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Pozzolanic Reactivity of Pulverized Ceramic Waste as Partial Substitute for Cement and Supplementary Cementitious Materials in Concrete

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ABSTRACT: The pozzolanic reactivity of the adhesive stabiliser enhances the performance of supplementary cementitious materials (SCMs) in mortar compositions, and alternative ways of reducing carbonic emission of cement (CO_2) have been a global concern. Hence, the objective of this paper is to investigate the pozzolanic reactivity of pulverised ceramic waste (CW) as partial substitution for cement and supplementary cementitious materials in concrete making using appropriate standard methods after water-cured for 7, 14, and 28 days. From resilient test, the compressive strength of bricks with sole cement has a higher resistance 1.55, 1.59 and 1.64MPa of 7, 14, and 28 water cured days, respectively. The study unveiled characterisation of CW's properties as a potential recycling material for cementitious compositions with its partial replacement for cement at (CW01-05% to CM09-05% of 10%) and its equal substitution for SCMs at (CW30%/GD30%/RS30% of 90%). The results revealed strength of 1.18, 1.24, 1.34, 1.41 and 1.49MPa, respectively for the mixtures at water curing for 7 days, 1.24, 1.29, 1.36, 1.44, 1.52MPa at water curing for 14 days, and 28 days of water curing has the highest strength of 1.26, 1.32, 1.39, 1.52, 1.60Mpa. In conclusion, CW has a substantial influence on compressive strength of cementitious bricks and can serve as a partial substitute for cement compositions.

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Portland cement (PC) has been a primal substance for stabilising supplementary cementitious materials (SCMs) in concrete technology and adhesive material for civil construction. Globally, the demand for cement in civil structures have been increasingly high due to the growth in population and economic development (Belaïd, 2022). United Nations Environment Sustainable Building and Climate Initiative has warned against the health hazard in the carbonic emission of cement-based supplements in cementitious compositions and encourages research into alternative possibilities to minimize the cement dosage over the next 30 years (Scrivener and John, 2018). In the quest for substitute solutions, the possibility of reducing carbonic emissions of cement CO_2 with alternative adhesive material has been a concern in concrete technology. Alternative possibilities through pozzolanic nonbiodegradable wastes have been the focus for improvement of cement and concrete construction and environmental sustainability.

Exploration of the potentials of environmental wastes as a partial replacement for Portland cement and supplementary cementitious materials (SCMs) in cement and concrete production has been under examination (Ajadi, 2024; Miller, *et al.,* 2018; Schmidt, *et al.*, 2018; Ajadi, 2024). The objective has been a derivative possibility of eco-efficient cementitious stabiliser with economical values for

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optimum benefits leading to viable solutions for low-CO_2 cement-based supplements. Utilisation of waste materials as enhancements in cementitious compositions unveils wastes from landfilled pits, reduces the hazards posed to ecological niches, and provides optimal value of function that offer additional economic and environmental benefits. These efforts aim to prevent the accumulation of solid wastes and promote recycling practices (Lassinantti, *et al.,* 2018; Sepehri and Sarrafzadeh, 2018). In addition, alternative search to minimize the severe pollution by waste materials result and indiscriminate strewing on the earth's surface has been the most critical issues and global environmental concerns.

Some wastes cannot be recycled or incorporated back into to their initial state due to transubstantiation that the raw materials have undergone through the rigorous firing process during manufacturing (Blackett, *et al.,* 2018), but could be pulverised entirely for highly developed products. Consequently, the difficulty in recycling and underutilization in Nigerian context (Kalilu and Ajadi, 2021) means majority are strewed indiscriminately in the environment as waste materials. Most heat-transmuted wastes are commonly disposed of in dumps or landfills in Nigeria. The reuse of heat-transmuted waste is an innovative option that can improve the economy, protect natural resources, and reduce environmental pollution (Zengrong, *et al.,* 2023). Besides the ecological benefit and economic improvement, Matos and Sousa-Coutinho (2024), Lothenbach *et al.* (2011) and Jensen *et al.* (2016) affirmed that partial replacement of these materials as supplementary cementitious materials provides mechanical strength, reduce shrinkage and cracking risk, and offer engineering advantages.

The feasibility of recycling some of these materials has been the major concern in many countries (Tam, *et al.,* 2018; Cicek, *et al.,* 2018). Amid the waste materials experimented as a partial replacement for supplementary cementitious materials by different scholars include cullet (Ajadi, 2024; Matos and Sousa-Coutinho, 2014) fly ash (Zhang, *et al.,* 2023), waste foundry sand [Salman, *et al.,* 2022; Bhardwaj and Kumar, 2017), ground granulated blast furnace slag (Ramakrishnan, *et al.,* 2017), limestone filler (Courard, *et al.,* 2011), silica fume (Cohen and Bentur, 1988; Detwiler and Mehta, 1989), metakaolin (Convile and Lee, 2005), and bentonite (Blatz, *et al.,* 2002). Kelestermer *et al.* (2014) empirically examined mortar compositions prepared with cement, glass fibre and marble dust for the enhancement of freeze-thaw resistance. Aside from lower hardened reactivity of some of these materials when compared with cement and oftentimes demands chemical treatment to enhance the performance (Paul, *et al.,* 2018), their utilisation gives rise to value-added products.

Research on concrete technology has equally affirmed the influence of particle size density (PSD) as a factor that leads to an optimal solidity of cement composition. However, heat-transmuted solid ceramic waste of opalescent structure has been investigated as a supplementary material in the production of concrete (Awoyera, *et al.,* 2018; Belhouchet, *et al.,* 2018). Feasibility of ceramic waste as fine and coarse aggregates (Piyaphanuwat and Asavapisit, 2017; El-Dieb and Kanaan, 2018; Kannan, *et al.,* 2017), and civil concrete is the most viable option for reusing and valorisation of ceramic waste (Arias-Ocampo and Rojas-Gonzalez, 2024). The addition of discarded porcelain electrical insulators into the production cycle is an attractive option (Rodríguez, *et al.,* 2019) and porcelain microstructures are produced from mullite reaction between kaolinitic clay, feldspar and crystalline phases of quartz at a vitreous phase (Romero and Pérez, 2015). Ceramic products are fragile, its waste occurs as a result of production failure, poor quality control on the final ware and mishandling during storage and installation (Meng, *et al.,* 2019).

The reuse of ceramic waste in cementitious mixes at 20 to 50% mass was discovered to increase the corrosion resistance and mechanical strength of concrete composition (Portella, *et al.,* 2002). The influence of using ceramic waste as a supplementary material in construction were identified (Keshavarz and Mostofinejad, 2019) and its aggregate in the production of concrete (Bhogilal and Tejas, 2018; Huseien, *et al.,* 2020). The pozzolanic reactivity of pulverised ceramic waste encouraged several researchers to use it as a fine aggregate (Caligaris, *et al.,* 2000; Kannan, *et al.,* 2017). As supplementary material for concrete, Sekar *et al.* (2011) found that the compressive strength of concrete composed with pulverised ceramic insulator wastes was lower than the strength of conventional concrete. Nonetheless, it was found in the results of some of these studies that ceramic waste increased mechanical properties of the concrete when substitutes with conventional supplementary materials.

Other submissions show that the pozzolanic properties and adhesive reactivity of pulverised ceramic waste (PCW) are enhanced with particle size reduction and can partially substitute for cement (Siddique, *et al.,* 2018; Siddique, *et al.,* 2019). Any pozzolanic materials pulverised below 75µm is very reactive, particularly below 38µm (Patel, *et al.*, 2018; Du and Tan, 2017; Lu, *et al.*, 2021). The pozzolanic reactivity of ceramic waste is enhanced by the particle size (Matos and Sousa-Coutinho, 2012]. Few studies also reported that concrete durability improved when ceramic waste is used as a cement replacement (Portella, *et al.*, 2006; Kannan, *et al.*, 2017). Pulverised ceramic waste of vitreous composition possesses hardened properties and adhesive characteristics in cementitious mixes that indurate mortars under compressive strength and resistance at break (Keshavarz, *et al.*, 2019; Du and Tan, 2017). These properties were characterised through pulverised samples, solid test bricks, water absorption properties and compressive strength.

The study, therefore, investigates the hardened reactivity of pulverised ceramic waste as partial substitution for cement and supplementary cementitious materials in concrete making. The specific objectives of the study are: to substitute pulverised ceramic waste partially for cement in an attempt to reduce the carbonic emission of cement dosage in cementitious construction; to assess the pozzolanic reactivity of pulverised ceramic waste in refining pore formations and capillary actions of concrete mixes during water absorption tests; to mechanically examine the performance of ceramic waste properties in concrete mixes during compressive strength examinations, and to offer alternative ways of utilising ceramic waste in improving cementitious compositions and minimizing its hazard in the environment.

MATERIALS AND METHODS

Figure 1 explains the procedures for material collection, phases of samples treatment, elemental analysis of pulverised samples, and mechanical examination of test bricks through water absorption capacity and compressive strength.

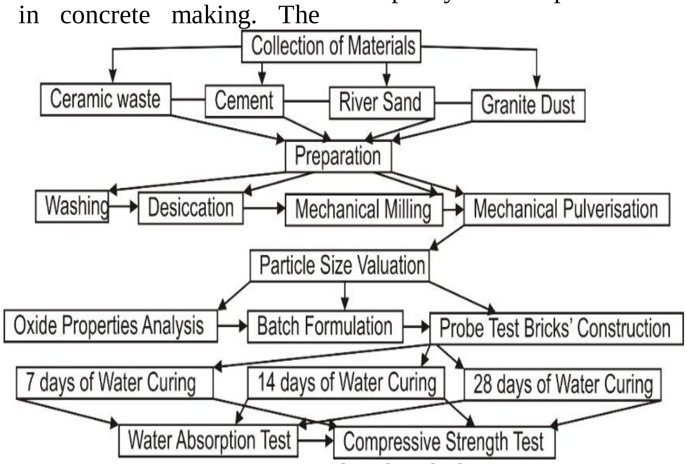

Fig 1: Materials and Methods

Sample collection: Ceramic wastes of sanitary wares, porcelain floor tiles, porcelain electrical insulator and utensil wares were unearthed from landfilled pits and dumps (Plate 1), washed to remove fibres and contaminants (Plate 2) and dried for accuracy during oxide properties analysis. The other two supplementary materials (granite dust and river sand) for this study were collected from a drilling pit and erosion path respectively in Ogbomoso, Nigeria. The Portland cement produced by Dangote Company (BlocMaster Portland Limestone Cement 42.5R) was purchased as an adhesive material for this research (Plate 3) and potable water was obtained from the borehole at Department of Fine and Applied Arts, Ladoke Akintola University of Technology, Ogbomoso.

Sample preparations: The ceramic waste was hammer milled separately with a crushed machine into a coarse aggregate (CA) (Plate 4). Thereafter, the coarse ceramic waste was pulverised into two aggregates.

Plate 1: Samples' collection

Plate 2 Washing of Samples

Plate 3 Cement

Plate 4‘ Ceramic Waste (CA)

A portion of the coarse waste was powdered into cement density (CD) as a partial replacement for cement aggregate (Plate 5). Some portion of the ceramic waste was also pulverised at particle size of other samples as supplementary materials (granite dust and river sand) (Plates 6-8). The machine was regulated into these two sizes through minutes and speed of rotation by operation.

Sample Testing and analysis: The densities of the materials after mechanical pulverisation were determined with the Laser Method (kg/m^3) as presented in Table 1

Plate 5. Ceramic Waste (CD)

Plate 6 Ceramic Waste (SCM)

Plate 7. Granite dust (SCM)

Plate 8. River sand (SCM)

Table 1. Particle Densities of Ceramic Waste (CM/SCM), Cement, Granite dust, and River Sand

Materials	**Ceramic waste (CD)**	**Cement**	**Granite dust**	**River sand**	**Ceramic waste (SCM)**
Density (Kg/m^3)	3110	3110	2280	2280	2280

As can be deduced in Table 1, ceramic waste which was used as a partial cement substitution was pulverised in equal density with cement for aggregative homogeneity and hardened reactivity. The responsiveness of pozzolanic materials in cementitious compositions can be highly activated when pulverised into a finest particle size (Patel, *et al.*, 2019; Du and Tan, 2017; Lu, *et al.*, 2021). Aside, pozzolanic reactivity of ceramic waste is improve by the nanoparticle density (Matos and Sousa-Coutinho, 2012) which enhances the solidity of mortar in concrete (Grissom, 2024). Oxide properties of the ceramic waste with other supplementary cementitious materials were determined in a tandem accelerator machine (1.7MV Tandem Pelletron Model: 5SDH) (Plate 9) at Centre for Energy Research and Development, Obafemi Awolowo University, Ile-Ife. The properties of each material were analysed through Particle Induced X-ray Emission for comparative analysis of their chemical components.

Studio Practices: The samples were measured (Plate 10) as batch compositions to mould 18 probe test bricks (PTB) for three different water-cured days. The compositions were mixed based on batch composition on dry weights state in Jar Mill machine (Plate 11) as sole cement (10%) to the admixture of conventional SCMs (granite dust and river sand) at equal ratio as probe test control (PTC_0). Subsequently, Pulverised ceramic waste was substituted for cement in admixture of granite dust, river sand and ceramic waste as SCMs for the probe test bricks$_{1-5}$ (PTB_{1-5}) as shown in Table 2.

Plate 9: 1.7 MV Tandem Pelletron (Model: 5SDH)

Table 2: Batch Compositions of the Probe Test Bricks

Probe Test Bricks	**PTC_0**	**PTB_1**	**PTB_2**	**PTB_3**	**PTB_4**	**PTB_5**
Ceramic Waste (CM)	-	01	02	03	04	05
Cement	10	09	08	07	06	05
Granite Dust	45	30	30	30	30	30
River Sand	45	30	30	30	30	30
Ceramic Waste (SCM)	-	30	30	30	30	30
Total	100	100	100	100	100	100

Plate 10 Measuring the Samples

Plate 11 Sample mixing in Jar Mill Machine

Equimolar test bricks were made from the mixed compositions in Table 2 in a wooden mould designed with dimension of 50mm in width, 100mm in length, and 30mm in thickness (50 x 100 x 30mm), and compacted with a manual machine with 60ml distilled water. Each batch composition was used to mould three probe test bricks for water curing at 7, 14, and 28 days. The bricks were inscribed with alphabetical identification A-F (Plate 12) representing batch compositions 0-5 for easy assessment of mechanical properties during examination.

Plate 12 Probe Test Bricks

Water Absorption Analysis: After compaction, the probe test bricks were allowed to desiccate for eight (8) days at ambient temperature in the studio. Pore formations, capillary actions and interfacial transition zones determine intermolecular force and performance characteristics of surface tension in the concrete. Six (6) solid test bricks were selected from each of the batch compositions for examination of water absorption capacity through liquid porosity test of 24 hours water immersion. The weight unit of each of each probe test bricks for the water absorption experiment were taken at total dehydration state in kilogram (kg) before they were drenched in the water. After, 24 hours of water immersion, the specimens were measured again for weight differential analysis (kg). The rate of water porosity and retention were determined as shown in the statistical equation (1):

$$\text{That is: } \frac{IWTB - DWTB}{DWTB} \times 100 \quad (1)$$

Where: Dried Weight of Test Brick = *(DWTB)* at total dehydration Immersed Weight of Test Brick = *(IWTB)* after 24 hours of water immersion; Retention Capacity Rate = *(RCR);* Retention Capacity in Percentage = *(RCP)*

Compressive Strenght Analysis: After conducting water absorption test, the probe test bricks were exposed to air desiccation for another 72 hours before commencing the water curing exercise. Three probe test bricks moulded from each batch composition were distinguished to represent the selected days of water curing.

The specimens were immersed separately in properly labelled three containers with water to indicate the three (3) selected days (7, 14, 28) for the mechanical strength test under compressive evaluation. The resistance to break of the probe test bricks were examined through compressive technique, and this assessment was done with the digitally powered universal testing machine (Model Instron 3369K1781) at Centre for Energy Research and Development, Obafemi Awolowo University, Ile-Ife. The measurements of all probe test bricks are as follows: anvil height of 14.95mm, thickness of 149.04mm, and width of 45.05mm. The measurement was done to ensure the weight against the compressive strength (MPa) which was calculated as shown in Equation (2):

$$\text{Compressive strength (MPa)} = \frac{Force\ (N)\ or\ Load}{Area\ (M^2)}$$
$$\text{Pascal (Pa)} = N/M^2 \quad (2)$$

RESULTS AND DISCUSSION

Chemical oxide of Ceramic waste, River sand, Granite dust, and Cement: Table 3 present the percentage of chemical oxides in ceramic waste, river sand, granite dust, and cement, that was examined through Particle Induced X-ray Emission.

As can be seen from Table 3, the major elements in the ceramic waste are siliceous oxide (60.5%), aluminium oxide (19.6%), calcium oxide (9.85%), and sodium oxide (4.75%) which slightly differ in percentage from the composition of cement. As stated by ASTM C618, to categorise particular material as pozzolanic materials, its chemical composition (SiO_2+Al_20_3+Fe_2O_3) has to be greater than 70% (ASTM, 2007; ASTM, 2000). These highlighted oxides enhance the pozzolanic reactivity of ceramic waste in cementitious compositions and provide compaction characteristics that optimise the adhesive attribute of cementitious hardened reactivity.

Calcium is the highest oxide in the composition of cement at 63.04%, with siliceous oxide at 21.33%, aluminium oxide at 4.83% and iron at 3.52% as other major elements. This slight difference may have a responsive impact on the probe test bricks through variation in batch mixes and equally influence resilience properties in each of the compositions during mechanical examination.

The percentage of calcium oxide in materials indurates hardened reactivity of the cementitious compositions, enhances the strength of concrete, and decreases the porosity of mortars (Matos and Sousa-Coutinho, 2024). However, water absorption capacity (WAC) was tested as well as compressive strength (CS), which was examined through a mechanical instrument for load resistance.

Table 3: Oxide properties of Ceramic waste, River sand, Granite dust, and cement (% by mass)

Oxides	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	Fe_2O_3	Cl	PbO	SrO	Total
Ceramic waste	4.75	0.75	19.60	60.50	0.12	-	1.90	9.85	0.59	1.53	-	-	0.40	100
River sand	6.74	0.86	4.42	72.46	0.13	-	3.48	3.99	0.41	3.80	-	2.28	1.33	100
Granite dust	4.90	0.88	11.82	70.18	0.18	0.12	6.10	2.20	0.30	3.03	-	0.05	0.24	100
Cement	0.45	1.91	4.83	21.33	-	2.85	0.73	63.04	-	3.52	0.94	0.40	-	100

Water Absorption Rate: The water absorption result was 2.62, 3.25, 3.34, 3.56, 3.88 and 3.97 for the PTC_0, PTB_1, PTB_2, PTB_3, PTB_4 and PTB_5 respectively. Higher water absorption suggests connectivity of pores, movement of water within the voids, and a weakened interfacial transition (Salman, *et al.*, 2022; ASTM, 2000; Naik, *et al.*, 2003). Using pulverised ceramic waste as a fine aggregate and supplementary cementitious material slightly reduces the interfacial transition zones in probe test bricks through the pozzolanic reactivity provided by calcium hydroxide reaction. The correlation coefficient in the water absorption chart (Figure 2) indicates that the decrease in cement quantity in the compositions increases porosity amounts and water absorption rate.

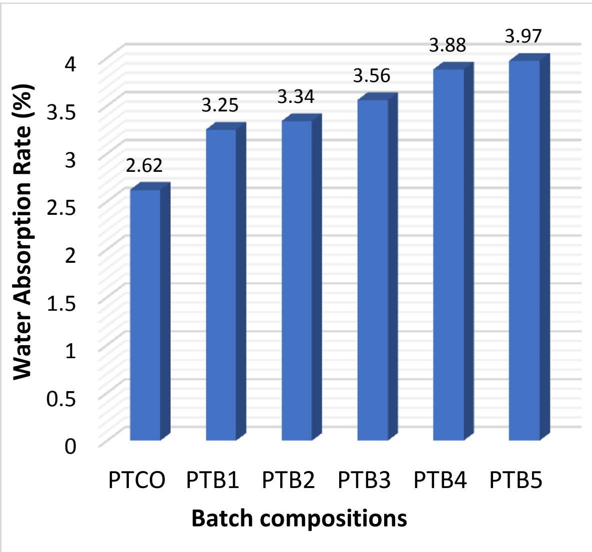

Fig 2: Water Absorption Rate of the Probe Test Bricks

The reduction in the water resistance of probe test bricks modified with aggregates of ceramic waste to the probe test control, which was solely mixed with cement, can be attributed to the diminution in the percentage of calcium oxide through the decrease in cement ratio or compaction technique which may give room for pore formations and capillary actions.

These indicate that decrease in cement quantity weaken interfacial zones and intermolecular bonds and these may equally reduce the compressive strength. With the result in Figure 2 and recommendation of 12% maximum water sorption to sandcrete block by (Nigerian Industrial Standard 978:2007), pore refinement can be observed in the microstructure reaction due to the pozzolanic behaviour of the ceramic waste aggregates in the compositions (Caligaris, *et al.*, 2000; Kannan, *et al.*, 2017; Kamali and Ghahremaninezhad, 2016). The result show that all the probe test bricks are below (ASTM, 2000) requirement. The hardened responsiveness of pulverised ceramic waste in the compositions provides surface tension and depression of liquids in capillaries (Scrivener, *et al.*, 2017; Ajadi, 2024).

Compressive Strength: Figure 3 presents the compressive strength results of probe test bricks modified with partial replacement of ceramic waste aggregates as cement and supplementary cementitious material at 7, 14 and 28 days. The strength of concrete often depends on the pozzolanic behaviour of the materials in the compositions and pore structure, such as porosity and pore connectivity.

As can be perceived, the ceramic waste aggregates as a partial replacement in cement and supplementary cementitious material in PTB_1-PTB_5 compositions resulted in an approximate performance to sole cement mix PTC_0 in compression. According to published studies, the compressive strength of mortars/concretes with pulverised is usually improve with the addition of pulverised ceramic waste (Awoyera, *et al.*, 2018; Belhouchet, *et al.*, 2019; Piyaphanuwat and Asavapisit, 2017; El-Dieb and Kanaan, 2018).

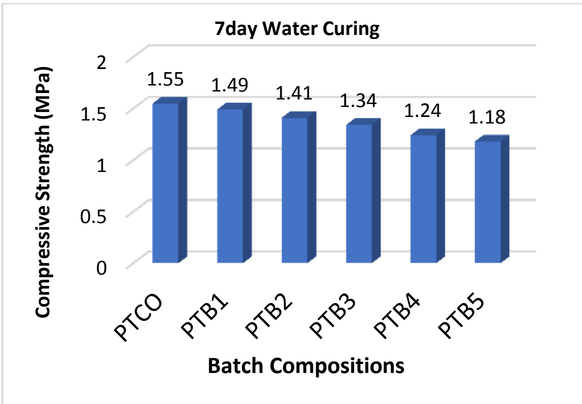

Fig 3: Compressive Strength of the Probe Test Bricks in 7-day of water Curing

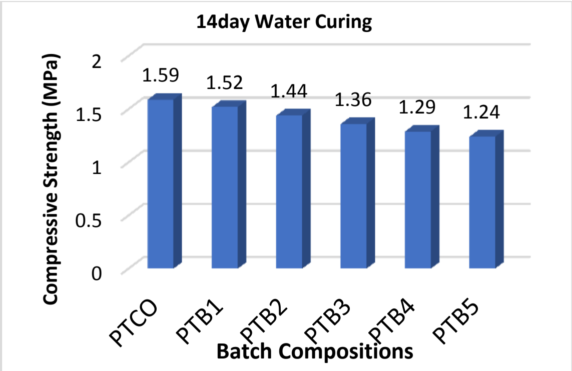

Fig 4: Compressive Strength of the Probe Test Bricks in 14-day of water Curing

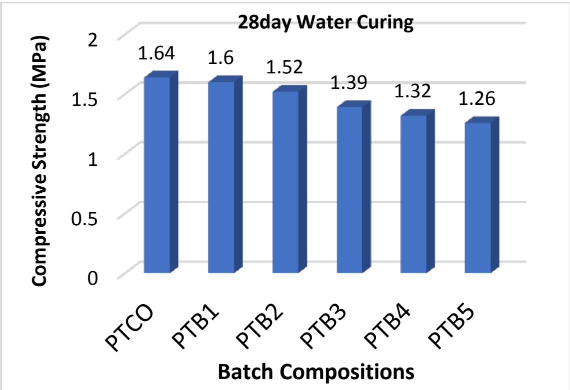

Fig 5: Compressive Strength of the Probe Test Bricks in 28-day of water Curing

From the Figures 3, 4 and 5, the compressive strength results obtained in this experiment are described separately in curing ages. The water curing ages enhance the strength with resistant improvement at the 28th day. Water curing of a cementitious composition with ceramic waste improves performance rate of cement in the manufacture of concrete (Portella, *et al.*, 2019; Arias-Ocampo and Rojas-Gonzalez, 2023). The compressive strength of bricks with sole cement is with the strength of 1.55, 1.59 and 1.64Mpa for 7, 14 and 28 water-cured days, respectively. The study unveiled the characterisation of CW's properties as a potential recycling material for cementitious compositions with its replacement for cement at (CW01-05% to CM09-05% of 10%) and its equal substitution for SCMs at (CW30%/GD30% /RS30% of 90%). The results revealed strength of 1.18, 1.24, 1.34, 1.41 and 1.49MPa, respectively, for the mixtures at water curing for 7 days, 1.24, 1.29, 1.36, 1.44, 1.52MPa at water curing for 14 days, and 28 days of water curing have the highest strengths of 1.26, 1.32, 1.39, 1.52, 1.60MPa. The result could not reach PTC_0 at each curing age, but were not far from the compressive rate. The implication of this result is that the cementitious paste modified with ceramic waste aggregates lack slight hardened performance compared to sole cement composition (Lu, *et al.*, 2021).

Conclusions: The influence of pulverised ceramic waste as aggregates in cementitious compositions has been examined through water absorption capacity and compressive strength. It can be firmly presumed that parameters such as density and compaction techniques can influence the strength of cementitious concrete. Since this waste is suitable for coarse aggregates of supplementary cementitious materials, and partial substitution in cement aggregate, the water curing age of concrete mixed with ceramic waste may need to be increased to optmise their strenght as well as resillence during loading. This will provide more successful application of this waste as a SCM for conventional concrete mixtures. The pozzolanic responsiveness of this waste in concrete mixes suggest compaction characteristics that enhance the adhesive strength of cementitious hardened reactivity. The study unveils an alternative way of recycling ceramic waste and reveals the waste as potential admixture for reduction of carbonic emissions of cement CO_2 reduction

Declaration of Conflict of Interest:
The author declares no conflict of interest.

Data Availability Statement:
Data are available upon request from the author or corresponding author.

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