The Use of Waste Ceramic Concrete for a Cleaner and Sustainable Environment - A Comprehensive Study of Mechanical and Microstructural Properties

Hadee Mohammed Najm (gk4071@myamu.ac.in)
ZH College of Engineering and Technology, Aligarh Muslim University
Shakeel Ahmad
ZH College of Engineering and Technology, Aligarh Muslim University

Research Article

Keywords: Ceramic Waste, Concrete, Mechanical analysis, microstructure analysis , Ceramic Floor Tiles, SEM

Posted Date: May 9th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1616616/v1

Abstract

Increased construction activity combined with a continued reliance on conventional concrete materials resulted in material scarcity and increased construction costs. So, in this study, an attempt has been made to find the optimal use of ceramic powder and ceramic aggregate (both fine and coarse) as a possible replacement for ordinary portland cement (OPC 43 grade) and natural aggregate (fine and coarse), respectively in concrete. The present study aims to investigate the mechanical & microstructural 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 mechanical analysis of waste ceramic concrete 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. Waste ceramic concrete exhibits improved morphological properties as a result of increased pore filling with dense and compact structure, as well as increased C–H crystals and denser structure in pastes as a result of the incorporation of ceramic materials into the concrete mix.The present experimental research shows that the choice of using ceramic waste as a partial replacement to prepare concrete has benefited from the economic, environmental, and technological points of view. Moreover, it offers a possibility for improving the durability of concrete, which has vital importance.

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 CO_2 and 0.39E Tons of CO_2 in fuel emissions, representing a total of 0.94E Tons of CO_2 [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 for 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 with 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 by ***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 behaviour 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 aggregates. 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 cast with ceramic floor tiles as a replacement for cement with percentages- of 10%, 20%, 30% and 40%. Testing of compressive strength and water absorption was 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 the mechanical and microstructure performance.

2. Experimental Work

2.1 Materials

The materials used in this study included Ordinary Portland Cement (OPC) 43-grade, Natural Coarse Aggregate (NCA)/stones, river sand, ceramic floor tiles have been used as described below.

2.1.1 Cement

In this study, two types of cement have been used the first one was 43 grade of Ordinary Portland Cement (OPC) conforming to IS: 8112-1989 and the second one was ceramic cement (C_{WC}). The main constituents of OPC (43 grade) and ceramic cement (C_{WC}) are lime-silica (calcium silicate) compounds. The laboratory tests were conducted to determine the physical properties of OPC and CWC according to IS codes. Table 1 & 2 summarizes the chemical and physical properties of OPC (43 grade) and C_{WC}.

2.1.2 Aggregate

In this study, two types of aggregate have been used, the first one was natural aggregate and the second one was ceramic aggregate. Ceramic has been used in both as coarse aggregate (A_{WC}) and fine aggregate (S_{WC}). Low porosity but high strength make ceramic aggregate ideal for use in construction. The ceramic is manufactured from clay, feldspar, granite, and silica under high pressure and heat for use as flooring and façade material in buildings because of its beauty, strength properties, and heat resistance.

Ceramics that are baked at high temperatures become vitreous with low porosity and extremely low water absorption, and are referred to as 'artificial stones'.Due to their extremely high strength, they cannot be easily recycled back into the manufacturing process and are, therefore, typically dumped and released into the environment.

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- A_{WC}); 4.75mm (waste ceramic sand- S_{WC}) (Figure 1 & 2).

Both aggregates were graded according to IS code as shown in Figures 3 & 4. The natural and ceramic aggregates thus obtained were characterized in terms of normal consistency, specific gravity, finesse modules, maximum size, density (kg/m³), water absorption, crushing value and impact value as reported in Table 1.

Table 1 Properties of used material

Physical Properties	Cement–OPC	NCA	Sand	C_{WC}	A_{WC}	S_{WC}
Normal Consistency (%)	32	-	-	8	-	-
Specific Gravity	3.15	2.84	2.64	2	2.31	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 Modulus	-	6.99	2.65	-	6.98	2.2
Maximum Size	75 µm	0.02 m	4.75 mm	75 µm	0.02 m	4.75 mm
Density (kg/m^3)	1440	1550	1650	-	-	-
Water Absorption (%)	-	0.23	2.24	-	0.55	2.52
Crushing value (%)	-	34	-	-	20.86	-
Impact Value (%)	-	24	-	-	27	-
NCA: Natural Coarse Aggregate	A_{WC}: Waste Ceramic Aggregate		S_{WC}: Waste Ceramic Sand		C_{WC}: 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

2.2 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 moulds 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 are shown in Fig. 5".

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}
Water (kg/m³)	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
C_{WC} (kg/m³)	-	-	-	-	-	-	19	38	57	76	114	38	38
NCA (kg/m³)	1118	1006	894	783	559	0	894	894	894	894	894	894	894
A_{WC} (kg/m³)	-	112	224	335	559	1118	224	224	224	224	224	224	224
Sand (kg/m³)	609	609	609	609	609	609	609	609	609	609	609	579	548
S_{WC} (kg/m³)	-	-	-	-	-	-	-	-	-	-	-	30	61
PC: plain concrete							**WCC**: Waste Ceramic Cement Concrete						
WAC: Waste Ceramic Aggregate Concrete							**WSC**: Waste Ceramic Sand Concrete						

2.3 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 (A_{WC}) of the same size (0.02m and 0.01m) having 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% A_{WC} constant, the Phase 2 testing samples were prepared by replacing OPC with 5%, 10%, 15%, 20% and 30% with Waste Ceramic Cement (C_{WC}) powder passing through a 75μm sieve named ***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 of 20% WCA and 10% WCC, the samples were cast by river sand replacement- 5%, 10%, 15%, 20% and 30% with Waste Ceramic Sand (S_{WC}) 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%A_{WC}, 10% S_{WC} and 10% C_{WC}.

"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		

2.4 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	
Tensile Strength **(IS: 516-1959)**	(2000 KN) Compressive Testing Machine at Horizontal	hardened concrete	After 28 Days of Curing	
Flexural Strength **(IS: 516-1959)**	Two-point load test	hardened concrete	After 28 Days of Curing	
Combined Flexural and Torsion Strength (IS: 516-1959)	Two-point load test + Torsion Girder	hardened concrete	After 28 Days of Curing	

2.5 Concrete Mix Microstructure

The microstructure and chemical analysis of modified concrete specimens were carried out using scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) techniques. In this study, the scanning electron microscope JSM6510LV (JEOL, Japan) was used, with an accelerating voltage of 30.0 kV. In order to conduct EDS analysis, the surface of samples was ground and polished to an ultra-smooth finish and then coated with carbon or gold.The specimens in this study were coated in gold.

3 Results And Discussion

3.1 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-0A_{WC}) to 21.55MPa for WAC-100A_{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-10A_{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 behaviour 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 with 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 is 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.

3.2 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 (C_{WC}). 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 (C_{WC}) as a replacement for 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 conclude that CS in specimens containing ceramic powder without ceramic aggregate was lower than in specimens containing both.

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

Concrete's TS can be reduced in part by replacing C_{WC} in some places. Findings show that reduction ranges for TS are greater than those for Cs. Samples WCC-30% reduced splitting TS the most, while specimens WCC-5% reduced splitting TS the least. Chart 7 shows that the average splitting TS of WCC-5% was 12.19% lower than the reference model (WCC-0%).

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 a 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 in specimens containing both. The Pozzolanic behaviour 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], who 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 in 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 of normal concreting cement, which implied that 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.

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 (S_{WC}) 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], who 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 by ***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%, whereas the concrete with ceramic sand only (without ceramic powder & ceramic aggregate) was decreased by 33.33% [26].

This means that specimens containing S_{WC} without A_{WC} and C_{WC} were found to have a higher reduction in TS than specimens containing all ceramic material in the same model.

3.3.3 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], who concluded the effect of ceramic sand on concrete flexural strength. On the basis of comparison between previous studies [27] and the 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 to the findings of ***Siddesha H.*** [26], who 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 fine ceramic aggregate.

3.3.4 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 mixed 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).

2.4.3 Microstructure Analysis

The analyses of SEM and EDS intended to investigate the morphological properties of Plain concrete(pc) and waste ceramic optimal concrete (WOC) containing 10 % ceramic cement, 10 % ceramic sand and 20% ceramic aggregate, as shown in figs 8,9 and 10. The PC sample is selected as a reference model; the WOC sample is selected based on the optimal performance of each group of ceramic replacements. All the selected samples have taken from failed samples in a compressive strength test.

The SEM micrographs of PC have shown clear visibility of hexagonal plate-shaped crystals of CH and C-S-H gels. The SEM micrographs have also shown a presence of hydrous calcium-aluminate hydrate characterized by a needle-like structure. Several voids, pores, mixed distribution of C-S-H and C-H gel and needle-like ettringite crystal with visible micro-cracks inside the structure have been detected, as shown in Figure 6.

The result of the PC has shown a ceramic particle reacted with prism-shaped columns, which mainly consisted of Al and Si, which means that both components are the main chemical reaction that forms this binder, and this agrees with the conclusion of Siddique and Mehta [35].

The SEM micrographs of WOC have shown a little porous on the surface and a small scale of possible micro-cracks. It has been noticed an amount of C-S-H gel appears to have decomposed into finer particles, remains of calcium hydroxide crystals. The test has also shown an appearance of small round particles as unreacted cement and a sign of feldspar covering the surface area, which correlates in a positive way with the strength behaviour under compression [34], as shown in Figure 7.

It becomes difficult to fill the inter-granular space between the grains when the ceramic material is added to the mixture. Therefore, the addition of the spherical particles (ceramic waste) can work as a lubricant, reducing the inside friction among the grain. In addition, it was detected by Senff et al.[33] Due to orientation and settlement, the packing of particles formed from spherical grain is superior for isotropic structure.

The experiment results have shown an improvement in the internal microstructure of cement paste due to the addition of ceramic material, which acts as a promoter and filler amid hydration of pozzolanic and cement with free C-H. Moreover, the WOC samples have revealed a more uniform and filled structure in comparison to PC. It is noteworthy that C-S-H gel improved in the form of a ‘ stand-alone’ cluster, joined together with needle hydrates because of the deposition of $Ca\ (OH)_2$ crystal, which extends in the OPC paste. Likewise, a dense and compacted structure was shown in the microstructure of cement pastes containing ceramic waste that fills fine pores. The $Ca\ (OH)_2$ or C-H crystal has been reduced due to the ceramic cement pozzolanic action with free portlandite to produce new C-S-H.

Nanoparticles were observed in the concrete to perform as an activator and accelerate the cement hydration process. They also perform as an important part of cement paste during the formation of the size of $Ca\ (OH)_2$ crystal [45]. The SEM micrographs show some ceramic particles readily react with C-H to produce a new form of C-S-H, enhancing the concrete strength. The SEM micrographs have shown a black and white mass which is C-S-H gel spread on the aggregate and performed as a binder in concrete. All mixes have needle hydrates, but the degree of crystallisation varies from mix to mix.

Energy-dispersive spectroscopy (EDS) was used to investigate the microchemistry of the selected samples. It has been used to obtain a localized chemical analysis using an X-ray spectrum emitted through a solid sample bombarded with electrons focused beam.

When using the X-rays, distinct positions along the line are detected, while the SEM electron rays scan across the specimen along a predetermined line across the specimen. A detailed analysis of the X-ray energy spectrum is provided at each position.A plot of the relative elemental concentration along the line for each element versus is obtained. The elemental weight of the PC and WOC specimens is shown in Figure 8 & 9 . The detected main elements of PC concrete are C,O,F,Mg,Al,Si,Ca and Fe and C,O,F,Mg,Al,Si,S,K,Ca,Ti,Fe,Zr and Au for WOC concrete as sown in the Table 6 & 7.

Table 6 PC element

Standard	Element	Weight%	Atomic%
$CaCO_3$	C	8.77	14.26
SiO_2	O	52.67	64.29
MgF_2	F	0.9	0.73
MgO	Mg	0.60	0.47
Al_2O_3	Al	2.05	1.48
SiO_2	Si	9.56	6.64
Wollastonite	Ca	25.41	12.38
Fe	Fe	0.64	0.22
	Totals	100.00	

Table 7 WOC element

Standard	Element	Weight%	Atomic%
$CaCO_3$	C	8.12	13.64
SiO_2	O	51.72	65.27
MgF_2	F	5.36	5.69
MgO	Mg	0.48	0.4
Al_2O_3	Al	1.43	1.07
SiO_2	Si	3.97	2.85
FeS2	S	0.2	0.12
K	MAD-10 Feldspar	0.57	0.29
Ca	Wollastonite	25.41	12.38
Ti	Ti	0.03	0.01
Fe	Fe	0.56	0.2
Zr	Zr	0.4	0.09
Au	Au	8.33	0.85
	Totals	100.00	

Conclusion

The present study looked into the compressive, tensile, flexural, and combined (flexural and torsional) strengths of concrete made from 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 A_{WC} 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 A_{WC} 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% A_{WC} constant), the CS of specimens with the replacement of cement by C_{WC}- 5%, 10%, were found to be greater than the reference concrete whereas, for 15-30% C_{WC} 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 C_{WC}. FS of the specimen with 5% C_{WC} 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 C_{WC} was taken as 10% as a replacement of OPC in WCC (with 20% A_{WC} 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% A_{WC} constant & 10% C_{WC} constant), TS were found to be decreasing as the percentage (%) of S_{WC} increases (from 5% to 30% as replacement of sand). The CS were found to be increasing as the percentage (%) of S_{WC} increases (from 5% to 10% as replacement of sand). Further, FS of specimens with 5-10% S_{WC} was found to be greater than the reference concrete, whereas for 15-30% S_{WC} the FS was found to be less than the reference concrete. Also, the UBS of specimens with 5% to 30% S_{WC} was found to be higher than the reference concrete specimens (WSC-0%). Finally, the optimal percentage as 20% A_{WC}, 10% C_{WC} and 10% S_{WC} 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).
- Concrete with ceramic materials has a dense and compacted microstructure, which fills fine pores. The pozzolanic action of ceramic cement with free Portlandite increases the amount of Ca(OH)2 or C–H crystals.
- The choice of using ceramic waste as a partial replacement to prepare concrete has benefit from the economic, environmental, and technological points of view. Moreover, it offers a possibility for improving the durability of concrete, which has vital importance.
- With less embodied energy and emissions, ceramic-modified concrete creates new functionalities that may help address environmental sustainability concerns.

Declarations

Funding: No funding is 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.

References

1. Heidari, A., & Tavakoli, D. (2013). A study of the mechanical properties of ground ceramic powder concrete incorporating nano-SiO2 particles. *Construction and Building Materials*, *38*, 255-264. https://doi.org/10.1016/j.conbuildmat.2012.07.110
2. Pacheco-Torgal, F., & Jalali, S. (2011). Compressive strength and durability properties of ceramic wastes based concrete. http://hdl.handle.net/1822/14459
3. Amin, S. K., Sibak, H. A., El-Sherbiny, S. A., & Abadir, M. F. (2016). An overview of ceramic wastes management in construction. *International Journal of Applied Engineering Research*, *11*(4), 2680-2685. https://doi.org/10.1016/j.conbuildmat.2015.03.028
4. Farinha, C., De Brito, J., & Veiga, R. (2015). Incorporation of fine sanitary ware aggregates in coating mortars. *Construction and Building Materials*, *83*, 194-206. https://doi.org/10.1016/j.conbuildmat.2011.12.075
5. Medina, C., Frías, M., & De Rojas, M. S. (2012). Microstructure and properties of recycled concretes using ceramic sanitary ware industry waste as coarse aggregate. *Construction and Building Materials*, *31*, 112-118. https://doi.org/10.1016/j.cemconcomp.2011.08.015
6. Medina, C., De Rojas, M. S., & Frías, M. (2012). Reuse of sanitary ceramic wastes as coarse aggregate in eco-efficient concretes. *Cement and concrete composites*, *34*(1), 48-54. https://doi.org/10.1016/j.conbuildmat.2012.08.023
7. Medina, C., Frías, M., de Rojas, M. S., Thomas, C., & Polanco, J. A. (2012). Gas permeability in concrete containing recycled ceramic sanitary ware aggregate. *Construction and Building Materials*, *37*, 597-605. https://doi.org/10.1016/j.cemconcomp.2010.02.004
8. Torkittikul, P., & Chaipanich, A. (2010). Utilization of ceramic waste as fine aggregate within Portland cement and fly ash concretes. *cement and concrete composites*, *32*(6), 440-449. https://doi.org/10.1016/j.conbuildmat.2014.04.037
9. Alves, A. V., Vieira, T. F., De Brito, J., & Correia, J. R. (2014). Mechanical properties of structural concrete with fine recycled ceramic aggregates. *Construction and Building Materials*, *64*, 103-113. https://doi.org/10.1016/j.conbuildmat.2018.11.033
10. Keshavarz, Z., & Mostofinejad, D. (2019). Porcelain and red ceramic wastes used as replacements for coarse aggregate in concrete. *Construction and Building Materials*, *195*, 218-230. https://doi.org/10.1016/j.hbrcj.2016.11.003
11. Awoyera, P. O., Ndambuki, J. M., Akinmusuru, J. O., & Omole, D. O. (2018). Characterization of ceramic waste aggregate concrete. *HBRC journal*, *14*(3), 282-287. https://doi.org/10.1016/j.conbuildmat.2017.07.219

12. Rashid, K., Razzaq, A., Ahmad, M., Rashid, T., & Tariq, S. (2017). Experimental and analytical selection of sustainable recycled concrete with ceramic waste aggregate. *Construction and Building Materials*, *154*, 829-840. https://doi.org/10.1016/j.cemconcomp.2010.02.004
13. Torkittikul, P., & Chaipanich, A. (2010). Utilization of ceramic waste as fine aggregate within Portland cement and fly ash concretes. *cement and concrete composites*, *32*(6), 440-449. https://doi.org/10.1016/j.proeng.2015.06.199
14. Gonzalez-Corominas, A., & Etxeberria, M. (2014). Properties of high performance concrete made with recycled fine ceramic and coarse mixed aggregates. *Construction and building materials*, *68*, 618-626. https://doi.org/10.1617/s11527-008-9411-9
15. Gomes, M., & de Brito, J. (2009). Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance. *Materials and structures*, *42*(5), 663-675. https://doi.org/10.1016/j.conbuildmat.2018.01.052
16. Nepomuceno, M. C., Isidoro, R. A., & Catarino, J. P. (2018). Mechanical performance evaluation of concrete made with recycled ceramic coarse aggregates from industrial brick waste. *Construction and Building Materials*, *165*, 284-294. https://doi.org/10.1016/j.conbuildmat.2018.01.052
17. Sekar, M. (2017). Partial replacement of coarse aggregate by waste ceramic tile in concrete. *International Journal for Research in Applied Science and Engineering Technology*, *5*(3), 473-479. https://doi.org/10.1016/j.conbuildmat.2018.01.052
18. Correia, J. R., de Brito, J., & Pereira, A. S. (2006). Effects on concrete durability of using recycled ceramic aggregates. *Materials and structures*, *39*(2), 169-177. https://doi.org/10.1617/s11527-005-9014-7
19. Dharma, F. C. (2018, December). The effect of thermal treatments on recycled alternative aggregates toward concrete properties. In *IOP Conference Series: Earth and Environmental Science* (Vol. 195, No. 1, p. 012023). IOP Publishing.
20. Anderson, D. J., Smith, S. T., & Au, F. T. (2016). Mechanical properties of concrete utilizing waste ceramic as coarse aggregate. *Construction and Building Materials*, *117*, 20-28. https://doi.org/10.1016/j.conbuildmat.2016.04.153
21. Lavat, A. E., Trezza, M. A., & Poggi, M. (2009). Characterization of ceramic roof tile wastes as pozzolanic admixture. *Waste management*, *29*(5), 1666-1674. https://doi.org/10.1016/j.wasman.2008.10.019
22. Puertas, F., García-Díaz, I., Barba, A., Gazulla, M. F., Palacios, M., Gómez, M. P., & Martínez-Ramírez, S. (2008). Ceramic wastes as alternative raw materials for Portland cement clinker production. *Cement and Concrete Composites*, *30*(9), 798-805. https://doi.org/10.1016/j.cemconcomp.2008.06.003
23. Shamsaei, M., Khafajeh, R., Tehrani, H. G., & Aghayan, I. (2020). Experimental evaluation of ceramic waste as filler in hot mix asphalt. *Clean Technologies and Environmental Policy*, *22*(2), 535-543. https://doi.org/10.1007/s10098-019-01788-9
24. Modarres, A., Hesami, S., Soltaninejad, M., & Madani, H. (2018). Application of coal waste in sustainable roller compacted concrete pavement-environmental and technical assessment. *International Journal of Pavement Engineering*, *19*(8), 748-761. https://doi.org/10.1080/10298436.2016.1205747
25. Leite, M. (2001). Evaluation of the Mechanical Properties of Concrete Made with Recycled Aggregates from Construction and Demolition Waste. PhD thesis on Civil Engineering, School of Engineering, Federal University of Rio Grande do Sul, Porto Alegre, Brazil., 270 pp. (in Portuguese).
26. Siddesha, H. (2011). Experimental Studies on the Effect of Ceramic fine aggregate on the Strength properties of concrete. *Int. J. Adv. Eng. Sci. Technol*, *1*(1), 71-76.
27. Reddy, M. V., & Reddy, C. N. V. S. (2007). An experimental study on use of Rock flour and insulator ceramic scrap in concrete. *Journal-Institution Of Engineers India Part Me Mechanical Engineering Division*, *88*(G), 47.
28. Nayana, A. M., & Rakesh, P. (2018). Strength and durability study on cement mortar with ceramic waste and micro-silica. *Materials Today: Proceedings*, *5*(11), 24780-24791. https://doi.org/10.1016/j.matpr.2018.10.276
29. Mohammed, H., & Ahmed, S. (2020). Mechanical Performance Evaluation of Concrete with Waste Coarse Ceramic Aggregate. In *Smart Cities—Opportunities and Challenges* (pp. 593-605). Springer, Singapore.
30. Najm, H. M., & Ahmad, S. (2021). The effect of metallic and non-metallic fiber on the mechanical properties of waste ceramic concrete. *Innovative Infrastructure Solutions*, *6*(4), 1-15. https://doi.org/10.1007/s41062-021-00571-4
31. Standard, I. (1959). Method of tests for strength of concrete. Bureau of Indian Standards, Manak Bhavan, 9.
32. Najm, H. M., Ahmad, S., & Submitter, Y. (2021). Artificial Neural Networks for Evaluation & Prediction of the Mechanical Properties of Waste Ceramic Optimal Concrete Exposed to Elevated Temperature. *Available at SSRN 4032028*. http://dx.doi.org/10.2139/ssrn.4032028
33. Najm, H. M., & Ahmad, S. (2021). Effect of elevated temperatures exposure on the mechanical properties of waste ceramic concrete reinforced with hybrid fibers materials. *Sigma J. Eng. Nat. Sci*.
34. Najm, H. M., & Ahmad, S. (2022). Mechanical and microstructural characterization of waste ceramic optimal concrete reinforced by hybrid fibers materials. *Revista Ingenieria de Construccion*

Chart

Chart 1-15 are available in Supplementary Files section.

Figures

Figure 1

(a) Commercial cement (b) river sand (c) Natural Coarse Aggregates (NCA)-0.01m (d) Natural Coarse Aggregates (NCA)-0.02m

Figure 2

(a) waste ceramic cement (C_{WC})-75μm (b) waste ceramic sand (S_{WC})-0.00475m (c) waste ceramic aggregate (A_{WC})-0.01m (d) waste ceramic aggregate (A_{WC})-0.02m

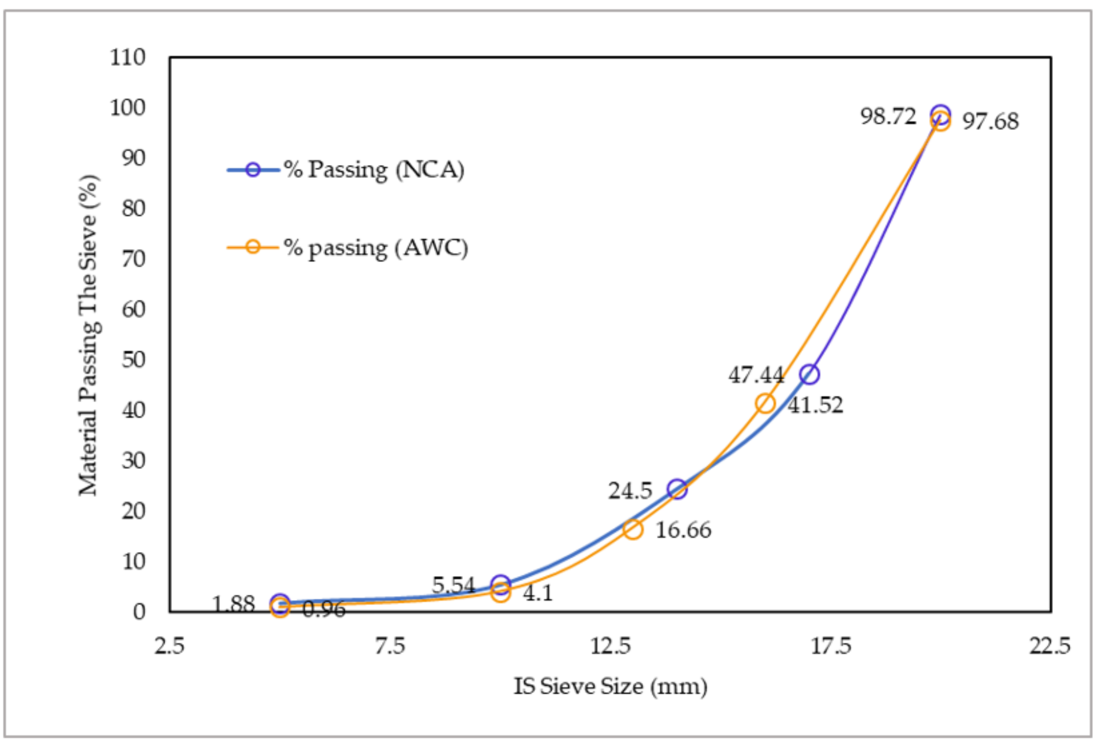

Figure 3

Particle Size Distribution of Natural Coarse Aggregate & Ceramic Coarse Aggregate

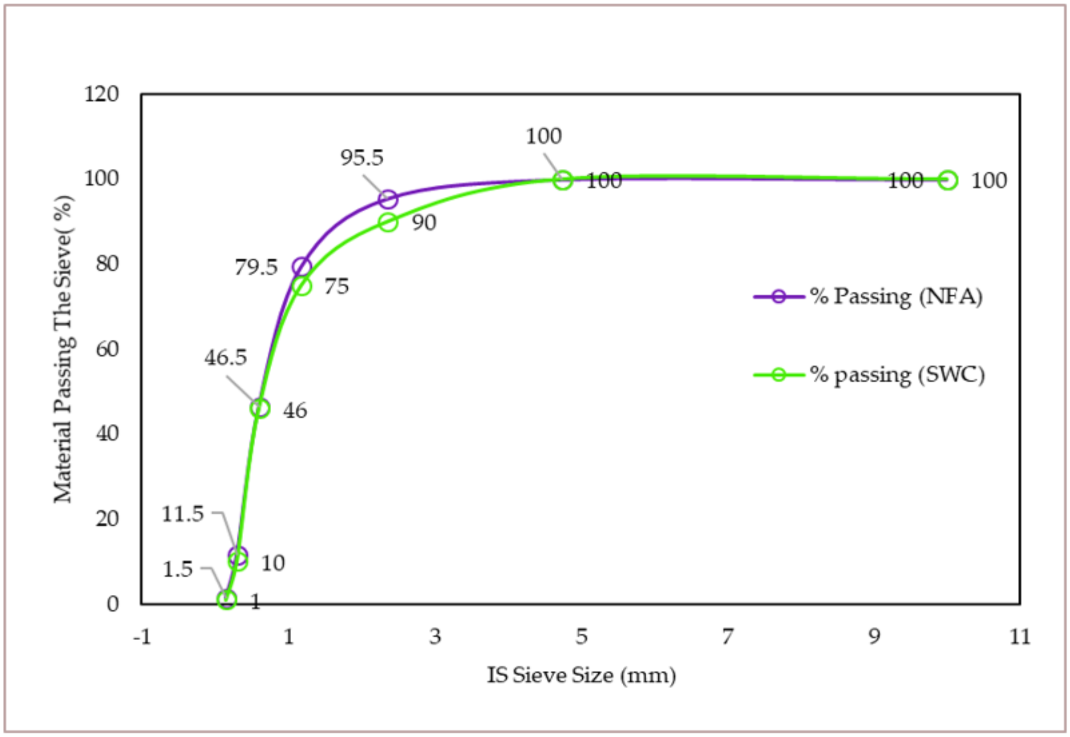

Figure 4

Particle Size Distribution of Natural Fine Aggregate & Ceramic Fine Aggregate

Figure 5

Specimen: cubes, cylinders and beams

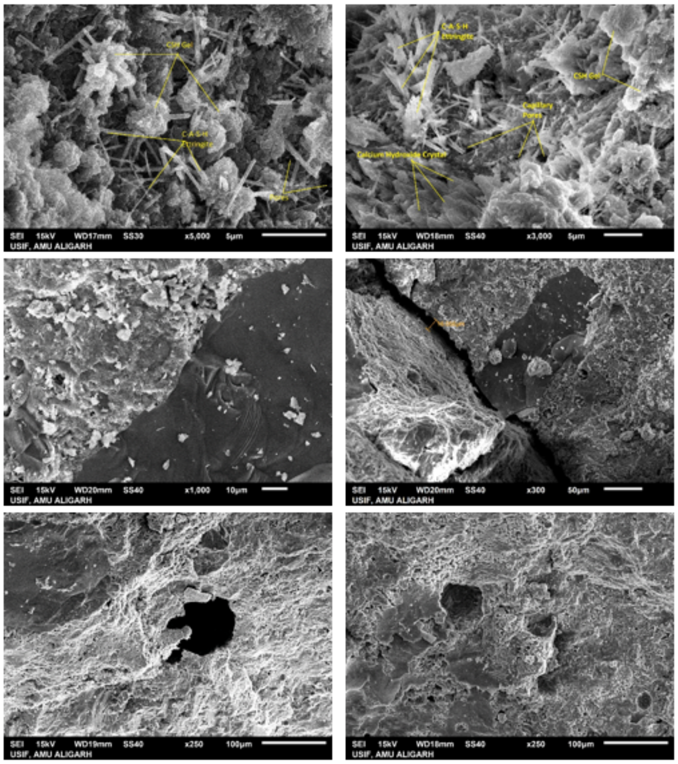

Figure 6

SEM of PC Concrete

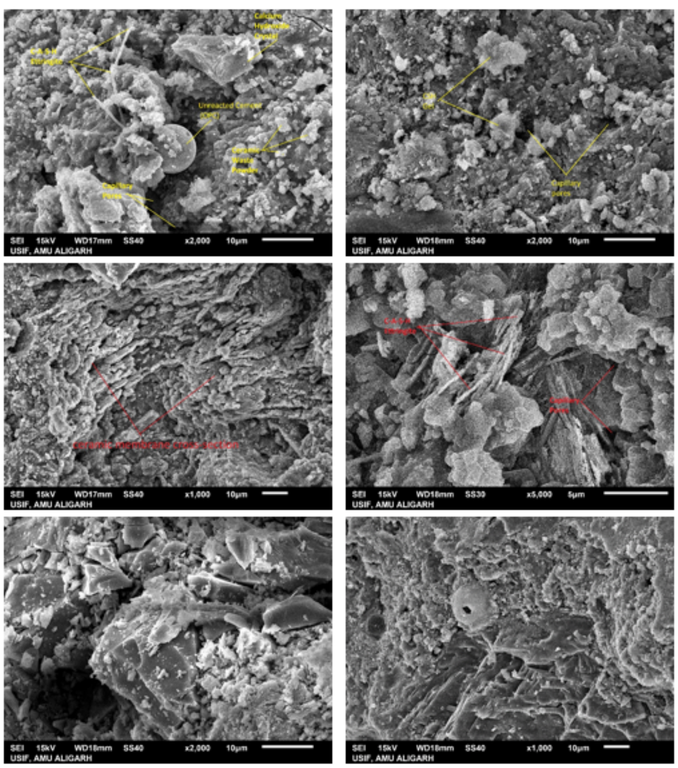

Figure 7

SEM of WOC Concrete

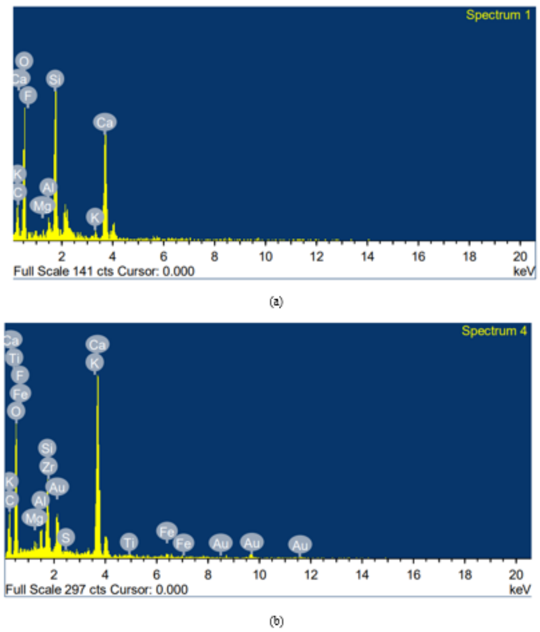

Figure 8

SEM of : a) PC and b) WOC element Concrete

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- c1.png
- c2.png
- c3.png
- c4.png
- c5.png
- c6.png
- c7.png
- c8.png
- c9.png
- c10.png
- c11.png
- c12.png
- c13.png
- c14.png
- c15.png