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Recycling of ceramic tile waste into construction materials

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ABSTRACT

The rapid growth of the global construction industry has resulted in the generation of large amounts of ceramic solid waste, such as ceramic tile waste (CTW). The efficient waste recycling into high-value products is considered to contribute to the realization of sustainable development goals. The preparation of construction materials, such as foam ceramics, concrete, and ceramic tiles, using CTW has recently piqued significant interest. In this regard, this study presents an overview of the technologies for recycling CTW into construction materials. CTW is primarily composed of SiO_2 and Al_2O_3, including two minerals, namely, quartz and mullite. Furthermore, CTW has not only been identified as potential substitutes for conventional concrete aggregates but also as substitutes for ceramic raw materials in the industrial production of ceramic tiles. Foam ceramics can be synthesized from polishing tile waste using silicon carbide contained in the polishing tile waste as a foaming agent. In this review, current achievements in CTW recycling are highlighted. The pending challenges and the points to be considered for further research are also discussed. It is hoped that this review serves as a preliminary step to promote the widespread adoption of CTW as feedstocks for construction materials by construction industries.

1. Introduction

Ceramic tiles are exquisite and have smooth surfaces and high brightness, making people sensuous in their daily lives (Li et al., 2019a, b). Therefore, ceramic tiles are undoubtedly among the most popular ceramic products used by the public in building decoration products (Li et al., 2023a, b). However, this inevitably leads to the generation of a large amount of ceramic tile waste (CTW) during the production process of ceramic tiles and demolition waste (Fig. 1) (Zimbili et al., 2014). According to Manufacturing Economic Studies (MECS), global ceramic tile production reached 18,339 million sqm in 2021, which was a 7.2% increase compared with 17,101 million sqm in 2020 (MECS, 2022). The indicates a high global demand for ceramic tiles. It was also expected that global ceramic tile consumption would reach 18,209 million sqm in 2022 (MECS, 2021, 2022).

Improperly treated CTW pollute groundwater, air, and soil (Ahmad et al., 2023), having negative impacts on human health. Landfilling is a typical method for disposing of CTW (Wang et al., 2018). However, landfilling CTW can cause soil pollution, as CTW are difficult to degrade (Packrisamy and Jayakumar, 2022). The species contained in CTW (e.g., Pb and Cd) influence the properties of soil, which further alters its porosity and permeability, making the land barren (Mangi et al., 2022). Although CTW mainly contain silicate, which has a great potential for use in recycled ceramic products, most CTW still end up in landfills with low economic returns (Pang et al., 2023). These issues necessitate the recycling of CTW for reuse as value-added products (e.g., foam ceramic, concrete, and ceramic tiles).

CTW can be upgraded to environmentally friendly construction materials. A recycling approach for using waste as raw material for the production of its corresponding virgin product is preferable (El-Fadaly et al., 2010). Incorporating CTW into ceramic tiles is a trend in this manner. For example, paving bricks (Penteado et al., 2016; Wattanasiriwech et al., 2009), porcelain tiles (Ke et al., 2016), unfired bricks (Seco et al., 2018), and foam ceramics (de Sousa et al., 2022; Wang et al., 2019, 2021) can be derived from CTW. Furthermore, CTW are potential cement supplementary cementitious materials (SCMs) for the preparation of other construction materials, such as ultra-high-performance concrete (UHPC) and seawater concrete (Amin et al., 2020; Li et al., 2023a, b). Considering that recycling of CTW as construction materials contribute to not only making cities more sustainable but also minimizing waste generation, it clearly helps to achieve the Sustainable Development Goals of the United Nations (UN SDG; in particular, SDGs

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Fig. 1. A picture of CTW. Reprinted from (Packrisamy and Jayakumar, 2022), Copyright (2022), with permission from Springer Nature.

11 and 12).

In this regard, this review aims to provide a critical overview of various CTW recycling methods that use them as valuable resources to reduce the loss of mineral resources and promote economic benefits. To this end, the latest achievements in the recycling of CTW are introduced, and the limitations of current approaches are discussed. Future research recommendations to overcome these limitations are also discussed.

2. Types of CTW

Ceramic tiles exhibit diverse properties, each uniquely suited for particular applications. A comprehensive understanding and differentiation of these tiles are crucial for enhancing the efficiency of recycling processes. According to their production technology and characteristics, ceramic tiles can be categorized into polished tiles, glazed tiles, rectified tiles and vitrified tiles. Ceramic tile surfaces are typically finely polished to give them a dazzling luster and good flatness (Wang et al., 2021). Silicon carbide (SiC) is commonly used as an abrasive to polish ceramic tiles. While polishing ceramic tiles, SiC is worn away by the SiC abrasive and mixed with CTW resulting in polishing tile waste (Liang et al., 2021).

Glazed tiles are characterized by their surface being glazed and coated with a layer of glaze (Izam et al., 2023). The glaze offers various color and design possibilities (Pradell and Molera, 2020), showcasing a broader spectrum of colors and patterns in comparison to polished tiles. However, due to the glazed surface, the wear resistance of glazed tiles is not as robust as that of polished tiles.

Rectified tiles are a specialized type of tile that undergoes precise cutting, resulting in a super smooth surface and perfectly straight edges. This precision allows for minimal grout lines and creates a seamless appearance. Furthermore, these tiles are engineered to be durable, offering resistance against scratches and stains.

Vitrified tiles are made of quartz sand and clay, fired in precise proportions (Matthew and Fatile, 2014). They are characterized by their dense, non-porous structure, rendering them the toughest among ceramic tiles (Nataraja et al., 2022). As a result, vitrified tiles that are highly resistant to water absorption, surpassing glazed and polished tiles in hardness, flexural strength, as well as resistance to acids and alkalis.

Ceramic tiles can be categorized into floor tiles and wall tiles on their distinct functional roles. A standard floor tile composition typically comprises around 50% clay, 40% feldspar, and 10% quartz, with a firing temperature of 1180 °C. However, the composition of wall tiles exhibits variations compared to floor tiles. In wall tile production, calcite is used as a substitute for feldspar in the recipe, and the firing temperature is reduced to 1080 °C (Elçi, 2016).

The residual byproducts generated from the aforementioned ceramic tiles manufacturing processes collectively constitute CTW, primarily sourced from construction and demolition activities.

3. Pretreatment of CTW for the production of construction materials

Prior to the transformation of CTW into construction materials, treatment of CTW is required because CTW is too large to be directly used as feedstock (Senthamarai and Manoharan, 2005) and polishing tile waste is typically discharged in the form of slurry (Gan, 2010). To minimize the variation in the quality of recycled materials from CTW, CTW are typically processed as follows. First, moisture is removed by heating the waste in an oven at 105 °C for 8 h (Li et al., 2019a, b; Penteado et al., 2016) or in a vacuum oven at 50 °C for 3 days (Pang et al., 2023). The dried material is then sieved through 40–200 mesh (Kırsever et al., 2023). Finally, a light gray dry powder is obtained (Li et al., 2020). The resultant material is used as the raw material or additive in the preparation of foam ceramics, concrete, and ceramic tiles, as discussed in Section 3. The properties of pretreated CTW associated with the pretreatment conditions are summarized in Table 1.

The characteristics of CTW (e.g., elemental composition and phase composition) are highly associated with the conditions of their parent materials and the parameters of the ceramic manufacturing process (e.g., clay source and firing temperature) (Khan et al., 2016). The elemental compositions of various CTW are listed in Table 2. As shown in Table 2, CTW are mainly composed of SiO_2 and Al_2O_3, with other minor components, including Ca, Mg, Fe, Ti, K, and Na. This may allow CTW to be used as substitutes for the natural components of ceramic materials. In addition, polishing tile waste tends to contain more organic components than other types of CTW. There are two primary sources of organic components in CPW. The first one is the grinding heads commonly used in magnesium oxychloride cement as a binder, which decompose into CPW during the ceramic manufacturing process. The second is flocculants (e.g., hydrolyzed acrylamide and polyacrylamide), which are added during the treatment of polishing waste residue, remaining as CPW (Huining Huang et al., 2012).

During the ceramic tile manufacturing process, ceramics easily become brittle, leading to CTW. Thus, the phase of CTW is identical to that of ceramic tiles (Fig. 2a) (Ray et al., 2021), mainly including two minerals, namely, quartz and mullite (Shui et al., 2011). Enamel layers are found on the CTW surface, which provide high strength, good resistance to wear, heat, and fire, chemical inertness, and longevity (Medina et al., 2012). Polished tiles involve glass, quartz, and mullite crystal phases. Polishing tile waste also involves these phases, along with a small amount of SiC, magnesium hydroxide, and magnesium chloride hydrate (Shui et al., 2011) that originate from the abrasive in the polishing tool (Fig. 2b) (Huining Huang et al., 2012).

Scanning electron microscope (SEM) images of CTW are shown in Fig. 3. As shown in Fig. 3a and b, CTW particles are irregular and angular in shape, and fine (submicron) particles adhere to large particles (Li et al., 2020).

The particle size distributions (PSDs) of CTW are highly associated with the ceramic manufacturing process conditions (e.g., rough polishing, fine polishing, and edge grinding process) (Huining Huang et al., 2012). For instance, the PSD of CPW generated in a ceramics factory in Foshan, China, was between 0.1 and 30 μm with a minimum diameter of 3.6 μm (Shui et al., 2011); thus, it is an ultrafine powder. The representative PSD patterns of CTW are shown in Fig. 4. As shown in Fig. 4a and b, more than 50 vol% of CTW had particle sizes ranging from 5 to 10 μm. The median particle sizes (D50) of CTW were 9.684 and 8.484 μm, respectively.

Table 1
Pretreatment conditions for CTW and the properties of pretreated CTW.

Entry	CTW type	Thermal treatment		Sieve size	Properties		Ref.
		Temperature (°C)	Time (h)		Shape	Particle size (μm)	
1	Polishing tile waste	50	48	–	porous	D_{50} = 9.684	Li et al. (2023a, b)
2	Wall and floor ceramic tile	–	–	10 mm	–	D_{50} = 500	Amin et al. (2020)
3	Polishing tile waste	50	72	200 mesh	irregular	D_{50} = 5.3	Tian et al. (2023)
4	Polishing tile waste	–	–	–	–	D_{50} = 10	Pang et al. (2023)
5	Polishing tile waste	105	8	1.18 mm	irregular angular	D_{50} = 11.5	Li et al. (2020)
6	Polishing tile waste	100	10	40 mesh	–	–	Wang et al. (2018)
7	Polishing tile waste	110	24	200 mesh	–	–	Kırsever et al. (2023)
8	Polishing tile waste	70	24	75 μm	–	D_{50} = 5.48	Medeiros et al. (2021)
9	Ceramic tile waste	–	–	45 μm	–	D_{50} = 35	Samadi et al. (2020)
10	Polishing tile waste	108	8	1.18 mm	–	–	Li et al. (2019a, b)

Table 2
Elemental compositions of CTW (wt%).

Entry	CTW type	SiO_2	Al_2O_3	K_2O	Na_2O	CaO	Fe_2O_3	MgO	TiO_2	SO_3	P_2O_5	Others	L.O.I.[d]	Ref.
1	Polishing tile waste	67.21	17.74	1.63	3.18	1.99	1.95	2.3	–	0.17	0.07	–	3.33	Li et al. (2023a, b)
2	Wall and floor ceramic tile	54.2	16.21	1.8	1.89	16.12	5.79	0.5	1.26	0.31	–	0.26 [a]	1.66	Amin et al. (2020)
3	Porcelain tile and red ceramic wastes	72.79	19.13	3.02	0.28	1.7	0.86	1.37	0.36	–	0.12	–	0.19	Keshavarz and Mostofinejad (2019)
4	Polishing tile waste	57.94	18.92	0.4	2.46	6.82	0.86	1.62	0.43	–	–	–	–	Tian et al. (2023)
5	Polishing tile waste	68.06	17.83	–	4.37	2.12	1.99	11.50	–	0.12	0.151	0.073[a]	–	Pang et al. (2023)
6	Polishing tile waste	66.34	20.11	–	–	1.29	0.63	0.95	–	–	–	–	–	Li et al. (2020)
7	Polishing tile waste	71.64	17.12	1.75	3.23	0.73	0.56	1.28	0.32	–	–		–	Wang et al. (2019)
8	Polishing tile waste	59.22	17.25	2.9	1.48	3.15	1.23	1.86	–	–	–		5.01	Wang et al. (2021)
9	Polishing tile waste	68.77	21.74	2.39	2.64	1.32	0.79	1.02	0.49	–	–	–	0.95	Wang et al. (2018)
10	Polishing tile waste	64.8	19.93	1.24	6.23	1.00	0.56	4.5	0.47	–	0.13	1.37 [b]	–	Kırsever et al. (2023)
11	Polishing tile waste	69.25	13.78	4.52		5.74	0.32	4.1	–	–	–		–	Wang et al. (2023a, b)
12	Polishing tile waste	68.7	20.9	1.9	2.58	0.5	0.66	2.05	–	–	–	0.62 [c]	2.09	Liang et al. (2021)
13	Polishing tile waste	63.61	22.84	4.01	–	1.06	0.90	7.05	0.16	0.02	–	0.35 [a]	3.33	Medeiros et al. (2021)
14	Ceramic waste	78.62	10.56	1.48	3.37	0.99	1.00	0.07	–	–	–	–	2.36	Zhu et al. (2018)

[a] MnO.
[b] ZrO_2, SO_2, Cl, BaO.
[c] Carbon.
[d] Loss on ignition.

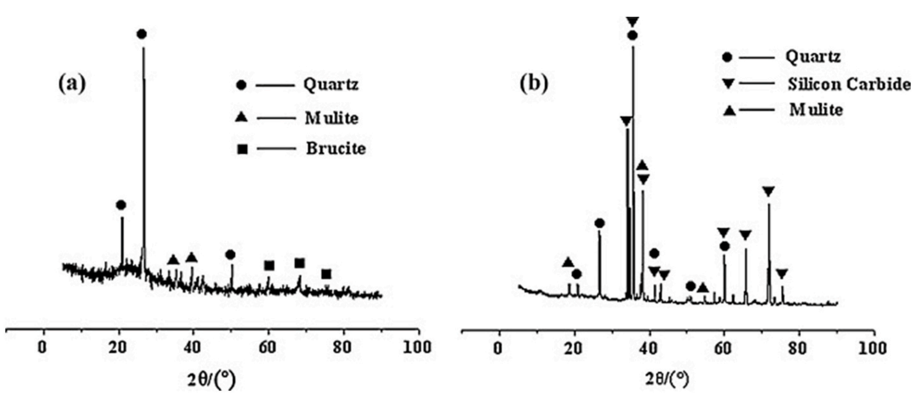

Fig. 2. X-ray diffraction patterns of (a) CTW and (b) polishing tile waste. Reprinted from (Shui et al., 2011), Copyright (2011), with permission from Elsevier.

4. Construction materials derived from CTW

4.1. Production of foam ceramics from CTW

Foam ceramic, also known as porous ceramic, is an advanced functional material with a porous structure, excellent mechanical properties, chemical corrosion resistance, and thermal insulation properties (Kaynakli, 2012). It is frequently used as building insulation materials, fireproof materials, and eco-friendly energy-saving exterior materials (Monich et al., 2020). Polishing tile waste is an ideal feedstock for manufacturing foam ceramics because it can be directly foamed by SiC without the addition of a foaming agent. Moreover, SiO_2 and Al_2O_3 in polishing tile waste can contribute to increasing thermal stability and wear resistance of the ceramic body (Xiong et al., 2022). Polishing tile waste typically contains 1–5-wt% SiC, and SiC in polishing tile waste undergoes a series of oxidation reactions to generate gas during sintering (Bernardin et al., 2006). Gas generation leads to volume expansion of the ceramic body of polishing tile waste caused by ceramic foaming, resulting in the formation of foam ceramics. The production of foam ceramics from polishing tile waste through direct oxidation of SiC is the

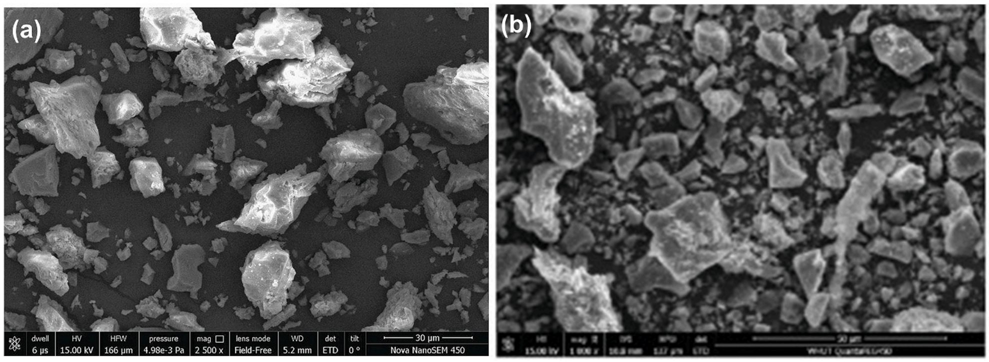

Fig. 3. (a) SEM image of CTW. Reprinted from (Saxena and Gupta, 2022), Copyright (2022), with permission from Springer Nature. (b) SEM image of polishing CTW. Reprinted from (Tian et al., 2023), Copyright (2023), with permission from Elsevier.

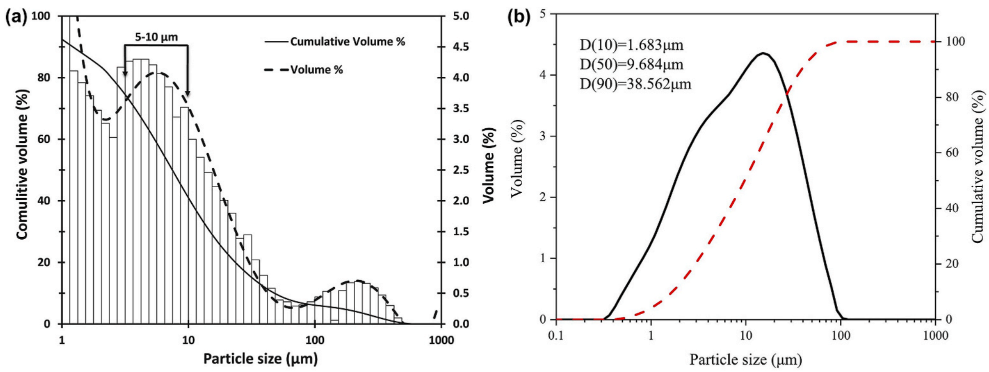

Fig. 4. (a) PSD pattern of CTW. Reprtinted from (El-Dieb and Kanaan, 2018), Copyright (2018), with permission from Elsevier. (b) PSD pattern of polishing tile waste. Reprinted from (Li et al., 2023a, b), Copyright (2023), with permission from Elsevier.

simplest and least expensive direct foaming method. Bernardin et al. investigated the effect of the oxidation temperature on the SiC expansion process to produce porous ceramics from polishing tile waste (Bernardin et al., 2006). At 1000 °C, SiC particles decompose into SiO_2 and CO_2, and CO_2 acts as an expansion agent at 1200 °C, resulting in the expansion of a melted form of polishing tile waste.

There are several methods for producing foam ceramics from polishing tile waste, including the particle accumulation method (Wang et al., 2015), particle-stabilized foam method (Meng et al., 2021), organic foam impregnation method (Pu et al., 2007), inorganic gel casting method (Monich et al., 2020), additive foaming agent method (Wang et al., 2018), and direct foaming method (de Sousa et al., 2022; Wang et al., 2018).

The particle accumulation method involves accumulating raw ceramic particles with the addition of a sintering additive (e.g., Al_2O_3 or Y_2O_3 powder). The sintering additive is typically fine particles of a size similar to that of raw ceramic particles (Li et al., 2019a, b). During sintering, the sintering additive particles melt to combine with ceramic particles. Consequently, the holes between ceramic particles are retained, resulting in a pore structure (Wang et al., 2015). In the particle-stabilized foam method, a stabilizer with high attachment energy (e.g., sodium dodecyl sulfate) is added to be irreversibly attached to air–water interfaces (Huo et al., 2016). Consequently, a coating is formed on the porous structure produced by a foaming agent to stabilize the foam (Li et al., 2019a, b).

The organic foam impregnation method involves the following procedure (Binner and Reichert, 1996). First, an organic foam with a three-dimensional network structure is fully immersed into the prepared ceramic slurry. The excess slurry is then removed from the foam board surface. This leads to foam ceramics after drying and sintering at 1600 °C for 2 h (Zhang, 2022).

In the inorganic gel casting method, organic monomers (e.g., C–S–H) and alkaline activators are added to the ceramic raw materials for alkali activation. Subsequently, the monomers in the suspension are subjected to an inorganic polymerization reaction, leading to the formation of a gel (Zhou et al., 2023). The suspension is then thoroughly mixed by ball milling to prepare a foam structure. The resultant is then cast in a mold and cured at room temperature for 24 h. After curing, the sample is sintered to transform it into a highly stable foam ceramic (Siddika et al., 2022).

The additive foaming agent method involves the addition of a foaming agent (e.g., Na_2SiO_3) to the ceramic raw materials. Thermal treatment of the mixture at high temperatures (e.g., 980 °C) decomposes the pore-forming agent, resulting in the formation of pores (i.e., foam ceramic) (Liu et al., 2016).

The direct foaming method entails continuous foaming in the ceramic suspension. Then, the ceramic suspension is dried, followed by sintering to obtain foam ceramics with unidirectional channels. Because of thermal instability, foam tends to aggregate and form larger pores. Therefore, surfactants are typically added to stabilize the foam in the ceramic suspension (Kırsever et al., 2023). This method is most widely used because of its simplicity and inexpensiveness and the high porosity of the resultant foam ceramic (up to 95%) (Barg et al., 2008).

Tables 3 and 4 summarize studies using polishing tile waste to prepare foam ceramics. For example, Wang et al. synthesized foam ceramics from polishing tile waste using SiC contained in polishing tile waste as a foaming agent and ammonium heptamolybdate ($(NH_4)_6Mo_7O_{24}$) as a sintering additive (entry 1 of Table 3). The polishing tile waste-derived foam ceramic produced with 2-wt% $(NH_4)_6Mo_7O_{24}$ loading and sintering at 1200 °C for 30 min exhibited excellent properties, including a low bulk density of 0.362 g/cm^3, an average pore size of 0.94 mm, a uniform pore size distribution, and a high compressive strength of 8.16 MPa

Table 3
Recycling methods of polishing tile waste to produce foam ceramics.

Entry	Additive dosage (%)		Ceramic foam production condition								Ref.
	Polishing tile waste	Other supplement	Wet-ball milling		1^{st} drying	Sieving (mesh)	Compacting (MPa)	2^{nd} drying	Sintering		
			RPM	Time (h)					Condition	Heating rate (°C/min)	
1	94–100	$(NH_4)_6Mo_7O_{24}·4H_2O$ (0–6)	400	2	100 °C; 10 h	60	15	–	1080–1240 °C; 0.5 h	5	Wang et al. (2019)
2	100	–	–	0.5	–	325	20–40	100 °C; 2 h	1200 °C; 2 h	5–20	de Sousa et al. (2022)
3	100	SiC (0–1) Na_3PO_4 (0–4) polyvinyl alcohol (4)	400	12	110 °C; 24 h	–	30	–	700–1300 °C; 2 h	10	Wang et al. (2018)
4	0–75	Na_2CO_3 (2.5) Zeolite (25–100)	180	2	100 °C; 72 h	–	60	110 °C; 24 h	1150 °C; 2 h	10	Kırsever et al. (2023)
5	0–90	shale (0–90) SiC (0.5) kaolinite (10)	400	12	–	–	–	110 °C; 24 h	1150 °C; 0.5 h	–	Wang et al. (2023a, b)
6	0–75	fly ash (25–100)	300	0.5	–	200	–	110 °C; 24 h	1275 °C; 0.5 h	3	Liang et al. (2021)

Table 4
Properties of foam ceramics made from polishing tile waste.

Entry	Average pore diameter (mm)	Total porosity (%)	Bulk density (g/cm^3)	Water absorption rate (%)	Flexural strength (MPa)	Compressive strength (MPa)	Thermal conductivity (W/m/K)	Ref.
1	0.94	–	0.362	–	–	8.16	–	Wang et al. (2019)
2	0.106–0.206	–	0.77–0.83	–	–	–	–	de Sousa et al. (2022)
3	–	–	0.2–1.8	–	–	–	–	Wang et al. (2018)
4	–	21.8–81.94	0.45–1.85	–	0.84–6.18	–	0.21–0.80	Kırsever et al. (2023)
5	–	–	0.225	–	–	1.95	0.065	Wang et al. (2023a, b)
6	1.2	79.4	0.55	–	–	–	–	Liang et al. (2021)
7	0.025–0.1	15.49	0.68	27.33	–	13.07	–	Fu et al. (2023)

(entry 1 of Table 4). de Sousa et al. prepared a foam ceramic from polishing tile waste (entry 2 of Table 3). The foam ceramic had a firing temperature of 1200 °C and a firing time of 1 h. This resulted in the highest linear expansion, lowest apparent density, largest pores, and lowest tensile strength because of the increase in porosity caused by the presence of SiC (entry 2 of Table 4). Fu et al. effectively controlled the pore structure and properties of porous ceramics by controlling the holding time while using a high volume of polishing tile waste as the raw material. Under a holding time of 30 min, the volume density reached 0.68 g/cm^3, while water absorption and apparent porosity were 27.33% and 15.49%, respectively. The compressive strength reached 13.07 MPa, and the pore size distribution was mainly between 25 μm and 100 μm (entry 7 of Table 4).

The effects of foam stabilizers (e.g., sodium phosphate) on the porosity, pore size distribution, and performance of foam ceramics have been explored. Wang et al. produced a foam ceramic from polishing tile waste by adding SiC as a foaming agent and sodium phosphate as a foaming stabilizer (entry 3 of Table 3). The addition of 1% SiC and 2%–3% sodium phosphate resulted in a foam ceramic with a continuous pore structure (entry 3 of Table 4).

Polishing tile waste can be mixed with other wastes for foam ceramic production to improve the waste utilization rate. Kırsever et al. synthesized foam ceramics by varying the polishing tile waste loading from 0 to 75 wt% on natural zeolite (entry 4 of Table 3). The increase in the CTW loading increased the number of pores and pore size because the SiC particles contained in polishing tile waste were decomposed into gases (e.g., SiO_2 and CO_2) that played a role in expanding the pores. The total porosity (21.80%–81.94%), density of the light foams (0.45–1.85 g/cm^3), flexural strength (0.84–6.18 MPa), and thermal conductivity at 25 °C (0.21–0.80 W/m/K) were highly associated with the polishing tile waste composition (entry 4 of Table 4). Wang et al. prepared foam ceramics from mixtures of polishing tile waste and shale (entry 5 of Table 3). When the polishing tile waste and shale contents were 30% and 60%, respectively, a foam ceramic with a bulk density of 0.225 g/cm^3 was prepared. It exhibited high compressive strength (1.95 MPa) and thermal conductivity (0.065 W/m/K) (entry 5 of Table 4). Liang et al. used a mixture of polishing tile waste and fly ash as the feedstock to prepare porous ceramic foam materials potentially used for building partition walls and ceilings (entry 6 of Table 3). The feedstock was sintered at 925 °C. During the sintering of the mixture, borax was used as the fluxing agent. When 18-wt% borax was added to the CTW/fly ash mixture, the sintering temperature of the foam ceramic was reduced by 300 °C, and the passive oxidation of SiC was accelerated, thereby promoting the foaming process. The foam ceramic produced from the mixture of polishing CTW and fly ash had a homogenous porous structure, high average pore diameter, low bulk density, high compressive strength, and high porosity compared with the foam ceramic produced from only CTW (entry 6 of Table 4).

The properties of the foam ceramics prepared from polishing tile waste are compared in Fig. 5. Different sources of polishing tile waste and other additions of the initial raw materials can affect pore formation. The average pore diameter of foam ceramics varies from 0 to 1.5 mm, which can influence the porosity of the foam ceramics. The bulk density is highly related to the shape and distribution of pores in porous

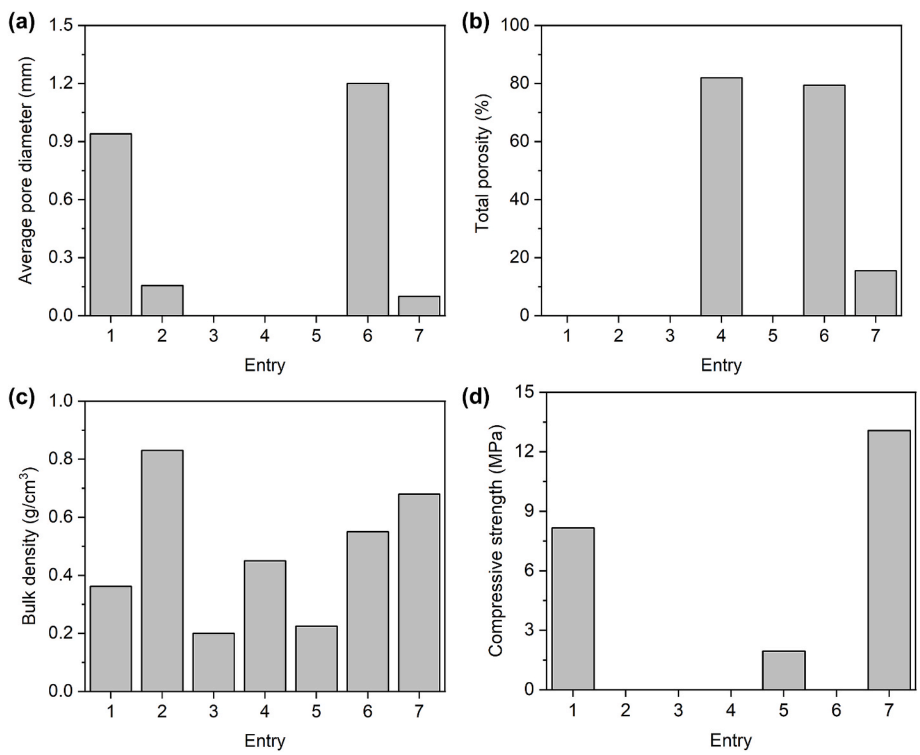

Fig. 5. Properties of foam ceramics produced from polishing tile waste: (a) average pore diameter, (b) total porosity, (c) bulk density, and (d) compressive strength. The entry numbers shown on the X-axis correspond to those in Tables 3 and 4 (For entry 2: all values is with a compaction pressure of 20 MPa, a firing temperature of 1170 °C and a firing time of 60 min; For entry 3: all values is with SiC loading of 1 wt% and Na_3PO_4 loading of 3 wt% and a firing temperature of 1300 °C; For entry 4: all the values is with CPW loading of 75 wt%; For entry 7: the average pore diameter is the highest value with a holding time of 30 min).

ceramics. There are two types of pores: open and closed (Salleh et al., 2021). Open pores reduce the compression strength (Ali et al., 2017), whereas closed pores can increase the compressive strength of foam ceramics (Arezki et al., 2016).

The composition of polishing tile waste primarily consists of SiO_2 and Al_2O_3, resembles traditional mineral raw materials. Originating from polishing process, polishing tile waste contains SiC resulting from the wear of polishing heads. Consequently, it possesses the requisite constituents for the production of foam ceramics. In most studies, the sintering temperature ranging from 900 °C to 1200 °C and holding time ranging from 0.5 h to 2 h. With increasing holding time, the average pore diameter of foam ceramics expands. However, the strength diminishes, failing to meet the requirements of foam ceramics. To mitigate this issue, researchers employ the addition of foaming agents (e.g., SiC) and other high-hardness waste materials, to attain the intended porous structure.

In order to minimize energy consumption, certain scholars have introduced fluxing agent (e.g., borax) to lower the sintering temperature to below 900 °C. This initiative not only mitigates carbon emissions but also aligns with objectives of sustainable development. Thus, by controlling parameters such as sintering temperature, raw material content, and holding time throughout the manufacturing process, the properties of foam ceramics can be effectively regulated to meet specific performance requirements.

4.2. *Use in concrete*

Concrete primarily consists of aggregates and a cementitious paste. Aggregates form the skeleton structure, while the cementitious paste fills the voids within the skeleton and facilitates the flow of the concrete (Bednarska and Koniorczyk, 2020).

4.2.1. *Concrete aggregate*

Coarse aggregate constitutes a pivotal component of the concrete, often representing more than 50% of the total concrete volume (Wang et al., 2020). It has a significant impact on the mechanical properties and durability of hardened concrete and the workability of fresh concrete. CTW with a large particle size identified as potential substitutes for conventional concrete aggregates (Suzuki et al., 2009) (Tables 5 and 6).

A considerable body of research has emerged, providing comprehensive summaries of the mechanical properties of CTW across diverse proportions of concrete aggregate replacement. Bommisetty et al. studied the variations in strength characteristics of concrete caused by incremental replacement of coarse aggregate with CTW. Upon reaching a replacement ratio of 20%, the concrete exhibited optimal compressive strength of 35.55 N/mm^2, marking a 10.09% enhancement compared to conventional concrete. Similarly, the ultimate splitting tensile strength peaked at 4.1 N/mm^2, representing a notable 28.9% improvement over conventional concrete. Moreover, the flexural strength reached its zenith at 5.43 N/mm^2, reflecting an 8.27% increase compared to conventional concrete (Bommisetty et al., 2019).

Goyal et al. compared the concrete properties (e.g., compressive strength, flexural strength, and tensile strength) when replacing 0%, 5%, 10%, 15%, 20%, and 25% CTW (entry 12 of Table 5). The 15% CTW proportion led to the highest mechanical properties, improving the 28-day compressive strength by 17.29%, the 28-day flexural strength by 3%, and the 28-day tensile strength by 9% (entry 8 of Table 6).

Roig-Flores et al. studied the reutilization of a specific type of CTW consisting only of stoneware and porcelain tiles as recycled aggregate in concrete. When varying proportions of CTW are used in place of natural coarse aggregate, workability is generally improved while compressive strength remains the same or increases. When different proportions of CTW are used instead of natural fine aggregate, although the workability of the concrete is still improved, the compressive strength decreases slightly compared to conventional concrete (Roig-Flores et al., 2023)

Table 5
Recycling methods of concrete composite produced from CTW.

Entry	CTW type	Additive dosage (kg/m^3)								Stirring (min)	Stewing (h)	Compressing		Curing			Ref.
		CTW	Cement	Aggregate		Water	Silica fume	Fly ash	Super plasticizer			Condition	Time (day)	Temperature (°C)	Time (h)	RH (%)	
				Fine	Coarse												
1	Polishing tile waste	0–5	750	990	–	168	200	200	–	5	24	mold	–	24	24	95	Li et al. (2023a, b)
2	Fired glazed wall and floor ceramic tile wastes	494	350	719	1173	175	0–30	–	–	–	–	mold	–	–	24	–	Amin et al. (2020)
3	Porcelain and red ceramic wastes	196, 293, 588, 785	400	802	–	216	–	802	–	–	24	500 kN	3, 7, 28, 56	Room temperature	24	95	Keshavarz and Mostofinejad (2019)
4	Polishing tile waste	0–190	190–380	650	–	w/b (0.5)	–	–	–	5	24	mold	–	24	24	95	Amin et al. (2020)
5	Polishing tile waste	0–20	70–100	–	–	w/b (0.4)	–	–	–	–	–	–	–	–	–	–	Pang et al. (2023)
6	Polishing tile waste	0–203	647–1044	1032	–	253–331	–	–	–	–	–	mold	28	–	–	–	Li et al. (2020)
7	Polishing tile waste	527–621	800–1000	527–621	–	180	0–300	–	–	–	–	mold	1, 7, 28, 56, 91	22, 200, 400	2	–	Li et al. (2023a, b)
8	Polishing tile waste	0–10	425	1298	–	229	47	–	1.89	–	–	mold	–	20	–	–	Obaid et al. (2021)
9	Polishing tile waste	0–138.18	322–460	–	1013.34	184.24	–	–	–	–	24	mold	1	–	24	–	Medeiros et al. (2021)
10	Bone china ceramic waste	0–40	330–550	975	–	200	–	–	–	–	–	–	–	–	–	–	Gautam et al. (2022)
11	Waste ceramic	55–275 & 0–485	220–550	365–1460	–	w/b (0.48)	–	–	–	–	24	mold	1	27	24	85	Samadi et al. (2020)
12	Ceramic tiles waste	0–275	424	630	975–1300	w/b (0.35)	–	–	0.60	–	–	mold	–	–	–	–	Goyal et al. (2022)

RH = relative humidity

Table 6
Comparing representative characteristics of concrete produced from CTW.

Entry	CTW type	CTW content	Compressive strength (MPa)	Flexural Strength (MPa)	Tensile strength (MPa)	Elasticity modulus (GPa)	Water absorption (%)	Electric flux (C)	Ref.
1	Polishing tile waste	30%	124.65	21.52	–	–	–	–	Li et al. (2023a, b)
2	Ceramic waste	10%	152	13	10.2	45.3	–	–	Amin et al. (2020)
3	Porcelain waste	870.7 kg/m^3	42	6.3	2.9	–	2	2	Keshavarz and Mostofinejad (2019)
4	Polishing tile waste	10%	47.94	–	–	–	4.91	–	Medeiros et al. (2021)
5	Bone china ceramic waste	40%	35.03	3.06	–	–	4.2	–	Gautam et al. (2022)
6	Ceramic waste	30%	76.2	6.1	4.9	43.14	–	–	Zareei et al. (2019)
7	Waste ceramic	20%	53.35	–	–	–	–	–	Samadi et al. (2020)
8	Ceramic tiles waste	220 kg/m^3	47	6.66	3.4	–	–	–	Goyal et al. (2022)

A study conducted by Sivakumar et al. revealed a significant correlation between the mechanical properties and the incorporation of ceramic waste as aggregate in concrete. The substitution of both fine and coarse aggregates with ceramic waste resulted in an increase in strength, with increases of 13.9%, 8.7%, and 15.6% observed in compressive, flexural, and split tensile strength respectively, compared to conventional concrete. However, it was noted that the workability of concrete with replaced fine aggregates, replaced coarse aggregates, and combined replacements was inferior to that of conventional concrete (Sivakumar et al., 2022).

The density of recycled waste ceramic tile aggregate is typically lower than that of natural aggregate. Moreover, owing to the flake-like morphology of CTW, aggregates obtained through manual crushing and screening tend to have a higher proportion of flaky particles, characterized by rough surface textures and increased porosity (Arasan et al., 2010). Consequently, the cement slurry's fluidity is compromised, resulting in CTW recycled aggregate concrete less Workabily than conventional concrete.

Building upon the utilization of CTW as a substitute for natural aggregates in recycled concrete preparation, additional scholars have explored co-recycling ways with other waste materials, aiming to minimize waste generation.

Amin et al. investigated the effectiveness of replacing silica fume (SF) and metakaolin with cement to improve UHPC using CTW as the coarse aggregate (entry 2 of Table 5). When the SiO_2/CaO ratio was increased from 0.59 to 2.98, the 28-day compressive strength of the SF-containing UHPC increased from 133.1 to 146.6 MPa because of the improved microstructure and denser matrix (entry 2 of Table 6).

Keshavarz and Mostofinejad used CTW and ordinary red ceramic waste as substitutes for coarse concrete aggregate (entry 3 of Table 5). CTW increased the concrete compressive strength by up to 41%, whereas the red ceramic waste increased it by up to 29%. CTW also increased the tensile and flexural strengths and water absorption by up to 41%, 67%, and 54%, respectively (entry 3 of Table 6).

Li et al. investigated the properties of concrete with CTW aggregate (coarse or fine) exposed to elevated temperatures (e.g., 200 °C, 400 °C, 600 °C, and 800 °C) (entry 7 of Table 5). The compressive strength of the concrete with CTW coarse aggregate gradually decreased from 41.0 to 15.7 MPa with increasing temperature from 25 °C to 800 °C. However, that of the concrete with CTW fine aggregate increased by 0.8% after heating at 200 °C. Therefore, it was recommended that CTW fine aggregate be used in recycled concrete instead of CTW coarse aggregate.

Zareei et al. investigated the effect of the combined use of wollastonite particles and recycled waste ceramic aggregate (RWCA) on the properties of high strength concrete and found that replacing coarse aggregate with RWCA can improve the strength and durability of concrete. For instance, the 28-day compressive strength was increased by 24% in a mixture with 50% wollastonite content with reference concrete. The strength retention at 800 °C for the mixture with RWCA was 16% higher than that of the mixture without RWCA (entry 6 of Table 6).

In Fig. 6, the properties (e.g., compressive strength, flexural strength, tensile strength, and water absorption) of the concrete produced by adding CTW are presented. Adding CTW to concrete aggregates changed their properties, and the changes varied according to the source of CTW. The reduction in compressive strength may be because the rough structure of CTW aggregates resulted in increased porosity in the concrete and the presence of an increased percentage of flaky ceramic aggregates (Ray et al., 2021). The increase in compressive strength could have contributed to the irregular shape, rough surface, and hardness of CTW, leading to a superior specific surface area. The flexural strength was mostly decreased by adding CTW as aggregate replacements. Moreover, tensile strength is less influenced by CTW than sample concrete. Because of its porous structure, the water absorption of concrete using bone china ceramic aggregates increases (Gautam et al., 2022). The internal porosity of concrete using polishing tile waste as aggregates is filled with fine particles of the polishing tile waste, resulting in a decline in water absorption.

CTW are commonly subjected to crushing and screening processes to attain a particle size compatible with concrete aggregate, facilitating their incorporation as a substitute for natural aggregate in concrete production. The optimum proportion of CTW typically falls within the range of 20%–50%. An excessive content of CTW aggregate can lead to too many flaky particles within the recycled aggregate, characterized by a roughened surface texture. This phenomenon hindered the flow characteristics of the cement, resulting in a lower workability in comparison to conventional concrete.

Furthermore, the early-stage strength of recycled concrete exhibits a propensity for instability. After complete hydration is achieved, the cement tends to experience an initial increase in strength, followed by a decline in strength over time.

To address these challenges and uphold the quality standards of recycled concrete, adjustments to the cement content may need to be adjusted on a case-specific basis. Through regulation of mix proportions and monitoring of the hydration kinetics, the performance attributes of recycled concrete can be optimized.

4.2.2. SCM in concrete

CTW can be effective pozzolan when ground to appropriate fineness, then can be mixed with concrete mortar (Table 7). The utilization of CTW as both a binder and a fine aggregate source (entry 11 of Table 5) markedly improved the compressive strength of the mortar and provided higher resistance to adverse environmental conditions (e.g., sulfate solution containing 5% Na_2SO_4) (entry 7 of Table 6).

Gautam et al. investigated the incorporation of bone china ceramic waste (BCCW) into self-compacting concrete (SCC) as a partial substitute

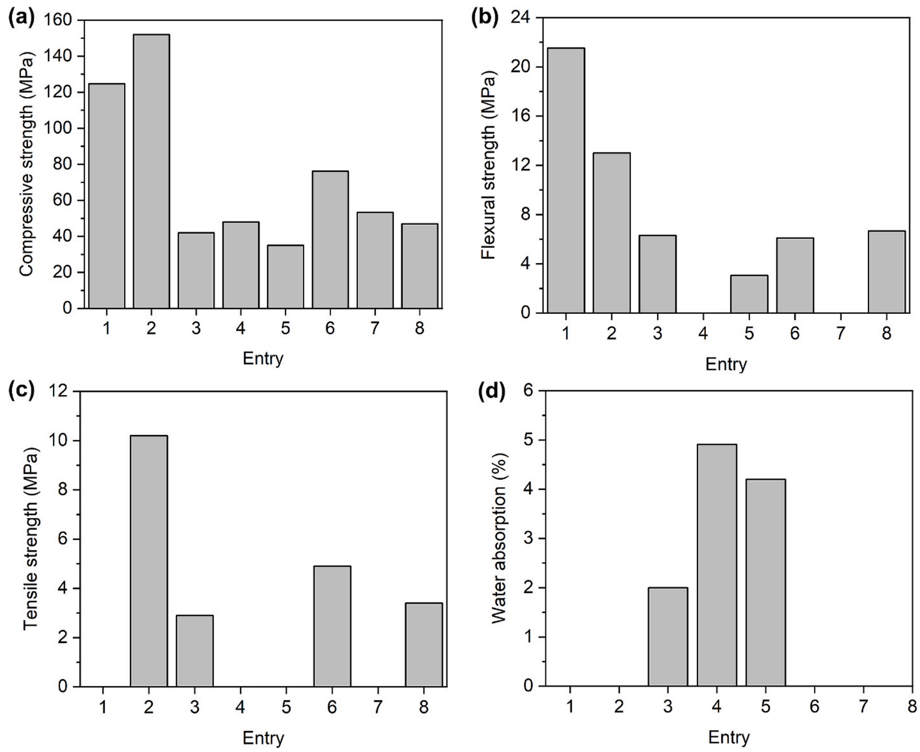

Fig. 6. Properties of concrete produced from CTW: (a) compressive strength, (b) flexural strength, (c) tensile strength, and (d) water absorption. The entry numbers shown on the X-axis correspond to those in Tables 5 and 6

Table 7
Characteristics of concrete mortars recycled from CTW.

Entry	CTW type	CTW content (%)	Slump/flow spread (mm)	Pore volume (cm^3/g)	Setting time (min)	Compressive strength (MPa)	Flexural strength (MPa)	Water absorption (%)	Ref.
1	Polishing tile waste	30	246	0.0017	6	116.5	–	–	Tian et al. (2023)
2	Polishing tile waste	10	–	0.18	42	70.9	8.6	–	Pang et al. (2023)
3	Polishing tile waste	10	167	–	–	74	8.9	10.4	Obaid et al. (2021)
4	Polishing tile waste	20	230	–	–	–	–	–	Li et al. (2019a, b)
5	Ceramic tile demolition waste	30	55.0	–	–	47.5	–	–	de Matos et al. (2021)
6	Ceramic waste powder	25	157.4	–	71	39.88	5.44	–	Mohit and Sharifi (2019)
7	Ceramic tiles powder	20	26	–	–	14.76	7.76	–	Bhargav and Kansal (2020)

for cement (entry 10 of Table 5). Incorporating up to 10% BCCW into SCC enhanced the compressive and flexural strengths by up to 44.9 MPa and 5.24 MPa, respectively (entry 5 of Table 6).

Cement acts as glue that binds various aggregates, forming concrete. Polishing tile waste, as an inorganic nonmetallic waste, has been used as an SCM in concrete. For instance, Li et al. used CPW to prepare UHPC (entry 1 of Table 5). The UHPC exhibited a compressive strength of >120 MPa for 28 days regardless of the cement replacement ratio with polishing tile waste (entry 1 of Table 6). Applying polishing tile waste to cement also enhanced the resistance of concrete to chloride penetration (Wang et al. (2023a, b). Li et al. evaluated the reutilization of polishing tile waste as an SCM in concrete. It was confirmed that the compressive strength and chloride resistance of the concrete were improved by adding 20% polishing tile waste (entry 6 of Table 5). Medeiros et al. partially replaced cement and sand with polishing tile waste and scheelite residue, respectively, to produce eco-efficient concrete and investigated the physico-mechanical properties and durability of the concrete (entry 9 of Table 5). The 15% polishing tile waste dosage was found to be optimal for improving the compressive strength by 26.6% and obtaining equivalent or higher chloride ion penetration resistance compared with the reference sample without polishing tile waste (entry 4 of Table 6).

Pereira-de-Oliveira et al. verified the pozzolanic activity of CTW via the Compressive Strength Activity Index test of mortars produced by partial CTW replacement of cement in different proportions at 7, 28, and 90 days (Pereira-de-Oliveira et al., 2012). The compressive strength of the mortar incorporated with CTW increased by 25% and 30% from 28 to 90 days when the CTW ratio was 20% and 40%, respectively.

Tian et al. used polishing tile waste to partially replace granulated blast furnace slag (slag) to prepare an alkali-activated slag/CPW (AASC) cementitious material. The compressive strength of the pastes containing polishing tile waste was decreased compared with that of the reference sample because of the dilution effect of polishing tile waste. When the CTW content was 30%, additional calcium–aluminate–silicate-hydrate gels were formed in the AASC pastes, and the compressive strength (116.5 MPa) was equal to that of the reference sample (126.3 MPa). Therefore, replacing the slag with 30% CTW was the optimal proportion to prepare the cementitious material (entry 1 of Table 7).

Pang et al. added mineral admixtures consisting of calcium carbide slag (CCS) and polishing tile waste to cement-based composites (entry 5 of Table 5). The composite mortars had lower compressive and flexural strengths than typical cement mortars, particularly at an early age (e.g., 1–3 days). The pozzolanic reaction between CTW and CCS promoted the compressive strength of the composite mortars at a later age (28–90 days). The micropores on the composite contributed to enhancing the capillary pressure and increasing autogenous shrinkage (entry 2 of Table 7).

Obaid et al. tested four mortar mixtures using three types of tile waste (marble, granite, and ceramic) for replacing fine aggregate in concrete. In all mixtures, cement was partially replaced with a 10% SF (entry 8 of Table 5). The CTW aggregates with 10% SF exhibited superior performance compared with the other mixtures, increasing compressive strength by 99%, flexural strength by 53%, and water absorption resistance by 17% (entry 3 of Table 7). The addition of 20 vol% polishing tile waste as paste replacement to cement reduced the cement content by 33%, increased the 7 and 28-day cube strengths by at least 85%, and densified the microstructure (entry 4 of Table 7) (Li et al., 2023a, b).

de Matos et al. produced a Portland cement-based concrete mortar by mixing 0–30-wt% CTW. The recycled mortar progressively increased the static yield stress and mortar viscosity while reducing the interparticle distance of the mortar system. It also had up to 5% higher compressive strength at 1 and 7 days than a limestone-based concrete mortar when containing the same CTW content (entry 5 of Table 7).

Mohit et al. employed CTW as an alternative cementitious material. An increase in the CTW content in cement decreased the expansion associated with the alkali–silica reaction. The specimen containing 10% CTW as a cementitious material exhibited the highest compressive strength of 39.88 MPa (entry 6 of Table 7). Bhargav and Kansal found that cement recycled from CTW has high concrete density and self-weight compared with cement without CTW. In addition, the compressive strength of the concrete containing up to 15% CTW (32.27 MPa) was comparable to that of standard concrete (29.1 MPa) (entry 7 of Table 7).

Fig. 7 shows the fresh (e.g., flow spread rate and setting time) and hardened properties (e.g., compressive strength and flexural strength) of the mortar. The reduction in the flow rate can be attributed to the angularity with the high surface hardness of CTW, decreasing workability by increasing the friction with the cement paste (Obaid et al., 2021). The setting time has been extended with the addition of CTW because it has the effect of evenly distributing cement particles (Alsaif, 2021). Similar to concrete incorporated with CTW, the changes in compressive and flexural strengths of mortars produced from CTW vary depending on the source of CTW. The strength properties have been improved because of the higher compressive and flexural strengths of CTW than natural aggregate and the enhanced bonding between the replaced aggregate and the cement paste (Mohit and Sharifi, 2019).

In particular, the incorporation of polishing tile waste into concrete is regarded as a promising method to enhance concrete's resistance to chloride ion penetration, owing to its pozzolanic characteristics. As the dosage and specific surface area increase, the resistance of concrete to chloride ion penetration is improved.

4.3. Production of ceramic tiles

In ceramic tile manufactories, CTW is divided into unfired and fired wastes according to whether or not it experiences a sintering process. Currently, the simplest method is to add unfired ceramic powders into the ceramic body preparation stage (Gan, 2010). The recycling rate of unfired waste in some manufacturers in Italy reaches up to 100% (Boschi et al., 2023). According to reports from the British Ceramic Research Association, some ceramic tile manufacturers in the UK use >40% recycling CTW.

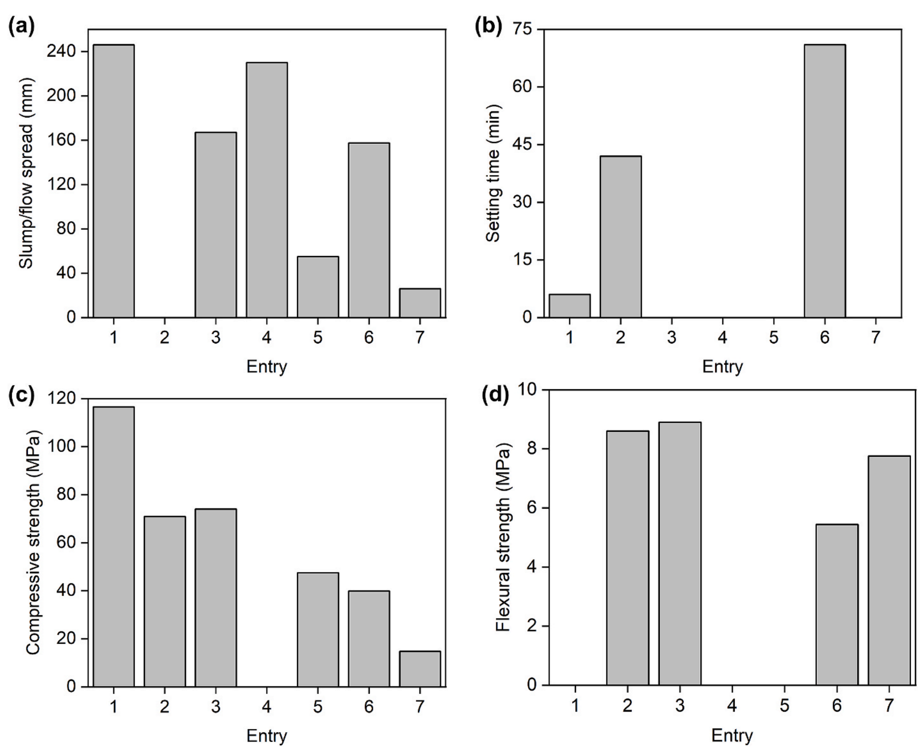

Fig. 7. Properties of concrete mortar produced from CTW: (a) slump/flow spread; (b) setting time; (c) compressive strength; (d) flexural strength. The entry numbers shown on the X-axis correspond to those in Table 7.

Ceramic tiles exhibit diverse compositions based on the quarry of their raw material or their intended uses. Table 8 summarizes several studies using CTW to prepare ceramic tiles. For instance, Yang et al. prepared permeable bricks by recycling 82-wt% CTW as aggregate. The permeability, flexural strength, and apparent porosity of the obtained permeable bricks were 3.2×10^{-2} cm/s, 6.8 MPa, and 28%, respectively. They also successfully produced 100 permeable bricks (140 × 280 × 80 mm) with high permeability of 3.0×10^{-2} cm/s, a flexural strength of 6.3 MPa, and a relatively high apparent porosity of 26% (entry 1 of Table 8).

Wattanasiriwech et al. synthesized paving blocks using CTW as the main component by mixing them with Portland cement, followed by a compacting process. The compressive strength of the blocks containing 25–30-wt% CTW exceeded the standard requirement (35 MPa) after 7 days of curing (entry 4 of Table 8). Dubale et al. attempted to produce fired bricks using demolished CTW, laterite, and alluvial soils. The fired bricks satisfied Indian Hazardous Waste Management Rules and American Society for Testing and Materials (ASTM C62-13a) when applying 35- wt% and 40-wt% demolished CTW at firing temperatures of 850 °C and 900 °C, respectively (entry 5 of Table 8).

To obtain more amorphous pozzolans before preparing paving bricks, Utami et al. proposed the thermal treatment of CTW before the addition of CTW to the raw material of the paving bricks. When CTW was thermally treated in a furnace at 900 °C, the compressive strength increased by 5.9% and water absorption decreased by 14.5%, compared with the paving brick sample made with CTW treated at 750 °C (entry 6 of Table 8). Azevedo et al. evaluated the potential of preparing geopolymer ceramic tiles containing CTW. CTW was ground and homogenized in a medium sieve to achieve particle sizes suitable for use in ceramic materials (e.g., 9.01 μm). The resultant geopolymer ceramic tiles had water absorption of <4% and flexural strength of 17.51 MPa (entry 7 of Table 8).

In addition, CPW is considered a raw material for ceramic tile production. Wang et al. prepared ceramic tiles using CPW (10–30 wt%) as a raw material at temperatures, ranging from 1125 °C to 1200 °C (Wang et al., 2021). Ke et al. obtained porcelain tiles with various amounts of CPW (10–70 wt%) after firing at 1100–1180 °C. The specimens with 50-wt% CPW fired at 1120 °C had water absorption of 0.12%, a bulk density of 2.49 g/cm^3, and flexural strength of 47 MPa (entry 3 of Table 8), which were superior to those of porcelain tiles ISO 13006 standard (water absorption of ≤0.5% and flexural strength of ≥35 MPa). Penteado et al. also used CPW as a partial replacement for cement and sand by replacing 30% of fine aggregate or 20% of cement with CPW, producing paving blocks that met the standard compression strength requirement of 50 MPa for heavy vehicle traffic (entry 2 of Table 8).

Fig. 8 shows the properties of ceramic tiles recycled from CTW. The bulk density ranges from 1 to 3 g/cm^3. Many processing parameters influence the strength of the ceramic tiles. Compaction pressure plays a significant role in bulk density (Wattanasiriwech et al., 2009). The compressive strength, water absorption, and flexural strength of the ceramic tiles differed because of CTW resources. However, recycled ceramic tiles (e.g., paving blocks, permeable bricks, and porcelain tiles) meet regional standards.

When prepare ceramic tiles using CTW as a raw material, the blending amount of CTW can vary widely, ranging from 10% to 80%. CTW exhibits excellent wear resistance and high hardness, making it an ideal aggregate for preparing permeable bricks. Permeable bricks play a crucial role in the construction of sponge cities, as they effectively reduce urban runoff, alleviate urban waterlogging, reduce the heat island effect.

When incorporating CTW as a substitute for cement in paving brick production, the resulting bricks exhibit heightened water absorption and porosity relative to traditional one. The water absorption rate can even exceed 10%, significantly increasing the excellent quality and durability of the manufactured paving bricks. These approaches not only contribute to ecological protection but also promote resource conservation and sustainable development.

5. Summary and outlook

CTW are representative construction wastes in modern society. Thus, the recycling of CTW is important to achieve sustainable construction waste management. Nevertheless, large amounts of CTW are still landfilled, which have negative impacts on the environment. Therefore, many studies have been conducted to effectively recycle CTW into construction materials. Different construction materials, such as foam ceramics, concrete, and ceramic tiles, can be produced from CTW. In this work, many research articles were reviewed and analyzed to provde a comprehensive survey of various methods that allow CTW recycling into construction materials. Through the literature survey, the following points could be drawn.

Foam ceramics can be produced from polishing tile waste via various routes, including direct foaming, inorganic gel casting, particle accumulation, particle-stabilized foam, organic foam impregnation, and additive foaming agent methods. Among these, the direct foaming method has been the most widely used, whereas the inorganic gel casting method has been recently developed. The processes for producing foam ceramics from polishing tile waste are well-established even at industrial scales. However, the characteristics of polishing tile waste (e.g., composition, microstructure, and particle size) are highly dependent on the manufacturing conditions of virgin products; therefore, subsequent research on the pore structure and shape of foam ceramics can be conducted, and the polishing tile waste foaming mechanism can be investigated to improve the strength of the foam. Standardizing the polishing tile waste recycling method for high-quality foam ceramics is difficult. The need for sintering at high temperatures (e.g., 1100 °C) for a certain time (e.g., 2 h) may increase operating costs and contribute to greenhouse gas emissions. To address these issues,

Table 8
Characteristics of ceramic tiles recycled from CTW.

Entry	Target product	CTW type	Waste content (%)	Compression strength (MPa)	Flexural strength (MPa)	Water absorption (%)	Bulk density (g/cm^3)	Porosity (%)	Ref.
1	Permeable bricks	Ceramic waste	84	–	6.3	–	1.78	26	Yang et al. (2020)
2	Paving block	Polishing tile waste	20	66.0	–	4.88	–	11.22	Penteado et al. (2016)
3	Porcelain tiles	Polishing tile waste	50	–	47	0.12	2.49	–	Ke et al. (2016)
4	Paving block	Dry ceramic waste mud	25	43.2	–	–	–	–	Wattanasiriwech et al. (2009)
5	Fired brick	Floor and wall tile waste	35	7.2	–	18.4	1.32	–	Dubale et al. (2022)
6	Paving block	Roof tile waste	10	20.36	–	10.27	–	–	Utami et al. (2019)
7	Ceramic roof tiles	Clay bricks waste	–	–	17.51	<4	–	–	Azevedo et al. (2020)

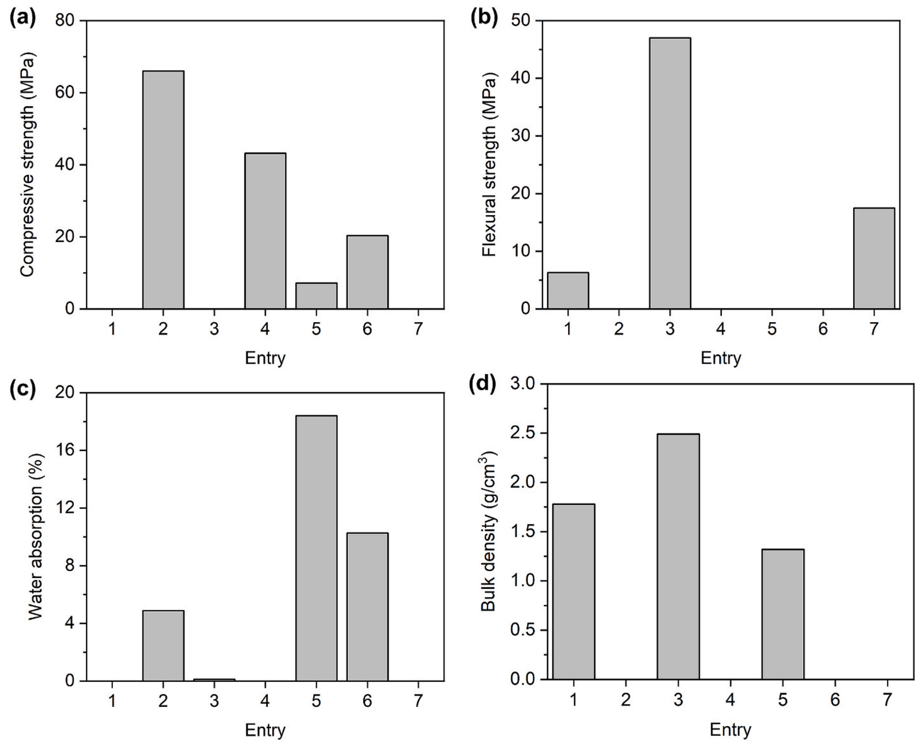

Fig. 8. Properties of ceramic tiles produced from CTW: (a) compressive strength, (b) flexural strength, (c) water absorption, and (d) bulk density. The entry numbers shown on the X-axis correspond to those in Table 8.

standardizing the quality of raw materials is crucial, which guarantees constant high-quality recycled products. To this end, during industrial manufacturing, the details of each production batch should be specified, including raw material specifications, process parameters, and quality control results. Moreover, the development of an energy-efficient sintering process that can operate under milder conditions is most likely a breakthrough.

CTW can be recycled to replace either traditional aggregates or SCMs in concrete. This review primarily synthesizes data pertaining to the mix proportions and performance evaluations of CTW recycled concrete. The efficacy of concrete mix designs profoundly influences compliance with standards and adherence to budgetary constraints within concrete projects. While significant research have focused on integrating suitable proportions of CTW into concrete, relatively limited attention has been devoted to investigating the influence of aggregate particle characteristics and the slurry-to-aggregate ratio on the properties of CTW recycled aggregate concrete. The influence of incorporating CTW as aggregates into concrete on basic physical and mechanical properties requires further research from a microstructure perspective (e.g., irregular shape and rough surface). Moreover, properties, such as fire resistance, sulfate corrosion resistance, frost resistance, and gas permeability have still not been investigated.

Ceramic tiles can be prepared by recycling CTW. Ceramic tile production from CTW has been demonstrated in several engineering projects. However, the recycling rate of CTW into ceramic tiles is still low; therefore, research on maximizing the utilization of CTW will reduce the dependence on traditional raw materials for ceramic tiles. Many processing parameters affect the strength of blocks through different mechanisms. Establishing proper CTW collection, separation, and transportation to recycling centers, considering local conditions, is critical to ensuring a stable supply of CTW. Moreover, exploring new combinations of CTW and other solid wastes can improve the final recycling product performance and reduce production costs.

There is currently a lack of universal standards and specifications in the production and application of concrete prepared using CTW, which are associated with the quality of concrete. Therefore, it is necessary to make technical adjustments for CTW from different sources and optimize the production process (e.g., mixing ratio, mortar formula, and sintering temperature). The lack of adequate evidence has led to inconsistencies between the different studies.

CRediT authorship contribution statement

Shuting Fu: Writing – original draft, Methodology, Investigation. **Jechan Lee:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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