

Review

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A review on ceramic waste-based concrete: A step toward sustainable concrete

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Abstract: Ceramic waste (CW) has a significant negative environmental influence on the society. However, CW may benefit the environment if it is handled carefully and recycled in concrete production. Recycling CW may lessen the demand for raw materials and waste disposal, thereby preserving natural resources and lowering greenhouse gas emissions. Numerous studies discuss the possibility of CW utilization as concrete ingredients. However, data are spread, making it difficult for the reader or user to assess the benefits and drawbacks of using CW in concrete, which limits its applications. To study the benefits and drawbacks of using CW in concrete and provide the guidelines to the consumer with relevant information, a detailed review is required. Therefore, this study is carried out to collect all relevant updated information from published articles. The major topics of this article include the general history of CW, physical and chemical features, and the influence on concrete parameters including fresh, strength, elevated temperature, and cost benefits. Results indicate that CW decreased concrete flowability and strength. However, with up to 10% substitution, the results are satisfactory, and concrete can be used for a normal-strength structure.

Furthermore, the review also identifies the research gaps that need to be investigated.

Keywords: ceramic waste, sustainable concrete, flowability and compressive strength

1 Introduction

The building sector makes a significant involvement in the development of infrastructure in any place where concrete is utilized as the primary material [1–5]. In the previous three centuries, concrete has been the most widely used man-made substance on Earth. The sustainability of green construction has recently gained widespread acceptance around the globe [6]. Therefore, the development of sustainable materials that result in the preservation of natural resources, the lessening of carbon dioxide (CO₂) emissions, the economic utilization of waste materials, and the production of durable materials is essential. Therefore, several researchers focused on improving the sustainability of construction industries [7–10].

Each year, a substantial quantity of waste is produced, which causes a hazard to the ecosystem and necessitates a substantial amount of energy and cash to manage [11–14]. By adding wastes as a partial substitute for conventional constituents in concrete, these difficulties may be handled [15–19]. Annually, a large quantity of CW is generated, and researchers are considering reusing it to create sustainable concrete [20].

Ceramic materials have been used for a long time for a range of functions and continue to be a popular material utilized for creating items such as earthenware, sanitary ware, and high-voltage electric insulators. Ceramic floor and wall tiles, as well as other clay construction bricks, are often utilized as building materials. Figure 1 displays different CW types.

Building construction and the consumption of material supplies both expand as developing countries transform into industrialized ones. This is occurring at a time when

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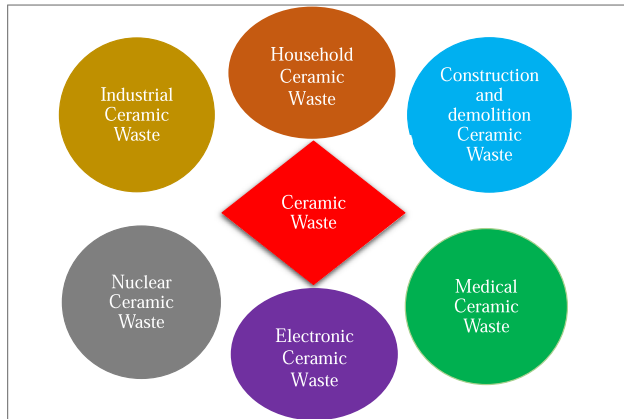


Figure 1: Types of ceramic waste.

the world community is concentrating more and more on sustainability as the challenge of global climate change becomes more obvious and widely accepted [21–24]. Reuse and recycling are frequent recommendations for enhancing the sustainability of development and are used in

many Aspects of growth and society [25–30]. However, one area that might require some work to increase sustainable development is the construction and demolition waste [31–33].

During the manufacturing process in the ceramic industries, typically 15–30% turn into a waste product. These wastes pollute the groundwater, the air, and the land. Mostly, the CW is not currently recycled in any way. Therefore, the industrial dumped CW in pits or neighboring unoccupied areas. Ceramic waste (CW) is dangerous and requires large area for disposal [34]. Ceramic companies are under pressure to find a disposal solution because of the daily accumulation of CW [35]. CW is one of the products that is produced in large quantities during the production of ceramics used in sanitary, tiling, and refractory activities [36]. CW is estimated to make up around 30% of the daily production of tiles (totaling roughly 22 billion tonnes worldwide each year). CW's incorrect disposal might cause harmful elements including barium, copper, and cadmium to seep into the groundwater, reducing the groundwater's quality and soil fertility [37].

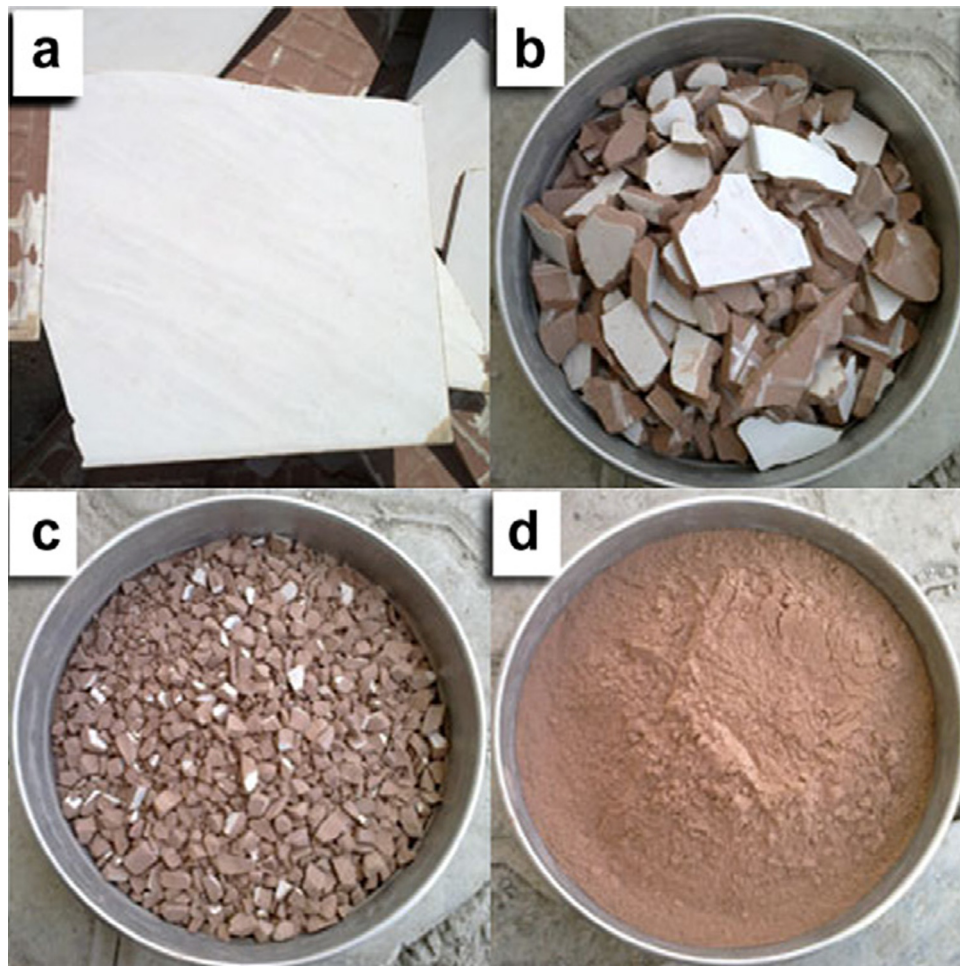


Figure 2: Preparation process: (a) raw ceramic, (b) grinding by hammer, (c) grinding by jaw crusher, and (d) powder by air jet mill [43].

The manufacture of cement composites from CW is a perfect match for a sustainable development plan. Several articles discuss the possibility of numerous CW types as energetic additives to materials made of Portland cement [38,39], with the majority of them focusing on their impact on the characteristics of mortars and concrete when used in place of natural aggregates [40,41]. Concrete using ceramic aggregate has a more refined pore structure, with fewer macropores and more capillary pores. When compared to the typical aggregate, it is shown at the microlevel that the interfacial transition zone (ITZ) also makes it compact. Zircon in CW does not migrate to cement paste and does not even hinder the chemical reaction [42]. These elements lead to the development of strength along with durability in terms of resistance to ecological, organic, and inorganic causes. Figure 2 shows the preparation procedure of CW for concrete production.

The characteristics of concretes made from waste ceramic tile aggregate were examined. The properties of ceramic aggregate were measured and ground for use in concrete as a replacement for coarse aggregates ranging from 0 to 40% and 0 to 100%. The findings revealed not only an increase in compressive capacity but also a reduction in unit weight [44]. According to a study that examined the acceptability of broken tiles as coarse aggregates in the manufacture of concrete, the compressive capacity and density of the concrete with 100% crushed granite have maximum values and those with 100% broken tiles have minimum values. According to previous studies, substituting crushed granite with a composition of between 39 and 57% broken tiles produced good results [45]. The study looked at the impact of CW as a partial substitute for crushed and sand in concrete and found that the compressive capacity enhanced for all combinations, with the blend including 10% crushed tiles and 20% tile powder having the maximum compressive capacity. According to them, the optimal proportion of coarse aggregate that may be replaced with broken tiles is 10% [46].

Recycling CW offers several advantages, such as lowering the volume of waste dumped in landfills, preserving natural resources, and lowering greenhouse gas emissions related to the manufacture of new ceramic materials. Recycling CW may also open new employment possibilities and advance the circular economy. The usage of CW as a concrete additive is thoroughly reviewed in this article. The authors discuss the general background, types of CW, the properties of CW, and the potential benefits of using CW in concrete. In addition, the authors present a thorough analysis of the literature on the use of CW in concrete, including the impact of CW on the fresh, mechanical, thermal, and cost benefits associated with the use of

CW in concrete production. The reader or user may get an idea of the benefits and drawbacks of CW in concrete without carrying out any tests, which saves both time and money. Finally, the authors recommend future research ideas that will further improve its performance.

2 Physical and chemical properties

Depending on the kind of ceramic material used and any glazes or coatings added, CW may have a variety of colors. However, ceramic is mostly gray in color. The specific gravity of CW may vary from around 2.16 [47] to 1.89 [48], depending on the nature and makeup of the ceramic material. In contrast, the specific gravity of cement is normally ~3.15. This implies that, on average, CW is less dense than cement. However, this does not always imply that CW is weaker or less durable than cement. CW may be utilized as a partial replacement for cement in concrete mixes, and studies have shown that it can increase the strength and durability of the resultant concrete.

CW is typically recognized for its low water absorption, *i.e.*, 0.10% [47] compared to many other forms of porous materials. This is due to the fact that CW is often burned at high temperatures, causing it to become thick and less porous. Water absorption in CW varies based on parameters such as ceramic material and firing temperature, but it is typically acceptable, usually less than 5%. Aggregate, on the other hand, may have a broad variety of water absorption rates based on its porosity and content. The minimal water absorption of CW, 0.10% [47], makes it stand out from other porous materials. Contrarily, the aggregate may absorb water at various speeds depending on its composition and porosity.

CW may come from several sources, such as broken or discarded ceramics, and the resultant particles can come in various forms and sizes. However, certain CW particles may be more angular or irregular in form owing to the weathering or crushing of the parent material. While cement particles might have elongated or angular forms, they are primarily created by grinding and milling procedures. Figure 3 displays a comparison between ceramic and cement particles. Similarly to this, Senthamarai and Manoharan [49] indicated that the surface roughness of the CW aggregate was smoother than that of crushed aggregate.

The chemical makeup of cement varies based on the type of cement. Portland cement, the most popular form of cement, has 65–75% calcium oxide (CaO), 20–25% silicon dioxide (SiO₂), and trace quantities of other oxides such as alumina, iron oxide, and magnesium oxide. Other forms of cement, such as slag cement and pozzolanic cement, may

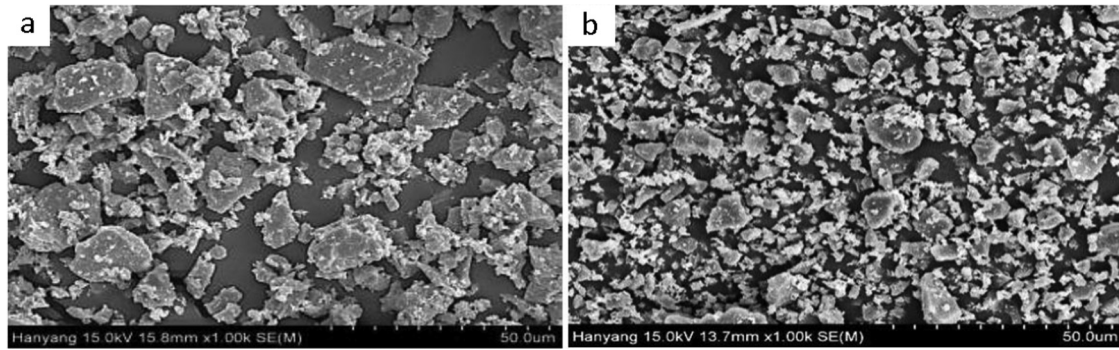


Figure 3: SEM: (a) cement and (b) CW [50].

Table 1: Chemical composition of CW

Ref.	[51]	[52]	[53]	[54]	[35]
SiO ₂	75.4	67.3	64.56	55.3	68.11
Al ₂ O ₃	9.10	19.8	15.07	18.3	16.48
Fe ₂ O ₃	1.90	2.5	6.01	6.22	0.59
MgO	1.88	2.0	2.04	0.39	1.61
CaO	8.60	2.3	4.15	11.06	0.85
Na ₂ O	—	—	—	0.68	3.78
K ₂ O	—	—	—	1.20	3.14

have various compositions. CW, on the other hand, is a broad name that may apply to a wide range of materials, including porcelain, stoneware, earthenware, and tiles. CW's chemical makeup varies depending on the kind of ceramic, but it often comprises oxides like silicon dioxide, aluminum oxide, and magnesium oxide, as well as other elements like calcium, salt, and potassium. The chemical composition of CW utilized in concrete is presented in Table 1 based on previous research.

Overall, the chemical composition of CW depicts that it can be used as a cementitious material in the manufacture of cement, which can help to reduce the amount of cement required and thus decrease the carbon footprint of cement production.

3 Fresh concrete

3.1 Bleeding

When concrete bleeds, free water in the blend rises to the top and generates a cement paste known as “laitance” on the surface. Concrete bleeds when free water rises to the top and coarse particles settle down. Continuous channels are created by the water moving upward as it moves from the bottom to the top. The structure's permeability, which reduces the strength and durability of the concrete, is often caused by these

continual bleeding channels. Figure 4 illustrates how ceramic aggregate affects concrete bleeding at various water-to-cement ratios (w/c). The bleeding becomes dangerous as the w/c increases. This is due to the tendency of the extra water in the blend to move toward the concrete's surface and accumulate there. All three bone China ceramic concrete blends with 100% bone China aggregates had bleeding rates of 2.09, 1.68, and 2.1% for w/c of 0.35, 0.45, and 0.55, respectively.

The amount of bone China aggregate in concrete increases the amount of water lost *via* bleeding. The internal water that the bone China aggregate had absorbed slowly leaked back into the concrete mixture, increasing the amount of water bleeding. Furthermore, the form of CW particles is often angular and uneven, which may lead to more interlocking and a tighter packing of the particles in the concrete mix. This may lead to diminished workability of the concrete, which in turn can raise the possibility of bleeding as more water is trapped and later released. In addition, Siddique *et al.* [55] found that using large doses of the superplasticizer to make bone ceramic concrete mixes appropriate and workable led to significant water loss *via* bleeding. The greater length of bleeding was due to a longer setting time that was brought on by the higher superplasticizer dose. Additionally, compared to natural sand, bone ceramic aggregates are finer and lighter. This causes laitance to build on the top surface of freshly blended ceramic concrete, increasing the quantity of bleeding water. Maintaining the water-to-cement ratio, using the right admixtures, and mixed designs that may assist in lowering the risk of bleeding can help manage bleeding in concrete. Proper curing and preservation of the concrete during its early phases of hardening may also assist in avoiding bleeding and assure proper strength and durability.

3.2 Workability

In general, the use of CW in concrete construction might result in a reduction in the slump flow, particularly at greater replacement rates as demonstrated in Figure 5.

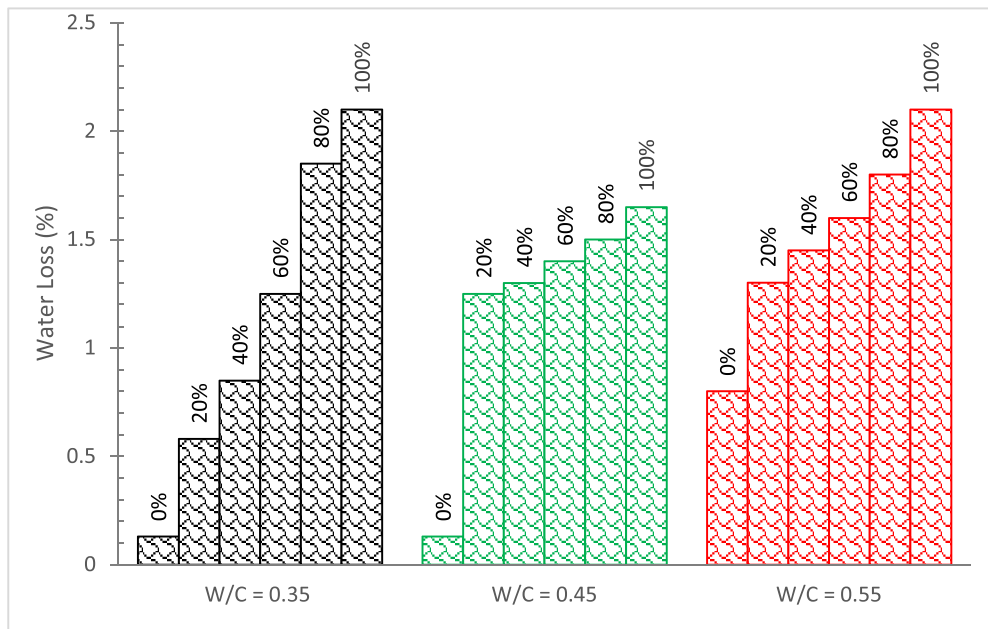


Figure 4: Bleeding of CW concrete [55].

However, this can be mitigated using chemical admixtures, such as plasticizers, which can enhance the flowability and consistency of the concrete. The decrease in slump flow with the substitution of CW as cement can be ascribed to the pozzolanic action. Gautam *et al.* [56] observed the pozzolanic action of ceramic powder of bone china. Concrete's workability or consistency may be affected by the reduction in the free water that results from the reaction

between calcium hydroxide and CW. Additionally, the slump flow of the concrete can be significantly affected by CW, which is frequently used in place of natural aggregates in concrete production. This is because CW has a larger surface area and is more porous than conventional aggregates, which may result in an increase in water demand and a decrease in flowability. According to Habert [23], the slump value decreased when recycled coarse

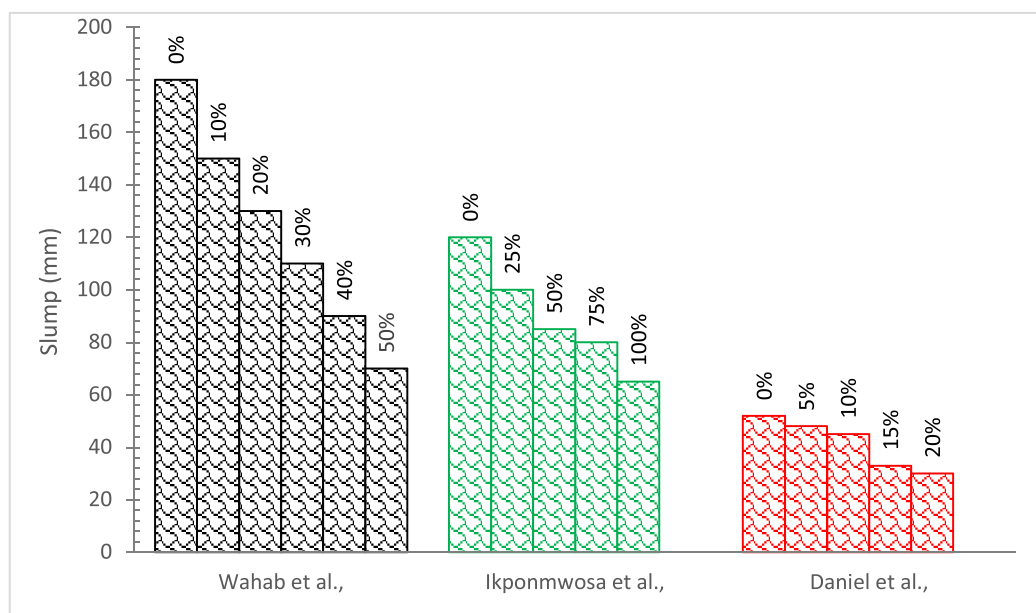


Figure 5: Slump flow of CW concrete [47,57,58].

ceramic aggregate was used in place of coarse natural aggregate for all mixes while maintaining a constant weight-to-cement ratio.

However, at 20, 40, 60, and 80%, the slump value is the same at 110 and 100 mm, respectively. Tavakoli *et al.* [46] found that the slump value lowers up to a 50% ceramic sand replacement percentage before rising again. Additionally, Jackiewicz-Rek *et al.* showed that adding more ceramic filler to mortar reduces its consistency and flexibility [59]. According to Ikponmwosa and Ehikhuenmen, the increased water absorption capacity and the angular structure of the CW might explain why the slump value rises with an enhanced ceramic proportion [47]. The surface roughness of the employed fine ceramic aggregate was shown to have uneven particle shape, rough surface texture, and sharp edges as indicated by scanning electron microscopy (Figure 6), which reduce concrete flowability.

The presoaked ceramic aggregate was used by Anderson *et al.* [31] before being added to the concrete. Results show that the ceramic particle's angularity is larger than that of the crushing aggregate, which would predict a decline in workability. However, the results of the slump indicate that the angularity had no effect in this area. The increase in a slump was more significantly impacted by the saturated series which has higher average water. The additional water on the ceramic aggregates' surface that did not evaporate within the definite time for air-drying the aggregates' surface before mixing is probably what caused the greater slump in the saturated mixes. Amin *et al.* [60] also discovered that replacing 10, 15, 20, and 25% of the coarse aggregate with porous CW aggregate resulted in slump values that were 9.09, 22.72, 36.36, and 45.45% higher, respectively. Water-soluble polymers may have been added, acting as a plasticizer and lubricant for the flow of fresh concrete, which may have increased slump.

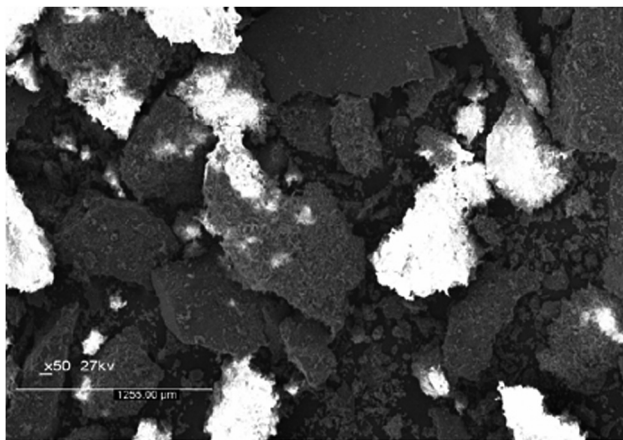


Figure 6: SEM of fine CW [57].

3.3 Air content

The interaction of sulfate attack and freeze–thaw damage may destroy concrete, although optimal air entrainment will protect it from these negative consequences [61]. Figure 7 shows the air content with different percentages of CW. The entrainment of air also promotes the workability of the concrete for placing purposes and facilitates a decrease in the sand and water contents of the mix. In a study by Van Lam *et al.* [7], the substitution ratio of CW did not impact the entrained air of fresh mortar. According to Ben Nakhi and Alhumoud [62], adding more recycled aggregate did not significantly alter the air content. The air content was 2.5% for aggregate mixes with 0% recycled material and 100% recycled material, respectively. CW, however, made the combination less flowable and required a greater admixture dosage. Ling and Poon [27] stated that increasing the quantity of the admixture used led to an increase in the air content in the freshly mix concrete, which in turn led to an increase in the total amount of air in the hardened concrete, leading to the pores in surface area and the micropore proportion. According to Zegardlo *et al.* [63], the greater porosity of ceramic aggregate is what caused the concrete density to decrease. There was still some air trapped in the ceramic aggregate particles because the cement paste had not reached the holes in the ceramic aggregate. Therefore, CW reduced fresh density and increased porosity but had no impact on the air content.

3.4 Fresh density

Figure 8 demonstrates that using CW in place of sand results in a slight decrease in the bulk density of mixes. This is likely because CW aggregate particles have a lower

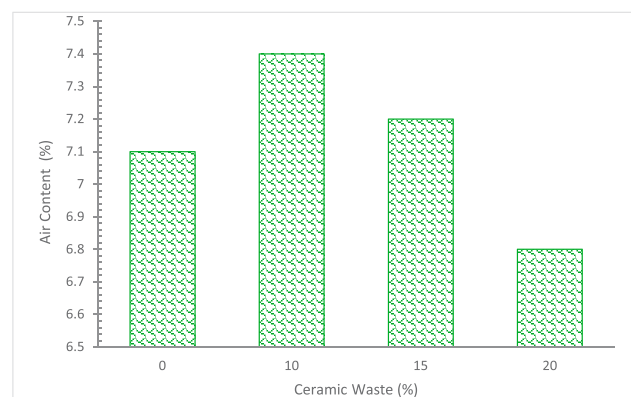


Figure 7: Air content of CW concrete [59].

density than natural sand particles. Similar findings from Ben Nakhi and Alhumoud [62] showed that the density and air content of fresh concrete dropped as the proportion of recycled particles increased. According to Elçi [64], the fresh densities of concrete made using wall and floor tile aggregate were 1,914 and 2,036 $\text{kg}\cdot\text{m}^{-3}$, respectively, whereas the concrete made with control limestone had a density of 2,377 $\text{kg}\cdot\text{m}^{-3}$. Low fresh density was reportedly caused by the floor tile and wall tile aggregates due to reduced particle density. According to Lesovik *et al.* [65], recycled concrete aggregate has a lower density of roughly 20% and a larger porosity than the natural coarse aggregate.

The fresh density steadily reduced, and the density of the CW was inversely proportional to the percentage of cement substitute. The specific weight of the CW, which was 0.4 times the value of the specific weight of the cement, caused the drop in fresh density [54]. According to Siddique *et al.* [55], using aggregate made entirely of bone in China enhanced the fresh density of concrete mixes by an average of 7%. The greater superplasticizer dosages added to fresh concrete mixes incorporating bone China aggregate produced better consolidation due to decreased viscosity, which raises the fresh density of concrete. The use of CW may result in the reduction in fresh density but it may not necessarily have a substantial effect on the concrete's overall strength and durability.

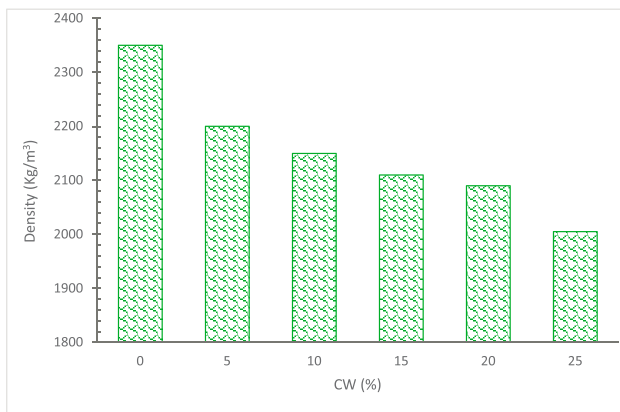


Figure 8: Fresh density of CW [66].

4 Strength properties

4.1 Compressive strength (CS)

Figure 9 and Table 2 depict the concrete CS with various CW percentages. It can be noted that most researchers claimed that the concrete CS decreased with the substitution of CW. However, according to Arbili *et al.* [33], concrete's CS increases when ceramic powder as a cement substitute increases up to 30% by weight. But when cement is further replaced with ceramic powder (beyond 30%), the strength

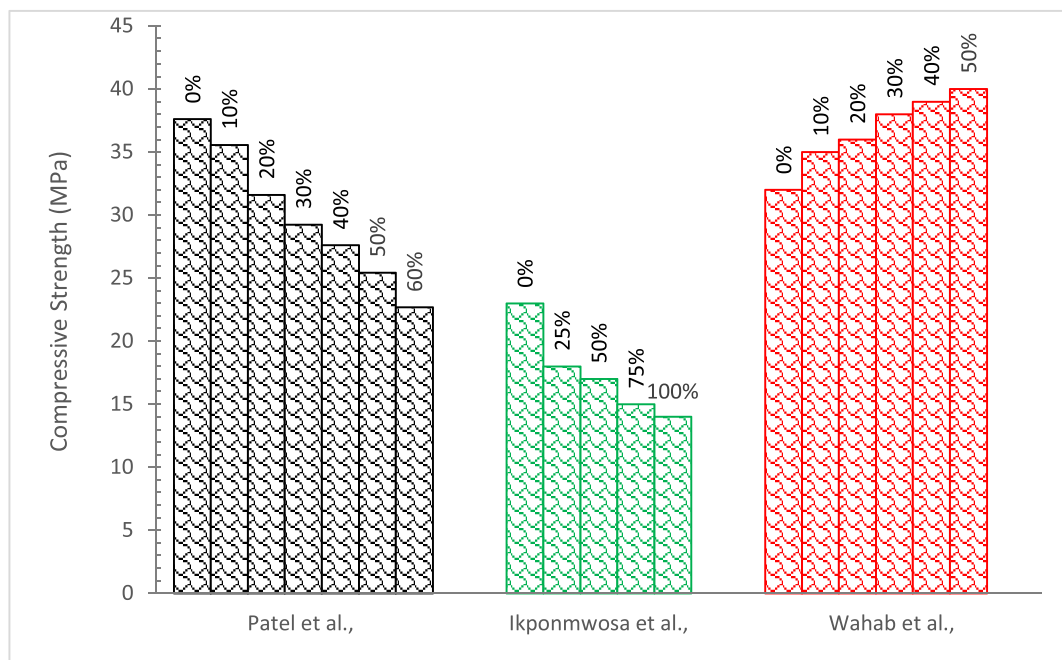


Figure 9: Compressive strength of the CW concrete [47,57,68].

Table 2: Summary of fresh and strength properties of CW-based concrete

Ref. Substitution range (%)	Replace	w/c	Optimum (%)	Slump (mm)	Days	Compression strength (optimum%)	Split tensile strength (optimum%)	Flexure strength (optimum%)	Conclusions
[48] 0–30	Cement	—	10	—	3	-13.17	-6.21	-7.85	In early ages (3 and 7 days), strength decreased while at later ages (28 days), it increased
[68] 0–60	Cement	0.46	10	Declined	7	-2.19	-6.89	-9.92	
[51] 0–20	Fine aggregate	0.50	10	—	28	+16.9	+4.63	+9.74	Flowability and strength decreased
[52] 0–20	Cement	0.50	10	—	28	-5.42	-9.02	-3.97	Strength properties improved
[53] 0–30	Coarse aggregate	0.60	10	—	28	+49.64	+26.58	+7.40	
[74] 0–30	Cement	—	30	—	28	-12.41	-3.86	-12.65	Strength properties decreased
[54] 0–40	Cement	0.50	5	—	56	-8.68	-12.93	-3.28	
[47] 0–100	Coarse aggregate	0.60	25	Declined	7	+11.11	+150.0	—	Strength properties improved
[35] 0 to 50	Cement	0.50	10	—	28	+50.00	+50.00	+0.90	Strength properties decreased
[59] 0–20	Fine aggregate	0.50	20	—	7	+18.75	-11.37	-27.04	
[31] 0–100	Coarse aggregate	0.55	20	Declined	14	-11.10	-17.73	-29.89	
[75] 0–25	Coarse aggregate	0.50	20	—	28	-13.11	-34.13	-22.60	CS improved while the flexural strength decreased
[58] 0–20	Fine aggregate	0.50	5	Declined	7	+1.25	—	—	
[57] 0–50	Coarse aggregate	0.55	10	Decreased	14	+3.07	—	-5.47	Flowability and strength decreased
					28	+0.88	—	—	
					28	-21.73	-20.90	—	
					7	+3.22	-9.91	-30.44	CS improved while the tensile and flexural strength decreased
					28	-4.01	-4.90	-13.61	
					56	+5.12	+1.86	-13.48	Strength improved
					7	+11.76	—	+30.90	
					28	+6.970	+7.41	+15.00	Compressive and tensile strength improved while flexural strength decreased
					28	+1.94	—	-7.14	Strength improved
					28	+10.09	+28.93	+8.38	
					7	-20.39	—	+11.88	Flowability and strength decreased
					28	-12.96	—	-32.00	
					7	+14.28	—	—	CS improved while flowability and flexural strength decreased
					28	+9.37	-14.28	-7.84	

Note: w/c = water to cement ratio + = increased – = decreased.

of the concrete decreases. Additionally, the concrete with a 30% cement substitution of CW achieves a CS of $22.98 \text{ N}\cdot\text{mm}^{-2}$ while lowering cement costs by up to 12.67%, making it more cost-effective than conventional concrete without sacrificing strength. Similarly, Hilal *et al.* [67] also concluded that CW increased the concrete CS. Therefore, it becomes technically possible and commercially viable. CW includes reactive elements such as silica and alumina, which may react with the cement to generate extra cementitious compounds that contribute to the strength of the concrete.

Although research is being conducted on the use of CW as a cement substitute material, it is not yet extensively employed in the building sector. Some of the difficulties in employing CW as a cement substitute include variations in the material properties and probable durability concerns over time. However, scientists are still looking at methods to improve the use of CW in the manufacture of cement, such as by altering the particle size and adding chemicals to enhance the qualities of the finished product. This is a field of ongoing study due to the sustainability advantages of employing waste materials as a cement substitute. Although CW has the potential to replace cement, a detailed study is still required to fully understand this possibility and to establish best practices for its use.

The effectiveness of common mortars was used to show that recycling waste from the ceramics industry and the destruction of red-clay bricks or tiles could be done in a way that would utilize less or no natural aggregates. Results are excellent up to at least a 20% replacement ratio of CW for sand [69]. According to Medina *et al.* [42], the CS improved as the substitution ratio of CW increased because the mixes that included ceramics were more compact and had less porosity than standard concrete. According to Guerra *et al.* [70], concrete specimens with natural crush stone aggregates substituted with 5, 7, and 9% ceramic aggregate presented improved CS at all curing ages. Singh and Srivastava [36], however, looked at the outcomes of utilizing 20, 50, and 100% fine ceramic aggregate. At 28, 32, and 42 days, respectively, it was discovered that the CS was almost 32, 33.5, and 42.5% lesser than that of the reference concrete blend. The decrease in strength was caused by an increase in the water-to-cement ratio (w/c). According to Devadas Manoharan and Senthamarai [71], using CW to partly substitute instead of crushed stone coarse aggregate did not affect the CS. Similarly, Tor-kittikul and Chaipanich [72] found that the CS of concrete with 50% ceramic aggregate was almost equal to the reference sample. They concluded that, among the fly ash concrete compositions, the one containing just recycled ceramic aggregate had the maximum CS. Siddique *et al.*

[73] also showed that the ceramic aggregate's angularity and roughness lead to a larger need for cement paste to fill the surface area, which results in more voids in concrete. However, the ceramic aggregate's pozzolanic activity neutralizes this phenomenon by helping to create hydration products that preserve or increase CS. Rahmawati *et al.* [16] examined the replacement of coarse aggregate with industrial CW. According to the results, the concrete's CS was just 3.8% less than that of the reference mix. Therefore, there is a slight change between the qualities of normal concrete and those made with coarse aggregate from CW. According to Jiménez *et al.* [40], using up to 40% of a recycled aggregate made from ceramic wall waste may have somewhat enhanced the mechanical qualities of the masonry mortars.

4.2 Tensile strength (TS)

The concrete TS with varying CW percentages is presented in Figure 10. The concrete TS was slightly reduced with the replacement of CW. Awoyera *et al.* [76] studied the strength of CW aggregate concrete. CW as a fine and coarse aggregate replaced the concrete fine and coarse aggregate of 25, 50, 75, and 100%, respectively. Results depict that the strength properties of CW concretes improved as the percentage of natural aggregate replacement increased.

According to Higashiyama *et al.* [41], the TS of mortar improved as the quantity of CW used to replace natural aggregate increased. They also discovered that with a replacement proportion of 25% ceramic fine particles, the TS increased by roughly 12% when associated with the control sample. Anderson *et al.* [31] showed that the integration of ceramic tile waste enhances the concrete TS, except for 100% replacement, which shows a maximum of 6.5% deterioration in TS. According to Medina *et al.* [77], the presence of ceramic aggregates caused the pore arrangement to be refined, resulting in an increase in the volume of capillary pores and a decrease in the volume of macro-pores which caused more strength. According to Medina *et al.* [42], mixes with ceramic waste are more compact and have less porosity than ordinary concrete, which results in an improvement in TS with an increase in the replacement ratio. Siddique *et al.* [73] discovered that surplus water present during concrete mixing progressively evaporates, resulting in cavities. Because of the relatively rough surface of ceramic aggregate, a higher volume of cement paste is required to ensure sufficient coverage, which also generates voids. Because of the angular form of the ceramic aggregate, there is a higher proportion

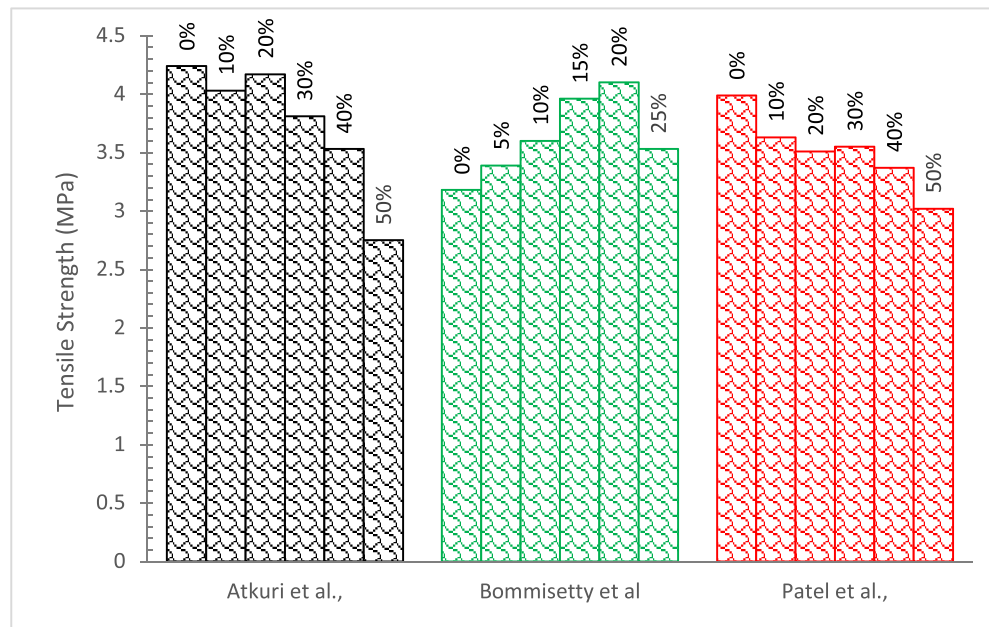


Figure 10: Tensile strength of CW concrete [35,68,75].

of voids in the concrete. The increasing void causes a reduction in the concrete strength capability.

The TS of ceramic mortar was observed to increase with curing age. It may be linked to the pozzolanic reaction that occurred between the active silica and calcium hydroxide, which was generated during the cement's hydration phase. Furthermore, owing to the pozzolanic character of CW, the TS for ceramic mortar at 7 days was lesser than that of the cement mortar [78]. According to Heidari and Tavakoli [43], the TS of ceramic mortar was 2.85 MPa after 7 days of curing, which is roughly 4% less than the 2.95 MPa obtained for cement mortar. However, the TS of ceramic mortar improved with time when compared to cement mortar. For example, after 90 days, the TS of ceramic mortar was found to be 4.45 MPa, which is about 15% greater than that of cement mortar during the same curing period. Bai *et al.* [79] also observed that the concrete strength increased with increasing curing time. The pozzolanic reaction often moves more slowly than other cementitious reactions such as the hydration of cement. This is due to the gradual chemical reaction that takes place over time when the pozzolanic material (silica) and calcium hydroxide react with each other in the presence of water. The kind and quantity of pozzolan used, the environment's temperature and humidity, as well as the particle size of the pozzolan, may all affect how quickly the reaction occurs. The pozzolanic reaction's slow speed influences the rate gain of strength. However, the slow rate may be advantageous in certain circumstances. As the reaction products have more time to fill in the pores and gaps in

the concrete matrix, the slower reaction, for instance, may produce denser and more durable concrete. Pozzolanic compounds may also aid in lowering the heat of hydration, which can be problematic in large quantities of concrete transfers or in warm areas.

4.3 Flexural strength (FS)

Figure 11 depicts the flexural strength (FS) of concrete made with various CW percentages. The concrete FS with the substitution of CW increased up to certain percentages and then decreased. Silva *et al.* [69] also showed that the CS and FS increase with the substitution of fine aggregate by brick waste up to around 20–40% and that both attributes deteriorated at higher replacement ratios. The increased quantity of fines with the substitution levels of brick waste that filled gaps and the pozzolanic action of the brick particles may be responsible for this enhancement in the mean values of CS and FS. The rough surface texture of the CW aggregate, which provides increased surface area, contributes to the improvement in mechanical strength. Additionally, this offers sufficient bonding between the cement paste and the CW aggregate [42]. Halicka *et al.* [80] substituted ceramic tiles for 5, 10, 15, and 20% of sand in concrete and found that the concrete with ceramic tiles had 7-day FS that were greater than those of the reference sample, excluding the concrete where ceramic tiles made up 20% of the fine aggregate.

However, according to Anderson *et al.* [31], replacing 100% ceramic tile waste results in a 25% reduction in FS. In

general, the cement's reduced ability to adhere to ceramic tile aggregate results in the formation of weaker concrete. Recycled concrete was used by Mukai and Kikuchi, [81] for structural purposes. They created several reinforced concrete beams with 150 mm × 150 mm cross sections and 1,800 mm in length using recycled aggregates at substitution ratios of 15 and 30%. The findings showed that there was no appreciable difference between the control sample and the beams made using waste materials in terms of their FS. Reinforced concrete beams measuring 300 mm × 460 mm and 3,000 mm in length were tested by Arezoumandi *et al.* [82]. It was shown that the overlay of the RCA inclusion beams had a similar FS to the control beam. Five reinforced concrete beams with CW were evaluated for their FS performance under static loads to failure [50]. Under the applied stress, the strength of the reinforced concrete beam constructed of CW and traditional concrete exhibited a similar pattern, with an identical number of fractures produced over the length of the beam. Because of the longitudinal reinforcing bar and consequent concrete fracture in the compression area, all beams failed in flexure. When compared to the control beam, the performance of beams containing 100% CW as fine and coarse particles was satisfactory. Therefore, CW was shown to be effective in the manufacturing of sustainable concrete.

4.4 Adhesive strength

The term “adhesive strength” describes an adhesive's capacity to adhere to the surface and join two surfaces. The average adhesive strength of mortars, which varied between 0.37 and 0.45 MPa, was not affected by the substitution of up to 40% fine aggregate with CW [40]. Therefore, it implies that the mortar's capacity to adhere to a surface was not adversely affected by using wasted CW instead of sand. The particle size distribution, shape, surface texture, and mineral content of the CW may be comparable to those of natural sand in terms of physical and chemical aspects. As a result, the mortar made from recycled CW can be guaranteed to have comparable adhesive strength and bonding qualities to the mortar made from natural sand. Silva *et al.* [69] also found values in the range of 0.34–0.43 MPa. The authors also discovered that the adhesive strength was increased in comparison to the control mortar by the addition of aggregates made from waste bricks of various sizes. Corinaldesi and Moriconi [83] also discovered that recycled aggregate mortars had greater mortar–brick bond strength than the control sample.

Overall, the absence of a negative effect of CW on the adhesive strength may indicate that CW might be a workable and sustainable substitute for natural sand in certain applications, thereby minimizing waste from dump sites and eliminating the determined environmental impact.

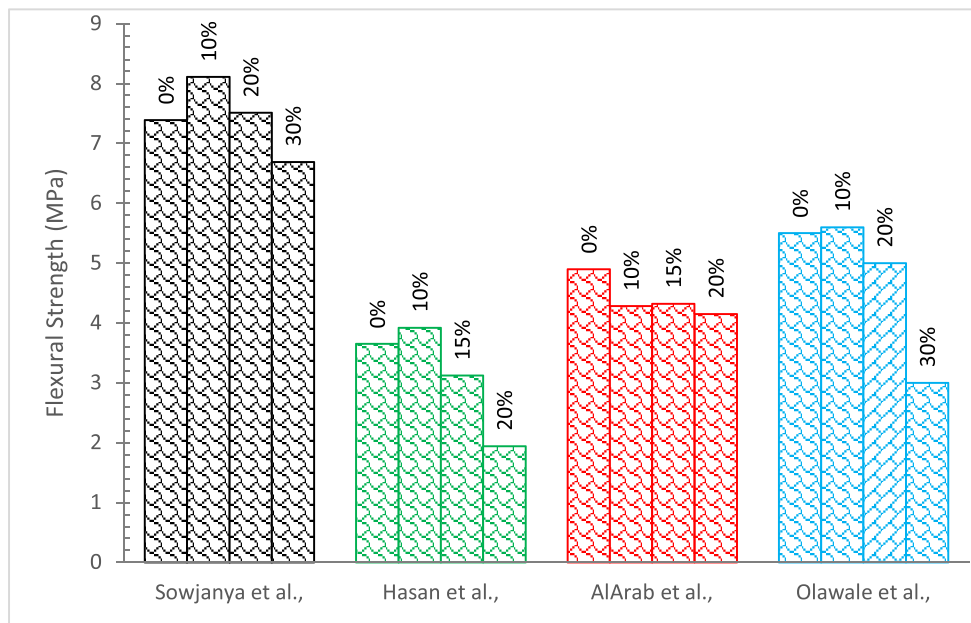


Figure 11: Flexural strength of ceramic concrete [48,51–53].

4.5 Failure pattern

Visual inspection of the examined specimens reveals that when aggregate replacement is increased, the failure mechanism changes slightly. The positions, angles, and number of fractures that occurred in the examined specimens did not significantly alter since the overall test damage characteristics were identical. But when the composition of the aggregates varied, the failure mechanism inside the fractures and around the aggregates altered as well. The control sample aggregates would break and crack with the high connection between the paste and the aggregate surface, as is typical of materials used in normal concrete construction. The failure cracks in the CW sample had a weak bond between the paste and the aggregate, as shown by the fact that many of the ceramic aggregates inside them just pushed out or dragged away from the adjacent mortar, as shown in Figure 12.

According to El-Dieb *et al.* [37], the addition of CW delays the development of strength. This is primarily due to a dilution impact that diminishes the connections in the hydrating gel. The porous nature of the ceramic may have encouraged water infiltration within the fragments, which under freezing temperatures could raise the concrete's susceptibility to break and constituent bond delamination [84]. This shows that the ITZ, or the area right around the aggregate particles with a distinct mortar internal structure, compared to that of the mortar in the cement mass, does not have a strong bond between the materials as the natural aggregate does. This may be caused by several factors, including the angular aggregate shape, the flat and smooth surface qualities of the CW, and the moisture absorption capacity, but the surface texture has probably the biggest impact. The ceramic tile material utilized in this research is naturally flat and smooth on at least two of the

sides, with the remaining sides of any particular crumpled CW aggregate being rougher in contrast. Furthermore, the tiles' top surface is coated, making it much smoother than the bottom. The lowered tensile and FSs are likely caused by the poorer cohesiveness between the cement pastes and the CW particles.

4.6 Load deflection

The load-deflection performance of beams exposed to increasing static stress at a rate of $1 \text{ kN} \cdot \text{min}^{-1}$ is presented in Figure 13. First, the load-deflection performance of all beams showed a trend toward similarity, with the linear behavior indicating equal stiffness. However, as the load increased, the beams started to fracture along with some increase in deflection.

The reference concrete beam had the largest deflection of 28.46 mm at the mid-span for the ultimate load when compared to other beams. At the maximal load, recycled

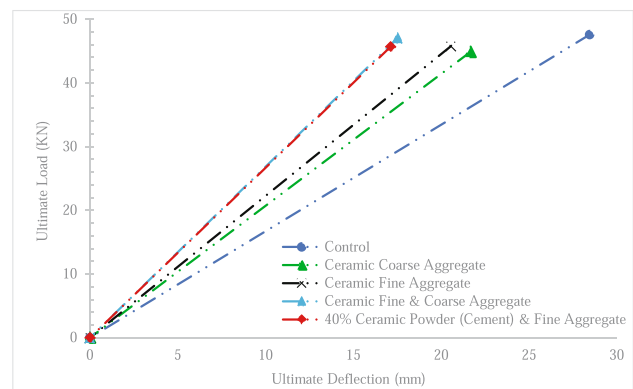


Figure 13: Load deflection of CW concrete [50].

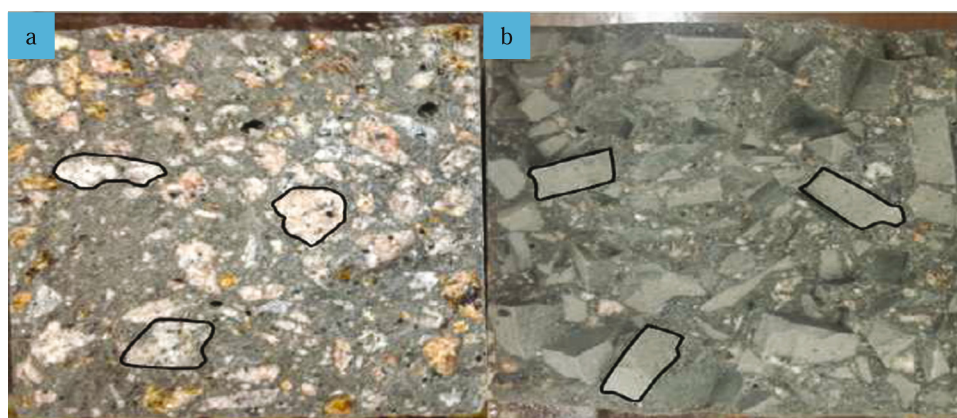


Figure 12: Replacement of (a) 0 and (b) 100% coarse aggregate [31].

aggregate in beams was deflected by 17.52 mm. The physical properties of the ceramic material used to generate recycled aggregate, which produces better stiffness than reference concrete, may be the reason for the observed enhancement in the ultimate load. To enhance the mechanical qualities of cementitious materials or as a filler in composites, CW is often employed. While the inclusion of CW might increase the material's hardness and CS, it may also decrease its ductility, or capacity to bend without breaking. According to Grondin *et al.* [85], the findings demonstrate that recycled aggregate is more brittle than regular concrete, and the numerical analysis demonstrates that fractures may form through the brittle recycled aggregates. This is because ceramics are brittle by nature and often break under stress as opposed to deforming plastically. The unique material composition and processing circumstances determine the amount of CW that will alter a material's ductility. However, methods like modifying the form and size of the CW particles or using other materials in the composite may be able to counteract any unfavorable impacts on ductility. In this regard, this review suggests the addition of fiber materials such as steel fibers [86], carbon nanofibers [87], and nylon fibers [88], *etc.*, in CW-based concrete which improves the ductility and avoid undesirable brittle failure.

4.7 Crack pattern

The cracking behavior of beams made of a material that includes CW may be impacted. The stiffness and hardness of CW are often high, which may boost the material's elastic modulus and CS. Therefore, the beam may become stiffer and stronger, which may lessen the chance of breaking and enhance the beam's ability to support more force. Figure 14 shows the location of the created fractures throughout the length of the beams.

The first crack is in the zone of pure moments in the middle of all beams. In addition, the pure moment area of the beam recycled coarse aggregate and reference concrete exhibited 25% crack development, compared to just 17% in the pure moment region of the specimen recycled aggregate. This variation may be caused by the properties of the ceramic materials utilized in the beam designs and the increased ultimate load capacity of the suggested beams. Furthermore, the number of fractures in various beams ranged from 12 to 16. CW may be used as a filler, filling up any holes or pores and boosting the density of the material. This may assist in increasing the material's overall stiffness and strength, which will increase its resistance to breaking under stress. Additionally, certain forms of CW, particularly those that are fibrous in nature, may aid in

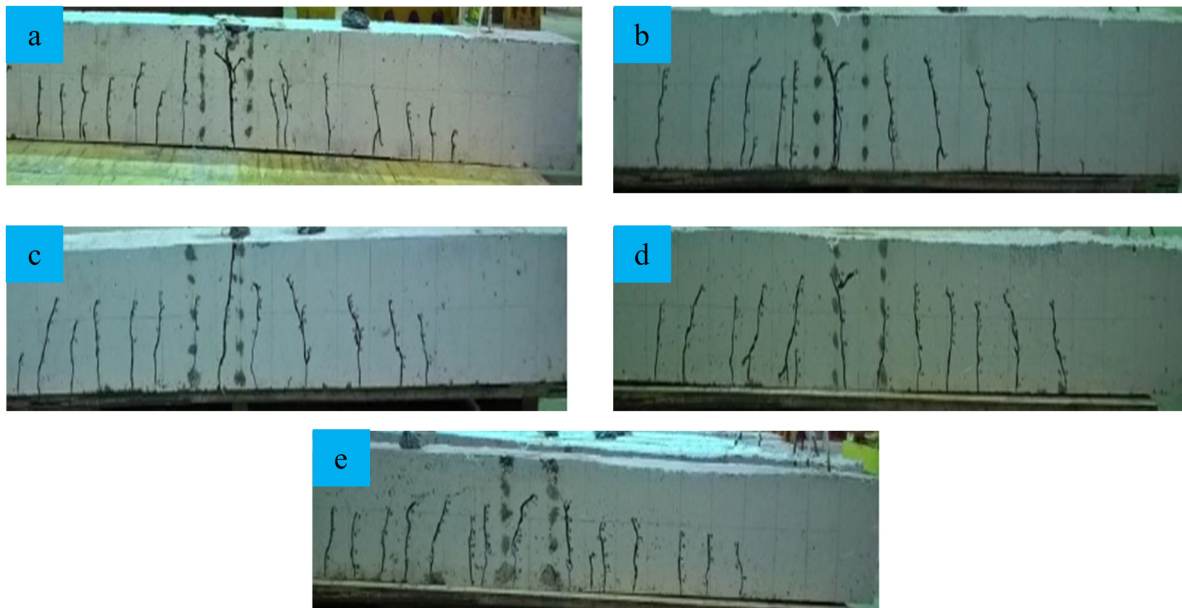


Figure 14: (a) Control, (b) ceramic coarse aggregate, (c) ceramic fine aggregate, (d) ceramic fine and coarse aggregate, and (e) 40% ceramic powder (cement) and fine aggregate [50].

boosting the material's TS, which can aid in preventing fractures.

4.8 Elastic modulus

The concrete elastic modulus with various CW percentages is presented in Figure 15. The concrete elasticity was noticeably increased with the addition of the CW substitution. The improvement was noted beyond the 35% addition of CW. The 100% replacement specimens produced the highest elastic modulus value of 27.4 GPa, which is 26.9% greater than the 21.6 GPa determined in the control sample.

This increase is comparable to the aggregate replacement ratio, indicating a clear correlation between the elastic modulus and the fraction of angular aggregates [89]. The harder the material, the greater the elastic modulus. It was found that replacing a portion of the cement in concrete with CW (10, 20, and 40%) had no negative effects on the concrete's elastic modulus [90]. This was due to the ceramic powder's micro-filler action, which produced a denser concrete structure. When replacing floor and wall tiles by 100%, the elastic modulus increases by 26.9% [31]. The 28-day modulus of elasticity of the concrete marginally decreased when fine ceramic aggregate was used instead of 15 and 30% of the fine aggregate [91].

Furthermore, AlArab *et al.* [52] found that CW decreased the concrete elastic modulus. This is described by the fact that porous ceramic reduces the rigidity of concrete, causing greater stresses for a given weight. According to Ariffin *et al.* [78], there are four other explanations for the decrease in elastic modulus. There are four reasons why ceramic aggregates are less rigid than natural aggregates: (i) coarse ceramic aggregates are less stiffer than natural aggregates; (ii) fine CW with minor stiffness results in less

stiff cement pastes; (iii) the angular shapes of the aggregates cause holes; and (iv) the smooth surface of the CW aggregates deteriorates the connection between itself and the paste. Both positive and negative impacts on the elastic modulus might result from adding CW to a substance. CW is often used as a filler material, which may increase the material's stiffness and strength. However, excessive waste or waste that is not evenly distributed throughout the material may lead to flaws, weaken the overall structure, and lower the elastic modulus.

4.9 Impact resistance

The capacity of concrete to endure repeated impacts and absorb energy without negatively affecting cracking and spalling is known as impact resistance [92]. Figure 16 shows how the impact resistance of geopolymer specimens is affected when ceramic particles are present because it functions as a replacement for tiny particles. By increasing the proportion of fine CW from 50 to 70%, the specimens' resistance to early fractures and failure was increased by 46.8 and 49.9%, respectively. The amount of CW in the material increased from 50 to 70%, and 10% of the slag was substituted with fly ash, which led to an increase in early failure and cracking of 57 and 60%, respectively. According to Mukai and Kikuchi [81], the rubberized concrete beam was exposed to impact energy when a micro-crack appeared for the first time under an impact load. As the rubber content increased, so did the impact energy of the beam. The impact energies of the beam at the first crack were 21.6, 22.6, 28.8, and 47.3 J when the rubber contents were 0, 20, 40, and 60%, respectively. When silica fume was added, the impact energy at the initial fracture increased. The impact energies at the first crack were 23, 24.7, 35, and 56.6 J when the silica fume concentration was 10% and the rubber contents were 0, 20, 40, and 60%, respectively.

The mechanical qualities of the concrete are enhanced when CW is included in the mix as a filler. The concrete matrix's spaces may be filled with CW particles, enhancing the material's density and limiting the size of impact-related fractures. Furthermore, the impact test's failure pattern might be impacted by the substitution CW. The distribution, composition, shape, size, and degree of impact of the CW particles in the material all influence the failure pattern. Figure 17 shows the failure pattern that might take place in specimens created using a considerable quantity of CW. According to the results, specimens with a high concentration of CW displayed little cracking because of

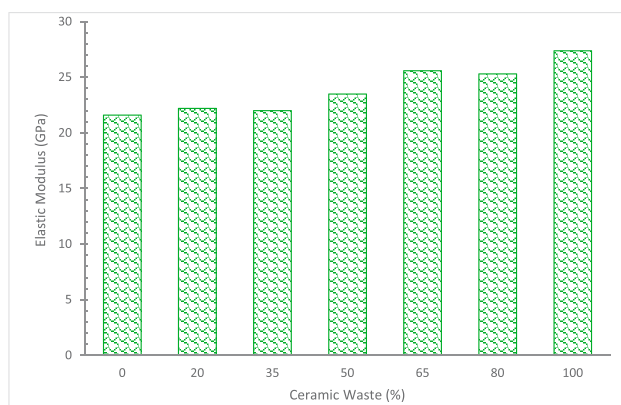


Figure 15: Elastic modulus of ceramic concrete [31].

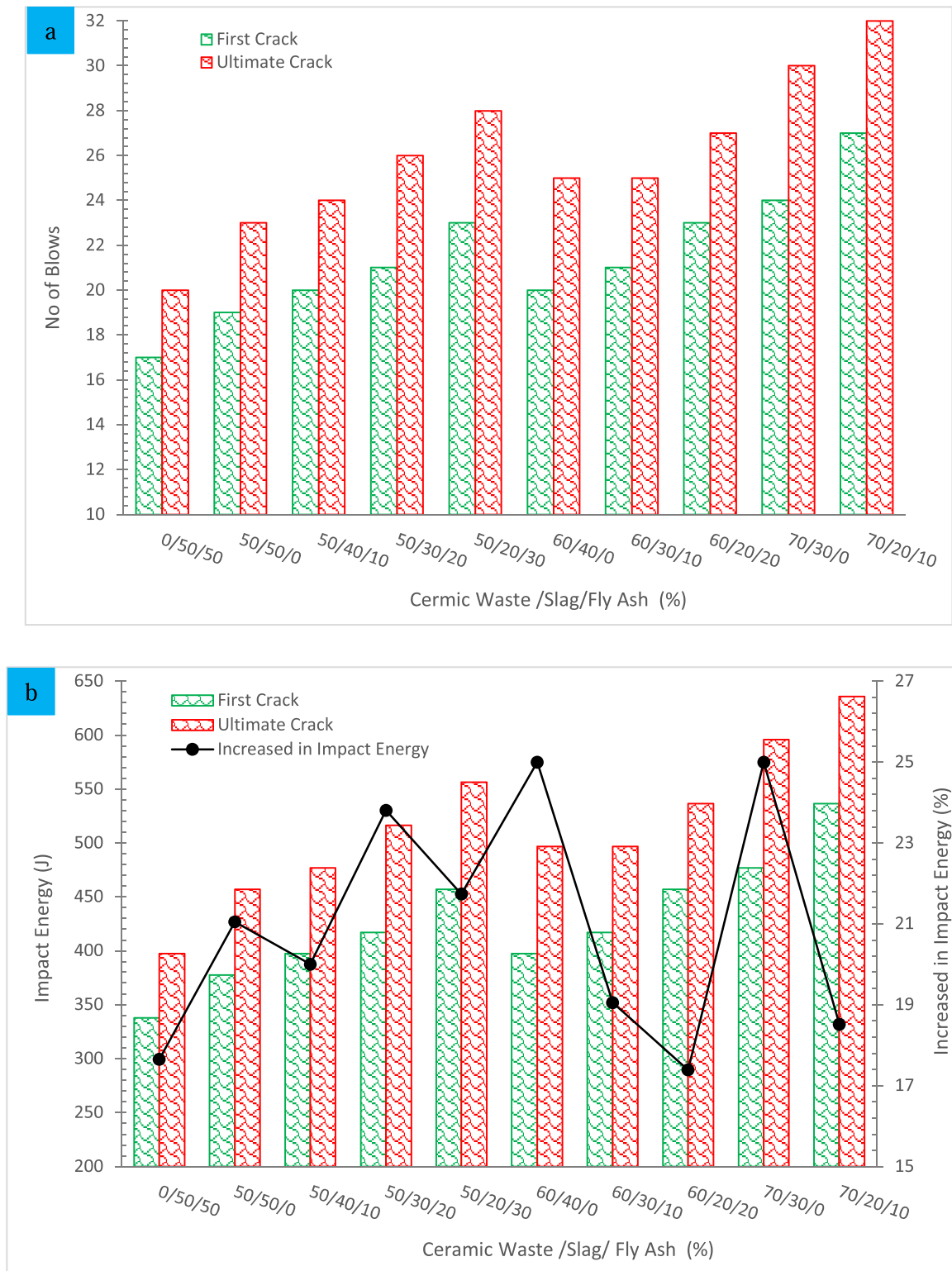


Figure 16: Impact resistance of CW concrete: (a) number of blows, and (b) impact energy for the first crack and ultimate crack [93].

the CW's filler action, which collected more energy and prevented the specimens from collapsing suddenly [93]. The hardness of the material may be increased if the CW

is evenly distributed throughout and fully incorporated. In this situation, the material can break ductility, undergoing further plastic deformation before ultimate fracture. The

impact capacity was significantly increased and the beginning and spread of mortar cracks were postponed as a consequence of the impact energy being absorbed by CW as opposed to being transmitted to the nearby blast furnace slag. This was accomplished by postponing the beginning of the mortar's breaking. When reinforced structures are exposed to both impact and dynamic loads, the impact resistance of such structures increases significantly because of the addition of rubber particles.

5 Performance at high temperatures

5.1 Visual observation

As shown in Figure 18(a), a concrete specimen that was not subjected to high temperatures is in dark gray. Additionally, there were no surface fractures to be seen. This depicts the form and color of a concrete specimen in its natural state while curing at laboratory temperatures. The surface modifications of the concrete specimen subjected to a temperature of 200 °C for 2 h are shown in Figure 18(b). The concrete's color changed to a pale gray. No fissures could be seen on the concrete sample's surface along with this color shift. The evaporation of the capillary pore water was responsible for the difference in color between the samples exposed to 200°C and the control samples.

The evaporation of chemically bound water, also known as non-vaporized water, which was a component of the cement hydrate compounds and could not be released from the cement paste until chemical decomposition took place, is the primary cause of the color change, widening, and spreading of cracks above 200°C. Small voids that are filled with water inside a substance are called capillary pores. When a substance is subjected to high temperatures, the heat may cause the capillary pore water to evaporate, leaving behind a dry, porous structure. Because of this moisture loss, the material color may alter, often appearing lighter or disappearing.

According to Figure 18(c) and (d), the water in the compounds CSH and CH is released at 400 and 600°C, respectively. At 800°C, it was found that fractures widened because of the aggregate's disintegration, which converted CaCO_3 into CaO and CO_2 . The aggregate's color also changed to a reddish color.

Figure 19 shows the prismatic specimens after 30 days in a setting with increased heat (1,000°C). After this time, it was found that concrete specimens based on gravel aggregate lost their cohesiveness and that when picked up, around 40% of the sample mass was broken. The fact that samples of concrete with gravel aggregate lost their cohesiveness at high temperatures shows that the concrete may have been subjected to thermal stress, which may have led the material to expand and contract quickly, causing cracking and loss of cohesiveness. This may occur when concrete is subjected to extreme temperatures (as those in a fire) and then quickly cooled. Precautions have to be taken to protect the concrete from heat damage, such

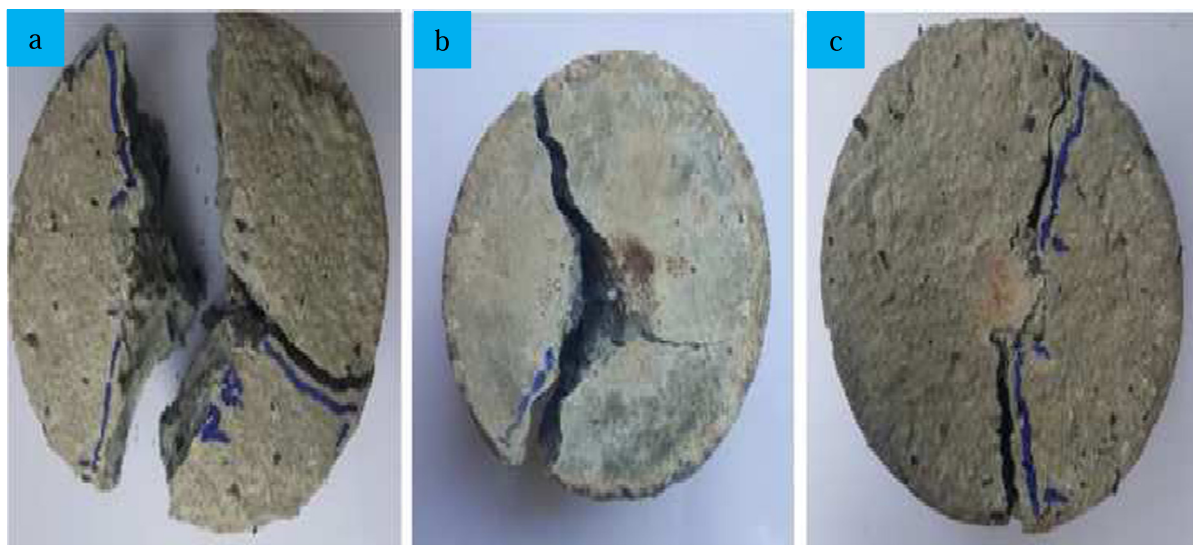


Figure 17: Failure pattern: (a) 0%, (b) 50%, and (c) 70% CW concrete [93].

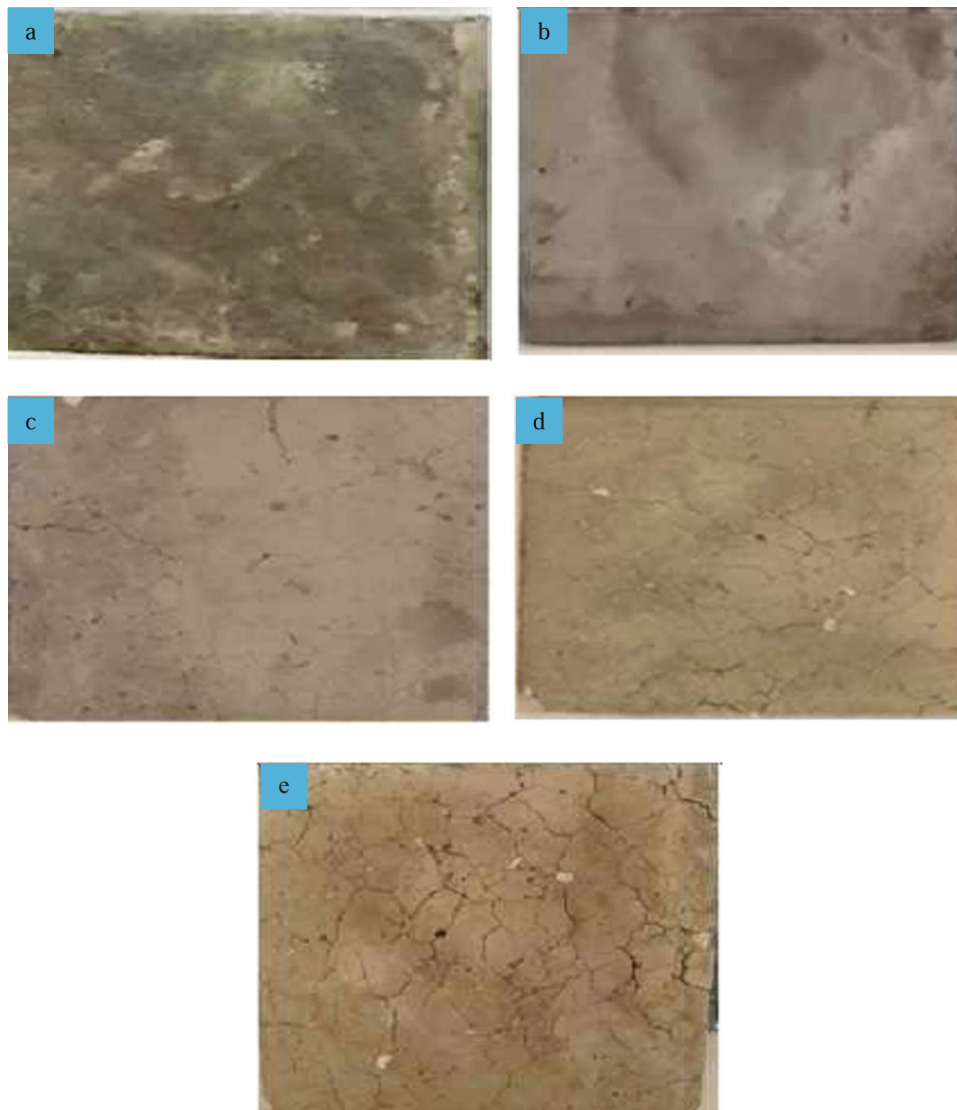


Figure 18: (a) Room temperature, (b) 200°C, (c) 400°C, (d) 600°C, and (e) 800°C [60].

as utilizing fire-resistant materials, constructing insulation, or improving ventilation and circulation to remove heat.

However, fissures and a little mass reduction were seen in concrete samples built using granite aggregates. It is anticipated that concrete constructed using granite aggregates would be comparatively strong, long-lasting, and heat-resistant. It is still possible, nonetheless, for granite-based concrete to fracture or lose strength when subjected to high temperatures or thermal stress. However, owing to the material's increased thermal stability, concrete built with ceramic aggregates may be more heat resistant. Ceramic materials are often used in high-temperature applications because they can endure intense heat without degrading or losing their structural integrity.

5.2 Strength loss

In comparison to the reference combination, the mixes containing crushed brick and tile aggregate exhibit significant reductions in FS but lower reductions in compressive capacity up to a temperature of 200°C, as shown in Figure 20. This suggests that the various unique properties of aggregates may have different effects on how well the concrete performs at high temperatures. Additionally, it increases the possibility that the differing thermal expansion and contraction characteristics of the aggregates may have an impact on how well they respond to various kinds of loads [94].

The combination with crushed brick aggregate lost both of its strengths (flexural and compressive) more



Figure 19: Deterioration of the sample exposed to 30 days at elevated temperature: (a) gravel aggregate, (b) granite aggregate, and (c) ceramic aggregate [80].

slowly than the reference mixture from 200 to 1,000°C, which is much more noticeable in the case of the mixture with crushed tile aggregates. The thermal qualities of the aggregates may enable the concrete to better tolerate high temperatures and avoid quick deterioration or damage, explaining the slower rate of strength loss in the combinations containing crushed brick and tile aggregate. Additionally, the aggregates probably enhanced the concrete mix's thermal stability, assisting in maintaining its strength and structural

integrity at higher temperatures. The improved fire resistance of such combinations may be explained by the fact that concretes including crushed bricks and/or tiles have lower thermal conductivity than concretes containing natural materials [95]. Thermal conductivity is the capacity of a material to transport heat through its mass, and materials with lower thermal conductivity are often better equipped to resist heat transfer and keep their structural integrity at high temperatures. The concrete mixture produced by mixing crushed brick or tile with natural aggregates may have a lower thermal conductivity than the one produced by mixing natural aggregates, which could help to slow down the rate at which the concrete heats up and possibly prevent it from reaching temperatures that could cause rapid degradation or failure.

5.3 SEM

The microstructure of the concrete provides information about its engineering qualities. Figure 21 shows SEM images that were heated to 400°C. Due to the difference in the coefficients of thermal expansion of the aggregate and the cement paste, it was observed that the high temperatures induced a fracture in the bonding zone between the paste and the aggregate. According to Kuan *et al.* [84], the ITZ for normal-strength concrete is commonly regarded as the weakest part of the cement paste matrix.

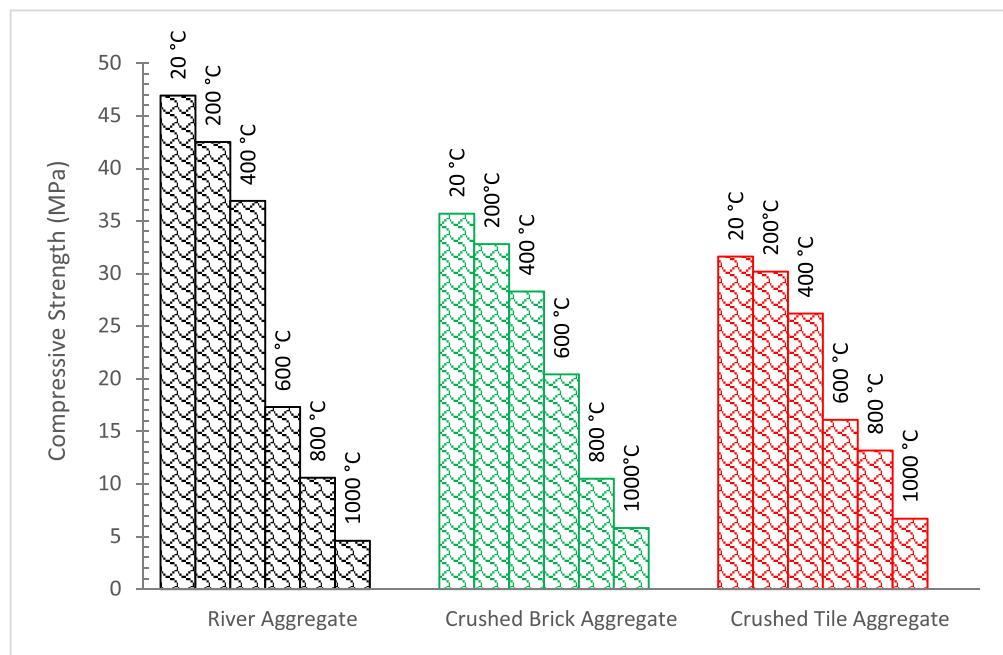


Figure 20: Compressive strength of different types of aggregates exposed to high temperatures [94].

This improves our knowledge of the factors that lead to fractures on the surface and the interior of concrete. The damage to the concrete's qualities was less when exposed to temperatures of 400°C or fewer than what was seen when the samples were exposed to temperatures greater than 400°C. Concrete degradation is primarily caused by differences in how aggregate and cement paste react to heat strain. In addition to the cement matrix expanding due to water evaporation and the dissolving of cement composites, high temperatures also cause the aggregate to expand. As the temperature drops once again, the aggregate starts to contract, which widens and multiplies the number of fractures. According to Kodur [96], the elastic modulus is reduced at high temperatures by the breakdown of bonds in the microstructure of cement paste and the disintegration of hydrated products. The degree of the reduction is dependent on moisture loss, high-temperature creep, and the kind of aggregate.

6 Cost benefits

The expenses of producing 1 m³ of concrete with replacements of CW from 0 to 100% as coarse aggregate at intervals of 25% are illustrated in Figure 22. Technically, CW is a waste material that is often formed in ceramic manufacturing industries, such as pottery and tile manufacturing, among others. Therefore, CW has no economic value. However, CW used in concrete requires some expenses of transporting, crushing, and grinding to the required particle sizes.

Ikponmwosa and Ehikhuenmen [47] included all these costs while performing a cost-benefit analysis associated with CW in concrete production. It can be noted that the cost per cubic meter of concrete decreased with the substitution of CW, although 100% substitution of CW decreased the cost of concrete per cubic meter by 13.06%. However, based on the negative impact of CW on concrete

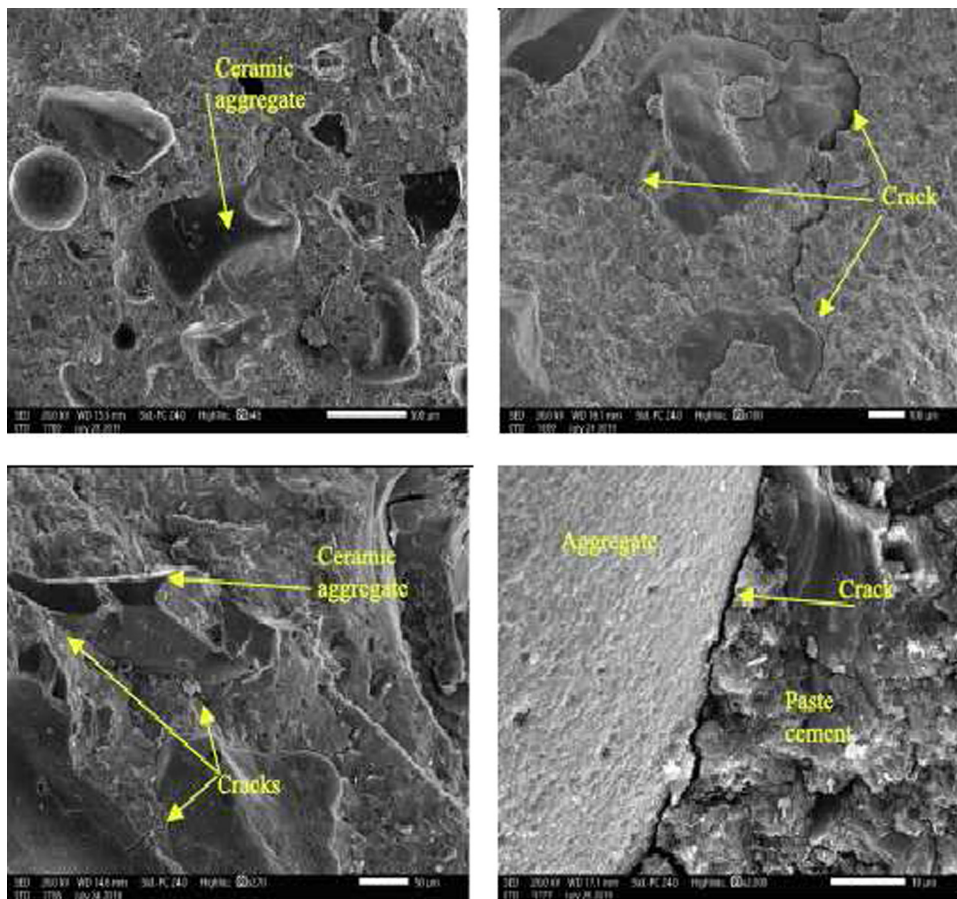


Figure 21: SEM of ceramic aggregate-based concrete exposed to high temperatures [60].

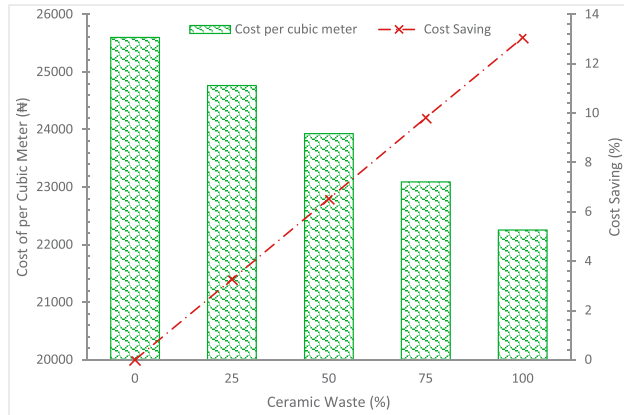


Figure 22: Cost benefits of ceramic concrete [47].

performance such as decreased flowability and strength properties, Ikponmwosa and Ehikhuenmen [47] recommend using CW by up to 75% as coarse aggregate which saves the cost of concrete per cubic meter by 9.81%. Gautam *et al.* [97] concluded that the usage of CW in the building industry not only decreases construction material costs but also contributes to achieving the goal of sustainability. The information is less as the authors only used CW as coarse aggregate. Therefore, they recommend more detailed studies on developing the benefits of concrete with CW as cement or fine aggregate replacement.

7 Conclusions

This review summarized studies already carried out on the application of CW in concrete by different researchers. This study includes the general history of CW, physical and chemical features, and the influence on concrete parameters including fresh properties, strength properties, performance at elevated temperatures, and cost benefits. The detailed conclusions are as follows:

- Bleeding increases with CW due to the internal water that the ceramic aggregate has absorbed slowly leaking back into the concrete mixture, increasing the amount of water bleeding.
- The concrete flowability decreased with CW due to the rough surface texture. Also, a decrease in fresh density was observed due to the low specific gravity of CW. Furthermore, CW did not considerably alter the air content.
- The strength properties of concrete decreased with the substitution of CW, although some researchers observed improvement in strength properties with the substitution of CW. Ceramic aggregates are typically less dense and less durable than traditional aggregates such as

crushed stone or gravel, which can result in a higher porosity in the concrete when they are used as an aggregate. Higher porosity in concrete can lead to a reduction in the overall strength of the concrete. However, up to 10% CW, a slight decrease in strength was observed indicating that the CW up to 10% can be used for normal-strength concrete.

- Concrete performance with the substitution of ceramic at high temperatures improved significantly. The rate of decrease in strength in crushed tile aggregates is less than in concrete made with natural river aggregate and brick aggregate. Ceramic materials have a superior melting point and are resistant to thermal shock, making them suitable for use in high-temperature applications.
- The cost–benefit analysis shows that CW of up to 75% can be used for structural application which saves the concrete cost of 9.81%.

Overall, the use of ceramic aggregates in concrete has the potential to achieve sustainable goals by preserving natural resources, reducing cost, energy conversions, solving waste dumping issues, reducing carbon dioxide emissions, and improving thermal insulation properties. However, it is important to carefully evaluate the specific type and composition of the ceramic aggregate and to ensure that it is used in the appropriate proportion and curing conditions to avoid any negative impact on concrete strength.

8 Recommendations

Several researchers show that CW can be used in concrete. However, this review recommends some aspects that should be explored before being used practically.

- Concrete strength properties decreased with CW, particularly at higher proportions due to the porous nature which absorbs more water and decreased flowability. The absorbed water also decreased durability aspects. Therefore, we recommend filler materials that fill the voids in CW and improve its flowability. In this regard, secondary cementitious materials such as silica fume or fly ash will be more beneficial but a detailed study is required.
- Several researchers claimed that CW improved sustainability. However, the information is less, and we recommend detailed studies on life cycle assessment and cost–benefit analysis associated with the utilization of CW in concrete.

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