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Performance Evaluation of Concrete Incorporating Ceramic Waste as Supplementary Cementitious Material

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by

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(2K23/STE/503)

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I, Kapil Agrawal, M. Tech (Structural Engineering) student, having **Roll no: 2K23/STE/503**, hereby certify that the work which is being presented in the dissertation entitled "**Performance Evaluation of Concrete Incorporating Ceramic Waste as Supplementary Cementitious Material**" in the partial fulfilment of the requirements of the award of the Degree **Master of Technology in Structural Engineering**, submitted in the **Department of Civil Engineering, Delhi Technological University** is an authentic record of my work carried out under the supervision of Prof. Nirendra Dev and Prof. Ritu Raj, Department of Civil Engineering, Delhi Technological University, Delhi. I have not submitted the matter presented in this dissertation for the award of any other degree of this or any other institute.

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ABSTRACT

The growth of building sector has led to a huge increase in cement demand. Cement is still required for construction works. However, the cement manufacture is causing enormous environmental damage. The process of manufacturing emits significant volumes of CO_2, almost as much as cement production, which worsens the effects of air pollution and causes global warming. Furthermore, cement production requires significant amounts of natural resources, such limestone. Such issues have resulted in an increased search for alternate and sustainable materials. The substitution of wastes for cement is a promising way to reduce environmental consequences and to enhance waste management.

The purpose of this study is to decrease the use of cement by the use of ceramic waste in cement to alleviate the consequences of construction on the ecosystem. Recycled ceramic electrical insulators were collected and treated for use in mortar and concrete. The pozzolanic activity of CW was evaluated by the standard procedures, i.e. SAI, Saturated lime and Frattini tests. The results showed that the ceramic waste possesses a high pozzolanic property to react with calcium hydroxide and increase the strength. These results indicate that CW can be used to substitute up to 20% of cement in mortar. However, further research is needed, especially on long-term durability, to better comprehend its performance.

Besides mortar, extensive experimental research on concrete were carried out by replacing part of cement with CW at 5%, 10%, 15%, 20% etc. Different tests have been carried out to define the behaviour of the changed concrete. The workability was evaluated by slump cone test and the mechanical qualities were evaluated by split tensile, flexural and compressive tests. The durability and long-term behaviour of the material were assessed by water absorption and penetration tests.

The trial outcomes were positive. The properties of concrete were improved by utilisation of ceramic waste till the optimum substitution of 15%. At this level the concrete showed more strength and more durability compared to regular concrete. This enhancement is due to the tiny particle size of ceramic waste that fills micro-holes in the matrix leading to a more compact and dense structure. But the mechanical and durability qualities were reduced when the replacement amount was more than 15%. In addition, the increased surface area and lower specific gravity of ceramic waste resulted in a minor decrease in workability.

In summary, outcomes suggest that waste originating from ceramic electrical insulators is a viable and sustainable option for partially replacing cement in concrete, with an optimal substitution rate of 15%. This strategy lowers ecological impact of cement production while promoting recycling of waste. Embracing these practices promotes the adoption of more eco-friendly, sustainable construction methods, which are vital to the industry's future.

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ABBREVIATIONS AND ACRONYMS

SAI TEST	Strength Activity Test
SL TEST	Saturated lime Test
CW	Ceramic Waste
CF Test	Compaction Factor Test

CHAPTER 1
INTRODUCTION

1.1 General

Significant quantities of waste from ceramic insulators are produced in the electricity sector, primarily due to the frequent breakage of high-voltage insulators during service. Damaged ceramic insulators are not reusable, resulting in substantial waste accumulation. Recent research has explored utilising this waste as an alternative to coarse or fine aggregates in construction.

1.2 Environmental studies or issues

The history of construction demonstrates that industry growth is closely linked to increased use of raw materials, which has significantly impacted ecological systems. The building industry generates substantial waste, and as the industry expands, waste and pollution continue to accumulate. Reusing waste materials for various applications is required to mitigate environmental impacts.

Infrastructure development keeps accelerating, causing a proportional escalation of environmental impact. Large-scale consumption of cement and other construction materials undermines sustainability, primarily due to the resulting considerable CO_2 emissions from cement production. CO_2, as a greenhouse gas, contributes significantly to global warming —a serious worldwide issue that demands immediate action, alongside other environmental challenges.

Recent studies have investigated the integration of waste materials into concrete to lessen the impact on the environment. Materials like silica fume, fly ash, and industrial by-products are utilised in certain aspects of construction. Similarly, studies have investigated the use of CW as an alternative to coarse and fine aggregates. Utilisation of ceramic waste within concrete presents an environmentally friendly alternative.

1.3 Different activities and tests

SAI test serves as a method for determining the pozzolanic behaviour of material. In SAI test, compressive strength of the control sample is evaluated against that of the sample containing the waste material.

The Frattini test is a direct method for determining the pozzolanic activity of a material by measuring the concentrations of Ca2+ and OH– ions. The pozzolanic activity is subsequently determined from these measured concentrations.

The SL is a condensed form of the Frattini examination and is also considered a direct method. The SL test typically requires a longer testing period compared to Frattini test.

The Frattini test, SL test, and SAI test are all mortar-based methods for determining the pozzolanic activity of materials.

In concrete, various tests are employed to assess strength and density, including mechanical property, durability, and carbonation tests. Mechanical and durability tests are highly effective when it comes to evaluating the extent to which ceramic waste has replaced cement. These tests yield insights into the physical characteristics, strength, and longevity of concrete.

To evaluate the performance of concrete, tests such as compressive, split cylinder, and flexure tests are conducted, along with workability analysis. Mechanical properties are closely linked to concrete strength and are critical for defining structural stability over time.

Workability is a critical factor in determining whether concrete can be handled with ease and placed on-site. Two primary tests are employed to evaluate workability: the CF test and slump cone test. Although CF gives precise outcomes with less inaccuracy, it is less frequently employed on-site because of the complexity of the equipment and weight. Consequently, the slump cone test is generally preferred on-site because it is faster, simpler, and more convenient.

Durability tests assess long-term performance of concrete in construction industry. Common durability tests include the sulphate attack, acid attack, carbonation, water penetration, and water absorption test. Concrete permeability is determined by the water penetration test.

1.4 Objective

Goal of this research is to use CW as a replacement for cement in mortar and concrete. In mortar, material's pozzolanic activity is evaluated. If pozzolanic properties are confirmed, up to 20% of the cement may be replaced in accordance with British standards. The pozzolanic activity is assessed using SAI, Frattini, and SL test.

For concrete, replacement is evaluated through a range of tests, such as mechanical property assessments (compressive, flexural, split tensile, and non-destructive) and durability tests.

1.5 Scope of Study

Investigating these materials facilitates the assessment of the optimal cement replacement percentage in concrete. Materials demonstrating pozzolanic activity may replace up to 20% of the cement in mortar and up to 15% in concrete. Such studies contribute to environmental sustainability by encouraging the utilisation of waste materials and reducing the high

requirement for cement in mortar and concrete. Nevertheless, additional study is necessary to ensure the effective application of these waste materials.

CHAPTER 2

LITERATURE REVIEWS

Researchers are currently seeking ways to increase construction efficiency by reducing cement used in mortar and concrete. One method is to substitute a part of the cement with by-products like rice husk, fly ash and other industrial by-products. Such solutions can help reducing the environmental impact of building, while keeping less garbage in landfills. In this study, ceramic waste, a substance that is normally thrown after usage, was used as a partial replacement of cement in the range of 5% to 20%. The study is dedicated to the examination of the ecological advantages and the possible effects on the strength and durability of the final material in concrete mixtures with the inclusion of ceramic waste. The focus is on the strength and durability of the final material and looks for practical solutions balancing sustainability with performance.

Amr S. El-Dieb et al. (2018) Their findings demonstrate that ceramic powder is most efficient as a cement substitute when used at levels up to 20%. In the study, ceramic powder was incorporated as a partial substitute in proportions ranging from 10% to 40%. The findings indicate that strength and longevity characteristics is improved to a maximum of 20% replacement level, with no significant performance gains observed beyond this threshold.[1]

Zimbili et al. (2014) Ceramic waste can enhance concrete's strength and durability characteristics when utilised as a substitute for cement or aggregates. Ceramic has been shown to exhibit pozzolanic activity and can replace 11–14% of cement, with performance comparable to other pozzolanic materials.[2]

Kannan et al. (2017) The researchers utilised ceramic powder as a partial alternative to cement in proportions ranging from 10% to 40%. Their findings demonstrated that replacement levels up to 40% were assessed through Microstructural, mechanical, and durability analyses of concrete mixtures. When compared to conventional concrete, microstructural research showed that adding CW powder did not significantly alter cement hydration.[3]

Luiz Renato Steiner et al. (2015) This investigation indicates that waste produced during polishing of 'porcellanitic' and 'monopteros' types generates substantial waste that requires depositing in managed landfill sites. The study demonstrated that substituting up to 15% of cement with these CW materials is feasible, as evaluated by strength under compression, pozzolanic activity rating, heat response (calorimetry), and autogenous shrinkage.[4]

S.M.A. El-Gamal et al. (2017) investigated the application of CW as a material to improve the thermal resistance and mechanical characteristics of hardened ordinary Portland cement (OPC). The primary objective was to utilise waste such as CW to enhance the properties of

OPC. Cement blends were produced by partially replacing OPC with CW at 5%, 10%, and 20% by mass. The findings indicate that replacing OPC with a maximum of 15% CW optimises mechanical characteristics and thermal resistance, as demonstrated by strength in compression assessed after 1, 3, 7, 28, and 90 days of curing.[5]

Jackiewicz-Reka et al. (2015) conducted studies examining the characteristics of cement mortars enhanced with CW fillers. According to study, using hygienic ceramic fillers in place of some fine aggregate can result in up to 20% based on weight of the cement, improves compressive and bending while reducing shrinkage. Result was analysed in the context of existing literature regarding impact of CW on fresh and hardened concrete. The effect of CW was assessed with respect to workability, mechanical properties, and freeze-thaw resistance.[6]

Awoyera, P.O. et al. (2017) According to study, mortar sample with 10% ceramic and 100% ceramic aggregate in place of cement and sand, outperformed the reference and other mixtures in terms of strength. The observed strength advantage may be explained by the larger quantities of ettringite, portlandite, and calcite in the optimal mix ratio compared to the reference blend, according to microstructural analysis. Although crushed ceramic material exhibits low reactivity, its use at appropriate concentrations can enhance bonding in cement-based mixture.[7]

Senthamarai et. al. (2011) The study shows incorporation of ceramic industry waste as a partial replacement for coarse aggregates in concrete. Concrete with up to 30% CW exhibited comparable or improved durability, particularly in terms of moisture absorption and chemical durability.[8]

Rashid et al. (2018) The findings indicate by using CW aggregate in place of 30% of standard aggregate yields high compressive strength, reduces environmental impact, and results in a sustainable concrete mix. This conclusion is supported by both the Analytic Hierarchy Process and the Technique for Order Preference by Similarity to Ideal Solution analyses (Siddique et al., 2018, pp. 1242-1251). In their research, both experimental and analytical methods were used to develop environmentally friendly recycled concrete by incorporating ceramic waste as a coarse aggregate. To meet the design objectives, conventional aggregates were partially replaced with ceramic waste aggregates at different proportions. The study evaluated the concrete, in fresh and hardened state, for mixes containing conventional and ceramic-waste aggregates.[9]

Serkan Subas et al. (2017). CW powder can be effectively utilised as a substance that fills in self-consolidating concrete up to a replacement level of 15%. The study concluded that finely ground WCP improves the overall performance of self-consolidating concrete when both strength and flowability characteristics are considered together. It was also observed

that filler materials with sizes less than 0.0125 cm significantly enhance properties, mechanical strength, and longevity of the concrete. In this investigation, granulated waste ceramic powder was used as replacement for cement in self-consolidating concrete mixtures prepared with a binder content of 550 kg/m³.[11]

CHAPTER 3
MATERIAL CHARACTERIZATION

3.1 Materials used in mortar

The selection of mortar materials is made to fulfil best outcomes regarding workability, longevity and strength. Incorporation of finely powdered CW as a partial cement replacement improves particle packing, may enhance mechanical properties, and promotes sustainable construction practices through waste utilisation.

3.1.1 Cement

43-grade regular Portland cement was used in all concrete works in this study, chosen for its proven strength, durability, and suitability for structural applications in accordance with relevant standards.

3.1.2 Ceramic

Due to high voltage in the electricity board, some insulators get damaged or broken. These insulators are made of ceramic material. Broken ceramic insulators could be recycled and employed as a substitute for cement.



Figure 1: Ceramic Material (Insulator) breaks down under high voltage.

3.1.2.1 Method for producing the powdered ceramic material

First, insulators were collected and broken into aggregates ranging from 20 mm to 40 mm using a hammer. These pieces were then processed in an abrasion machine for about an hour, producing a mixture of powder and coarse particles. Following processing, the material was passed through a series of sieves with varying mesh sizes, and the fraction that passed the 90-micron sieve was gathered to be used as ceramic powder.



Figure 2: After the abrasion of the ceramic material sieving and find out 90-micron fine powder

3.1.3 Sand

For both mortar and concrete, we chose sand passing through 4.75 mm IS sieve. This sort of sand has a uniform size of particles which makes the mix easier to work with and helps assure the strength and longevity of the finished satisfying the required building standards. Sand was used as fine aggregate for both mortar and concrete mixes with consistent particle-size distribution and optimal workability as per relevant specifications.

3.2 Material used in concrete other than mortar

3.2.1 Coarse aggregate

In preparing the concrete mix, we used coarse aggregate having nominal size 20 mm. Selecting above aggregate size provided essential stability and strength for the concrete while also ensuring good workability and a uniform texture in the final mix, consistent with standard construction practices.

3.2.2 Superplasticizer

In the concrete mix, we incorporated Fosroc Auramix 400 as a superplasticiser. Additionally, Fosroc Auramix 400 helps achieve higher strength and a more durable final product, in line with modern construction requirements.

CHAPTER 4

METHODOLOGY

4.1 Methodology in mortar

A structured experimental plan was designed to evaluate the performance of mortar incorporating ceramic waste. The methodology includes material characterisation, mix design, specimen casting, curing, and assessment of mechanical properties.

4.1.1 Physical properties of CW

Ceramic waste is predominantly produced from damaged or discarded electrical insulators, which frequently fracture under high-voltage conditions during service or handling. These insulators are fabricated from high-quality, durable ceramic materials engineered to endure mechanical and electrical stresses. Consequently, even after breakage, the material retains substantial engineering properties, positioning it as a valuable resource rather than mere waste.

Rather than being disposed of in landfills, this material can be effectively repurposed for construction applications, thereby supporting sustainable development and minimising waste. To facilitate reuse, the collected ceramic insulator waste is first cleaned to remove impurities and then ground into a fine powder. This transformation is achieved using mechanical methods such as crushing, grinding, or abrasion, selected based on the desired fineness and the available equipment.

After the ceramic material is processed into powder, it is important to evaluate its physical characteristics to determine its suitability as a replacement for cement in mortar or concrete. Key physical attributes, including particle size range, degree of fineness, specific gravity, bulk density, and surface texture, are systematically examined. These characteristics significantly influences workability, strength, and performance of mortar.

Evaluating these parameters ensures that ceramic powder can be utilised effectively and consistently in construction practices. A thorough understanding of its physical behaviour enables appropriate proportioning in mix design, thereby improving both the performance and sustainability of the resulting mortar.

Table 1: Physical characteristics of CW material

S.No.	Physical quantities	Results of CW material
1.	Ph	9.8
2.	Specific gravity	2.31
3.	Loose bulk density (kg/m^3)	615.7

4.1.2 Chemical properties of waste material

The chemical properties of ceramic waste have been examined in the research paper by A. **Roulal, et al.** (2009) [12]

According to this research paper, the ceramic electrical insulator has the following chemical composition.

Fired = 1350 ^{0}C and Sintered = 1500 ^{0}C

Table 2: chemical characteristics of CW material

S.N.	Chemical oxides (from test)	Result (in %)
1.	Al_2O_3	50
2.	ZrO_2	0.0
3.	BaO	7.79
4.	(Na-K) O_2	2.65
5.	SiO_2	39.25
6.	Rest	0.78

4.1.3 Mould preparation and mortar mixing

After chemical and physical characteristics of the CW material, perform flow table test to determine workability, which indicates the water content of the mix.

Make mortar cubes and prepare a 50 x 50 x 50 mm³ mould for testing over the course of seven and twenty-eight days.

Table 3: Proportion of the mortar's mixture (for the 6 cubes of size 50*50*50 mm^3):

S.No.	constituents	Quantity required (in kg)
1.	Cement	0.4
2.	Pozzolana	0.1
3.	Sand	1.5
4.	Water	0.242

4.2 Concrete methodology

This involves replacing cement with ceramic insulator material, which passes through a 90-micron sieve, at replacement levels of 5, 10, 15, and 20 per cent. These replacement levels are compared to the control mix. Tests were conducted on days 7 and 28. Mechanical characteristics, such as compressive strength, flexural strength, and split tensile strength, along with durability aspects like water absorption and water permeability, were examined. Concrete mixtures were produced using ceramic insulator waste as a replacement for cement.

Water/Cement (W/C) ratio of 0.45 remained same across all concrete sample mixes, which were designed as per IS codes (456 and 10262).

Table 4: IS codes for material tests:

S.No.	Test for specific gravity	CODE
1.	Cement	IS 4031 (PART-11) 1988
2.	Fine aggregate	IS 2386 (PART-3) 1963
3	Coarse aggregate	IS 2386 (PART-3) 1963

Table 5: The necessary test results for mix proportion:

S.N.	Constituents of concrete test	Outcomes
1.	Specific gravity (Cement)	3.12
2.	Specific gravity (Fine Aggregate)	2.7
3.	Specific gravity (Coarse Aggregate(20mm))	2.73
4.	Water absorption (Coarse Aggregate)	0.3 %
5.	Water absorption (Fine Aggregate)	0.9%
6.	Sand zone	Zone –II
7.	Cement	OPC 43-grade

4.2.1 Concrete mix proportion methodology

Using CW to fully replace cement is not practical for concrete or structural applications, and there is not any code for designing with this material. In this research, the mix proportions were determined based on trial casting rather than by aiming for a set concrete grade. The focus was on keeping the Water/Cement constant and adjusting other parameters to vary the replacement percentage. The trial mix was used with a Water/Cement ratio of 0.45The tables below display the mix specifics.

IS Codes (456 and 10262) serve as the foundation for this combination design.

Table 6: Mix design using varying percentages of CW at a Water/Cement of 0.45

S.N.	Replacement (in %)	Water Kg/m^3	Cement Kg/m^3	Ceramic waste (Kg/m^3)	20mm (Kg/m^3)	Sand (Kg/m^3)	Super P. (kg/m^3) (0.5%)
1.	Control or 0	180	400	0	1174	712	2
2.	5	180	380	20	1174	712	2

3.	10	180	360	40	1174	712	2
4.	15	180	340	60	1174	712	2
5.	20	180	320	80	1174	712	2

4.2.2 Weighing process

Weight, expressed in grams or kilograms, is used to measure the components of concrete , including cement, sand, coarse aggregate, water, ceramic waste, and superplasticizer.

4.2.3 Procedure for concrete mixing

Begin by loading the coarse and fine into the mixer for mixing them for two minutes. Afterwards, introduce the cement and continue mixing for an additional five minutes. Once the dry ingredients are well mixed, add the specified amounts of water and superplasticiser, then mix for 30 minutes approximately. After mixing, check workability and use it to fill the mould.

4.2.4 Process of preparation of specimens

To prepare the specimen, get the mould (150*150*150 mm3) of cube, the cylinder (150 mm diameter, 300 mm height) and the beam (100*100*500 mm3), and ready for concrete pouring. Before adding concrete, oil all inner surfaces of mould to keep the concrete from sticking. Fill mould with concrete in 3 layers and use a vibrating table to vibrate each layer.

4.2.5 Process of curing of the specimen

After a twenty-four-hour casting period, extract the specimen from the mould and place it in the curing tank for 7, 28, etc., as needed.



Figure 3: Concrete mixture for mixing of concrete

CHAPTER 5

EXPERIMENTAL PROGRAM

5.1 Experimental program in mortar

The experimental program included SAI test, SL test, and Frattini test to comprehensively evaluate pozzolanic reactivity of ceramic waste powder. The SAI test was performed to contrast strength of mortar containing CW with that of control mortar. The saturated lime test assessed the ceramic powder's ability to fix calcium hydroxide from a lime solution, indicating pozzolanic reactivity. Additionally, the Frattini test was employed to assess the reduction in calcium ion concentration in solution, further confirming the pozzolanic potential of the CW material.

5.1.1 SAI test

The SAI test assesses pozzolanic activity by assessing the strength (compressive) of mortar or concrete where certain cement is substituted with the experimental material. SAI is calculated as a percentage: Pozzolan-containing mortar compressive strength divided by that of a control mortar, multiplied by 100. A higher SAI indicates greater pozzolanic reactivity and more effective cement replacement.

5.1.1.1 Principle

The Strength Activity Index (SAI) test follows BS EN 196-1:2016, the current standard for determining the strength of mortars containing pozzolanic materials. A pozzolan is considered active if its SAI reaches at least 80% of that of the control mortar. The cement-to-sand ratio is set at 1:3, using 500 grams of OPC and 1500 grams of standard sand (zone 2) to produce six 50 mm cube specimens. Water content is adjusted using a flow table test to maintain consistent workability. The control mortar contains only OPC, whereas the test mix replaces 20% of the cement with pozzolanic material, with all other proportions unchanged.

5.1.1.2 Flow table test

This test were conducted as per EN 1015-3:2007 to evaluate mortar workability. Cement/Sand of 1:3 by mass was used. Water was poured in gradually until the mortar reached a flow diameter of 210 ± 5 mm after 15 drops. The mortar was filled into a truncated cone mould in two separate layers, each tamped 10 times, before removing the mould and operating the flow table. This procedure determined the water-to-binder (cement) ratio required to achieve the desired workability for subsequent strength and pozzolanic activity tests.

5.1.1.3 Process and calculation

In the SAI test, after preparation, make the mortar and place it on the vibrator table to vibrate. After 24 hours, demould the sample; place it in the curing tank for 6 and 27 days at 23 °C. Determine the strength of the mortar sample after 7 and 28 days. For SAI test, take average of three samples and compare the waste material's strength with the results from the control mortar.

The SAI test is represented or reported as per the following instructions:

$$SAI = \frac{\text{Compressive strength of test pozzolan in MPa}}{\text{Compressive strength of control in MPa}} * 100$$

If the strength achieved by the pozzolanic material is at least 80% of that of the control, the material is considered to exhibit pozzolanic activity.

5.1.2 Frattini test

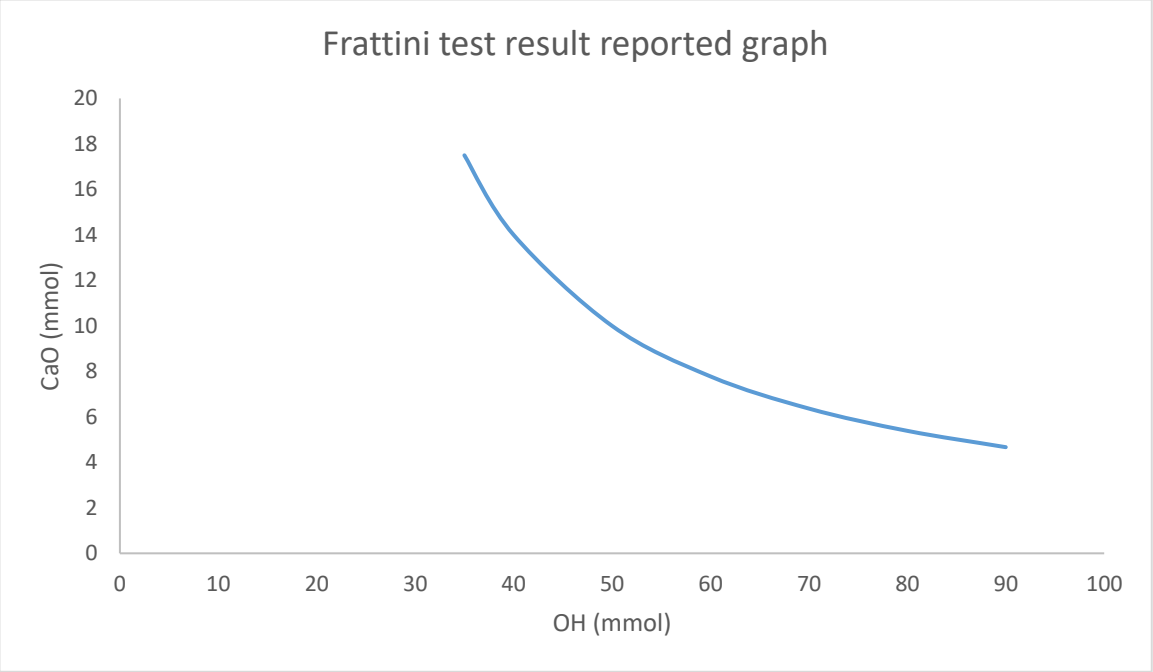
This is a chemical method for measuring pozzolanic reactivity by measuring a material's ability to fix calcium hydroxide from solution. Mixture of cement and pozzolanic material is reacted at controlled temperature, usually for 8 or 15 days. Afterward, the concentrations of calcium and hydroxide ions are measured. If these concentrations are below the calcium hydroxide saturation curve, The pozzolanic substance has interacted with and depleted calcium hydroxide, hence validating its pozzolanic action.

5.1.2.1 Principle

This test is conducted as per EN 196-5. In this procedure, a sample consisting of one hundred millilitres of water and 20 g of cement is prepared. For comparative analysis, 20% of the cement is replaced with pozzolanic material. The samples are placed in sealed bottles and incubated at 40° Celsius temperature. After 8 days, samples are filtered using press and Whatman 542 filter paper. The hydroxide ion (OH-) concentration is determined by titrating the sample with HCl solution using methyl orange as the indicator. Calcium ion (Ca2+) concentration is measured using a pattern indicator and ethylenediaminetetraacetic acid (EDTA) solution. Prior to EDTA titration, the level of pH is adjusted to 12.5 by adding NaOH solution, if necessary. The results are interpreted using the standard graph provided below, which is based on BS196-5-2011

This graph is made by following the standard formula:

$$\text{Max Calcium oxide concentration} = \frac{350}{\text{OH concentration} - 15}$$



Control sample is inside range of graph, as indicated by code and graph itself. If the pozzolanic materials fall below the graph line, they show pozzolanic activity and thus have pozzolanic properties.

5.1.2.2 Chemical Substances

Materials and reagents used in test include 0.1 mol/L hydrochloric acid (HCl) solution, methyl orange indicator, EDTA solution, Patton and Reeder indicator, calcium carbonate ($CaCO_3$), sodium carbonate, ammonium purpurate (murexide), and sodium hydroxide(NaOH).

Prior to conducting experiment, proper standardization of solutions is required. Two solutions that need to be standardized are HCl solution and EDTA solution.

5.1.2.3 Standardisation (EDTA Solution)

To standardize EDTA solution, first take a 400 mL flask and pour in 100 ml water. Then slowly add 10 ml concentrated HCl and mix the solution properly using a glass rod. After thorough mixing, add more water until the total volume reaches 1000 ml.

Next, transfer 50 mL of the calcium solution into a beaker and dilute it with an appropriate amount of water to make the procedure convenient. The pH of the solution should then be adjusted and maintained at around 12.5 by adding NaOH solution.

5.1.2.4 Determination of end point

Patton and reader indicator is added to solution, solution changes colour from purple to blue.

$$\text{f1 factor} = f_1 = \frac{m1}{V1} * 16.652$$

Here, m_1 = mass of CaCO3, in grams, and V_1 = titrated volume used for EDTA solution, in millilitres.



Figure 4: Ca^{2+} end point determination

EDTA titration end point is visually identified by a colour change from purple or pink to blue.

5.1.2.5 Standardisation (HCL solution)

Weigh 0.2 ± 0.0001 g of sodium carbonate and add it to a 250 mL flask containing 50–75 mL of the sample solution

f_2 factor, $f_2 = \frac{m2}{V2} * 188.70$

Here m_2 = mass of sodium carbonate in gm and V_2 = titrated volume HCL, in mililiteres

5.1.2.6 Procedure

The sample is stored in a sealed bottle and kept in an incubator at a constant temperature of 40°C for periods of 8 days and 15 days. If satisfactory results are obtained after 8 days, further testing for 15 days is not necessary. After the 8-day period, the sample is removed and immediately filtered using a vacuum filter at room temperature. The solution and sample are then prepared according to the procedure described in the principle section, followed by titration.



Figure 5: Determination of the endpoint of OH-

(I) Determine the OH^- concentration

OH^- (in millimole/litre) = $2*V_3*f_2$

Here, V_3 = titrated volume HCL of 0.1 mol/litre, and f_2 = factor HCL of 0.1 mol/litre solution

(II) CaO determination

CaO (in millimole/litre) = $0.6 \times V_4 \times f_1$

where V_4 = titrated volume EDTA and f_1 = factor for EDTA

(III) Calculation and presentation of result

(IV) Evaluation of results

5.1.3 SL test

SL test evaluates pozzolanic activity by measuring a material's ability to consume calcium hydroxide from a SL solution. A specified amount of pozzolanic substance is mixed with the solution and kept at a controlled temperature for 7 or 8 days. After this period, the remaining calcium hydroxide concentration is measured. A significant decrease confirms the material's pozzolanic activity.

5.1.3.1 Principle

This test is a modified or simplified version of Frattini test. A measured amount of lime is initially added, and remaining lime is determined at the end of process because amount consumed can then be evaluated. solid particles are retained over the filter paper.

In this test, sand is expected to show zero pozzolanic activity, only lime solution is maintained in sample. Sample is stored at a temperature and protected from CO_2 exposure, as temperature variations can affect the results, and lime reacts with CO_2 to form calcium carbonate.

5.1.3.2 Procedure

In sample preparation, take 75 mL of SL solution, add 1g material, mix in bottle. This SL solution is prepared by mixing 2 g of lime with 1 L of distilled water. A sample is taken in a sealed bottle and incubated at a temperature (40 °C) for one, three, seven and twenty-eight days. Then procedure is the same as in Frattini.

5.2 Experimental Programme in Concrete

The experimental program for concrete involved a systematic evaluation of properties to assess performance and longevity. The workability of concrete batches were evaluated using slump test to preserve uniformity of consistency in all the batches. Mechanical characterisation was performed by testing standard cube specimens for compressive strength and split cylinder test for split tensile strength. Further, flexural strength of concrete was studied by conducting flexural tests on beam samples. Durability was evaluated by conducting the tests of water absorption and the water penetration of selected samples. This extensive set of tests has given an insight into the effect of modifications in the mix on the workability, mechanical performance and long term durability of the concrete.

5.2.1 Workability test

Concrete workability can be evaluated through various techniques, such as slump cone test, flow table, CF test etc. Although CF provides more accurate results, it is not commonly used on construction sites due to the equipment's complexity and bulkiness. In contrast, slump test is the widely used test in the field because it is quick and requires minimal apparatus, delivering results within a minute. Other methods, such as the flow table and Vee-Bee tests, are typically used in laboratory settings for highly workable and low-workability concrete.

The slump measurement was obtained with the help of an apparatus conforming to IS 7320:1974, and the procedure described in IS 1199:1959



Figure 6: Slump test for workability

5.2.2 Mechanical properties test

Mechanical properties tests are fundamental for calculating structural performance. Commonly include strength in compression, split test, which evaluates resistance against forces in tension; and flexural (bending) strength, which determines its ability to resist stresses in bending. Collectively, these tests provide a thorough evaluation of concrete's strength and load-bearing capacity, confirming its suitability for diverse structural applications.

5.2.2.1 Strength test in compression

The compressive strength of the concrete was assessed following the guidelines of IS 516 (Part 1/Sec 1): 2021, a standard that supersedes the older IS 516:1959. This regulation outlines the methods for evaluating hardened concrete samples, including measuring strength at 7 and 28 days. Standard cubes of size 150 × 150 × 150 mm^3 were utilised. For every set 3 cubes were tested, and the mean strength was expressed in megapascals (MPa).

Prior testing, cubes were taken out of curing, and their surface water was wiped off. Specimen was positioned in CTM with rough, uncast surfaces perpendicular to the loading plates to maintain uniform distribution of load. Casting surfaces (top and bottom) did not contact the platens during testing. The load was applied gradually and uniformly at a constant rate until the specimen failed, and the maximum load (P) at the point of failure was noted.

Calculation of strength in compression was carried out using following formula:

Compressive strength = P / A

In this formula, P represents the peak applied load (N), and **A** denotes the c/s area of cube in square millimetres (mm^2). This value directly measures the concrete's capacity to withstand axial compressive forces and serves as a primary indicator of structural performance.



Figure 7: 150 mm cubic specimen for evaluating compressive strength



Figure 8: Compression test in the compression testing machine (CTM)

5.2.2.2 Strength of concrete in flexure

Concrete beam flexural strength was determined based on IS 516 (Part 2/Sec 1): 2021, which has taken the place of IS 516:1959. This procedure, known as the modulus of rupture test, utilises the third-point (two-point) loading technique for evaluating concrete's tensile strength under bending. Standard beam specimens measuring 500 × 100 × 100 mm^3 were cast, followed by a 28-day curing period for this purpose.

Before testing, the beams are taken out of the curing process, cleaned to remove surface moisture, and positioned in the flexural testing machine with a 400 mm span between supports. Each beam is supported at both ends with a 50 mm overhang, and two-point loads are applied at third points, spaced 133 mm apart within the span. This configuration eliminates shear force at the centre of beam.

Load is applied gradually and uniformly, increasing at a steady pace till failure. The peak load (P) is recorded at failure for each specimen. Three beams from every batch are tested, and the mean flexural strength is recorded.

The modulus of rupture, also known as flexural strength, is determined using the following equation:

Flexural strength (Flexural strength) (f_r) = (P × L) / (b × d^2)

- P = load applied at failure (N)
- L = Supported span length (mm), in this case 40 cm
- b = Width of beam (mm), in this case 10 cm
- d = Depth of the beam (mm), in this case 10 cm

This test yields essential data on concrete's capacity to resist bending under flexural loads.



Figure 9: Flexural testing machine at beam size (100*100*500 mm^3)



Figure 10: Beam after flexural test at the beam fails

5.2.2.3 Split test for tension

Split test was evaluated in accordance with IS 5816:1999, which outlines the procedure for tensile strength testing of concrete using cylindrical specimens. Cylinders measuring 300 mm in height and 150 mm in diameter were cast using concrete. After 28 days curing, Surface moisture was wiped off the specimens before they were placed horizontally between platens of CTM.

During testing, load was applied gradually and uniformly along length each cylinder till failure, ensuring that loading line was aligned with the cylinder's generator. This procedure generates tensile stresses normal to the direction of loading, resulting in cylinder to split along its diameter. For each mix, three cylinders were tested, and the mean value was recorded as the split tensile strength.

The split tensile strength (fct) was determined using the following equation:

$$\text{Tensile strength of cylinder } = \frac{2P}{\pi DL}$$

where:

- P = Peak load to the specimen (N)
- D = Diameter (mm)
- L = Length (mm)

This test plays crucial role in evaluating tensile characteristics of concrete, which are vital for determining performance in elements subjected to tension, including pavements, pipes, and prestressed members.



Figure 11: After the split tensile test (Test for the strength of the cylinder)

5.2.2.4 UPV test

UPV was performed as per **IS 13311 (Part 1): 1992**, which outlines procedures for non-destructive testing of concrete using UPV methods. This method is employed to evaluate the consistency, quality, and integrity of concrete in both laboratory and field environments.

During the UPV test, the transmitter and receiver are placed on opposite sides of the concrete specimen. The transmitter sends an ultrasonic pulse through the concrete, which is then received by the receiver located on the other side.. An electronic timing device records the transit time (T) required for the pulse to traverse the known path length (L) between the transducers.

The code specifies that the pulse velocity (V) is computed with following equation:

$$V = L / T$$

Higher pulse velocity values generally represent dense and good-quality concrete, while lower velocities may indicate the presence of cracks, voids, or other internal defects. Non-destructive test is effective for quality control, evaluating uniformity, and detecting flaws within concrete structures.

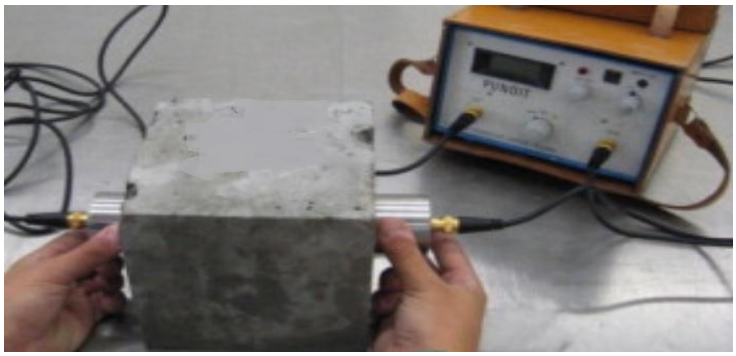


Figure 12: UPV test performance in the cube

5.3 Durability test

To assess the durability, water penetration and water absorption were performed in accordance with the relevant standards. The water penetration test evaluates the depth to which water can penetrate concrete under pressure, indicating the concrete's resistance to water and the ingress of harmful substances. The absorption test determines the quantity of water taken up by the concrete specimen when immersed, reflecting the material's porosity and durability in aggressive environments. Together, these tests provide important details about permeability and durability of concrete mixes.

5.3.1 Water absorption test

This test was conducted in accordance with **IS 1124:1974**, which specifies the method for determining water absorption of building stones and is widely adopted for concrete as well.

For this test, 150 mm concrete cubes were cast and cured for 27 days. Following the curing period, each sample was taken out of the tank, surface-dried at room temperature for 1–2 hours and weighed to obtain the initial mass (W_1). The cubes were subsequently dried in an oven at 105 ± 5 °C for 24 ± 2 hours and weighed again to obtain oven-dry mass (W_2).

Water absorption was determined using following equation, in accordance with IS 1124:1974.:

Water absorption = $W = \frac{(W1-W2)}{W2} * 100$

where:

W_1 = weight of the sample after surface drying at room temperature

W_2 = oven-dry weight of the sample after 24 hours at 105 ± 5 °C

This test provides an important measure of concrete's porosity and permeability, both of which significantly influence its durability and ability to withstand aggressive environmental conditions. Reduced water absorption values indicate denser, less permeable concrete, which is generally more durable and less susceptible to deterioration.

5.3.2 Water penetration test

The water penetration test followed DIN 1048 (Part 5), which measures concrete permeability by assessing the extent of water penetration under pressure. Lower permeability indicates greater resistance to water and aggressive agents, making this test an indicator of concrete longevity. After 28 days of standard curing, 150 mm × 150 mm × 150 mm concrete cubes were oven-dried at least for 24 hours. The DIN test apparatus is designed for 150 mm cubes; smaller sizes, such as 100 mm, are not compatible.

During the test, a continuous water pressure of 0.5 N/mm² is exerted on one side of the sample for 72 hours. Afterwards, samples are taken out and dried for about 5 minutes, and split to measure the extent of water penetration. The maximum extent recorded as the test result provides a direct assessment of the concrete’s resistance to water ingress and long-term durability, particularly for structures exposed to harsh environments.



Figure 13: Water penetration (DIN permeability) test

CHAPTER 6

RESULT AND DISCUSSION

6.1 Mortar test results and Discussion

This section presents and discusses results of experimental investigations into mortar mixes that use CW as a partial replacement for cement. Key parameters evaluated include pozzolanic activity, workability, compressive strength, and bending strength.

6.1.1 Strength activity test

As per BS 3892, a material is considered to exhibit pozzolanic properties in mortar if the SAI is equal to or greater than 80%. Similarly, as per ASTM C618, a SAI value of 75% or higher indicates sufficient pozzolanic activity. The SAI results are determined by taking mean strength in compression for three mortar cubes for each mix. Prior to conducting the SAI test, the optimal water/cement for each mix is determined using flow table to ensure consistent workability.

Based on BS 3892, if SAI result ≥ 80%, and based on ASTM C618, if SAI result ≥ 75%, then the material shows pozzolanic activity in mortar.

Prior conducting SAI test, the water/cement was determined using the flow table, as presented below.

Table 7: Flow table results

S.N.	Sand (g)	Cement (g)	CW (20%) (g)	Water (g)	Water/Cement	Flow length (mm)
1.	480	160	0	102	0.64	204
2.	480	128	32	101	0.63	204

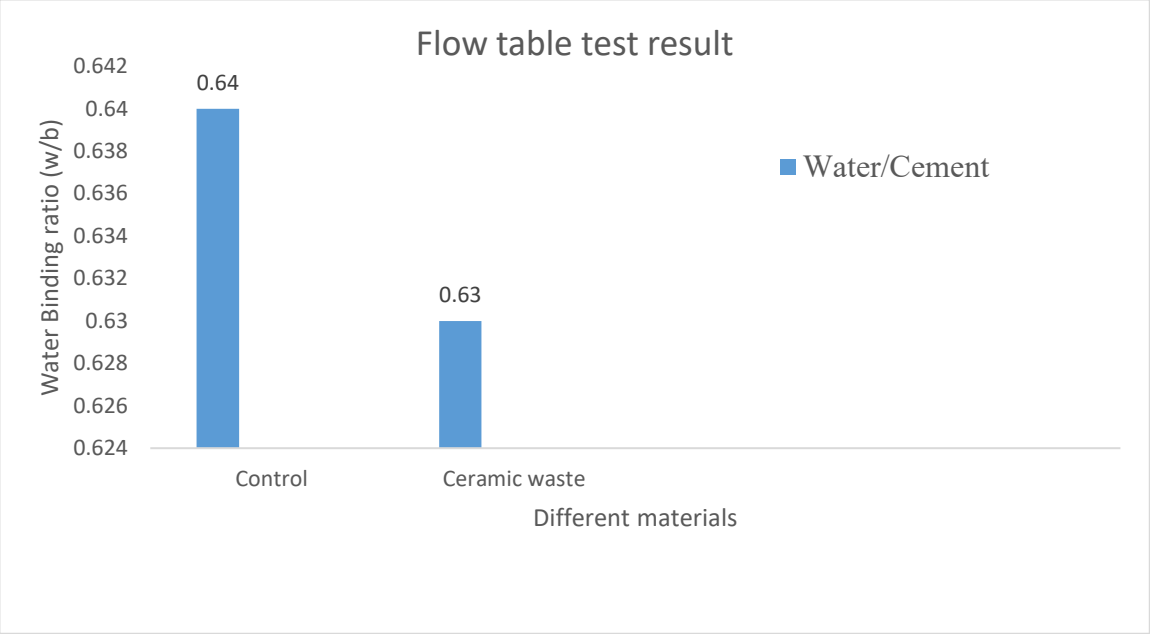


Figure 14: Flow table test to assess mortar workability

Flow table test results showed that mortar containing CW material required less water compared to the control mortar mix. This indicates that a lower water/cement can be achieved while still maintaining workability similar to that of the control mix.

Table 8: Seven days SAI results

S.No.	Mortar	Seven days strength (MPa)	SAI
1.	Control mix	9.6	1
2.	CW 20% replacement	8.5	0.885

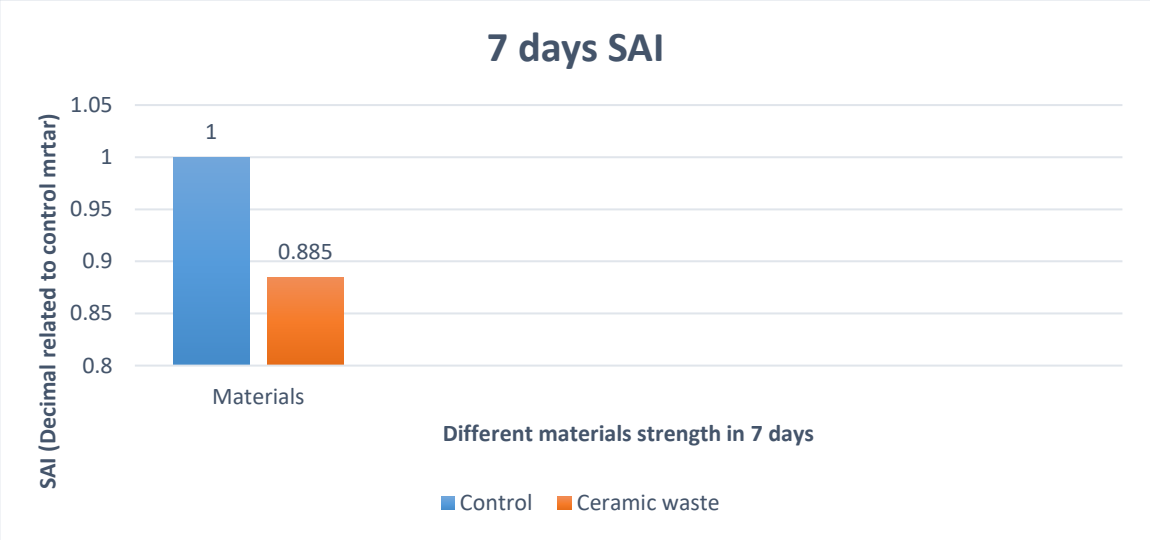


Figure 15: Seven days SAI

At seven days, the SAI value is 0.885, meaning the ceramic waste material achieves 88.5% of the control mix mortar's strength. This meets the pozzolanic criteria specified in BS 3892 and ASTM C618.

Table 9: Twenty-eight-days SAI

S.N.	Mortar	Twenty-eight-days Strength (MPa)	SAI
1.	Control mix	13	1
2.	CW replacement 20%	12.5	0.96

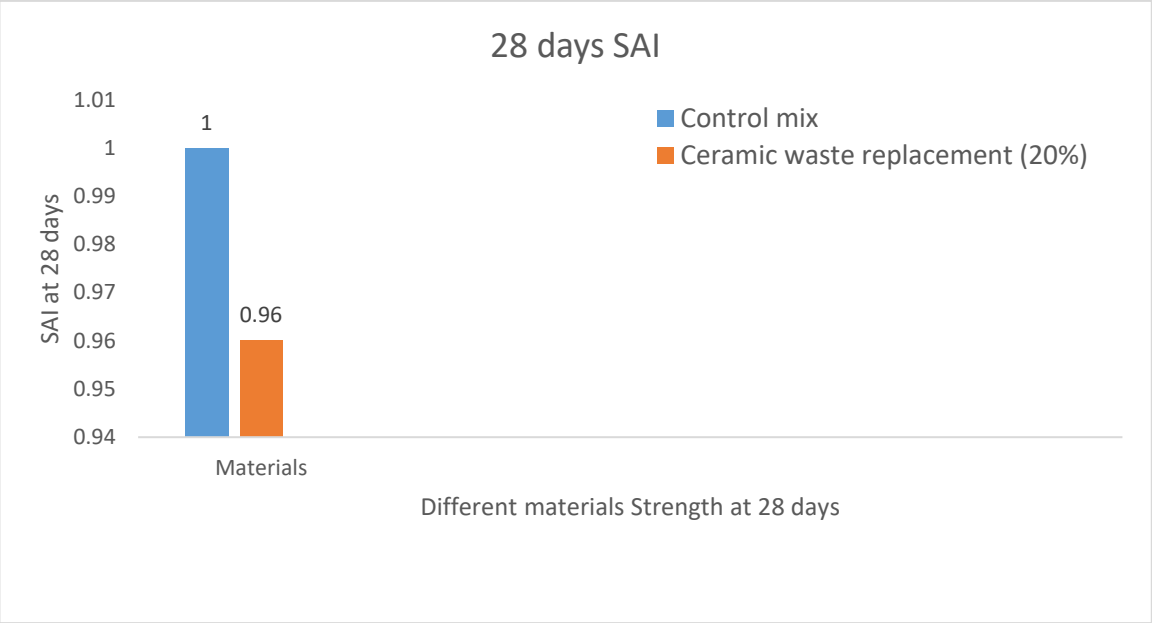


Figure 16: Twenty-eight-days SAI

At twenty-eight-days, SAI is 0.96, indicating that CW material achieves 96% of strength of control mortar mix. As per BS 3892 and ASTM-C618, this result demonstrates pozzolanic activity at 28 days.

The results at seven and twenty-eight-days represents an increase in strength percentage over time, reflecting enhanced pozzolanic reactivity of CW. Therefore, CW demonstrates pozzolanic reactivity when incorporated into mortar.

6.1.2 Frattini test

Table 10: Eight days Frattini results

Constituents	OH^- (mmol $l^{-1)}$	CaO (mmol l^{-1})	Theoretical maximum CaO (mmol l^{-1})	CaO reduction in percentage

Portland Cement 43 Grade	46.80	10.92	11	0.7
Ceramic waste	40.80	10.20	13.7	24.7

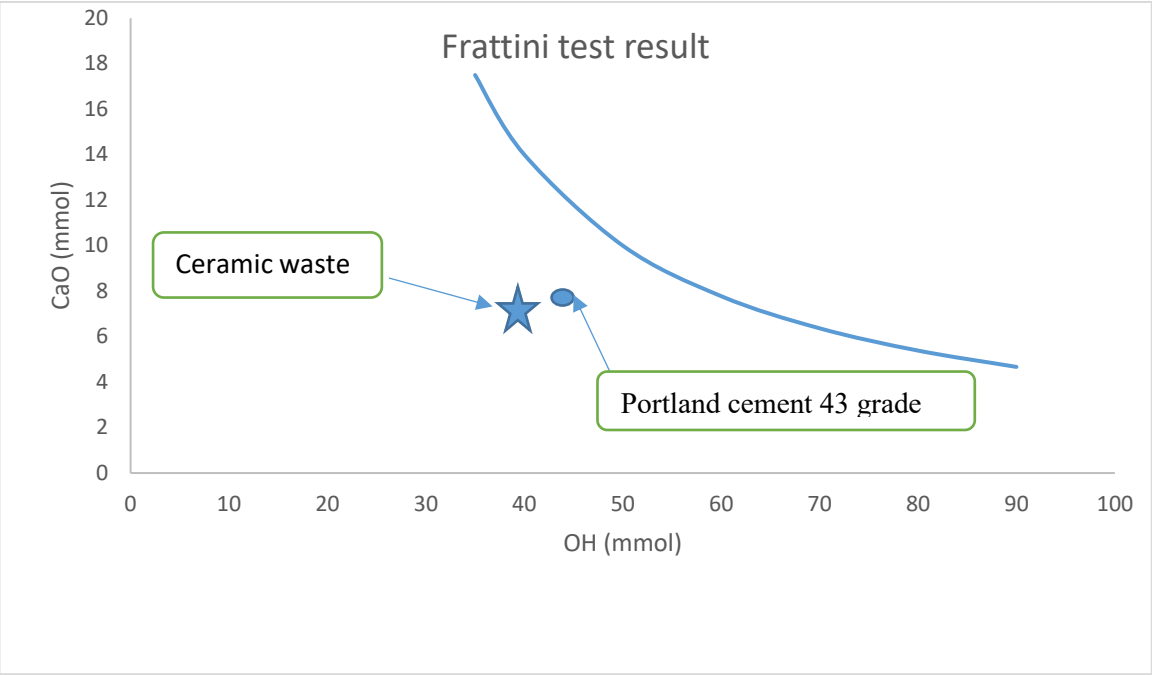


Figure 17: Frattini test analysis of CW with control

In Frattini, a point plotted below lime saturation curve indicates that the material consumes calcium ions (Ca^{2+}) from solution, confirming presence of pozzolanic activity. If plotted point lies above curve, material does not exhibit pozzolanic behaviour. When point falls directly on curve, material is considered to have negligible or zero pozzolanic activity.

As per table, a positive CaO reduction percentage represents pozzolanic action in mortar. Two samples were tested: one with cement only and another with 20% replacement. Results are based on mean of three readings.

Table shows that CW material produced a positive CaO reduction value, confirming its pozzolanicity.

Graph indicates that the Ca2+ and OH- concentrations in CW material fall below lime saturation line. This demonstrates that material consumes calcium hydroxide and exhibits pozzolanic activity in solution.

6.1.3 Saturated lime test

For the SL test, average the results from three specimens for each reading. Conduct titrations at one, three, seven, and twenty-eight-days to determine Ca (OH)2 removal, expressed as

percentage CaO removal. Compare samples with 20% ceramic waste replacing cement by weight to control samples without replacement.

Table 11: one, three, seven and twenty-eight days SL results

S.N.	Replacement	Duration of titration (in days)	OH^-	CaO	Max. CaO	CaO removal (in percentage)
1.	Control (0%)	1	27.71	25.80	27.53	27.76
2.		3	30.09	22.75	23.19	36.30
3.		7	26.52	25.98	30.38	27.25
4.		28	28.56	24.88	25.81	30.32
5.	Ceramic waste (20%)	1	27.69	15.18	18.72	57.49
6.		3	35.10	9.82	17.14	72.50
7.		7	33.54	9.19	18.87	74.26
8.		28	32.79	5.63	18.37	84.23

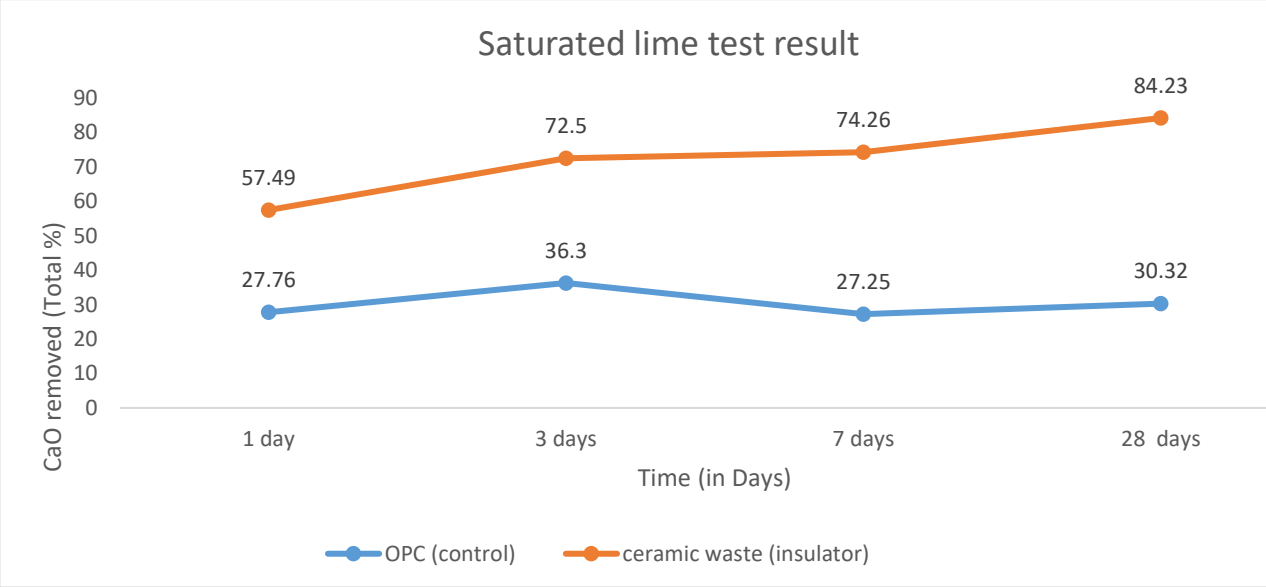


Figure 18: Saturated lime test for comparison of control mortar and ceramic waste

According to the graph, ceramic waste material increases the percentage of CaO removal over time, indicating that Ca $(OH)_2$ removal is higher in the ceramic waste material than in the control solution. So, it shows the material's pozzolanic property and activity.

6.2 Results and discussion in concrete

This section presents and discusses the experimental findings on concrete mixes incorporating ceramic waste powder as a partial substitute for cement. The performance of

these mixes was evaluated in terms of workability, mechanical strength, and durability characteristics.

6.2.1 Fresh concrete (Workability) test

The workability of fresh concrete was evaluated using the slump test. The findings revealed that the slump values gradually reduced as proportion of CW powder used as a cement replacement increased. This reduction is mainly due to the higher surface area and angular shape of particles, which tend to absorb more water and increase internal friction within the mix. Despite the decrease, slump values for all mixes stayed within acceptable ranges for practical placement and compaction, confirming that incorporating ceramic waste powder does not negatively impact concrete workability at optimal replacement levels.

Table 12: Concrete workability

S. No.	Percentage replacement of cement with CW (%)	Workability (mm)
1.	Control	107
2.	5	105
3.	10	98
4.	15	96
5.	20	87

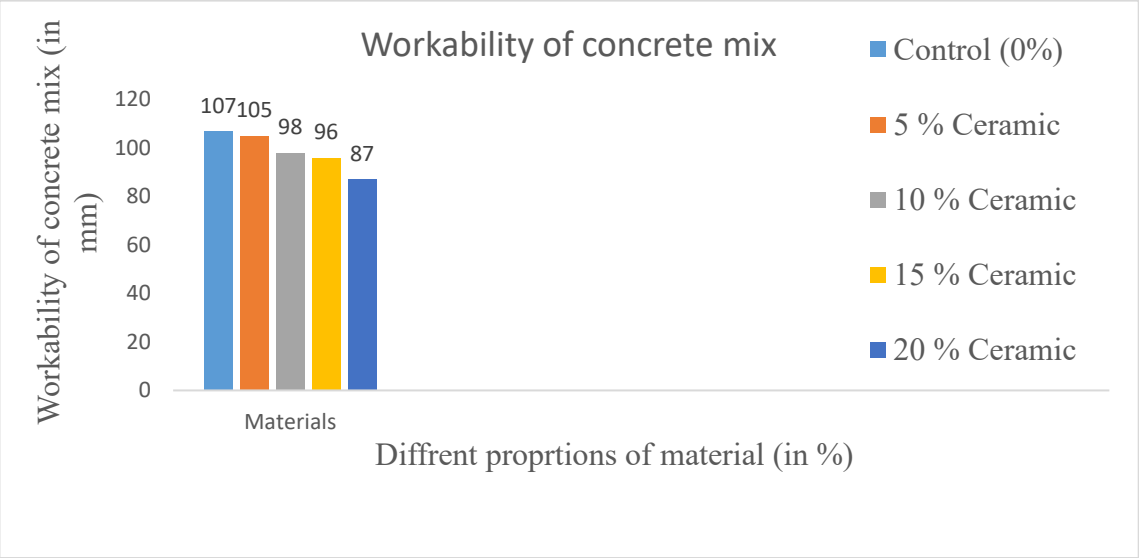


Figure 19: Workability with varying CW percentage

6.2.2 Mechanical properties test

The mechanical properties of concrete mixes with ceramic waste powder were evaluated through compressive, split tensile, and flexural strength tests at designated curing periods.

6.2.2.1 Strength test in compression

Strength in compression was determined at seven and twenty-eight days. Results represent mean strength obtained from three cubes.

Table 13: Seven days compressive strength results for different CW replacement percentage

S.N.	Percentage replacement of cement with CW (%)	Seven days compressive strength (MPa)	Comparisons (%)
1.	Control (0%)	26.54	100 %
2.	5	24.96	94.05%
3.	10	23.563	88.78%
4.	15	22.71	85.57%
5.	20	19.64	74%

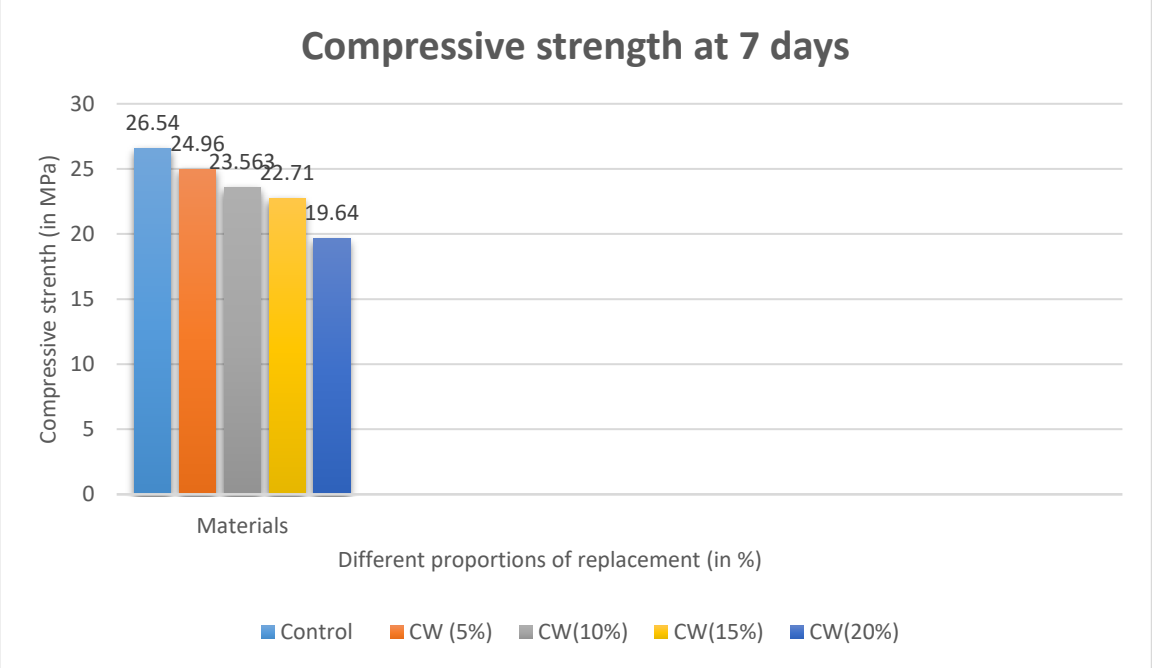


Figure 20: Seven days compressive strength results for different CW replacement percentage

Seven-day compressive strength decreases as ceramic percentage replacement increases. When up to 15% of the cement is replaced with ceramic waste, compressive strength remains above 80% of the control sample. However, at 20% ceramic waste replacement, the strength falls below 80% of the reference mix.

Table 14: Twenty-eight-days compressive strength results for different CW replacement of replacement percentage

S.No.	Percentage replacement of cement with CW (%)	28 days compressive strength (in MPa)	Comparisons (%)
1.	Control (0%)	28.97	100 %
2.	5	28.01	96.68 %
3.	10	25.98	89.67 %
4.	15	25.70	87.21 %
5.	20	20.12	68.24 %

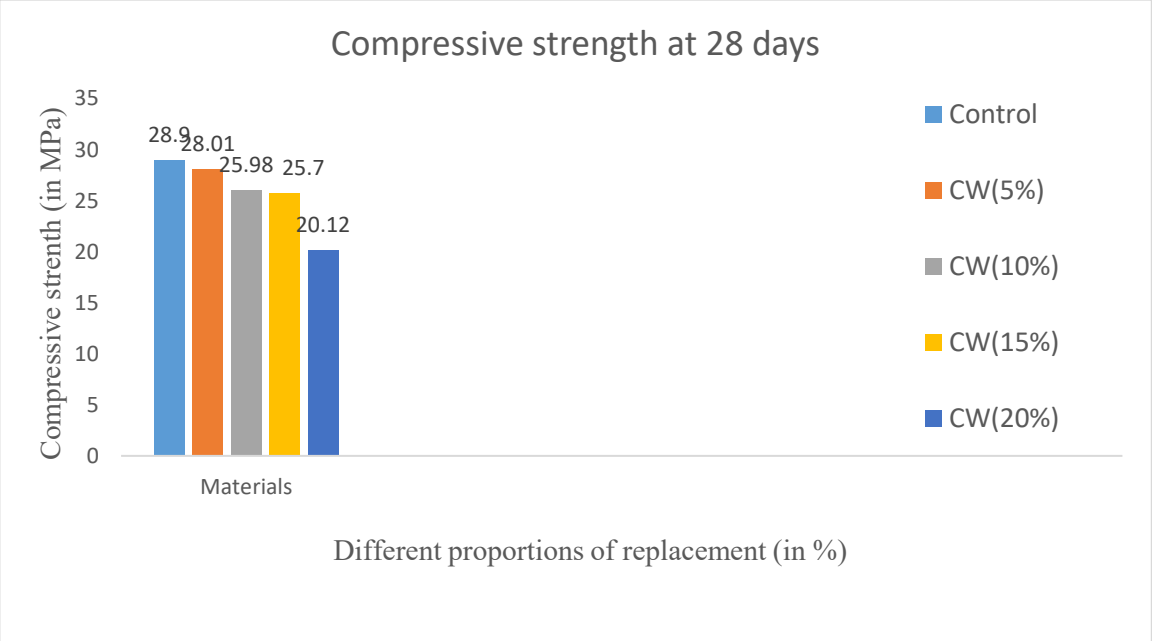


Figure 21: Twenty-eight-days compressive strength results for different CW replacement percentage

28-day compressive strength decreases as the ceramic replacement percentage increases. The compressive strength remains above 80% of reference sample up to 15% CW. However, at 20% ceramic waste replacement, strength falls below 80% of the control, indicating reduced performance at this substitution level.

6.2.2.2 Flexural strength test

After seven and twenty-eight days of curing, the strength of concrete in bending was assessed, using average values obtained from three separate specimens.

Table 15: Seven days flexural strength for different CW replacement percentage

S.N.	Percentage replacement of cement with CW (%)	Seven days flexural strength (MPa)	Comparisons (%)
1.	Control	6.98	100 %

2.	5	6.6	94.55 %
3.	10	6.25	89.54 %
4.	15	6	85.96 %
5.	20	5.875	84.17 %

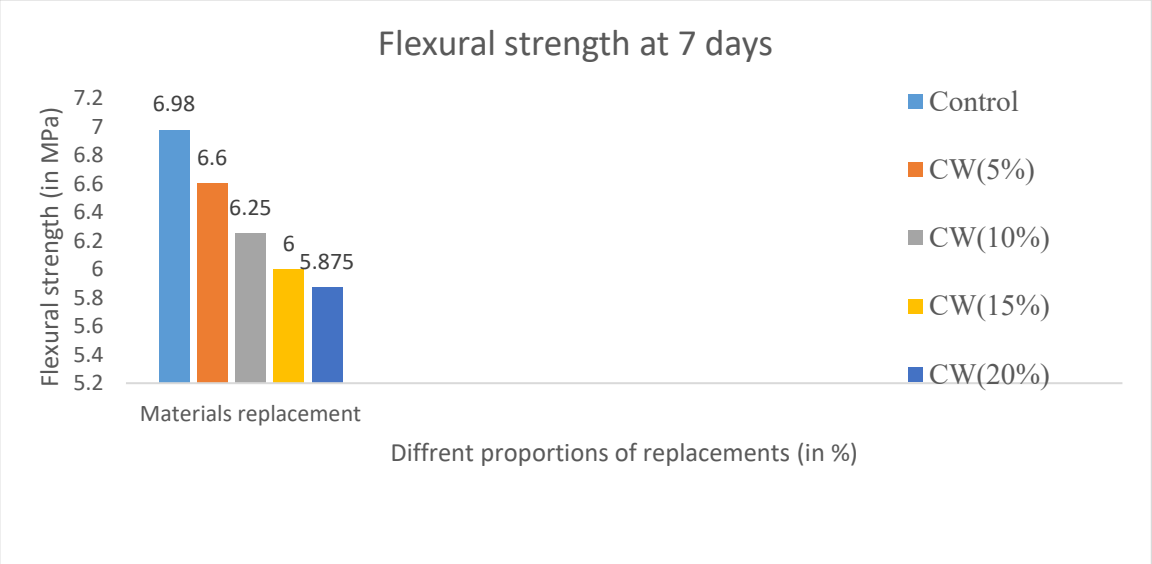


Figure 22: Seven days flexural strength for different CW replacement percentage

At 7 days, concrete flexural strength decreases as ceramic waste percentage increases. However, even at 20% replacement, the flexural strength remains above 80% of the control, showing less than a 20% reduction. This indicates that up to 20% replacement of ceramic waste does not substantially affect the early-age flexural performance of concrete, with all values staying above 80% of the control.

Table 16: Twenty-eight-days flexural strength for different CW replacement percentage

S.N.	Percentage replacement of cement with CW (%)	Twenty-eight-days flexural strength (MPa)	comparisons (%)
1.	Control	10	100 %
2.	5	9.40	94 %
3.	10	9.125	91.25 %
4.	15	8.54	85.4 %
5.	20	7.25	72.5 %

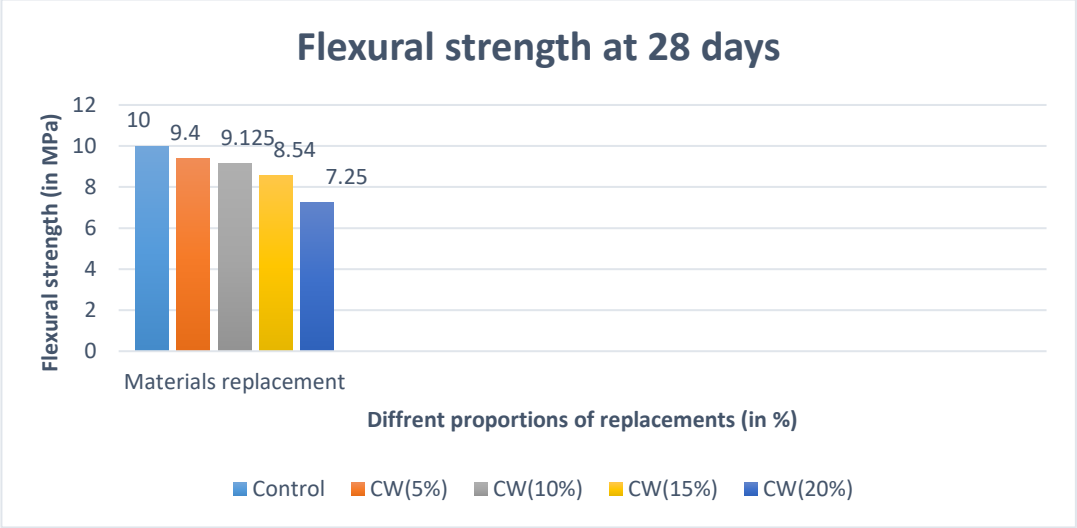


Figure 23: Twenty-eight-days flexural strength for different CW replacement percentage

28 days strength in bending decreases as percentage of ceramic material increases. The results are calculated from the mean of three beam specimens, each measuring 100 × 100 × 500 mm. These findings indicate that flexural strength with ceramic material replacement remains above 80% compared to control concrete, but drops below 80% at 20% ceramic replacement.

6.2.2.3 Split tensile test

Split strength in tension was measured at seven and twenty-eight days. The outcome represents mean (average) strength of three concrete cubes.

Table 17: Seven days split cylinder result for different CW replacement percentage

S.N.	Percentage replacement of cement with CW (%)	Seven days split cylinder strength (MPa)	Comparison (%)
1.	Control	3.35	100 %
2.	5	3.22	96.12 %
3.	10	3.05	91.04 %
4.	15	2.88	85.97 %
5.	20	2.05	61.2 %

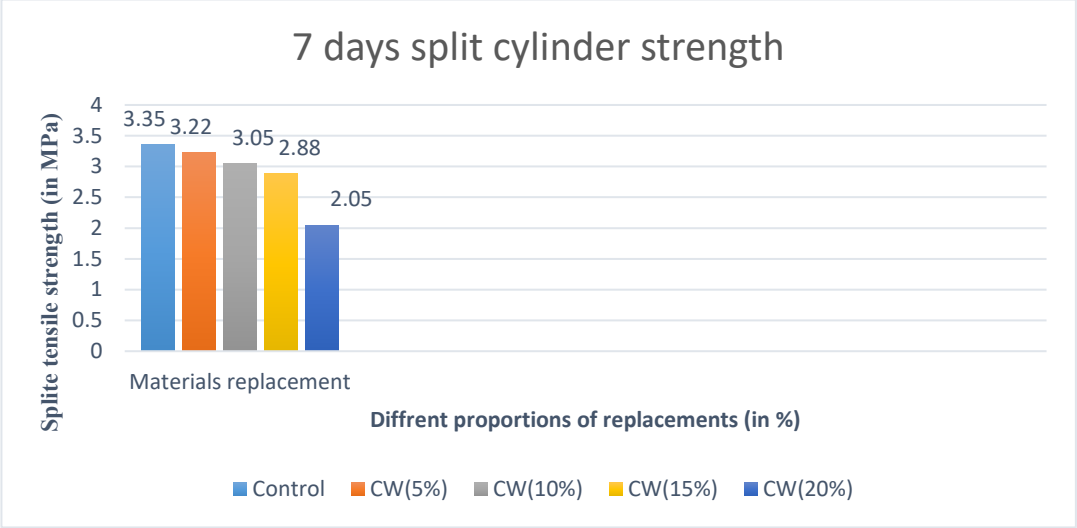


Figure 24: Seven days split cylinder result for different CW replacement percentage

The seven-day concrete split tensile strength decreases as percentage of CW increases. When ceramic waste replaces up to 15% of the aggregate, the split tensile strength remains above 80%. However, at 20% replacement, the seven-day strength falls below 80%, indicating reduced concrete performance at this substitution level.

Table 18: Twenty-eight-days Split cylinder tensile strength result for different CW replacement percentage.

S.No.	Percentage replacement of cement with CW (%)	Twenty-eight-days split cylinder strength (MPa)	Comparison (%)
1.	Control	4.15	100 %
2.	5	3.93	94.7 %
3.	10	3.73	89.88 %
4.	15	3.52	84.82 %
5.	20	2.98	71.81 %

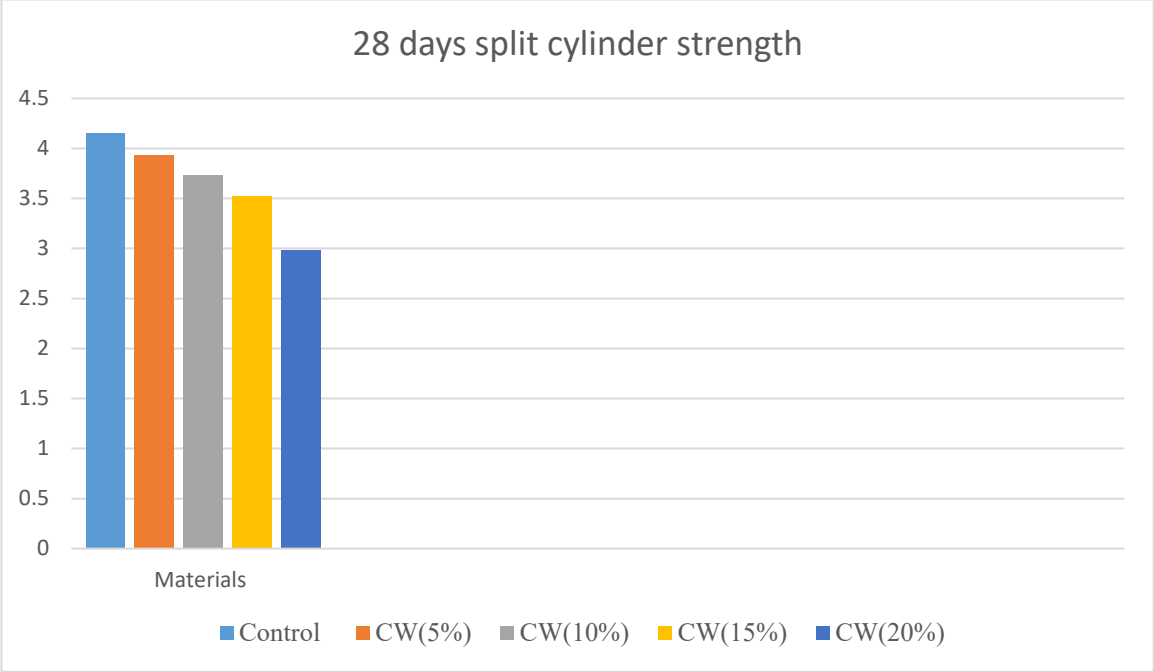


Figure 25: Twenty-eight-days split cylinder result for different CW replacement percentage

28-day split strength decreases with increase in CW percentage. CW material's split tensile strength exceeds 80% up to 15% replacement, but at 20% replacement, the 28-day strength falls below 80%, so concrete performance is poor at 20%.

6.2.3 Non-destructive test

6.2.3.1 UPV test

According to twenty-eight-day strength test by UPV, strength of concrete decreases with increase in CW percentage. Strength of CW material is more than 75% up to 15% replacement, but at 20% replacement, the 28-day strength of the concrete is less than 75%, so, the concrete showed reduced performance when the replacement level reached 20%.

Table 19: UPV test result

S.No.	Percentage replacement of cement with CW (%)	UPV reading (in time) (microsecond)	Pulse Velocity by crossing probing (in km/sec)	Concrete quality grading (As per IS13311 part 1:1992)
1.	Control	19	5.26	Excellent
2.	5	21	4.76	Excellent
3.	10	23	4.35	Good
4.	15	26	3.85	Good
5.	20	28	3.57	Medium

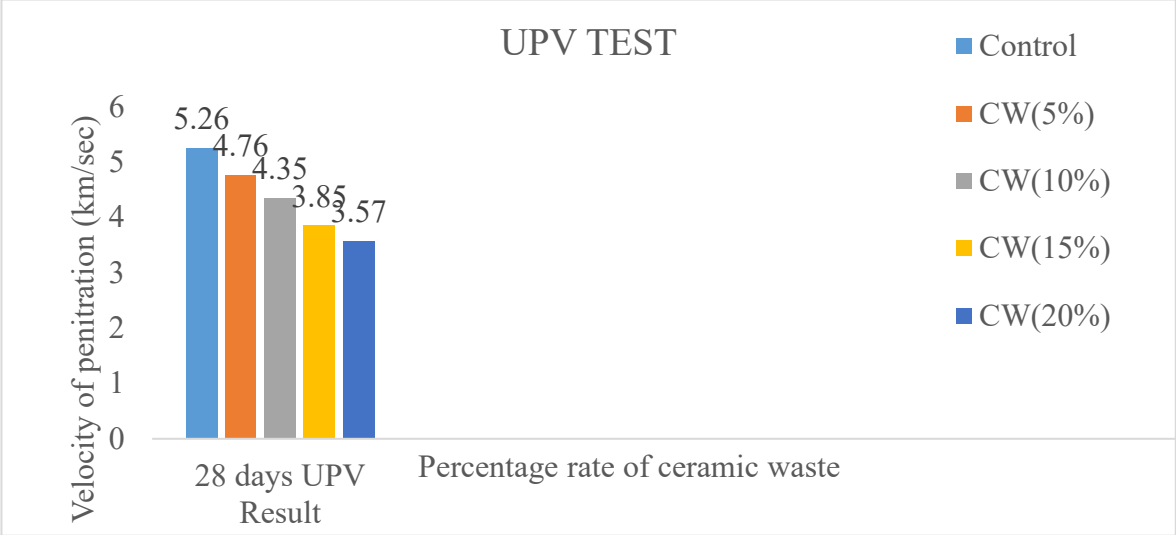


Figure 26: UPV test result with CW material

The result of the UPV test is described as per IS 13311 Part 1:1992. According to this code, as percentage of CW increases, quality of concrete decreases: from excellent to good, then to medium.

6.2.4 Durability test

6.2.4.1 Water absorption test

Outcome of the water absorption test is average of three specimens. Cubes measuring 100 × 100 × 100 mm³ were utilised for this test. Following twenty-eight-days curing, the specimens were dried for 1 hour, then dried at 110 ± 10 °C for twenty-four hours. Readings were then recorded, and absorption of water was calculated.

Table 20: Twenty-eight-days water absorption results with different CW percentage

S.N.	Percentage replacement of cement with CW (%)	28 days water absorption (%)	Comparison (%)
1.	Control	2.56	100 %
2.	5	2.36	92.2 %
3.	10	2.35	91.79 %
4.	15	2.16	84.375 %
5.	20	2.15	83.98 %

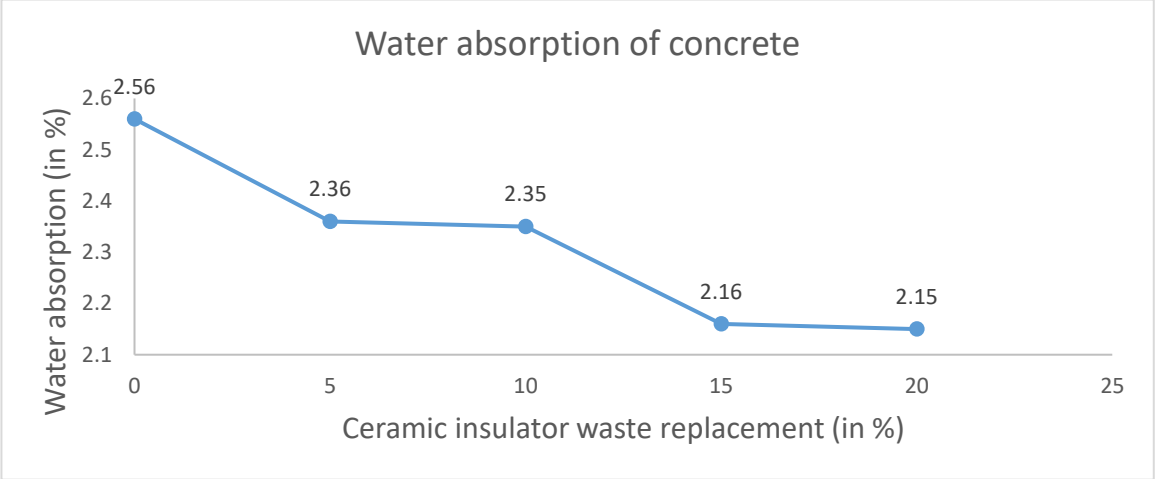


Figure 27: twenty-eight-days water absorption with different CW percentage

Water absorption results indicate that increasing proportion of CW in concrete decreases the ceramic material's water absorption. This occurs because ceramic waste absorbs water during mixing.

6.2.4.2 Water Penetration Test

For the water penetration test, use the DIN test on the concrete. In this test, take the average of the three cubes' depth results of size 150*150*150 mm^3.

Table 21: twenty-eight-days water penetration result with diffrenet CW percentage

S.N.	Percentage replacement of cement with CW (%)	Twenty-eight-days water penetration depth (cm)	Comparison (%)
1.	Control	6.2	100 %
2.	5	5.5	88.70 %
3.	10	5.0	86.64 %
4.	15	3.7	59.67 %
5.	20	3.2	51.61 %

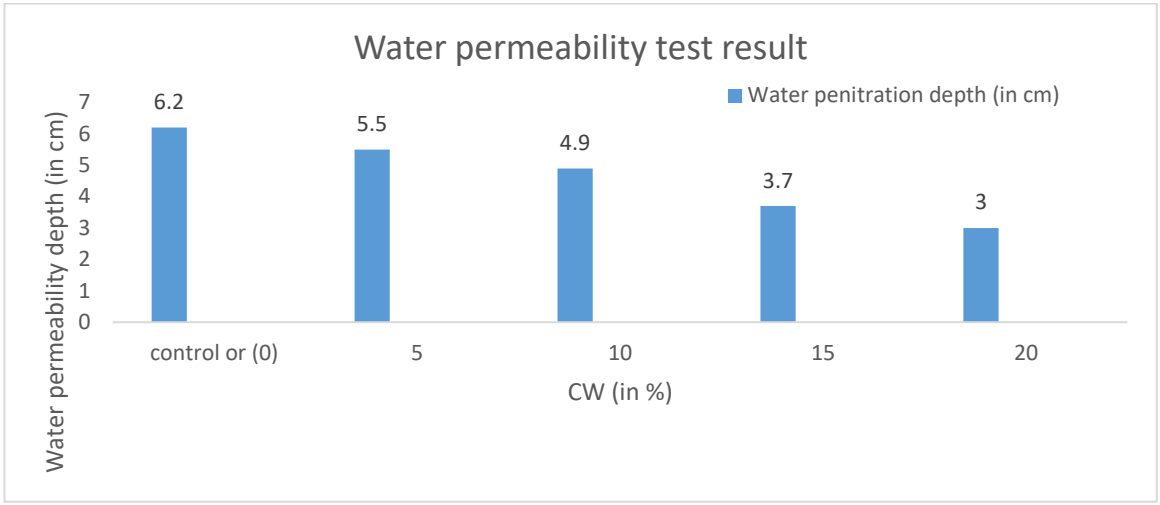


Figure 28: twenty-eight-days water penetration result with different CW percentage

Test results reveal that the depth of water penetration in concrete cubes reduces as percentage of CW material used for replacement increases. This depth increases because the ceramic material fills the voids in concrete, reducing its porosity.

CHAPTER 7
CONCLUSION

This study set out to determine suitability of using ceramic insulator waste as a supplementary cementitious material in mortar and concrete. Work has led to several important findings:

1. **Pozzolanic Activity:** Ceramic insulator waste shows strong pozzolanic properties, as demonstrated by SAI, Frattini and SL test. When replacing up to 20% of cement in mortar, CW consistently met established standards set by both British and ASTM codes.

2. **Workability:** Introducing CW into concrete mixes led to a gradual reduction in workability because of material's increased surface area and angular shape. However, up to a 15% replacement, the slump values remained within a practical and usable range.

3. **Mechanical characteristics:** The concrete's compressive, flexural, and split tensile strengths were maintained above 80% of reference mix when up to 15% of the cement was substituted with ceramic waste. Beyond this replacement level, a noticeable decline in strength was observed, suggesting 15% as the optimal limit for maintaining structural performance.

4. **Durability:** The inclusion of ceramic waste improved durability-related characteristics of concrete up to the 15% replacement level. Both water absorption and penetration decreased, indicating a denser and less porous matrix. When the replacement exceeded 15%, these benefits diminished or reversed.

5. **Non-destructive Testing:** Ultrasonic pulse velocity (UPV) tests supported these results, indicating that concrete quality remained acceptable up to 15% replacement, but began to decline at higher levels.

In conclusion, the ceramic insulator waste can be considered as a feasible and sustainable partial replacement of cement in concrete and the optimum replacement level was found to be 15%. This method is useful for recycling of industrial waste and at the same time it keeps the necessary mechanical and durability features.

Further research is recommended for wider adoption and practical application, in particular long term durability tests on resistance to acid attack, chloride penetration, carbonation, freeze-thaw cycles and shrinkage, and microstructural analysis.

CHAPTER 8

FUTURE SCOPE

The present study revealed that ceramic waste can be efficiently substituted for cement up to 20% in mortar and 15% in concrete but there is still much scope for additional research and improvement in this field.

Firstly, further durability testing is required to completely understand the long term behaviour of cementitious systems using ceramic waste. Future studies should involve the assessment of environmental circumstances e.g. acid attack etc. These variables are particularly relevant for structures subjected to harsh climates or sea settings where chemical durability is a major concern the current study demonstrates that up to 20% of cement in mortar and 15% in concrete can be effectively replaced with ceramic waste, there remains significant potential for further research and development in this area.

Furthermore, a detailed microstructural investigation by means of modern methods such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) will provide information on the interaction of ceramic waste with the cement matrix and its effect on the development of hydration products. Optimisation of the particle size, replacement ratio and processing procedures for ceramic waste can be achieved through knowledge of these mechanisms.

Another intriguing path is to extend the scope of the research to even higher levels of replacement. The present work set feasible limitations of replacement for concrete and mortar at 15 % and 20 %, respectively, although future work may allow further increases using novel admixtures, extra ingredients or curing techniques without loss of performance.

Expanding the scope of research to explore even higher replacement levels is another promising direction. While this study established 15% and 20% as practical replacement limits for concrete and mortar, respectively, innovative admixtures, supplementary materials, or alternative curing methods may enable safe increases in these percentages in the future without compromising performance.

Moreover, field tests and pilot studies are suggested to validate laboratory results. This would assist bridge the gap between research and large-scale implementation, offering valuable feedback on workability, setting time and in-service durability.

Finally, a more comprehensive environmental and economic evaluation, involving lifecycle analysis and cost-benefit studies, would provide more light on the overall sustainability and practical benefits of employing ceramic waste in construction.

By pursuing these research directions, we can unlock the full potential of CW as a sustainable resource in construction, contributing to both environmental conservation and the development of innovative materials.

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