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Ultra high-performance concrete using industrial waste performs mechanically and microstructurally.

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ABSTRACT *This study discusses the findings and the impacts of industrial waste on workability, mechanical properties, and microstructure properties. This study primarily focuses on combining ecologically friendly components to produce sustainable UHPC mixes. The purpose of this study is to clarify if employing various by-product materials as a partial substitute for the used PC may increase the sustainability of UHPC. To maintain a high level of sustainability for UHPC, industrial waste materials (IWM) such as ceramic waste powder (CWP), brick waste powder (BWP), and marble waste powder (MWP) were utilized as a partial replacement for PC. At 5%, 10%, and up to 15% of the binder mass, CWP, BWP, and MWP were used to produce the affordable UHPC. To produce UHPC with high strength and a high workable diameter, silica fume was used at 15% as a replacement for cement. The goal is to define and establish the maximum replacement rates for sustainable materials at which UHPC may still operate at an exceptionally high level. Freshness, mechanical properties, and microstructure of sustainable UHPC were investigated..*

KEYWORDS *Ultra-High-Performance concrete (UHPC), Industrial waste Compressive strength, Tensile strength, Microstructural performance*

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I. INTRODUCTION

Ordinary Portland cement production contributes to around 7–18% of worldwide carbon dioxide (CO2) emissions. Generated by calculations emits one ton of CO2 into the environment. An expansion in Ordinary Portland cement production to meet the enormous concrete demand for infrastructure projects in certain densely populated nations would inevitably have a severe environmental effect. Furthermore, cement concrete's use as a construction material has increased steadily because of its in-situ flexibility, simplicity of use, durability, fire resistance, and great strength. However, Ordinary Portland cement, one of the binders, is costly and pollutes the environment throughout production. It is well known that the production of Ordinary Portland cement consumes significant energy while emitting considerable CO2 [10] However, Ordinary Portland cement remains the most commonly used binder in concrete, driving a hunt for more environmentally acceptable alternatives.

Conventional concrete (CC), also known as normal-strength concrete[27], no longer satisfies the requirements for carrying out these works due to advancements in cement science and technology and the demand for thinner and bolder constructions. Alternative concretes and cementitious mixes with superior qualities than CC evolved to fill this demand. High-strength concrete [27].High-performance concrete (HPC)[10,27] and, more recently, ultra-high-performance concrete (UHPC)[18,26] fall under this category. Due to the lack of technical standards that offer adequate definitions for these materials, it is widespread for these phrases to be used interchangeably. NBR 8953[21], NBR 6118 [1], ACI 363[20], ACI 318[24], and BS EN 1992[23] are a few standards for concrete construction that distinguish between two classes of concrete based on characteristic compressive strength (fcu). For example, Class I and Class II concrete have compressive forces ranging from 20 to 50 MPa and 55 to 100 MPa, respectively. Class I, whereas class II concretes are related to High-performance concrete. On the other side, the UHPC has even more demanding standards. With a fluidity equal to or greater than HPC and low porosity, some authors recommend a minimum strength of 120 MPa[6,22], while others call for a minimum of 150 MPa[5,8]. Theoretically, some concrete with strength above class II may have mechanical properties above H.S.C. or HPC. In other words, the UHPC would fit into a strength class III made of these materials. To attain these qualities, the w/c ratio is between 0.2 and 0.3 in conjunction with a very high cement consumption of around 800 to 1000 kg/m3. Additionally, because UHPC is often made without including coarse particles, which would potentially transform it into mortar, the flow table test may be used to assess its workability. Several writers advise that flow table measurements be more significant than 260 mm without applying blows to the material.

UHPC is constructed from materials that are either expensive or include much material, which boosts the cost of manufacturing and could prohibit UHPC from being employed more widely in the development sector[19]. Recent studies[16] noted that utilizing cement with unusually high cement contents would raise the hydration heat, cause exogenous shrinkages, and impact the total cost of the UHPC. This deficit must be filled by restoring a portion of the sizeable amount used for cement. The fresh and hardened characteristics of UHPCs may be significantly impacted, while expenses are also reduced by merging or consolidating S.C.M.s. Cement and even silica fume must thus be replaced by pozzolanic materials such as fly ash, GBFS, and industrial wastes (ceramic powder, marble powder, brick powder, etc. The primary sustainability requirement will be satisfied by substituting these additional cementitious materials for a sizable portion of the Portland cement used[13]. It also serves an important and valuable purpose. S.C.M.s might provide the raw materials required to produce UHPC, increasing demand and constricting supply [7]. However, according to Matte and Moranville [5], UHPC has a super-thick microstructure, making it a material with excellent mechanical properties and astoundingly improved strength characteristics. This makes UHPC a material that is mainly impermeable in addition to the previously mentioned superior properties.

The study contributes to the development of environmentally friendly concrete (UHPC). Data from several studies suggests that cement content, S.C.M. type, fine aggregate content, and curing process all impact the mechanical, durability, and microstructural properties of UHPC. In addition, this current study intends to evaluate the effectiveness of different ratios of (ceramic powder, marble powder, and brick powder) on the mechanical, durability, and microstructural characteristics of UHPC. Scanning electron microscopy (S.E.M.) and thermogravimetric analysis (TG/DTG) were used to investigate the microstructural cfeaturesof UHPC. Finally, the ecological parameters were also evaluated based on the energy content and carbon dioxide emissions (CO2), and tables are strongly recommended.

II. Materials

Ordinary Portland cement (CEM I 52.5 N) The cement utilized in this study came from Egypt's Lafarge Cement Company (LAFARGE). This cement complies with BS EN 197-1/2011. Laboratory testing confirmed the cement's chemical composition and physical characteristics (according to E.S.S. No. 2421/2005), indicating practical, concrete work. In the mixing process, a pure source of water was utilized. The water-to-binder ratio was 0.38 in all mixtures. The silica fume used in this investigation is ASTM C 1240-05, densified with a specific gravity of 2.29. Silica fume enhanced the mix's cementitious material to achieve high composite strength. Silica fume had an average particle size of 13.0 µm. The fly ash used in this investigation is low-calcium fly ash (Type F) with a specific gravity of 2.26, which meets the standards of ASTM C 618. The fly ash utilized in this investigation came from Egypt's Sika Company. Both were received from the Sika Company. The Natural Sand has a specific gravity of 2.56. The size of the Natural sand particles is linked to the extent needed by particle packing theory to provide the best homogeneity. In this study, three industrial waste materials, such as ceramic waste powder (C.W.P.), brick waste powder (B.W.P.), and marble waste powder (M.W.P.), were utilized as a partial replacement for cement. Chemical admixtures often enhance specific characteristics of fresh and hardened concrete. A high-range water-reducing admixture (superplasticizer) was used to achieve high strength for the generated concrete and increase the workability of the fresh concrete mixtures. In this investigation, Sika Company's (Sika ViscoCrete® 3425) superplasticizer with a changed polycarboxylate basis was employed. The Viscocrete-3425 had a specific weight of 1.05.

III. Combining Ingredients

The ultra-high-performance concrete mixes were created using the EMMA program and previous research, in which the quantities of materials and their specific weights were first imposed. Then, the total amount of all portions was determined to investigate the best design method. Table 1. shows the combined ingredients of concrete mixes according to design.

CEM I	575 kg/m3-668 kg/m3
Sand	1150 kg/m3
Silica fume	210 kg/m3
Fly ash	260 kg/m3
Steel fiber	0%,1%and 2%
(Ceramic-Brick-Marble)	5%,10% and 15%

Table 1 Combined ingredients

IV. Flowability and fresh density

The flowability of freshly mixed concrete was evaluated using the small slump cone test. The fresh concrete was then poured into sample molds. A vibrating table was used to provide good compaction during the installation of concrete as well as to compress concrete in molds. The typical curing process was 24 hours at room temperature before demolding, followed by a 28-day water cure at 20 C. The UHPC specimens underwent a 48-hour heat curing process at 80°C. Additionally, the ready samples underwent a 48-hour autoclave cure. At Tanta University's Faculty of Engineering, all concrete models were mixed, dried, and tested in the Strength of Materials Laboratory.

Compressive strength

Before testing, the samples were taken from the curing tank and allowed to dry in the lab for roughly two hours. According to BS EN 12390-3:2019, the compressive strength has been measured 7, 28, and 90 days after casting. At each testing age, three specimen cubes (10*10*10 cm) from each mixture were examined, and the average was taken. The compressive test was conducted using a hydraulic testing machine in the Tanta University's College of Engineering laboratory.

Tensile strength

The tensile strength of concrete specimens was determined using Brazilian splitting tensile strength. The tests were performed at 7, 28, and 56 days, with duplicate samples for each date. The ASTM standard was followed for testing the splitting tensile strength. During each specimen test, the machine established and maintained a loading rate of 0.067 MPa/min and a sensitivity of 80 kN. Compressive force was used to load the specimen throughout the length of the cylinders.

Analysis using a scanning electron microscope (S.E.M.), energy-dispersive x-ray spectroscopy (E.D.S.), and Thermogravimetric (TG/DTG) Analysis

A material is scanned by an electron microscope called scanning electron microscopy (S.E.M.) to produce images. Several signals that provide details on the sample's compositional and topographic analyses are produced due to the interaction of these electrons with the sample's atoms. Because tungsten has the highest melting point of all metals, the electron beam in a traditional S.E.M. is produced by an electron cannon attached to a tungsten filament (which serves as the cathode) and electrically heated.

In general, high-resolution scans of S.E.M. samples even ones better than 1 nanometer—are possible. The basic idea behind S.E.M. analysis is finding secondary electrons produced by sample atoms due to the electron beam's excitation.

The geopolymer specimen samples were heated in a nitrogen environment at ten °C/min with a temperature range of 20-1000°C for thermogravimetric examination. STA 449 F3, NETZSCH, Germany, was used for the analysis

Workability & Fresh Density TEST

The results indicated that the presence of steel fiber reduces the workability of the affordable UHPC. The reduction factor of workability reached 15.6% and 25.1% for 1% and 2%, respectively. The flowability gradually decreased with the increase in the replacement percentage of ceramic waste content, up to 15%, as a partial replacement of Portland cement. In other words, the slump flow values of UHPC incorporating C.W.P. decreased and reached 179 mm, 171 mm, and 160 mm for CWP5 (5% C.W.P.), CWP10 (10% C.W.P.), and CWP15 (15% C.W.P.), respectively. The flowability values of UHPC incorporating B.W.P. gradually decreased and reached 161 mm, 156 mm, and 142 mm for BWP5 (5% B.W.P.), BWP10 (10% B.W.P.), and BWP15 (15% B.W.P.), respectively. As a result, when B.W.P. Replacement was increased as opposed to P.C. replacement, UHPC fluidity increased, which was lower than the CWP15 mixtures. The flowability of UHPC incorporating M.W.P. was slightly reduced and reached 192 mm, 188 mm, and 185 mm for MWP5 (5% M.W.P.), MWP10 (10% M.W.P.), and MWP15 (15% M.W.P.), respectively. As a result, when M.W.P. Replacement was increased as opposed to P.C. replacement, UHPC fluidity decreased, which was higher than the CWP15 mixtures.[4,11]

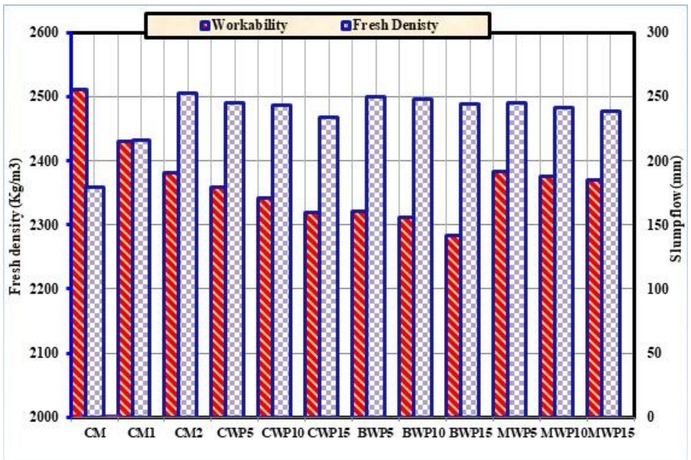

Figure 1:Workability and Fresh Density

Compressive strength

Fig. 2 indicates the effects of steel fiber. Figs. 3,4, and 5 show the effects of industrial waste on the compressive strength (Fcu) of concrete that contains 2% steel fiber after 3, 7, 28, 56, and 90 days of curing. The compressive strength of normal UHPC was 102 MPa without steel fiber. With the addition of 1% steel fibers, the compressive strength of UHPC increased by 106 MPa. When the steel fiber content is 2%, the highest compressive strengths are obtained, which were 76.0, 86, 121, and 151.80 MPa at 3, 7, 28, and 90, respectively. The compressive strength of UHPC with 5% C.W.P. content can reach 111 MPa and 130.2 MPa at 28 and 56 days, respectively. This is a 14.1 and 13.4% reduction from the control mixture's values. It can be shown that UHPC's compressive strength increased with C.W.P. below 5%. This might be explained by the fact that C.W.P. with pozzolanic activity can interact with C.H. to encourage cement hydration and generate more CS-H gel. The compressive strength of UHPC increased with the increase in curing time, and at the same age, the compressive strength of UHPC increased with an increase in B.W.P. substitution amount of up to 10%. The 28-d strength of a 15% substitution rate can be reduced from 121 MPa to 112 MPa. The optimal M.W.P. content for UHPC specimens is a 10% replacement of Portland cement. The compressive strength at the optimal M.W.P. content increases by 7.5%, 7.77%, and 8.9%, respectively, compared to the control concrete at 3d, 7d, and 28d.[4,8,12,14,17]

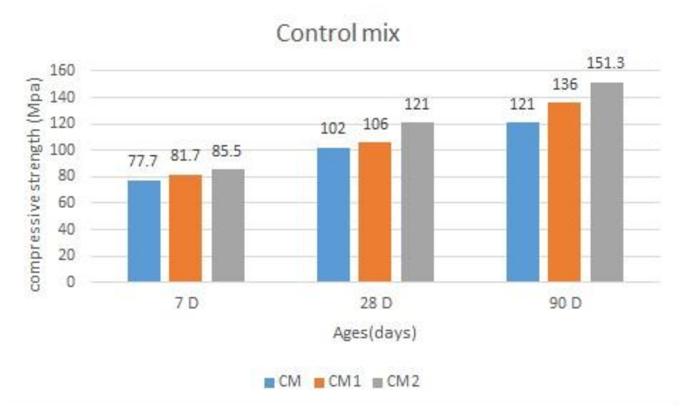

Figure 2 The steel fiber effect on compressive strength

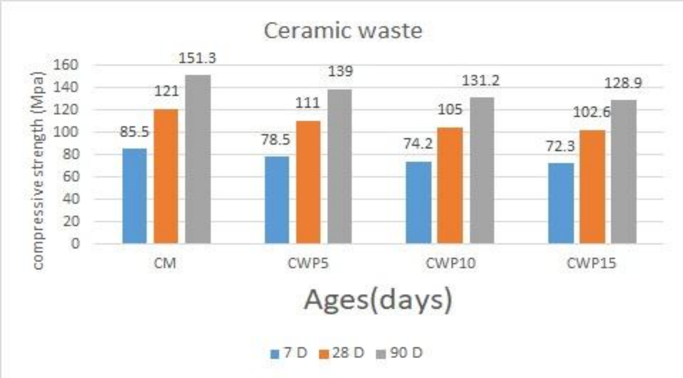

Figure 3 The ceramic impact on compressive strength

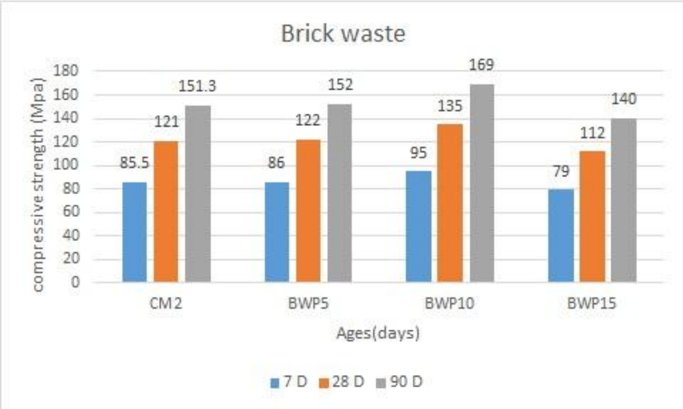

Figure 4 The impact of Brick waste on compressive strength

Figure 5 The impact of marble waste on compressive strength

Tensile strength test

Fig. 6 indicates the effects of steel fiber, and Figs. 7, 8, and 9 show the impact of industrial wastes on the tensile strength of concrete that contains 2% steel fiber after 3, 7, 28, 56, and 90 days of curing. The optimum C.W.P. content for compressive strength is 10%, and the optimum C.W.P. percentage for tensile strength is the same. C.W.P. should not be higher than 15% when using the tensile strength of CM2 as the benchmark. The 3-day tensile strengths of BWP5, BWP10, and BWP15 are 19.07%, 4.24%, 27.3%, and 14.83% lower than those of the control mixture. This is mainly because B.W.P. integration reduces the quantity of new hydration products in the UHPC mixture, reducing the compactness of the microstructure. The ideal M.W.P. for tensile strength is 10%, which is also the ideal M.W.P. for compressive strength. The maximum allowed

M.W.P. content relative to the control mixture is 15%. Additionally, the increase in tensile strength is more significant than that of the control mixture. [14]

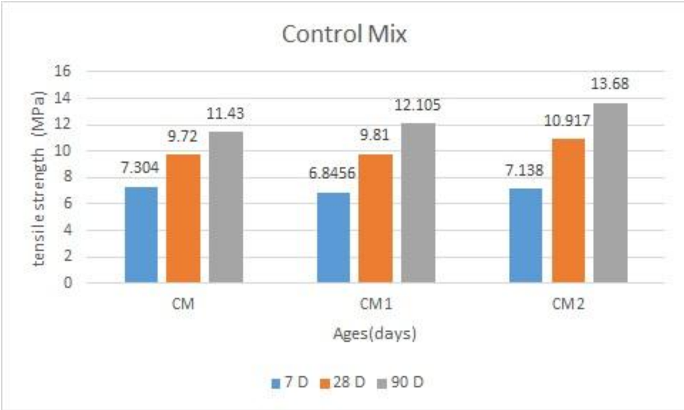

Figure 6 The effect of steel Fiber on tensile strength

Figure 7 The effect of ceramic waste on tensile strength

Figure 8 The effect of brick waste on tensile strength.

Figure 9 The impact of marble waste on tensile strength

Scanning Electron Microscope (S.E.M.)

S.E.M. shows microstructure micrographs of the control mix of UHPC (CM2) samples after 28 days. It was seen in Figure (10-1) that the microstructure of the UHPC contains a few quantities of incompletely reacted and a distributed number of unreacted cement nanoparticles, but the microstructure is generally thick and compressed. Figure (10-2) shows that the sample forms relatively dense hydration products, and the C.W.P. can also be found in the picture, uniformly distributed in the matrix.

It can be seen from the photo that hydration products adhere to and grow on the surface of C.W.P. With the increase of C.W.P. content, the number of "growth sites" also increases, which is conducive to the transfer and growth of hydration products. At the same time, the content of practical reaction components in cementitious materials is decreased by the increase of the C.W.P., which causes a decrease in the production of hydration products.

However, the content of hydration products is stable due to the decrease in the concentration of active components in the cementing material. The interaction of the two mechanisms results in the exact content of hydration products of the C.W.P.- UHPC with an appropriate amount of C.W.P., and the macroscopic properties are stable. The microcracks and micropores of UHPC were reduced compared to the control mixture. It indicates that the microstructure of UHPC becomes denser. The results of the influence of brick powder content on the microstructure of UHPC are prepared by replacing cement and analyzing the changes in the microstructure of the UHPC matrix when using optimum brick powder content. When 10% brick powder content is added, the structure is more compact, and the large proportion of amorphous SiO_2 in the M.W.P. and the packing capability of the UHPC matrix may be attributed to the enhancement in the microstructure and properties of the UHPC. Several elements were exhibited, including

1-the excellent smoothness and spherical properties, which assisted in replacing the water caught between the fine and coarse particles

2- The influence on the flow of the blend (reduces flow reluctance) as a well-dispersed multiphase system with an intensive microstructure and low permeability.

3-The interaction with calcium hydroxide led to the creation of an extra gel, which caused the result of a thick and strong C-S- H gel. [9,11,15]

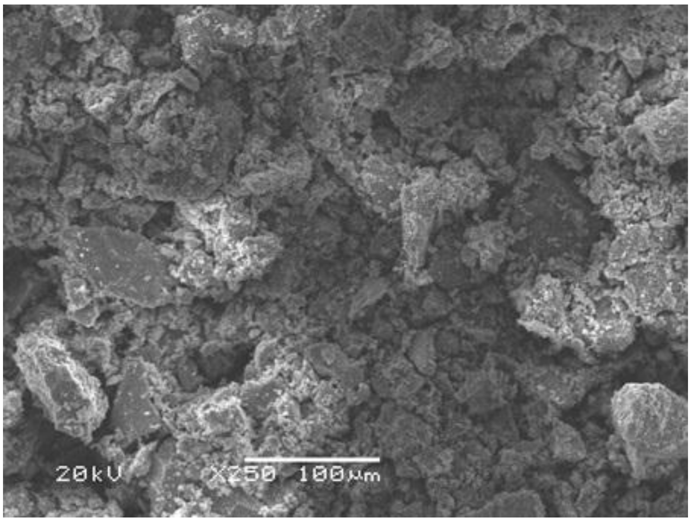

Figure 10 SEM for control mix

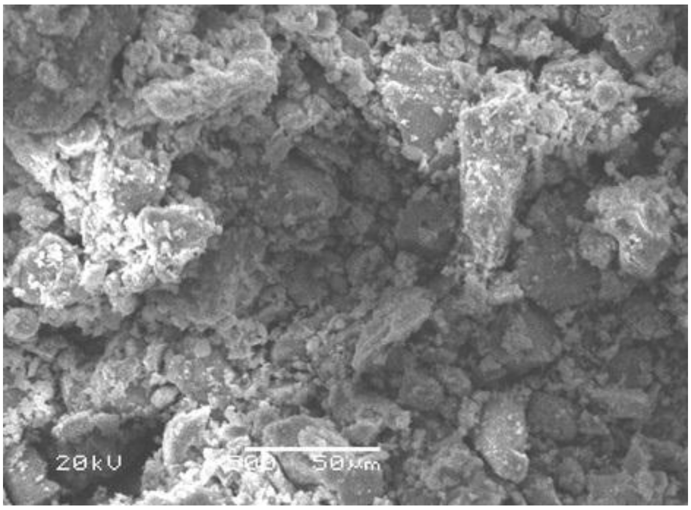

Figure 11 SEM for Ceramic waste material

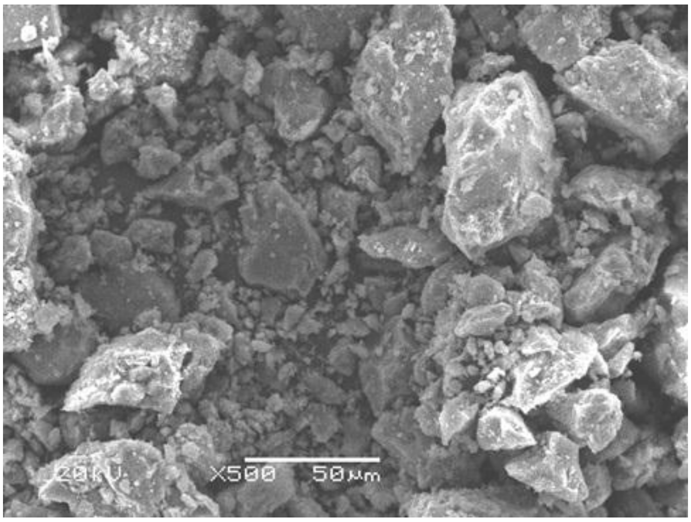

Figure 12 SEM for Brick waste material

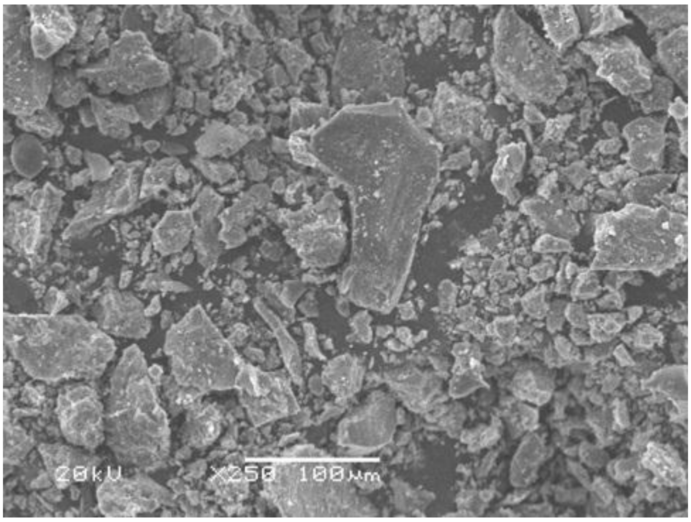

Figure 13 SEM for Marble waste material

Energy dispersive spectrometer (E.D.S.)

E.D.S. analyses of UHPC specimens containing different percentages of ceramic, marble, and brick wastes indicate a change in the Ca/Si ratio in samples containing 10% ceramic, marble, and brick wastes. Figure 11-1 shows the E.D.S. of the control mix free of byproduct materials. In the case of 10% C.W.P. (Figure 11-2) as a partial cement replacement, the Ca/Si ratio increase is attributed to the number of unreacted C.W.P. particles [30]. While, in the case of 10% B.W.P. (Figure 11-3) as a partial replacement of cement, the Ca/Si ratio decrease is attributed to the reduction in the number of unreacted C.W.P. particles reflecting improved mechanical properties.

Simultaneously, in the case of 10% M.W.P. (Figure 11-4) as a partial cement replacement, the Ca/Si ratio increase is attributed to the number of unreacted marble particles. It is observed in the E.D.S. results that the replacement of nano silica for cement in UHPC leads to the formation of more C-S-H and a small C.H. content in the matrix [81]. Thus, desirable UHPC properties may be achieved by replacing 10% brick powder with cement. Based on the E.D.S. results, the average internal Ca/Si C- S-H ratio decreases with increasing limestone replacement for cement. Moreover, the UHPC containing ceramic and marble waste has lower molar ratios of Ca/Si than those containing brick waste, indicating that the specimens containing ceramic and marble waste have a lower C-S-H content than those in the control mixture.[5,8,25]

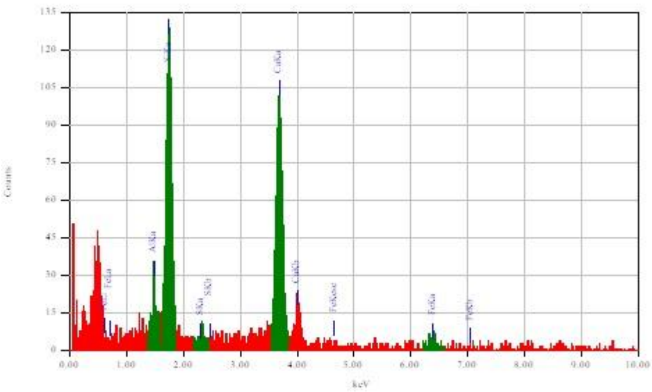

Figure 14 EDS for Control mix

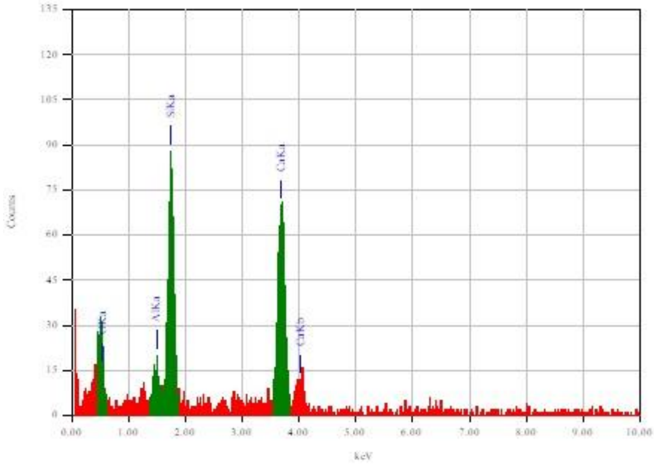

Figure 15 EDS for Ceramic Waste

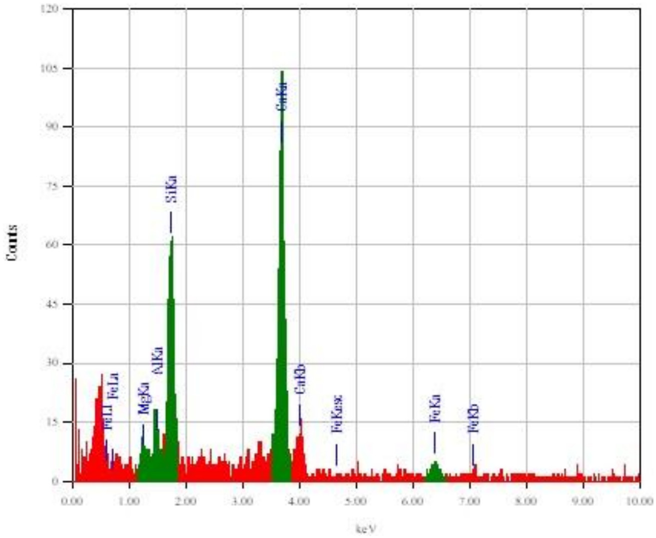

Figure 16 EDS for Brick waste

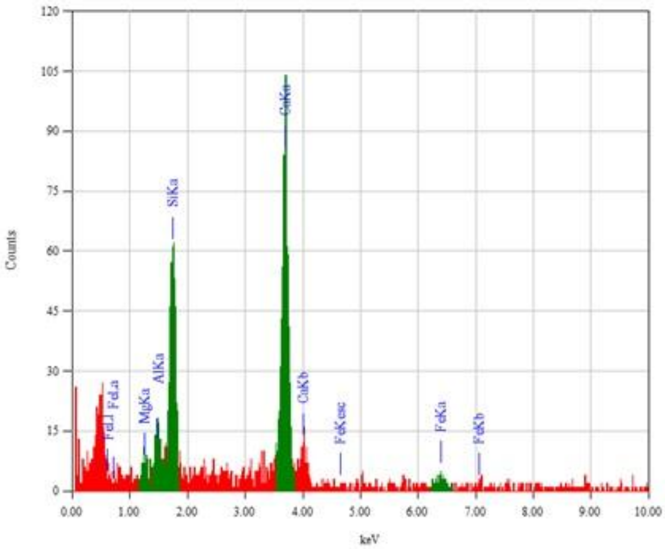

Figure 17 EDS for Marble waste

Thermogravimetric analysis (TGA) and differential thermal analysis (D.T.G.)

The mass loss increases when the amount of waste materials is increased, indicating that more reaction products are produced when waste materials are present. Additionally, the sample lacking waste materials exhibits more significant mass loss than the sample containing all the brick powder elements. At the same time, samples containing waste from the ceramic and marble industries experienced more significant mass loss than the control combination. Waste materials (marble powder) are fillers in the matrix since they are non-reactive materials and do not participate in chemical reactions or produce extra hydration products. There were four distinct D.T.G. peaks across the samples. The first peak occurs at about 100 °C, caused by the evaporation of free water or the existence of C- S-H and ettringite. The presence of ettringite, however, could not be inferred from the D.T.G. peaks because ettringite begins to dissolve when concrete is subjected to temperatures above 70 °C. This peak strengthens as the B.W.P. concentration rises, meaning more C-S-H was produced because of the B.W.P. addition. This increased C-S-H generation allowed the CF5 series to reach its maximum strength by including the highest B.W.P. dosage. A second peak can be seen at about 300 °C; according to the literature, katoite (C3AH6) is responsible for this peak. Additionally, there were no portlandite-specific peaks to be seen, which may have been caused by an accelerated pozzolanic reaction that resulted in portlandite being consumed by silica fume during high-temperature curing. At temperatures between 700 and 750 °C, all the specimens exhibit brief peaks caused by calcite breakdown (CaCO3). On samples with a more significant waste content, a last peak between 800 and 900 °C can be seen. According to earlier research, wollastonite's (CaSiO3) breakdown is the cause of this peak. Wollastonite is known to crystallize from C-S-H at these temperatures (800–900 °C), and it has been observed in prior investigations utilizing UHPC. The reaction generated more hydration products and improved the samples' compressive and tensile strengths.[2,3,11,16,24]

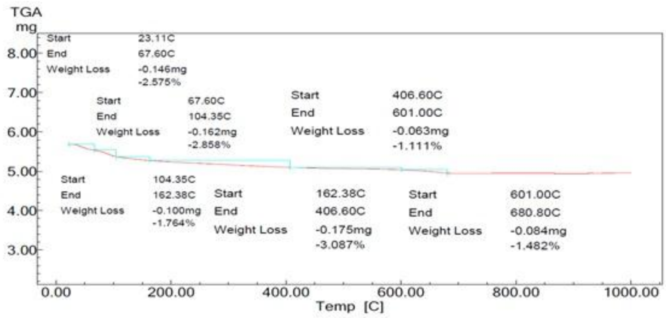

Figure 18 TGA/DTG for control mix

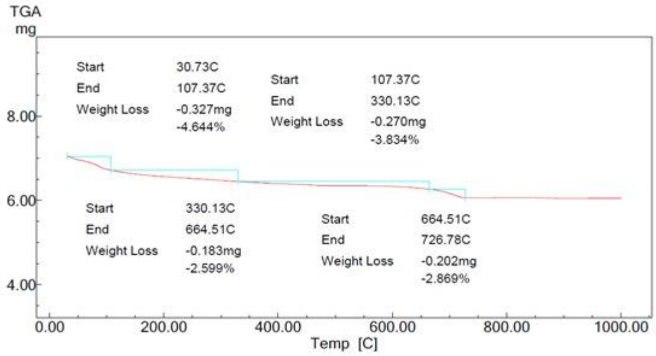

Figure 19 TGA/DTG for Ceramic Waste

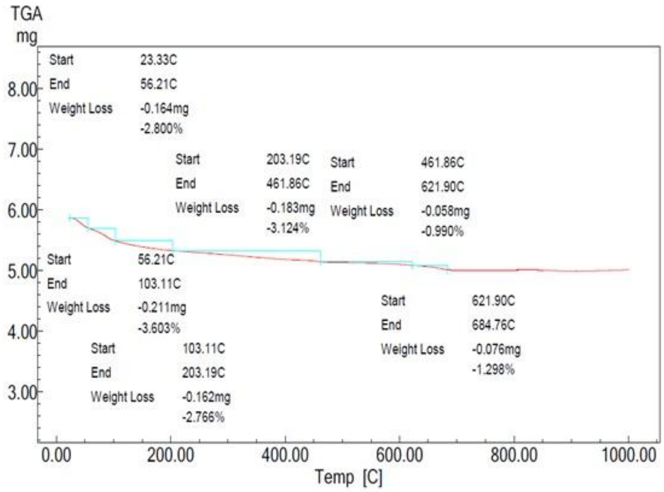

Figure 20 TGA/DTG for Brick Waste

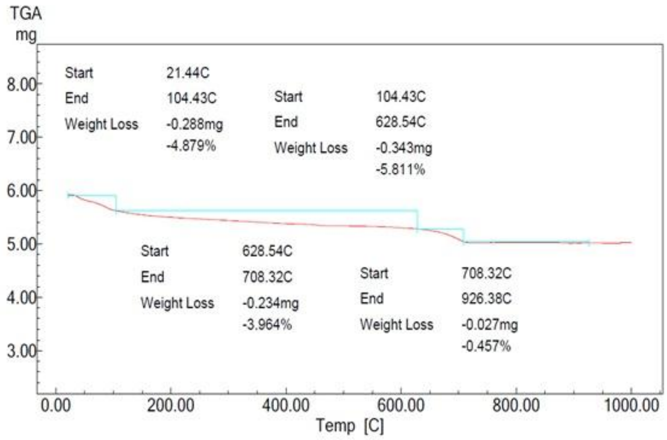

Figure 21 TGA/DTG for Marble Waste

Conclusions

This study discussed the findings and the impacts of industrial waste on workability, mechanical properties, and microstructure properties. This study primarily combines ecologically friendly components to produce sustainable UHPC mixes. This study aims to clarify whether employing various byproduct materials as a partial substitute for the used P.C. may increase the sustainability of UHPC. The compressive strength test findings were also confirmed by investigating the microstructure characteristics of concrete using S.E.M., E.D.S., and TGA. Based on this study, the following conclusions can be drawn:

• The results indicated that steel fiber reduces the workability of the affordable UHPC. The reduction factor of workability reached 15.6% and 25.1% for 1% and 2%, respectively.

•The addition of steel fiber could improve the mechanical strength of concrete by delaying the initiation and propagation of micro- and macro-cracks. In addition, the average spaces between steel fibers would reduce with an increase in steel fiber content, which leads to an improvement in the capacity to sustain loads.

•The compressive strength of UHPC increased with the increase in curing time, and at the same age, the compressive strength of UHPC increased with an increase in B.W.P. substitution amount of up to 10%. The 28-d strength of a 15% substitution rate can be reduced from 121 MPa to 112 MPa.

•With the increase in age and 10% B.W.P. content, the strength at 7 d, 28 d, and 56 d of UHPC increased by 11.6%, 58%, and 84.1%, respectively, compared with that at the third day. The low early strength of BWP-UHPC is due to the large specific surface area of brick powder, which adsorbs part of the water and reduces the hydration reaction rate.

• S.E.M. photographs of the morphology of the UHPC samples indicate a high-density microstructure with relatively few capillary holes, particularly when 5% marble powder is added, and these S.E.M. findings confirmed the mechanical properties results. Furthermore, TGA experiments show that larger brick waste powder dosages result in less mass loss but only a certain amount of replacement.

• The brick waste content negatively impacts the thermal behavior of the samples, as evaluated by TGA and D.T.G. analysis. The control mix maintained 94.8% of its weight while incorporating ceramic, brick, and marble powder, which lost 7.27%, 8.09%, and 6.01% of their weight, respectively.

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