in non-renewable energy consumption [9]. The use of RCA for producing RAC has gained significant attention in research. Much of this research focuses on examining the impact of RCA on the mechanical and durability properties of concrete [10]. Nevertheless, the behavior of the RAC at elevated temperatures is yet to be fully explored.

The properties of concrete that contain ordinary Portland cement (OPC) at elevated temperatures have been thoroughly examined in earlier studies [11]. To enable the widespread adoption of RAs in the construction industry, several challenges must still be addressed, particularly the performance of RAC under extreme conditions, such as exposure to fire [12]. With the global acceleration of urbanization and modernization, the frequency of fire incidents has risen due to increased population density and the growing scale of cities. Statistics show that during the previous few decades, there have been about 300,000 urban fire occurrences in Europe and millions in other nations US, UK, China, as shown in Fig. 1 [13–17].

Despite substantial progress in recent years, certain challenges remain unresolved, hindering the widespread adoption of RCA. One such issue is their fire resistance, the behavior of RAs under elevated temperatures.

This study seeks to investigate the performance of concrete incorporated with recycled fine and R-CoAs in different percentages (0, 25, 50, 75, and 100%) following exposure to different high temperatures (20 °C–800 °C).

2 Experimental program

The experimental work done in the investigation of the behavior of RAC was conducted in a few key stages: production and preparation of RA samples, mixing and curing methods, exposure to heating and cooling cycles, and subsequent testing. Each of these phases are elaborated in detail in Sections 2.1 to 2.4.

2.1 Materials

The cementitious material used in all mixes was Cem I 52.5 N OPC, which complied with applicable EN 197-1:2011 standard [18]. To maintain the necessary slump of 40 ± 20 mm, a water-reducing admixture (MasterGlenium 300) was incorporated in varying dosages across the mixes. Table 2 gives a thorough summary of the chemical composition based on data from the manufacturer.

The fine aggregate used in the concrete mixtures included both natural and recycled sand, while natural and recycled quartzite were utilized as coarse aggregates. All aggregates complied with the requirements specified in EN 12620:2002+A1:2008 standard [19].

Detailed information on the particle size distribution, mix ratios, and specific gravity of the aggregates is provided in Table 3. Standard potable water, meeting the specifications of EN 1008:2002 standard [20], was used for both mixing and curing the concrete samples.

2.1.1 Recycled aggregate (RA) source material

The RAs utilized in this study were produced from laboratory cast concrete specimens known as parent concrete (RA0). After adequate curing, the hardened parent concrete specimens (RA0) were tested and fragmented using a hydraulic compression splitter to obtain manageable small blocks

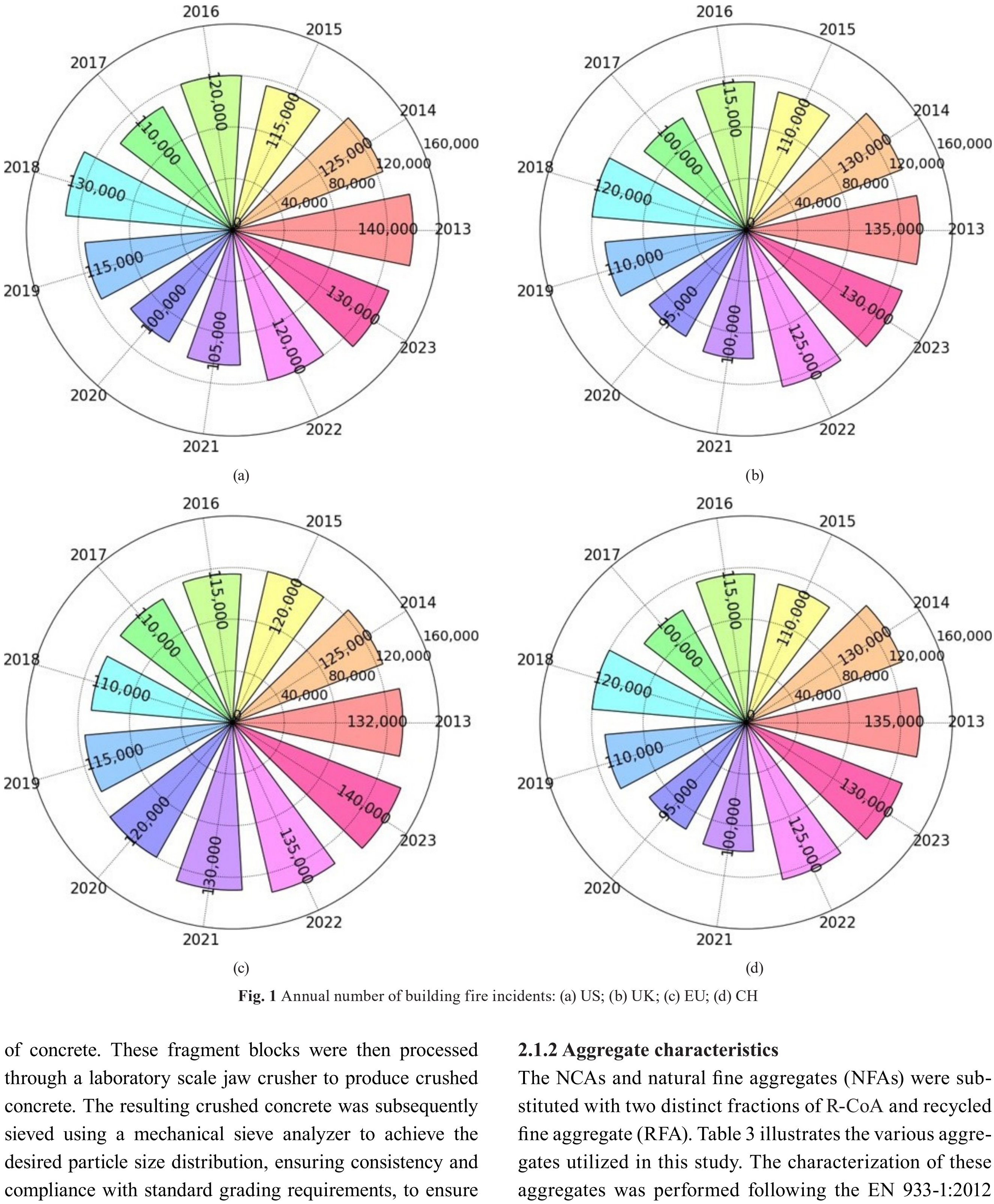


Fig. 1 Annual number of building fire incidents: (a) US; (b) UK; (c) EU; (d) CH

of concrete. These fragment blocks were then processed through a laboratory scale jaw crusher to produce crushed concrete. The resulting crushed concrete was subsequently sieved using a mechanical sieve analyzer to achieve the desired particle size distribution, ensuring consistency and compliance with standard grading requirements, to ensure material cleanliness and consistency. The aggregates were thoroughly examined to eliminate the dust, or other impurities. Finally, the cleaned aggregates were stored in sealed polyethylene bags to prevent contamination and moisture ingress prior to their use in concrete mixing.

2.1.2 Aggregate characteristics

The NCAs and natural fine aggregates (NFAs) were substituted with two distinct fractions of R-CoA and recycled fine aggregate (RFA). Table 3 illustrates the various aggregates utilized in this study. The characterization of these aggregates was performed following the EN 933-1:2012 standard [21], categorizing fine aggregates as those with a diameter less than 4 mm (sand) and coarse aggregates as those exceeding 4 mm (gravel), with an upper particle size limit of 11 mm. The particle size distributions of natural and R-CoAs were comparable, with natural gravel

Table 2 Properties of cement

Elements	Chemical composition (%)	Class requirement
SiO_2	19.73	(N)* EN 197-1:2011 standard [18]
Fe_2O_3	3.21	
Al_2O_3	5.55	
CaO	65.02	
MgO	1.44	
SO_3	2.88	
Na_2O	–	
K_2O	0.78	
Cl	0.0048	
Specific surface area	4500	
Color	Grey	

* (N): standards for the Exposure Class Requirement

Table 3 The particle size, mixing ratio of aggregates

Concrete mix designation	Fine aggregate		Coarse aggregate	
	Natural	Recycled	Natural	Recycled
MK0-RA25	–	–	–	–
Particle size (mm)	0/4	0/4	4/8	4/11
Mixing ratio (%)	32	11	43	14
MK0-RA50	–	–	–	–
Particle size (mm)	0/4	0/4	4/8	4/11
Mixing ratio (%)	21	22	29	28
MK0-RA75	–	–	–	–
Particle size (mm)	0/4	0/4	4/8	4/11
Mixing ratio (%)	10	33	15	42
MK0-RA100	–	–	–	–
Particle size (mm)	0/4	0/4	4/8	4/11
Mixing ratio (%)	0	43	0	57

exhibiting slightly finer particles than the recycled gravel. In contrast, noticeable disparities were evident between natural and RFA, as RFA displayed larger particle sizes and a less uniform gradation compared to (NFA). This was attributed to a greater hardness of the RAs. Table 4 gives the detailed properties of recycled and NAs.

2.2 Mix proportion

Four distinct concrete mixtures were designed with a water to cement (w/c) ratio of 0.45 and 390 kg of cementitious material per cubic meter. These formulations comprised recycled concrete mixes containing 25% recycled fine and coarse aggregate, along with three additional mixes incorporating RFA and R-CoA at varying proportions 50%, 75%, and 100%, respectively. The detailed proportions of each concrete mix, categorized by the varying RA content, are summarized in Table 5.

Table 4 Physical properties of recycled and NA

MK0	Recycled	Natural
Density (kg/dm^3)	1.8	2.6
Particle size (mm)	4/11	4/8
Water absorption (%)	3.5	–
Surface texture	Angular/rough	Round
Type	quartz	Quartz
Minerology	SiO_2	SiO_2
Moisture content	0	0

Table 5 Mix proportion of concrete containing RFA and R-CoA (kg/m^3)

Mix	RA0	RA25	RA50	RA75	RA100
Percentage (%)	0	25	50	75	100
Cem* (kg/m^3)	390	390	390	390	390
NFA (kg/m^3)	782.4	558.9	382.1	182.0	–
NCA (kg/m^3)	1037.1	776.9	527.7	272.9	–
RFA (kg/m^3)	–	140.4	286	429.1	559.1
RCA (kg/m^3)	–	185.9	364	546.1	741.1
Water (kg/m^3)	175.5	175.5	175.5	175.5	175.5
SP** (kg/m^3)	0.096	0.026	–	–	–
Water adjustment (kg/m^3)	136.5	145.5	158.9	192.7	217.4

* Cem: cement
** SP: superplasticizer

2.3 Mixing, casting, curing, heating, and cooling details

The mixing, casting, and compaction of concrete incorporating with RFA and R-CoA were conducted in compliance with EN 12350-5:2019 standard [22]. A motorized rotating pan mixer was employed for the mixing process, ensuring uniform distribution of materials. The fresh concrete mix was then poured into molds and compacted using a vibrating table. After casting, the molds were left under laboratory conditions for 24 h. Subsequently, the hardened concrete specimens were demolded and immersed in a water tank maintained at a controlled temperature of 23 ± 1 °C for 7 days to ensure proper curing prior to testing.

Before testing at elevated temperatures, the specimens were removed from the curing water tank after 7 days and conditioned under laboratory conditions for approximately 28 days. To ensure uniform drying, the specimens were oven-dried at 60 °C for 6 days. The concrete specimens were subjected to heating in an electric muffle furnace at predetermined target temperatures of 20 °C, 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, 600 °C, and 800 °C. During heating, the specimens were placed in the furnace at ambient temperature, with the temperature gradually raised at a controlled rate of 5 °C to 6 °C/min until the target temperatures were achieved. The specimens were maintained at the steady-state temperatures for 2 h to reach thermal equilibrium. After heating, the furnace was turned off, the furnace door was opened, and the specimens were allowed to cool gradually in ambient air over a 24 h period.

2.4 Testing procedure and methods

The compressive strength (f_c) and flexural tensile strength (f_l) of concrete mixes incorporating 25%, 50%, 75%, and 100% RFAs and R-CoAs were evaluated. These tests were conducted in accordance with EN 12390-3:2019 standard [23] and EN 12390-5:2019 standard [24], respectively. Cubic specimens (15 cm sides) were tested for f_c at 14 and 28 days, while prism specimens (27 × 7 × 7 cm) were tested for flexure tensile strength (f_l) over an average 28-day period. Additionally, post-fire compressive strength (f_{cp}) tests were performed on half-prisms specimens (7 cm sides) exposed to temperatures of 20, 100, 200, 300, 400, 500, 600, and 800°C at an average curing age of 28 days.

The f_c was measured using a 3000 kN capacity compression machine, applying a loading rate of 0.6 MPa/s as shown in Fig. 2. f_l tests were carried out using a flexural tensile testing machine in accordance with EN 12390-5:2019 standard [24]. For each test, three samples were evaluated, and the average values were recorded to ensure accuracy and reliability.

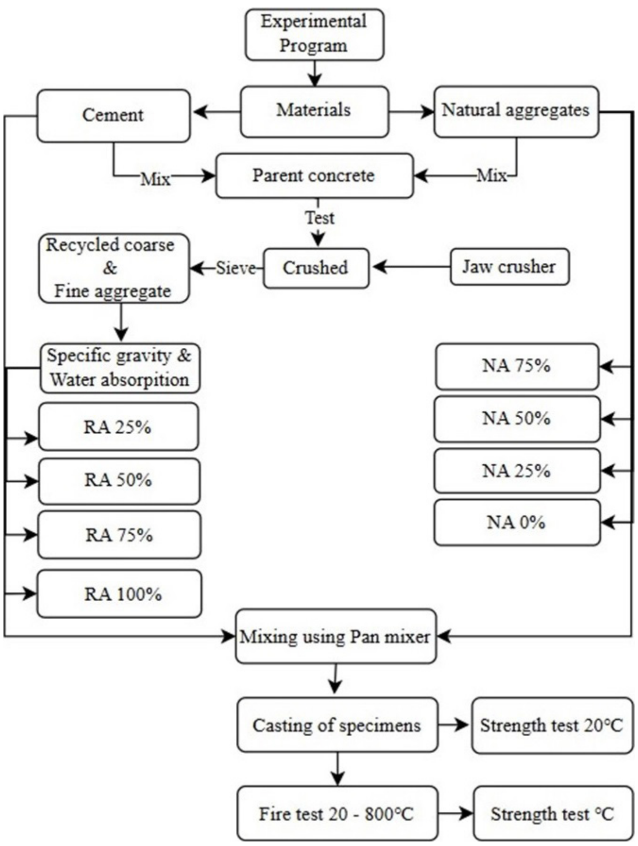


Fig. 2 Flow diagram of RA

3 Test results and discussion

Several plots have been generated based on the test results and findings are discussed below to understand the various physical and mechanical properties of concrete under elevated temperature.

3.1 Compressive strength (f_c)

The f_c of the various concrete mixes outlined in Table 4, measured at room temperature (f_c = 20 °C), is illustrated in Fig. 3. For each mix, the average strength values obtained from three tested specimens are presented, along with the corresponding standard deviation represented as error bars. The f_c was evaluated by calculating the ratio of the failure load sustained by the cube specimen under compression, applied at a uniform loading rate of 0.6 MPa/s. The cubes were tested at 14 and 28 days strength. The f_c of the specimens measured at room temperature was used as a baseline for evaluating their relative strength after exposure to elevated temperatures. From Fig. 3 it has been observed that the percentage of RA in concrete mixes has a significant impact on their f_c. The RA0 (control mixture without RA) consistently exhibits high f_c at both 14 and 28 days, as NA generally ensures superior bonding and strength retention compared to RA. However, RA25 achieves the highest strength at both time intervals, surpassing RA0 at 14 days and maintaining this advantage at 28 days. This remarkable strength enhancement can be attributed to the moderate incorporation (25%) of RA, which potentially improves particle packing, mix optimization, and overall compaction. Furthermore, the limited substitution of RA does not considerably impact the interfacial transition zone (ITZ), allowing the concrete to retain its structural integrity and strength effectively. Xiao et al. [25] and Martínez-Lage et al. [26] also observed the f_c of RAC declines as the

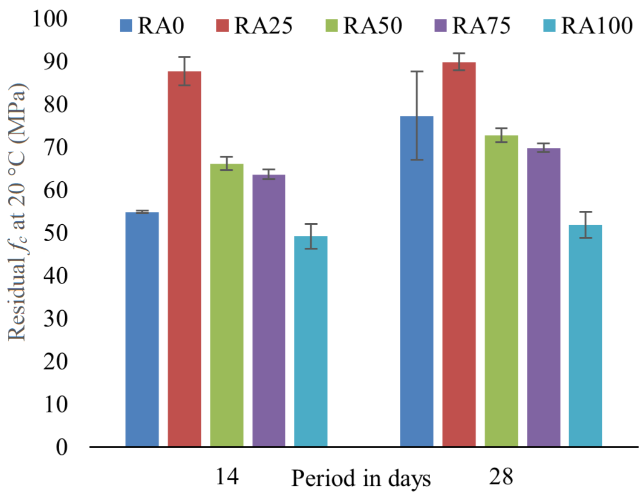


Fig. 3 Pre fire fc of different RAC

proportion of R-CoA increases. Tijani et al. [27] reveals using RA that does not meet with the standards leads to a more significant decrease in f_c. Yousuf and Hlavička [28] investigates that incorporating 20% RA in concrete has a negligible effect on its f_c compared to traditional or conventional concrete. However, at 100% RA replacement, a significant reduction in strength occurs, primarily due to the RAs' inherent porosity and weaknesses.

The mix containing 25% RAs (RA25) has the highest strength, indicating that partial replacement can improve the performance f_c of concrete. This improvement is likely due to better matrix compatibility, interfacial bonding, and optimized particle packing, which reduces voids and increases density. Additionally, the rough texture of RAs enhances mechanical interlocking with the cement matrix, while residual cementitious material on the RA surface contributes to further pozzolanic activity, improving the microstructure. Also at lower replacement levels, the combined effect of NAs and RAs, along with the superplasticizer (SP), enhances the concrete's performance. The improved dispersion of cement particles, aided by the SP, minimizes voids and micro-cracks within the concrete matrix. SPs enhance the cement paste's flowability, ensuring better bonding between the RAs and the new cement paste. This reduces the formation of weak ITZ. This creates a denser microstructure, increasing the overall strength. Salem and Burdette [29] suggests that improvement in the f_c of recycled concrete (RC) can be attributed to the rough texture and absorption capacity of the adhered mortar in the RAs. These characteristics enhance the bonding and interlocking between the cement paste and the RAs, resulting in better performance compared to conventional concrete, but Abed and Lubloy [30] observed RAC has higher porosity due to the adhered mortar attached to the original aggregate causing the appearance of multiple ITZ. Etxeberria et al. [31] also demonstrates that the newly formed ITZ between the RA and the cement paste proved to be effective. This ITZ exhibited a lower water to cement ratio compared to the adhered mortar in the recycled aggregate and the new cement paste. As a result, the ITZ was significantly denser than the adhered mortar (old paste), which is inherently weaker.

Fig. 4 illustrates the variation in residual f_c (MPa) of concrete specimens with different RA replacement levels (RA0, RA25, RA50, RA75, and RA100) subjected to increasing temperatures ranging from 20 °C to 800 °C. During which the specimens were meticulously pre-dried for six days in a moderately heated oven at 60 °C, following 28 days of curing to eliminate any residual moisture content within the specimen to reduce the risk of spalling during the heating process and ensuring more reliable test outcomes effective. This ITZ exhibited a lower water-to-cement ratio compared to the adhered mortar in the RA and the new cement paste. As a result, the ITZ was significantly denser than the adhered mortar (old paste), which is inherently weaker. Kou and Poon [32] suggested that the f_c of RAC depends not only on the quality of the RA but also on the characteristics of the original parent concrete.

However, as the RA percentage increases to 50%, 75%, and 100%, f_c decreases. This reduction is mainly due to the inferior properties of RA compared to NAs, including weaker ITZ, increased porosity, and a greater prevalence of internal flaws and microcracks. These defects act as stress concentrators under load, leading to a substantial loss of strength. At higher replacement levels, the cumulative disadvantages of RA dominate, compromising the mechanical integrity of the concrete. Despite this, all mixes exhibit notable strength gains over time, especially within the first 14 days, followed by a slower rate of increase up to 28 days. Rahal [33] observed that compared to RAC, normal aggregate concrete (NAC) achieved a higher percentage of its 28-day strength within the first 7 days. However, RAC showed a greater percentage of strength gain after this initial period, including beyond the 28 days. On average, the 56 day strength was 7% higher than the 28 day strength for RAC, while for NAC, it was 4% higher, indicates RAC exhibits continued strength development over time. Moreover Martínez-Lage et al. [26] investigated that the decrease in the f_c was more pronounced in recycled concretes incorporating SP, likely due to the interaction between the admixture and the fines present in the waste material.

It has been observed that the f_c of concrete specimens decreases as the temperature increases, showing the detrimental impact of elevated temperatures on concrete's mechanical properties. The rate of strength loss increases significantly beyond 400 °C, with almost all mixes reaching minimal strength at 800 °C. However, 25% replacement shows a rise in f_c that peaks at about 82 N/mm^2 at 200 °C, this is because the moderate heat at lower temperatures can improve the microstructure of concrete by filling micro voids and enhancing the hydration of unreacted cement particles [34], this phenomenon is attributed to the improved quality of the ITZ between the quarzitic aggregates and the new mortar. But RA25 shows gradual decline in f_c beyond 200 °C but still higher than the rest of the substitutions. Temperatures exceeding 200 °C cause the matrix water to evaporate, which weakens the binding and causes microcracking. Zega and Di Maio [34] further investigated that when specimens were exposed to

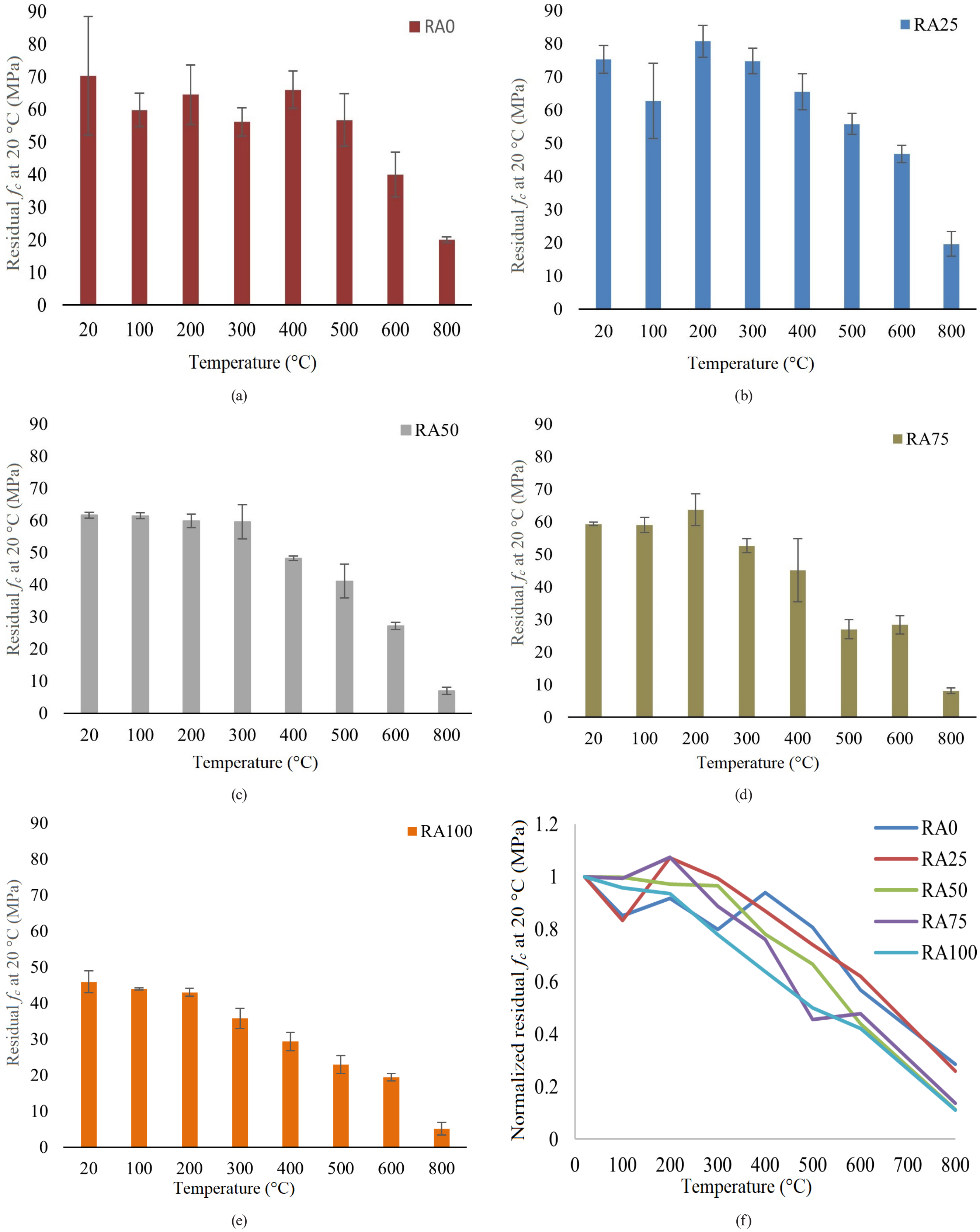


Fig. 4 Post fire fc of RAC at different substitution: (a) RA0; (b) RA25; (c) RA50; (d) RA75; (e) RA100; (f) Normalized curve of all individual data

a temperature of 500 °C for 1 h and subsequently cooled to ambient conditions. The samples prepared using crushed quartz aggregate and recycled quartz aggregate demonstrated enhanced residual strength.

Moreover, the concrete that contains higher substitution of RA: RA50, RA75, and RA100 has weaker and more porous ITZs, which causes strength loss to occur more quickly. It has also been observed at 400–600 °C the f_c of all blends decreases significantly in which RA25 drops to about 50 N/mm^2, Significant reductions are seen in RA50 and RA75, which reach about 30 to 40 N/mm^2. Further, RA100 falls to about 25 N/mm^2, since the rate of microstructural deterioration increases between 400 °C and 600 °C. The cement matrix undergoes significant cracking, and the weaker mechanical properties of RAs become more evident. Furthermore, the differential in thermal expansion between the cement paste and the aggregates causes thermal stresses to rise [35]. The f_c exhibited an initial increase and subsequently followed by a drop while maintaining a consistent RCA content. Furthermore, the strength reached the maximum value at 400 °C, where the f_cs of RC30 (25%, 50%, and 100% RCA) reached their highest, showing reductions of 4%, 14%, and 19%, respectively.

As the temperature raises from 600–800 °C All mixtures have a sharp decline in f_c, RA25 loses almost 75% of its initial strength, falling to 20 N/mm^2. Similar patterns are seen by RA50 and RA75, which decrease to 10–20 N/mm^2. The deterioration of RA100 is the worst, approaching 10 N/mm^2. This sewer strength loss is due, at 600–800 °C all mixtures have a sharp decline in f_c because the calcium silicate hydrate (C-S-H) gel loses a lot of strength when it is dehydrated. Microcracks and other flaws in the RAs of RA50, RA75, and RA100 increase stress concentrations and hasten structural collapse. Salahuddin et al. [36] also observed that for concrete mixtures exposed to 200 °C, an increase in the proportion of RAs led to a reduction in residual f_c. At 400 °C, the differences in residual strength between concrete mixtures with varying percentages of RAs diminished significantly, and this trend persisted even at an exposure temperature of 600 °C. When opposed to RA25, where mechanical interlocking is initially superior, the weak ITZs in RA mixtures worsen strength degradation. Zhang et al. [35] found that the exposure at 800 °C had the pronounced impact and resulting in the greatest degradation. However, On the other hand, RAC's strength reduction ratio following treatment at 20°C was comparable to that following treatment at 200 °C. It demonstrated how the high temperature treatment for waste concrete might somewhat mitigate the adverse effects of raising the replacement ratio, which was most likely caused by the RCA's declining adherent mortar content.

3.2 Flexure tensile strength (f_l)

Fig. 5 illustrates there is a general decrease in f_l as the temperature increases, all the concrete mixtures show a significant decrease in f_l as the temperature ranges from 20–800 °C. This decline reflects the degradation of the concrete matrix and weakening of the cement paste-aggregate bond strength at elevated temperatures. Hawileh et al. [37] also observed the f_l decreases as both the temperature and the percentage of RA increase. When concrete specimens were exposed to a temperature of 200 °C, the reduction in flexural tensile strength (f_l) was observed to be 11.49%, 15.16%, 14.72%, and 32.82% for RA replacement levels of 0%, 50%, 75%, and 100%, respectively. However, in comparison to higher RA combinations (RA75 and RA100), mixtures with a smaller percentage of RA (RA25 and RA50) demonstrate higher flexural tensile strength throughout all temperature ranges. This phenomenon is likely due to the higher quality and mechanical characteristics, Higher mechanical strength, better resistance to heat induced deterioration, reduced porosity of NAs over RAs may likely because of the residual cement mortar attached to RA reduces the bond strength between the aggregate and the adhered mortar, resulting in weak zones that hasten the deterioration of the strength under thermal stresses. RA typically have higher water absorption and increased porosity which promotes rapid loss of free and bound water at elevated temperatures, resulting in microstructural damage and cracking. In comparison to natural virgin aggregates, the interface between RA and cement paste is weaker and more porous, which lowers f_l and exacerbates thermal degradation. A similar pattern was observed as the temperature increased from 200 °C to 400 °C [37], with f_l reductions ranging from 23.04% to 27.59% for specimens with lower percentages of RA. However, for specimens with 100% RA, the reduction in f_l was more pronounced, reaching 32.82%. Moreover, it is observed till 300 °C, a moderate reduction in flexural tensile strength is observed. At this stage, dehydration of the cement pastes and micro-cracking due to thermal expansion are dominant, but the matrix still retains some strength. This phenomenon is likely due to the development of heat stresses and the loss of free water inside the concrete matrix. Also, during this phase localized micro cracking is induced by the concrete component' linear thermal expansion. Dwaikat and Kodur [38] illustrates that the pore pressure can reach values as high as 8 MPa, significantly exceeding the tensile strength of concrete,

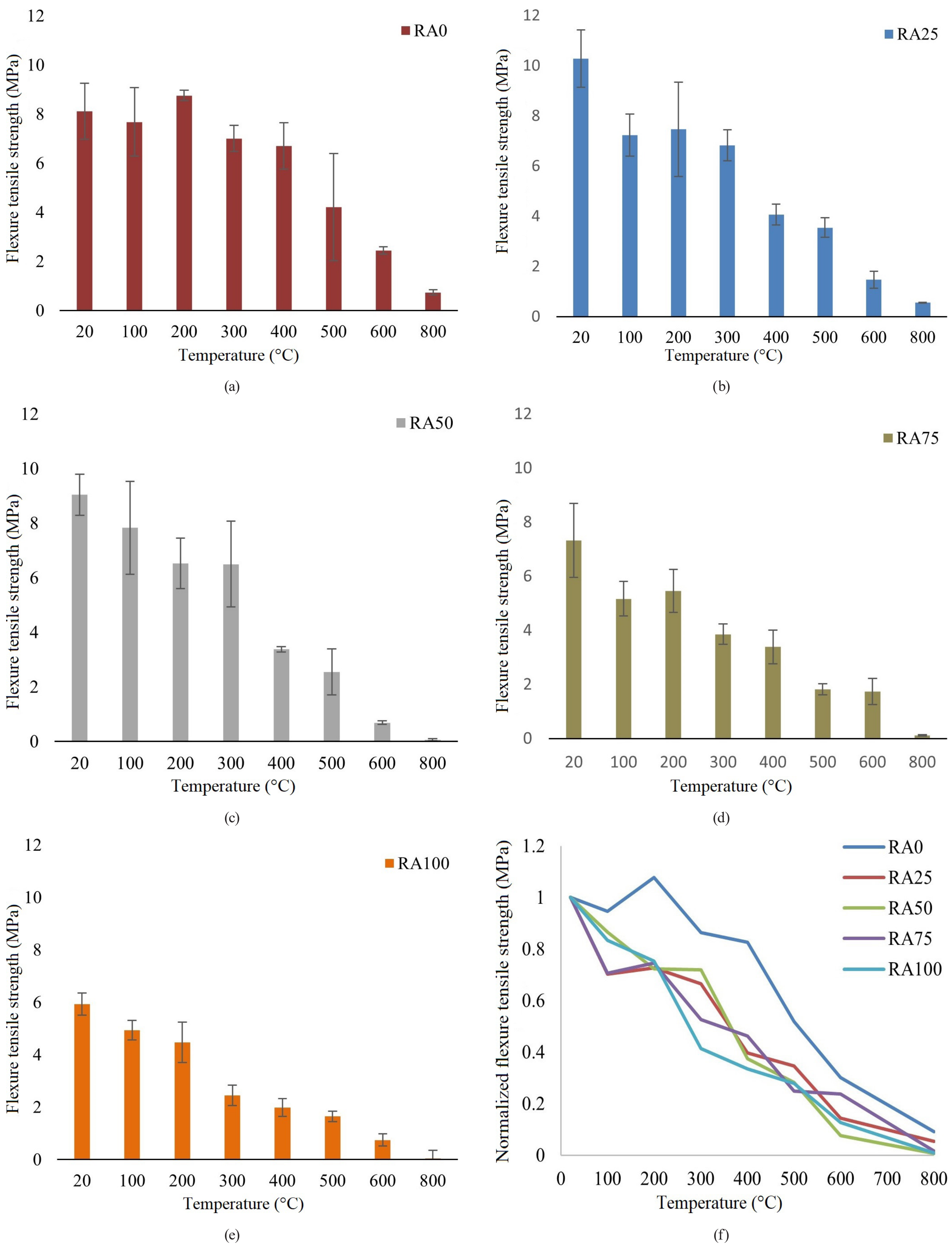


Fig. 5 Post fire f_l of RAC at different substitution: (a) RA0; (b) RA25; (c) RA50; (d) RA75; (e) RA100; (f) normalized curve of all individual data

which is approximately 5 MPa. This excessive pressure can lead to a severe form of cracking commonly referred to as thermal spalling in concrete. Gawin et al. [39] also mentions thermal spalling is generally attributed to two main factors, the accumulation of high pore pressure near the heated surface of the concrete, caused by the rapid evaporation of moisture, and the release of stored energy due to thermal stresses, which arise from high levels of restrained strains induced by thermal gradients.

More noticeable decrease in f_l has been observed as the temperature ranges from 300–600 °C, when temperatures rise from 300–600 °C strength loss accelerates because of the thermal dehydration of $Ca(OH)_2$ and the onset of C-S-H instability in cement matrix. As RAs have a weaker ITZ and higher porosity, which worsens fracture propagation under heat loading, loss of cohesion between the old and new cement paste and possible thermal incompatibility between the cement paste and the RA, the flexural tensile strength drop is particularly noticeable in RA75 and RA100. Beyond 600 °C all the mixtures show a sharp decline in flexural tensile strength which falls nearly to the zero as the temperature reached to 800 °C. At these extreme temperatures, entire decomposition of C-S-H and disintegration of the cement matrix occur.

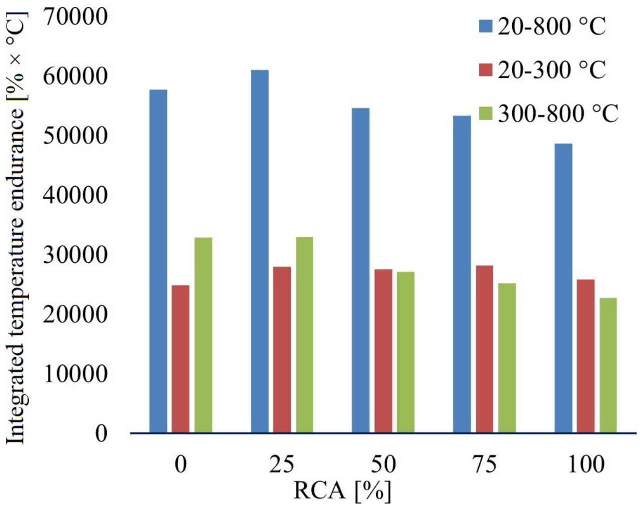
Moreover, the mixtures with higher RA content shows rapid deterioration due to their diminished intrinsic mechanical properties and reduced ability to with stand heat load leading to loss of f_l but RA0 outperformed all the substitution. Gawin et al. [39] observed the release of chemically bound water from C-S-H becomes pronounced at temperatures exceeding 110 °C. The dehydration of hydrated calcium silicate, combined with the thermal expansion of aggregates, generates internal stresses, leading to the formation of microcracks from 300 °C onward. Calcium hydroxide $Ca(OH)_2$, a key compound in cement paste, begins to dissociate around 530 °C, contributing to concrete shrinkage. The effects of high temperatures become significantly more pronounced beyond 500 °C, with most changes at this stage considered irreversible. Further decomposition of C-S-H gel, the primary strength-giving component of cement paste, occurs above 600 °C, and by 800 °C, concrete typically exhibits severe deterioration. In general, it can be seen from Fig. 3 that RA0 outperformed all the replacement substitutions but RA25 and RA50 perform better among all replacement levels since they contain a larger percentage of durable NAs while RA75 and RA100 which break down more quickly because aggregates with intrinsic flaws disintegrate more quickly. Due to matrix disintegration and thermal cracking, strength drastically decreases above 600 °C in all cases.

4 Temperature endurance

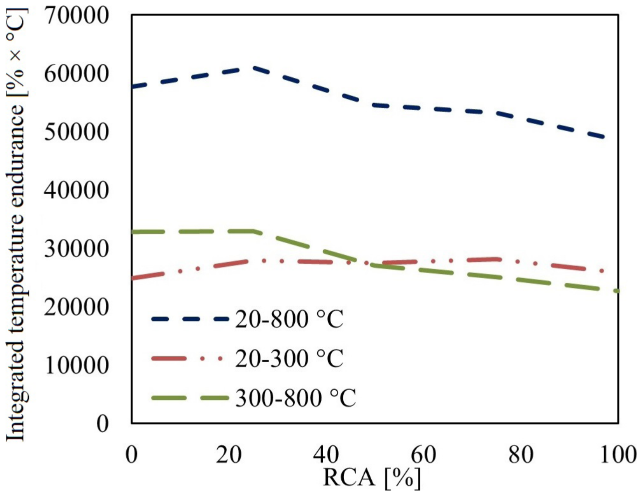
Temperature endurance plays a pivotal role in determining the durability and performance of concrete under extreme environmental conditions. To assess this property, standard testing method fire resistance tests [40], was utilized to evaluate the temperature endurance of concrete samples incorporated with RAC.

The data derived from the f_c measurements can also be assessed by another method, integrated temperature endurance (ITE) value, representing the total area under the residual f_c curves offers an alternative approach for analyzing data [41, 42]. The definite integrals were computed using the chained trapezoidal rule approach. Given the axis unit of measurement in the diagram, the ITE unit is expressed as [% × °C]. The computation of these definite integrals, whether across the entire curve 20–800°C or within a specific temperature range for instance (20–300 °C and 300–800 °C) [43].

From Fig. 6 The study implies that RCA inclusion has a minimal impact on overall temperature endurance since total ITE (20–800 °C) is comparatively constant across all RCA incorporation levels. However, when the RCA concentration rises, ITE falls in the higher temperature range (300–800° C), suggesting a loss in fire resistance at elevated temperatures. On the other hand, ITE marginally improves with RCA in the lower temperature range (20–300 °C) indicating improved retention f_c at moderate temperatures. Concrete undergoes significant phase transformations when exposed to elevated temperatures, which impact its microstructure, strength, and durability. The thermal behavior of RCA concrete is particularly influenced by these transformations, as RCA contains residual mortar, and a weaker ITZ compared to NA concrete. C-S-H which is the primary binding gel in hardened cement paste, responsible for strength, undergoes partial dihydroxylation, causing a gradual reduction in cohesion bonding between paste and aggregate as the temperature increases from 100–300 °C. Also, Portlandite ($Ca(OH)_2$) is formed during cement hydration and contributes to the concrete's alkaline stability. At around 400–450 °C, portlandite begins to decompose into calcium oxide (CaO) and water vapor, this decomposition leads to volume reduction and pore



(a)



(b)

Fig. 6 ITE at different RAC% age: (a) ITE bar representation; (b) ITE curve representation

formation, weakening the matrix and making it more susceptible to cracking [44]. Moreover, RCA with siliceous aggregates (such as quartz) undergoes a different transformation, where quartz expands rapidly above 550 °C known as the *α*–*β* quartz transformation, leading to additional internal stresses [44]. Fehérvári [43] revealed that Cem I 52.5 N OPC exhibits higher relative residual f_c at lower temperatures. However, despite significant strength losses at mid and high temperatures. Hlavička [45] observed regarding f_c, the findings indicate that the ITE consistently declines at a 25% replacement level of RCA, suggesting an accelerated degradation rate. At 50% RCA content, the ITE remains relatively stable or exhibits a slight increase. When the RCA content reaches 75%, two distinct patterns emerge with lower strength RCA (RCA mix2), the ITE continues to decline, indicating a heightened degradation rate, whereas with higher-strength RCA (RCA mix1 and RCA mix2), the ITE shows a further increase, implying a reduction in degradation tendency.

5 Conclusions

Based on experimental investigation and observation, the following conclusions have been concluded:

- f_c at ambient temperature increases when NAs are partially substituted with 25% RA, this improvement is ascribed to improved particle packing, and adhered mortar contributing to pozzolanic activity, which results in strong and denser microstructure.
- The combined effect of natural and RAs with a SP improves concrete performance. The SP enhances cement particle dispersion, reduces voids, and strengthens the bond between RAs and new cement paste, the SP increases the flowability of the cement paste, coat the surface of RAs more effectively, minimizing weak ITZ. This creates a denser microstructure, boosting overall strength.
- A steady decrease in f_c is noted as the RA concentration rises to 50%, 75%, and 100%. This reduction results from the intrinsic flaws in RAs, which negatively impact the mechanical performance of the concrete matrix. These flaws include increased porosity, microcracks, and weaker ITZ.
- As temperatures rise, particularly above 400 °C, the f_c of RAC decreases dramatically. While RA25 shows improved strength at 200 °C (82 N/mm^2) due to enhanced hydration, all mixes experience sharp declines between 600–800 °C, retaining minimal strength (10–20 N/mm^2). This severe degradation is attributed to the dehydration of C-S-H gel and the development of microcracks, exacerbated by flaws in RAs.
- Flexural tensile strength decreases significantly with temperature, reflecting degradation of the concrete matrix and weakening of the cement paste-aggregate bond. Mixtures with lower RA content (RA25 and RA50) show higher strength due to better mechanical properties and reduced porosity, while higher RA content (RA75 and RA100) exhibits greater strength loss due to weaker bonds. Up to 300 °C, strength reduction is moderate, driven by dehydration and microcracking. Beyond 300 °C, loss accelerates due to thermal dehydration of $Ca(OH)_2$ and C-S-H instability, with

a sharp decline beyond 600 °C, as the cement matrix disintegrates, particularly in higher RA mixtures.

- Post-fire, compressive and f_t decline sharply, particularly above 400 °C, due to C-S-H gel dehydration, microcracking, and weakened ITZs in higher RA mixtures.
- Substitution up to 25% of NAs with RAs provides a viable approach to reducing environmental impact while maintaining good mechanical performance. This substitution not only helps conserve natural resources but also reduces construction waste, contributing to more sustainable building practices.
- RCA has minimal effect on overall temperature endurance but reduces fire resistance at high temperatures while improving strength retention at moderate levels.

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