



## OPEN Experimental investigation of sustainable concrete production using ceramic waste powder as partial fine aggregate replacement

Khawaja Adeel Tariq<sup>1</sup>, Wajid Ali Adil<sup>2</sup>, Amina Salhi<sup>3</sup> & Aashir Waleed<sup>4</sup>

This study investigates the feasibility of using ceramic waste powder as a partial replacement for fine aggregate in concrete, addressing the dual challenges of ceramic industrial waste management and sustainable development of construction materials. Ceramic waste was collected from three major industrial units (Ocean Ceramics, Ghani Ceramics, and Qiang Sheng Ceramics) at the Faisalabad Industrial Estate, Pakistan, which collectively generate approximately 1.06 million tons of ceramic waste annually. The waste was processed into a fine powder and characterized by X-ray Fluorescence (XRF), revealing a high silica content (approximately 71.4%) and significant alumina and sodium oxide phases. Concrete mixtures were prepared with ceramic powder replacement levels of 0% (control), 10%, 20%, 30%, 40%, and 50% by volume of fine aggregate. Results demonstrated that 30% replacement optimally enhanced compressive and flexural strength by 10.5% and 5.92%, respectively, compared to control concrete, while 20% replacement optimally improved tensile strength by 4.68%. XRD analysis confirmed that 30% replacement promoted beneficial pozzolanic reactions, reducing portlandite content and increasing calcium-silicate-hydrate (C-S-H) gel formation, thereby densifying the microstructure. However, workability decreased progressively with increasing ceramic content due to higher water absorption and particle angularity. Beyond 30% replacement, mechanical properties declined due to increased porosity and reduced cement hydration products. Cost analysis indicates that a 30% replacement reduces manufacturing costs by approximately 2.3% for 3 m<sup>3</sup> of concrete incorporating ceramic waste. This study demonstrates that ceramic waste powder can be effectively used as a sustainable fine aggregate substitute in concrete up to 30%, offering both environmental benefits through waste reduction and economic advantages while maintaining or enhancing structural performance.

**Keywords** Ceramic tile waste powder, Sustainable concrete, Mechanical strength, XRD analysis, Waste management, Cost analysis

### Abbreviations

ACI	American concrete institute
ASTM	American society for testing and materials
C&D	Construction and demolition
CaCO <sub>3</sub>	Calcite
Ca (OH) <sub>2</sub>	Portlandite
CPEC	China–Pakistan economic corridor
C-S-H	Calcium-silicate-hydrate
EDS	Energy-dispersive X-ray spectroscopy
LCA	Life-cycle assessment
MIP	Mercury intrusion porosimetry

<sup>1</sup>Department of Civil Engineering, University of Engineering and Technology Lahore (Narowal Campus), Narowal, Punjab, Pakistan. <sup>2</sup>Faisalabad Industrial Estate Development & Management Company, Faisalabad, Punjab, Pakistan. <sup>3</sup>Department of Information Systems College of Computer and Information Sciences, Princess Nourah bint Abdulrahman University, 84428, Riyadh 11671, Saudi Arabia. <sup>4</sup>Department of Electrical, Electronics, and Telecommunication Engineering, University of Engineering and Technology Lahore (Faisalabad Campus), Faisalabad, Punjab, Pakistan. ✉email: khawaja.adeel@uet.edu.pk; aashir.walid@uet.edu.pk

MPa	Megapascal
PKR	Pakistani rupee
SiO <sub>2</sub>	Silicon dioxide
XRD	X-ray diffraction
XRF	X-ray fluorescence
USD	United states dollar

The rapid worldwide infrastructure development, driven by the construction of new buildings and the large-scale demolition of existing ones, generates substantial construction and demolition (C&D) waste<sup>1,2</sup>. Conventional disposal of C&D waste requires large areas for landfilling, which is a significant source of safety, social, and environmental issues. Achieving viable reuse of C&D waste reduces C&D waste production and has been a principal area of research in environmental science and civil engineering over the last few decades<sup>3</sup>. A primary technique for resource recovery from C&D waste is the treatment of inert constituents by crushing and grinding to produce recycled powders and aggregates, which can be used as replacements for cement and natural aggregates<sup>4,5</sup>. Concrete is a principal material widely used in infrastructural development and contemporary construction<sup>6</sup>. The enormous demand for cement concrete due to its favorable characteristics, such as moldability, strength, durability, and good fire resistance<sup>7,8</sup>. Supplementary cementitious materials, plastics, construction and demolition debris are typical examples of waste and by-product materials<sup>9</sup>. Researchers have studied recycled waste marble<sup>10</sup>, recycled aluminum waste<sup>11</sup>, recycled aggregate concrete<sup>12</sup>, recycled glass<sup>13</sup>, recycled plastic waste<sup>14</sup>, recycled coal bottom ash<sup>15</sup>, recycled asphalt pavement<sup>16</sup>, polymer-type waste<sup>17</sup>, red mud<sup>18</sup>, granite waste, rice husk, marble dust<sup>19</sup>, fire clay<sup>20</sup>, glass waste<sup>21</sup>, sanitary ware waste<sup>22</sup>, nanomaterials<sup>23</sup>, and tire waste<sup>24</sup>. Unfortunately, the efficient disposal solution for these wastes incurs additional costs beyond those of manufacturing. The use of industrial waste as a raw material in concrete production is the most effective and efficient method for its utilization<sup>25</sup>.

Ceramic waste, a significant component of C&D waste, can be used as a building material to reduce demand for natural materials, thereby offering ecological advantages<sup>26,27</sup>. There are two techniques to reuse ceramic waste. In the first technique, recycled ceramic aggregate can be produced by crushing and screening ceramic waste, thereby replacing stone aggregates and natural sand in recycled concrete<sup>28</sup>. Nevertheless, natural aggregates exhibit superior physical and mechanical properties compared with recycled ceramic aggregates<sup>29</sup>. The durability and strength of recycled concrete are reduced when recycled ceramic aggregate is used, with notable degradation at high replacement levels<sup>30</sup>. In the second technique, ceramic waste fines can be produced by crushing and grinding ceramic waste to a grain size of less than 150 µm<sup>31</sup>. Based on the origin of raw materials, ceramic waste can be classified into two categories. One classification is based on waste from fired ceramics in the structural ceramics industry, which uses red pastes exclusively to produce commodities such as roof tiles, bricks, and blocks. The instant classification is based on waste from fired ceramics produced by stoneware ceramic industries, including sanitary ware, wall tiles, and flooring<sup>32</sup>. The most important environmental effects of waste ceramics include air pollution, ozone layer depletion, eutrophication, acidification, and climate change<sup>33</sup>. Ceramic tile waste is used by researchers as an alternative coarse aggregate, with pieces ranging from 4.75 mm to 20 mm<sup>34</sup>. The durability of ceramic-waste concrete was investigated by researchers, who found that such concrete can improve resistance to chloride penetration, freezing–thawing cycles, and sulfate attack when appropriately dosed<sup>35</sup>. Ceramic waste ground into microparticles has been shown to replace up to 20% of the cementitious material while maintaining or improving mechanical and durability characteristics<sup>36,37</sup>. Ceramic tile powder can affect cement hydration kinetics and microstructure<sup>38</sup>. Hence, the utilization of ceramic waste powder in construction materials offers significant environmental and economic benefits.

In recent years, the rapid expansion of ceramic tile manufacturing industries in world has resulted in the generation of significant quantities of ceramic waste during cutting, polishing, and finishing processes. Disposal of this industrial waste presents both environmental and economic challenges. At the same time, the construction industry faces increasing pressure to reduce dependence on natural aggregates and to adopt more sustainable materials. These circumstances create an opportunity to investigate the potential reuse of locally generated ceramic waste as a partial replacement for fine aggregates in concrete production.

## Problem statement & research novelty

Although numerous studies have investigated the use of ceramic waste in concrete, most focus on waste derived from demolition debris or sanitary ceramic products. Limited information is available on the utilization of industrial ceramic tile waste generated directly by large-scale manufacturing facilities, particularly in the rapidly expanding ceramic industry in developing regions such as Faisalabad under the China–Pakistan Economic Corridor (CPEC). Furthermore, few studies integrate regional waste generation analysis, mechanical performance evaluation, microstructural characterization, and economic feasibility within a single investigation.

Moreover, in Faisalabad, Pakistan, many ceramic industrial units, such as Time Ceramics, Humei Ceramics, Qiang Sheng Ceramics, Ghani Ceramics, Ocean Ceramics, and Orient Ceramics, among others, manufacture ceramic products at the Faisalabad Industrial Estate Development & Management Company. Different studies have recommended that approximately 30% of the total material is generated as waste during the manufacturing of ceramics<sup>39</sup>. The proper reuse of ceramic waste from industrial units is a viable solution for a healthy, neat environment and for sustainable development. The production and disposal of ceramic waste are significant sources of environmental harm that must be prevented. Based on these concepts, ceramic waste powder, which is inexpensive and abundant is incorporated as a partial replacement for fine aggregate in concrete. Information on selected ceramic industrial units at the Faisalabad Industrial Estate Development & Management Company is presented in Table 1, along with the calculation of annual ceramic waste generation, assuming an average waste-floor tile thickness of 6.0 millimeters. According to Table 1, only some ceramic industrial units produce

Name of Industrial Unit	Land Area (Acres)	Capacity per Year (m <sup>2</sup> )	Ceramic Waste per Year (tons)
Time Ceramics	101.7	65	289,575
Ghani Ceramics	27	18.25	80,190
Orient Ceramics	37	15	66,825
Humei Ceramics	91.54	54.40	240,570
Qiang Sheng Ceramics	82.56	60	267,300
Ocean Ceramics	78.60	25.65	115,830
TOTAL			1,060,290

**Table 1.** Ceramic industrial units operating within Faisalabad Industrial Estate, Pakistan, with their respective land areas, annual production capacities, and estimated ceramic waste generation (assuming 6.0 mm average floor tile thickness and 30% waste generation rate).



**Fig. 1.** Photograph showing collected ceramic floor tile waste from open dumping areas within ceramic industrial units at Faisalabad Industrial Estate, illustrating the raw material source before processing (crushing, washing, and grinding).

1,060,290 tons of ceramic waste per year, which may be used as a partial replacement for fine aggregate in concrete to protect the environment and natural resources.

Faisalabad, Pakistan's waste management infrastructure already struggles with organic, construction and demolition wastes. Using ceramic tiles made from waste and landfill materials is a sustainable solution. Natural aggregate extraction, transport, and processing contribute to greenhouse gas emissions. Using locally available ceramic waste can reduce transport and process energy use and lower the carbon footprint. Newly established Chinese ceramic units in Faisalabad, Pakistan, under the CPEC project, are producing 1.06 million tons/year of ceramic waste, and their utilization has not yet been systematically investigated in the literature.

The originality of this study lies in demonstrating that ceramic waste powder does not simply weaken or lighten concrete, as often assumed. Instead, the research identifies a clear microstructural optimization point where density, compressive strength, and durability indicators align.

## Materials and methods

### Ceramic floor tile waste powder

Identifying the nearest and most accessible source of ceramic waste was the primary challenge of this study. To address this, the research team visited several ceramic industrial units in the Faisalabad Industrial Estate to observe the manufacturing processes and assess the availability of waste materials. The visits confirmed that enough ceramic waste was available at no cost and could be collected without difficulty. For research purposes, ceramic waste was obtained from Ocean Ceramics, Ghani Ceramics, and Qiang Sheng Ceramics. The waste was collected from open dumping areas within the industrial premises (as shown in Fig. 1). The broken and damaged floor tile pieces from these three units were first thoroughly washed with water. The cleaned tiles were then air-

Sr. No.	Chemical Composition	M/S Ghani Ceramics (Pvt.) Ltd	M/S Ocean Ceramics (Pvt.) Ltd	M/S Qiang Sheng Ceramics (Pvt.) Ltd
1	Silicon dioxide	71.35	71.40	71.38
2	Aluminum oxide	13.75	13.72	13.77
3	Ferric oxide	0.55	0.53	0.57
4	Calcium oxide	0.015	0.017	0.018
5	Potassium oxide	0.03	0.025	0.028
6	Titanium dioxide	0.07	0.066	0.067
7	Sodium oxide	12.89	12.91	12.90
8	Magnesium oxide	0.92	0.91	0.90
9	Sulfur trioxide	0.01	0.011	0.013
10	Loss on ignition	0.13	0.12	0.11

**Table 2.** Chemical composition (oxide analysis) of ceramic waste powder obtained from three industrial sources (Ghani Ceramics, Ocean Ceramics, and Qiang Sheng Ceramics) determined by X-ray Fluorescence (XRF) spectroscopy, showing predominantly silicon dioxide ( $\approx 71.4\%$ ) with significant aluminum and sodium oxides.

Sr. No.	Parameters	Permissible Values	Concentration sample	Standard	Remarks
1	pH	6.5–8.0.5.0	7.4	ASTM C1602/C1602M	Within Range
2	Sulfate (mg/L)	1000	34.9	ASTM C1602/C1602M	Within Limits
3	Chloride (mg/L)	500	30	ASTM C1602/C1602M	Within Limits
4	Alkalinity as $\text{CaCO}_3$ (mg/L)	1000	100	ASTM C1602/C1602M	Within Limits

**Table 3.** Physicochemical properties of mixing water sourced from M-3 Industrial City, Faisalabad, compared with permissible limits specified in ASTM C1602/C1602M, confirming suitability for concrete production.

dried in the sunlight for approximately three hours. After drying, the large tile pieces were crushed using a jaw crusher to produce smaller particles suitable for further grinding. After grinding, the ceramic waste powder was sieved to ensure particles were less than  $150\ \mu\text{m}$ , making it comparable to the size range of fine aggregate particles used in concrete mixtures. From each industrial source, 15 kg of broken tile material was processed in a ball mill for 1 h to achieve a fine aggregate.

Ceramic waste was collected from three ceramic manufacturing units (Ocean Ceramics, Ghani Ceramics, and Qiang Sheng Ceramics) and used individually in experimental mixes. For XRD characterization, a representative blended sample was prepared by combining equal proportions of the three ceramic powders to identify the dominant mineralogical phases of the ceramic waste used in this study.

The X-ray Fluorescence (XRF) test is an essential analytical technique for rapidly and non-destructively determining the chemical composition of materials. The X-ray Fluorescence (XRF) test was performed on samples of Ocean Ceramics, Ghani Ceramics, and Qiang Sheng Ceramics (Table 2). The XRF results indicate that the ceramic powder is predominantly composed of Silicon dioxide ( $\text{SiO}_2$ ) and contains a considerable amount of Aluminum oxide, along with moderate amounts of Sodium oxide. The high  $\text{SiO}_2$  content implies that the ceramic powder is rich in silica, which contributes to improved particle packing and may enhance the interfacial transition zone between aggregate and cement paste.

### Water analysis

Tap water from M-3 Industrial City, Faisalabad, Pakistan, was used for concrete mixing. The results of the water investigation are presented in Table 3. It indicates that the available water for concrete mixing is suitable for use.

### Cement

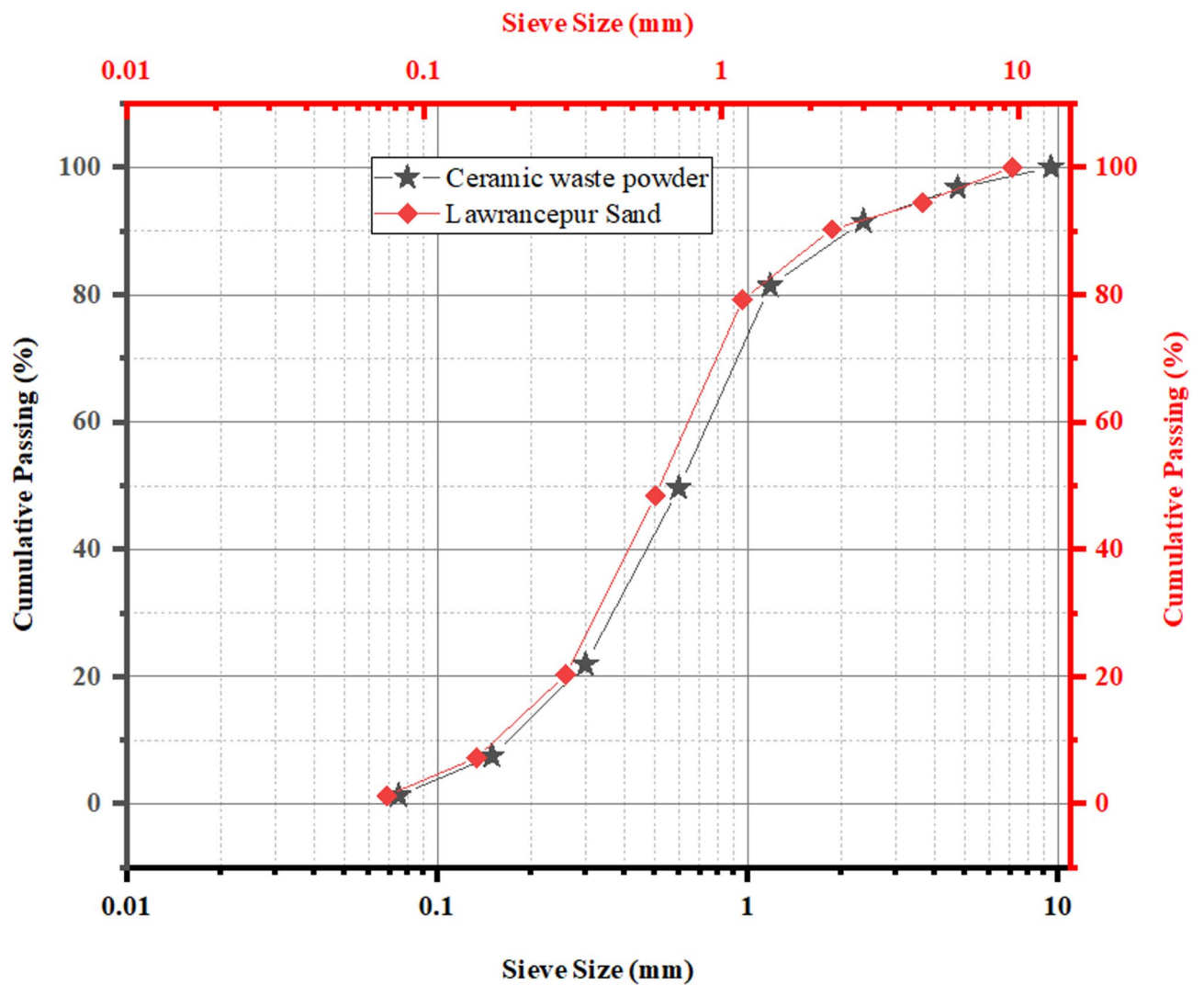
Physical tests on Ordinary Portland cement (Brand Lucky) were conducted in accordance with ASTM/BS EN standards, and the details of the physical tests on cement for construction are given in Table 4. The results of the physical tests on the cements listed in Table 4 indicate that cement (Brand Lucky) is suitable for concrete production.

### Fine aggregate

In accordance with AASHTO T-27, the fineness modulus of Lawrencepur sand and ceramic waste powder was calculated based on sieve analysis. The computed value of the fineness modulus of Lawrencepur sand was 2.513 and 2.599 for ceramic waste powder. The gradation curves for fine aggregates and ceramic waste powder are shown in Fig. 2. The specific densities of sand and ceramic waste powder are about  $2776\ \text{kg/m}^3$  and  $2700\ \text{kg/m}^3$ , respectively. The cumulative passing percentages of Lawrencepur sand and ceramic waste are presented in Table 5, along with the AASHTO specification limits. The results indicate that the cumulative passing percentage of fine aggregates, such as Lawrencepur sand and ceramic waste powder, is within the AASHTO specification limits.

Sr.No.	Description	Observed value
1	Standard consistency (ASTM C187-16)	23.1%
2	Setting time initial (ASTM C191-13)	2 h 15 Min
3	Setting time final (ASTM C191-13)	5 h 20 Min
4	Fineness of cement ASTM C204-18)	8%
5	Expansion (Soundness value) (BS EN196-3)	7 mm
6	Specific density (ASTM C188-17)	3150 kg/m <sup>3</sup>
7	Compressive strength of mortar cubes (1:2.75, w/c=0.485) (ASTM C109-16) compressive strength (3-day) compressive strength (7-day)	1760 Psi 2760 Psi
8	Compressive strength of concrete 4" cubes (1:2:4, w/c=0.55) compressive strength (3-day) compressive strength (7-day)	1735 Psi 2575 Psi

**Table 4.** Physical properties and strength characteristics of Ordinary Portland Cement (Lucky Brand).



**Fig. 2.** Particle size distribution (gradation curves) of Lawrencepur sand and ceramic waste powder compared against AASHTO upper and lower specification limits, demonstrating compliance of both materials with standard fine aggregate requirements.

Sieve Size (mm)	Cumulative passing (%) for Lawrencepur sand	Cumulative passing (%) for ceramic waste powder	AASHTO Specification Limit
9.5	100	100	100
4.75	96.8	95.5	95–100
2.36	91.5	90.3	----
1.18	81.4	79.3	45–85
0.6	49.6	48.5	----
0.3	21.9	20.3	10–30
0.15	7.5	7.3	2–10
0.075	1.3	1.3	0–3
Fineness Modulus	2.513	2.599	

**Table 5.** Sieve analysis results showing cumulative passing percentages of Lawrencepur sand and ceramic waste powder, with corresponding fineness modulus values and comparison to AASHTO specification limits for fine aggregates.

Sieve size (mm)	25	19	12.5	9.5	4.75	2.36
Passing % of 19.0 mm aggregate	100	100	28.4	6.3	0.4	0.0
Passing % of 12.5 mm aggregate	100	100	93.7	39.8	1.8	0.9
Combination of Aggregates according to AASHTO M-43						
40% of 19.0 mm aggregate	40	40	11.4	2.5	0.2	0
60% of 12.5 mm aggregate	60	60	56.2	23.9	1.1	0.54
Blend grading	100	100	67.6	26.4	1.2	0.54
AASHTO M-43 Specifications (%)	100	90–100	-	20–55	0–10	-

**Table 6.** Blended grading of coarse aggregates (40% 19.0 mm aggregate + 60% 12.5 mm aggregate) with cumulative passing percentages at each sieve size, demonstrating compliance with AASHTO M-43 specification limits for combined aggregates.

### Coarse aggregate

Sieve analysis of coarse aggregate is a fundamental test performed in the construction-site material-testing laboratory. Different aggregate sizes are used in the production of concrete. The grain-size distribution of coarse aggregates of various sizes is called gradation. The sieve analysis test is performed on aggregates to determine the particle-size distribution. To produce workable concrete, the correct sieve analysis of coarse aggregates is critical, as is reducing the voids between aggregate particles. In this investigation, two coarse aggregate sizes, 19.0 mm and 12.5 mm, were used in the production of concrete. Based on the passing percentages of the 19.0 mm and 12.5 mm aggregates, the aggregate combination was finalized in accordance with the AASHTO M-43 specification limits. The combination of Aggregates/Blend of Aggregates is given in Table 6. The specific density of coarse aggregate is 2844 kg/m<sup>3</sup>. The graphical representation of the aggregate combination is shown in Fig. 3. The coarse aggregates used have a maximum size of 19 mm and a minimum size of 12.5 mm.

### Mix design and proportions

For one cubic meter of concrete, the mix design proportions were calculated in accordance with ACI 211.1, and a complete detail of the control and blend design is provided in Table 7.

### Curing condition and mixing procedure of concrete

All specimens were cured in a water tank at 23 ± 2 °C and at relative humidity above 95% until testing. Concrete was mixed in a mixer machine. First, the dry components (cement, fine aggregate, and coarse aggregate) were mixed for 2 min. Water was gradually added, and mixing was continued for an additional 3 min until a uniform mix was achieved.

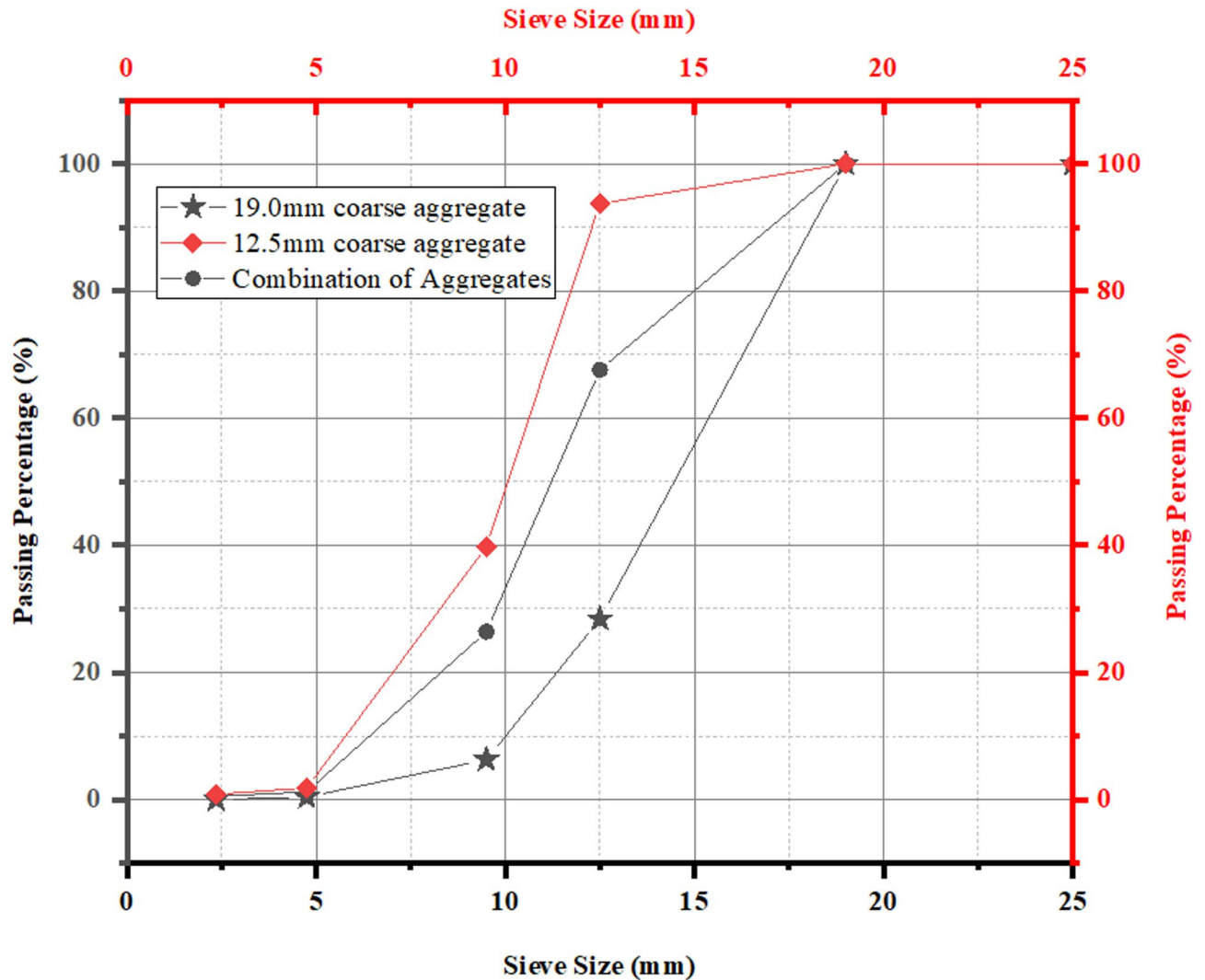
## Results and discussions

### Fresh properties of concrete

#### Slump test

This test is used for measuring concrete workability. It is the initial, rapid test that provides information on the consistency of concrete workability. The testing mould is a frustum of a cone with a top width of 10 cm, a bottom width of 20 cm, and a height of 30 cm. The slump values for control-mix concrete and concrete with ceramic waste powder as an aggregate substitute are shown in Fig. 4.

In addition to using 10% ceramic waste powder collected from Ghani Ceramics as an acceptable aggregate replacement in the control concrete mix, a 40% slump reduction was observed. Similarly, when 20%, 30%, 40%, and 50% ceramic waste powder (Ghani ceramics) were added to the control concrete mix as an acceptable aggregate replacement, slump reductions of 43.3%, 47.8%, 54.4%, and 55.5% were observed, respectively. Slump



**Fig. 3.** Aggregate blending curves for combined coarse aggregates (40% 19.0 mm and 60% 12.5 mm) showing cumulative passing percentages at each sieve size relative to AASHTO M-43 specification limits for optimal gradation.

test results indicate that slump values decrease with the inclusion of ceramic waste powder as an aggregate replacement at varying percentages relative to the control concrete blend. The lower slump values are because of more water absorption, porosity, high surface roughness, and angularity of particles of ceramic waste as compared to Lawrencepur sand, and a similar comment was given by previous researchers, such as a slump value for the control mix was 48 mm, whereas 11 mm for concrete with sanitary ceramic waste as aggregate<sup>40</sup>.

Ceramic aggregates tend to absorb more water than natural aggregates, reducing the amount of free water available for lubrication. While moderate reductions in slump (such as at 30% replacement) may still be manageable with proper vibration, higher replacement levels (40–50%) could require the use of superplasticizers or slight mix adjustments to maintain ease of placement.

### Hard properties of concrete

#### *Density of concrete*

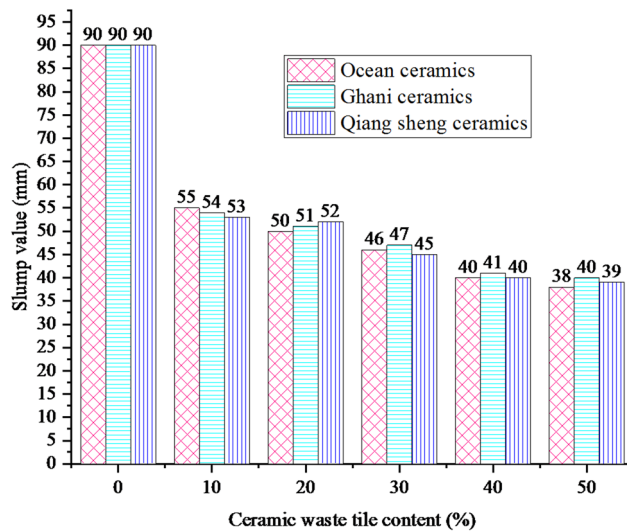
Unit weight of concrete is calculated, and details of the unit weight of all blends are given in Table 8. Based on the results for the concrete blend unit weight, the unit weight increased with the inclusion of ceramic waste powder in the control mix as an acceptable aggregate replacement. The unit weight of concrete was 2310 kg/m<sup>3</sup>, whereas 2474 kg/m<sup>3</sup> for concrete with 50% ceramic waste powder as a substitute for fine aggregate; the difference was approximately 7%. The increase in density may be attributed to improved particle packing and filler effects of the ceramic powder.

#### *Water absorption test*

A water absorption test was performed for various replacement levels of ceramic waste (Ghani ceramics). The results are presented in Fig. 5. The experimental results indicate that water absorption initially increases

Mix	Materials (kg/m <sup>3</sup> )				
	Cement	Water	Gravel	Sand	Ceramic waste
Control	373	205.4	1073	709	0
Waste from Ocean Ceramics					
10%	373	205.4	1073	638	71
20%	373	205.4	1073	567	142
30%	373	205.4	1073	496	213
40%	373	205.4	1073	425	284
50%	373	205.4	1073	354.5	354.5
Waste from Ghani Ceramics					
10%	373	205.4	1073	638	71
20%	373	205.4	1073	567	142
30%	373	205.4	1073	496	213
40%	373	205.4	1073	425	284
50%	373	205.4	1073	354.5	354.5
Waste from Qiang Sheng Ceramics					
10%	373	205.4	1073	638	71
20%	373	205.4	1073	567	142
30%	373	205.4	1073	496	213
40%	373	205.4	1073	425	284
50%	373	205.4	1073	354.5	354.5

**Table 7.** Mix proportions (kg/m<sup>3</sup>) for control concrete and ceramic waste concrete mixtures with replacement levels of 10%, 20%, 30%, 40%, and 50% of fine aggregate by volume, showing material quantities per cubic meter for each industrial waste source.



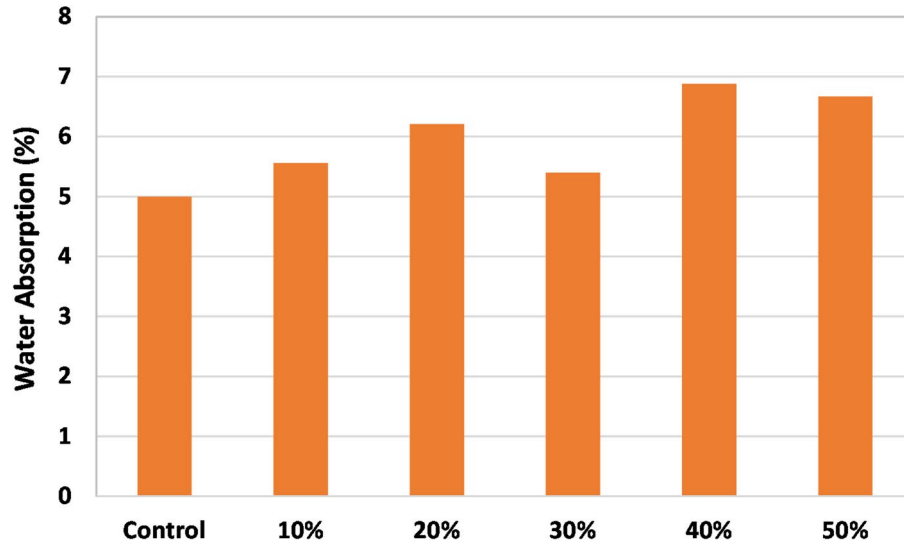
**Fig. 4.** Variation in concrete slump values (workability) with increasing ceramic waste powder replacement levels (0% to 50%) for three industrial sources, showing progressive reduction in workability due to higher water absorption and particle angularity of ceramic waste.

from about 5% (control) to 6.21% at 20% ceramic replacement. However, a noticeable reduction occurs at 30% replacement, where water absorption decreases to 5.4%, before increasing again at 40% and 50% replacement levels. Interestingly, compressive strength was also observed to be maximum at 30% (Fig. 6), suggesting this level as the optimum replacement percentage. At 30% replacement, the ceramic particles are likely to improve gradation and packing density.

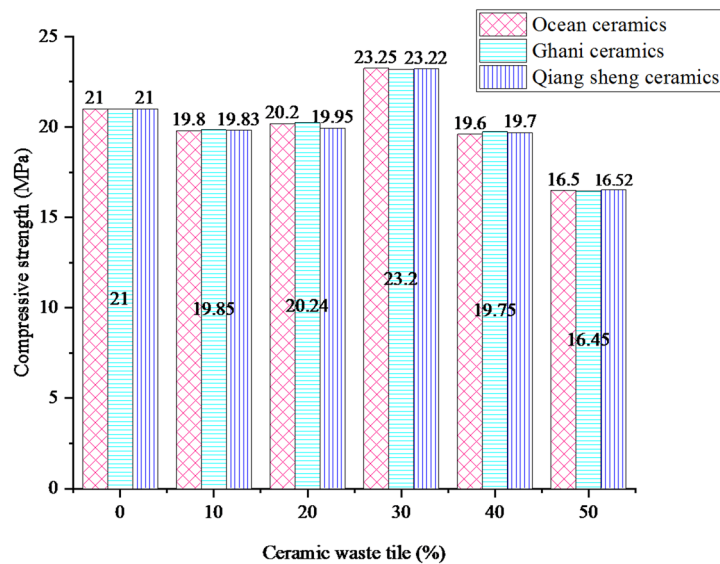
Water absorption showed a non-linear trend, decreasing to 30% replacement after increasing at 20%. This supports the interpretation that an optimal packing threshold exists, where void reduction and improved interfacial bonding enhance performance before porosity becomes dominant.

Replacement level of ceramic waste as fine aggregates	Ocean Ceramic	Ghani Ceramic	Qiang Sheng Ceramic
	Concrete Density in (kg/m <sup>3</sup> )		
Control mix	2310	2308	2311
10% substitution of ceramic waste	2316	2313	2317
20% substitution of ceramic waste	2322	2324	2320
30% substitution of ceramic waste	2389	2391	2390
40% substitution of ceramic waste	2425	2422	2426
50% substitution of ceramic waste	2474	2475	2426

**Table 8.** Hardened density of concrete (kg/m<sup>3</sup>) at 28 days for all replacement levels and ceramic waste sources, indicating a progressive increase in unit weight with higher ceramic content due to improved particle packing.



**Fig. 5.** Water absorption characteristics of concrete at various ceramic waste replacement levels (0% to 50%) from Ghani Ceramics, showing non-linear behavior with minimum absorption at 30% replacement corresponding to optimal particle packing density.



**Fig. 6.** Compressive strength development of concrete at 28 days for all replacement levels (0% to 50%) and ceramic waste sources, demonstrating maximum strength enhancement (10.7% increase) at 30% replacement, followed by a decline at higher substitution levels.

## Mechanical test

Each reported result represents the average value obtained from three specimens tested under identical conditions. The experimental scatter was relatively small, with the maximum deviation among replicate specimens remaining below approximately 5%, indicating good repeatability and reliability of the test results.

### Compression strength test

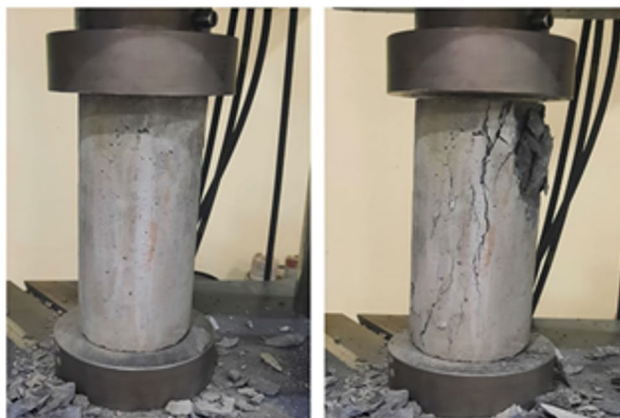
For testing the compressive strength of concrete in accordance with ASTM C39, a hydraulic universal testing machine (IBMU4 Series) was used. The cylindrical concrete specimens, 300 mm in height and 150 mm in diameter, were tested to determine their compressive strength. A total of nine (09) concrete cylindrical samples were prepared for the control mix design; three (03) cylinders were tested for compressive strength at seven (07) days, and three (03) cylinders were tested at fourteen (14) days. The remaining three (03) cylinders were checked for compression at twenty-eight (28) days. The number of concrete cylindrical samples prepared from the waste of ceramics industrial units, such as Ocean Ceramics Pvt. Ltd, Ghani Ceramics Pvt. Ltd and Qiang Sheng Ceramics Pvt. Ltd were nine (09) for each industrial unit and for each replacement level.

For all replacement levels of aggregate by ceramic tile waste as fine aggregate from 10% to 50%, number of concrete cylindrical samples were one hundred and thirty-five (135) from which forty-five (45) cylinders were tested for compression at the age of seven (07) days, forty-five (45) cylinders were tested for compression at the age of fourteen (14) days and remaining forty-five (45) cylinders were checked for compression at twenty-eight (28) days. The average compressive strength of the control mix at twenty-eight (28) days was 21.0 MPa. In addition to 10%, 20%, 30%, 40%, and 50% ceramic waste (Ghani ceramics) powder in the control mix as an acceptable aggregate substitution, the average compressive strength at twenty-eight (28) days was 19.85 MPa, 20.24 MPa, 23.2 MPa, 19.75 MPa, and 16.45 MPa, respectively was represented in the shape of graph as shown in Fig. 6.

The consequences of concrete's compressive strength are evident that 5.5% reduction was observed in compressive strength of concrete in comparison to control blend by inclusion of 10% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate, 3.6% reduction was observed in compressive strength in comparison to control blend by inclusion of 20% ceramic tile waste as substitution of fine aggregate, 10.5% increase was observed in compressive strength of concrete in comparison to control blend by inclusion of 30% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate, 5.9% reduction was observed in compressive strength of concrete in comparison to control blend by inclusion of 40% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate and 21.7% reduction was observed in compressive strength of concrete in comparison to control blend by inclusion of 50% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate. Previous researchers observed similar trends: 20% replacement of fine aggregate with sanitary ceramic filler in concrete increases mechanical characteristics, and 50% replacement of sand with fine ceramic aggregate slightly increases compressive strength<sup>41,42</sup>. Based on a detailed review of the results, the optimal utilization rate of ceramic tile waste as a substitute for fine aggregate in concrete production was 30%. The test images are shown in Fig. 7.

The initial reduction at 10–20% replacement may be attributed to the higher porosity and water absorption of ceramic aggregates. These characteristics can weaken the interfacial transition zone between cement paste and aggregate, thereby slightly reducing load-transfer efficiency. The increase in strength at 30% suggests an optimum replacement level. At this percentage, improved particle packing and better gradation may have reduced internal voids. The rough surface texture of ceramic particles likely enhanced mechanical interlocking with the cement matrix, strengthening the bond. Further excess ceramic content can increase the void ratio, reduce effective cement paste bonding, and weaken matrix continuity, leading to a significant loss of strength.

The improvement in compressive strength at the 30% replacement level may also be attributed to improved particle packing and microstructural densification of the cement matrix. The finer ceramic powder particles



**Fig. 7.** Typical failure modes of cylindrical concrete specimens (150 mm diameter × 300 mm height) after compressive strength testing, showing characteristic cone and shear failure patterns across different replacement levels.

likely act as micro-fillers, reducing internal voids and enhancing the bond between aggregates and cement paste within the interfacial transition zone.

#### Splitting tensile strength test

The concrete cylindrical specimens, 300 mm in height and 150 mm in diameter, were tested to determine tensile strength in accordance with ASTM C496. A total of nine (09) concrete cylindrical samples were prepared for the control blend design, of which three (03) were tested for tension at seven (07) days and three (03) at fourteen (14) days. The remaining three (03) cylinders were checked at twenty-eight (28) days. The number of concrete cylindrical samples prepared from the waste of ceramics industrial units, such as Ocean Ceramics Pvt. Ltd, Ghani Ceramics Pvt. Ltd and Qiang Sheng Ceramics Pvt. Ltd were nine (09) for each industrial unit and for each replacement level. For all replacement levels of fine aggregate by ceramic tile waste as fine aggregate from 10% to 50%, number of concrete cylindrical samples were one hundred and thirty-five (135) from which forty-five (45) cylinders were tested for tension at the age of seven (07) days, forty-five (45) cylinders were checked for tension at fourteen (14) days and remaining forty-five (45) cylinders were checked for tension at twenty-eight (28) days.

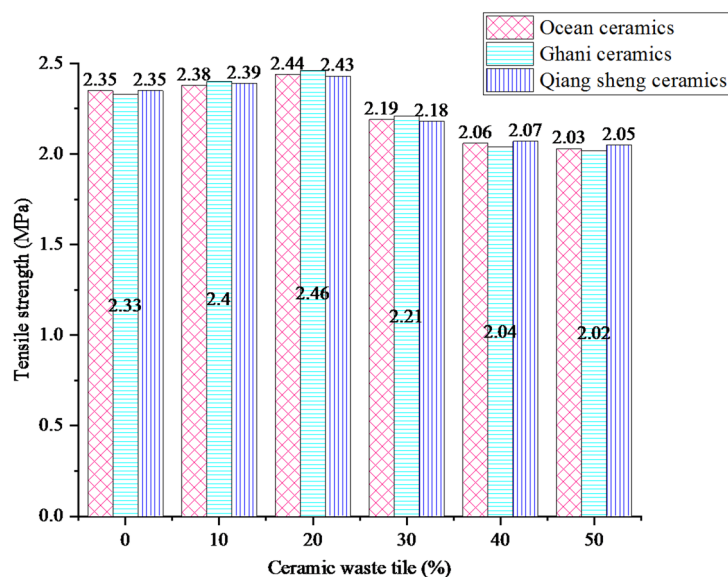
The tensile strength of the control blend at the age of twenty-eight (28) days was 2.35 MPa. In addition of 10%, 20%, 30%, 40% and 50% ceramic waste powder (Ghani ceramics) in the control blend as an acceptable aggregate substitution, the average tensile strength of concrete at twenty-eight (28) days was 2.40 MPa, 2.46 MPa, 2.21 MPa, 2.04 MPa, and 2.02 MPa, as shown in Fig. 8. The consequences of concrete's tension strength are evident that 2.13% increase was noticed in tension strength of concrete in comparison to control blend by inclusion of 10% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate, 4.68% increase was noticed in tension strength in comparison to control blend by inclusion of 20% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate, 5.95% reduction was noticed in tension strength in comparison to control blend by inclusion of 30% ceramic tile waste (Ghani ceramics) over as substitution of fine aggregate, 13.19% reduction was noticed in tension strength in comparison to control blend by inclusion of 40% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate and 14.04% reduction was noticed tension strength in comparison to control blend by inclusion of 50% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate.

Based on a detailed review of the results, the optimal utilization rate of ceramic tile waste as a substitute for fine aggregate in concrete production was 20%. Previous researchers studied 0, 25, 50, 75, and 100% replacement of natural aggregate with ceramic waste and observed an increase in the splitting tensile strength of recycled ceramic concrete as the substitution level increased<sup>43</sup>. The test images are shown in Fig. 9.

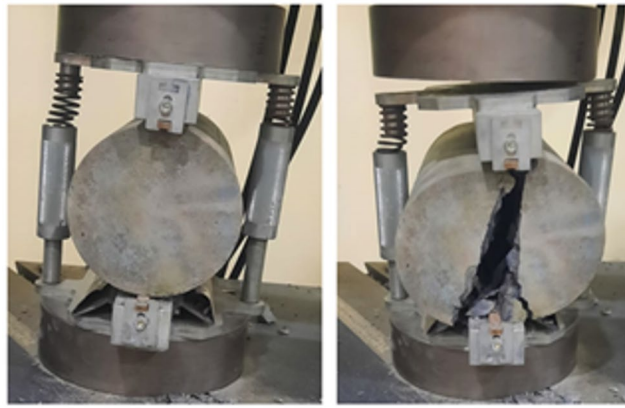
The slight improvement at 10–20% replacement can be attributed to better mechanical interlocking between the rough ceramic particles and the cement paste. The angular shape of ceramic aggregates enhances bond characteristics in the interfacial transition zone, which plays a more critical role in tensile behavior than in compression. Improved bonding at moderate replacement levels helps resist crack initiation and propagation, resulting in marginally higher tensile strength. However, beyond 20% replacement, the tensile strength decreases. Tensile performance is highly sensitive to microcracks and internal voids. As ceramic content increases, the higher porosity and brittleness of ceramic aggregates contribute to stress concentration points within the matrix.

#### Flexural strength test

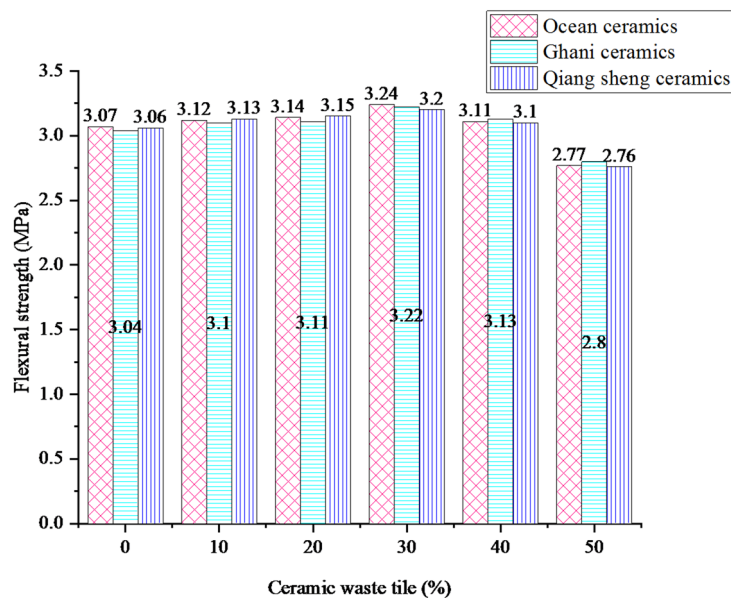
Concrete beam specimens measuring 100 mm in width, 100 mm in height, and 400 mm in length were tested to determine flexural strength in accordance with ASTM C78. The number of concrete beam samples prepared for



**Fig. 8.** Splitting tensile strength of concrete at 28 days for all replacement levels and ceramic waste sources, showing maximum improvement (4% increase) at 20% replacement with subsequent decline at higher substitution levels.



**Fig. 9.** Failure patterns of cylindrical concrete specimens after splitting tensile strength testing, illustrating typical tensile fracture surfaces and crack propagation path.



**Fig. 10.** Flexural strength of concrete beam specimens (100 mm × 100 mm × 400 mm) at 28 days for all replacement levels and ceramic waste sources, showing maximum enhancement (5.92% increase) at 30% replacement.

control mix design were nine (09) from which three (03) beams were checked for flexural strength at seven (07) days, three (03) beams were checked for flexural strength at fourteen (14) days and remaining three (03) beams were checked for flexural strength at twenty-eight (28) days.

The number of concrete beam samples prepared from the waste of ceramics industrial units, such as Ocean Ceramics Pvt. Ltd; Ghani Ceramics Pvt. Ltd and Qiang Sheng Ceramics Pvt. Ltd were nine (09) for each industrial unit and for each replacement level. For all replacement levels of fine aggregate with ceramic tile waste as fine aggregate from 10% to 50%, the number of concrete beams samples were one hundred and thirty-five (135) from which forty-five (45) beams were checked for flexural strength at seven (07) days, forty-five (45) beams were checked for flexural strength at the age of fourteen (14) days. The remaining forty-five (45) beams were checked for flexural strength at twenty-eight (28) days. The average flexural strength of the control mix at the age of twenty-eight (28) days was 3.04 MPa. At addition of 10%, 20%, 30%, 40% and 50% ceramic waste powder in control blend as an acceptable aggregate substitution, the average flexural strength of concrete at twenty-eight (28) days was 3.1 MPa, 3.12 MPa, 3.22 MPa, 3.13 MPa and 2.8 MPa, respectively as represented in the shape of a graph as shown in Fig. 10.

The consequences of concrete's flexural strength are evident that 1.97% increase was observed in flexural strength in comparison control blend by inclusion of 10% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate, 2.63% increase was noticed in flexural strength in comparison to control blend by inclusion of 20% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate, 5.92% increase was noticed in flexural

strength in comparison to control blend by inclusion of 30% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate, 2.96% reduction was noticed in flexural strength in comparison to control blend by inclusion of 40% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate and 7.89% reduction was noticed in flexural strength as in contrast to control blend by inclusion of 50% ceramic tile waste (Ghani ceramics) as substitution of fine aggregate. Based on a detailed review of the results, the optimal utilization rate of ceramic tile waste as a substitute for fine aggregate in concrete production was 30%. The test images are shown in Fig. 11.

### X-ray diffraction (XRD) analysis

The X-ray diffraction (XRD) patterns of concrete with different replacement levels of ceramic powder (10%, 20%, 30%, and 50%) are shown in Fig. 12 and were analyzed and compared with those of the control sample to investigate phase evolution and microstructural changes. The diffraction patterns primarily show the presence of crystalline phases associated with cement hydration products and ceramic powder minerals. Across all samples, the major identifiable phases include quartz ( $\text{SiO}_2$ ), portlandite ( $\text{Ca}(\text{OH})_2$ ), calcite ( $\text{CaCO}_3$ ), and residual clinker minerals such as belite ( $\text{C}_2\text{S}$ ), along with minor contributions from ceramic-derived phases such as mullite ( $\text{Al}_6\text{Si}_2\text{O}_{13}$ ). A broad hump observed at approximately  $20^\circ\text{--}35^\circ$  ( $2\theta$ ) in all patterns corresponds to amorphous calcium silicate hydrate (C–S–H) gel, the principal hydration product responsible for strength development in cementitious systems. The ceramic powders used in this study originate from fired ceramic tiles produced through similar manufacturing processes and raw material compositions. Therefore, a representative blended sample was used for XRD analysis to identify the dominant crystalline phases present in the ceramic waste used in the study. The XRD analysis therefore represents the overall mineralogical characteristics of the ceramic waste incorporated in the concrete mixtures.

For the 10% ceramic powder replacement, the diffraction pattern shows strong peaks corresponding to quartz and portlandite, indicating the typical hydration behavior of cement with a moderate contribution from ceramic minerals. The presence of pronounced portlandite peaks suggests that the pozzolanic reaction between the ceramic powder and calcium hydroxide remains limited at this replacement level. When the ceramic content increases to 20%, a slight reduction in the intensity of the portlandite peaks is observed, along with relatively stronger quartz-related peaks originating from the ceramic powder. This indicates that part of the calcium hydroxide produced during hydration is consumed through a pozzolanic reaction with the silica and alumina present in the ceramic powder, leading to additional formation of C–S–H gel.

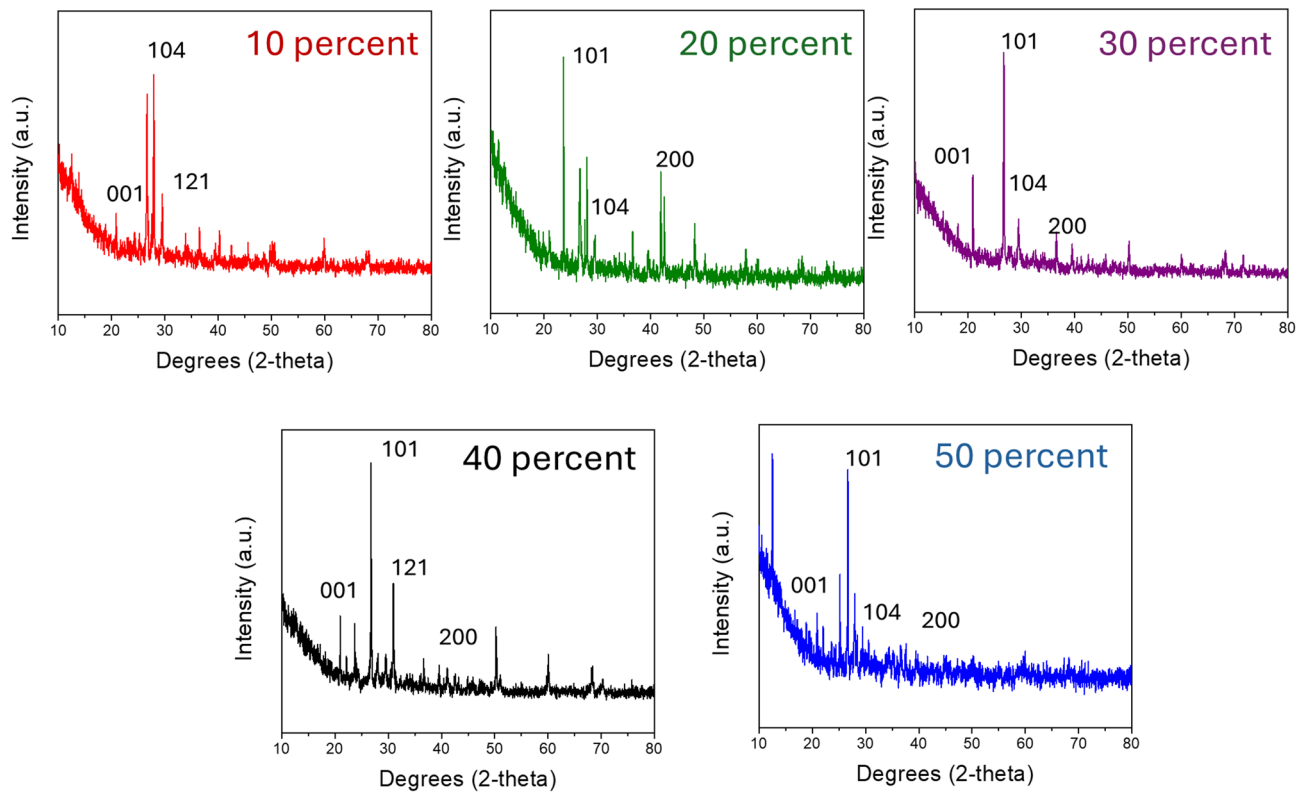
The 30% ceramic powder replacement sample exhibits the most balanced phase composition among all mixes. The diffraction pattern shows comparatively reduced portlandite peak intensity and a more pronounced amorphous hump associated with C–S–H gel formation. This suggests a higher degree of pozzolanic reaction, where the silica-rich ceramic powder reacts with calcium hydroxide to generate additional secondary C–S–H. The enhanced formation of C–S–H gel contributes to a denser microstructure, which correlates well with the experimentally observed optimum mechanical strength and reduced water absorption for this mixture. The presence of stable crystalline phases such as quartz and mullite further contributes to the filler effect and microstructural refinement. For the 50% ceramic powder replacement, the diffraction pattern shows stronger peaks corresponding to quartz and ceramic-derived minerals, while the relative intensities of cement hydration phases decrease.

The reduced amount of cement available for hydration limits the production of calcium silicate hydrate gel. Although ceramic powder introduces crystalline phases, excessive replacement of cement reduces the formation of hydration products, resulting in a less cohesive microstructure than in the 30% mixture. This behavior is consistent with the comparatively lower mechanical performance observed in the experimental tests.

Overall, the comparative XRD analysis confirms that moderate replacement levels of ceramic powder promote beneficial pozzolanic reactions and microstructural densification. Among the investigated compositions, the 30% replacement level shows the most favorable balance between cement hydration products and ceramic mineral phases, leading to enhanced formation of C–S–H gel and improved microstructural compactness. This



**Fig. 11.** Photographs of flexural strength test setup and failure patterns of beam specimens, showing crack propagation and fracture surfaces for control and ceramic waste concrete mixtures.



**Fig. 12.** X-ray diffraction (XRD) patterns of concrete incorporating different ceramic powder replacement levels (10%, 20%, 30%, and 50%). The diffraction patterns reveal the presence of typical cement hydration products and ceramic phases, including quartz, portlandite, calcite, and mullite. Variation in peak intensities indicates the influence of ceramic powder content on the formation of hydration products and the overall microstructural evolution of the cementitious matrix.

finding is in strong agreement with the mechanical strength and water absorption results, confirming that 30% replacement of ceramic powder provides optimal performance for the concrete system studied.

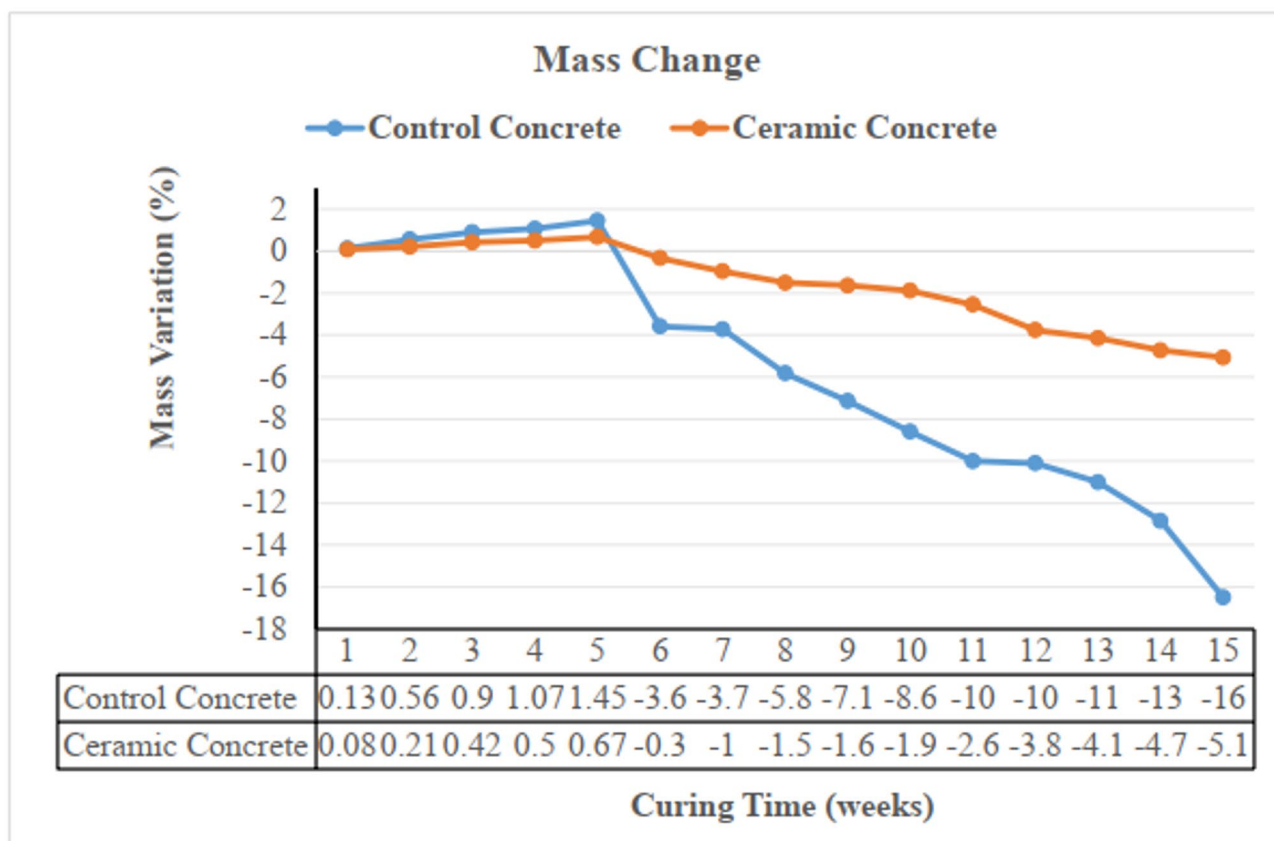
#### ACID immersion test

A sulfuric acid immersion test was conducted for the optimum replacement level. During this study, both conventional and ceramic-based concrete samples showed a slight increase in mass over the first 5 weeks of exposure to a 5% sulfuric acid solution<sup>44</sup>Fig. 13,. This increase is mainly attributed to the formation of ettringite within the cementitious matrix. However, as the exposure period continued, a gradual decrease in mass was recorded. The reduction occurred because crack formation and surface spalling led to material detachment from the specimen surface. The detrimental effects of sulfate ingress through vulnerable surface regions have been widely reported in prior research. Sulfate ions react chemically with hydration products of cement to generate expansive compounds such as ettringite and gypsum. The formation of these products induces internal stresses that promote cracking, weaken matrix bonds, reduce stiffness and strength, and accelerate the overall degradation of concrete.

In contrast, the concrete containing ceramic powder exhibited comparatively improved resistance against acidic exposure. The enhanced performance can be attributed to the higher water absorption capacity of the ceramic powder, which lowers the mixture's effective water–cement ratio. In addition, the presence of ceramic particles contributes to a denser microstructure, which limits the penetration of aggressive ions. As a result, the beneficial effect of ceramic powder on compactness and microstructural stability counteracts the deterioration mechanisms observed in the control concrete<sup>44</sup>. Quantitatively, the mass change in the control concrete increased by approximately 1.450% after five weeks of immersion in the 5% sulfuric acid solution, while the ceramic concrete exhibited a smaller increase of 0.669% under identical conditions. After 15 weeks of exposure, the control concrete showed a significant mass reduction of about 16.49%, whereas the ceramic concrete experienced a comparatively smaller loss of about 5.062%<sup>44</sup>.

#### Cost comparison

In this part of the study, the quantities of constituent materials were estimated for 3 m<sup>3</sup> of concrete, and a cost comparison was carried out between the control mix and the ceramic-modified concrete using prevailing local market prices of materials, as presented in the Table 9. The cost of ceramic waste dust was considered negligible because it was obtained directly from industrial leftovers available within the manufacturing premises. The



**Fig. 13.** Mass change in control concrete and concrete with 30% ceramic waste powder upon immersion in a 5% sulfuric acid solution over 15 weeks, demonstrating improved acid resistance of the ceramic-modified concrete<sup>44</sup>.

Sr. No.	Description	Quantity of material	Rate (PKR)	Amount (PKR)
Control Concrete (0% ceramic waste and 100% fine aggregate)				
1	Cement	22.49 bags	Rs. 1,490/bag	Rs.33,510/-
2	Sand	1.52 m <sup>3</sup>	Rs. 1.70/m <sup>3</sup>	Rs.3,218/-
3	Coarse aggregate	2.30 m <sup>3</sup>	Rs. 3.40/m <sup>3</sup>	Rs.9,755/-
Total cost of control concrete				Rs.46,483/-
Ceramic Concrete (30% ceramic waste and 70% fine aggregate)				
4	Cement	22.49 bags	Rs. 1,490/bag	Rs.33,510/-
5	Sand	1.06 ft <sup>3</sup>	Rs. 1.70/m <sup>3</sup>	Rs.2,126/-
6	Ceramic waste powder	0.46 ft <sup>3</sup>	Rs. 0	Rs.0/-
7	Coarse aggregate	2.30 m <sup>3</sup>	Rs. 3.40/m <sup>3</sup>	Rs.9,755/-
Total cost of ceramic concrete				Rs.45,391/-

**Table 9.** Comparative cost analysis (in Pakistani Rupees, PKR) between standard concrete and ceramic waste-incorporated at 30% replacement, demonstrating cost reduction (conversion rate: 1 USD = 279.81 PKR as of March 13, 2026; 1 cement bag = 50 kg).

results summarized in the table indicate that using ceramic waste in concrete production reduced overall costs, making ceramic concrete approximately 2.3% more economical than the conventional control mix at the same volume of 3 m<sup>3</sup>.

### Conclusions & future recommendations

This study systematically evaluated the feasibility of partially replacing fine aggregate with ceramic waste powder at substitution levels of 0%, 10%, 20%, 30%, 40%, and 50%. The following conclusions are drawn from the experimental investigation:

## Mechanical performance

**Compressive Strength:** Incorporating ceramic waste powder exhibited a nonlinear effect on compressive strength. At 30% replacement, compressive strength increased by approximately 10.7% compared to the control mix, establishing this as the optimum level. This improvement is attributed to enhanced particle packing, improved interfacial bonding between ceramic particles and cement paste, and beneficial filler effects, collectively resulting in a denser microstructure. Beyond 30% replacement, however, compressive strength declined due to increased porosity and disrupted matrix continuity from excessive ceramic content.

**Tensile Strength:** A modest improvement of approximately 4% in splitting tensile strength was observed at 20% replacement. This enhancement stems from improved mechanical interlocking between the rough, angular ceramic particles and the cement matrix. The decline in tensile strength at higher replacement levels reflects the sensitivity of tensile behavior to internal voids and microcracks, which become more prevalent as the ceramic content exceeds the optimal threshold.

**Flexural Strength:** Flexural performance followed a trend similar to that of compressive strength, with a 5% increase at 30% replacement. This consistency in flexural and compressive behavior supports identifying 30% as the optimal replacement level for structural applications, particularly for members primarily subjected to compressive and flexural stresses.

**Workability:** A progressive reduction in workability accompanied increasing ceramic content, with slump values decreasing by up to 55.5% at 50% replacement. This decline is attributed to the higher water-absorption capacity, angular particle morphology, and greater roughness of ceramic waste compared with natural sand. From a practical construction perspective, moderate reductions in slump can still be managed through adequate vibration during placement. However, mixes with higher ceramic replacement levels may require superplasticizers or slight adjustments in water content to maintain adequate pumpability and ease of placement.

The combined mechanical, durability-related, and microstructural analyses demonstrate that ceramic waste powder can be effectively utilized as a sustainable partial replacement for fine aggregates, with optimal performance observed at approximately 30% replacement.

## Sustainability implications

The partial substitution of natural sand with ceramic waste powder offers demonstrable environmental benefits. Utilizing approximately 1.06 million tons of ceramic waste generated annually in Faisalabad's industrial sector reduces landfill disposal requirements, conserves diminishing natural aggregate resources, and supports circular economy principles in construction. The findings confirm that up to 30% replacement can be adopted without compromising—and indeed enhancing—structural performance, achieving an optimal balance between environmental responsibility and engineering efficiency.

The reuse of ceramic manufacturing waste not only reduces the demand for natural sand but also helps mitigate landfill disposal issues associated with ceramic industry by-products, thereby contributing to more sustainable construction practices.

## Study limitations

This investigation focused exclusively on short-term mechanical properties and fresh concrete characteristics. Long-term durability parameters—including chloride penetration resistance, carbonation depth, sulfate attack resistance, freeze-thaw performance, drying shrinkage, and creep behavior—remain unexamined and warrant further investigation.

## Recommendations for future research

Based on the findings and limitations of this study, the following research directions are proposed:

- i. **Long-Term Durability Assessment:** Comprehensive evaluation of durability characteristics, including permeability, chloride ingress, carbonation resistance, sulfate attack, and freeze-thaw cycling, to establish the long-term service life of ceramic waste concrete.
- ii. **Mix Optimization Studies:** Investigation of different water-cement ratios and the incorporation of chemical admixtures (superplasticizers, air-entraining agents) to enhance workability and mechanical performance at higher replacement levels.
- iii. **Microstructural Characterization:** Advanced microstructural analysis using energy-dispersive X-ray spectroscopy (EDS), and mercury intrusion porosimetry (MIP) to quantify the relationship between ceramic content, pore structure evolution, and mechanical behavior.
- iv. **Life-Cycle Assessment:** Comprehensive environmental impact quantification through life-cycle assessment (LCA) methodology to holistically evaluate the carbon footprint, energy consumption, and ecological benefits of ceramic waste utilization in concrete production.
- v. **Field-Scale Applications:** Pilot-scale demonstrations and field trials of concrete ceramic waste in non-structural and structural elements to validate laboratory findings under actual service conditions.
- vi. **Acid Resistance Characterization:** Further investigation of the observed enhanced acid resistance to understand the underlying mechanisms and quantify performance in aggressive chemical environments.

The proper reuse of ceramic waste from industrial units presents a viable pathway toward environmental protection and sustainable infrastructure development, meriting continued research and industrial adoption.

## Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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## Author contributions

Khawaja Adeel Tariq: Conceptualization, methodology, investigation, data curation, writing – original draft preparation. Wajid Ali Adil: Experimental work, material collection, data analysis, validation. Amina Salhi: Literature review, manuscript editing, and visualization. Aashir Waleed: Supervision, methodology development, critical review, and manuscript editing. All authors have read and approved the final manuscript.

## Declarations

### Competing interests

The authors declare no competing interests.

### Additional information

**Correspondence** and requests for materials should be addressed to K.A.T. or A.W.

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