Chapter 29-1. Ceramic waste: reuse as a recycled aggregate

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Abstract

Gran cantidad de residuos cerámicos de diversos tipos (procedentes de ladrillos, tejas, baldosas de revestimiento, cerámica sanitaria…) son originados tanto durante sus procesos de fabricación, como durante la construcción y demolición de edificios. Debido a su largo período de biodegradación, depositar residuos cerámicos inertes en vertederos origina impactos visuales y ambientales significativos. Por otro lado, la industria de la construcción consume gran cantidad de energía y materias primas naturales, siendo el hormigón y el cemento Portland los materiales más comúnmente utilizados. Este capítulo resume diversos estudios desarrollados con el fin de reutilizar y valorizar diferentes tipos de residuos cerámicos como árido reciclado en la fabricación de hormigón.

Keywords

Ceramic waste; recycled aggregate; compressive strength; durability; sustainability.

List of abbreviations

Ceramic waste (CW); brick ceramic waste (BCW); ceramic sanitary ware (CSW); tiles ceramic waste (TCW); ceramic waste from polishing tiles (PTCW); ceramic pots (CP); construction and demolition waste (CDW);; ceramic waste aggregates (CWA); natural coarse aggregates (NCA); recycled coarse aggregate (RCA); recycled fine aggregate (RFA); interfacial transition zone (ITZ); ultrahigh-performance concretes (UHPC); self-compacting concrete (SCC); volume percentage (vol.%); greenhouse gas emissions (GHG); embodied energy (EE).

1. Introduction

Large amounts of ceramic products, such as bricks, roof tiles, sanitary ware or wall and floor tiles, are manufactured worldwide, which produces significant amounts of ceramic waste (CW) because products are discarded for commercial reasons or are landfilled at the end of their useful life [1]. As observed in [2,3], approximately 3% to 7% of ceramic products are rejected for sale because of technical imperfections, such as nicks, cracks or glaze deficiencies. Global ceramic tiles production has significantly increased from the 9,515 million m^2 manufactured in 2010 [4] to the 16,093 million m^2 produced in 2020 [5]. Similarly, the world sanitary ware production has also significantly grown from the 216.6 million pieces produced in 2004 to the 349.3 (equivalent to 7.7 million tons) manufactured in 2014 [6]. An advantage of recycling this CW is that it is usually not adhered to other construction materials, such as gypsum or Portland cement (PC) [7]. The global production of other significant ceramic products, such as bricks and roof tiles, has also followed a similar trend because, as reported by the Spanish Association of Manufacturers of Bricks and Clay Roofing Tiles (HYSPALIT) [8], 3.9 million tons of these ceramic products were produced by Spanish companies in 2014, which progressively rose to the 6.3 million tons manufactured in 2021.

Significant amounts of CW are also produced by the construction sector because, according to the European Environment Agency [9], 374 million tons of construction and demolition waste (CDW) were produced by the European Union in 2016, which implies more than one third of all produced waste. As highlighted by Lasseuguette et al. [10], CW is the largest worldwide contributor to CDW with between 8% and 54% of CDW ceramic materials [11].

CW is chemically inert, non-toxic and non-biodegradable with high strength and melting points, a long service live and good durability, and has a visual impact when landfilled [7,12-15]. As vast amounts of CW derive from production rates and construction and demolition practices, CW materials are promising candidates to be used for developing new construction products that are more environmental-friendly. However, a significant amount of CW is simply landfilled or used in low-grade recovery applications like backfilling and road sub-bases [16]. In order to better understand CW reutilisation and valorisation, to identify further research areas and to facilitate knowledge transfer to industry, this paper reviews the use of CW as a recycled aggregate in concrete. As summarized in Figure 1, the bibliographic search focused on the works conducted from 2010 to the present-day (2022), and applications of CW recycled aggregates different than concrete, such as asphalt, manufacture of ceramic tiles or PC production, were discarded. Following these criteria, 93 bibliographic references were found, of which 86 were research articles, 3 book chapters and 4 reviews. After reading them all, only the most significant and representative works that used CW as recycled aggregate in concrete were included.

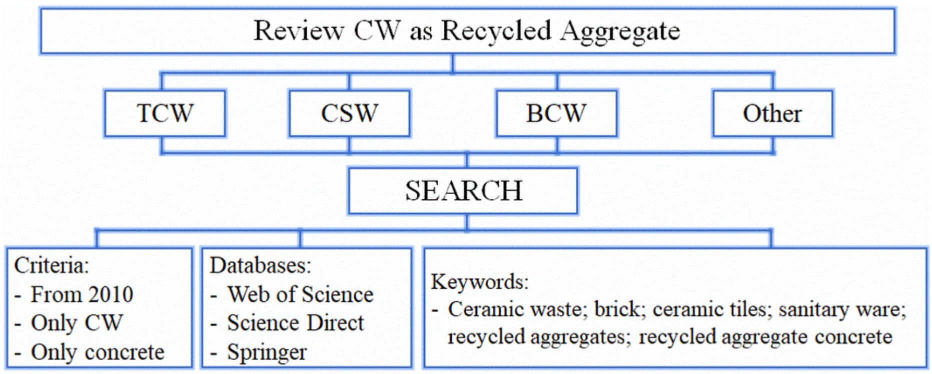


Figure 1 – Review on CW as a recycled aggregate.

2. CW physical properties

CW is generated worldwide and can be safely reused as a recycled aggregate by simply adapting particle size distribution. Several studies have used crushed CW particles like that presented in Figure 2 as recycled aggregates in concrete. These CW particles are irregular, have sharp edges, and may present a smooth or rough surface depending on their porosity (a wide range of water absorption values, WA, has been reported) [17].

Figure 2. Crushed CW particles obtained from bricks, tiles and sanitary ware.

Table 1 summarises the physical properties of CW used as a recycled aggregate. CW density was generally lower than that of natural aggregates, which implies bigger waste volumes for a given replacement percentage (usually specified as weight). This generally improves the system's packing due to the larger surface area and volumetric concentration of the CW particles [18,19].

Table 1 – Physical properties of CW used as a recycled aggregate.

	Gravel		Sand	
CW	Density, g/cm^3	Water absorption, %	Density, g/cm^3	Water absorption, %
BCW	0.97-2.4	1.8-18.3	1.0-2.5	0.7-18.4
	[11,17]		[11,17,20]	
TCW	1.27-2.4	1.4-11.6	1.2-2.6	6.3-17.2
	[11,17]		[11,17,20]	
CSW	1.25-2.6	0.5-2.9	1.2-2.8	0.2-2.5
	[11,17]		[11,17,20]	
Not specified	1.8-2.6	0.6-17.8	2.1-3.0	0.2-12.6
	[13,21]		[13,21]	

3. Ceramic waste as a recycled aggregate in mortar and concrete

3.1. CW as fine aggregates in mortars

Employing CW as an aggregate in mortars and concrete is a good valorisation option because aggregates production demands less energy compared to that required to obtain a fine powder. A few references have investigated using CW as a fine aggregate in mortars, and they generally observed an improvement in mechanical strength. The most significant works are summarised below.

Awoyera et al. [22] studied the use of floor and wall tiles (TCW) as both pozzolan and a recycled aggregate (from 2 to 4.75 mm) and compared the properties of the mortars developed with others made with river sand and lateritic soil. All the mortars were made with a water/binder ratio of 0.6, and the reference sample was prepared with PC 32.5 and river sand. The mortars in which PC was partially replaced with TCW (10%, 20% and 30% of PC) were prepared with different types of aggregates: laterite (series M), CW (series N) and a mixture of both (series F). Similar water absorption values were obtained with the river sand and CW aggregates (2.24% and 2.52%, respectively), with slightly higher results when using laterite (4.7%). The highest dry bulk density was for the mortar made with river sand, which was explained by its higher specific gravity. The mortars made with CW had the highest flexural and compressive strengths.

The work by Samadi et al. [19] used TCW as pozzolan and as an aggregate (TCWA) with 25%, 50%, 75% and 100% replacement percentages of river sand with TCWA. Similar properties were recorded for river sand and TCWA, which presented water absorption values of 1.8% and 1.3%, respectively. The compressive strength values of the mortars made with the different TCWA percentages were similar to that obtained for the reference mortar (natural sand), regardless of the curing age. In some cases, the strength of the TCWA mortars was even higher than that of the mortar prepared with natural river sand (i.e. 55.2 and 57.4 MPa were obtained by the natural sand and the

100% TCWA mortars after 90 curing days, respectively). Replacing river sand with TCWA enhanced durability in Na_2SO_4 solutions.

CSW was used as a fine aggregate (< 0.05 mm, CSWA) in the research work published by Jackiewicz-Rek et al. [23], in which natural sand was replaced with CSWA (10%, 15% and 20% of cement weight). The mortars with CSWA had lower plasticity and retained workability for longer periods of time. The shrinkage of these mortars increased with bigger amounts of CSWA. The enhancement of mechanical properties with higher CSWA contents was more significant for short curing ages, insofar as the flexural and compressive strength values of the 20% CSWA mortars cured for 2 days increased by 50% and 42% compared to the mortar made with natural sand, respectively. This improvement was 12% and 11% after 56 curing days.

Lam et al. [24] combined the use of BCW as pozzolan in PC mortars with CWA to replace 50% and 100% of natural aggregates. Although the water absorption of the CWA used in that study was relatively high (8.2%), it fell within the range reported for other CW materials employed as recycled aggregates (Table 1). The very rough surface of CWA improved the interfacial transition zone between aggregates and the binding matrix, and enhanced samples' compressive strength compared to those developed with natural aggregates. Additionally, the alkali-silica reaction tests of the utilised CWA were negative.

CWA has also been used in lime mortars [25]. Torres et al. [25] worked with three different residual ceramic aggregate types (obtained from BCW, TCW and ceramic pots, CP) to develop natural hydraulic lime (NHL) mortars with aggregate/binder ratios of 4 (30 vol.% of CWA) and 3 (20 and 40 vol.% of CWA). The BCW aggregate (BCWA) mortars had the lowest bulk density and the greatest open porosity, which was attributed to the properties of this ceramic aggregate. The mortars developed with CWA always provided better compressive strength values than the control mortar. Indeed after 28 curing days, the compressive strengths of the 30 vol.% CWA lime mortars prepared with an aggregate/binder ratio of 3 were 7, 6 and 6.5 MPa for the BCWA, TCWA and CPA samples, respectively, while the corresponding reference mortar gave 1 MPa.

3.2. CW as fine and coarse aggregates in concrete

Many of the reviewed papers have used CW materials as fine and coarse aggregates in concretes. In order to cover different types of concrete and CW materials, some of them were selected. It must be highlighted that the water absorption values of the ceramic aggregates are generally higher than those presented by natural ones. This section begins by studying high- and ultrahigh-strength concretes.

3.2.1. High- and ultrahigh-strength concretes containing CW aggregates

Amin et al. [26] studied ultrahigh-performance concretes (UHPC) made by replacing PC with silica fume and metakaolin, and using natural sand and CW gravel. Coarse aggregates were crushed fractions of wall and floor tiles (TCWA) and these authors demonstrated that the interphase between these CW aggregates and the aggregate improved. The use of silica fume as mineral addition was more efficient than metakaolin.

Etxebarria and Gonzalez-Corominas [27] studied high-strength concretes developed using fine ceramic aggregates from a brick factory (FCA), and a mix of recycled aggregates obtained from a CDW plant (composed of 67% ceramics and masonry products, 10% raw aggregates and 22% concrete) as fine and coarse recycled aggregates. Up to 35 vol.% of natural sand and up to 30 vol.% of natural gravel were replaced with these recycled aggregates. The authors concluded that ceramic sand reduced the absorption capacity and improved the chloride resistance and compressive strengths of the developed concretes. However, low percentages of mixed recycled aggregates should be applied to achieve high-performance concrete properties.

CP were used as a filler (up to 30% PC) and a fine aggregate (CPA, up to 40%) to fabricate watertight concrete [28]. Compressive strengths of around 67 MPa were achieved using CP as a microfiller, which implies a 30% increment in relation to the reference concrete. Although using CP as recycled sand reduced the concrete samples' consistency due to higher water demand, similar compressive strength values to those of the reference sample were obtained when replacing up to 20% natural sand. Using CP as a microfiller improved the sealing of pores, which led to a reduction in water absorption and water penetration depths.

In 2016, Zegardło et al. [29] used CSWA as the only aggregate in UHPC. Two different fractions were employed (0-4 mm and 4-8 mm) at a 1:0.4 ratio. The concrete with CSWA provided a compressive strength of 120 MPa, which was 24.74% higher than the reference sample, made with basalt aggregates of the same size. Similarly, the tensile strength results of the CSWA concrete were 34.25% higher than those obtained with natural aggregates. The SEM images showed a better interfacial transition zone (ITZ) between CSWA and the binding matrix.

Mousavi et al. [30] worked with TCWA and CSWA to replace up to 30% natural coarse aggregates (NCA) in high-strength concretes. Silica fume was also used in these systems which, to maintain workability constant, required bigger amounts of superplasticiser with increasing recycled aggregates contents. All the prepared concretes achieved more than 60 MPa, with 20% optimum percentages for both types of recycled aggregates. Higher water absorption values were recorded in the concretes developed with recycled CW, which was attributed to the higher absorption values of ceramic particles.

Xu et al. [31] investigated the use of three different CW types (wall tiles, floor tiles and household ceramics) to replace up to 30% NCA in high-performance concrete. As observed in Table 2, which summarises the physical properties of the CW employed in this study, wall tiles had the highest capacity to absorb and store water. All the ceramic aggregates were presaturated at 23ºC for 72 hours, and compressive strength was evaluated after 3, 7 and 28 curing days. The best results were obtained with the wall tiles aggregates, whose strength values were higher than for the reference concrete, regardless of the applied replacement percentage. With floor tiles, the optimum replacement percentage was 10%, and the household ceramic samples' strength was always lower than that of the reference one. The authors attributed this behaviour to the presence of larger amounts of glaze on household ceramics surfaces, which made the bonding between paste and aggregates difficult. All the CW aggregates reduced concretes' autogenous shrinkage, especially within the first 72 hours, which was explained by bigger porosity of the ceramic particles.

Table 2 – Physical properties of different CW types. Adapted from [31].

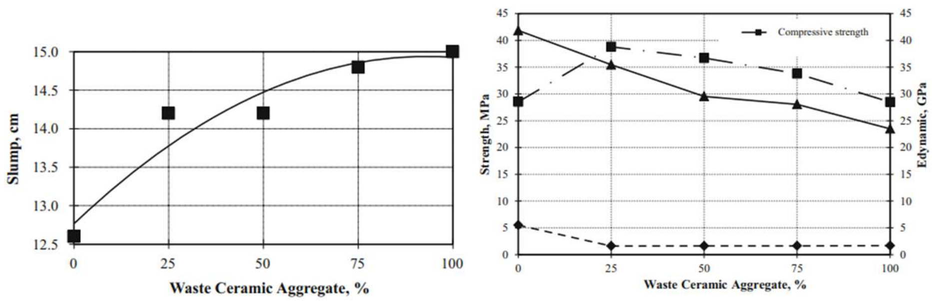
	Wall tiles	Floor tiles	Household ceramics
Water absorption (%)	10.5	6.1	2.3
Porosity (%)	37.1	17.7	6.3
Closed porosity (%)	18.5	20.9	60.6
Open porosity (%)	81.5	79.5	39.4

Zareei et al. [32] replaced 20%, 40% and 60% of natural gravel with CW in high-strength concrete, and studied the influence of waste carpet fibres (1 vol.%). All the concretes were made with a constant superplasticiser quantity (1.5%) and a water/cement ratio of 0.37. Workability (slump cone test) reduced with the addition of CW and carpet fibres, and higher compressive strength values were obtained in the concretes containing recycled aggregates. The optimum replacement percentage was 40%, which provided compressive strength, flexural strength and elastic modulus of 80.5 MPa, 6.31 MPa and 42.8 GPa, respectively, after 28 curing days. The reference concrete respectively gave 75.9 MPa, 6.2 MPa and 41.6 GPa for the same properties when cured for the same period. Conversely, the addition of waste carpet fibres generally worsened the studied systems' mechanical properties, except for the flexural strength values, which were similar to those of the concretes developed without fibres. The authors attributed the variation in mechanical properties to increased concrete porosity when carpet fibres were incorporated. The rises in the water absorption values of the concretes containing CW aggregates were explained by the higher water absorption of the ceramic aggregates when compared to the natural ones.

3.2.2. Traditional concretes containing CW aggregates

In traditional moderate-strength concretes, Bommisetty et al. [33] studied the partial replacement (0% to 25%) of NCA with TCWA. A 20% optimum replacement percentage was reported, which provided compressive strength, split tensile strength and flexural strength of 35.55 MPa, 3.53 MPa and 5 MPa, respectively, after 28 curing days. These results were slightly higher than those obtained by the reference concrete (0% replacement) when cured for the same period (32.29 MPa, 3.18 MPa and 5.02 MPa, respectively). Similar results were obtained by García-González et al. [34] when replacing 100% natural gravel with CSWA. The physical properties of CSWA were compared to those of siliceous gravel, and particles within the 4-12.5 mm range were used for both types of aggregates. The apparent density, water absorption and Los Angeles coefficient of natural siliceous gravel were 2.64 kg/dm^3, 0.23% and 33, respectively, and these values were respectively 2.41 kg/dm^3, 0.55% and 20 for CSWA. The compressive strength of the 100% CSWA gravel concrete (36.9 MPa) was similar to that obtained by the reference sample (36.51 MPa). Both types of concrete also obtained similar tensile strength and tensile splitting strength values.

Canbaz [35] replaced 25%, 50%, 75% and 100% of natural aggregates with CSWA in concrete, and studied their behaviour when exposed to high temperatures. Figure 3a shows the developed concretes' workability, while their compressive strength, dynamic modulus of elasticity and flexural strength are plotted in Figure 3b. As observed, the presence of CSWA enhanced the concrete samples' workability. The compressive strength values of CSWA samples varied between 38.8 MPa (optimum, with 25% CSWA) and 28.5 MPa (100% CSWA), with the latter coming close to the reference concrete's strength (close to 30 MPa). Conversely, the flexural strength and dynamic modulus of elasticity progressively decreased with higher CSWA contents. This was attributed to the rough surface of CSWA, which worsened the adhesion between the binding paste and aggregates. Loss of strength occurred in all the concretes exposed to temperature (100ºC, 400ºC, 700ºC, 900ºC), except for that made with 100% CSWA, whose compressive strength was not affected by high temperatures.



a b

Figure 3 – a) Slump values of fresh concretes; b) compressive, flexural strength and dynamic elasticity modulus [35].

Medina et al. [3] replaced up to 25% natural gravel with CSWA. These authors observed that compressive and splitting tensile strengths improved by approximately 11.04% and 25.65% (28 curing days), respectively, compared to the reference samples. The 25% CSWA concrete's porosity increased by 4.2% *versus* the reference concrete. The microstructural studies revealed that including CSWA not only promoted pore refinement in the system, but also enhanced the ITZ between paste and aggregates. In a later study [36], the gas permeability of the developed CSWA concretes was analysed, and reported oxygen permeability coefficients of $6.4x10^{-7}$ m^2 for the reference concrete and of $6.57x10^{-17}$ m^2 for the 25% CSWA concretes. These values fall within the range of conventional concretes. The penetration and carbonation depth values of the 25% CSWA concretes lowered in relation to the reference concrete. In another publication [37], the authors demonstrated that the higher porosity values recorded for the concretes developed with CW recycled aggregates did not imply significantly higher water permeability values. Thus while the reference concrete's total water absorption was of 2.11%, that of the 25% CSWA sample was 3.08%. The average depth penetration values slightly increased in the concretes developed with CSWA. Further studies were conducted by Medina et al. [38] to assess the durability of CSWA concretes. In [38], the damage that occurred in the ITZ after exposing these concrete samples to 56 freeze-thaw cycles was analysed. According to the obtained results, this damage can be divided into two groups: de-bonding between the paste/aggregate in the ITZ; microcracking of paste. The SEM analyses demonstrated that paste was more intensively cracked in the concretes made with natural aggregates than in those developed with CSWA. The deepness of the cracks in the ITZ zone of the CSWA concretes was shallower than those recorded in the reference sample.

González et al. [39] proposed using BCW as a recycled aggregate (BCWA) to manufacture middle-strength concrete. The aim was to develop suitable dosages to be employed when manufacturing future prestressed products. The authors studied the fresh and hardened properties of the concrete samples developed by replacing up to 100% of coarse and fine natural aggregates with BCWA. Table 3 summarises the results obtained after 28 curing days. As observed, the 100% BCWA concrete presented the largest amounts of occluded air (7%), which must be lower than 6% for prestressed products. The density and compressive strength values progressively lowered with increasing amounts of BCWA, and loss of strength was acceptable when replacing up to 50% natural aggregates. However, the modulus of elasticity significantly decreased with more than 35% BCWA. These results led the authors to conclude that BCWA could be a good candidate to manufacture concretes for prestressed applications when moderate amounts of natural aggregates are replaced.

Table 3 – Properties of the reference concrete and those developed using 0% to 100% BCWA. Adapted from [39].

Property	Percentage of BCWA					
	0%	20%	35%	50%	70%	100%
Occluded air (%)	4.6	4.8	5.1	5.7	5.7	7.0
Density (kg/m3)	2380	2340	2250	2230	2150	2000
Comp. strength (MPa)	59.8	55.6	52.8	54.1	46.8	43.4
Mod. Elasticity (GPa)	42	36	31	28.5	22.5	16.5
Water absorption (%)	5.0	5.9	8.9	10.3	11.1	14.7

Similar results were obtained by Nepomuceno et al. [40], since the flexural and compressive strength of the BCWA concretes developed in their study also decreased with increasing the quantities of recycled aggregate. However, loss of strength was not significant because compressive, flexural, and tensile splitting strengths diminished by 11.1%, 5.8% and 22.2%, respectively, when replacing 75% natural gravel. The conclusions were similar to those previously reported by Suárez et al. [41], and the authors [40] considered using up to 30% BCWA a good option when valorising this BCW as a recycled aggregate in concrete.

Gayarre et al. [42] conducted an interesting and different research work. They used 20%, 35%, 50% and 70% BCWA to replace natural aggregates when manufacturing prestressed joists. No negative effects on mechanical properties were observed with up to 35% BCWA, and an improvement was even recorded when replacing 20% natural particles. As in previous studies [39,40], replacement percentages higher than 35% were not recommended for producing loss of strength.

To enhance thermal concrete performance, Gharibi et al. [43] used a ceramic electrical insulator waste to replace fine and coarse natural aggregates. Different particle sizes were obtained when crushing this CW and sieving it with metal grids of different dimensions. Low cement contents and water/cement ratios were used to increase concrete samples' thermal conductivity, which provided the opportunity to study the role of the CW insulator when applied as a recycled aggregate. Eleven mixtures were fabricated, including the reference concrete. In some, only fine aggregates were replaced (up to 100%, IFA series). Others were prepared by replacing only coarse aggregates (ICA series). The third serie was developed by replacing simultaneously natural fine and coarse aggregates (IFCA series). Although the compressive strength of all the concretes made with recycled aggregates improved compared to that of the reference concrete (no matter what the particle size fraction of CW aggregates was), different behaviours were observed. For example in the ICA series, compressive strength progressively increased with higher CW contents, and series IFA and IFCA exhibited optimum strength with 50% substitution. The authors attributed these behaviours to a reduction in roughness and to the amount of filler with the fine recycled fraction. The lowest thermal conductivity value (0.812 W/mK) was obtained when replacing 100% natural aggregates with a combination of fine and coarse CW particles (IFCA100), and was significantly lower than that recorded for the reference concrete (1.575 W/mK).

Senthamarai et al. [44] also used ceramic insulator waste, but to completely replace natural gravel in concrete. Six different dosages were mixed by varying the water/cement ratio (0.35 to 0.6), and these concrete samples' properties were compared to the corresponding concretes developed with crushed granite as a coarse aggregate. Similar compressive strength results were obtained for the recycled aggregate and conventional concretes insofar as 51 MPa and 53 MPa were recorded in the mixes prepared with a 0.35 water/cement ratio, respectively. In a later study, Senthamarai et al. [45] applied the same dosages to investigate the permeation characteristics (water absorption, volume of pores, sorptivity, chloride diffusion) of concrete made by replacing 100% natural aggregates with ceramic insulation wastes. The dominant factor that influenced the analysed properties was the water/cement ratio. Although the water absorption values recorded for recycled aggregate concretes were higher than those presented by conventional concrete, they were all lower than 10%, which denotes good quality concrete. The concretes containing ceramic aggregates also presented larger pore volumes than the reference concrete, which varied from 13% to 18% in the concretes mixed with a water/cement ratio of 0.35 and 0.6, respectively. The sorptivity and rapid chloride penetration test (RCPT) values were also higher for the CW concretes, and the RCPT result obtained by the CW aggregate concrete developed with the highest water/cement ratio was higher than that recorded for conventional concrete (6,081 and 2,825 for the CW and conventional concretes, respectively). The authors stated that the smooth ceramic insulation waste surface accounted for all these results, which promoted a weak interface between recycled aggregates and binding paste. So to enhance these concretes' permeation characteristics, a suggestion was made: using mineral additions, such as fly ash, when employing ceramic insulator waste as a recycled aggregate.

Concretes with compressive strength values of approximately 50 MPa were developed by Goyal et al. [46] by replacing up to 25% NCA with TCWA. The authors observed that in order to maintain constant workability, larger amounts of superplasticiser were required with increasing recycled aggregate contents. The flexural and compressive strength values of the developed TCWA concretes were higher than those obtained for the reference sample, and 15% substitution was optimum. The higher permeability values exhibited by the recycled aggregate concretes compared to the reference sample were attributed to CW particles' porous nature. The concrete containing 15% TCWA provided the shallowest abrasion depths (0.8 mm), and were significantly better than those recorded for the reference concrete (1.8 mm).

Rashid et al. [47] also used TCWA to replace NCA (up to 30%). Although no superplasticiser was employed in their study because they applied a high water/cement ratio (0.55), the slump values lowered with increasing amounts of TCWA. Like most studies conducted about using CW as recycled aggregates in concrete, the bulk density values of the hardened concretes lowered with increasing TCWA contents. Although minor variations in the compressive strength results were observed when replacing 10% natural aggregates with TCWA, the strength values improved by 20% (compared to the reference sample) in the mixes containing 20% and 30% TCWA, and cured for 28 days, and by around 30% in that prepared with 30% TCWA and cured for 56 days. The authors attributed this enhancement in mechanical properties to a better ITZ between CW aggregates and the binding matrix, along with the pozzolanic reaction of part of TCWA.

Different results were reported by Sivakumar et al. [48], who also used TCWA to replace coarse and fine aggregates in concrete. In their study, two series of mixes were prepared by replacing up to 50% natural sand and gravel (separately, with 10% increments). An additional one was prepared by simultaneously replacing up to 50% of fine and coarse aggregates. Although no improvement in the compressive strength results was observed when replacing natural gravel with the coarse TCWA fraction, the mixes containing 30% TCW sand and 20% of a TCWA gravel and sand mixture gave compressive strength values that were 8% and 13.9% higher than the reference ones, respectively. The flexural and split strengths obtained for the latter one improved by 8.7% and 15.6%, respectively, compared to the reference concrete.

3.2.3. Self-compacting concrete developed with CW recycled aggregates

CW materials have also been used as recycled aggregates in self-compacting concrete (SCC). Gautam et al. [49] replaced up to 50% river sand with china cups and plates CW (particle size smaller than 0.08 mm). Bigger amounts of superplasticiser were used with replacing percentages above 20%. Given the marked importance of fresh state properties in SCC, the authors analysed slump flow, T500 Time, V-funnel time, J-ring and L-box evolution of the fresh mixtures. Flexural and compressive strengths, together with the ultrasonic pulse velocity, of the hardened samples were also assessed. The reduction in the slump flow values with increasing amounts of CW was attributed to the larger specific surface area and irregular shaped ceramic particles. According to the other fresh state results, adding up to 20% of this CW was beneficial for SCC. Similarly, higher compressive and flexural strength values (compared to the reference sample) were recorded in the SCCs developed by replacing 10% and 20% river sand with this CW. The authors concluded that this ceramic powder was beneficial due to its pozzolanic effect and the consequent capacity to fill existing pores.

Meena et al. [50] also developed SCC, but by using TCWA to replace up to 100% natural sand (20% increments). Although the fresh state properties of the SCC concretes worsened with increasing TCWA contents, all the mixtures exhibited acceptable limits. All the SCCs developed with TCWA exhibited higher compressive strengths than the reference sample, with 60% being the optimum replacement percentage. The incorporation of TCWA also enhanced concretes' abrasion resistance. When exposed to high temperatures (up to 1,000ºC), all the developed concretes exhibited moderate weight losses up to 600ºC, which became more pronounced as of 800ºC. The strength loss of the 60% TCWA SCC was approximately 15 MPa after being exposed to 1,000ºC.

3.2.4. Pervious concrete containing CW aggregates

A case of pervious concrete being fabricated with CW foam was published in the paper by Jiang and Cheng [51]. Although pervious concrete does not normally contain fine aggregates, in their study these authors explored the possibility of adding crushed CW as a fine aggregate. The inclusion of this type of foamed CW enhanced compressive strength (around 40 MPa *vs.* 27.5 MPa for the reference concrete), and the permeability and porosity values were maintained. These results were very significant because the compressive strength values of this concrete type normally fall within the 7 to 25 MPa range.

The enhancement of the ITZ in concretes containing CW aggregates was studied by Siddique et al. [52] by means of lateral force microscopy. The authors used bone china ceramic aggregates to substitute up to 100 vol.% natural sand (20% increments). The introduction of this CW led to a smooth surface topography of the ITZ. Additionally, a dense formation of CSH gel was observed around recycled aggregates, which promoted a stronger microstructure compared to that noted in conventional concrete. In a later study, Siddique et al. [53] resorted to the same system to investigate the performance of concretes made with bone china CW under adverse conditions. Concrete samples were developed with different water/cement ratios (0.35, 0.45 and 0.55). The compressive strength of the mixes prepared with water/cement ratios of 0.35 varied from 39 MPa for the natural sand concrete to 44 MPa, for that made with 100% recycled sand. In the mixes prepared with a water/cement ratio of 0.55, compressive strength values varied from 22 MPa to 30 MPa for the concretes containing 0% and 100% CW, respectively. Higher porosity values were recorded with increasing water/binder ratios and CW contents. Although CW particles' rough surface required larger amounts of cement paste to provide an appropriate covering, the formation of bigger quantities of CSH in the CW concretes improved resistance to some tests, such as abrasion. Better results were also obtained in the CW concretes after freeze-thaw cycles. This was explained by the higher percentage of voids in the recycled aggregate samples, which promoted the accommodation of water by safeguarding concrete against internal stress. The good results of the chloride penetration corrosion tests run with these recycled aggregate concretes were attributed to the higher tortuosity of their pores compared to the reference sample. The authors concluded that replacing from 40% to 60% of natural aggregates with this CW type provided high durability, along with enhanced environmental and ecological behaviours.

4. Sustainability and carbon footprint

Reusing waste is one of the most important issues in circular economy. The vast economic growth in the last century has provoked the mass use of energy and natural resources and, due to linear economy processes, large amounts of different waste types are generated. In most cases, they are simply landfilled, which provides no additional benefit. In the last few decades, a critical approach to the reduction, recycling, reusing and valorisation focus is being developed in different fields. The construction industry represents more than 40% of the global energy use and more than 35% of global CO_2 emissions [54].

Concrete is the single most widely manufactured product used worldwide (30 Gt/year) and its production is responsible for 8% anthropogenic greenhouse gas emissions (GHG) and 3% energy demand [55]. The main concrete components are cement and aggregates (coarse and fine, 60-75% per weight of concrete), the last ones are usually obtained from natural (non-renewable) resources. In many countries, the scarce availability of coarse and fine aggregates motivates conducting alternative studies about the different solid waste types generated by agricultural, mining, industrial and urban activities.

CWs (tiles, pavements, red clay bricks, bone china ceramic, sanitary ware, ceramic houseware goods, etc.) are good candidates for replacing a natural aggregate because they are produced worldwide, are chemically and mechanically stable, and can be crushed to obtain different aggregate finenesses. These alternative aggregates are also compatible with the alkaline medium generated in concrete pores.

In terms of environmental issues, the use of aggregates in concrete does not represent a strong impact because low energy use is involved in all industrial preparation processes. Although moderate water use and dust generation are the principal aspects to consider, neither is especially detrimental to the environment. The energy required for preparing 1 kg of concrete (typical composition of 350 kg/m^3 of PC, a 0.48 water/cement ratio and 30 MPa at 28 curing days) is about 0.893 MJ, of which only 0.056 MJ is associated with the aggregate [56]. The main problem with aggregates is their transportation due to the scarce availability of natural resources close to concrete production plants, or the vicinity of quarries to cities or protected zones.

Rashid et al. [47] studied the effect of replacing NCA (Margalla crush, a fossiliferous limestone rock) with a CW obtained from CSW. This alternative gravel worsened concrete workability, but enhanced compressive strength development. The authors observed a linear reduction in the carbon footprint when a natural aggregate was replaced with CW. The CO_2 footprint (expressed as kg-CO_2/m^3) associated with the coarse aggregate dropped from 3.2 for the control concrete to 2.2 for the 30% replaced concrete. Replacements of 20% and 30% yielded the best carbon footprint results for the concrete samples cured for 63 days.

Replacing fine aggregates with CW has also been studied. Samadi et al. [57] analysed 0-100% replacement of natural sand in cement mortars by considering energy use, GHG emissions and economic cost. Ceramic tiles were crushed to make fine particles and the sample was sieved in accordance with ASTM C33-13. No significant effect on lowering GHG emissions was observed because of the low energy use during crushing (0.003 ton CO_2/ton CW) and the low impact of natural fine aggregates (0.009 ton CO_2/ton natural sand). Similar behaviour was observed for energy use because the specific values for fine aggregates were 0.134 GJ/ton for natural sand and 0.111 GJ/ton for CW. The cost of the recycled sand mortars slightly lowered from 380 Malaysian dollars (RM) per m^3 for the reference mortar to 341 RM/m^3 for those with 100% replacement.

Finally, Siddique et al. [53] analysed the role of fine bone china ceramic aggregates (FBA) at different replacement levels: 20%, 40%, 60%, 80% and 100%. The differences found in the embodied energy (EE) results were very small: the control concrete had an EE of 2,044 MJ/m^3 and the sample with the highest replacement level (100%) had 2,061 MJ/m^3. The optimum replacement was 60% with an EE of 2026 MJ/m^3. A similar trend was obtained for embodied CO_2 emissions with values of 366.88, 367.20, 366.21, 365.52, 367.44 and 367.06 kgCO_2e/m^3 for the 0%, 20%, 40%, 60%, 80% and 100% replacements, respectively. The optimum cost was for the 100% replacement, which yielded a 12.94% reduction compared to the control concrete. The authors highlighted that the reactivity characteristics of the FBA enhanced concrete durability (abrasion, freeze-thawing, drying-wetting, chloride penetration and reinforcement corrosion), and this advantage had to be considered in the sustainability analysis.

5. Conclusions

Population growth has significantly increased the use of natural resources and energy. Employing CW as a recycled aggregate in concrete has been reviewed in this paper. The following conclusions have been reached:

- The different studies that have employed fine CWA to replace natural sand in mortars generally report an improvement in the compressive strength results with increasing CW contents.
- Numerous references have been found about employing recycled CW to replace fine and coarse aggregates in concrete. Although higher water absorption values are generally recorded in recycled aggregate concretes compared to the reference samples, compressive strength values and the ITZ generally improve with recycled ceramic particles. Several studies report optimum replacement percentages coming close to 30%.
- CW aggregates have been successfully used in different concrete types, ranging from traditional to more specific ones, such as permeable concretes. In most cases, recycled aggregates concretes require bigger amounts of plasticiser so that workability remains constant.

This review has evidenced that CW can be successfully reused to develop recycled aggregates mortars and concrete with similar properties to traditional ones. This contributes to minimize the amounts of landfilled waste and to reduce the consumption of natural resources and energy.

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