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A Comprehensive Examination of the Compressive Test Results of Concrete Formulations Modified by The Insertion of Ceramic Powder and High-Density Polyethylene Illustrates Nuanced Changes in the Structural Performance Attributes of the Resultant Composite Materials

Mayank Parekh [1,*], S.B.Joshi [2]

Abstract

It is becoming crucial to transition from a traditional, utilization-based society to a sustainable one, resulting of the decline in the natural environment, depletion of natural resources, and decreased capacity for final waste disposal. As the populatio grows, so will the demand for concrete. The major goal of this research is to look at the possible technical benefits of using extruded recycled high-density-polyethylene (HDPE) fibers into structural concrete. The mechanical properties of the concrete were tested and compared with plain concrete, and rest combinations of Ø 2mm HDPE, with 0.50%, 0.75%, 1% and 1.25% volume fraction of fibres and Ceramic powder, with 10%, 20%, 30% and 40%. In varying sets of percentages, and tests were performed, mainly focusing on compressive tests at 7, 14 and 28-days. The specific percentages of both materials were selected based on a combination of prior research findings and preliminary experimental trials. Previous studies indicated that HDPE fiber content beyond 1.25% can lead to workability issues, while ceramic powder replacement above 40% could negatively impact compressive strength. These values were chosen to balance mechanical performance and material feasibility. Fibres mainly aided in providing post-cracking remedial measures, while ceramic powder aided in reducing the amount of cement required. This article showcases an experimental examination of using ceramic waste for limited cement replacement in structural concrete, and HDPE as an additive material. Ceramic waste poses numerous environmental issues, but also has cementitious properties. The objective was to evaluate the performance of cement concrete incorporating varying proportions of replacement and additive materials. It is important to acknowledge that this performance may differ based on the cement grade or the chemical composition of ceramic waste powder

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Keywords: Concrete technology, pollution, cementitious, sustainability, natural environment, HDPE – high density polyethylene, ductility, recycling

INTRODUCTION

At present, in many emerging nations, sustainability is prime problem. Creating societies in a way that allows individuals to live easily without excessively consuming natural resources is part of the sustainability concept. Roles and contributions from both the collective and the individual are essential in this regard. "The United

Nations Sustainable Development Goals" [1,2] for the next 15 years have a direct link to the construction industry, which include: industrial innovation and infrastructure, as well as, sustainable cities and communities. Industrialized countries must reduce emissions and make making use of earth's resources, such as energy, in a more responsible manner, while developing countries should avoid from the errors of the past [3]. It is expected that, in the upcoming years, cement production in growing nations will significantly rise, which will lead to an increase in greenhouse gas emissions.

A concrete need is expected to arise as a outcome of different benefits, and this demand is expected to double in the following 30 years. This requirement for concrete may be supplied without any additional greenhouse gas emissions if cement is replaced by another chemical with cementing properties. The usage of cement concrete in structural applications results in excellent performance in all contemporary building projects across the world, allowing them to fulfil the world's growing urbanization demand.

Current Scenario

In the present time, sustainability is a major problem in many developing countries. Creating a sustainable society requires enabling citizens to live comfortably while minimizing dependence on natural resources. Group and individual actions are of great relevance to this end. "The United Nations Sustainable Development Goals" for the next 15 years, which include industrial development and infrastructure, and sustainable cities and communities, are closely linked to the construction industry. Developed nations are asked to reduce their emissions and consumption of the planet's reserves, such as energy, as developing countries are anticipated to avoid the missteps of the past [3]. Sometime nano materials could be used for the process of manufacturing cement concrete to amplify the strength [4]. It may happen that in the coming years, emerging countries are expected to grow cement output significantly, thus heightening the greenhouse gas dilemma. The outcomes of this study illustrate the viability of partially replacing recycled ceramic aggregate and ceramic fume for conventional aggregate and binder materials. In terms of replacement ratios, small differences in the characteristics of recycled ceramic concrete were noticed, both positive and negative, demonstrating its acceptability for practical applications [5].

Construction is among the largest sector in India, accounting for GDP of 10% [6, 7]. The trending and futuristic demand for cement in India is huge as infrastructure projects are at their peak.[14, 15] Projects in the construction industry stand out at INR 10 Lakh Crore: 33% increase in capital expenditure. PM Awas Yojana expenditure increases by 66% to over 79,000 cr. Urban Infrastructure Development Fund: INR 10,000 crores expenditure per year for creation of urban infrastructure in Tier 2 and Tier 3 cities. The cement industry is responsible for up to 5% of total global CO_2 emissions [8]. Cement production capacity in India currently stands at 298 million tonnes per annum. [9]. Producing 1 ton of cement requires 293.07 kilowatt hours of energy, which is roughly equivalent to 400 pounds of coal, and produces nearly 1 ton of CO_2 [10, 11]. Therefore, The overall CO_2 production by the cement industry in India is therefore 298 million tonnes/year. Also, CO_2 production of whole country is given below in Figure 1 from CEEW Analysis, as year wise CO_2 production is being increasing rapidly.

According to Rule 17(3) regarding the management of plastic waste Rule, 2016, as modified, each State Pollution Control Board or Committee on Pollution Control is expected to compile and submit the Annual Report to the Pollution Control Board by July 31st of each year. Moreover, as required by Rule 17(4) of the PWM Rules, 2016 (as modified), the 'Central Pollution Control Board' must prepare an exhaustive report based on the use and arrangement of plastic waste. Every year on August 31st, this report and its recommendations must be delivered to the Central Government.

A comprehensive annual report for the consolidated fiscal year 2019–20 has been carefully compiled in conjunction with the regulations outlined in the 'Plastic Waste Management Regulations' of 2018. Thirty-five State Pollution Control Committees and Boards contributed information for this study. It offers a detailed summary of the current implementation of Plastic Waste Management Rules across each State and Union Territory, organized on a state-by-state basis.

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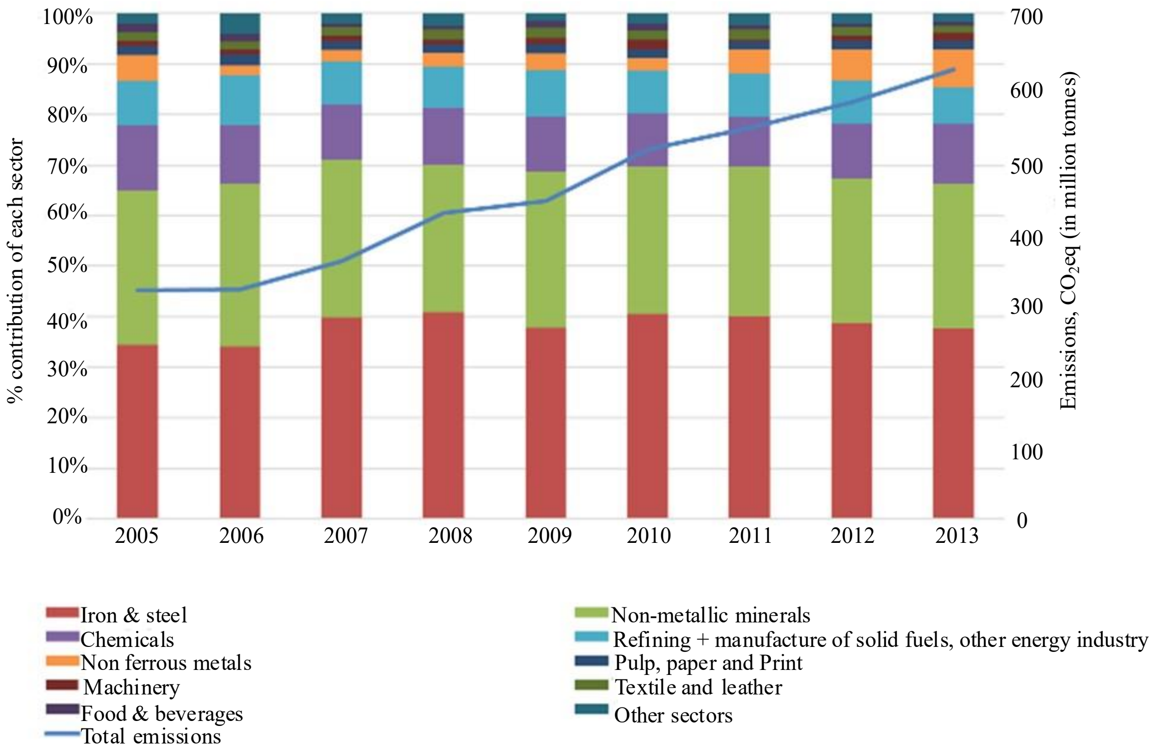

Figure 1. Year on year growth of CO2 emission and dominant sectors [12].

One of the primary reasons of environmental problems has been the inappropriate disposal of solid waste[17], which includes things like water bottles, polythene bags, disposable glasses, cement bags, and cold drink bottles[18, 19]. By investigating the use of non-biodegradable solid waste components in concrete, this study aims to alleviate this issue[20].

The estimation of per capita plastic garbage creation is according to state-submitted reports. One noteworthy finding is that per capita plastic garbage creation has nearly doubled in the previous five years. Figure 2 depicts the state-by-state per capita garbage generation for 2019-20. The largest per capita plastic trash creation was recorded in Goa, Delhi, and Kerala, Nagaland, Sikkim, and Tripura had the lowest per capita plastic trash output.

The idea to include post-consumer waste and byproduct polymers into concrete utilized in construction project's purpose was spurred by developments in concrete technology and the increasing demand for sustainable and eco-friendly building projects. Two different methods to practical application and study have emerged from this concept. Concrete is initially used as a medium for accepting polymer waste without severely impairing its strength. It is used to partially replace sand aggregate with raw plastic granulate. [21–25]. The subsequent stage of investigation focuses on using processed resins to make polymer concrete. [26, 27].

Given that concrete confined with steel or poly-propylene (PP) fibers that are readily accessible on the market is more resilient than unreinforced concrete [28,39], recycling plastic is another viable method for improving the material's qualities [40].

Even while concrete reinforced with steel or poly-propylene (PP) fibers that are easily accessible for purchase is more resilient than plain concrete [28, 29], recycling plastic to make fibers is another possible option. These fibers can be used in addition to traditional steel rebar's as a supplementary kind of reinforcement for concrete [16].

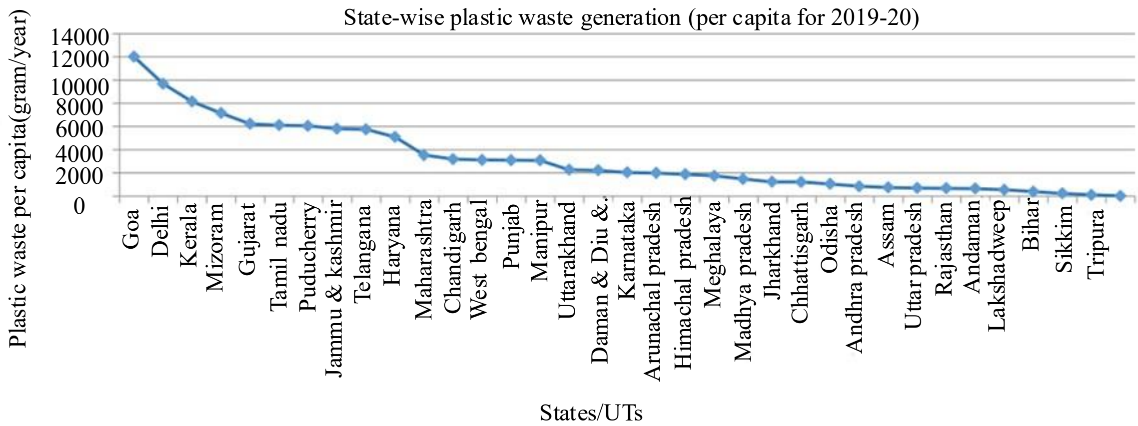

Figure 2. Generation of Plastic waste Per Capita State/UT wise (Source – CPCB, Delhi)[13].

High-density polyethylene (HDPE), which has physical and chemical qualities similar to PP, is another polymer ideal for mass manufacturing of fibers and recycling [36]. Although HDPE and concrete have a low bond strength, research by Kobayashi [41] revealed that when textured or ribbed surfaces are used, HDPE fibers can improve ductility and post-cracking flexural toughness in concrete. This results in essentially equivalent mechanical characteristics, including impact resistance, as shown in PP and high-modulus polyethylene fiber-reinforced concretes [42]. Despite these findings, the original application of HDPE fibers in building did not acquire general adoption[30, 31].

Following that, Bhavi et al. [43] tested concrete examples with 0.2-1.0% volume fractions of HDPE fibers generated from discarded plastic containers[32, 33]. As per availability of the results of their strength evaluations, the integration of 0.6% volume of HDPE fibers improves the compressive, tensile, flexural, and impact strengths of concrete by up to 15%, 23%, 22%, and 200%, respectively. However, increasing fiber volumes of 0.8% and 1.0% provided minor advantages[38]. Yin et al. [44] underline the significance of additional research into the qualities and benefits of using HDPE Fiber-Reinforced Concrete (FRC) in their recent review on concrete reinforced with polymer/synthetic fibers.[34, 35]

MATERIALS AND PROPERTIES

The goal of this research is to mix ceramic waste powder into concrete as well as HDPE Fibers as additive material and assess its performance, notably compressive strength, after 7, 14 and 28 days. The concrete mix which is used in this investigation met the M-20 standard (as defined by IS 456 (2000)) and contained varied amounts of ceramic waste (0%, 10%, 20%, 30%, and 40%., The following materials were utilized in this process and are described in detail:

Cement

This study made use of conventional Portland cement, especially grade 53. Testing was used to establish the initial and final setting times, which resulted in recorded values of 35 minutes for the initial setting time and 60 minutes for the final setting time. The specific gravity of the he cements utilized in this study was determined to be 3.14.

Aggregate

Fine aggregate was sourced from a nearby sand provider for laboratory research. The fine aggregates' specific gravity was measured to be 2.62.

As shown in Table 1, A local provider provided well-graded aggregates with a size less than 20 mm and a specific gravity of 2.81. Sieve analysis (IS 383) was used to verify the particle sizes of both fine and coarse aggregates.

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Table 1. Physical Parameters of Fine and Coarse Aggregate.

Parameters	Fine aggregate	Coarse aggregate
Particle Size	2.36 mm (passing 100%)	20 mm (standard size)
Specific Gravity	2.62	2.81
Bulk Density (kg/m³)	1560	1490
Water Absorption (%)	1.2	0.6
Moisture Content (%)	4	1.5
Fineness Modulus	2.8	7.1
Surface Texture	Smooth	Rough
Shape	Rounded	Angular
Crushing Value	N/A	25%
Impact Value	N/A	20%
Abrasion Resistance	N/A	High (up to 40% loss)
Soundness	Good	Good
Silt Content (%)	2.5	0.8

Table 2. Physical Parameters of Ceramic Powder.

Property	Ceramic powder
Particle Size	5 µm
Specific Gravity	2.5
Bulk Density (kg/m³)	850
Surface Area (m²/g)	10
Porosity	8%
Water Absorption (%)	0.2%
Moisture Content (%)	0.1%
Thermal Conductivity (W/m·K)	1.5
Melting Point (°C)	~1500°C
Color	White to off-white
pH	Neutral (7)

Table 3. Chemical Composition of ceramic powder and cement.

Chemical composition	Ceramic powder (%)	Cement (%)
Lime (CaO)	4.57	62
Silica (SiO2)	62.8	22
Alumina	17.5	5.55
Magnesium	0.75	1
Calcium sulphate	4.04	4

Ceramic Powder

Physical parameter values for ceramic waste powder vary depending on variables such as ceramic material type, processing procedures, and waste source. Various tests for physical parameters of ceramic powder have been performed in Laboratory and various results are show in Table 2.

It relies on which kind of ceramic waste is to be used, which might include oxides, silicates, and other chemicals Silica (SiO_2), alumina (Al_2O_3), and other ceramic components are examples of value.

It is critical to recognize that the particular numbers might vary significantly depending on the unique features of the ceramic waste and the specific procedures used during its manufacturing. Various tests for chemical parameters of ceramic powder have been performed in Laboratory and various results are show in Table 3

HDPE

In the context of concrete, the HDPE fibers used in the experiment were derived from recycled materials and lacked certified engineering properties. The primary objective was to assess their impact on concrete with low to moderate compressive strength, specifically for M20 Grade Concrete. The mix was designed to achieve a fresh mix slump of 75 mm.

In a view of HDPE fibres, HDPE (CAS no. 9002-88-4 [26]) was used—a synthetic polymer known for its chemical inertness when exposed to different acids and alkalis. It has a molecular structure made up of continuous chains of $(CH_2)n$ methylene.

As seen in Figure 3, HDPE Fiber are taken with 2 mm width and 60 mm length, the molecular chains of HDPE have a three-dimensional structure, Additional chains of (CH2) groups branch out from the main line, culminating in a saturated (CH3) methyl group. Notably, HDPE has a greater strength-to-density ratio than other polyethylene's due to its longer main chains & shorter secondary chains, which makes its manufacturing process more expensive. The recycled plastic employed in this study comes from a mixed stock that is mostly made up of diverse post-consumer garbage, most notably from home appliances.

The diameter of these fibers was 2 mm, and their aspect ratios (L/D) were kept constant at 30 as shown in Figure 3. It is worth noting that the melting and ignition temperatures for recycled HDPE—128 °C and 446 °C, respectively—are some short of lower than those for virgin HDPE. Some basic tests have been performed in Laboratory and related results are show in Table 4.

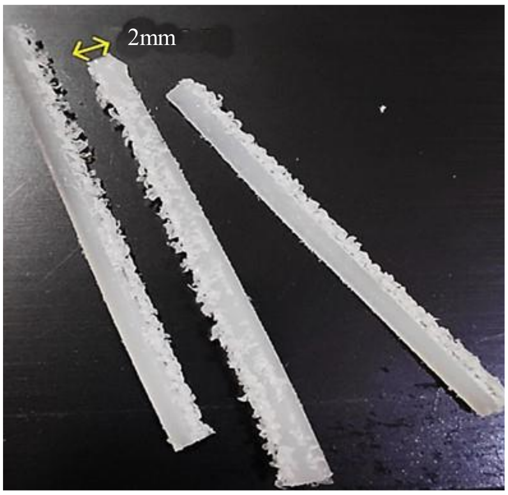

Figure 3. HDPE Fibers.

Table 4. Physical Property of HDPE Fibers.

Property	Units	Recycled HDPE
Yield strength	MPa	11.9
Elastic modulus	GPa	0.499
Ultimate strength	MPa	36.5
Yield strain	%	3.8
Ultimate strain	%	27
Density	g/cm3	0.952
Thermal expansion	1/K	11.76 x 10-6
Melting point	°C	128
Flash point	°C	446
Ignition point	°C	488

METHODOLOGY

This research investigates the compressive and tensile strengths of M-20 grade concrete, commonly applied in structural construction. The concrete mix was designed per IS 10262: 2019 standards[36, 37], maintaining a water-cement ratio of 0.5. The materials used included ordinary Portland cement (OPC), river sand as fine aggregate, and crushed stone as coarse aggregate. Cube specimens measuring 150 mm x 150 mm x 150 mm were prepared for compressive strength testing, while cylinders with a 150 mm diameter and 300 mm height were cast for split tensile strength testing. After casting, specimens were cured in water at 27±2°C for two intervals: 7 and 28 days. Testing procedure was carried out following IS 516: 1959 for compressive strength and IS 5816: 1999 for split tensile strength. To ensure uniform HDPE fiber distribution, an optimized mixing sequence was employed, incorporating HDPE fibers gradually during the mixing process.

Test Procedure

Compressive strength testing of concrete cubes

- *Specimen preparation:* Concrete was cast in 150 mm cube molds, with the mix poured in three layers and compacted with a tamping rod to reduce air voids. The molds were left undisturbed for 24 hours.
- *Curing*: After 24 hours, the moulds were removed, and the cubes were cured in a water tank maintained at 27±2°C. Testing was scheduled after 7,14 and 28 days of curing.
- *Testing setup:* At the designated curing times, the specimens were removed from the tank, surface-dried, and placed on the platen of a compression testing machine (CTM) with a capacity of 2000 kN.
- *Load application*: A gradual load was applied at approximately 140 kg/cm² per minute until the cube specimen fractured, and the maximum load was recorded.
- *Calculation*: Compressive strength (in MPa) was determined by dividing the failure load by the cross-sectional area of the cube (150 mm x 150 mm).

All compressive tests were conducted under standard laboratory conditions per IS-516(1959) guidelines.

Split tensile strength testing of concrete cylinders

- *Specimen preparation:* Cylindrical specimens were cast with a diameter of 150 mm and height of 300 mm, compacted in three layers, and demolded after 24 hours.
- *Curing*: After demolding, the cylinders were placed in water at 27±2°C and cured for 28 days.
- *Testing setup*: On testing days, the specimens were removed, surface-dried, and laid horizontally between the platens of the CTM.
- *Load application*: The load was applied gradually along the length of the cylinder until failure occurred along the vertical axis.
- *Calculation*: The split tensile strength (in MPa) was calculated using the formula as per coda l provision.

EXPERIMENTAL DATA

Compressive Test Results and Discussion

The experimental program, which is presented in the following sections, contained 288 trials on concrete cubes of M20 concrete Mix

For all trial mix, the experimentally determined, characteristic compressive strength of cube, FCK (Cube) from 7-, 14- and 28-days concrete specimens are Graphically represented below.

As shown in Figure 4, At 7 days, the compressive strength of M20 concrete shows a notable improvement with 10% to 20% ceramic powder replacement, reaching a peak of 16.3 MPa for 1.00% HDPE and 20% ceramic powder. Plain concrete achieved 13.5 MPa, while 10% ceramic replacement improved strength to 14.2 MPa. Beyond 20% replacement, strength decreases, confirming excess ceramic powder negatively affects early hydration. HDPE fibres enhance strength due to their crack-bridging effect. However, 1.25% HDPE begins to show a decline, likely due to poor bonding. At 40% replacement, strength drops to 11.5 MPa, making it unsuitable for load-bearing applications.

As shown in Figure 5. After 14 days, concrete continues to gain strength as hydration progresses. Plain concrete reaches 18.5 MPa, while 10% and 20% ceramic powder replacement show superior strength at 19.2 MPa and 19.8 MPa, respectively. The highest value, 22.5 MPa, is achieved with 1.00% HDPE and 20% ceramic powder, demonstrating the optimal combination for strength gain. However, 30% replacement leads to a drop to 18.0 MPa, and 40% replacement falls further to 16.0 MPa. Excess ceramic powder reduces cementitious binding. HDPE fibres improve toughness, but above 1.00% dosage, a decline occurs, highlighting a limit to fibre reinforcement efficiency.

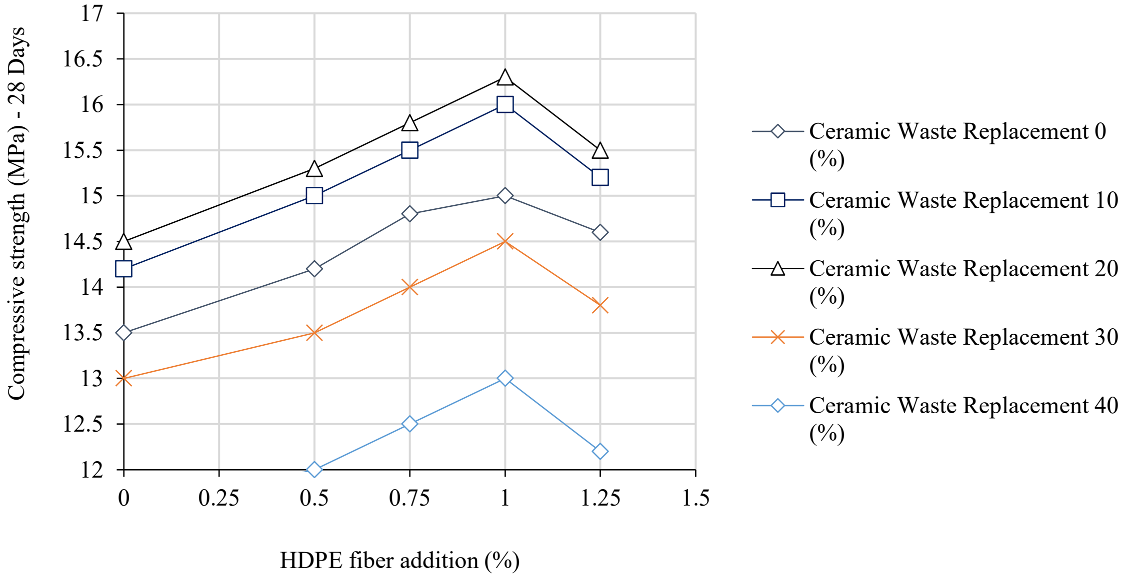

Figure 4. Compressive strength (MPa) - 7 days.

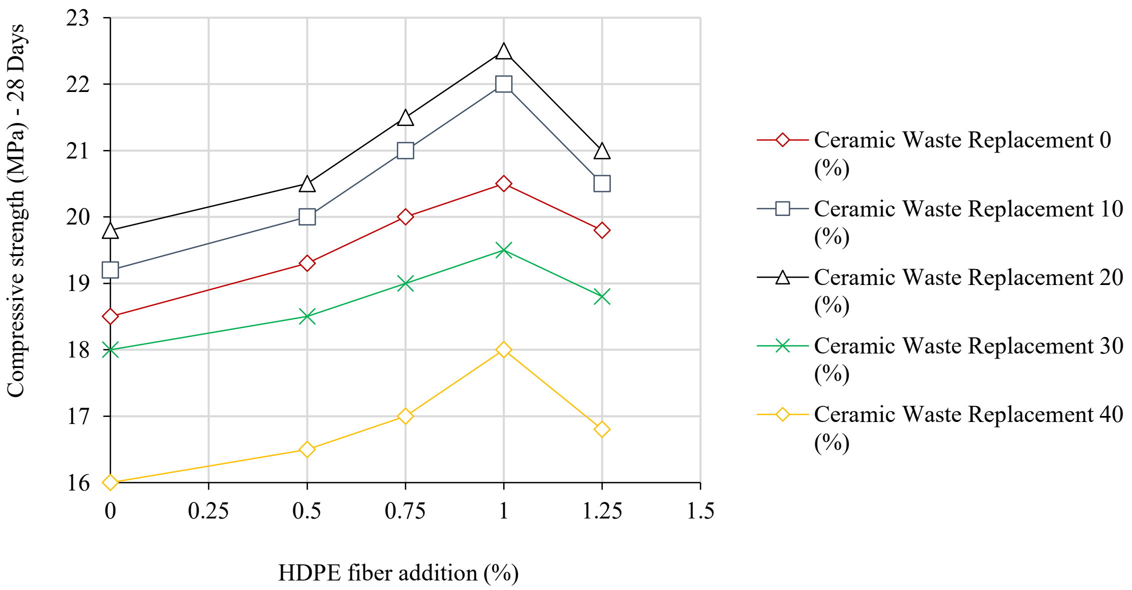

Figure 5. Compressive strength (MPa) - 14 days.

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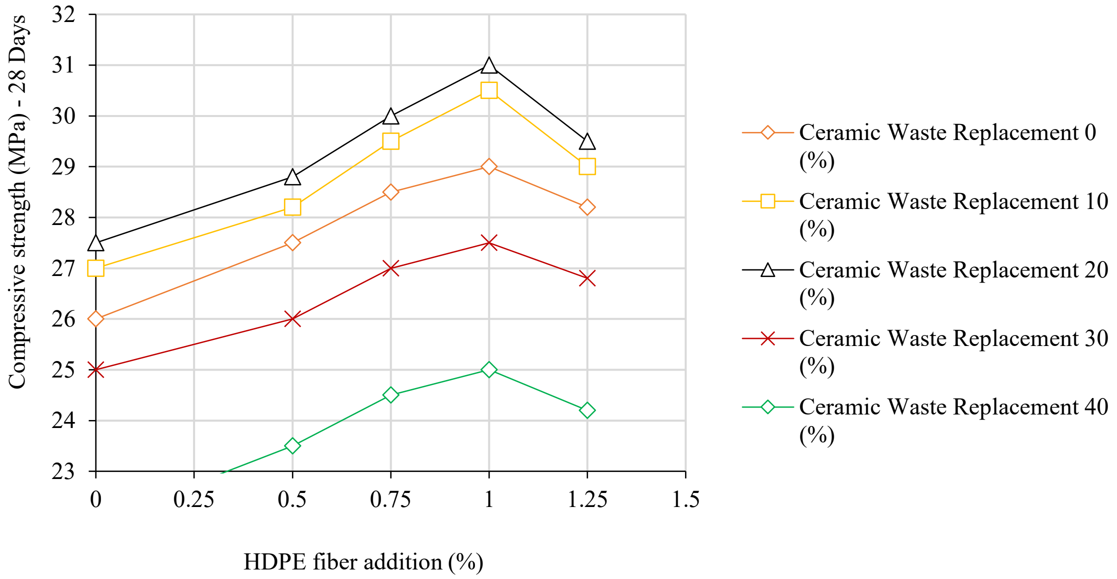

Figure 6. Compressive strength (MPa) - 28 days.

As shown in Figure 6, At 28 days, the concrete reaches its full design strength. Plain concrete achieves 26.0 MPa, while 10% and 20% ceramic powder replacement improve it to 27.0 MPa and 27.5 MPa, respectively. The highest compressive strength, 31.0 MPa, is recorded at 1.00% HDPE and 20% ceramic powder replacement, making it the most effective combination. Strength declines beyond 20% ceramic replacement, dropping to 25.0 MPa at 30% and 22.0 MPa at 40%, confirming excessive replacement weakens the matrix. HDPE fibres enhance ductility and toughness, but 1.25% addition sees slight strength reduction, reinforcing the 1.00% HDPE + 20% ceramic powder as the optimal mix.

Tensile Test Results and Discussion

The experimental program, detailed in the following sections, included 75 trials on concrete cylinders of M20 concrete mix. For all trial mixes, the experimentally determined characteristic tensile strength, from 28-day concrete specimens is graphically represented below.

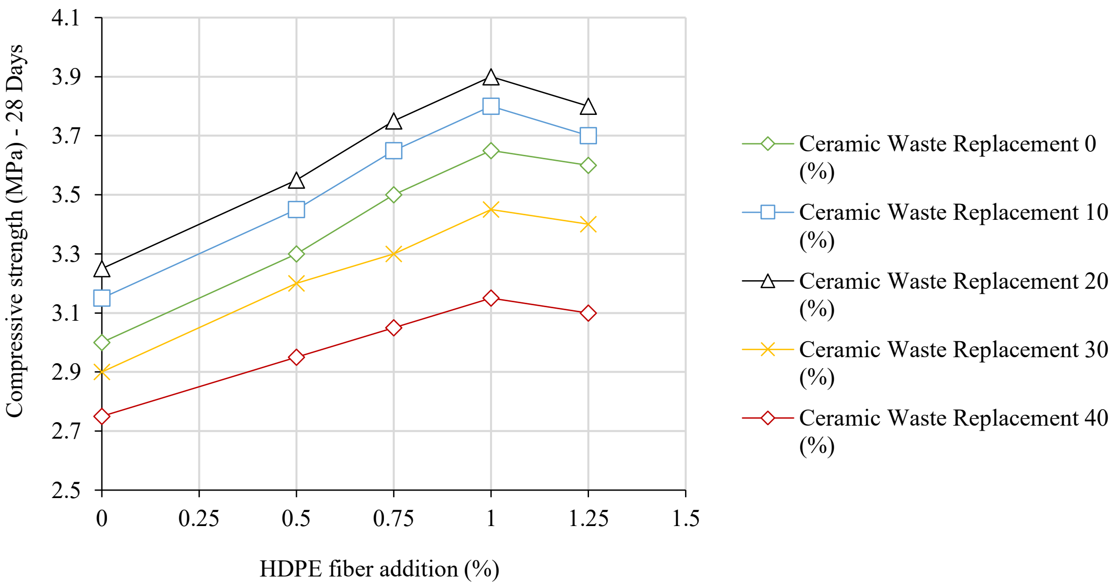

Figure 7. Tensile strength (MPa) - 28 days.

As shown in Figure7, At 28 days, the concrete reaches peak tensile strength. Plain concrete achieves 3.00 MPa, while 10% and 20% ceramic powder replacement improve it to 3.15 MPa and 3.25 MPa, respectively. The highest split tensile strength, 3.90 MPa, is achieved with 1.00% HDPE + 20% ceramic powder, proving it as the best combination. 30% replacement causes a decline to 2.90 MPa, and 40% drops further to 2.75 MPa, making high ceramic content unsuitable. HDPE enhances tensile resistance, but 1.25% shows slight strength reduction, reinforcing 1.00% HDPE + 20% ceramic powder as the best-performing mix for tensile properties.

Chemical and Physical Mechanisms of Cement Reduction Using Ceramic Powder

Chemical mechanisms

Ceramic powder, particularly rich in silica (SiO_2) and alumina (Al_2O_3), undergoes a pozzolanic reaction when introduced into the concrete mix. This reaction occurs between the ceramic powder and the calcium hydroxide ($Ca(OH)_2$) that is naturally produced during cement hydration. As a result, additional calcium silicate hydrate (C-S-H) gel forms, which enhances the strength, durability, and overall performance of the concrete.

Key chemical reactions

Cement Hydration Reaction (Primary reaction between cement and water)

$$2C_3S + 6H_2O \rightarrow 3C{-}S{-}H + 3Ca(OH)_2$$

$$2C_2S + 4H_2O \rightarrow 3C{-}S{-}H + Ca(OH)_2$$

(C_3S = Tricalcium Silicate, C_2S = Dicalcium Silicate, C-S-H = Calcium Silicate Hydrate)

Pozzolanic Reaction (Reaction between ceramic powder and calcium hydroxide)

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow C{-}S{-}H$$

$$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow C{-}A{-}H$$

$$CaO + Ca(OH)_2 + H_2O \rightarrow C{-}A{-}H + CO_2$$

(C-A-H = Calcium Aluminate Hydrate, which improves durability and strength)

These secondary reactions consume excess calcium hydroxide ($Ca(OH)_2$), reducing the risk of alkali-silica reaction and enhancing long-term durability.

Physical mechanisms

Filler effect

Micromorphology of Ceramic Powder test report as shown in Figure 8, the fine particles of ceramic powder help fill voids within the concrete matrix, leading to improved packing density and reduced permeability. Microstructural Enhancement: The additional C-S-H and C-A-H phases refine the pore structure, increasing mechanical strength and durability.

By combining chemical reactions and physical improvements, ceramic powder reduces cement consumption while maintaining or even enhancing the structural integrity of concrete, making it a sustainable and high-performance alternative.

MATHEMATICAL MODEL

Using both compressive (fc) and tensile (ft) strengths as outcomes, we can create a dual regression model that predicts each strength value based on the ceramic waste replacement (C) and HDPE fiber addition (F). Here, I'll provide separate regression equations for compressive and tensile strengths.

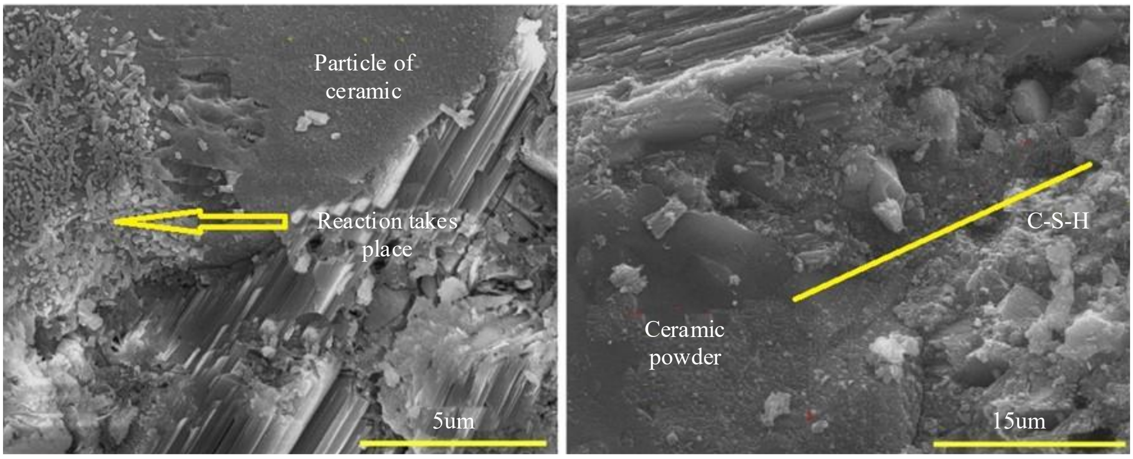

Figure 8. Micromorphology of ceramic powder in concrete.

Regression Model for Compressive Strength

$$fc=\alpha+\beta1\cdot C+\beta2\cdot F+\beta3\cdot C2+\beta4\cdot F2+\beta5(C\cdot F) \quad (1)$$

Hypothetical Coefficients

Using regression analysis on the compressive strength data, let's assume the coefficients are estimated as follows:

$$\alpha=22.0,\beta1=-0.06,\beta2=0.5,\beta3=-0.002,\beta4=-0.4,\beta5=0.003 \quad (2)$$

Thus, the compressive strength model becomes:

$$fc=22.0-0.06\cdot C+0.5\cdot F-0.002\cdot C2-0.4\cdot F2+0.003(C\cdot F) \quad (3)$$

Regression Model for Tensile Strength

$$ft=\gamma+\delta1\cdot C+\delta2\cdot F+\delta3\cdot C2+\delta4\cdot F2+\delta5(C\cdot F) \quad (4)$$

Hypothetical coefficients: Similarly, for tensile strength, assume the coefficients are:

$$\gamma=2.3,\delta1=-0.02,\delta2=0.4,\delta3=-0.001,\delta4=-0.3,\delta5=0.002 \quad (5)$$

Thus, the compressive strength model becomes:

$$fc=22.0-0.06\cdot C+0.5\cdot F-0.002\cdot C2-0.4\cdot F2+0.003(C\cdot F) \quad (6)$$

CONCLUSION

The strength tests demonstrated that the incorporation of HDPE fibres and partial cement replacement with ceramic powder substantially improved concrete performance. Plain M20 concrete attained 26.0 MPa after 28 days, but 10% and 20% ceramic powder supplementation enhanced compressive strength to 27.0 MPa and 27.5 MPa, respectively. The maximum strength, 31.0 MPa, was obtained with 1.00% HDPE + 20% ceramic powder, proving it as the best combination. However, above 20% replacement, strength dropped with 30% at 25.0 MPa and 40% at 22.0 MPa, indicating weak bonding. Similarly, HDPE fibres increased ductility and crack resistance, although surpassing 1.00% (up to 1.25%) resulted in slightly lower strength due to fibre clustering.

Plain concrete had a split tensile strength of 3.00 MPa, but adding 10% or 20% ceramic powder raised it to 3.15 MPa and 3.25 MPa, respectively. The maximum strength, 3.90 MPa, was attained with 1.00% HDPE + 20% ceramic powder, however it reduced after 20% replacement.

Overall, the most promising results were obtained with 1.00% HDPE fibres and 10% to 20% ceramic powder substitution; strength was decreased when these limitations were exceeded. For the best strength, durability, and workability, a blend of 1.00% HDPE and 20% ceramic powder replacement is advised.

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