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Influence of mechanical activation on the behavior of green high-strength mortar including ceramic waste

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Solid waste management is a significant environmental issue for countries because of the need for huge landfills. The ceramic tile waste powder (CWP) is one of the wastes. Conversely, cement production, the main ingredient in concrete, emits large quantities of greenhouse gases, a significant environmental concern. Therefore, substituting some of the cement in concrete with CWP is an issue that deserves investigation to reduce the environmental impact of both materials. Accordingly, this study aims to investigate the influence of the grinding time and proportion of CWP as a substitute for cement on the properties of high-strength mortar (HSM). Three grinding times (10, 15, and 20 minutes) and three replacement percentages (10%, 20%, and 30% by weight) for CWP were adopted for each time. Ten mixtures (including the reference mixture) were executed. The fresh (flow rate), mechanical (compressive strength) durability (ultrasonic pulse velocity, dynamic elastic modulus, water absorption, density, percentage of voids and electrical resistivity) and microstructural properties were examined. The life cycle assessment (LCA) was also addressed. The results showed that the mechanical activation had a pronounced effect on the durability properties (especially water absorption and percentage of voids) more than on the compressive strength. Generally, a sustainable HSM (with more than 70 MPa of compressive strength) can be produced in which 30% of the cement was replaced with CWP with almost comparable performance to the CWP-free mortar. Furthermore, LCA results showed that mortars containing 30% CWP ground for 15 mins (GT15CWP30) had the lowest GWP per MPa.

Keywords: *high strength mortar, ceramic tile waste powder, grinding time, mechanical and durability properties, life cycle assessment*

1. Introduction

Utilization of industrial by-products in the development of sustainable cement composites (concrete, mortar, and paste) has gained significant attention among researchers globally. This is primarily driven by the dual objective of addressing the environmental issues associated with the accumulation of industrial waste and the increasing demand for more sustainable and durable construction materials. Among the most studied industrial by-products, fly ash (a by-product from coal combustion) [1, 2] and ground granulated blast furnace slag (GGBFS, a by-product from iron and steel production) are at the forefront [3, 4]. When used as partial substitutes for cement, these materials can impart enhanced properties to the cement composites, such as improved workability, resistance to cracking, and enhanced durability against aggressive environments. Research has shown that these by-products can often enhance the microstructure of the cementitious matrix, leading to a denser and more refined material [5, 6]. For instance, fly ash and GGBFS particles act as micro-fillers, refining the pore structure and contributing to the pozzolanic reaction, further strengthening the matrix. [7, 8].

Furthermore, other by-products like silica fume (from silicon and ferrosilicon industries) and rice husk ash (from rice mills) have also been investigated for their potential benefits in cement composites [9–12]. The common thread across these research endeavors is the aspiration to balance sustainability and performance. As the construction

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industry accounts for a significant portion of global carbon emissions, largely due to cement production, the successful integration of these by-products not only promises a reduction in the industry's carbon footprint but also promotes the circular economy concept, wherein waste materials are reintroduced into the production cycle, reducing environmental impact and resource consumption.

The high demand for ceramic tile waste as a partial substitute for cement in mortar development has become increasingly evident in recent years [13]. This trend is primarily driven by a growing awareness of sustainable construction practices and the need to manage the increasing amounts of ceramic waste generated from construction and demolition activities. Ceramic tiles, extensively used in construction for their aesthetics and durability, often lead to significant waste due to breakage during installation or the renovation of old structures [14, 15]. The integration of ground ceramic tile waste into mortar formulations presents multiple benefits. Firstly, it serves as a resource-efficient way to reduce the disposal of ceramic waste in landfills, promoting environmental sustainability. Secondly, ceramic waste, when finely ground, possesses pozzolanic properties. This means that in the presence of water and calcium hydroxide (a product of cement hydration), it can react to form calcium silicate hydrates, which are the primary binding agents in cementitious systems [16, 17]. Consequently, incorporating ceramic tile waste in mortar can improve mechanical properties, including enhanced compressive strength and reduced permeability. Another driving factor for this trend is the economic benefit: using ceramic waste as a replacement can reduce the overall cost of mortar production as it offsets the need for a portion of cement, which is typically more expensive [18, 19]. Moreover, the recycling process of ceramic tiles into a powdery form suitable for mortar integration has been streamlined, making it a more viable option. The increasing shift towards using ceramic tile waste in mortar formulations symbolizes the construction industry's broader movement towards sustainable and resource-efficient practices [20].

Ceramic tiles, typically made of clay, feldspar, sand, and other natural substances, are frequently discarded during production, installation, and even renovations [21, 22]. However, a critical challenge associated with directly utilizing ceramic tile waste in high-strength mortar formulation is its inherent properties and irregular particle size distribution. The distinctive properties of raw ceramic waste might not immediately lend the required binding ability and pozzolanic activity typical for achieving high strength in mortars [23, 24]. For a component to replace or partially substitute cement, the main binder in mortars should exhibit properties that either mimic or synergize with cement, promoting strength and durability. Researchers have found that the key to unlocking the potential of ceramic tile waste lies in its mechanical activation [25, 26]. Mechanical activation refers to refining and altering a material's physical and even chemical properties through external mechanical forces [27, 28]. When ceramic tile waste undergoes mechanical activation, its particle size can be reduced to a level conducive to its utilization in mortar formulations, consequently improving its binding potential [29, 30]. Furthermore, the refined particles might undergo physicochemical transformations that could endow the waste with pozzolanic characteristics, which enables it to react with the calcium hydroxide in cement to form compounds that contribute to strength [31, 32].

The potential advantages of mechanical activation are manifold. Firstly, it develops the production of fine particles, which can fill in the voids between the larger particles in the mortar matrix, leading to a denser and stronger matrix [33, 34]. This micro-filling effect can considerably enhance the overall compressive strength of the mortar. Secondly, mechanically activated ceramic tile waste might exhibit latent hydraulic properties, meaning they can initiate binding reactions similar to cement upon contact with water. This property can further augment the strength and durability of the mortar [6, 35]. Moreover, the pozzolanic reactions mentioned earlier can lead to the formation of additional calcium silicate hydrate (C-S-H) gel, the primary strength-giving compound in cementitious systems [36, 37]. Mechanical activation modifies the amorphous nature of ceramic waste, making it more chemically reactive. This transformation allows the activated ceramic waste to effectively bind with $Ca(OH)_2$ to make extra C-S-H gel, a critical factor in enhancing the mortar's strength and durability [38, 39]. From a practical standpoint, integrating mechanically activated ceramic tile waste in mortar formulation can not only help reduce cement usage, leading to economic benefits, but it can also help control the carbon footprint of construction [40, 41]. Additionally, the reuse of ceramic tile waste aids in addressing the waste disposal issue, ensuring a circular economy in the construction industry [42, 43].

Few research studies found by the author have addressed the effect of mechanical activation on ceramic tile waste powder on the properties of high-strength mortar. Also, limited research in Iraq has studied this type of locally produced waste. While the potential benefits of mechanical activation in using ceramic tile waste in high-strength mortar are evident, currently there is a gap in the knowledge regarding its practical applicability and the optimization of mechanical activation techniques for various types of ceramic waste. Additionally, there is a great need to understand the environmental impact of replacing cement with ceramic tile waste powder. This gap in knowledge highlights the need for further research and development in this area, with opportunities for researchers to explore innovative methods and test the effectiveness of mechanical activation on different types of ceramic waste to unlock its full potential in sustainable construction practices. In this research, various tests were conducted to study the effect of mechanical activation of ceramic tile waste powder in terms of freshness, mechanical, durability, and microstructural properties as well as life cycle assessment (LCA) of cement mortar.

2. Experimental program

2.1. Cement

Limestone cement of the CEM II/A-L 42.5 R type was employed in all high-strength mortar (HSM) blends. Cement has a specific gravity of 3.05, a particle size of 17.99 μm, and a specific surface area of 399 m^2/kg. Table 1 details the characteristics of cement that satisfy Iraqi Standard No. 5 [44] and BS EN 197-1 [45]. Figure 1 depicts the distribution of cement particles based on their diameters. The cement's initial and final setting times are recorded as 2.5 and 3.4 hours, respectively.

Table 1. The chemical composition of cement and CWP

Oxide	**Content, %**	
	CWP	**Cement**
CaO	6.50	60.51
Al_2O_3	11.98	3.194
SiO_2	49.04	16.91
Fe_2O_3	1.44	4.360
MgO	0.83	2.479
K_2O	1.48	0.495
Na_2O	0.89	1.429
SO_3	0.19	3.146
TiO_2	0.48	—

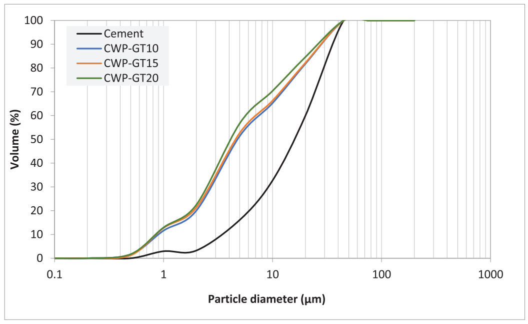

Fig. 1. The particle size distribution of cement and CWP with different grinding times

2.1.1. Fine aggregate

The high-strength mortar (HSM) formulations utilized through locally available sources include fine aggregate (natural sand) with a particle size ranging from 0.15 to 4.75 mm. The findings of the fine aggregate's gradation, as depicted in Figure 2, indicate its compliance with Iraqi Standard No. 45 [46].

2.1.2. Ceramic tile waste powder

Crushed ceramic tiles used in flooring (locally available) were broken into small pieces and then

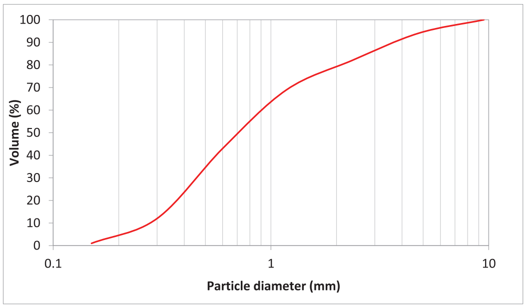

Fig. 2. Findings from the sieve analysis of the sand

Fig. 3. The CWP after grinding

ground into powder (Fig. 3) using an electric grinder. Three grinding times (GT) were adopted to study the impact of grinding time (mechanical activation) on the performance of the ceramic tile waste powder (CWP) as an alternative to cement in high-strength mortar; the times used were 10 min, 15 min, and 20 min. The particle size distribution for each grinding time and chemical properties of CWP are presented in Figure 1 and Table 1, respectively. The fineness values of CWP were 542, 588, and 610 cm^2/kg for the grinding times of 10 (or GT10), 15 (or GT15), and 20 (or GT20) minutes, respectively.

According to Table 1, CWP is mainly made up of 49.05% silica, 11.98% alumina, and 6.5% calcium oxide. The percentages for the remaining components, such as iron and potassium oxide, were less than 2%. Generally, most pozzolanic materials consist of silica-alumina and a smaller percentage of calcium oxide. On the other hand, cement is rich in calcium oxide, which is the primary compound responsible for its properties (hydration).

Figure 1 showed that all grades of grinding CWP resulted in smaller particle sizes than cement. This enhances the filling effect of these grains between sand and cement or even between cement grains. The figure also indicated that the grinding times of 10 and 15 minutes led to almost identical grain sizes, and a grinding time of 20 minutes was slightly finer than either of them. The surface area values shown above match this behavior.

2.1.3. Water

In each batch of HSM, potable tap water was used to mix the HSM ingredients.

2.1.4. Superplasticizer

Glenium 54, a commercially accessible superplasticizer, was employed to enhance the workability of fresh HSM mixtures. Glenium 54 has been found to conform to the standards specified in ASTM C494 Types A and F [47].

2.2. Mix proportions

For this investigation, ten HSM mixes were cast, including one control mix and nine additional mixtures in which cement was replaced with CWP. The HSM mixtures were divided into three groups based on grinding time (GT): The GT10 group (10 min GT), the GT15 group (15 min GT), and the GT20 group (20 min GT). Each group consists of three blends in which cement was replaced with CWP in percentages of 10%, 20%, and 30% by weight. The amounts of water, binder, sand, and superplasticizer in each mixture were the same. Table 2 lists the individual components of each mixture.

According to the ACI 116 definition [48], pozzolanic materials are chemically active (by reacting with calcium hydroxide resulting from cement hydration) when they are finely ground. Also, when these materials (with potential pozzolanic activity) are softer than cement, they will have a physical effect of filling the spaces between the cement grains and the aggregate or between the coarser

Table 2. Mix details of high=strength mortars as a binder (CWP + cement) weight ratio

Mix designation*	Group type	Sand	Cement	CWP	Water/binder	Superplasticizer
Control	—	2.75	1	0.0	0.30	0.0186
GT10CWP10	GT10	2.75	0.90	0.10	0.30	0.0186
GT10CWP20		2.75	0.80	0.20	0.30	0.0186
GT10CWP30		2.75	0.70	0.30	0.30	0.0186
GT15CWP10	GT15	2.75	0.90	0.10	0.30	0.0186
GT15CWP20		2.75	0.80	0.20	0.30	0.0186
GT15CWP30		2.75	0.70	0.30	0.30	0.0186
GT20CWP10	GT20	2.75	0.90	0.10	0.30	0.0186
GT20CWP20		2.75	0.80	0.20	0.30	0.0186
GT20CWP30		2.75	0.70	0.30	0.30	0.0186

*GT, grinding time; CWP, ceramic tile waste powder.

cement grains. Therefore, adopting several grinding grades in this study was done to explore to what extent the increasing fineness of ceramic affects the different properties of high-strength mortar.

2.3. Mixing and curing procedures

The HSM raw ingredients were blended using an electric mixer with two rotational speeds (285 and 140 rpm), which adhered to the ASTM C109 [49] standard. The following procedure was used for the mixing process.

To create the fresh mortar, a blending process was conducted for one minute at a rotational speed of 140 rpm, incorporating the dry components, including cement, sand, and CWP. Following that, the water and superplasticizer were introduced, and the mixing procedure was sustained at a consistent velocity for two minutes. Ultimately, the rotational speed was elevated to 285 rpm, and the moist constituents were subjected to an extra minute of blending.

After the mortar was completely mixed, it was poured into standardized molds with dimensions of $40\times40\times160$ mm^3 and $50\times50\times50$ mm^3. After around 23 to 24 hours, the molds were removed, and subsequently the hardened samples were submersed in water until the test.

2.4. Experimental tests

2.4.1. Flow rate

Following mortar mixing, the flow rate was assessed in accordance with ASTM C1437 [50].

2.4.2. Compressive strength

In accordance with the requirements specified in BS EN 196-1 [51], prism halves of $40\times40\times80$ mm^3 were used to assess the compressive strength. The experiment was performed on two curing ages, specifically at the 28-day age and subsequently at the 56-day age. Three measurements were recorded at each time point, and a mean value was computed. The experiment was conducted with a compressive-flexural machine of the MATEST S.r.l. brand, located in Treviolo, Italy, with a load capacity ranging from 50 to 300 kilonewtons.

2.4.3. Water absorption, percentage of permeable voids, and bulk density

In order to assess the water absorption, dry bulk density, and percentage of permeable voids, cubic specimens were employed in accordance with the specifications outlined in ASTM C642 [52] after 28 days of curing. The permeable voids test was carried out by placing the mortar samples in the oven and drying them at a temperature of 105°C until the weight was constant. After taking it out of the oven and cooling it to room temperature, it was weighed (dm). Then, it was immersed in water for several days (until the constant weight), then boiled for 5 hours, and after cooling, its weight was taken (wm) in the air in a saturated, dry surface condition. Then, its weight was taken while completely immersed in water (bm), and the percentage of permeable voids was calculated according to the following equation:

$$\text{Voids }(\%) = 100 * (\text{bm–dm})/(\text{bm–wm}) \quad (1)$$

A set of three cubes was used, and the average weight was calculated.

2.4.4. Ultrasonic pulse velocity and dynamic elastic modulus

The ultrasonic pulse velocity (UPV) and dynamic elastic modulus (Ed) were determined using a device from the MATEST company according to ASTM C597 [53]. They were measured using a 50-mm cube at 28 days of age. An average of three readings were taken for each result. The Ed was measured according to the following equation:

$$v = \sqrt{\frac{\text{Ed}\,(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad (2)$$

Where: ρ represents the density, μ represents the dynamic Poisson's ratio and Ed represents the dynamic elastic modulus. After rearranging the terms of equation (2) and applying the value of Poisson's ratio (0.2), it takes the following form:

$$\text{Ed} = 1.111\,\rho\,\upsilon^2 \quad (3)$$

2.4.5. Electrical resistivity

The electrical resistivity of HSM samples was examined using the two-metal plate method [54]. To conduct this test, a 50-mm cube was placed between two plates, with a moist sponge inserted to ensure electrical conductivity. An LCR meter was used to determine the impedance at a frequency of 1000 Hz [55]. The LCR DE-5000 manufactured by the DER EE company (Taiwan) was used for the experiment. The electrical resistivity of the HSM was then calculated using equation (4). The equation requires measuring the electrical impedance value of the sample with the provided device. The result is multiplied by the surface area of the sample and divided by its height. This test was conducted at 28 days of aging, and an average of three readings were recorded for each outcome.

$$ER = \frac{A}{L}R \quad (4)$$

Where:

R is the impedance; L is the specimen height in cm; ER is the electrical resistivity (kΩ. cm); and A is the cross-sectional area of the specimen (in cm^2).

2.4.6. Microstructural analysis

The microstructure examination was carried out with a scanning electron microscope (SEM) of the hardened mortar samples using an Axia ChemiSEM (Thermo Fisher Scientific).

2.5. Life cycle assessment

Life cycle assessment (LCA) is a holistic method that can be employed to assess the environmental impacts of a product or process. LCA can provide a comprehensive perspective about the sustainability of products and/or processes that significantly aids decision-makers in identifying opportunities to reduce the overall environmental burdens of different products/processes that all lead to the development of eco-friendly products/processes. Therefore, as part of this research, an LCA of each of the mixtures was conducted using the OpenLCA software. The main aim of this section is to provide information regarding the environmental impacts of the new mixtures and directly compare them with the control mixture. The method of the LCA employed in this research is the CML-IA method. The CML-IA method was first introduced in 1992 by the University of Leiden, and its name is derived from the acronym Centrum voor Milieukunde (CML) that refers to the center for environmental science [56]. This method is required by the European EN 15978 and EN 15804 standards [57].

In this research, the ceramic tile waste powder is considered to be a waste material according to the definition of waste materials [58]. The system boundaries used in this research are "cradle to gate" and the scope followed in this research consists of the following:

- The targeted product is 1 m^3 of mortar.
- The calculated environmental impact is the 100-year global warming potential (GWP) of mortars made with different contents of ceramic tile waste powder.

- Since not all mixtures provided the same compressive strength, and in order to conduct a fair comparison, the normalization approach was employed in this research. The normalization was conducted on the basis of GWP impact per MPa of the compressive strength of the mortar at 28 days and 56 days of curing.

3. Results and discussion

3.1. Flow rate

The results of the flow rate test are illustrated in Figure 4. The findings indicated that substituting cement with CWP enhanced the flowability at varying proportions. This trend was observed across all the grinding time groups and replacement ratios. The GT15, GT10, and GT20 mixtures showed enhancement percentages of 12.52%–16.99%, 1.34%–16.99%, and 11.18%–20.72%, respectively, when replaced at 10%, 20%, and 30%. Gautam et al. [59] achieved similar results with up to 20% cement replacement with bone China ceramic waste. The results also showed that for most ratios, the flow rate increased when the replacement ratio was increased from 10% to 30% at a given grinding time. Except for the GT10/CWP30 mixture, the improvement rate remained constant when the CWP content was increased from 20% to 30% (16.99% higher than the reference mixture). The GT20 group recorded the highest increase in flow rate (20.72% more than the control mix) at 30% substitution of CWP. The increased workability of the fresh mortar containing CWP can be attributed to the additional free water released due to the filling effect of the fine ceramic waste particles within the mortar pastes [60]. Additionally, with increasing grinding, the sharp edges of the particles break off, bringing the shape of the particles closer to spherical [61]. This process reduces the friction between the particles, which ultimately leads to improved workability.

3.2. Compressive strength

The outcomes of the compressive strength test carried out at 28 and 56 days of age for the reference mixture and those containing CWP are displayed in Figure 5. At 28 days, it was observed that the compressive strength did not follow a consistent pattern for each mixing time.

The findings revealed that the compressive strength of the GT10 group was not affected up to the replacement rate of 20%. At 30% CWP content, however, the strength decreased by 16.73%. The GT15 group recorded a similar strength to the control mixture at a 10% replacement ratio, but it fell slightly afterwards (declined by 7.38% and 5.58% at 20% and 30% CWP content, respectively). In the case of the GT20 group, the mixture with 20% CWP content showed a slight decrease in compressive strength (4.27%). For replacement ratios of 10% and 30%, however, the strength was lower than the reference sample by 21.81% and 14.93%, respectively.

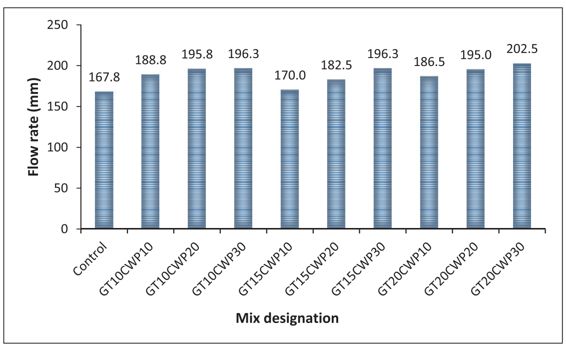

Fig. 4. Flow rate results of high-strength mortar with and without CWP

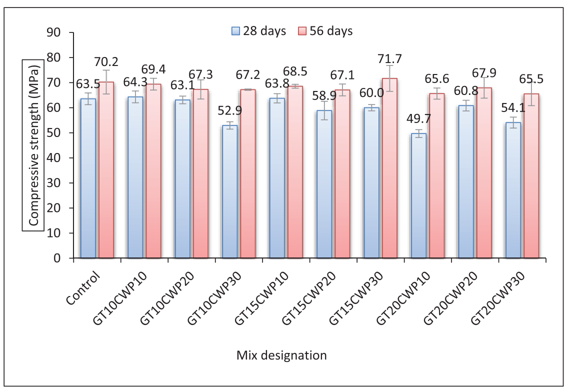

Fig. 5. Compressive strength findings at 28 and 56 days of high strength mortar with and without CWP

Some CWP-based mixtures with 10% or 20% content recorded compressive strength equal to or close to the control mixture despite the reduction of cement content (the main binder). This was due to the filling effect of the ceramic particles, as they were smaller in size than the cement particles [62]. The CWP granules can fill the pores between the aggregate and the cement paste, thus increasing the density of the microstructure and contributing to increasing the compressive strength. Moreover, the pozzolanic activity of the CWP also contributed to reducing the strength decline [63]. When the CWP content reaches 30%, however, there is insufficient calcium hydroxide to react with all the CWP particles, resulting in some remaining unreacted. This leads to a reduction in the cement content and an increase in the effective water-to-cement ratio, ultimately decreasing compressive strength [64].

After 56 days, most of the mixtures that showed significant strength reduction at 28 days had regained a significant amount of strength. This behavior was more evident in mixtures containing 30% CWP, regardless of the grinding time. This is because the continuous hydration of cement and the manufacturing of more calcium hydroxide, which chemically reacts with CWP, thus producing more CSH and subsequently reducing the drop in compressive strength [22]. Moreover, it was found that the compressive strength values were convergent for all replacement ratios and grinding times, as the extent of the reduction in compressive strength ranged between 1.19% and 6.68% compared to the control sample. However, the GT15CWP30 mix recorded an increase of 2.08% in compressive strength. These results indicate that increasing the grinding time led to close values in compressive strength at later curing ages (56 days). Previous studies have also identified similar trends in their findings [42, 65, 66].

Moreover, although the compressive strength for a mixing time of 15 min gave slightly positive results, it can be noted that varying the grinding times of the CWP within the range of 10 to 20 min did not lead to a significant difference in the compressive strength, especially at later ages (56 days). This behavior was observed for the corresponding proportions with different grinding times.

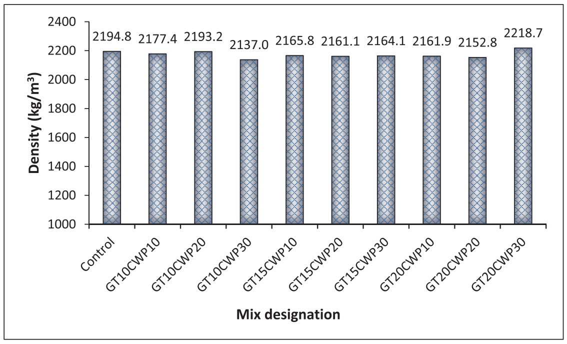

Fig. 6. Bulk density results of high-strength mortar with and without CWP

This indicates the possibility of being satisfied with a specific grinding time in order to reduce the energy consumption associated with increasing the grinding time.

3.3. Density

The density results are displayed in Figure 6. The results demonstrated that the substitution of cement with CWP, within a range of 10% to 30% at various grinding times, did not affect the density of the hardened HSM significantly. Similar behavior (no significant change in mortar density) was also recorded previously when replacing 20% of the cement with ceramic waste [67]. The highest reduction in density was only 2.64%, which was observed in the GT30CWP10 mixture. Replacing CWP with cement did not significantly affect density despite its lower specific gravity compared to cement. This may be because the fine particles of CWP enhanced the compactability of the mortar through the filling effect, thereby contributing to the densification of the microstructure of HSM. This effect overcame the reduction in density resulting from the presence of CWP. Moreover, CWP particles' internal curing may improve density [68, 69]. Water in the fresh mix supplied by CWP helps build dense CSH gel. This dense CSH gel maximizes the mix density [68, 70].

3.4. Water absorption

The results of the absorption test are presented in Figure 7. The findings indicate that, for the GT10 group, the mixture containing 10% CWP

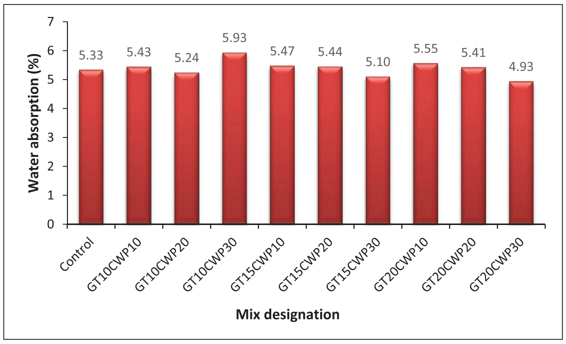

Fig. 7. Water absorption results of high-strength mortar with and without CWP

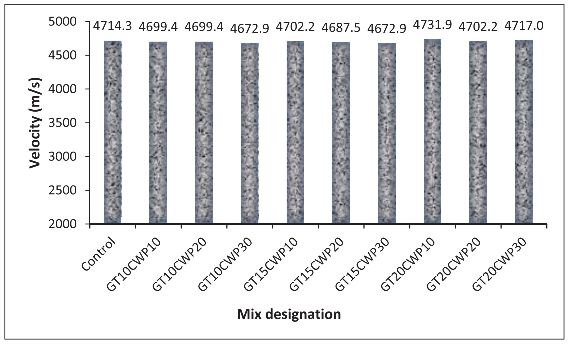

Fig. 8. UPV results of high-strength mortar with and without CWP

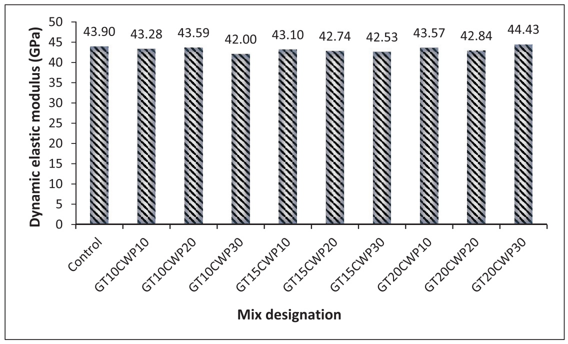

Fig. 9. Dynamic of elasticity results of high-strength mortar with and without CWP

showed a slightly higher absorption rate (2.02%) than the reference mix. Meanwhile, it was observed that the sample with 20% CWP content had a slight decrease of 1.67% compared to the control sample. However, the high replacement rate (30%) increased the mortar absorption by about 11.3%.

Furthermore, the behavior of the GT15 and GT20 groups was similar, as the highest absorption rate was observed with low content (10%). Additionally, water absorption tends to decrease with increasing CWP content, recording a lower absorption rate of 4.31% and 7.66% at the CWP content of 30% for the GT15 and GT20 groups, respectively. The improvement can be explained by the filling effect of CWP particles, due to their small size in comparison to cement (packing effect), as well as their pozzolanic activity, which enhances the resistance to water absorption [71]. It led to the closure of the permeable pores inside the mortar, improving its resistance to water absorption compared to the control specimen. Moreover, according to the literature [72, 73], if the absorption values are less than 10%, the mortar or concrete is considered to be durable. The water absorption values in this study were less than 6%. Therefore, the HSM produced is considered to be durable.

3.5. Ultrasonic pulse velocity

Figure 8 displayed the findings of the UPV examination. It was found that the UPV values of the control mix and the mixture containing CWP as a substitute for cement were equal, indicating that the velocity of the ultrasonic pulse was not affected by the substitution. It is important to note that UPV is influenced by the density and modulus of elasticity of materials [74]. On the other hand, based on the literature [75], the concrete or mortar quality can be categorized depending on the range of pulse velocity values. For instance, excellent, good, doubtable, poor, and very poor quality are associated with a pulse velocity range of more than 4500, 3500–4500, 3000–3500, 2000–3000, and less than 2000 m/s, respectively [76]. The UPV values obtained in this study were higher than 4670 m/s, indicating that the produced mortar is of excellent quality.

3.6. Dynamic modulus of elasticity

The findings of the study on the dynamic elastic modulus are presented in Figure 9. The research indicated that using CWP with different grinding degrees was either comparable to or slightly lower than the reference sample (without replacement).

Kulovaná et al. also observed a slight decrease in elastic modulus after the replacement of cement with CWP [77]. The elastic modulus values for all HSM mixtures were between 42 and 43.9 GPa. The lowest value of modulus of elasticity was observed in the GT10CWP30 mixture, which was 4.34% less than the reference mixture. The elastic modulus values for the GT15 group decreased with increasing CWP content, but the reduction was within the range of 1.83% to 3.12%. The decrease in the dynamic elastic modulus did not exceed 2.41% for GT20 group mixtures. Despite the dilution effect due to the reduction of cement by 30%, the modulus of elasticity did not decrease significantly. These findings can be interpretated according to Kuan et al. [78] who stated that the Al_2O_3 and SiO_2 present in the ceramic powders underwent a pozzolanic reaction with the hydration products of the cement to form a more compact calcium aluminate and hydrated C-S-H gel. As a result, the cementitious materials were able to be more effectively filled with regenerated coagulation, leading to an improvement in the bonding performance between the aggregate and the cement paste.

3.7. Electrical resistivity

The electrical resistivity test is essential because it is linked to the corrosion of the steel reinforcement inside the concrete. The higher the electrical resistivity levels, the better the concrete's resistance to rebar corrosion. The findings of the resistivity test are illustrated in Figure 10.

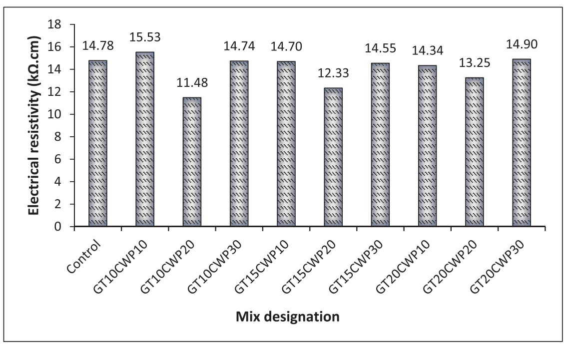

Fig. 10. Electrical resistivity results of high strength mortar with and without CWP

The results pointed out that all mixtures, except for the 10% replacement ratio for group GR10, had electrical resistivity equal to or less than the control mixture. The resistance of GR10 improved by 5.11%. However, the lowest electrical resistivity was observed at a replacement rate of 20% for all grinding time groups. The lowest value was 11.48 kΩ.cm (for the GT10CWP20 mix) compared to 14.78 kΩ.cm for the reference mixture. The cause of the reduced resistivity of some mixtures may be because electrical resistivity depends on the structural composition of the gaps and the extent of their connection to each other, and not just the size or number of voids [79, 80]. The results also revealed that replacing cement with 30% CWP showed electrical resistance nearly equivalent to the reference mixture. This effect was observed for all groups. These results indicated that the electrical resistivity was not negatively impacted at this ratio, despite the reduction in cement content. This is due to the interaction of CWP with calcium hydroxide resulting from cement hydration and the formation of an additional gel [80]. The intermingling of fine CWP particles within the reduced cement voids within the mixture and improved electrical resistivity [22] also play a role. Moreover, the concrete protection level against corrosion can be classified [63, 81] on the basis of the electrical resistivity as follows: very high, high, low to moderate, low, and very low for the resistivity values of $>$20, 10 to 20, 5 to 10, and $<$5 kΩ.cm. In this study, all resistivity values were greater than 10 kΩ.cm. This means that the level of protection against rebar corrosion was high.

3.8. Percentage of permeable voids

Figure 11 shows the results of the percentage of permeable voids. The path of void percentages with different substitution levels followed water absorption results but with different values. This is expected because water absorption depends on the amount of moisture entering through the permeable voids. The results showed that for GT10 mixtures, replacing cement with 10% CWP resulted in void percentages equal to the plain HSM. The voids decreased by 5.63% for the 20% CWP mixture,

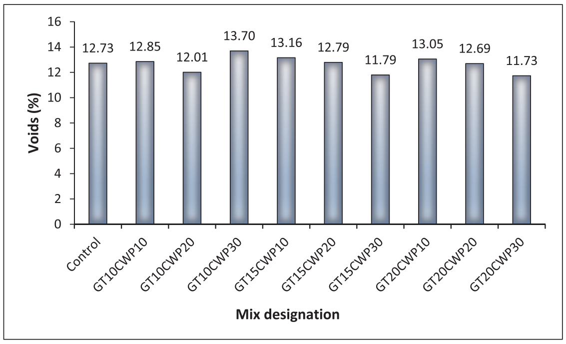

Fig. 11. Percentage of permeable void results of high strength mortar with and without CWP

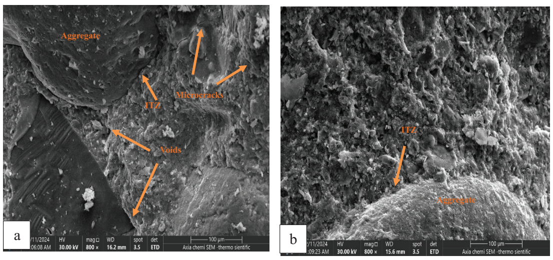

Fig. 12. SEM micrographs of the (a) control mixture and (b) mixture containing 30% CWP (GT15CWP30)

while they increased by 7.6% when replaced with 30% CWP. For GT15 and GT20, the behavior was similar, with increasing CWP content. The higher the CWP content, the smaller the volume of voids, recording a value of 7.33% and 7.81% less than that of the control mixture when replacing the cement with 30% CWP. Comparable outcomes have been reported in the literature [13]. The penetration of small CWP grains between the cement particles, in addition to reducing the content of soluble calcium hydroxide and its transformation into a solid substance—calcium silicate hydrates (CSH)—due to the pozzolanic reaction, contributed to closing the gaps or reducing their size compared to the mixture without CWP [82]. Similar findings were also recorded previously [68].

3.9. Microstructural analysis results

Figure 12 presents the SEM micrograph of the reference (control) and the GT15CWP30 mixtures. The figure shows that the control mixture had microcracks and air voids, as well as a cleavage in the interfacial transition zone (ITZ) between the aggregate and the cement paste. Moreover, there was inhomogeneity in its matrix. On the other hand, the 30% CWP-based mixture had fewer defects or even none at all. Additionally, the matrix was denser and more compacted, with fewer gaps compared to the reference specimen. This improvement is due to the fine ultra-ceramic granules filling the voids inside the matrix. These granules have a smaller diameter than cement, which helps to improve the microstructure of the mortar. The pozzolanic reaction of CWP also contributes to this improvement by consuming calcium hydroxide and replacing it with denser C-S-H gel.

3.10. Life cycle assessment results

Figure 13 shows the results of the GWP of all the mixtures. As can be seen from Figure 13, all the mixtures with different content of CWP and with different grinding times have showed lower GWP relative to the control mixture. Results also indicated that for the same grinding time, increasing the CWP resulted in decreasing the GWP of the mixtures.

The results of the normalization, GWP per the compressive strength of all mixtures at 28 days and 56 days, are provided in Figure 14. The results in Figure 14 clearly state that increasing the age of curing resulted in decreasing the kg CO_2 eq./MPa of all mixtures. According to Figure 14, the best mixtures that provided the lowest kg CO_2 eq./MPa is GT15CWP20 that showed a reduction of the kg CO_2 eq./MPa by about 20% relative to the control mixture.

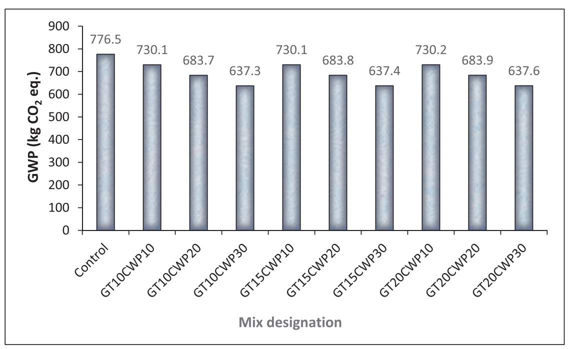

Fig. 13. Global warming potential (kg CO_2 eq.)

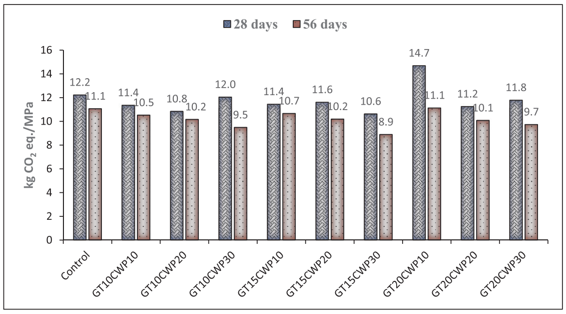

Fig. 14. kg CO_2 eq./MPa

4. Conclusions

The following conclusions are demonstrated:

1. Replacing cement with CWP improved the flowability of fresh mortar. The improvement also tends to increase with increasing grinding time. The highest improvement in flow rate was observed at 30% CWP content, which was 16.99%, 16.99%, and 20.72% for GR10, GR15, and GR20 groups, respectively.
2. The compressive strength of mixtures containing CWP showed fluctuations in behavior with different replacement rates and grinding times at 28 days. The lowest strength value was recorded in the GR20CWP10 mixture. At 56 days, however, the compressive strength was equivalent or slightly lower for all mixture groups, as the decrease in strength did not exceed 6.68% when replaced with 30% CWP. The highest compressive strength was for the GR15CWP0 mixture, at 2% higher than the reference mixture.
3. The results of density, UPV, and modulus of elasticity for HSM mixtures were not affected by replacing cement with CWP, as most of the mixtures had values similar to the control sample.
4. The water absorption and the percentage of permeable voids were in the same path. The highest increase in absorption and the percentage of permeable voids was observed for the (GT10CWP30) mixture, while the lowest absorption and voids were observed for the GT15CWP30 and GT20CWP30 mixtures compared to the control mixture.
5. Regarding electrical resistivity, the highest value was found in the (GT10CWP10) mixture, but the maximum reduction was recorded in mixtures containing 20% CWP, and the reduction in resistivity decreased with increasing grinding.
6. Increasing the grinding time had more impact on the durability properties, especially water absorption and voids ratio, than on the compressive strength. Therefore, a grinding time of 15 minutes can be considered appropriate to achieve a performance similar to that of the reference mixture.
7. Partial replacement of cement partially with different percentages of CWP and for different grinding times showed a reduction in the GWP of mortars relative to the control mixture.
8. According to the SEM results, replacing cement with CWP improved the mortar's microstructure and increased the ITZ's density.
9. Considering all the tests carried out, it is possible to produce an environmentally friendly HSM containing 30% CWP (ground for 15 minutes) as a replacement for cement without negatively affecting its various properties andwith a compressive strength of more than 70 MPa. Moreover, when the normalization approach was used to find the mixture with the optimum performance, results indicated that mortars made with 30% CWP that were ground for 15 mins (GT15CWP30) provided the lowest GWP per MPa.

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Conflicts of Interest

Authors have no conflict of interest to declare.

References

[1] Huseien GF, Sam ARM, Shah KW, Asaad MA, Tahir MM, Mirza J. Properties of ceramic tile waste based alkali-activated mortars incorporating GBFS and fly ash. *Constr Build Mater.* 2019;214:355–68. doi: 10.1016/j.conbuildmat.2019.04.154

[2] Hamad MA, Nasr M, Shubbar A, Al-Khafaji Z, Al Masoodi Z, Al-Hashimi O, et al. Production of ultra-high-performance concrete with low energy consumption and carbon footprint using supplementary cementitious materials instead of silica fume: a review. *Energies*. 2021;14(24):8291.

[3] Shoukry H, Perumal P, Abadel A, Alghamdi H, Alamri M, Abdel-Gawwad HA. Performance of limestone-calcined clay cement mortar incorporating high volume ferrochrome waste slag aggregate. *Constr Build Mater.* 2022;350:128928. doi: 10.1016/j.conbuildmat.2022.128928

[4] Alghamdi H, Shoukry H, Abadel AA, Khawaji M. Performance assessment of limestone calcined clay cement (LC3)-based lightweight green mortars incorporating recycled waste aggregate. *J Mater Res Technol.* 2023;23:2065–74. doi: 10.1016/j.jmrt.2023.01.133

[5] Albidah A, Abadel A, Alrshoudi F, Altheeb A, Abbas H, Al-Salloum Y. Bond strength between concrete substrate and metakaolin geopolymer repair mortars at ambient and elevated temperatures. *J Mater Res Technol.* 2020;9(5):10732–45. doi: 10.1016/j.jmrt.2020.07.092

[6] Abadel AA, Alghamdi H. Effect of high volume tile ceramic wastes on resistance of geopolymer mortars to abrasion and freezing-thawing cycles: experimental and deep learning modelling. *Ceram Int.* 2023;49(10):15065–81. doi: 10.1016/J.CERAMINT.2023.01.089

[7] Abadel AA. Experimental investigation for shear strengthening of reinforced self-compacting concrete beams using different strengthening schemes. *J Mater Res Technol.* 2021;15:1815–29. doi: 10.1016/j.jmrt.2021.09.012

[8] Abadel AA, Albidah AS, Altheeb AH, Alrshoudi FA, Abbas H, Al-Salloum YA. Effect of molar ratios on strength, microstructure and embodied energy of metakaolin geopolymer. *Adv Concr Constr*. 2021:127–40. doi: 10.12989/acc.2021.11.2.127

[9] Wasim M, Abadel A, Abu Bakar BH, Alshaikh IMH. Future directions for the application of zero carbon concrete in civil engineering – a review. *Case Stud Constr. Mater.* 2022;17:e01318. doi: 10.1016/j.cscm.2022.e01318

[10] Abdellatief M, Elrahman MA, Alanazi H, Abadel AA, Tahwia A. A state-of-the-art review on geopolymer foam concrete with solid waste materials: components, characteristics, and microstructure. *Innov Infrastruct Solut.* 2023;8(9):230. doi: 10.1007/s41062-023-01202-w

[11] Abadel AA, Alghamdi H, Alharbi YR, Alamri M, Khawaji M, Abdulaziz MAM, et al. Investigation of alkali-activated slag-based composite incorporating dehydrated cement powder and red mud. *Materials.* 2023;16(4):1551. doi: 10.3390/MA16041551

[12] Abed M, Nasr M, Hasan Z. Effect of silica fume/binder ratio on compressive strength development of reactive powder concrete under two curing systems. In: *MATEC Web Conf. EDP Sciences*. 2018; p. 02022.

[13] Li L, Liu W, You Q, Chen M, Zeng Q. Waste ceramic powder as a pozzolanic supplementary filler of cement for developing sustainable building materials. *J Clean Prod.* 2020;259:120853. doi: 10.1016/j.jclepro.2020.120853

[14] Xu F, Lin X, Zhou A. Effect of recycled ceramic aggregate on hydration heat and permeability of high performance concrete. *Cem Concr Compos.* 2023;137:104930. doi: 10.1016/j.cemconcomp.2023.104930

[15] Suzuki M, Seddik Meddah M, Sato R. Use of porous ceramic waste aggregates for internal curing of high-performance concrete. *Cem Concr Res.* 2009;39(5):373–81. doi: 10.1016/j.cemconres.2009.01.007

[16] Tahwia AM, Ellatief MA, Bassioni G, Heniegal AM, Elrahman MA. Influence of high temperature exposure on compressive strength and microstructure of ultra-high performance geopolymer concrete with waste glass and ceramic. *J Mater Res Technol.* 2023;23:5681–97. doi: 10.1016/j.jmrt.2023.02.177

[17] Liu J, Wu C, Liu Z, Li J, Xu S, Liu K, et al. Investigations on the response of ceramic ball aggregated and steel fibre reinforced geopolymer-based ultra-high performance concrete (G-UHPC) to projectile penetration. *Compos Struct.* 2021;255:112983. doi: 10.1016/j.compstruct.2020.112983

[18] Abd Ellatief M, Abadel AA, Federowicz K, Abd Elrahman M. Mechanical properties, high temperature resistance and microstructure of eco-friendly ultra-high performance geopolymer concrete: role of ceramic waste addition. *Constr Build Mater.* 2023;401:132677. doi: 10.1016/j.conbuildmat.2023.132677

[19] Reig L, Sanz MA, Borrachero MV, Monzó J, Soriano L, Payá J. Compressive strength and microstructure of alkali-activated mortars with high ceramic waste content. *Ceram Int.* 2017;43(16):13622–34. doi: 10.1016/j.ceramint.2017.07.072

[20] Amin M, Zeyad AM, Tayeh BA, Saad Agwa I. Engineering properties of self-cured normal and high strength concrete produced using polyethylene glycol and porous ceramic waste as coarse aggregate. *Constr Build Mater.* 2021;299:124243. doi: 10.1016/j.conbuildmat.2021.124243

[21] Sun Z, Cui H, An H, Tao D, Xu Y, Zhai J, et al. Synthesis and thermal behavior of geopolymer-type material from waste ceramic. *Constr Build Mater.* 2013;49:281–7. doi: 10.1016/j.conbuildmat.2013.08.063

[22] Kannan DM, Aboubakr SH, El-Dieb AS, Taha MMR. High performance concrete incorporating ceramic waste powder as large partial replacement of Portland cement. *Constr Build Mater.* 2017;144:35–41.

[23] Garg N, Shrivastava S. A review on utilization of recycled concrete aggregates (RCA) and ceramic fines in mortar application. *Mater Today Proc.* 2023;73:64–73. doi: 10.1016/j.matpr.2022.09.226

[24] Shoaei P, Musaeei HR, Mirlohi F, Narimani zamanabadi S, Ameri F, Bahrami N. Waste ceramic powder-based geopolymer mortars: effect of curing temperature and alkaline solution-to-binder ratio. *Constr Build Mater.* 2019;227:116686. doi: 10.1016/j.conbuildmat.2019.116686

[25] Ozawa M, Subedi Parajuli S, Uchida Y, Zhou B. Preventive effects of polypropylene and jute fibers on spalling of UHPC at high temperatures in combination with waste porous ceramic fine aggregate as an internal curing material. *Constr Build Mater.* 2019;206:219–25. doi: 10.1016/j.conbuildmat.2019.02.056

[26] Barsoum M. Fundamentals of ceramics. *Fundam Ceram.* 2003;441–464. doi: 10.1887/0750309024

[27] Huseien G, Mohd.Sam AR, Kwok Wei S, Mirza J. Effects of ceramic tile powder waste on properties of self-compacted alkali-activated concrete. *Constr Build Mater.* 2020;236: 117574. doi: 10.1016/j.conbuildmat.2019.117574

[28] Ahmad R, Ibrahim WMW, Abdullah MMAB, Sandu AV, Mortar NAM, Hashim N, Zailani WWA. Synthesis and characterization of fly ash based geopolymer ceramics: effect of NaOH concentration. *IOP Conf Ser Mater Sci Eng.* 2020;743:12014. doi: 10.1088/1757-899X/743/1/012014

[29] Valencia Isaza A, Mejía Arcila JM, Restrepo JW, Valencia García MF, Peña LVW. Performance and applications of lightweight geopolymer and alkali activated composites with incorporation of ceramic, polymeric and lignocellulosic wastes as aggregates: a review. *Heliyon*. 2023;e20044. doi: 10.1016/j.heliyon.2023.e20044

[30] Siddique S, Shrivastava S, Chaudhary S. Influence of ceramic waste on the fresh properties and compressive strength of concrete. *Eur J Environ Civ Eng.* 2019;23(2):212–25.

[31] Amin M, Tayeh BA, Agwa IS. Effect of using mineral admixtures and ceramic wastes as coarse aggregates on properties of ultrahigh-performance concrete. *J Clean Prod.* 2020;273:123073. doi: 10.1016/j.jclepro.2020.123073

[32] Cevik A, Alzeebaree R, Humur G, Niş A, Gülşan E. Effect of nano-silica on the chemical durability and mechanical performance of fly ash based geopolymer concrete. *Ceram Int.* 2018;44. doi: 10.1016/j.ceramint.2018.04.009

[33] Xu J, Niu X, Ma Q, Han Q. Mechanical properties and damage analysis of rubber cement mortar mixed with ceramic waste aggregate based on acoustic emission monitoring technology. *Constr Build Mater.* 2021;309:125084. doi: 10.1016/j.conbuildmat.2021125084

[34] Tutkun B, Beglarigale A, Yazici H. Alkali-silica reaction of sanitary ware ceramic wastes utilized as aggregate in ordinary and high-performance mortars. *Constr Build Mater.* 2022;319:126076. doi: 10.1016/j.conbuildmat.2021.126076

[35] Altheeb A. Engineering attributes of alkali-activated mortars containing ceramic tiles waste as aggregates replacement: effect of high-volume fly ash inclusion. *Mater Today Proc.* 2023. doi: 10.1016/j.matpr.2023.04.121

[36] Kherraf L, Hebhoub H, Abdelouahed A, Boughamssa W. Comparative study on the performance of sand-based mortars from marble, floor tile and cinder block waste. *J Build Eng.* 2022;45:103433. doi: 10.1016/j.jobe.2021.103433

[37] Zhang L, Shen H, Xu K, Huang W, Wang Y, Chen M, et al. Effect of ceramic waste tile as a fine aggregate on the mechanical properties of low-carbon ultrahigh performance concrete. *Constr Build Mater.* 2023;370:130595. doi: 10.1016/j.conbuildmat.2023.130595

[38] Cherene MGP, de Castro Xavier G, da Silva Barroso L, de Souza Moreira Oliveira J, de Azevedo ARG, Vieira CM, et al. Technological and microstructural perspective of the use of ceramic waste in cement-based mortars. *Constr Build Mater.* 2023;367:130256. doi: 10.1016/j.conbuildmat.2022.130256

[39] Meena RV, Beniwal AS, Jain A, Choudhary R, Mandolia R. Evaluating resistance of ceramic waste tile self-compacting concrete to sulphuric acid attack. *Constr Build Mater.* 2023;393:132042. doi: 10.1016/j.conbuildmat.2023.132042

[40] Suchithra S, Sowmiya M, Pavithran T. Effect of ceramic tile waste on strength parameters of concrete-a review. *Mater Today Proc.* 2022;65:975–82. doi: 10.1016/j.matpr.2022.03.610

[41] Manikandan KP, Nanthakumar P, Balachandar M, Gowri Shankar D, Vijayakumari G. Partial replacement of aggregate with ceramic tile in concrete. *Mater Today Proc.* 2023. doi: 10.1016/j.matpr.2023.05.214

[42] Ebrahimi M, Eslami A, Hajirasouliha I, Ramezanpour M, Pilakoutas K. Effect of ceramic waste powder as a binder replacement on the properties of cement- and lime-based mortars. *Constr Build Mater.* 2023;379:131146. doi: 10.1016/j.conbuildmat.2023.131146

[43] Taher MJ, Abed EH, Hashim MS. Using ceramic waste tile powder as a sustainable and eco-friendly partial cement replacement in concrete production. *Mater Today Proc.* 2023. doi: 10.1016/j.matpr.2023.04.060

[44] Iraqi Standard NO.5. Portland cement. Central Organization for Standardization and Quality Control, Baghdad, Iraq. 2019.

[45] BS EN 197-1. Cement, composition, specifications and conformity criteria for common cements. London, England: \British Standards Institution-BSI and CEN European Committee for Standardization; 2011.

[46] Iraqi Standard NO.45. Aggregate from natural sources for concrete and building construction. Central Organization for Standardization and Quality Control, Baghdad, Iraq; 1984.
[47] ASTM C494/C494M. Standard specification for chemical admixtures for concrete. West Conshohocken, PA; ASTM Unternatuinak, 2013.
[48] ACI 116R-00. Cement and concrete terminology, Michigan, USA: American Concrete Institute (ACI); 2000.
[49] ASTM C109/C109M. Standard test method for compressive strength of hydraulic cement mortars (using 2-in. or [50-mm] cube specimens). West Conshohocken, PA:ASTM International; 2013.
[50] ASTM C1437. Standard test method for flow of hydraulic cement mortar. West Conshohocken, PA: ASTM International; 2013.
[51] BS EN 196–1. Methods of testing cement. Determination of strength. British Standards Institution-BSI and CEN European Committee for Standardization; 2005.
[52] ASTM C642. Standard test method for density, absorption, and voids in hardened concrete. West Conshohocken, PA: ASTM International; 2013.
[53] ASTM C597. Standard test method for pulse velocity through concrete. West Conshohocken, PA: ASTM International; 2009.
[54] Gopalakrishnan R, Nithiyanantham S. Microstructural, mechanical, and electrical properties of copper slag admixtured cement mortar. *J Build Eng.* 2020;31:101375. doi: 10.1016/j.jobe.2020.101375
[55] Rusati PK, Song KI. Magnesium chloride and sulfate attacks on gravel-sand-cement-inorganic binder mixture. *Constr Build Mater.* 2018;187:565–71.
[56] Gabathuler H. The CML story: how environmental sciences entered the debate on LCA. *Int J Life Cycle Assess.* 2006;11:127–32.
[57] Van Gulck L, Wastiels L, Steeman M. How to evaluate circularity through an LCA study based on the standards EN 15804 and EN 15978. *Int J Life Cycle Assess.* 2022;27(12):1249–66.
[58] Robayo-Salazar RA, Mejía-Arcila JM, de Gutiérrez RM. Eco-efficient alkali-activated cement based on red clay brick wastes suitable for the manufacturing of building materials. *J Clean Prod.* 2017;166:242–52.
[59] Gautam L, Jain JK, Jain A, Kalla P. Recycling of bone china ceramic waste as cement replacement to produce sustainable self-compacting concrete. *Structures*. 2022;37:364–78. doi: 10.1016/j.istruc.2022.01.019
[60] Zhang P, Zhang P, Wu J, Guo Z, Zhang Y, Zheng Y. Mechanical properties and durability of sustainable concrete manufactured using ceramic waste: a review. *J Renew Mater.* 2023;11(2).
[61] Yao G, Wang Q, Wang Z, Wang J, Lyu X. Activation of hydration properties of iron ore tailings and their application as supplementary cementitious materials in cement. *Powder Technol.* 2020;360:863–71. doi: 10.1016/j.powtec.2019.11.002
[62] Mohit M, Haftbaradaran H, Riahi HT. Investigating the ternary cement containing Portland cement, ceramic waste powder, and limestone. *Constr Build Mater.* 2023;369:130596. doi: 10.1016/j.conbuildmat.2023.130596
[63] Alsaif A. Utilization of ceramic waste as partially cement substitute: a review. *Constr Build Mater.* 2021;300:124009. doi: 10.1016/j.conbuildmat.2021.124009
[64] El Dieb AS, Kanaan DM. Ceramic waste powder an alternative cement replacement–characterization and evaluation. *Sustain Mater Technol.* 2018;e00063.
[65] Tarekegn AG, Nuru R, Gebre Y. Partial replacement of cement with marble and ceramic waste powders in normal strength concrete. In: Woldegiorgis BH, Mequanint K, Getie MZ, Mulat EG, Assegie AA, editors. Advanment in Science and Technology: Materials and Energy. Cham, Switzerland: Springer; 2023. p. 407–18.
[66] Hasan ZA, Nasr MS, Abed MK. Combined effect of silica fume, and glass and ceramic waste on properties of high strength mortar reinforced with hybrid fibers. *Int Rev Civ Eng.* 2019;10(5):267–73.
[67] Nasr MS, Hussain TH, Najim WN. Properties of cement mortar containing biomass bottom ash and sanitary ceramic wastes as a partial replacement of cement. *Int J Civ Eng Technol.* 2018;9(10):153–65.
[68] Gautam L, Jain JK, Jain A, Kalla P. Valorization of bone-china ceramic powder waste along with granite waste in self-compacting concrete. *Constr Build Mater.* 2022;315: 125730.
[69] Siddique S, Shrivastava S, Chaudhary S, Gupta T. Strength and impact resistance properties of concrete containing fine bone china ceramic aggregate. *Constr Build Mater.* 2018;169:289–98.
[70] Siddique S, Shrivastava S, Chaudhary S. Durability properties of bone china ceramic fine aggregate concrete. *Constr Build Mater.* 2018;173:323–31.
[71] Li L, Liu W, You Q, Chen M, Zeng Q, Zhou C, et al. Relationships between microstructure and transport properties in mortar containing recycled ceramic powder. *J Clean Prod.* 2020;263:121384.
[72] Jain A, Sharma N, Choudhary R, Gupta R, Chaudhary S. Utilization of non-metalized plastic bag fibers along with fly ash in concrete. *Constr Build Mater.* 2021;291:123329.
[73] Abadel AA, Nasr MS, Shubbar A, Hashim TM, Tuladhar R. Potential use of rendering mortar waste powder as a cement replacement material: fresh, mechanical, durability and microstructural properties. *Sustainability*. 2023;15(15):11659.
[74] Hilal N, Hamah Sor N, Faraj RH. Development of eco-efficient lightweight self-compacting concrete with high volume of recycled EPS waste materials. *Environ Sci Pollut Res.* 2021;28(36):50028–51.
[75] Chao-Lung H, Le Anh-Tuan B, Chun-Tsun C. Effect of rice husk ash on the strength and durability characteristics of concrete. *Constr Build Mater.* 2011;25(9):3768–72.
[76] Demirel S, Öz HÖ, Güneş M, Çiner F, Adın S. Life-cycle assessment (LCA) aspects and strength characteristics

of self-compacting mortars (SCMs) incorporating fly ash and waste glass PET. *Int J Life Cycle Assess.* 2019;24:1139–53.

[77] Kulovaná T, Vejmelková E, Pokornι J, Siddique JA, Keppert M, Rovnaníková P, et al. Engineering properties of composite materials containing waste ceramic dust from advanced hollow brick production as a partial replacement of Portland cement. *J Build Phys.* 2016;40(1): 17–34.

[78] Kuan P, Hongxia Q, Kefan C. Reliability analysis of freeze–thaw damage of recycled ceramic powder concrete. *J Mater Civ Eng.* 2020;32(9):5020008.

[79] Shahroodi A. Development of test methods for assessment of concrete durability for use in performance-based specifications [MA Sc thesis]. Toronto, Canada: University of Toronto; 2010.

[80] El-Dieb AS, Kanaan DM. Ceramic waste powder an alternative cement replacement–characterization and evaluation. *Sustain Mater Technol.* 2018;17:e00063.

[81] Bremner T, Hover K, Poston R, Broomfield J, Joseph T, Price R, et al. ACI 222R-01 protection of metals in concrete against corrosion. Report by the American Concrete Institute, Farmington Hills, MI, USA. 2001.

[82] Gonzalez-Corominas A, Etxeberria M. Properties of high performance concrete made with recycled fine ceramic and coarse mixed aggregates. *Constr Build Mater.* 2014;68:618–26. doi: 10.1016/j.conbuildmat.2014.07.016

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