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Journal of Architectural Environment & Structural Engineering Research

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ARTICLE

Mechanical and Microstructural Analysis of Waste Ceramic Optimal Concrete Reinforced by Hybrid Fibers Materials: A Comprehensive Study

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ARTICLE INFO

Article history
Received: 7 July 2022
Revised: 8 August 2022
Accepted: 22 August 2022
Published Online: 1 September 2022

Keywords:
Hybrid fibers
Hooked end steel fiber
Crimped steel fiber
Polyvinyl alcohol fibers
Waste ceramic optimal concrete

ABSTRACT

Combining different types of fibers inside a concrete mixture was revealed to improve the strength properties of cementitious matrices by monitoring crack initiation and propagation. The contribution of hybrid fibers needs to be thoroughly investigated, considering various parameters such as fibers type and content. The present study aims to carry out some mechanical and microstructural characteristics of Waste Ceramic Optimal Concrete (WOC) reinforced by hybrid fibers. Reinforcement materials consist of three different fiber types: hook-ended steel fiber (HK), crimped steel fiber (CR) and polyvinyl alcohol (PVA) fibers and the effect of their addition on the waste ceramic composites' mechanical behaviour. Furthermore, a microstructural analysis was carried out to understand the waste ceramic matrix composition and its bonding to hybrid fibers. Results showed that the addition of hybrid fibers improved the strength characteristics of the ceramic waste composites. For instance, the existence of PVA-CR increased the tensile and flexural strength of the waste ceramic composite by 85.44% and 70.37%, respectively, with respect to the control sample (WOC). As well as hybrid fiber 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 hybrid fibers into the concrete mix. The present experimental research shows the choice of using steel fiber with PVA as a reinforcement material. The idea of adding hybrid fiber is to prepare the economic, environmental, and technological concrete. Moreover, it offers a possibility for improving concrete's durability, which is vital. Finally, it was concluded that steel fiber is more durable, and stiffer and provides adequate first crack strength and ultimate strength. In contrast, the PVA fiber is relatively flexible and improves the post-crack zone's toughness and strain capacity.

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DOI: https://doi.org/10.30564/jaeser.v5i3.4794

1. Introduction

Concrete can be described as a hard material with low-straining bulk. Reinforcing the concrete using small and randomly distributed fibres could address different issues such as the brittleness and the poor residence to crack of the concrete. In this regard, Kim and Park [1] refer to the significance of enhancing the concrete strength. They indicated that utilising the fibre in concrete will be an effective way to for filling the spacing and that will strengthen the concrete.

Banthia, N., et al. [2] state that applying the fibre in concrete provides enforcement at one and limited range of strain. Thus, several kinds of fiber with changes in constitutive responses, sizes, and functions must be combined to achieve an optimal response. The resulting fibre reinforced concrete mixture is frequently referred to as hybrid FRC, or HyFRC for short.

Regardless of all the mentioned above regarding the fibre efforts in the reinforced concrete, the mixing of the fibre to get a perfect performance of concrete is still quite limited, all the previous studies emphasised on normal or high-performance concrete's mechanical behaviour with hybrid fibers only. While the present study focuses on ceramic waste optimal concrete with hybrid fibers and there is no available data to demonstrate waste ceramic concrete reinforced by hybrid fiber and tested under compression, tension, flexure and combined (flexure and torsion). There is also a great deal of current interest in Synthetic fibers such as PVA & PP, and its performance in HyFRC has never been investigated. Accordingly, this study was undertaken to combine steel (Hooked ended and Crimped) and PVA-fibers in HyFRC and to assess the response under CS, TS, FS & FTS.

Waste ceramic optimal Concrete (WOC) is mainly related to the economic and sustainable concrete with improved mechanical properties (mechanical strength, durability, elasticity modules, etc.). The WOC can be prepared by the addition of waste ceramic as replacement of cement and aggregate (fine and coarse) concerning the size limitation for the maximum size of aggregates and cement (10 mm, 20 mm, and 75 micros) [3].

In terms of waste sutilisations which become a significant problem in recent times, waste ceramics may be used in place of cement and (fine and coarse) aggregate in the concrete mixes. In this way, it can eliminate environmental pollution and create value-added products. For example, in India, recently, an enormous quantity of ceramic waste tiles is produced. Therefore, nowadays, the study is mainly focused on reusing or recycling and recovering waste materials with the help of different applications; it has become the most important topic for research papers. For example, ceramic wastes as a result of tiles production, have been employed to be used as substitutes for coarse aggregate in concrete Keshavarz & Mostofinejad [4]. Also, A. Heidari & Tavakoli [5] has focused on using ceramic waste tiles as a Pozzolanic material in concrete. Torkittikul, & Chaipanich [6] studied the uses of ceramic waste tiles to replace fine aggregate (sand) for manufacturing mortar and concrete. Awoyera et al. [7] has focused on the mechanical properties of ceramic waste floors and wall tiles to replace aggregate in concrete.

Concrete with ceramic waste has economic efficiency, good flexural, and compression strength. It is inherently brittle and has low elasticity, low tensile strength, and low cracking resistance. To overcome the shortcomings of standard concrete, reinforced concrete was developed by incorporating two types of metallic fiber (crimped steel fiber and hook ended steel fiber) and non-metallic fiber (polyvinyl alcohol fiber and polypropylene fiber), was randomly dispersed discontinuously in the concrete. Since randomly dispersed fiber inhibits crack growth and propagation, fiber reinforced concrete has significantly higher

Most of the fiber-reinforced concrete used in experimental work contains only one type of fiber such as Crimped steel fiber with length 50 mm [8], Hook Ended steel fiber with length 60 mm [9] Polyvinyl Alcohol fiber with length 12 mm, Polypropylene fiber (PP) with length 12 mm [10].

The fiber may be combined for optimal response. So, in hybrid concretes, one fibre type is more durable and stiffer that providing the first crack strength and ultimate strength. In contrast, the second type of fiber is relatively flexible and improves toughness and stress capacity in the post-cracking zone [2].

To improve the brittle fracture characteristics and crack control and low tensile strength of concrete, research on fiber reinforced concrete has been steadily attracting attention since the 1960s. The initial researches on the mechanical properties of fiber-reinforced concrete focused on concrete using steel fibers only. It then expanded to studies using various synthetic fibers such as aramid and polyethene from the early 1980s. These fiber-reinforced concretes are generally limited to single fibers, but gradually, to secure high toughness along with crack control of concrete, starting in the late 1990s, hybrid fiber-reinforced concrete mixed with two or more fibers was developed.

Most studies on hybrid fiber reinforced concrete have been concentrated on high-performance concrete, which is being used in industries & lack behind in terms of economy and workability. In contrast, the current study focuses on waste ceramic optimal concrete with hybrid fibers (volume ratio 1% and 2%) [1].

Mixing of different fibers or using hybrid fibers of the same type having different lengths can effectively control the growth of cracks and improve the tensile strength of concrete. The hybridisation of fibers with different material properties effectively increases the strength and ductility of concrete, and the hybridisation of fibers of different lengths effectively controls micro-crack and macro-cracks. It is the most commonly used fiber in the field, although it reduces the flow of concrete and is very effective in improving strength and ductility.

Polyvinyl alcohol (PVA) fiber is a hydrophilic material that does not deteriorate the fluidity of concrete more severely and has low rigidity. It has good dispersibility while mixing concrete and is effective in controlling fine cracks. The hybridisation of steel-PVA fiber effectively secures concrete fluidity and increases strength and ductility.

According to Acikbas & Yaman [11] the combination of two types of matrix or two different types of reinforced materials will result in hybrid concrete, that is one of the classes of composite material.

The improvement of concrete mechanical properties results from concrete reinforcement with a single type of fiber, and has found in a limited range. In contrast, hybrid concrete with two or more types of fiber provides superior properties because cracks occur on various levels and in different sizes. Using several types of fiber with different lengths is the correct way to solve this problem. A good interactive relation between fibers, which is a well-designed composite system, creates the result in improving hybrid performances than mono fiber composite [12].

Tabatabaeian et al. [13] focused on the mechanical properties of hybrid fiber in the mixes of concrete where he used hook end steel fiber and crimped steel fiber both at the same time. Mechanical properties of concrete such as modulus of rupture, compressive strength, flexural strength, and tensile strength were tested. As a result, a slight increase was found in the compressive strength of hybrid concrete. While the modulus of rupture and tensile strength increased dramatically compared to the control specimens, this was because of the active use of steel fiber to control the crack propagation, reducing its growth, and providing a higher contact surface area was attributed.

Kim, & Park [14] examined hybrid fiber reinforced concrete with two types of synthetic fibers, i.e., polypropylene fiber (PP) and polyvinyl alcohol fiber (PVA) were considered in the study. The final results showed that PVA-hybrid fiber concrete had better properties than PP- hybrid fiber concrete. It was attributed to stronger hydrogen bonding by the hydrophilic PVA fiber, which led to superior resistance to crack propagation and microcracking.

It has been observed in the literature that there are existing experimental works to predict the behaviour of ceramic concrete or hybrid fiber concrete [15-24]. However, there is no available experimental work to evaluate the effect of adding Hooked end steel fiber (HK) +polyvinyl alcohol (PVA) or Crimped steel fiber (CR) + polyvinyl alcohol (PVA) with waste ceramic materials on the mechanical properties of concrete, as well as find out the optimal hybridisation of Hooked end steel fiber (HK) +polyvinyl alcohol (PVA) or Crimped steel fiber (CR) + polyvinyl alcohol (PVA), which is important to investigate under different loadings (Compressive, tensile, flexural and torsion); this study can be used to be a reference for future studies and provide extensive data for hybridisation of fibers with ceramic materials studies.

The rest sections of this paper are organised as follows. Research significance is briefly introduced in section 2. In section 3, experimental work is described in detail which include description of materials used, preparation of specimens & mix proportions. In section 4 results and discussion of the experimental results are analysed and discussed as effect of PVA-HK and PVA-CR hybrid fiber on compressive strength, tensile strength, flexural strength & combined flexural and torsion strength of WOC. Finally, conclusions are given in section 5.

Finally, the present research article highlights the following:

- The study focused on the mechanical and microstructural properties of waste ceramic optimal concrete (WOC) with hybrid fibers HK, CR and PVA.
- The study aimed to find out the optimal hybridisation of Hooked end steel fiber (HK) +polyvinyl alcohol (PVA) or Crimped steel fiber (CR) + polyvinyl alcohol (PVA).
- In hybridisation, one fibre type is more durable and stiffer than providing the first crack strength and ultimate strength and the second type of fiber is relatively flexible and improves toughness and stress capacity in the post-cracking zone.
- The results of the study have expected to add the knowledge guideline on the use of ceramic waste material to alleviate the negative ceramic impact on the environment and contribute to sustainable concrete production.

2. Research Significance

Fracture in concrete is a gradual, multi-scale process, occurring at both the micro and the macro levels. For fiber reinforced concrete, therefore, is very limiting when only one type and dimension of fiber is used as reinforcement. Such reinforcement clearly restricts crack growth at its own scale and has little or no influence on fracture processed at other scales. For maximum reinforcing efficiency, fibers of various types must be combined in a rational manner. In this paper, WOC-hybrid fiber reinforced concrete mixes carrying various combinations of steel and PVA fibers were studied under compression, tension, flexural and combined (flexural and torsion) loading, and performance was investigated.

3. Materials and Methods

3.1 Materials

The materials used in this study included Ordinary Portland Cement (OPC) 43-grade, Natural Coarse Aggregate (NCA)/stones, coarse river sand, ceramic floor tiles with three types of fiber Hook End Steel Fiber (HK), Crimped Steel Fiber (CR), and Polyvinyl Alcohol Fiber have been used as described below.

3.1.1 Cement

In this study, two types of cement were used the first one was 43 grade of Ordinary Portland Cement (OPC) conforming to IS: 8112-1989 and the second one waste ceramic cement (C_{WC}). The main constituents of OPC (43 grade) and 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. Tables 1 & 2 summarises the chemical and physical properties of OPC (43 grade) and C_{WC}.

3.1.2 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}). Ceramic aggregate is very compact with a low porosity but high strength. As the latest product of ceramic technology, it's manufactured from clay, feldspar, or 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.

Baking at high temperatures makes ceramics vitreous with low porosity and extremely low water absorption, often termed as artificial stones. Due to their very high strength, they cannot be easily recycled back into the manufacturing line and are, therefore, generally dumped and released as waste into the environment. It is, therefore, desirable to find ways to reuse them in beneficial ways.

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 10 mm (waste ceramic aggregate- A_{WC}); 4.75 mm (waste ceramic sand- S_{WC}) (Figures 2 & 3).

Both aggregates were graded according to IS code as shown in Figures 1 & 2. The natural and ceramic aggregates thus obtained were characterised 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.

3.1.3 Fibers

Three types of reinforcement materials, including Hook End Steel Fiber (HK), Crimped Steel Fiber (CR), and Polyvinyl Alcohol Fiber (PVA) have been used as shown in Figure 3 & Table 3. PVA fiber is a hydrophilic material having a hydroxyl group. It has excellent adhesion to cement matrix, excellent dispersibility, and is a micro synthetic short fiber with a diameter of 0.04 mm. Steel fibers are cut in pieces from manufactured bundles so that they are easily dispersed when mixed with concrete and have hooks at both ends to improve adhesion and fixing performance with cement matrix. Table 3 shows the properties of fibers used.

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

Figure 1. (a) Commercial cement; (b) river sand; (c) natural coarse aggregates (NCA)—10 mm; (d) natural coarse aggregates (NCA)—20 mm.

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

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

(a) (b) (c)

Figure 3. metallic and non-metallic fiber: (a) Crimped Steel fiber (CR; 60 mm) (b) Hook Ended steel fiber (HK; 60 mm) (c) Polyvinyl Alcohol fiber (PVA; 12 mm)

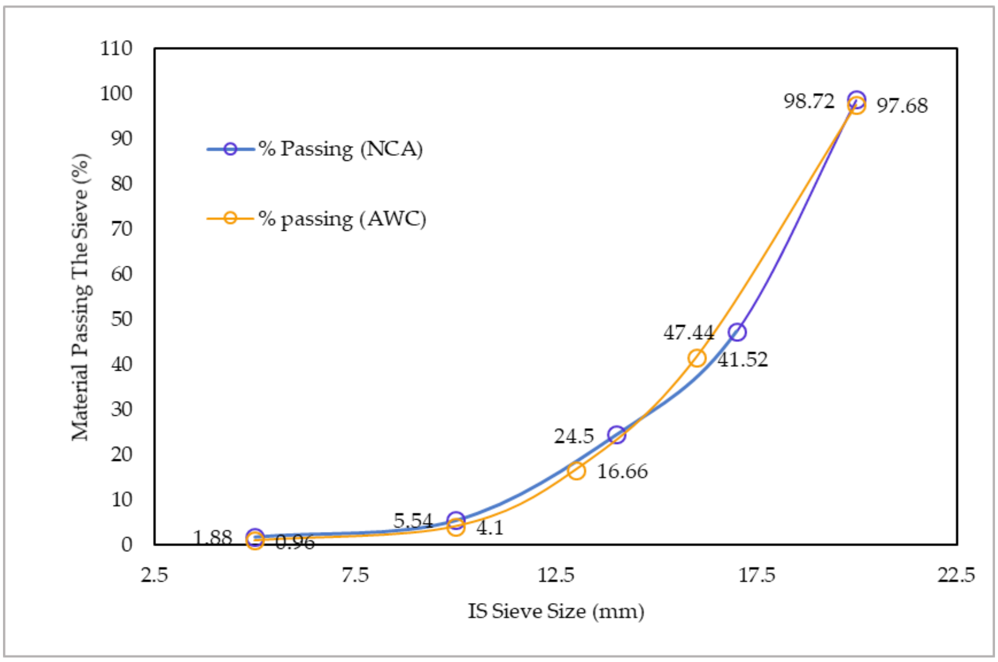


Figure 4. Particle Size Distribution of Natural Coarse Aggregate & Ceramic Coarse Aggregate

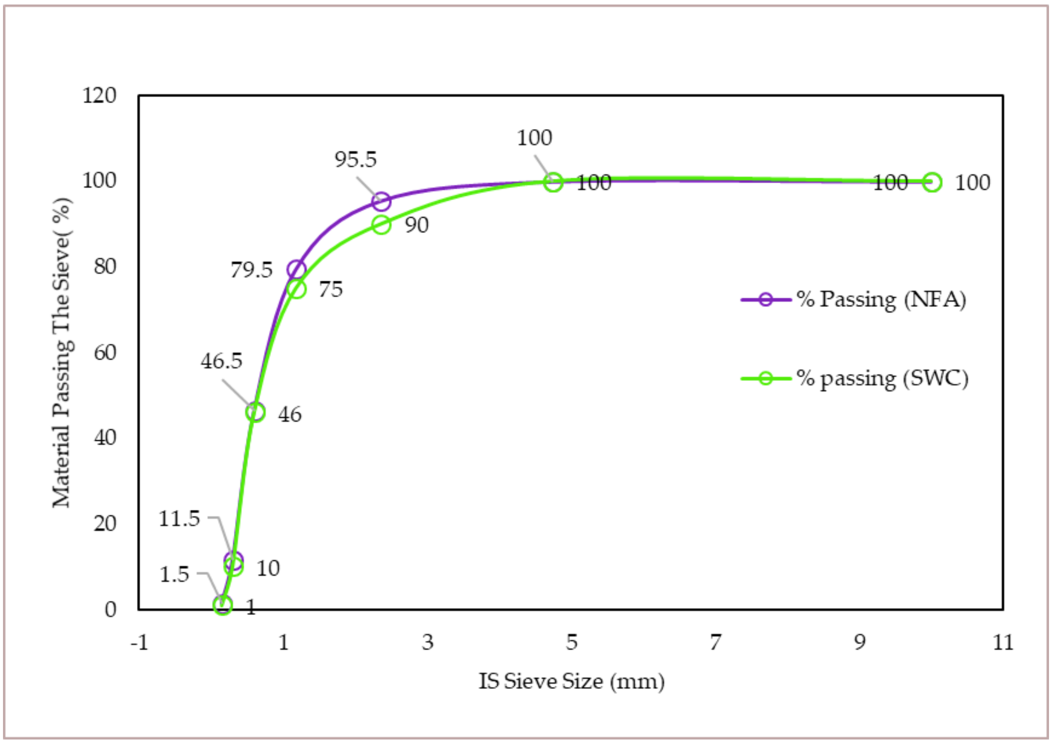


Figure 5. Particle Size Distribution of Natural Fine Aggregate & Ceramic Fine Aggregate

Table 1. Properties of Used Material

Physical Properties	**Cement – OPC**	**NCA**	**Sand**	**C_{WC}**	**A_{WC}**	**S_{WC}**
Normal consistency (%)	32	-	-	8	-	-
Specific Gravity	3.15	2.84	2.64	2	2.31	2.26
Initial setting time	42 minute	-	-	54 minutes	-	-
Final setting time	600 minute	-	-	680 minutes	-	-
7 days compressive strength	21.1 MPa	-	-	37	-	-
Finesse modules	-	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/m³)	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 Analyses of Waste Ceramic Powder and OPC

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

Table 3. Properties of Used Fibers

Fiber Type	CR	PVA
Surface	Plane	-
Cross-section	Circular	-
Anchorage	Continuous	Straight
Length (mm)	50 mm	12 mm
Diameter (mm)	1	0.04
Aspect ratio	50	300
Density (g/cm^3)	7.85	1.3
Tensile strength (MPa)	1250	1560
Elastic modulus (GPa)	200	41

3.2 Mix Design

Overall, 6 phases were carried out in this study as described below:

1) The first phase of mix design includes the control mix with ceramic waste material as a replacement of cement and aggregate (Fine & Coarse) without any addition of single or hybrid fibers named as Waste Ceramic Optimal Concrete (WOC).

2) The second Phase of mix design included the single addition of hook end steel fiber (50 mm length) with a volume ratio 1% named as HK-1-WOC.

3) The third Phase of mix design included the single addition of crimped steel fiber (50 mm length) with a volume ratio 1% named as CR-1-WOC.

4) the Fourth phase of the mix design included the single addition of polyvinyl alcohol fiber (12 mm length) with a volume ratio 1% named as PV-1-WOC.

5) The Fifth phase of the mix design included the hybrid addition of Hook ended steel fiber (1%, 50 mm length) and polyvinyl alcohol fiber (1%, 12 mm length) named as HK-1-WOC.

6) The Sixth phase of mix design included the hybrid addition of Crimped steel fiber (1%, 50 mm length) and polyvinyl alcohol fiber (1%, 12 mm length) named as CR-1-WOC.

*In every phase, 12 specimens have been cast, including 3 cubes, 3 cylinders and 6 beams. 3 cubes were tested under compression, 3 cylinders were tested under tension 3 beams were tested for flexural, and the remaining 3 beams were tested for the combined (flexural and torsional) strength test. Details are shown in Table 4.

Table 4. Description of Phase Testing of Total 72 Test Specimens

phase	Samples	Percentage of Fiber	Purpose of Casting: Compressive Strength (Cube)		Tensile Strength (Cylinder)		Flexural Strength (Beam)		Combined (Flexure + Torsional) Strength (beam)	
			N.	Size (mm)	N.	Size (mm)	N.	Size (mm)	N.	Size (mm)
Phase 1	WOC	0% of fiber	3	150*150*150	3	150 * 300	3	100*100*500	3	100*100*500
Phase 2	HK-1-WOC	1% of HK steel fiber	3	150*150*150	3	150 * 300	3	100*100*500	3	100*100*500
Phase 3	CR-1-WOC	1% of CR steel fiber	3	150*150*150	3	150 * 300	3	100*100*500	3	100*100*500
Phase 4	PVA-1-WOC	1% of PVA fiber	3	150*150*150	3	150 * 300	3	100*100*500	3	100*100*500
Phase 5	PVA-HK-WOC-2%	1% of PVA fiber and 1% of HK steel fiber	3	150*150*150	3	150 * 300	3	100*100*500	3	100*100*500
Phase 6	PVA-CR-WOC-2%	1% of PVA fiber and 1% of CR steel fiber	3	150*150*150	3	150 * 300	3	100*100*500	3	100*100*500

3.3 Preparation of Specimens

A total of 72 specimens were cast to investigate the mechanical properties of WOC with single and hybrid fiber and find its optimal use. For this purpose, 18 cubes (150 * 150 * 150 mm), 18 cylinders (150 * 300 mm), and 36 beams (100 * 100 * 500 mm) were cast with varying types of fiber (HK, CR and PVA). 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 addition of fiber are shown in Table 5.

3.4 Test Procedures

The properties of fresh and hardened WOC and WOC-Hybrid mixes were determined using test procedures adapted from those used for traditional Portland cement-based concrete. Test methods were selected to allow simple characterisation 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 characterisation of all mixtures was carried out through the tests detailed in Table 5.

3.5 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, Ja-pan) 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 coat-ed with carbon or gold. The specimens in this study were coated in gold.

Table 5. Mix Proportion

Mix Ingredients (kg/m^3)						
Material	**WOC**	**HK-1-WOC**	**CR-1-WOC**	**PVA-1-WOC**	**PVA-HK-WOC-2%**	**PVA-CR-WOC-2%**
Water	190	190	190	190	190	190
OPC (43 grade)	342	342	342	342	342	342
C_{WC}	38	38	38	38	38	38
NCA	894	894	894	894	894	894
A_{WC}	224	224	224	224	224	224
Sand	548	548	548	548	548	548
S_{WC}	61	61	61	61	61	61
Weight Proportion Fiber (by Volume of Concrete)						
PVA %	-	-	-	13	13	13
HK %	-	78	-	-	78	-
CR %	-	-	78	-	-	78

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	

4. Results and Discussion

Table 6 summarises the results of the mechanical properties of the mixed hybrid fiber ceramic concrete. The Compressive Strength (CS), Tensile Strength (TS), Flexural Strength (FS) and combined (flexural and torsional) strength (FTS) of concrete has been expressed as a percentage of the reference concrete. In addition, in order to evaluate the properties of hybrid fiber ceramic concrete, these experimental results have been compared with previous studies and with single PVA fiber or single HK and CR steel fiber mixed concrete.

4.1 Effect of PVA-HK and PVA-CR Hybrid Fiber on Compressive Strength of WOC

The compressive strength results of single and hybrid fiber concrete for all specimens at the ages of 28 days are shown in Chart 1 and Table. 6. The previous study shows that the compressive strength of fiber reinforced concrete is significantly influenced by fiber mix, fiber strength, fiber linearity, fiber adhesion, fiber distribution and fiber length. Increasing the fiber volume ratio contributes to increased compressive strength by increasing the resistance to the long transverse strain. On the other hand, microcracks that occur along the load direction during the maximum compressive stress in concrete are over-controlled by short fibers rather than long fibers, so the shorter the fiber length, the better the compressive strength increases.

An increment of 16.07% and 5.52% in CS was observed for HK-1-WOC and CR-1-WOC, respectively, w.r.t WOC. A significant effect has occurred by adding 1% steel fiber (HK or CR) on compressive strength exhibited in WOC concrete. The compressive strength increment is due to steel Fiber's presence, which enhancing mechanical bond strength. The matrix of the steel fiber will supply the delaying microcrack formation and detain the propagation. The increase in the steel fiber volume ratio changed WOC's strength response and allowed the specimens (WOC + fiber) to exhibit greater peak strength than the plain specimens (WOC). Unreinforced concrete (WOC) has shown more brittleness behaviour and the addition of steel fibers to it has shown more ductile fractures.

On the other hand, the compressive strength of hybrid fiber reinforced concrete PVA-CR-WOC and PVA-HK-WOC increased by 16.87%, 21.73% respectively compared to unreinforced concrete (WOC) as shown in Chart 5. The compressive strength of concrete reinforced with PVA fiber and steel fiber was larger than that of concrete reinforced with single steel fiber, it was attributed to stronger hydrogen bonding by the hydrophilic PVA fiber, which led to superior resistance to crack propagation and microcracking.

K. H. Yang [1] has reported more or less similar behaviour for the addition hybrid fiber. The mentioned study has observed that the CS in specimens containing Hybrid fiber (PVA-HK) without ceramic material was enhanced by 17.52% [1]. In contrast, in the present study, specimens containing hybrid fibers (PVA-HK) with ceramic material (PVA-HK-WOC) have been enhanced by 21.73%. This achievement may be due to the effective quantitation of the fibers into the ceramic waste tiles. Figure 4 shows compressive strength test specimens at failure.

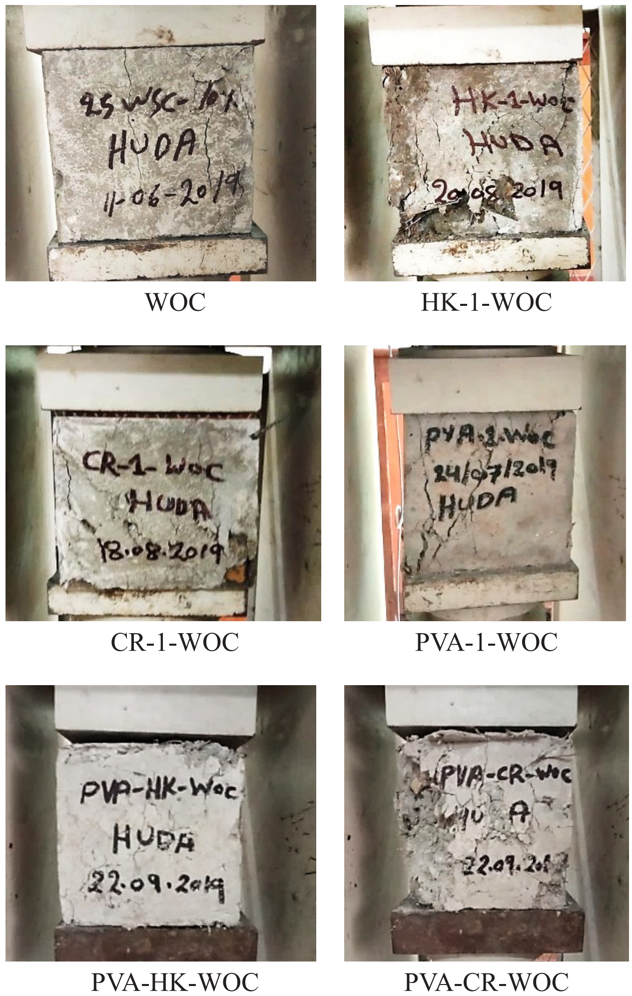


Figure 4. Compression test specimens: WOC, HK-1-WOC, CR-1-WOC, PVA-1-WOC, PVA-HK-WOC and PVA-CR-WOC CR-1-WOC at failure

4.2 Effect of PVA-HK and PVA-CR Hybrid Fiber on Tensile Strength of WOC

One of the easiest and most popular methods for indirect measurement of concrete's tensile strength is the split tensile strength test. The Tensile Strength results of single and hybrid fiber concrete for all specimens at the ages of

28 days are shown in Chart 2 and Table 6.

It can be seen from the results, the improvement in tensile strength by incorporating metallic fiber (HK or CR) and non-metallic fiber (PVA) exhibits a similar trend to that observed for compressive strength. The specimens reinforced with HK, CR, and PVA fiber show excellent enhancement in tensile strength ranging from 34.7% for HK-1-WOC, 50 % for CR-1-WOC, and 30.59% for PVA-1-WOC, respectively.

The results show that metallic fiber (HK or CR) hybridisation with non -metallic fiber (PVA) could improve the tensile strength of WOC concrete specimens. The tensile strength of PVA-HK-WOC and PVA-CR-WOC concrete was enhanced by 55.97% and 85.44%, respectively, compared to the reference model (WOC) as shown in Chart 5.

As compared to compressive strength, the tensile strength is more sensitive to the addition of hybrid fiber and highly effective at the same fibers volume ratio (1% PVA + 1% CR). It must be noted that the hybridisation of concrete by fibers must have two types of fibers, the first type of the used fibers (HK or CR) should be more durable and stiffer which provides the first crack strength and ultimate strength. Whereas the second type of used fibers (PVA) is relatively flexible, and improves toughness and stress capacity in the post-cracking zone.

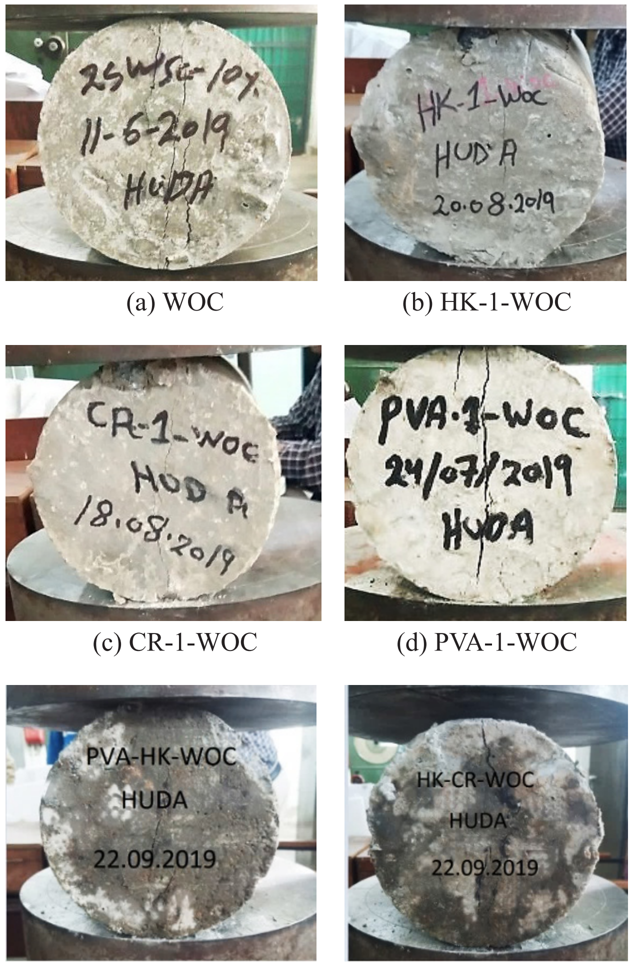
Yangs [1] has studied the effect of addition hybrid fibers (PVA-HK) on TS of concrete. On the basis of comparison between the mentioned study and the present study, it was observed that the TS in specimens containing hybrid fibers (PVA-HK) without ceramic material was enhanced by 63.36% [1] whereas the specimens containing hybrid fibers (PVA-HK) with ceramic material (PVA-HK-WOC) was enhanced by 55.97%. Figure 5 shows tensile strength test specimens at failure.

4.3 Effect of PVA-HK and PVA-CR Hybrid Fiber on Flexural Strength of WOC

Flexural strength is a needful parameter in assessing single and hybrid fiber's influence on the response of the concrete composites. The flexural strength reflects the ability of energy consumption of concrete after cracking. The flexural strength of single and hybrid fiber concrete is shown in Chart 3 and Table 6.

The addition of single fibers (HK, CR and PVA) improves the flexural strengths of WOC concrete by 33.34% for HK-1-WOC, 40.74% for CR-1-WOC and 9.62% for PVA-1-WOC as shown in Chart 5.

In this study, the flexural strength increased in the hybridisation models. Where the flexural strength was more significant for the addition of hybrid fiber (PVA-CR). The specimens of PVA-HK-WOC and PVA-CR-WOC showed an increment of 48.14% and 70.37%, respectively in the FS w.r.t reference model (WOC) as shown in Chart 5.



(a) WOC (b) HK-1-WOC

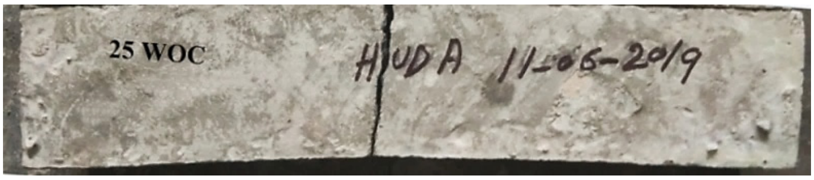
(c) CR-1-WOC (d) PVA-1-WOC

e) PVA-HK-WOC (f) PVA-CR-WOC

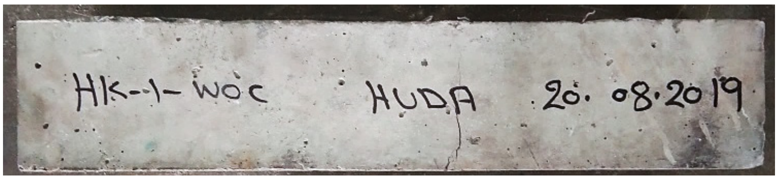
Figure 5. Tension test specimens: WOC, HK-1-WOC, CR-1-WOC, PVA-1-WOC, PVA-HK-WOC and PVA-CR-WOC CR-1-WOC at failure

One of the reasons for the higher performance of WOC-Hybrid fiber reinforced concrete is the PVA fibers effectively control the crack propagation at the bending crack tip and the steel fibers resist the widening of the crack width, thereby greatly enhancing concrete's flexural strength.

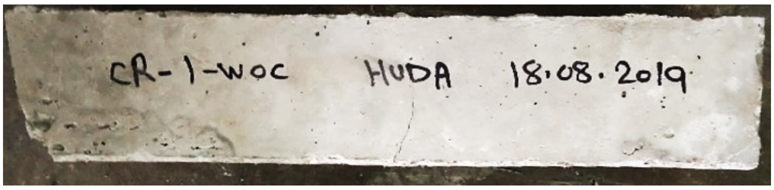
Yang [1] has reported more or less similar behaviour for the addition hybrid fiber. On the basis of comparison between mentioned study and the present study, it was observed that the FS in specimens containing hybrid fiber (PVA-HK) without ceramic material was enhanced by 61.14% [1] whereas, in specimens containing hybrid fibers (PVA-HK) with ceramic material (PVA-HK-WOC) was enhanced by 48.14%. Figure 6 shows flexural strength test specimens at failure.



(a) WOC

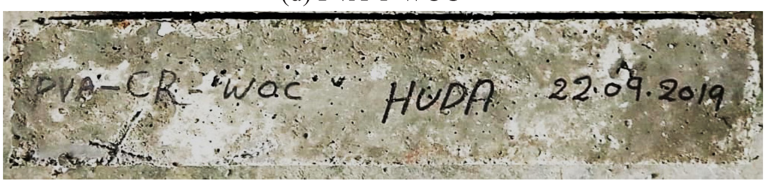


(b) HK-1-WOC

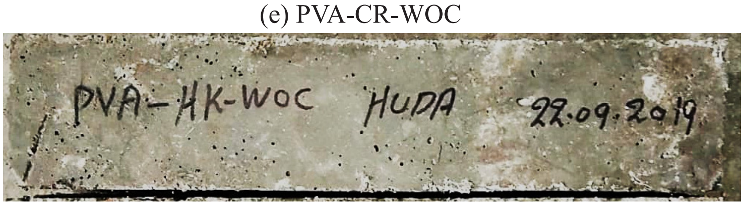


(c) CR-1-WOC

(d) PVA-1-WOC



(e) PVA-CR-WOC



(f) PVA-HK-WOC

Figure 6. Flexural test specimens: WOC, HK-1-WOC, CR-1-WOC, PVA-1-WOC, PVA-HK-WOC and PVA-CR-WOC CR-1-WOC at failure

4.4 Effect of PVA-HK and PVA-CR Hybrid Fiber on the Combined (Flexure and Torsion) Strength of WOC

The results of ultimate bending stress under torsion 243 N.mm, 254 N.mm and 265 N.mm for all specimens of single and hybrid fiber concrete are presented in Chart 4, Chart 5 and Table 6. As compared with the reference specimen (WOC), all the specimens with metallic (HK or CR), non-metallic (PVA), and hybrids fiber (PVA-HK, PVA-CR) have an excellent ultimate bending stress than samples without fiber where:

1) Values of UBS under torsion 243 N.mm for all specimens with single fiber (HK-1-WOC, CR-1-WOC, PVA-1-WOC) were higher than reference concrete (WOC), as 40.74%, 48.15%, and 3.7% respectively. Also, samples of hybrid fiber (PVA-HK-WOC and PVA-CR-WOC) under the same value of torsion have a higher value than reference concrete (WOC) as 55.55% and 77.78%, respectively.

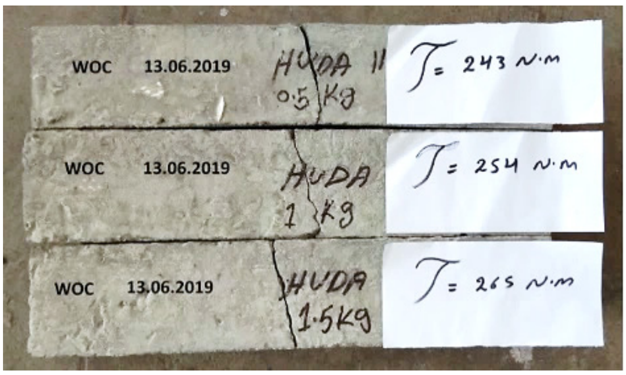
2) Values of UBS under torsion 254 N.mm for all spec-

imens with single fiber (HK-1-WOC, CR-1-WOC, PVA-1-WOC) were higher than reference concrete (WOC), as 41.67%, 50.00%, and 8.33% respectively. Also, samples of hybrid fiber (PVA-HK-WOC and PVA-CR-WOC) under the same value of torsion have a higher value than reference concrete (WOC) as 50.00% and 91.66% respectively.

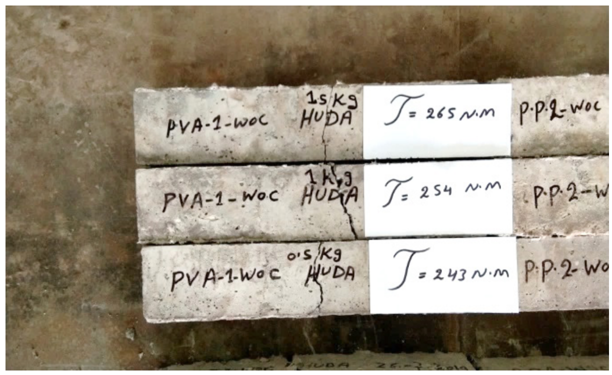
3) Values of UBS under torsion 265 N.mm for all specimens with single fiber (HK-1-WOC, CR-1-WOC, PVA-1-WOC) were higher than reference concrete (WOC), as 18.18%, 22.73%, and 9.09% respectively. Also, specimens of hybrid fiber (PVA-HK-WOC and PVA-CR-WOC) under the same value of torsion have a higher value than reference concrete (WOC) as 45.45% and 81.81% respectively.

4) specimens reinforced with hybrid (PVA-CR) fiber give the maximum UBS that was estimated as 91.66% higher under torsion 254 N.mm higher in comparison with reference specimen (WOC). It was also shown that specimens reinforced with the hybrid (PVA-HK) fiber demonstrated their effectiveness in providing semi- ductility to a concrete structure. It could be concluded that the UBS with hybrid fiber reinforcements has enhanced significantly, same as in the flexural and tensile strength.

5) Figure 7 shows combined (flexural and torsion) strength test specimens at failure.

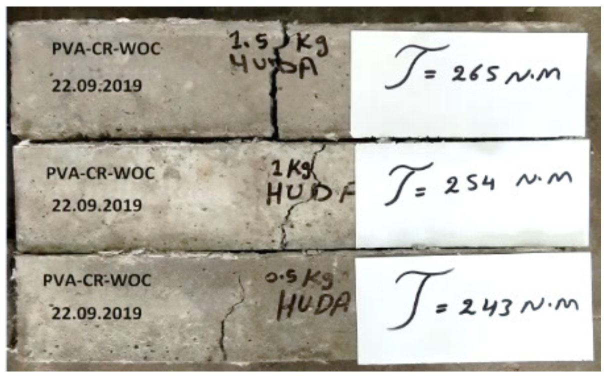


WOC

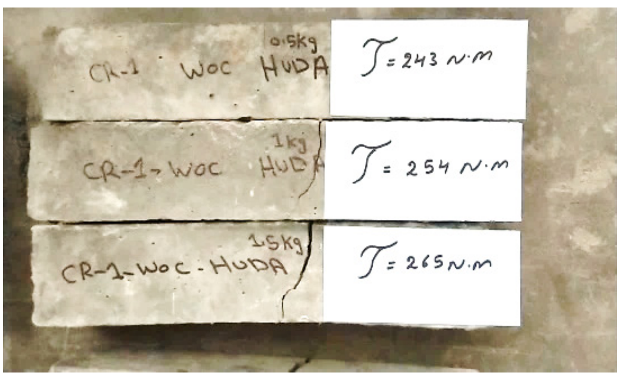


PVA-1-WOC

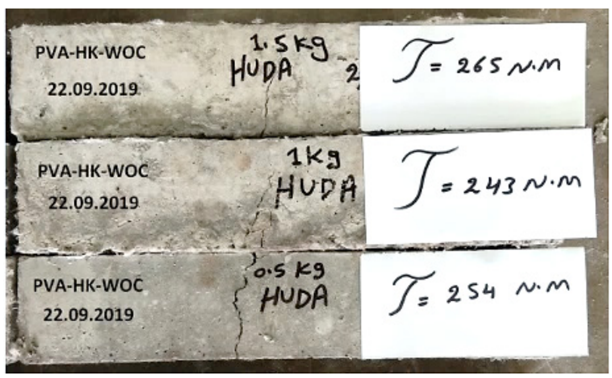
HK-1-WOC



PVA-CR-WOC



CR-1-WOC



PVA-HK-WOC

Figure 7. Combined (flexural and torsion) strength test specimens: WOC, HK-1-WOC, CR-1-WOC, PVA-1-WOC, PVA-HK-WOC and PVA-CR-WOC CR-1-WOC at failure

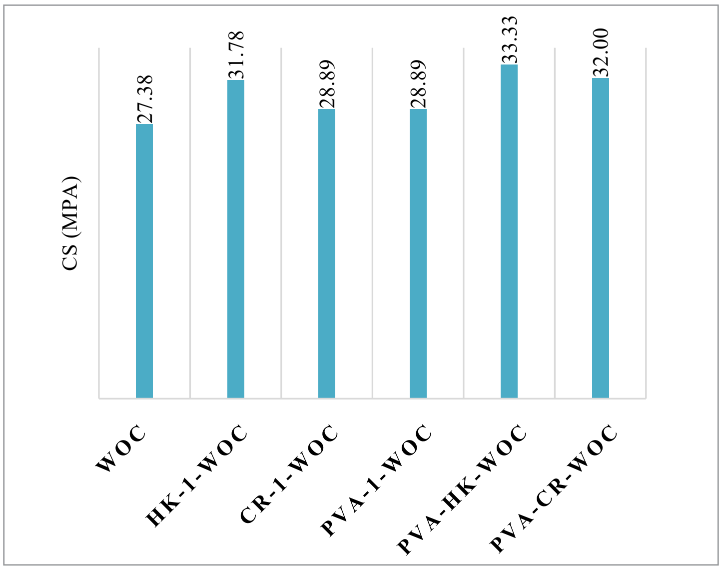


Chart 1. Average compressive strength (CS) for varying mixes with respect to the reference concrete model

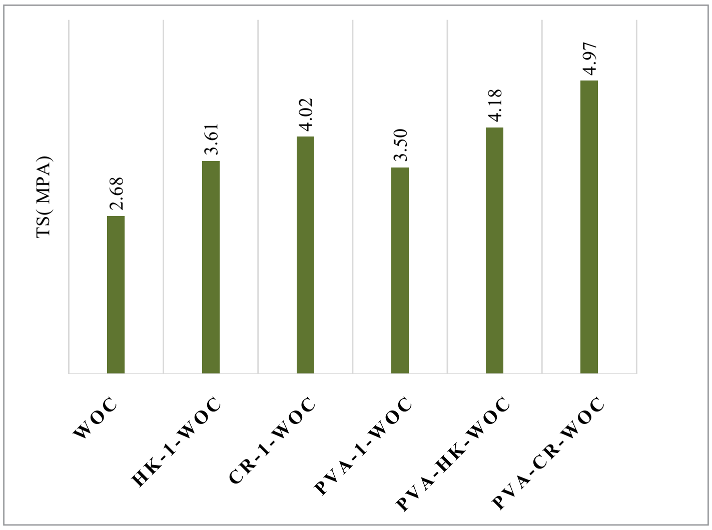


Chart 2. Average split tensile strength (TS) for varying mixes with respect to the reference concrete model

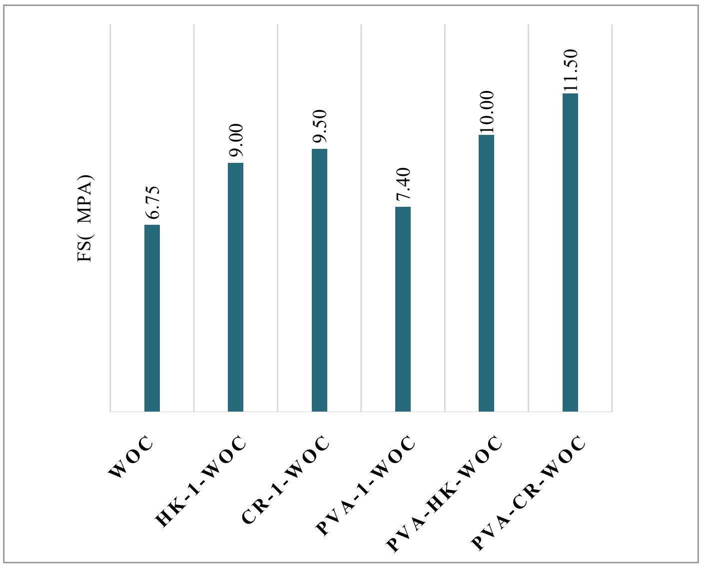


Chart 3. Average Flexural Strength (FS) for varying mixes with respect to the reference concrete model

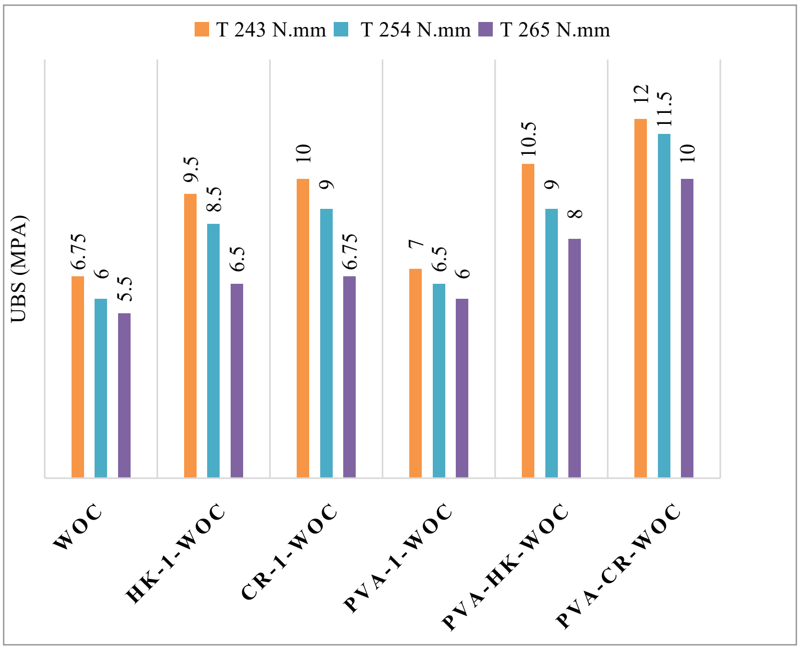


Chart 4. Average ultimate bending strength (UBS) for varying mixes in WOC with respect to the reference concrete model

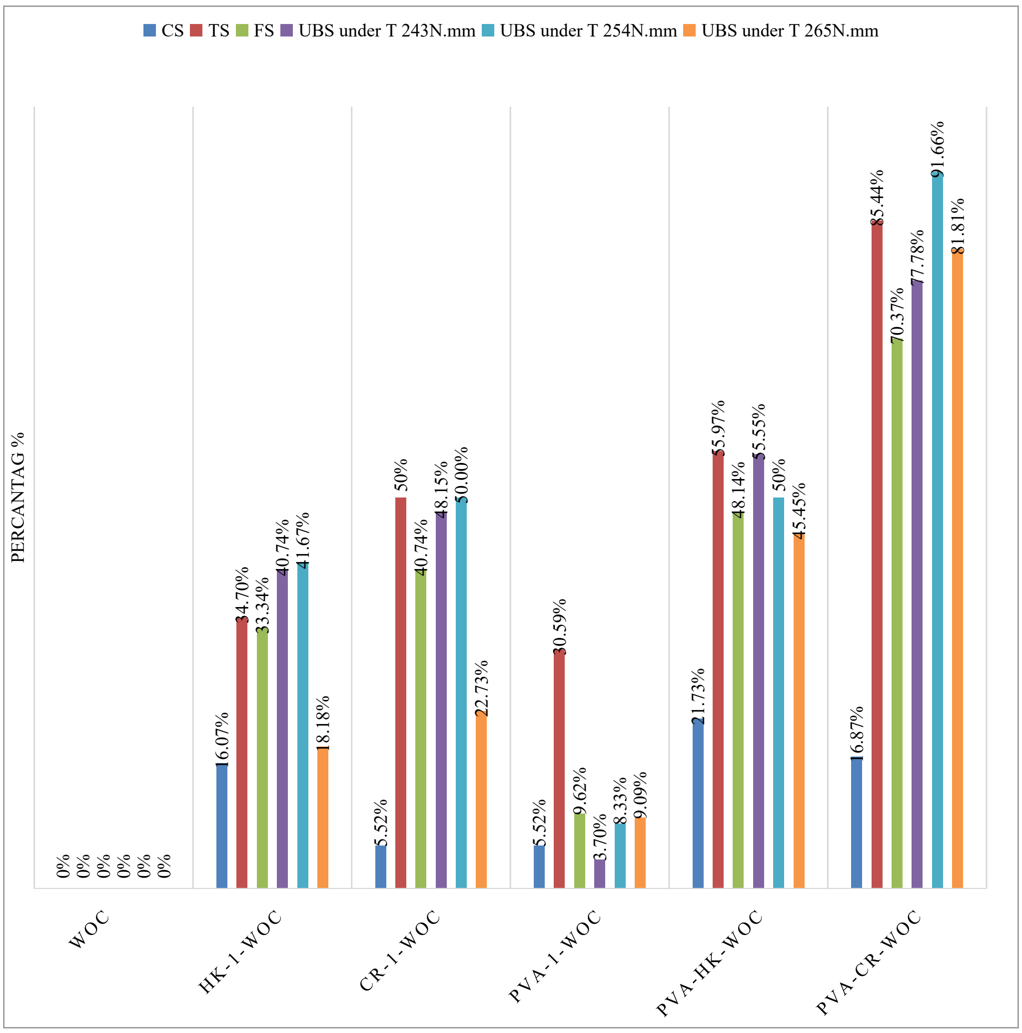


Chart 5. Overall Percentage of increment/ decrement of total tested results

Table 6. Average Compressive, Tensile, Flexural, Combined (Flexural and Torsional) Strength for Various Mixes

S No.	Sample Name	CS (%variation w.r.t to reference)	TS (%variation w.r.t to reference)	FS (%variation w.r.t to reference)	UBS MPa Under Torsion 243 N.mm (%variation w.r.t to reference)	UBS MPa under Torsion 254 N.mm (%variation w.r.t to reference)	UBS MPa Under Torsion 265 N.mm (%variation w.r.t to reference)
		MPa					
1	WOC (Reference)	27.38	2.68	6.75	6.75	6	5.5
2	HK-1%-WOC	31.78 (+16.07%)	3.61 (+34.7%)	9 (+33.34%)	9.5 (+40.74%)	8.5 (+41.67%)	6.5 (+18.18%)
3	CR-1%-WOC	28.89 (+5.52%)	4.02 (+50%)	9.5 (+40.74%)	10 (+48.15%)	9 (+50.00%)	6.75 (+22.73%)
5	PVA-1%-WOC	28.89 (+5.52%)	3.5 (+30.59%)	7.4 (+9.62%)	7 (+3.7%)	6.5 (+8.33%)	6 (+9.09%)
7	PVA-HK-WOC-2%	33.33 (+ 21.73%)	4.18 (+ 55.97%)	10.00 (+ 48.14%)	10.5 (+55.55%)	9 (+50%)	8 (+45.45%)
8	PVA-CR-WOC-2%	32 (+16.87%)	4.97 (+85.44%)	11.50 (+70.37%)	12.00 (+77.78%)	11.5 (+91.66)	10 (+81.81)

+: Increment - : Reduction

4.5 Microstructure Analysis

The analyses of SEM and EDS intended to investigate the morphological properties of plain concrete(pc), waste ceramic optimal concrete (WOC) and waste ceramic reinforced by hybrid fiber (WOC-Hybrid), as shown in Figures 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. The WOC-Hybrid sample is selected based on the optimal performance of each group of fiber additions. 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 characterised 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 [25].

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 and 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, 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. [26] Due to orientation and settlement, the packing of particles formed from spherical grain is superior to the 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. 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.

The surface of basalt fiber before mixing into concrete was smooth as presented in Figure 8; while cracks were observed on the surface of fiber after mixing into concrete. The embedded fiber in the hybrid mix indicated the proper bonding of PVA-CR fiber with that matrix as evident from Figure 8. The proper bond between matrix and PVA-CR fiber in hybrid fiber specimens bridge across the cracks and significantly enhanced the strength of hybrid concrete more than that of respective plain concrete as mentioned in the previous section. Figure 8 demonstrates the fiber breakage and surface damage (skin of fiber peeled off) of PVA fiber. The basalt fiber bridge across the cracks and fiber breakage was occurred due to the crack propagation that split the fiber into two parts and the surface damage was because of frictional forces between fiber and matrix during applied load. The cracks in the mix after fiber pull out and fracture of PVA-CR fiber after exposure to high temperature are illustrated in Figure 8. However, after fracturing of PVA-CR fiber due to pull out it was observed that the cement hydration products were attached on the surface which indicated the proper bond of fiber with composite ultimately resulted in higher energy consumption under applied load. On the other hand, it might be noted that still the hydration products are attached to that fiber surface which could be the cause of improved strength of all hybrid fiber composites as compared to that of respective plain concrete. Thus, the soptimised dosage of fiber in composites would play a positive role in the enhancement of mechanical performance than that of plain and ceramic concrete specimens.

Energy-dispersive spectroscopy (EDS) was used to investigate the microchemistry of the selected samples. It has been used to obtain a localised 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 Figures 8 & 9. The detected main elements of PC concrete are C, O, F, Mg, Al, Si, Ca, Fe and C, O, F, Mg, Al, Si, S, K, Ca, Ti, Fe, Zr, Au for WOC concrete as sown in the Tables 7, 8 and 9.

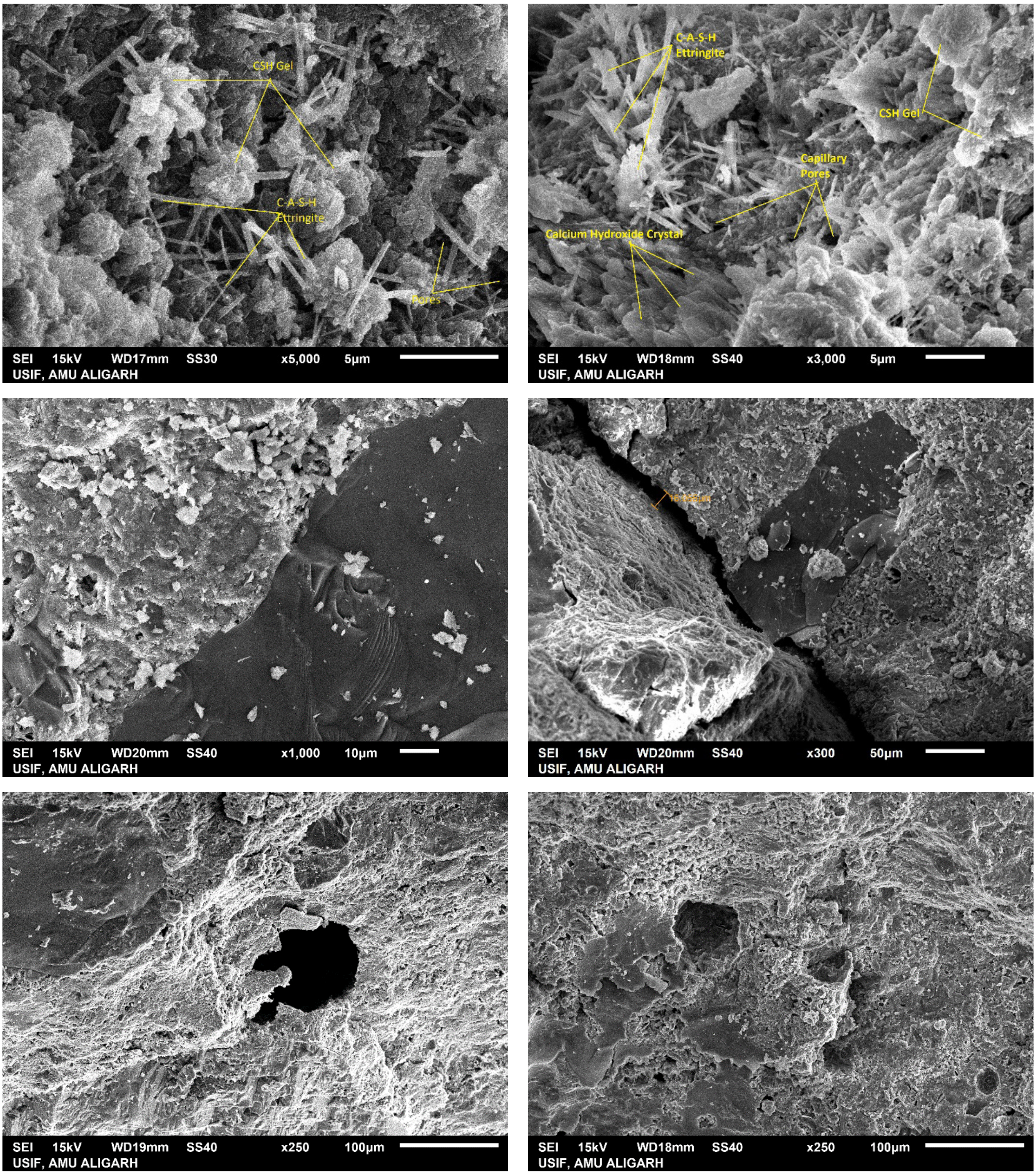


Figure 6. SEM of PC Concrete

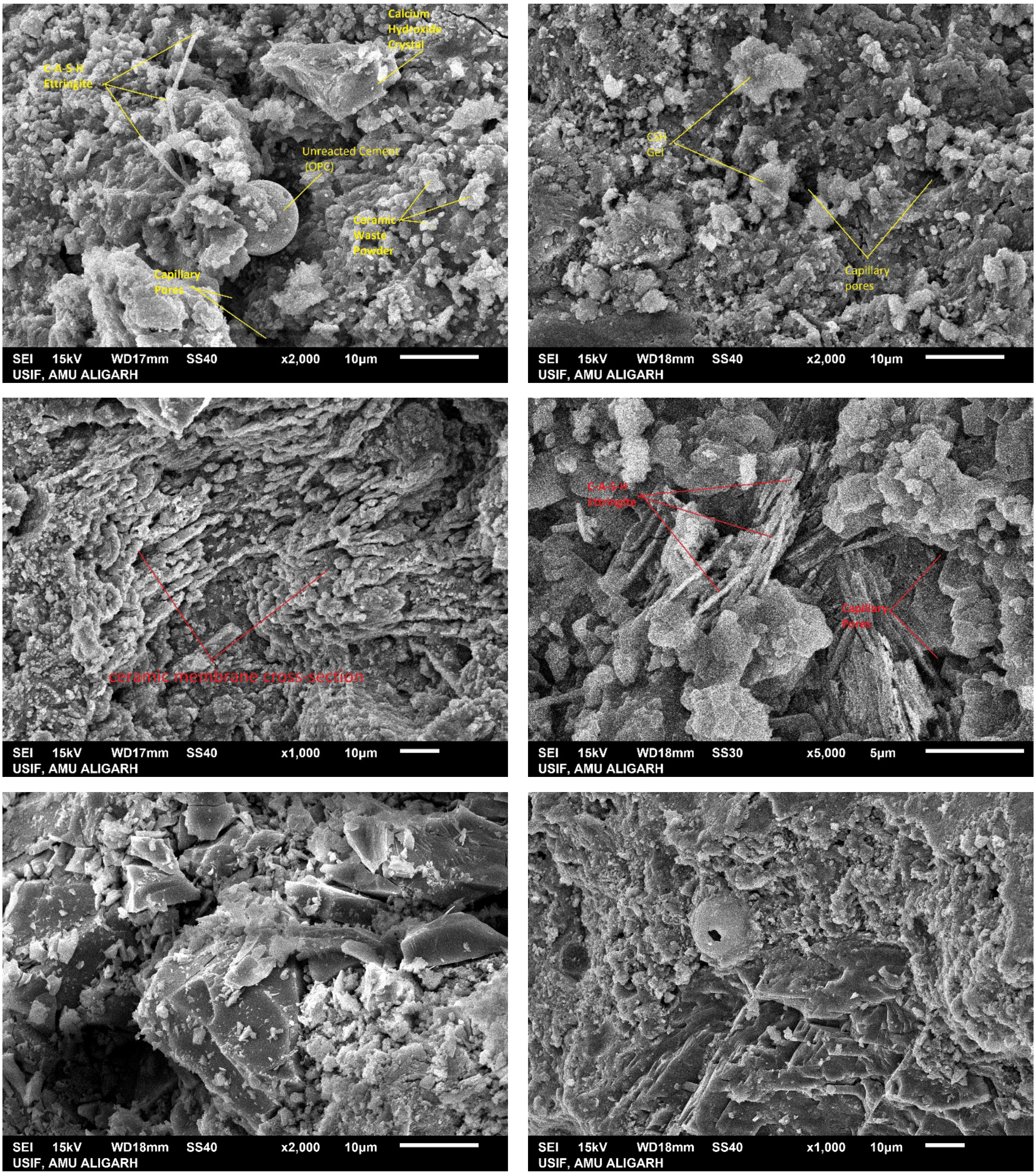


Figure 7. SEM of WOC Concrete

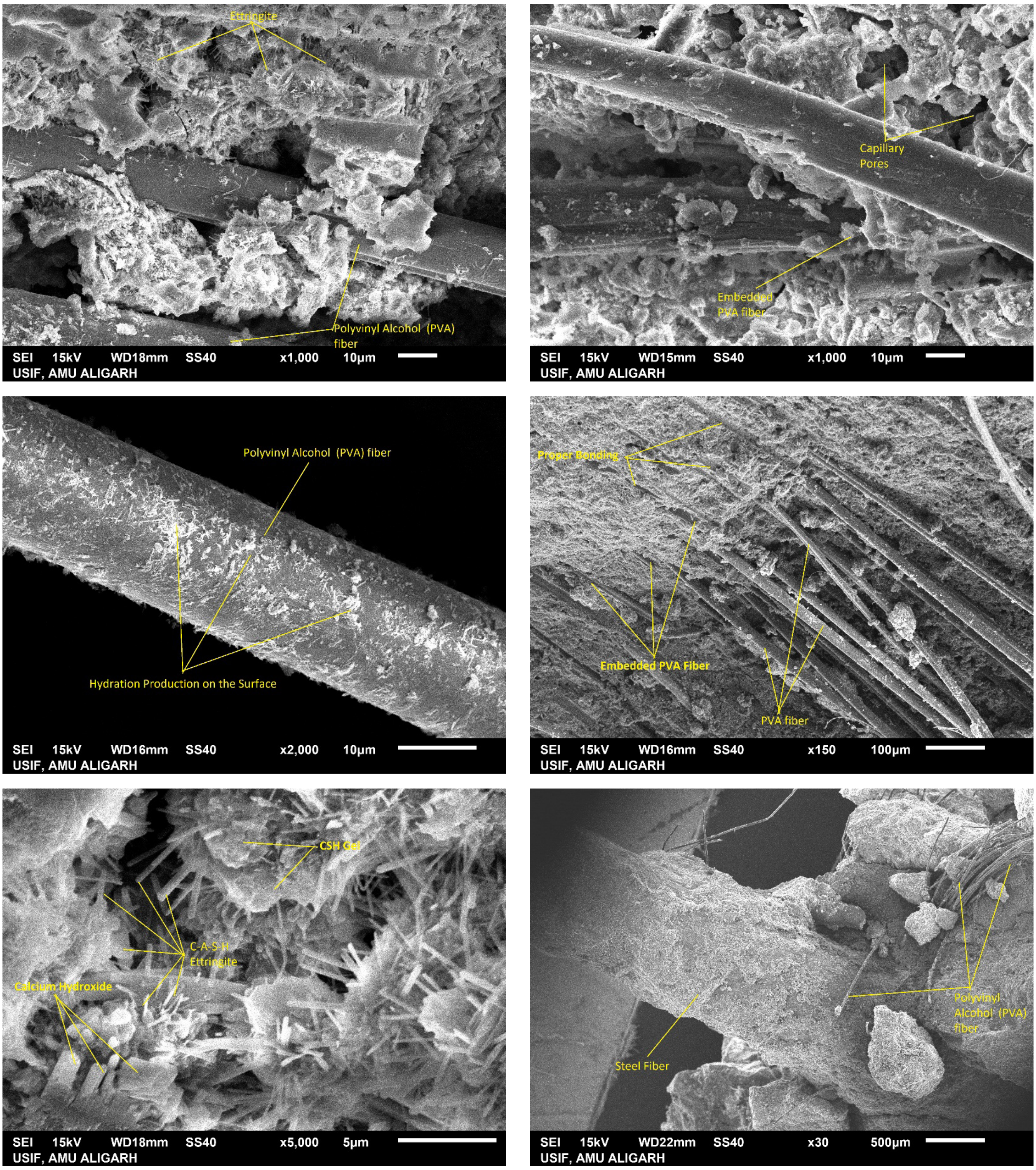
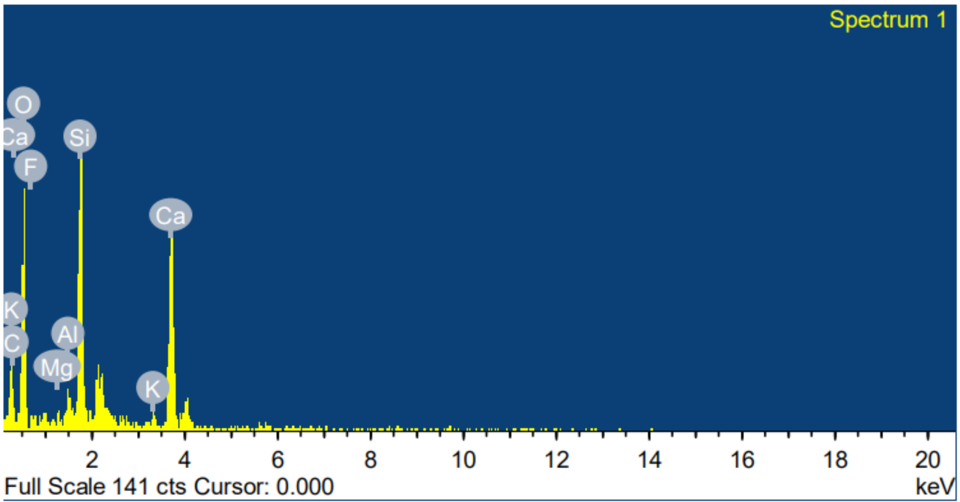
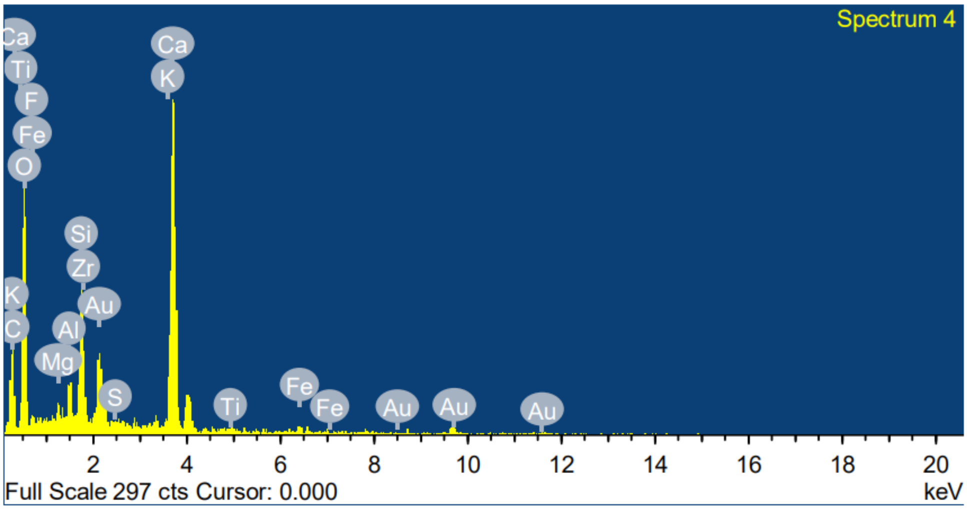


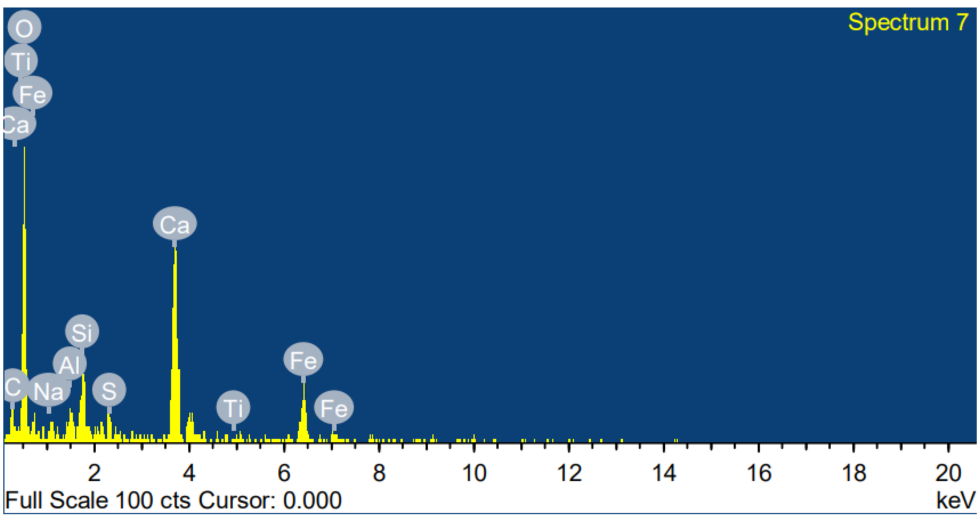
Figure 8. SEM of WOC-Hybrid Concrete



(a)



(b)



(c)

Figure 9. SEM of: a) PC, b) WOC and c) WOC-Hybrid element Concrete

Table 7. 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 8. 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	

Table 9. WOC-Hybrid element

Standard	Element	Weight%	Atomic%
$CaCO_3$	C	9.05	14.23
SiO_2	O	60.71	71.62
Albite	Na	0.98	0.8
Al_2O_3	Al	0.98	0.69
SiO_2	Si	2.62	1.76
FeS2	S	1.51	0.89
Ca	Wollastonite	13.97	6.58
Ti	Ti	0.10	0.04
Fe	Fe	10.07	3.4
	Totals	100.00	

5. Conclusions

The present study investigated the compressive, tensile, flexural and combined (flexural and torsional) strength of concrete made of hybrid fibers (Steel + PVA). The following conclusions can be drawn:

- Based on the present experimental investigations, hybrid fiber concrete offers several characteristics that cannot be achieved with a single fiber type. Besides, a balance of costs and performance with hybrid composites can be achieved.
- In CS tests, the CS of WOC concrete has increased with the addition of hybrid fibers (CR or HK and PVA). The specimens of PVA-HK-WOC have shown the highest CS values enhancement up to 21.73%. These results are attributed to stronger hydrogen bonding by the hydrophilic PVA fiber, which led to superior resistance to crack propagation and microcracking. For this reason, the increase in compressive strength of concrete reinforced with PVA fiber and hook-ended steel fiber is larger than concrete reinforced with single steel fiber. The specimens of PVA-CR-WOC have shown an enhancement in CS values up to 16.87%.
- In TS tests, TS of WOC concrete increased with the addition of hybrid fibers (CR or HK and PVA). The specimens of PVA-CR-WOC have shown an enhancement in TS value up to 85.44%. Whereas the specimens of PVA-HK-WOC have shown an enhancement in TS values up to 55.97%. This is because the steel fiber is stiffer and stronger than PVA and provides ultimate strength and adequate first crack strength. In contrast, the PVA fiber is relatively flexible and provides improved toughness and strain capacity in the post-crack zone.
- In FS tests, FS of WOC concrete increased with the addition of hybrid fibers (CR or HK and PVA). The specimens of PVA-CR-WOC have shown the highest FS value up to 70.73%. Whereas the specimens of PVA-HK-WOC showed enhancement in FS values up to 48.14%. This result is attributed the PVA fibers effectively controlling the crack propagation at the bending crack tip. The steel fibers resist the widening of the crack width, thereby greatly enhancing concrete's flexural strength.
- In FTS test, the UBS of WOC increased with the addition of hybrid fibers (CR or HK and PVA). The specimens of PVA-CR-WOC and PVA-HK-WOC have shown a great enhancement in UBS values under torsion 243 N.mm, 254 N.mm, 265 N.mm up to 77.78%, 91.66% and 81.81%; 55.55%, 50% and 45.45% respectively.

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 organisation or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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