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CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2022; 32 (3): 0085-0115
DOI: 10.2478/ceer-2022-0030

*Original Research Article*

# THE USE OF WASTE CERAMIC OPTIMAL CONCRETE FOR A CLEANER AND SUSTAINABLE ENVIRONMENT - A CASE STUDY OF MECHANICAL PROPERTIES-

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Abstract

The present study aims to find out the optimal use of ceramic powder and ceramic aggregate (both fine and coarse) as a possible substitute for Ordinary Portland Cement (OPC 43 grade) and natural aggregate (fine and coarse), respectively, in concrete, where focused on investigating the mechanical properties of waste ceramic concrete. The performance of this modified concrete was evaluated in terms of Compressive Strength (CS), Tensile Strength (TS), Flexural Strength (FS), and Combined Flexural and Torsional strength (FTS) obtained based on various experimental tests conducted on a total of 192 samples (48 cubes, 48 cylinders, 96 beams). The test results showed that ceramic waste material as a partial replacement for natural aggregate, cement, and fine aggregate provides better performance in terms of CS, TS, and FTS at optimal percentages- 20% ceramic aggregate, 10% ceramic powder, and 10% ceramic fine aggregate (Fineness Modulus 2.2) respectively in M25 grade concrete. Using ceramic waste as a partial replacement to prepare concrete has a lot of benefits from the economic, environmental, and technological point of view. Moreover, it offers a possibility for improving concrete's durability, which is vital.

Keywords: ceramic waste, concrete, mechanical performance, ceramic floor tiles, strength

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# 1. INTRODUCTION

Concrete is one of the most commonly consumed construction materials across the world. A large amount of non-renewable natural resources is exploited to produce materials like sand and aggregates. Also, cement production requires a high energy input (850 kcal per kg of Clinker). On the other hand, 1 ton of cement production generates 0.55E tons of chemical CO2 and 0.39E Tons of CO2 in fuel emissions, representing a total of 0.94E Tons of CO2 [1]. Continued population growth and construction progress will require more production of concrete (sand + aggregate + cement). As a result, rising sand, aggregate and cement demand raises concerns about the diminution of natural resources, energy sources and environmental imbalance. Concrete produced using ceramic waste as a replacement of natural aggregates, sand and cement can save enormous energy with considerable environmental benefits. Replacing natural sand with ceramic sand is an excellent alternative due to its high strength and durability. The strength obtained when replacing fine natural aggregates by fine ceramic aggregates are very promising. Also, such concrete can solve several ecological problems [2]. Moreover, a cost reduction of about 45% compared to traditional concrete can be achieved Heidari, A. et al. [1].

Mechanical properties of concrete are one of the essential concerns in designing, constructing, or maintaining structures. Therefore, this paper presents an experimental study to examine the mechanical properties of waste ceramic concrete. Ceramic waste is one of those industrially applicable wastes that can be used as a material replacement in concrete. Various types of ceramics such as roof, floor, and sanitary ceramics are currently used in construction, but some are brittle or breakable during production, shipping, or storage [3]. Based on various literature addition of these broken or leftover ceramic wastes in concrete generally improves the mechanical properties such as strength, durability, modulus of elasticity, etc. [4-9]. In past decades, both academia and industry have increasingly recognized and understood the value of sustainability and recycling. Recycled construction is one method that reduces dependence on the supply of natural resources to the construction industry.

Keshavarz Z, Mostofinejad D. [11] investigated the methods of production of concrete using ceramic waste tiles. Models were cast using porcelain waste tiles (25%, 50% and 100%) as mixtures used as substitutes for coarse aggregates in concrete. Mechanical properties such as compressive strength, tensile strength, flexural strength, and water absorption were determined. Porcelain waste tiles showed a 40% increase in mechanical properties- compressive strength, tensile strength, and flexural strength.

Awoyera PO et al. [11] focused on the mechanical behavior of concrete made using ceramic waste floor and wall tiles as a replacement. The samples were tested under compression and tension at 3days, 7days and 28days strength of curing. It was found that the compressive and tensile strength of ceramic concrete significantly increased compared to the reference concrete with the increase in curing age. Rashid, K. et al. [12] carried out experimental work to produce sustainable concrete using ceramic waste as coarse aggregate. To achieve the desired target different quantities of ceramic waste aggregates were replaced by normal aggregate. Sustainable concrete was chosen based on the best value for compression strength and its ecological impact. The experimental results concluded that concrete with 30% replacement of waste ceramic aggregates gives excellent compressive strength with less environmental effect. Torkittikul, P et al. [13] studied the feasibility of using ceramic waste tiles as a fine aggregate (sand) replacement for manufacturing mortar and concrete. Ceramic waste tiles were crushed and sieved to produce fine aggregate. The results showed that the temperatures used to produce these tiles (approximately 900°C) are sufficient to activate the Pozzolanic properties of clay. It also concluded that the concrete mixture performs better after optimization (10-15% replacement) with no morphological difference between cement mixed with ceramic waste powder and blended with other Pozzolanic materials. Heidari, A. et al. [1] also concentrated on the application of ceramic waste tiles as Pozzolanic material in concrete. The Concrete specimens were casted with ceramic floor tiles as a replacement of cement with percentages- 10%, 20%, 30% and 40%. Testing of compressive strength and water absorption were performed. The results showed that adding 20% of the ceramic floor tiles has no noticeable negative effect on concrete compressive strength.

The present study aims at investigating the mechanical properties of Waste Ceramic Concrete (WCC) developed by partial replacement of cement and aggregates (both fine and coarse) with ceramic waste powder and ceramic aggregates (fine and coarse) respectively based on the optimal percentages. Firstly, the natural coarse aggregates were replaced by 10%, 20%, 30%, 50% and 100% of the ceramic waste aggregates (size 0.02m and 0.01 m). Secondly, the fine natural aggregate was replaced by 5%, 10%, 15%, 20% and 30% of ceramic waste sand (0.00475m) keeping the optimal percentage of ceramic aggregate constant. Lastly, cement was replaced by 5%, 10%, 15%, 20%, and 30% of ceramic powder (75μm), keeping the optimal percentages of ceramic aggregates and ceramic sand constant. These samples were tested to determine the compressive, tensile, flexural, and combined (flexural and torsional).

The main contribution of this study can summarize as follows: (a) Investigate the fundamental properties of ceramic waste (powder, fine and coarse aggregates) obtained from the ceramic industry for its use as a possible alternative to a partially replaced concrete mixture with cement and normal aggregates (b) Examine the effect of incorporating ceramic waste as partial coarse aggregate replacement, partial fine aggregate replacement, and partial cement replacement on compressive, tensile, flexural and combined (flexural and torsional) strengths.

## 2. METHODS

### 3.1. Description of materials used

Locally available materials such as Ordinary Portland Cement (OPC) 43-grade, Natural Coarse Aggregate (NCA)/stones, coarse river sand, and ceramic floor tiles were used in the experimental work (in place of cement, sand, and coarse aggregate), as shown in Fig. 1. Aligarh's Ceramic Stores provided the waste ceramic floor tiles that were used in this project. Ceramic tiles were cleaned and dusted off before being hammered into various sizes: 20 mm and 10mm (waste ceramic aggregate- AWC); 4.75mm (waste ceramic sand- SWC) and; 75μm (waste ceramic cement- CWC) as shown in Fig. 2. The physical properties of ceramic waste floor tiles (AWC, SWC and CWC), OPC, river sand and natural aggregate are shown in Table 1, Table 2, Fig. 3 and Fig. 4.

(**a**) (**b**) (**c**) (**d**)

Fig. 1. (a) Commercial cement (b) river sand (c) Natural Coarse Aggregates (NCA)-10mm (d) Natural Coarse Aggregates (NCA)-20mm

**(a)** **(b)** **(c)** **(d)**

Fig. 2. (a) waste ceramic cement ($C_{WC}$)-75µm (b) waste ceramic sand ($S_{WC}$)-4.75mm (c) waste ceramic aggregate ($A_{WC}$)10mm (d) waste ceramic aggregate ($A_{WC}$)-20mm

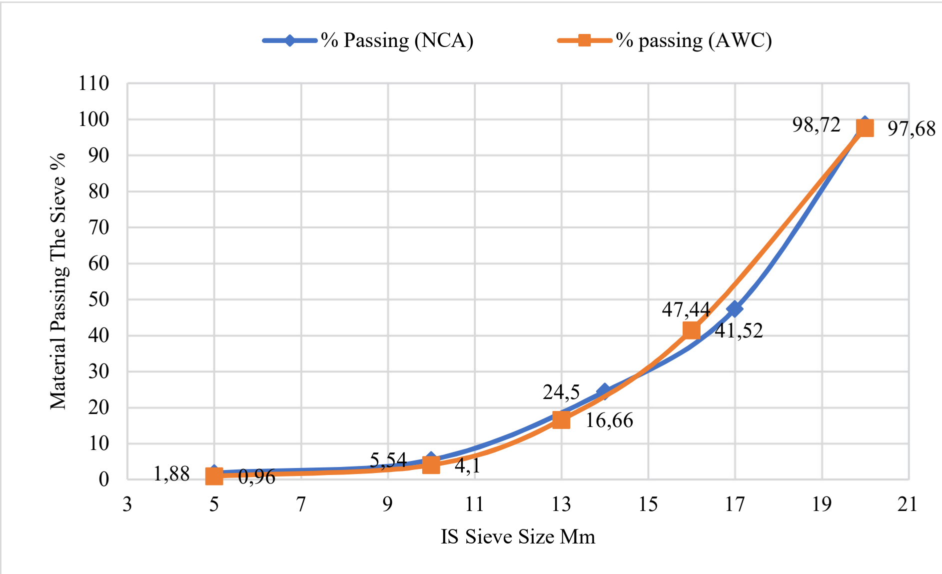


Fig. 3. Particle Size Distribution of Natural Coarse Aggregate & Ceramic Coarse Aggregate

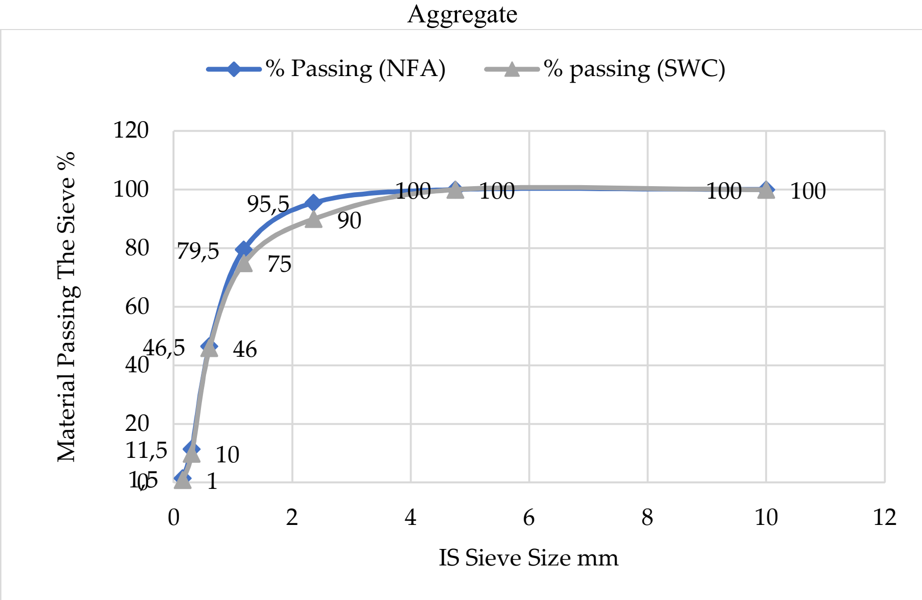


Fig. 4. Particle Size Distribution of Natural Fine Aggregate & Ceramic Fine Aggregate

Table 1. Properties of Used Material

| Physical Properties | Cement –OPC | NCA | Sand | $C_{WC}$ | $A_{WC}$ | $S_{WC}$ |
|---|---|---|---|---|---|---|
| Normal consistency (%) | 30 | – | – | 8 | – | – |
| Specific gravity | 3.6 | 2.55 | 2.6 | 2 | 2.35 | 2.26 |
| Initial setting time | 42 min | – | – | 54 min | – | – |
| Final setting time | 600 min | – | – | 680 min | – | – |
| 7 days compressive strength | 21.1 MPa | – | – | 37 | – | – |
| Fineness modules | 1.4 | 6.99 | 2.65 | 34.1 | 6.98 | 2.2 |
| Maximum size | – | 0.02 m | – | 75 µm | 0.02 m | – |
| Density (kg/m$^3$) | 3015 | 618 | 319 | 2570 | 1325 | 218 |
| Water absorption (%) | – | 0.25 | 1.6 | – | 4.5 | 2.52 |
| Crushing value (%) | – | 2.86 | – | – | 4.33 | – |
| Impact value (%) | – | **20** | – | – | 24.2 | – |

NCA: natural coarse aggregate, AWC: waste ceramic aggregate, SWC: waste ceramic sand, CWC: waste ceramic cement.

Table 2. Chemical analysis of $C_{WC}$ and cement (OPC 43)

| Materials | Waste Ceramic Powder ($C_{WC}$) | Cement (OPC 43) |
|---|---|---|
| $SiO_2$ | 68.85 | 22.18 |
| $Al_2O_3$ | 17 | 7.35 |
| $Fe_2O_3$ | 0.8 | 3.83 |
| CaO | 1.7 | 63.71 |
| $Na_2O$ | – | 0.28 |
| $K_2O$ | 1.63 | 0.11 |
| MgO | 2.5 | 0.95 |
| $TiO_2$ | 0.737 | 0.13 |
| MnO | 0.078 | 0.04 |
| LOI | 1.78 | 1.6 |

## 3.2. Preparation of Specimen

Plain concrete mix for M25 grade concrete has been designed keeping 0.5 water/cement ratio constant. To determine the best use of partial replacement in M25 grade concrete 192 specimens were cast. For the purpose, 48 cubes (0. 15 x0.15 x 0.15) m; 48 cylinders (0.15 x 0.3) m; and 96 beams (0.1 x 0.1 x 0.5) m were casted with varying percentages of ceramic replacement. The specimens were removed from the molds after 24 hours and placed in a curing tank for 28 days at a temperature of 27°C. Finally, the specimens were dried for 24 hours before testing. The mix proportions for concrete for different percentages of replacement are shown in Table 3. The dried specimen cubes, cylinders, and beams have been shown in Fig. 5.

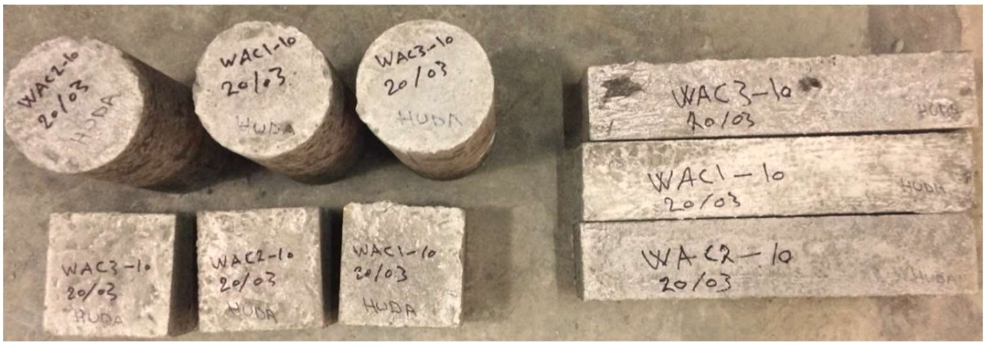

Fig. 5. Specimen: cubes, cylinders and beams

Table 3. Mix proportions for concrete

| Name | (PC) | WAC | | | | | WCC | | | | | WSC | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10%$A_{WC}$ | 20%$A_{WC}$ | 30%$A_{WC}$ | 50%$A_{WC}$ | 100%$A_{WC}$ | 5%$C_{WC}$ | 10%$C_{WC}$ | 15%$C_{WC}$ | 20%$C_{WC}$ | 30%$C_{WC}$ | 5%$S_{WC}$ | 10%$S_{WC}$ | 15%$S_{WC}$ | 20%$S_{WC}$ | 30%$S_{WC}$ |
| **Water (kg/ m³)** | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 | 190 |
| **OPC (kg/m³)** | 380 | 380 | 380 | 380 | 380 | 380 | 361 | 342 | 323 | 304 | 266 | 342 | 342 | 342 | 342 | 342 |
| **$C_{WC}$ (kg/ m³)** | - | - | - | - | - | - | 19 | 38 | 57 | 76 | 114 | 38 | 38 | 38 | 38 | 38 |
| **NCA (kg/ m³)** | 1118 | 1006 | 894 | 783 | 559 | 0 | 894 | 894 | 894 | 894 | 894 | 894 | 894 | 894 | 894 | 894 |
| **$A_{WC}$ (kg/ m³)** | - | 112 | 224 | 335 | 559 | 1118 | 224 | 224 | 224 | 224 | 224 | 224 | 224 | 224 | 224 | 224 |
| **Sand (kg/ m³)** | 609 | 609 | 609 | 609 | 609 | 609 | 609 | 609 | 609 | 609 | 609 | 579 | 548 | 518 | 487 | 426 |
| **$S_{WC}$ (kg/ m³)** | - | - | - | - | - | - | - | - | - | - | - | 30 | 61 | 91 | 122 | 183 |

**PC:** plain concrete **WCC**: Waste Ceramic Cement Concrete
**WAC:** Waste Ceramic Aggregate Concrete **WSC**: Waste Ceramic Sand Concrete

## 3.3. Mix proportions

The test was carried out in three phases as shown in Table 4, in Phase 1 18 cubes, 18 cylinders and 36 beams were cast replacing Natural Coarse Aggregate (NCA) with Waste Ceramic Aggregate (AWC) of same size (0.02m and 0.01m) having

Table 4. Description of Phase testing of total 192 test specimens into 16 groups

| phase | samples | Percentage of replacement | Cube | | Cylinder | | Beam | |
|---|---|---|---|---|---|---|---|---|
| | | | number | size | number | size | number | size |
| Phase 1 | PC/WAC | 0% replacement of NCA by $A_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WAC-10% | 10% replacement Of NCA by $A_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WAC-20% | 20% replacement Of NCA by $A_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WAC-30% | 30% replacement of NCA by $A_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WAC-50% | 50% replacement of NCA by $A_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WAC-100% | 100% replacement of NCA by $A_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| Phase 2 | WCC-0% | 0 % replacement of OPC by $C_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WCC-5% | 5 % replacement of OPC by $C_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WCC-10% | 10 % replacement of OPC by $C_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WCC-15% | 15 % replacement Of OPC by $C_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WCC-20% | 20 % replacement of OPC by $C_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WCC-30% | 30 % replacement of OPC by $C_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| Phase 3 | WSC-0% | 0 % replacement of NFA by $S_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WSC-5% | 5 % replacement Of NFA by $S_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WSC-10% | 10 % replacement Of NFA by $S_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WSC-15% | 15 % replacement of NFA by $S_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WSC-20% | 20 % replacement of NFA by $S_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |
| | WSC-30% | 30 % replacement Of NFA by $S_{WC}$ | 3 | 150*150*150 | 3 | 150*300 | 6 | 100*100*500 |

**NCA: Natural Coarse Aggregate** **NFA**: Natural Fine Aggregate **OPC**: Ordinary Portland Cement replacement percentages- 0%, 10%, 20%, 30%, 50% and 100% named as Waste Ceramic Aggregate Concrete (WAC). For each replacement percentage, three specimens were cast for testing. The 18 cubes were tested for compression, the 18 cylinders were tested for tension, the 18 beams were tested for flexure, and the remaining 18 beams were tested for combined (flexural and torsional) strength. Based on the results of Phase 1, the optimal testing percentage of coarse ceramic aggregate was 20%.

Keeping 20% AWC constant, the Phase 2 testing samples were prepared by replacing OPC by 5%, 10%, 15%, 20% and 30% with Waste Ceramic Cement (CWC) powder passing through 75μm sieve named as Waste Ceramic Cement Concrete (WCC). For each replacement, 3 cubes, 3 cylinders, and 6 beams were cast and tested for CS, TS, FS, and FTS. On the basis of Phase 2 results, the optimal ceramic cement replacement percentage was found as 10%.

Similarly, for Phase 3 keeping a constant optimal replacement percentage as 20% WCA and 10% WCC, the samples were casted by river sand replacement- 5%, 10%, 15%, 20% and 30% with Waste Ceramic Sand (SWC) having Fineness Modules =2.2 named as Waste Ceramic Sand Concrete (WSC). For each replacement, 3 cubes, 3 cylinders, and 6 beams were cast and tested for CS, TS, FS, and FTS. The final optimal replacements on the basis of overall results were found as 20%AWC, 10% SWC and 10% CWC.

### 3.4. Test Procedures

The properties of fresh and hardened WOC mixes were determined using test procedures adapted from those used for traditional Portland cement-based concrete. Test methods were selected to allow simple characterization of the mechanical properties of hardened mixes under short-term loading conditions. Table 4 illustrates the details of different phases of mixes and tests. First, the compressive strength test was done to investigate the compressive mechanical property. The second test was the tensile strength test which was conducted to investigate the tensile mechanical property. Then flexural strength test to investigate the flexural mechanical property. Finally, a combined test (flexural and torsion strength) investigated the ultimate bending stress under torsion. The characterization of all mixtures was carried out through the tests detailed in Table 5.

Table 5. Testing procedures on ceramic concrete

| Tests | Equipment | Sample | Condition | Formula |
|---|---|---|---|---|
| **Slump** | Abram cone | Fresh concrete | Immediately after mixing | - |
| **Compressive Strength (IS: 516-1959)** | (2000 KN) Compressive Testing Machine at Axial | hardened concrete | After 28 Days of Curing | $CS = \frac{P}{A}$ |
| **Tensile Strength (IS: 516-1959)** | (2000 KN) Compressive Testing Machine at Horizontal | hardened concrete | After 28 Days of Curing | $TS = \frac{2P}{\pi LD}$ |
| **Flexural Strength (IS: 516-1959)** | Two-point load test | hardened concrete | After 28 Days of Curing | $FT = \frac{P\ L}{b\ d^2}$ |
| **Combined Flexural and Torsion Strength (IS: 516-1959)** | Two-point load test + Torsion Girder | hardened concrete | After 28 Days of Curing | $\sigma = \frac{M\ Y}{I}$ |

# 3. RESULTS AND DISCUSSION

## 3.5. Phase 1- WAC

Coarse aggregates cannot be just considered a filler material. Instead, it has been recognized as one of the constituent materials that greatly influences the mechanical properties of concrete mix. Herein, the effect on concrete's compressive, tensile, flexural and combined (flexural and torsional) strength has been examined when WCA has replaced natural coarse aggregates with the same sizes (0.02m and 0.01m) having varying percentages in the mix.

### 3.1.1 Effect of $A_{WC}$ on the compressive strength (CS) of concrete

The results show that the CS decreases on increasing the Natural Coarse Aggregates (NCA) replacement percent by waste ceramic aggregates ($A_{WC}$) as shown in chart 5. The CS was found to vary between 31.1MPa for PC (WAC-0$A_{WC}$) to 21.55MPa for WAC-100$A_{WC}$. The percentage reduction in CS of WAC-10%, WAC-20%, WAC-30%, WAC-50% and WAC-100% has been compared with that of PC (WAC-0%) as shown in chart 1. A decrease in CS of about 7.4% and 30.72% were observed in WAC-10$A_{WC}$ and WAC-100%, respectively with respect to PC.

The curve mentioned previously in section two (Particle Size Distribution of Natural Coarse Aggregate & Ceramic Coarse Aggregate) concluded that both coarse ceramic aggregate and natural coarse aggregate fit within the confines of standard concrete aggregate, implying that coarse ceramic aggregate can be used in place of natural coarse aggregate in concrete.

The first observation is that ceramic coarse aggregate floor tiles have presented the lowest compressive strength from the results. This was expected because ceramic tiles are weaker and absorb more water than natural coarse aggregates.

The other possible explanation for the low compressive strength is that the coarse ceramic aggregate is poorer than the natural aggregate.

Another reason was the low crushing value of waste ceramic coarse aggregate (20.86%) in compression to natural coarse aggregate crushing value (34%). The crushing value of aggregate gives a relative measure of the resistance of an aggregate under a gradually applied compressive strength load.

More or less similar behavior of ceramic aggregate replacement has been reported by Alves, A. V., et al. [9], Gonzalez-Corominas, A. et al. [14], Sekar, M. [17], Correia, J. R., et al. [18].

### 3.1.2 Effect of $A_{WC}$ on the tensile strength (TS) of concrete

Similar to the CS test, TS was also found to be decreasing on increasing the natural coarse aggregates replacement percent by $A_{WC}$ as shown in chart 5. The TS was found to vary between 3.69MPa for PC (WAC-0%) to 2.95MPa for WAC-100%. The percentage reduction in TS of WAC- 10%, WAC-20%, WAC-30%, WAC-50% and WAC-100% has been compared with that of PC (WCA-0%) as shown in Chart 2. A decrease in TS of about 8.67% and 20.05% were observed in WAC-10% and WAC-100%, respectively with respect to PC. The reduction in tensile strength was expected due to the intrinsic properties of the adhered mortar and its low adhesiveness to ceramic.

The results of this study have shown a similar performance to other studies conducted by different researchers such as Gonzalez-Corominas, A. et al. [14]; Gomes, M. et al. [15] and; D.J.M. Martins [16].

### 3.1.3 Effect of $A_{WC}$ on the flexural strength (FS) of concrete

The FS was found to decrease from 6.08MPa for PC (WAC-0%) to 4.67MPa for WAC-100%, as shown in chart 5. Furthermore, the percentage reduction in FS of WAC-10%, WAC-20%, WAC-30%, WAC-50% and WAC-100% has been compared with that of PC (WAC-0%) as shown in Chart 3 wherein, a decrease in FS of about 8.67% and 20.05% were observed in WAC-10% and WAC-100% respectively with respect to PC.

As stated previously, the coarse ceramic aggregates reduced flexural strength. A higher replacement ratio of natural coarse aggregates by coarse ceramic aggregate resulted in a flexural strength loss of up to 5.6%.

The concrete (WAC- 20%) produced in the present study has shown the best mechanical performance compared to other mentioned studies such as Alves, A. V., et al. [9]; Nepomuceno, M. C., et al. [19]; Anderson, D. J., et al. [20].

### 3.1.4 Effect of $A_{WC}$ on the combined flexural and torsional strength (FTS) of concrete

The aggregate and cement paste interface are the weakest concrete zone, known as the interfacial transition zone. Therefore, different methodologies have been adapted to density the interfacial zone that can improve the mechanical strength of concrete.

The Ultimate Bending Stress (UBS) of WAC under torsion 243N.mm was found to vary from 3.25MPa to 2MPa; under torsion, 254N.mm was found to vary from 3MPa to 1.75 MPa and; under torsion 264N.mm was found to vary from 2.75MPa to 1.5MPa as shown in chart 5. However, the UBS of WAC-10% was 30.76%, 33.33%, and 36.36% greater than the PC/WAC-0% for torsion 243N.mm, 254N.mm and 265N.mm respectively as shown in Chart 4. Further, the UBS of WAC-20% under torsion 243N.mm, 254N.mm and 265N.mm were found to be equal to that of PC.

The major reason for a higher value of UBS may be related to the high impact value of waste ceramic coarse aggregate (27%) in compression to natural coarse aggregate impact value (24%), where the aggregate impact value in determining a measure of resistance to sudden impact or shock which differ from its resistance to gradually applied compressive load.

A study by Anderson, D. J., et al. [20] examined the impact of ceramic aggregate surface texture, angular aggregate shape, and water absorption on concrete torsional strength. The ceramic tile used in this study is flat and smooth on one side compared to other crushed ceramic tile aggregates.

Finally, on the basis of Phase 1 results, 20% $A_{WC}$ was adopted as the optimal replacement percentage for NCA.

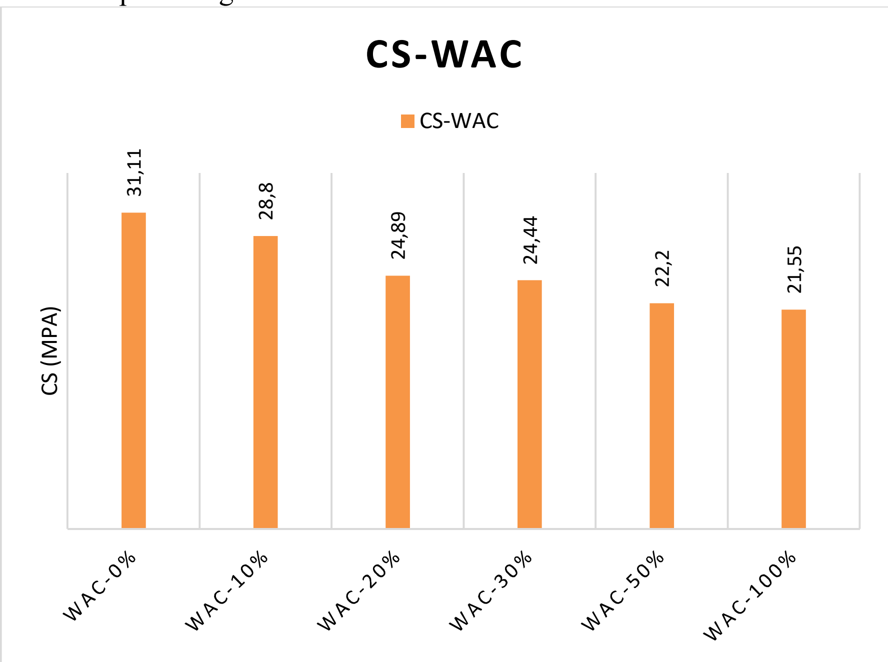


Chart 1. Average compressive strength (CS) for WAC mix

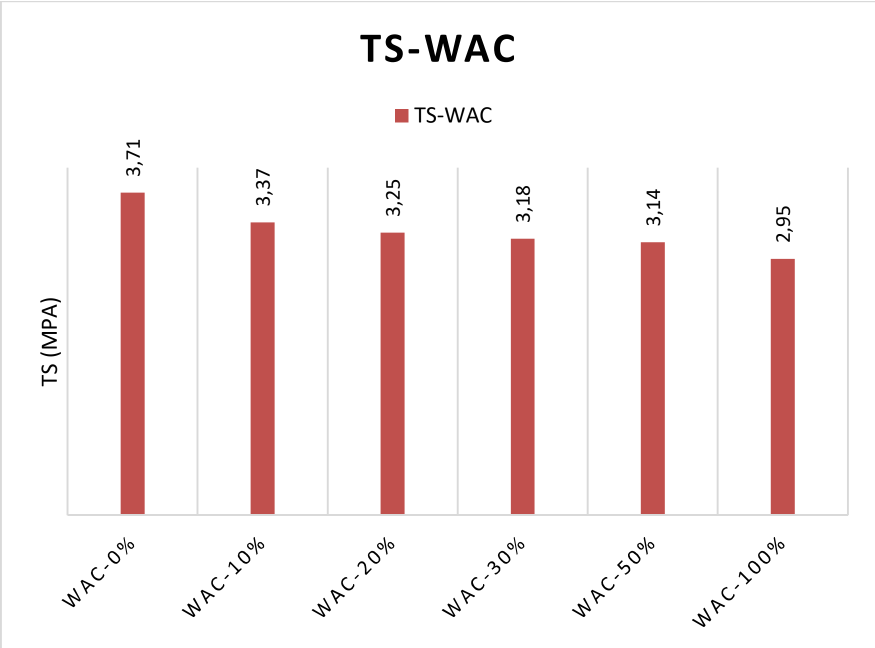


Chart 2. Average tensile strength (TS) for WAC mix

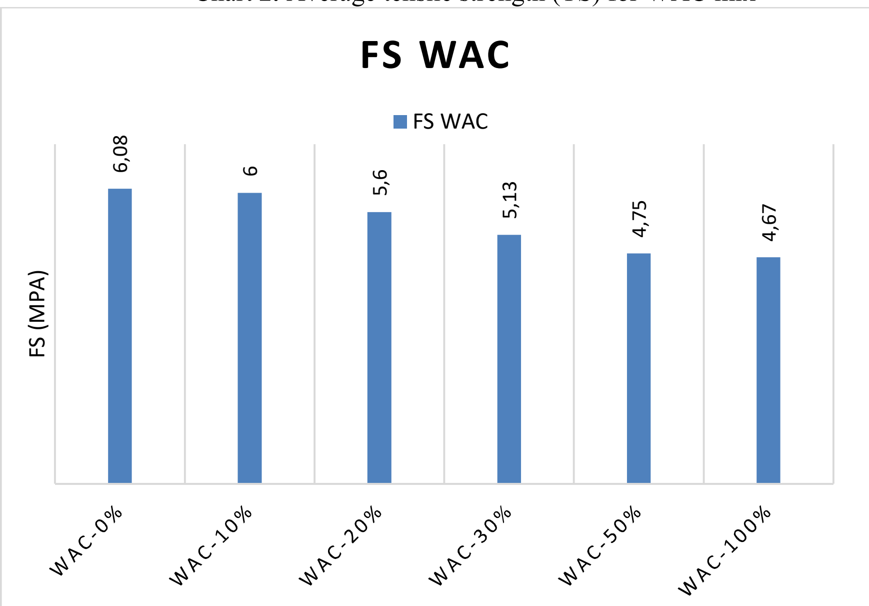


Chart 3. Average flexural strength (FS) for WAC mix

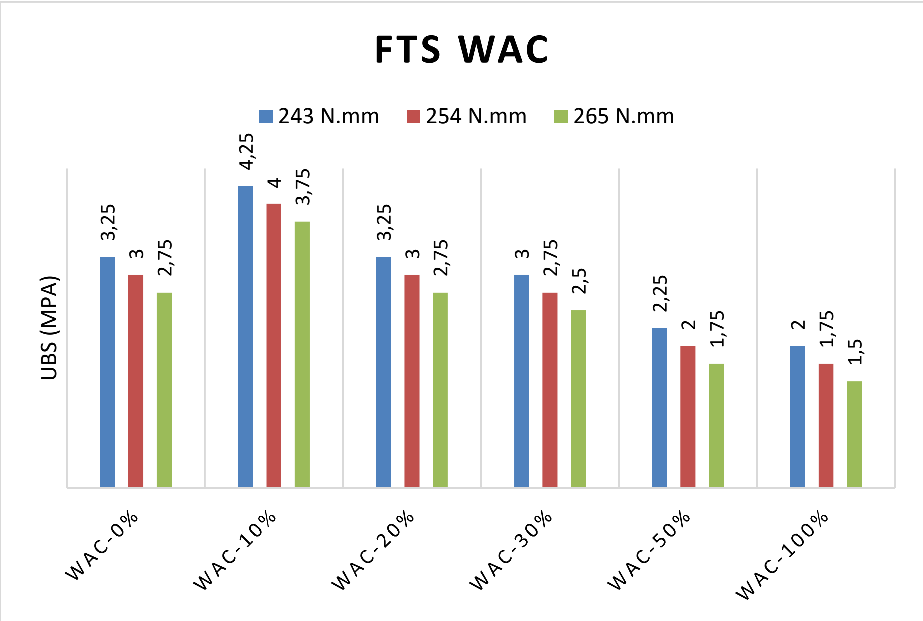


Chart 4. Average combined flexural and torsional strength (FTS) for WAC mix

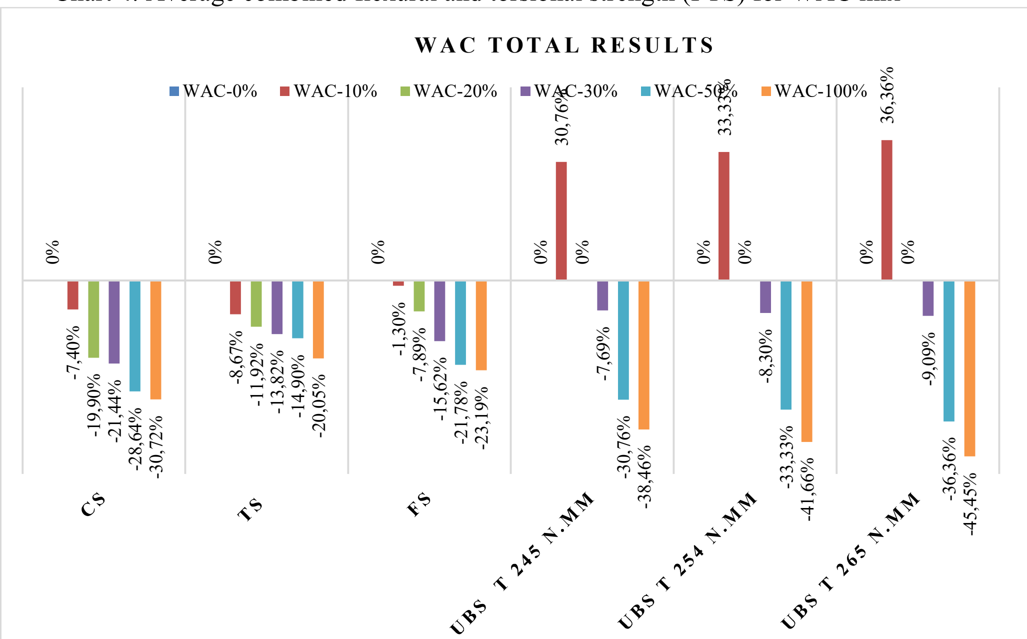


Chart 5. Overall Percentage of Increment/ Decrement of Total WAC Results

### 3.6. Phase 2- WCC

There is a tremendous saving of energy, cost (about 45%), and environmental pollution when replacing the cement with waste ceramic cement powder (CWC). Furthermore, authors and researchers such as Lavat, A. et al. [21] and Puertas F, et al. [22] have confirmed the pozzolanic nature of ceramic wastes. This section discusses the effect of using waste ceramic cement (CWC) as replacement of ordinary Portland cement (OPC 43 grade) on the mechanical properties of concrete: CS, TS, FS and FTS.

#### 3.2.1 Effect of $C_{WC}$ on the compressive strength (CS) of concrete keeping 20% $A_{WC}$ constant

The CS was found to vary between 31.11MPa for WCC-0% to 20MPa for WCC-30% as shown in Chart 6. The percentage increase/decrease in CS of WCC-5%, WCC-10%, WCC-15%, WCC-20% and WCC-30% compared with that of WCC-0% as shown in Chart 6.

An increase in CS of about 11.86% was observed in WCC-5%, whereas a decrease of about 10.70% was observed in WCC-15%, respectively with respect to WCC-0%. For low $C_{WC}$/OPC replacement volume ratios (5% to 10%), the likely Pozzolanic activity of $C_{WC}$ compensated the cement percentage reduction, where the mixture with WCC-10% was found to have the optimal value of CS (=32.89 MPa).

As mentioned in Table 2 (Chemical Analysis of $C_{WC}$ and OPC) that the chemical composition of the ceramic waste Powder mainly consisted of silica ($SiO_2$) and alumina ($Al_2O_3$). Both oxides presented around 85% of the total material mass. These higher percentages of silicate and aluminate in the ceramic waste powder material could indicate some Pozzolanic reactivity.

The mass fractions of ($SiO_2 + Al_2O_3 + Fe_2O_3$) in the ceramic waste powder conformed well to the requirement stated in IS 1489-1(1991) for natural pozzolana (i.e., >70%). On the other hand, the ceramic waste powder observed very small mass percentages of several oxides such as $Fe_2O_3$, CaO, MgO, and $SO_3$. Also, the $SO_3$ and the LOI conformed to IS 1489-1(1991) requirements. Therefore, ceramic waste powder qualified as a pozzolana material based on its mineral composition. WCC-30% had the lowest strength because it contained the maximum waste ceramic as a cement replacement.

Shamsaei, M. et al. [23] studied the effect of ceramic powder on concrete compressive strength. By comparing previous studies to the current study, it was determined that the compressive strength in specimens containing Waste Ceramic Cement ($C_{WC}$) only (10% replacement) was reduced by 6.77% [23]. In comparison, the compressive strength in specimens containing Waste Ceramic Cement ($C_{WC}$) (10% replacement) with Waste Ceramic Aggregate ($A_{WC}$) (20%

replacement) was enhanced by 5.72% (WCC-10%). This leads to conclusion that CS in specimens containing ceramic powder without ceramic aggregate was lower than specimens containing both.

### 3.2.2 Effect of $C_{WC}$ on the tensile strength (TS) of concrete keeping 20% $A_{WC}$ constant

The partial replacement of $C_{WC}$ has a role in reducing the TS of concrete. The reduction range for TS was found to be higher than the CS. The specimens of WCC-20$A_{WC}$-30$C_{WC}$ showed the highest reduction in splitting TS whereas, specimens WCC-20$A_{WC}$-5$C_{WC}$ showed less reduction in TS. The average splitting TS of WCC-5% was found to decrease by 12.19% compared to the reference model (WCC-0%) as shown in Chart 7.

Thus, the Pozzolanic effect of ceramic waste powder (WCC-5%, WCC-10%) on the mechanical properties of the mixture can be attributed to tensile strength [24].

The adverse effects of Pozzolanic material deficiency cannot be overcome for higher $C_{WC}$/OPC replacement ratio (30%). Heidari, A. et al. [1] reported that "The sole Pozzolanic activity of the ceramic waste powder, as reasonably hypothesized on the basis of its mineralogical composition discussed in the literature, was not able to provide compensation probably due to the likely lower availability of the cement hydration products (portlandite) necessary for its activation".

Shamsaei, M. et al. [23] studied the effect of ceramic powder on concrete tensile strength. By comparing previous studies to the current study, it was determined that the TS in specimens containing 10% Waste Ceramic Cement ($C_{WC}$) only was reduced by 19.65% [23] whereas, in specimens containing 10% Waste Ceramic Cement ($C_{WC}$) and 20% Waste Ceramic Aggregate ($A_{WC}$) was decreased by 19.78% (WCC-10%).

This concludes that the reduction in TS of specimens containing CWC without $A_{WC}$ was higher than specimens containing both. The Pozzolanic behavior of ceramic waste can be considered responsible for less reduction in tensile strength. Modarres et al. [24] referred that "the pozzolanic reaction produces a high percentage of calcium silicate hydrate, which improves the strength".

### 3.2.3 Effect of $C_{WC}$ on the flexural strength (FS) of concrete keeping 20% $A_{WC}$ constant

From Chart 8 & Chart 10, Specimens WCC-5% showed an increment of 0.82% in FS with respect to the reference model (WCC-0%) whereas, in specimens WCC-10%, WCC-15%, WCC-20% and WCC-30% the FS was found to show a decrement of 9.53%, 19.73%, 21.78% and 25.78% respectively compared to the reference model (WCC-0%).

The difference in the Flexural strength development of the samples WCC-0% and WCC-10% can be attributed to the Pozzolanic reaction.
Thus, the pozzolanic particles could be reasons that affect the FS. This finding has also been confirmed by Shamsaei M. et al. [23] where they studied the effect of ceramic powder on concrete FS. By comparing previous studies to the current study, it was determined that the FS in specimens containing 10% Waste Ceramic Cement ($C_{WC}$) only was reduced by 5.5% [23] whereas, in specimens containing 10% Waste Ceramic Cement ($C_{WC}$) and 20% Waste Ceramic Aggregate ($A_{WC}$) was reduced by 9.53% (WCC-10%).

This concludes that the reduction in TS of specimens containing $C_{WC}$ without $A_{WC}$ was higher than specimens containing both. Besides, with increases in the percentage of ceramic waste, the FS decreases slightly.

### 3.2.4 Effect of $C_{WC}$ on the combined flexural and torsional strength (FTS) of concrete keeping 20% $A_{WC}$ constant

The Ultimate Bending Stress (UBS) of WCC under torsion 243N.mm was found to vary from 3.25MPa (WCC-0%) to 4.5MPa (WCC-30%); under torsion, 254N.mm was found to vary from 3MPa (WCC-0%) to 3.75 MPa (WCC-30%) and; under torsion 264N.mm was found to vary from 2.75MPa (WCC-0%) to 3.5MPa (WCC-30%) as shown in chart 10.

Heidari, A. et al. [1] mentioned that ceramic powder and Ordinary Portland Cement (OPC) fit within the chemical properties for normal concreting cement, which implied the ceramic powder could replace OPC (43 Grade) in concrete.
The increased enhancement in UBS may be due to ceramic compounds containing Pozzolanic particles.

However, the UBS of WCC-10% was 69.23%, 67.67%, and 72.73% greater than the reference model for torsion 243N.mm, 254N.mm and 265N.mm respectively as shown in Chart 9.

Finally, on the basis of Phase 2 results, 10% $C_{WC}$ and 20% $A_{WC}$ were adopted as the optimal replacement percentage for cement and NCA, respectively.

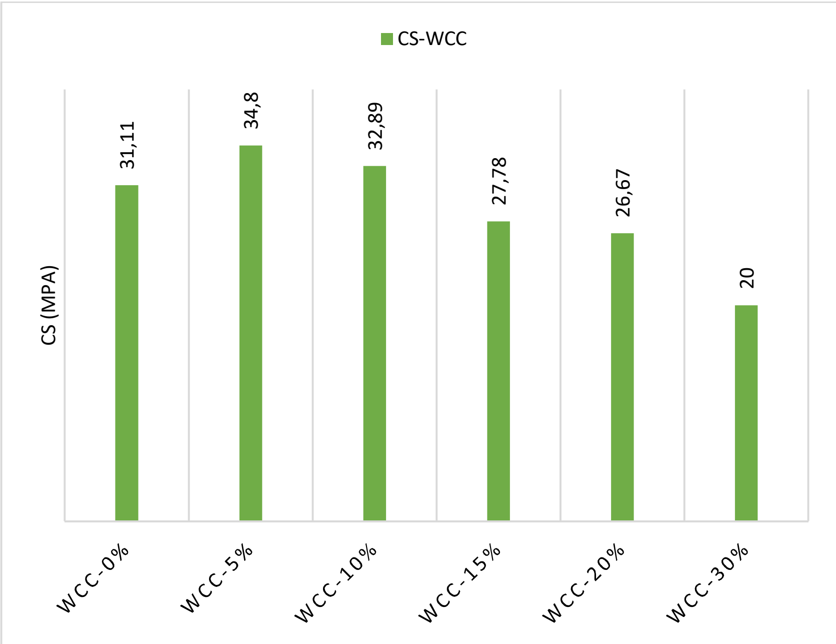


Chart 6. Average Compressive Strength (CS) for WCC mix

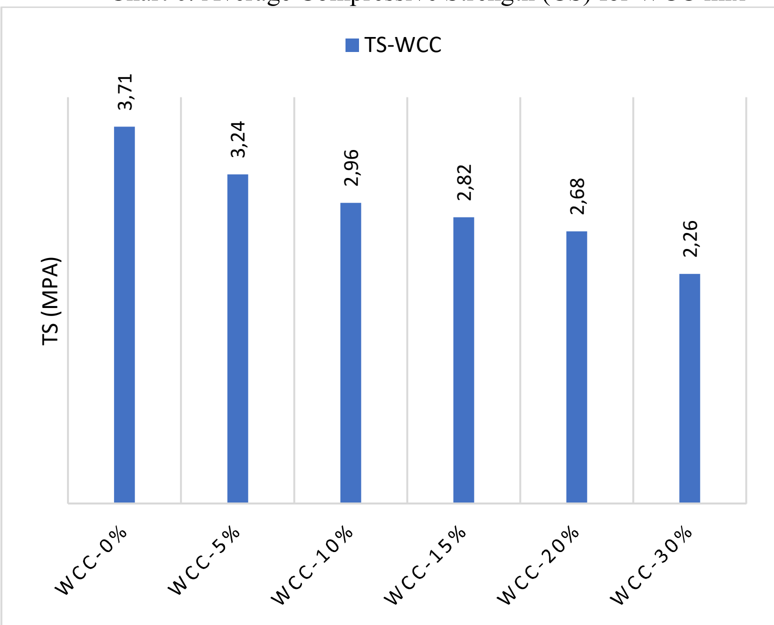


Chart 7. Average Tensile Strength (TS) for WCC mix

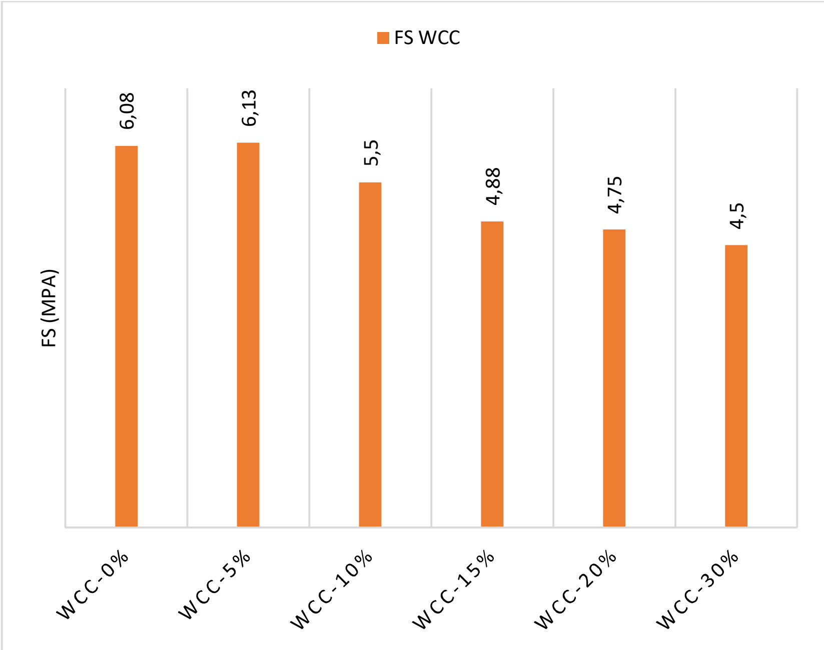


Chart 8. Average Flexural Strength (FS) for WCC mix

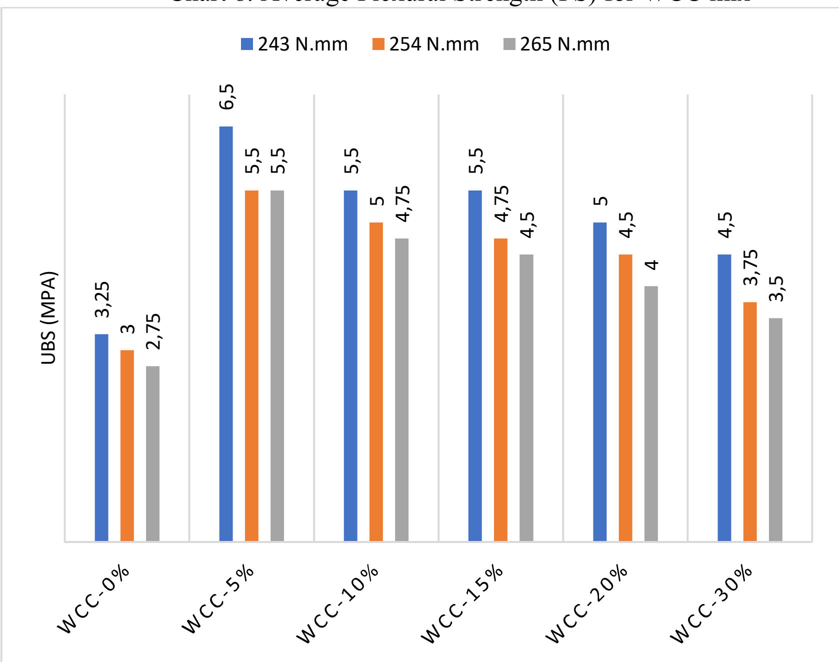


Chart 9. Average Combined Flexural and Torsional (FTS) for WCC mix

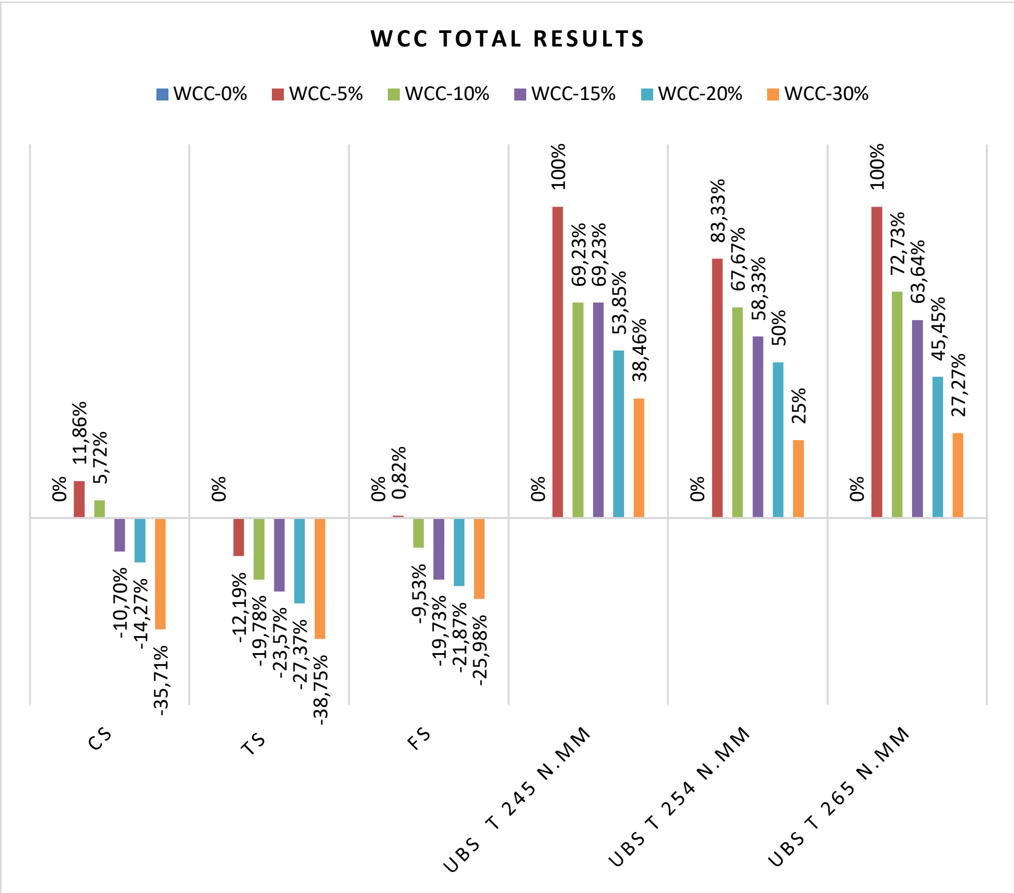


Chart 10. Overall Percentage of Increment/ Decrement of Total WCC Results

### 3.3. Phase 3 WSC

Using waste ceramic sand as a substitute for sand in concrete is a good step toward sustainability. This part discusses the effect of using the waste ceramic sand (SWC) as a partial replacement of river sand on the mechanical properties of concrete (CS, TS, FS and FTS).

#### 3.3.1 Effect of $S_{WC}$ on the compressive strength (CS) of concrete keeping 20% $A_{WC}$ and 10% $C_{WC}$ constant

Chart 15 shows that the CS decreases when the replacement ratio increases. At 28days of age, the maximum loss in strength, relative to the reference concrete, was found as 10.99%, 11.98%, 19.99%, 22.85%, and 27.12% in WSC-5%, WSC-10%, WSC-15%, WSC-20% and WSC-30% respectively as shown in Chart 11. Leite, M. et al. [25] despite the Pozzolanic nature of aggregate, their low porosity does not allow Pozzolanic reactions to occur, as in the case of Waste Ceramic Sand ($S_{WC}$). The experiment results show that the CS of waste ceramic concrete made by partial replacement of sand gives less compressive strength than the plain concrete.

This performance has been confirmed by Siddesha H. [26] where he studied the effect of ceramic sand on concrete CS. By comparing previous studies to the current study, it was determined that the decrease in CS of specimens WSC-10% was 11.98% (present study), whereas; in a specimen with only ceramic sand (10%) as a replacement (no ceramic aggregate and cement) was 12.5% [26]. For WSC-20%, the CS decreased by 22.85%, whereas in concrete with ceramic sand only (without ceramic powder & ceramic aggregate) was decreases by 16 % [26].

### 3.3.2 Effect of $S_{WC}$ on the tensile strength (TS) of concrete keeping 20% $A_{WC}$ and 10% $C_{WC}$ constant

The TS of various samples is shown in chart 15, indicating a reduction in the TS of WSC. The reduction may be the increase in porosity of the paste as the replacement ratio increases. For WSC mixes, a maximum reduction of 34.95% relative to the reference concrete has been found in WSC-30% as shown in chart 12.

From the results above indicating a reduction in the TS of WSC. The reduction may be the increase in porosity of the paste as the replacement ratio increases.
Awoyera PO et al. [11] mentioned that both fine ceramic aggregate and river sand fit within the confines of conventional concreting sand, implying that ceramic sand can be used in place of river sand in concrete.

On the basis of the comparison between previous studies Siddesha H. [26] and the present study, it was observed that the decrease in TS of specimens WSC-10% was 27.37% (present study), whereas; in the specimen with only ceramic sand (10%) as a replacement (no ceramic aggregate and cement) was 28.57% [26]. For WSC-20% the TS was decreased by 32.52%, where the concrete with ceramic sand only (without ceramic powder & ceramic aggregate) was decreased by 33.33% [26].

This leads to the conclusion that reduction in TS of specimens containing $S_{WC}$ without $A_{WC}$ and $C_{WC}$ was found to be higher than specimens containing all ceramic material together in the same model.

### 3.2.3 Effect of $S_{WC}$ on the flexural strength (FS) of concrete keeping 20% $A_{WC}$ and 10% $C_{WC}$ constant

From Chart 13, WSC-5% and WSC-10% showed an increment of 6.9% and 11% respectively in FS with respect to the reference model (WSC-0%) whereas, in specimens WSC-15%, WSC-20% and WSC-30% the FS was found to show a decrement of 13.65%, 19.73%, and 25.98% respectively compared to the reference model (WSC-0%).

The obtained results of FS up to 10% replacement are consistently close to the findings of Reddy, M. V.et al. [27], where he concluded the effect of ceramic sand on concrete flexural strength. On the basis of comparison between previous studies [27] and present study, it was found that the specimens containing 10% $S_{WC}$ only was enhanced by 1.58% [27] whereas, in specimens containing 10% $S_{WC}$ along with 10% $C_{WC}$ and 20% $A_{WC}$ was increased by 11% (WSC-10%).

The obtained results of FS beyond 10% $S_{WC}$ replacement were found to be analogous with the findings of Siddesha H. [26] where studied the effect of ceramic sand on concrete flexural strength. By comparing previous studies to the current study, it was determined that the FS in specimens containing 20% $S_{WC}$ only was decreased by 25% [26] whereas, in specimens containing 10% $S_{WC}$ along with 10% $C_{WC}$ and 20%$A_{WC}$ was decreased by 19.73% (WSC-10%). On the other hand, another study conducted by Medina C. et al. [7] showed an increase in FS as the percentage of the fine aggregate replacement (ceramic sanitary) increased. Ceramic fine aggregate concrete was able to achieve higher Flexural strength (up to 10% replacement) because of its higher early absorption capacity as well as the higher specific surface of the ceramic fine aggregate.

### 3.2.4 Effect of $S_{WC}$ on the combined flexural and torsional strength (FTS) of concrete keeping 20% $A_{WC}$ and 10% $C_{WC}$ constant

The Ultimate Bending Stress (UBS) of WSC under torsion 243N.mm was found to vary from 7.25MPa (WSC-0%) to 4.5MPa (WSC-30%); under torsion, 254N.mm was found to vary from 6.75MPa (WSC-0%) to 4.25 MPa (WSC-30%) and; under torsion 264N.mm was found to vary from 6.25MPa (WSC-0%) to 4 MPa (WSC-30%) as shown in Chart 14.

The UBS of WSC-10% was 107%, 100%, and 100% greater than the reference model for torsion 243N.mm, 254N.mm and 265N.mm respectively. These ultimate bending strength increases can be described by the filling effect of the ceramic waste sand.

According to Nayana A. M. et al. [28], the microstructure investigation reveals that the mortar mix with ceramic waste sand has fewer pores, improving flexural strength and durability.

Finally, on the basis of Phase 3 results, 10% Waste Ceramic Sand ($S_{WC}$), 10% Waste Ceramic Cement ($C_{WC}$) and 20% Waste Ceramic Aggregate ($A_{WC}$) were adopted as the optimal replacement percentage for sand, cement, and natural coarse aggregate, respectively named Waste Ceramic Optimal Concrete (WOC).

Chart 11. Average Compressive Strength (CS) for WSC mix

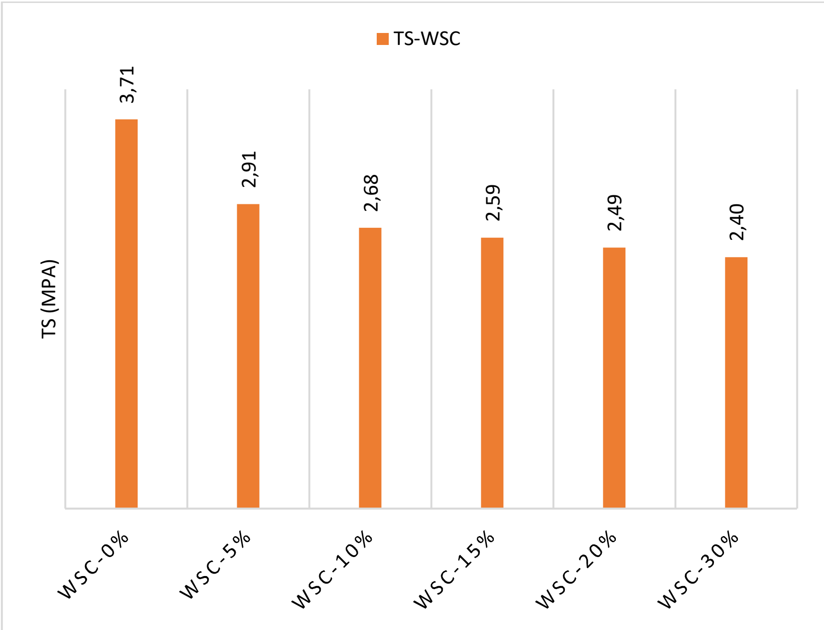


Chart 12. Average Tensile strength (TS) for WSC mix

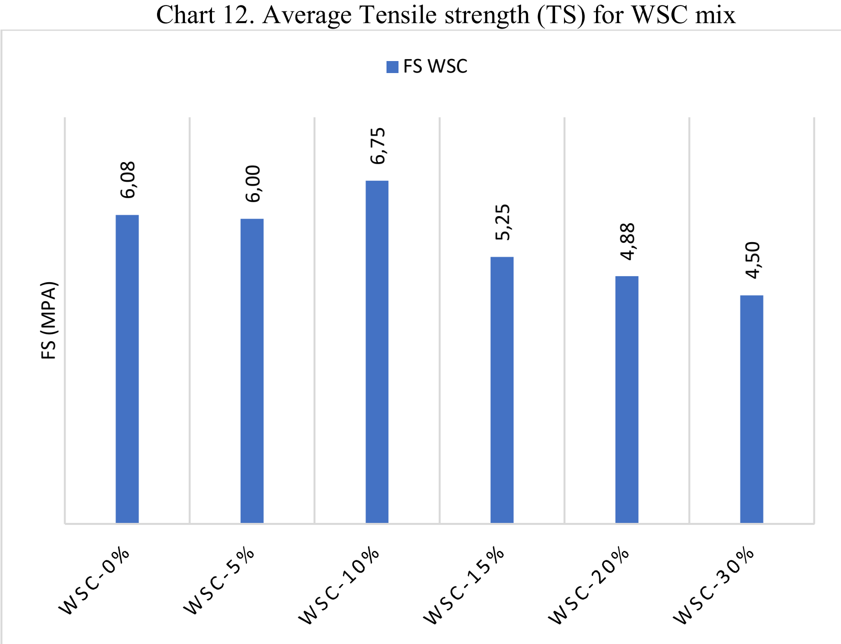


Chart 13. Average Flexural strength (FS) for WSC mix

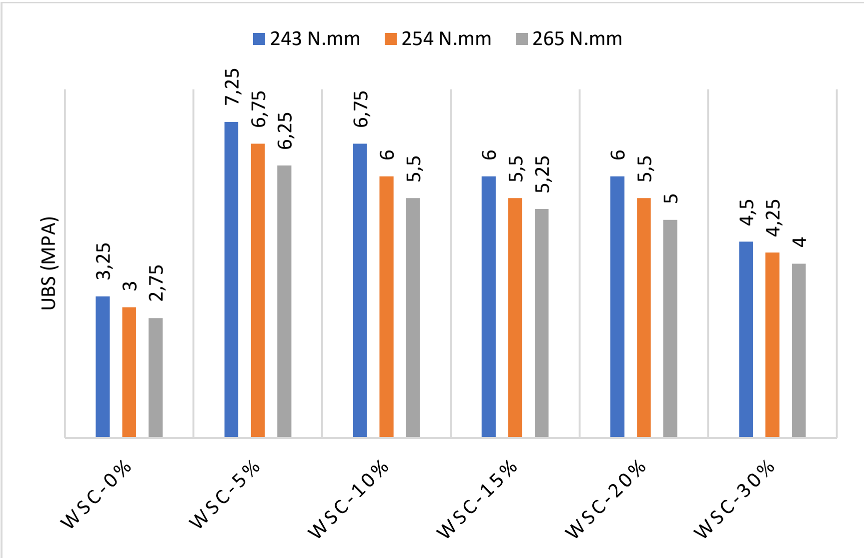


Chart 14. Average Combined Flexural and Torsional Strength (FTS) for WSC mix

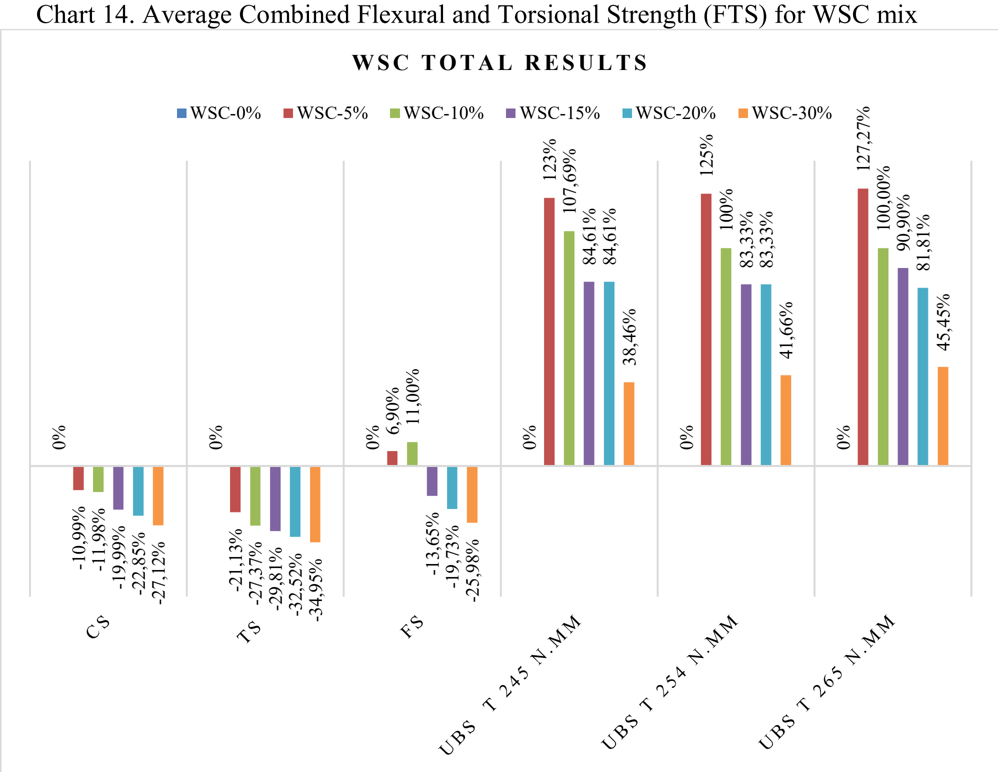


Chart 15. Overall Percentage of Increment/ Decrement of Total WSC Results

## 4. CONCLUSION

This study investigated the compressive, tensile, flexural and combined (flexural and torsional) strength of concrete made of the ceramic waste floor tiles as aggregate (both fine and coarse) and powder. The following conclusions can be drawn:

- Based on the present experimental investigations, it is feasible to use waste ceramic tiles grounded to desired fineness as replacement of cement, river sand, and natural coarse aggregates replacement to produce waste ceramic concrete.
- Application of waste ceramic with acceptable performance, where the experimental ceramic material as a substitute for cement and results allow aggregate in concrete prevents entry of wastes into the natural environment and curtails dumping. It can also be considered as a step toward sustainability.
- In the case of WAC, the CS, TS and FS were decreasing as the percentage (%) of AWC increases (from 10% to 100% as replacement of NCA) in the concrete specimens. Also, these strengths were found to be less than that of the PC. However, the UBS was found to be highest and greater than the PC for replacement 10% whereas, for replacement, 20% the UBS was found to be equal to the PC. Hence, the optimal percentage of AWC was taken as 20% as a replacement of NCA.
- Ceramic and natural materials both fit within the envelope of conventional concrete materials, implying that ceramic materials can be used in place of natural materials in concrete.
- In case of WCC (with 20% AWC constant), the CS of specimens with the replacement of cement by CWC- 5%, 10%, were found to be greater than the reference concrete whereas, for 15-30% CWC the CS was found be less than the reference concrete. TS of WCC were found to be less than the reference concrete for all the replacement percentages of CWC. FS of the specimen with 5% CWC was found to be greater than reference concrete and on further increasing the replacement percentage the FS was found to be less than the reference concrete (WCC-0%). However, the UBS was found to be higher than the reference concrete for all the replacement percentages. Therefore, the optimal percentage of CWC was taken as 10% as a replacement of OPC in WCC (with 20% AWC as constant).
- The wastes ceramic powder is similar in appearance to cement and include over 85% $Al_2O_3$ and $SiO_2$. Ceramic powder characteristics indicate that the material can be used to produce economical a d sustainable mixture as an alternative ingredient to partial replacement of cement.
- In case of WSC (with 20% AWC constant & 10% CWC constant), TS were found to be decreasing as the percentage (%) of SWC increases (from 5% to 30% as replacement of sand). The CS were found to be increasing as the percentage

(%) of SWC increases (from 5% to 10% as replacement of sand). Further, FS of specimens with 5-10% SWC was found to be greater than the reference concrete, whereas for 15-30% SWC the FS was found to be less than the reference concrete. Also, the UBS of specimens with 5% to 30% SWC was found to be higher than the reference concrete specimens (WSC-0%). Finally, the optimal percentage as 20% AWC, 10% CWC and 10% SWC were adopted as the replacement percentage for natural coarse aggregate, cement and sand, respectively in a waste ceramic optimal concrete mix.

- Ceramic fine aggregate and river sand fit within the envelope for normal concreting sand, implying that ceramic sand can replace river sand in concrete.
- It can be concluded that, within limits established in this work, concrete made with ceramic floor tiles debris as a replacement for part of the natural aggregates, cement and sand are quite effective in strength. It is even more ideal in the sustainable field than in the sustainable field of conventional concrete.
- Concrete made with up to 20% of coarse ceramic aggregates, 10% ceramic fine aggregate and 10 ceramic powder achieved a compressive strength of 27.38 MPa for M25 named Waste Ceramic Optimal Concrete (WOC).

**FUNDING:** No funding was received for conducting this study.

**FINANCIAL INTERESTS:** The authors declare they have no financial interests.

**CONFLICTS OF INTERESTS:** All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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*Editor received the manuscript: 24.11.2021*