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RESEARCH PAPER

High-Temperature Residual Compressive Strength in Concretes Bearing Construction and Demolition Waste (CDW): An Experimental Study

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Abstract
The steady rise in the amount of waste generated daily worldwide and its concomitant stockpiling poses significant environmental issues. In an attempt to alleviate that problem while reducing the consumption of natural resources and contributing to a more sustainable construction industry, concrete technology research has focused on replacing natural aggregate with different types of waste. Little is known about the behaviour of such waste materials at high temperatures, however. The present study consequently aimed to analyse the effect of high temperatures on compressive strength in recycled aggregate-bearing concretes. Masonry, mixed and concrete waste products, jointly known as construction and demolition waste, CDW, were used as partial replacements for the natural material at ratios of 20% or 30%. The specimens were subsequently tested for compressive strength at 20 °C and after exposure to temperatures of 350 °C and 500 °C. The findings showed that at 350 °C compressive strength declined by 21% in materials containing 20% masonry waste, while the decline in materials bearing mixed recycled and recycled concrete waste ranged from 0 to 5%. The concrete with 30% masonry waste in lieu of natural aggregate exhibited a 32% loss in strength at 500 °C, whereas the loss in the other materials studied under the same conditions did not exceed 9.5%. The highest performance under heat stress was observed for concretes bearing 20% mixed recycled aggregate.

Keywords Concrete · Compressive strength · Recycled aggregate · High temperature · Residual properties

1 Introduction

Although a considerable share of construction and demolition waste can be recycled, the mean recovery rate across the EU-28 is presently < 50%. That compares rather poorly with the 70% target for 2020 set by the Union's Waste Directive (2006). According to Spain's federation of construction and demolition waste recovery companies [Federación Española de Empresas Recicladoras de Residuos de Construcción y Demolición (2018)], over 75% of the CDW generated in Spain is managed irregularly. Eurostat (2018) statistics on waste that trace processing trends in the European Union fairly closely estimate Spain to generate around 40Mt of CDW yearly. Further to those numbers, the country is the fifth-largest producer of such waste in the EU (Del Rio et al. 2010). Approximately 10–20% of those materials is recycled for reuse as aggregate in construction.

Moreover, concrete is one of the construction materials best suited to accommodate unconventional components. Recycled CDW covers a wide range of types of refuse, including masonry (54%), concrete (12%) and asphalt waste and other minority components such as wood, glass and plastic (Waste Directive 2006).

The use of CDW in concrete has been intensively studied by a number of authors: Hachemi and Ounis (2015) reported smaller high temperature-induced weight loss in concrete bearing 20% masonry recycled aggregate (MRA) than in materials prepared with natural aggregates (with one exception at 350 °C). Concretes made with recycled masonry have been observed to be lighter weight than those made with natural aggregates (Akhtaruzzaman and Hasnat

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(1983); Khalaf and DeVenny (2004)), but to be slightly less workable (Mansur et al. (1999); Medina-Martínez et al. (2012)). Cachim (2009) found the latter to be rectifiable, however, by pre-soaking the aggregate to enable concrete mixing water to penetrate the various components uniformly for more effective late-age curing. The lower density and higher porosity and sorptivity reported in recycled masonry relative to natural aggregate have been shown to directly affect concrete mechanical properties, with compressive strength declining with rising replacement ratio. In contrast, Martins et al. (2016) observed that after exposure to high temperatures, particularly 400 °C and 600 °C, concrete with recycled masonry as the coarse aggregate exhibited higher mechanical performance than the conventional material. They believed the primary reasons for the decline in compressive strength to include CHS gel dehydration and expansion-induced spalling during the chemical conversion of $Ca(OH)_2$ to CaO.

The discrepancies detected in the literature merit a more detailed study. Hachemi and Ounis (2015), Akhtaruzzaman and Hasnat (1983) and Khalaf and DeVenny (2004) reported lower compressive strength in crushed brick aggregates at both ambient and high temperatures than in samples made with natural aggregates only. On the contrary, Martins et al. (2016) found compressive strength to be the same or similar in concretes irrespective of the nature of the aggregates (recycled or natural), although that depended on the w/c ratio, the origin of the aggregate, curing time and replacement ratio. Alizadeh et al. (2021) claimed the use of recycled masonry aggregate to have a negligible effect on high-temperature mechanical performance. According to Govindagowda et al. (2017), their suggested that concrete bearing aggregate with recycled masonry waste performed well at high temperatures, with performance comparable to that observed in conventional concrete. Concrete with 50% crushed masonry as a replacement for natural fine and coarse aggregate proved to be apt for elements exposed to temperatures up to 400 °C, above which significant declines in strength were recorded (Canbaz (2016)). Keshavarz and Mostofinejad (2020) contended that at higher replacement ratios porcelain coarse aggregates vested concrete with greater strength at temperatures of up to 600 °C. Similarly, Dey and Pal (2013) found that heat resistance up to 600 °C was high in conventional concrete containing crushed brick aggregate.

When exposed to heat, concretes bearing mixed recycled aggregate (MRA) underwent more severe weight loss at temperatures of ≥ 350 °C than analogous materials with natural aggregate. Laneyrie et al. (2016) and Kuo et al. (2013) attributed such behaviour to water evaporation-mediated hydrate decomposition at those temperatures. In contrast, at > 500 °C mass loss was greater in concrete bearing natural aggregate as a result of portlandite decomposition or decarbonation.

Density and sorptivity were the properties where recycled and conventional concrete differed most significantly. The bound mortar found in recycled aggregate hampers drying, raises shrinkage and creep substantially, lowers the modulus of deformation and increases strength loss. The high porosity of such bound mortar favours more intense water penetration in recycled concrete than found in the conventional material. The bound mortar-new mortar bond is a weak point in concrete bearing MRA.

Kou et al. (2014) reported that porosity rose with exposure to higher temperatures and rising replacement ratio: the higher the mixed recycled aggregate ratio, the softer concrete consistency. Xiao et al. (2013) contended that at ambient temperature compressive strength declined more steeply at higher replacement ratios, while Laneyrie et al. (2016) concluded that the residual performance in recycled and conventional concretes was generally similar but slightly better in the latter. Pliya et al. (2019) attributed a minor decline observed in compressive strength to the partial replacement of natural with mixed recycled aggregate. In contrast, Kou et al. (2014) found compressive strength to be higher in specimens bearing 20% mixed recycled instead of natural aggregate due, among others, to the higher porosity in the former. The resulting rise in the air content would prevent pressure from building up and with-it internal cracking.

The literature on concrete bearing recycled concrete aggregate (RCA) was also reviewed. Both Guo et al. (2014) and Shin et al. (2015) observed greater mass loss than in RCA-bearing concrete than in the conventional material between ambient temperature and 350 C. The higher water content in the former would determine such greater loss, accentuated in concretes with a higher w/c ratio. More bound water evaporated from the cement matrix in RCA than in conventional concrete at T = 250 to 350 °C, leading to a significant decline in strength in the former, although from 350 to 500 °C mass loss was more intense in conventional concrete.

According to Salau et al. (2015), RCA-bearing concrete compressive strength is practically identical to strength in conventional concrete for replacement ratios of up to 20%. Gales et al. (2016), Pérez-Benedicto et al. (2012), Tarela et al. (2015) and Rodriguez et al. (2015), however, found strength to be very similar at replacement ratios of 30% or higher (with differences depending on w/c ratio, origin of the aggregate and curing time). Xiao et al. (2012) contended that compressive strength was not significantly affected in concrete containing less than 30% recycled aggregates, while Limbachiya et al. (2004) reported that up to 30% coarse recycled concrete aggregate had no impact on compressive strength, although it induced declines at higher values, which climbed with the ratio. Varona et al. (2020) observed replacement of coarse aggregate with RCA to have a beneficial effect compressive strength after exposure to high temperatures, while Vieira et al. (2011) found no significant differences in the thermal response and post-fire mechanical behaviour between concrete made with RCA and conventional concrete. On the contrary, Shin et al. (2015) reported that the results for recycled and conventional concretes were not equal at any replacement ratio.

The foregoing appears to suggest a need to update present practice with transparent experimentation to ensure comparability of the results.

Replacing fines raises the amount of bound mortar in the concrete mix (cement + aggregates), one of the major problems posed by the use of recycled aggregates. With larger particle sizes the amount of such bound mortar declines, lowering the interfacial, i.e., the weakest areas. Recycled concrete compressive strength can therefore be optimised by controlling the replacement ratio and amount of mortar bonded to recycled aggregate surfaces. The significantly slower hardening observed in recycled aggregate-bearing than in conventional concrete may translate into stronger cement-recycled coarse aggregate bonds in the former. According to Pavón et al. (2012), such developments may contribute to offsetting the shortcomings of weaker aggregate in long-term curing. The thermal expansion taking place inside the material induces concrete cracking. The concomitant internal dehydration leads to strength loss. Cracks may begin to appear in materials tested at 500 °C or, further to Salau et al. (2015), at temperatures as low as 400 °C.

Although fire is one of the most potentially destructive hazards for built structures, there is a paucity of research on the residual properties of recycled coarse aggregate concretes after exposure to high temperatures. Assessing ambient and high temperature strength loss in these new CDW-containing materials enhances the understanding of the behaviour of concrete structures exposed to fire. In light of the growing use of construction and demolition waste-bearing materials, primarily to replace part of the aggregates in concrete mixes, greater technical information than presently available on their high-temperature performance is needed. Much more work is consequently in order to assess the behaviour of concrete bearing construction and demolition waste in the event of fire. The present study assessed residual compressive strength in concrete bearing recycled masonry (RMA), mixed recycled (MRA) and recycled concrete (RCA) aggregate after exposure to high temperatures.

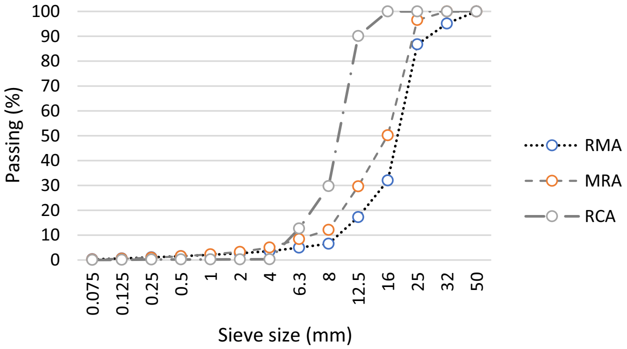


Fig. 1 Recycled aggregate particle size distribution

Table 1 Aggregate characteristics

Aggregate	SSDD* [kg/l]	Water sorptivity [%]	Maximum size [mm]	Moisture (min–max) [%]
RCA	2.380	6.14	12.5	0.61–2.29
RMA	2.211	9.80	32.0	0.42–0.89
MRA	2.463	3.97	25.0	0.38–0.83
Gravel 8–12	2.641	0.36	12.5	0.08–0.37
Gravel 4–8	2.640	0.40	8.0	0.10–1.71
Sand 0–4	2.631	0.05	4.0	0.04–1.31

*SSDD saturated surface dry density

2 Materials and Methods

2.1 Particle Size Distribution in the Recycled Aggregates

The high-temperature behaviour of a number of concretes containing recycled aggregates was assessed. The origin of the recycled aggregate informed the structure of the study. Preliminary tests were run on samples provided by recycling plants in the Spanish provinces of Madrid, Toledo and Guadalajara to determine the three types of recycled aggregates to be studied. The natural aggregate used was also characterised. The particle size distribution curves found for recycled masonry (RMA), mixed recycled (MRA) and recycled concrete (RCA) aggregate are graphed in Fig. 1.

Saturated surface dry density, water sorptivity, maximum particle size and maximum and minimum moisture values for the natural and recycled concretes studied are given in Table 1. Moisture was determined a few hours before mixing.

2.2 Experimental Methodology

The composition of the concrete mixes is listed in Table 2. The constant w/c ratio (0.46) applied throughout ensured

Table 2 Concrete composition

SSD weight [kg]	Recycled masonry aggregate				Recycled concrete aggregate				Mixed recycled aggregate				Natural aggregate	
	RMA 20		RMA 30		RCA20		RCA30		MRA20		MRA30		CTR	
	20%		30%		20%		30%		20%		30%		–	
Cement I 42,5 R	300		300		300		300		300		300		300	
Recycled aggregate	368	20%	551	30%	383	20%	574	30%	388	20%	582	30%	0	0%
Siliceous gravel 8–12	442	22%	301	15%	60	3%	60	3%	361	18%	281	14%	522	26%
Siliceous gravel 4–8	442	22%	301	15%	381	19%	281	14%	361	18%	301	15%	522	26%
Siliceous sand 0–4	718	36%	797	40%	1156	58%	1057	53%	877	44%	817	41%	957	48%
Water	138		137		138		138		139		139		139	
Rheobuild 1000 fluidiser	2.294		1.729		6.000		6.000		4.500		4.500		5.103	

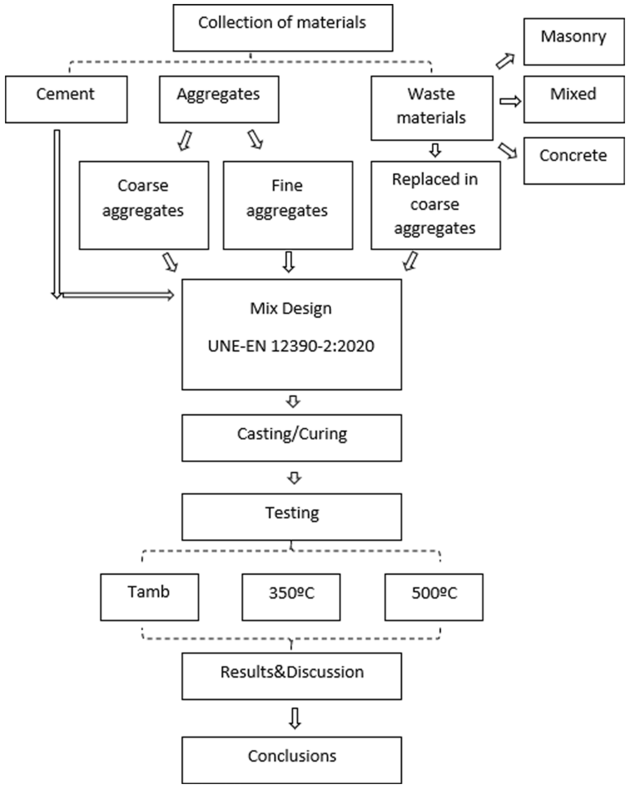


Fig. 2 Flowchart showing study stages

comparability among materials with the same starting conditions and varying aggregate origin, type and replacement ratio: 0, 20 or 30%. A CEM I 42.5 R cement was used to prepare all the concretes. The respective grading moduli were $MG_{RMA} = 10.45$, $MG_{MRA} = 9.89$ and $MG_{RCA} = 8.66$. The methodology flowchart is reproduced in Fig. 2.

2.3 Sample Preparation

The concretes were prepared as specified in Spanish and European standard UNE EN 12,390–2:2020 and batched as listed in Table 2. The seven 150 mm cubic specimens made for each type of aggregate and replacement ratio (Fig. 3) were cured for 24 h in a humidity chamber for 28 d at 100% RH. Three specimens not exposed to heat and one heated to 350 C were then tested for compressive strength. Analogously, one unheated specimen and one heated to 500 °C were tested after 42 d. The seventh specimen is presently in the humidity chamber in anticipation of future testing. Seven 150-mm cubic specimens were prepared for each replacement ratio and type of aggregate, for a total of 49 (7 control, 7 RMA20, 7 MRA20, 7 RCA20, 7 RMA30, 7 MRA30 and 7 RCA30). Samples exposed to heat treatment reached 350 C in 23 min and 500 °C in 27 min. The specimens were heated for 1 h after the oven reached the target temperature (350 or 500 °C). The oven was subsequently switched off,

Fig. 3 **a** Aggregates prepared for mixing with cement; **b** laboratory mixer to prepare test specimens

and the specimens left inside to gradually cool to ambient temperature. The aim was to minimise the gradient and raise the sample core to a temperature as close possible to 350 or 500 °C. That procedure prevented explosive spalling and microstructural analysis misreading due to distortions introduced by overly rapid cooling.

Fresh state consistency as determined with a standard mould was found to lie in a suitable range: 0.5 to 4.0 cm (Fig. 4). The materials containing natural aggregate were dryer than the characteristically more plastic concretes bearing recycled aggregate. Slump diameters were largest in the mixes with masonry recycled aggregate, followed by the materials with recycled mixed aggregate. The smallest slumps were recorded for the mixes prepared with recycled concrete aggregate (Table 3).

2.4 Thermal Exposure

The cubic specimens with 0, 20 or 30% recycled aggregate were heated to temperatures of 350 and 500 °C in a Nabertherm Mod. N20/HR compact chamber electric furnace featuring three-sided (two sides and floor) radiation. Due to the paucity of construction and demolition waste meeting the requirements determined by the study, only two of the seven specimens prepared for each replacement ratio and aggregate type were tested at 350 and 500 °C. That approach ensured reliable research results with a small number of samples while also ruling out the possibility of distortions owing to contaminated or otherwise altered raw materials. Once the target temperatures were reached, the specimens were left in the unheated furnace to cool to prevent thermal shock. Their compressive strengths were subsequently determined on an Ibertest 600kN universal test frame (Fig. 5).

3 Results and Discussion

The weight, density and compressive strength values given in Table 4 for the seven types of concrete after exposure to heat at 350 and 500 °C were consistent with the values reported in the literature.

3.1 High-Temperature Performance: Weight and Density

At ambient temperature, the weight loss in specimens bearing 20% recycled masonry aggregate (RMA) came to 2.0% and those with 30% replacement to 3.5%. Similar losses were observed for *t*he mixes bearing recycled concrete aggregate (RCA) (Fig. 6). While weight loss in the recycled masonry aggregate (RMA) mixes was 4.10% after exposure to T = 350 °C, the post-exposure loss at 500 °C was just 2.16% due to material rehydration. The concrete/aggregate incompatibility resulting from their higher siliceous aggregate content translated into greater weight gain in the specimen heated to 500 °C. The dehydration and rehydration occurring in concrete exposed to high temperatures alter the cement paste and therefore the properties of the material. At high temperatures, concrete dehydrates and rehydrates,

Fig. 4 Standard mould slump test

Table 3 Slump test results, density and air content in concrete mixes

Property	Unit	Results						
		RMA20	RMA30	MRA20	MRA30	RCA20	RCA30	CTR
Slump test (Abrams cone)	cm	3.5	4.0	2.0	2.5	0.5	1.0	1.5
Density	kg/m^3	2297	2265	2326	2316	2282	2290	2335
Air content	%	3.1	3.3	3.6	3.1	2.5	3.4	2.5

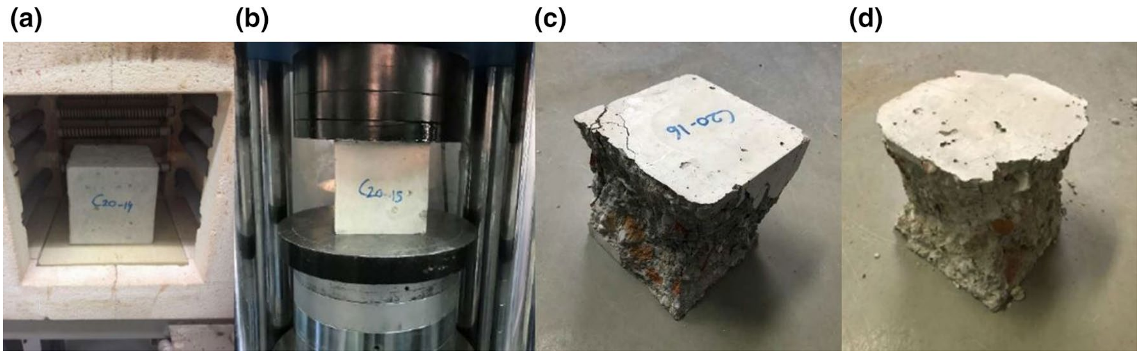
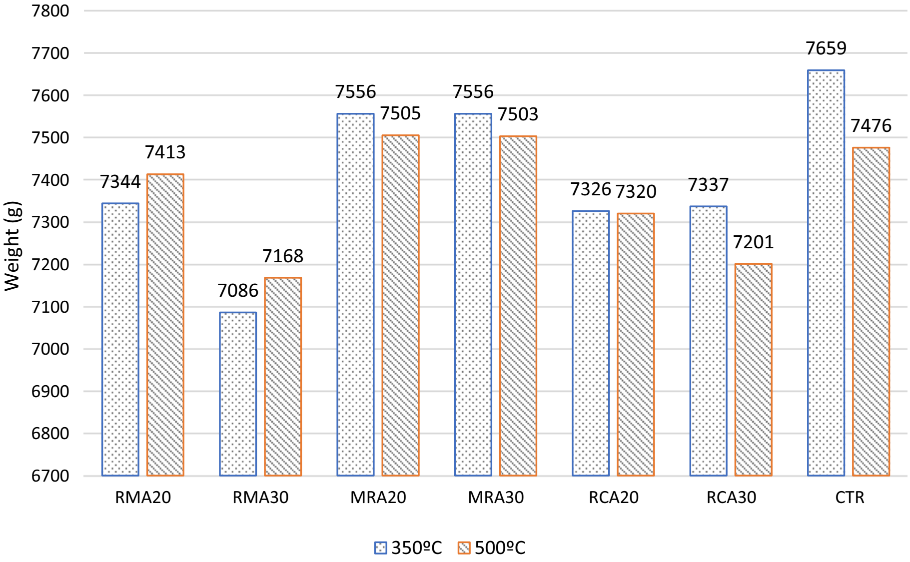


Fig. 5 **a** Test specimen in electric furnace; **b** specimen prepared for compressive strength test; specimen after heating to 500 °C for **c** 24 h; **d** 14 d

Table 4 Concrete weight, density and compressive strength

Property	Unit	Temp	Test results						
			RMA20	RMA30	MRA20	MRA30	RCA20	RCA30	CTR
Weight	g	20 °C	7714	7597	7976	7857	7689	7684	7877
	g	350 °C	7344	7086	7556	7556	7326	7337	7659
	g	500 °C	7413	7168	7505	7503	7320	7201	7476
Density	kg/m^3	20 °C	2285.7	2251.0	2363.2	2328.0	2278.2	2276.7	2334.0
	kg/m^3	350 °C	2176.0	2099.6	2238.8	2238.8	2170.7	2173.9	2269.3
	kg/m^3	500 °C	2196.4	2123.9	2223.7	2223.1	2168.9	2133.6	2215.1
Compressive strength	MPa	20 °C	45.7	44.5	57.6	56.0	55.1	52.7	59.3
	MPa	350 °C	40.6	40.5	51.6	50.9	49.0	49.4	51.6
	MPa	500 °C	35.5	31.7	48.2	43.5	42.3	42.3	46.7

Fig. 6 Concrete weight after exposure to heat



altering the cement paste and consequently material properties. Studies on cement paste exposed to such intensive heat have revealed a gradual change in the C-H-S gel. At ambient temperature, replacement of natural with mixed recycled aggregate (MRA) induced variations in weight of + 1.25 at 20% replacement and naught at 30%. In specimens bearing recycled concrete aggregate (RCA), weight loss after heating to 350 °C was similar in the 20 and 30% replacement materials (4.34 with 20 and 4.20 with 30% replacement). After exposure to T = 500 °C, recycled masonry and recycled concrete aggregate-bearing mixes exhibited similar behaviour (Fig. 7).

3.2 High-Temperature Performance: Residual Compressive Strength

At ambient temperature compressive strength in concrete with 20% masonry recycled aggregate declined by 23 and at 30% replacement, by 25%. That compared to the 7.2% loss at a 20% ratio and the 11.2% drop at 30% in recycled concrete-bearing materials.

At 20 C, the mixed recycled aggregate materials performed better than either of the other two types of concretes, with declines in compressive strength of 2.95 at 20 and 5.65 at 30% replacement.

The post-exposure values (at T = 350 °C) were similar for the two replacement ratios in the RMA- and RCA-containing mixes: 21.26% loss was recorded at 20 and 21.58 at 30% replacement in the former; and 4 at 20% and 4.29 at 30% replacement in the latter. The decline in compressive strength in mixed recycled aggregate-bearing specimens was strikingly small in comparison: 0 at 20% replacement and just 1.42 at 30%.

After the specimens were heated to 500 °C, compressive strength declined by 24% in 20% masonry recycled aggregate-bearing concrete and by 32% in the 30%-replaced specimens; and by 9.45% with 20% recycled concrete aggregate and 9.5% in the mixes bearing 30% RCA.

Mixed recycled aggregate concrete also performed better than the other two when heated to 500 °C, with declines in compressive strength of 3.2 at 20, and 9.45 at 30% replacement. Although after exposure to 350 °C, the concretes with the higher replacement ratio (30%) exhibited compressive strength similar to the values recorded for the lower percentage (20%), at 500 °C the decline was significantly steeper at the higher ratio.

The decline in concrete compressive strength attributable to high temperatures is plotted in Fig. 8, while inter-concrete performance is compared in the bar graphs in Fig. 9.

4 Conclusions

The optimal replacement ratios for the use of construction and demolition waste (CDW) in concrete must be determined to enhance construction element sustainability. The conclusions drawn from the performance of concrete specimens exposed to high temperatures as observed in the present experimental study are set out below.

Lowest performance was observed for specimens prepared with masonry recycled aggregate.

The specimens containing 20% mixed recycled aggregate performed better than the natural aggregate-bearing control at both 350 and 500 °C.

At 500 °C, the replacement ratio had a substantial impact on compressive strength, particularly in specimens bearing 30% recycled masonry aggregate.

Concretes prepared with recycled concrete aggregates performed well at both 20 and 30% replacement, with compressive strength declines of under 9.5%.

In terms of compressive strength values after exposure to high temperature, recycled masonry and recycled concrete aggregates proved to be apt alternatives for natural aggregate. The highest performance was recorded, however, for mixed recycled aggregate-bearing materials at both 20% and 30% replacement, for the presence of surface-bound mortar favoured stronger bonding between the cement and the coarse aggregate.

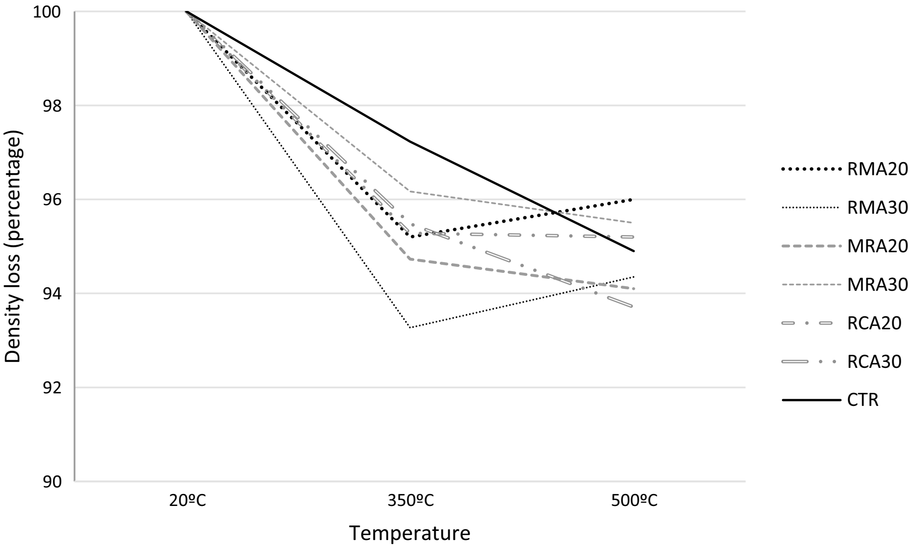


Fig. 7 Post-heat exposure density loss in CDW concretes (%) (Source: authors' formulation)

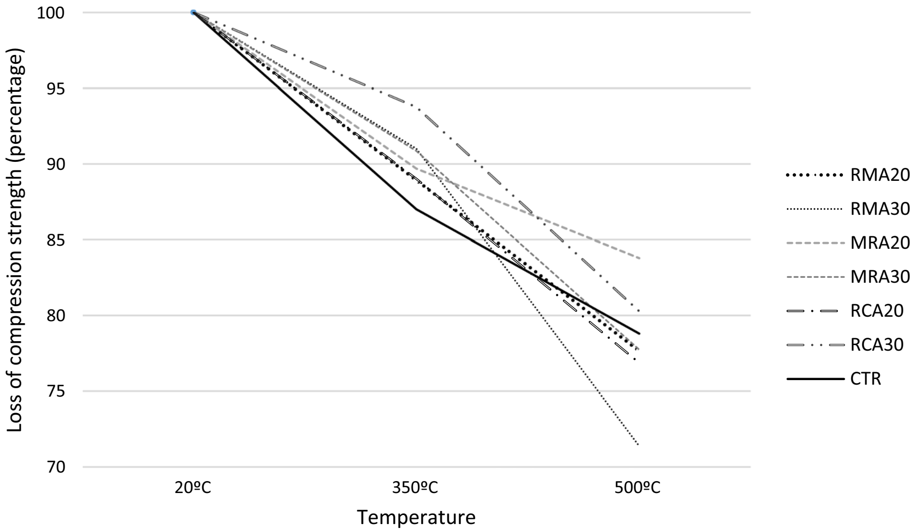


Fig. 8 Post-heat exposure compressive strength declines in CDW concretes (%)

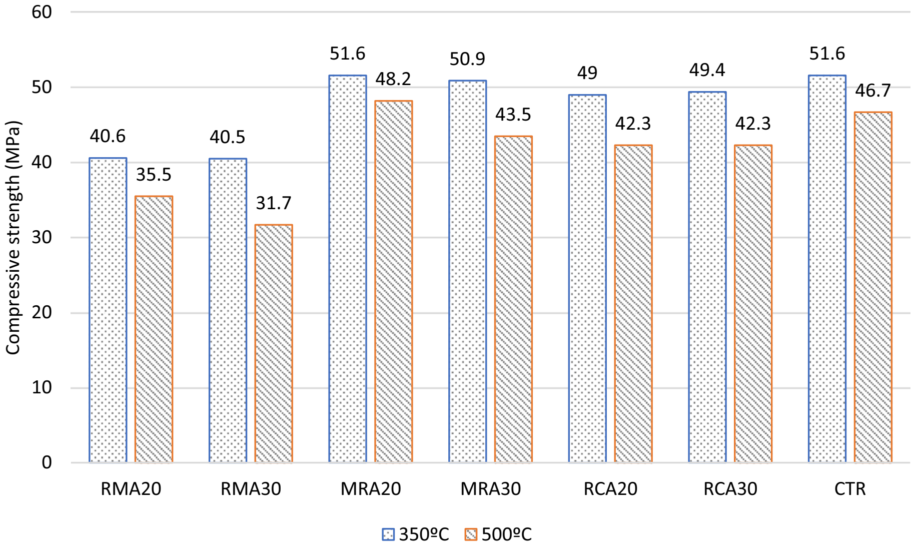


Fig. 9 Concrete compressive strength after exposure to T = 350 and 500 °C

In future, this line of research might be extended to include concrete bearing other types of construction and demolition waste, such as glass or polymers.
Another promising approach would be to explore the variation exhibited by such materials over time when exposed to high temperatures, in particular the possible effect of further cracking on strength loss.

The general conclusion drawn was that partially replacing natural with CDW aggregate may be an excellent approach to enhance concrete fire resistance.

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Authors Contributions MEM was involved in the conceptualization, formal analysis, investigation, writing-original draft, writing-review and editing and funding acquisition. ÁC contributed to the formal analysis, investigation, writing-review and editing and funding acquisition. IM helped in the formal analysis, investigation, writing-review and editing and funding acquisition. FJR contributed to the formal analysis, investigation, writing-review and editing.

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Data Availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of interest The authors declare that they have no competing interests.

References

Akhtaruzzaman AA, Hasnat A (1983) Properties of concrete using crushed brick as aggregate. ACI Con Int Design Constr 5(2):58–63

Alizadeh SMM, Rezaeian A, Rasoolan I, Tahmouresi B (2021) Compressive stress-strain model and residual strength of self-compacting concrete containing recycled ceramic aggregate after exposure to fire. J Build Eng 38:102206

Cachim PB (2009) Mechanical properties of brick aggregate concrete. Constr Build Mater 23(3):1292–1297

Canbaz M (2016) the effect of high temperature on concrete with waste ceramic aggregate. Iran J Sci Technol Trans Civ Eng 40:41–48

Debieb F, Kenai S (2008) The use of coarse and fine crushed bricks as aggregare in concrete. Constr Build Mater 22(5):886–893

Dey G, Pal J (2013) Use of Brick Aggregate in Standard Concrete and Its Performance in Elevated Temperature IACSIT. Int J Eng Technol 5(4):523–526

Waste Directive. (2006). "Protocolo de Gestión de residuos de construcción y demolición de la UE". Ref. Ares (2016)6914779 - 12/12/2016. PLAN REGIONAL DE RESIDUOS DE CONSTRUCCIÓN Y DEMOLICIÓN (2006–2016). Consejería de Medio Ambiente y Ordenación del Territorio. Comunidad de Madrid

EUROSTAT. (2018). https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics Federación Española de Empresas Recicladoras de Residuos de Construcción y Demolición. (2018).

Gales J, Parker T, Cree D, Green M (2016) Fire performance of sustainable recycled concrete aggregates: mechanical properties at elevated temperatures and current research needs. Fire Technol 52(3):817–845

Gowda G, Rao BS, Naik SM (2017) Behavior of recycled aggregate concrete on exposed to elevated temperature. Int J Civ Eng 4(6):5–13

Guo Y, Zhang J, Chen G, Xie Z (2014) Compressive behaviour of concrete structures incorporating recycled concrete aggregates, rubber crumb and reinforced with steel fibre, subjected to elevated temperatures. J Clean Prod 72:193–203

Hachemi S, Ounis A (2015) Performance of concrete containing crushed brick aggregate exposed to different fire temperatures. Eur J Environ Civ Eng 19(7):805–824

Keshavarz Z, Mostofinejad D (2020) Effects of high-temperature exposure on concrete containing waste porcelain coarse aggregates and steel chips. J Build Eng 29:101211

Khalaf F, DeVenny A (2004) Performance of brick aggregate concrete at high temperatures. J Mater Civ Eng 16:556–565

Kou SC, Poon CS, Etxeberria M (2014) Residue strength, water absorption and pore size distributions of recycled aggregate concrete after exposure to elevated temperatures. Cement Concr Compos 53:73–82

Kuo MF, Li SJ (2013) Recycled Concrete at Elevated High Temperature Duration. Appl Mech Mater 368–370:1099–1102

Laneyrie C, Beaucour A, Green MF, Hebert RL, Ledesert B, Noumowé A (2016) Influence of recycled coarse aggregates on normal and high-performance concrete subjected to elevated temperatures. Constr Build Mater 111:368–378

Limbachiya M E A Koulouris, A Roberts J J Fried A N (2004). Performance of recycled aggregate concrete. In: Proceeding of RILEM international symposium on environment-conscious materials and systems for sustainable development pp. 127-136

Mansur MA, Wee TH, Lee SC (1999) Crushed bricks as coarse aggregate for concrete. ACI Mater J 96(4):478–484

Martins DJ, Correia JR, De Brito J (2016) The effect of high temperature on the residual mechanical performance of concrete made with recycled ceramic coarse aggregates. Fire Mater 40(2):289–304

Medina-Martínez C, Sánchez de Rojas MI, Frías Rojas M (2012) Valorización de los residuos de la industria cerámica sanitaria como árido grueso reciclado en la fabricación de hormigones. Cem Hormig 954:20–31

Pavón E, Etxeberría M, Martínez I (2012) Propiedades del hormigón de árido reciclado fabricado con adiciones, activa e inerte. Revi De La Constr 10(3):4–15

Pérez-Benedicto JÁ, Río-Merino M, Peralta-Canudo JL, De la Rosa-La Mata M (2012) Características mecánicas de hormigones con áridos reciclados procedentes de los rechazos en prefabricación. Mater Constr 62(305):25–37

Pliya P, Cree D, Hajiloo H, Beaucou AL, Green MF, Noumowé A (2019) High-strength concrete containing recycled coarse aggregate subjected to elevated temperatures. Fire Technol 55:1477–1494

Del Rio, M., Izquierdo, P., Salto, I, Cruz, J.S. (2010). La regulación jurídica de los residuos de construcción demolición (RCD) en España. El caso de la Comunidad de Madrid. Informes de la Construcción 62 517, 81–86.

Rodríguez C Parra C Miñano I Martínez S Benito F.J. López J Sánchez I (2015) Propiedades mecánicas y acústicas de hormigones con áridos reciclados y neumáticos fuera de uso. Chapter II – The construction and demolition waste, its recycling and reuse opportunities. Proceedings of the II International and IV National Congress on Sustainable Construction and EcoEfficient Solutions. pp. 382–391

Salau MA, Oseafiana OJ, Oyegoke TO (2015) Effects of Elevated Temperature on Concrete with Recycled Coarse Aggregates In IOP Conference Series. Mater Sci Eng 96(1):012078

Shin W, Lee H, Baek S, Kim W, Kwon W, Kwak Y (2015) A Study on the Mechanical Properties of Concrete Using Recycled Coarse Aggregates at High Temperatures. J Archit Inst Korea Struct Constr 31(7):11–18

Tarela E, Letelier V, Osses R, Cárdenas JP, Moriconi G (2015) Analysis of the variables that affect the strength of concrete with recycled aggregates from prefabricated pipes. Congreso Internacional de Construcción Sostenible y Soluciones Ecoeficientes. Universidad de Sevilla, Departamento de Construcciones Arquitectónicas I, pp 478–504

Varona FB, Baeza-Brotons F, Tenza-Abril AJ, Baeza FJ, Bañón L (2020) Residual compressive strength of recycled aggregate concretes after high temperature exposure. Materials 13(8):1981

Vieira JPB, Correia JR, De Brito J (2011) Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates. Cem Concr Res 41:533–541

Xiao J, Li W, Poon C (2012) Recent studies on mechanical properties of recycled aggregate concrete in China-a review. Sci China Technol Sci 55(6):1463–1480

Xiao J, Fan Y, Tawana MM (2013) Residual compressive and flexural strength of a recycled aggregate concrete following elevated temperatures. Struct Concr 14(2):168–175