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Investigations on Effective Utilization of Industrial By-Products in Production of Eco-Friendly Mortar for Sustainable Construction

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ABSTRACT:

This study looks at how waste materials from industries, like fly ash, silica fume and GGBFS, can be used to make eco-friendly mortar. The goal is to reduce waste, lower environmental impact, and create more sustainable building materials. We collect industrial waste materials and mix them into mortar by replacing cement in varying percentage of industrial by-product and adding superplasticizer (PCE) to increase the fluidity, strength etc. We assessed the specific gravity of cement and sand to understand their density and quality. The fineness test was conducted to check the particle size, ensuring better bonding and strength in the mortar mix. Additionally, we measure the initial and final setting time of cement to determine how quickly it starts and completes hardening, which is crucial for workability and construction efficiency. We tested mortar's strength using a compressive strength test to see how well I holds up under pressure. Heat resistance test was done to check its stability at high temperature, ensuring durability at extreme temperature. Acid attack and sulphate attack test helped evaluate its resistance to chemical deterioration, making sure it withstands harsh environment.

Keywords: Eco-friendly mortar, sustainable construction, fly ash, silica fume, GGBFS, compressive strength, water absorption, heat resistance, acid resistance, sulphate resistance, PCE superplasticizer, durability, partial cement replacement, waste management.

Introduction:

Cement mortar consists of a combination of cement, sand, water, and occasionally additives, serving as a binding material in the construction industry. It is vital for tasks such as bricklaying, plastering, flooring, and structural repairs, offering strength and longevity. The proportion of cement to sand varies based on the intended use, influencing its workability, setting time, and overall strength. Proper curing is essential to ensure that the mortar achieves its maximum strength and minimizes the risk of cracking. Its adaptability makes it a crucial material in contemporary construction. Cement serves as the principal ingredient in mortar, functioning as the primary binder that unifies the mixture. It undergoes a chemical process with water known as hydration, which allows it to harden and develop strength over time. Nevertheless, the manufacturing of Ordinary Portland Cement (OPC) emits a considerable amount of carbon dioxide, contributing to environmental pollution. To mitigate this issue and enhance the sustainability of construction, industrial by-products such as fly ash, silica fume, and Ground Granulated Blast Furnace Slag (GGBFS) can be utilized as partial substitutes for cement. Fly ash is a fine powder created from the combustion of coal in thermal power plants. It enhances the workability of mortar, making mixing and application easier. Over time, it also increases compressive strength as it continues to react with lime in cement, filling voids and making the structure denser. Moreover, fly ash diminishes heat generation, which is advantageous for large-scale construction endeavors. Silica fume, a by-product from the silicon and ferro-silicon industries, comprises ultra-fine particles that significantly boost mortar density. This attribute aids in lowering permeability, rendering the structure highly resistant to moisture intrusion. Due to its fine nature, silica fume also enhances bonding among particles, improving both early and long-term strength. Its substantial pozzolanic activity makes it ideal for projects demanding high durability, including bridges and marine constructions. GGBFS (Ground Granulated Blast Furnace Slag) is another industrial by-product obtained from iron production in blast furnaces. When combined with cement, it improves sulfate resistance, increasing the durability of mortar in harsh environments, such as those with high groundwater levels. It also contributes to long-term strength development, enhancing the overall lifespan of structures. GGBFS is especially effective in minimizing shrinkage cracks, which assists in preserving the integrity of the mortar over time. In addition to enhancing mechanical and durability characteristics, employing these industrial by-products aids in waste management by reducing landfill disposal challenges. These materials also contribute to energy conservation, requiring less energy for processing than OPC. Furthermore, they improve heat and chemical resistance, as observed in our tests, making them suitable for extreme environmental conditions. By integrating fly ash, silica fume, and GGBFS into mortar production, we not only enhance its performance and sustainability but also promote eco-friendly construction. This method supports the circular economy by effectively utilizing waste materials, decreasing carbon emissions, and fostering cost-effective building solutions.

Several researchers have studied the use of industrial by-products like fly ash, silica fume, and GGBFS in cement mortar to improve sustainability and performance. Studies show that fly ash enhances workability and long-term strength, making it a suitable partial replacement for cement. Researchers found that using 20-30% fly ash in mortar improves compressive strength over time due to its pozzolanic reaction. Studies on silica fume highlight its role in increasing density and reducing permeability, which enhances durability and resistance to chemical attacks. Research indicates that 10-15% silica fume replacement significantly boosts early strength and bonding properties, making mortar more resistant to chloride penetration and water absorption. Investigations on GGBFS show that it improves sulfate resistance and thermal stability. Studies report that 40-50% GGBFS replacement enhances long-term durability, reduces heat generation during hydration, and minimizes cracking due to shrinkage. Researchers have confirmed that GGBFS-modified mortar performs well in harsh environments, such as marine and industrial zones. Additionally, research combining fly ash, silica fume, and GGBFS in mortar has demonstrated synergistic effects, enhancing overall strength, workability, and durability. Studies indicate that blended mortar mixes exhibit better resistance to acid and sulfate attacks, making them ideal for aggressive environments. Many studies have also explored the environmental benefits of using these by-products, showing a significant reduction in carbon emissions and promoting sustainable waste management. Economic analyses suggest that cement replacement with industrial by-products reduces construction costs while maintaining high-performance standards. Overall, the research confirms that incorporating fly ash, silica fume, and GGBFS into cement mortar not only improves structural performance but also contributes to eco-friendly and cost-effective construction solutions. In this study, we are replacing cement with industrial by-products—Fly Ash, Silica Fume, and GGBFS—at 20%, 30%, and 40% to create a more sustainable mortar mix. We use Polycarboxylate Ether (PCE) as a superplasticizer to improve workability and maintain consistency in all mixes.1. Fly Ash + Cement + PCE – In the first mix, we replace cement with Fly Ash at different percentages (20%, 30%, 40%). Fly Ash improves workability, slows down setting time, and enhances long-term strength.2. Silica Fume + Cement + PCE – In the second mix, we replace cement with Silica Fume in the same proportions. Since Silica Fume has very fine particles, it increases early strength, density, and resistance to water and chemicals, making the mix more durable.3. GGBFS + Cement + PCE – In the third mix, we replace cement with GGBFS at 20%, 30%, and 40%. GGBFS enhances sulfate resistance, reduces heat generation, and improves long-term durability, making the mortar suitable for harsh environments. Each mix is tested for workability, compressive strength, heat resistance, acid attack, and sulfate resistance to determine which combination provides the best balance of strength, durability, and eco-friendliness.

Apart from the methodology you are using, several other approaches can be used to investigate the effective utilization of industrial by-products in eco-friendly mortar for sustainable construction: Experimental Mix Design with Multiple by-products: Instead of testing each by-product separately, a combination of Fly Ash, Silica Fume, and GGBFS can be used in different proportions to evaluate synergistic effects. Optimized mix designs can be developed using statistical models like Response Surface Methodology (RSM) or Taguchi Method. Alkali-Activated Mortar (Geopolymer Mortar)Instead of using traditional cement, industrial by-products like Fly Ash and GGBFS can be alkali-activated using sodium hydroxide (NaOH) and sodium silicate to create a cement-free geopolymer mortar. This method drastically reduces carbon emissions while improving strength and durability. Nano-Technology Incorporation : Adding nano-silica or nano-clay along with Fly Ash or GGBFS can further improve particle packing, early strength gain, and durability. This methodology enhances pore refinement and reduces permeability. Self-Healing Mortar: Using bacteria-based self-healing technology, where bacteria like Bacillus species are introduced into mortar containing industrial by-products, helps in autonomous crack healing. The bacteria react with calcium carbonate to seal cracks over time. Fiber-Reinforced Eco-Friendly Mortar: Industrial by-products can be combined with natural or synthetic fibers (e.g., basalt fiber, coconut fiber, glass fiber) to improve tensile strength, toughness, and impact resistance.6. Thermal and Acoustic Performance Studies: Instead of only mechanical and chemical resistance tests, industrial by-product-based mortars can be tested for thermal insulation and sound absorption properties, making them suitable for energy-efficient buildings.7. Life Cycle Assessment (LCA) and Carbon Footprint Analysis: A sustainability assessment can be conducted to analyze the environmental impact, energy savings, and CO_2 reduction of using industrial by-products in mortar compared to traditional cement. By applying these advanced methodologies, the research can contribute to innovative, durable, and truly sustainable mortar solutions for eco-friendly construction.

By replacing cement with fly ash, silica fume, and GGBFS at 20%, 30%, and 40%, we expect to use less cement, which helps cut down carbon emissions and makes construction more eco-friendly. In terms of strength, mixes with silica fume and GGBFS are likely to show better long-term compressive strength, while the combination of silica fume and fly ash is expected to improve tensile and flexural strength because of the denser microstructure they create. We also anticipate the mortar to be more durable. Using fly ash and GGBFS should reduce heat generation during hydration, helping the mortar resist thermal cracking. Additionally, silica fume and GGBFS are expected to hold up better against acid and sulfate attacks, ensuring a longer lifespan in harsh environments. The addition of PCE (Polycarboxylate Ether) as a superplasticizer is likely to improve workability, making the mortar easier to handle while reducing water usage without compromising strength. From an environmental and economic perspective, this approach helps lower the carbon footprint and saves energy by reducing cement production. It also offers a cost-effective solution by using industrial waste, which is cheaper than traditional cement. Moreover, this method helps with waste management, as it gives a new purpose to by-products that would otherwise go to landfills, promoting a circular economy.

Materials and methods :

Materials:

This study uses Ordinary Portland Cement (OPC) 53 grade as the main binding material, tested according to IS 4031:1988 to ensure it meets standards for specific gravity, fineness, and setting time. Manufactured Sand (M-sand) was selected as the fine aggregate, following the guidelines in IS 383:2016, and was tested for properties like specific gravity and water absorption to maintain consistency in the mix. To promote sustainability, we replaced cement with industrial by-products at 20%, 30%, and 40%. Class F Fly Ash, as per IS 3812 (Part 1):2013, was added to improve workability and long-term strength. Silica Fume, meeting IS 15388:2003 standards, was included for its ability to increase early strength and durability, while Ground Granulated

Blast Furnace Slag (GGBFS), as specified by IS 16714:2018, was used to reduce heat of hydration and resist sulfate attacks, helping to minimize cracking. A Polycarboxylate Ether (PCE) superplasticizer, in line with IS 9103:1999, was used to enhance workability while reducing water demand. Potable water, compliant with IS 456:2000, was used for mixing and curing to maintain the overall quality of the mortar. This research aims to create a sustainable and eco-friendly mortar by studying how these materials influence compressive strength, heat resistance, acid attack, and sulfate resistance, offering a greener approach to construction.

Methods:

This study focuses on producing eco-friendly mortar by partially substituting cement with industrial by-products, including Fly Ash (Class F), Silica Fume, and Ground Granulated Blast Furnace Slag (GGBFS), at replacement levels of 20%, 30%, and 40%. Three distinct mortar mixes were designed, each combining Ordinary Portland Cement (OPC) 53 grade with one of the by-products and a Polycarboxylate Ether (PCE) superplasticizer to enhance workability and reduce water consumption. In the first mix, Fly Ash was introduced to improve workability and promote long-term strength development. The second mix incorporated Silica Fume, known for its ability to boost early strength and increase density. The third mix used GGBFS, valued for its sulfate resistance and ability to reduce thermal cracking. Tests were conducted on cement and sand to determine specific gravity, fineness, and setting times, ensuring consistency across all mixes. The mortar samples were further assessed for compressive strength, heat resistance, acid resistance, and sulfate resistance to evaluate their overall durability and performance. This methodology aimed to identify the optimal mix that balances strength, durability, and environmental sustainability, contributing to greener construction solutions.

Experimental Program:

Details of specimen:

This study involved casting 70.6 mm mortar cubes as per IS 10080:1982 to assess both compressive strength and durability of various mortar mixes. The testing process followed the guidelines outlined in IS 516 (Part 1):2020 for evaluating compressive strength. For each mix, where cement was partially replaced with industrial by-products — Fly Ash, Silica Fume, and GGBFS — at levels of 20%, 30%, and 40%, a total of 9 cubes were cast. These cubes were tested at specific curing periods — 3 cubes at 7 days, 3 cubes at 14 days, and 3 cubes at 28 days — to observe the progression of strength over time. After analyzing the results, the 30% replacement was identified as the optimal mix, exhibiting superior performance. To further evaluate its durability, an additional 9 cubes were cast specifically for the optimum mix and subjected to various hardened state tests, including heat resistance, acid attack, sulfate attack, and water absorption. These tests helped determine how well the optimized mortar could withstand aggressive environmental conditions, ensuring its potential for long-term sustainability in construction. In total, 36 cubes were cast for each by-product (including the optimum mix), resulting in 108 cubes across all combinations. This thorough approach provided a comprehensive understanding of both the mechanical strength and durability characteristics of eco-friendly mortar.

Test program:

In this study, various tests were conducted on materials to ensure quality and consistency before using them in mortar mixes. These tests followed Indian Standard (IS) code provisions to evaluate key properties such as fineness, specific gravity, consistency, and setting times. The fineness test on cement was performed as per IS 4031 (Part 1): 1996 to determine the particle size distribution, which affects the rate of hydration and strength development. Finer cement has a larger surface area, promoting better bonding and faster strength gain. Similarly, the fineness test on sand was conducted according to IS 2386 (Part 1): 1963, where the particle size distribution of sand was evaluated to ensure proper gradation, which is crucial for workability and strength. The specific gravity test on cement was carried out according to IS 4031 (Part 11): 1988 to measure the density of cement in relation to water. This helps in mix design calculations by ensuring the correct proportion of materials. Likewise, the specific gravity test on sand was conducted as per IS 2386 (Part 3): 1963, which is essential for determining the volume occupied by the sand in the mix. To evaluate the setting characteristics of cement, the initial and final setting times were tested in line with IS 4031 (Part 5): 1988. The initial setting time reflects the period before the cement starts losing plasticity, while the final setting time indicates when the cement fully hardens. These parameters are crucial for handling and placement during construction. Additionally, the consistency test was performed as per IS 4031 (Part 4): 1988 to determine the required water content to achieve standard consistency, ensuring proper hydration and workability.

Tests on Hardened Cubes

Once the mortar cubes were cast and cured, various hardened state tests were performed to assess mechanical and durability properties. These tests ensured that the optimized mortar mix could withstand different environmental conditions. The compressive strength test was conducted following IS 4031 (Part 6): 1988 to determine the load-bearing capacity of the mortar cubes. This is one of the most critical parameters for evaluating the structural performance of cementitious materials. The cubes were tested at 7, 14, and 28 days to observe strength progression over time. The water absorption test was carried out according to IS 12330 and IS 516, which measured the amount of water absorbed by the hardened cubes. Lower water absorption indicates better density and durability, essential for long-term performance in humid or wet environments. The heat resistance test was performed as per IS 456 and IS 516 to evaluate the mortar's ability to withstand high temperatures without cracking or losing strength. This is particularly important for structures exposed to elevated temperatures or fire hazards. To determine the resistance to aggressive chemical environments, the acid attack test was conducted according to IS 12330 and IS 516. In this test, the mortar cubes were immersed in acidic solutions, and weight loss and strength degradation were monitored. A lower reduction indicates better durability. Similarly, the sulfate attack test was carried out as per IS 12330 and IS 516 to assess the mortar's resistance to sulfate-rich environments, which can cause expansion and cracking. By observing weight loss and strength reduction over time, the sulfate resistance of the mortar was evaluated. These comprehensive tests ensured that the mortar developed in this study was not only strong but also durable enough to withstand harsh environmental conditions, promoting sustainable construction practices.

Results and Discussion:

Test on Fresh mortar and Materials:

Specific Gravity of Cement:

Specific gravity is a fundamental property of cement that reflects its density relative to water. It is crucial for accurate mix design calculations, as it determines the volume occupied by cement in the mix. For Ordinary Portland Cement (OPC) 53 Grade, the typical specific gravity ranges between 3.10 and 3.15, indicating the material's quality and purity.

Test Procedure:

The Le Chatelier Flask method, as specified in IS 4031 (Part 11): 1988, was used to determine the specific gravity. The steps followed were:

1. The empty Le Chatelier flask was weighed, and the initial weight (W_1) was recorded.
2. The flask was filled with kerosene (non-reactive to cement) up to a marked level, and the weight was noted (W_2).
3. 50g of OPC 53 grade cement was carefully added to the flask, displacing the kerosene. The final weight (W_3) was recorded after ensuring no air bubbles were trapped.
4. The final reading was taken after thorough mixing and stabilization.

Formula Used:

$$\text{Specific gravity(SG)} = \frac{W2-W1}{(W2-W1)-(W3-W4)}$$

Where:

- W_1 = Weight of the empty flask
- W_2 = Weight of the flask with kerosene
- W_3 = Weight of the flask with kerosene and cement
- W_4 = Weight of the flask with cement after kerosene displacement

Test Results:

The specific gravity value obtained for OPC 53 Grade cement was 3.14, which falls within the standard acceptable range (3.10 to 3.15). This result indicates the cement has appropriate density and is free from impurities or excessive moisture.

Detailed Discussion:

The measured value of 3.14 confirms that the OPC 53 grade cement used in this study is of high quality. The result demonstrates proper particle density, which is essential for maintaining a suitable water-to-cement ratio in the mix design.

A specific gravity lower than 3.10 could indicate the presence of moisture or porosity, potentially compromising strength. On the other hand, a value higher than 3.15 might suggest excessive fineness, which could lead to high water demand and poor workability.

Specific Gravity Test on M-S

Specific gravity is an essential property of fine aggregates like Manufactured Sand (M-Sand), as it indicates the density of the material relative to water. It plays a crucial role in determining the volume occupied by sand in the concrete or mortar mix, which directly affects the workability, strength, and durability of the final product. For M-Sand, the standard specific gravity generally falls in the range of 2.5 to 2.9, depending on the source and processing method.

Test Procedure:

The test was performed according to IS 2386 (Part 3): 1963 using the Pycnometer method. The steps involved were as follows:

1. Dry Weight (W_1): The M-sand sample was dried in an oven at 110°C for 24 hours to remove moisture. A known weight of the dry sample was taken.
2. Weight with Water (W_2): The dried sand was placed in a pycnometer, and water was added until it was fully submerged. The mixture was stirred to eliminate air bubbles, and the total weight was recorded.
3. Weight of Pycnometer with Water (W_3): The pycnometer was filled with only water (no sand) to the same level, and the weight was noted.
4. Weight of Empty Pycnometer (W_4): The empty pycnometer's weight was recorded before starting the test.

Formula Used:

$$\text{Specific gravity (SG)} = \frac{W1}{(W1+W3)-W2}$$

Where:

- W_1 = Weight of dry M-sand sample
- W_2 = Weight of pycnometer + sand + water
- W_3 = Weight of pycnometer + water
- W_4 = Weight of empty pycnometer

Test Results:

The specific gravity of the M-sand obtained from this test was 2.74, which falls well within the standard range of 2.5 to 2.9. This indicates that the sand has adequate density suitable for mortar and concrete production.

Detailed Discussion:

The result of 2.74 shows that the M-sand used in this study has a moderate density, making it a reliable aggregate for achieving good workability and strength in the final mix. A lower specific gravity (below 2.5) would indicate the presence of porous or lightweight particles, potentially leading to higher water demand and reduced strength. Conversely, an excessively high value (above 2.9) could point to heavier minerals, increasing the overall weight of the structure.

Fineness test on cement

Fineness of cement is a critical parameter that measures the particle size of cement. It directly influences the rate of hydration, heat of hydration, strength development, and workability. Finer cement particles offer a larger surface area for hydration, leading to higher early strength. However, excessive fineness can increase water demand and cause shrinkage. For OPC 53 Grade cement, the permissible limit for fineness (measured by percentage retained on a 90-micron sieve) should not exceed 10% as per IS 4031 (Part 1): 1996.

Test Procedure:

The sieve analysis method was used to determine the fineness of OPC 53 grade cement as per the following steps:

1. Weight of Sample: 100g of dry cement was taken for the test.
2. Sieve Analysis: The sample was placed on a 90-micron IS Sieve.
3. Sieving: The sieve was shaken manually or mechanically for 15 minutes, ensuring no lump formation.
4. Weighing Residue: The residue retained on the sieve was collected and weighed.
5. Calculating Fineness: The percentage of cement retained was calculated using the formula:

$$\text{Fineness(\%retained)} = \left(\frac{Weight\ of\ residue}{Weight\ of\ original\ sample}\right)*100$$

Test Results:

- Weight of original cement sample (W): 100g
- Weight of residue on the 90-micron sieve (R): 5.6g
- Fineness (% retained):

$$= \left(\frac{5.6}{100}\right)x100 = 5.6\%$$

Detailed Discussion:

The fineness value obtained was 5.6%, which is well below the maximum limit of 10% specified in IS 4031 (Part 1): 1996. This indicates that the OPC 53 grade cement used in this study is adequately fine, providing sufficient surface area for hydration and promoting early strength development.

Fineness test on Sand :

Fineness modulus (FM) of sand is a measure of its particle size distribution. It indicates whether the sand is coarse, medium, or fine, which directly affects the workability, strength, and durability of mortar and concrete. For M-sand (Manufactured Sand) used in construction, the fineness modulus should typically fall in the range of 2.6 to 3.0 for fine aggregate, as per IS 2386 (Part 1): 1963.

Test Procedure:

The fineness of M-sand was determined using sieve analysis as specified in IS 2386 (Part 1): 1963. The steps included:

1. Sample Preparation: A 1000g (1kg) dry sample of M-sand was taken.
2. Sieve Arrangement: A set of standard sieves was arranged in descending order of size: 4.75mm, 2.36mm, 1.18mm, 600µm, 300µm, and 150µm, with a pan at the bottom.
3. Sieving: The sample was placed on the top sieve, and the stack was mechanically or manually shaken for 10-15 minutes.

4. Weight Measurement: The material retained on each sieve was weighed, and the cumulative percentage retained was calculated.
5. Fineness Modulus (FM): FM was calculated by summing the cumulative percentage retained on all sieves and dividing by 100.

Sieve Analysis Data:

Sieve Size(mm)	Weight Retained(g)	%weight Retained	Cumulative %Retained
4.75	20	2	2
2.36	80	8	10
1.18	200	20	30
0.60	300	30	60
0.30	250	25	85
0.15	130	13	98
pan	20	2	100

Table.1

Fineness Modulus Calculation:

$$FM = \frac{2+10+30+60+85+98+100}{100}$$

$$FM = 3.85$$

Test Results:

The fineness modulus (FM) of M-sand obtained was 3.85, which is slightly above the standard range of 2.6 to 3.0 for fine aggregates.

Detailed Discussion:

The obtained FM value of 3.85 indicates that the M-sand used in this study is coarser than the ideal range for fine aggregates.

- Effect on Workability: A higher FM suggests larger particle sizes, which may reduce workability unless additional water or superplasticizer is used.
- Strength Development: Coarser sand improves the compressive strength due to better interlocking of particles but may compromise the surface finish of the mortar.
- Durability: Slightly coarser sand is beneficial in reducing shrinkage and cracking, making it suitable for high-strength mortar applications.
- Water Demand: Coarser sand typically requires less water compared to finer sand, which may improve overall strength if properly adjusted.

The result suggests that while the M-sand is slightly coarse, it remains suitable for structural applications, especially where higher compressive strength is required. Adjustments in water-cement ratio or superplasticizer dosage can mitigate any workability issues.

Initial and final testing on cement

The setting time of cement is crucial in determining how quickly or slowly cement transitions from a plastic to a hardened state. This property ensures sufficient time for mixing, transporting, placing, and finishing before hardening begins.

- Initial Setting Time: Time when the paste starts losing its plasticity.
- Final Setting Time: Time when the cement paste completely hardens.

For OPC 53 Grade Cement, as per IS 4031 (Part 5): 1988, the requirements are:

- Initial Setting Time: Minimum 30 minutes
- Final Setting Time: Maximum 600 minutes (10 hours)

Equipment Used:

- Vicat Apparatus with:
- 1 mm diameter needle for initial setting time
- Vicat needle with annular collar for final setting time
- Stopwatch for time recording
- Weighing scale and gauging trowel

Test Procedure:

1. **Preparation of Cement Paste:**

300g of OPC 53 grade cement was mixed with 0.85 times the water required for standard consistency.

2. **Initial Setting Time Measurement:**

The cement paste was placed in the Vicat mold, and the 1 mm needle was gently lowered to the surface at 2-minute intervals.
The time when the needle penetrated only 33-35 mm from the top or 5 mm from the bottom was noted as the initial setting time.

3. Final Setting Time Measurement:

The needle with annular collar was used to penetrate the paste at regular intervals.
The final setting time was recorded when the needle no longer penetrated and left only a faint surface mark.

Vicat Apparatus Result:

Parameter	Standard Requirements	Measured Values
Initial setting time	Minimum 30 minutes	42 minutes
Final setting time	Maximum 600 minutes(10hrs)	315 minutes

Table.2

Detailed Discussion:

The test results show that the initial setting time of 42 minutes is safely above the minimum limit of 30 minutes, offering sufficient workability time for mixing and placing the cement mix. This helps avoid premature setting, especially in hot weather conditions. The final setting time of 315 minutes (5 hours and 15 minutes) is well within the permissible limit of 600 minutes, indicating that the cement hardens at a reasonable rate, achieving the required early strength without rapid stiffening.

Test on Hardened Mortar

Compressive Strength Test

The compressive strength test is conducted to determine the ability of hardened mortar to withstand compressive loads. This property is essential for assessing the material's suitability for construction applications. According to IS 4031 (Part 6): 1988, compressive strength is tested at specific intervals (7 and 28 days) using 70.6 mm x 70.6 mm x 70.6 mm cube molds.

Test Procedure:

Cube Preparation:

- 70.6 mm cubes were cast using OPC 53 grade cement with industrial by-products such as fly ash (F), silica fume (S), and GGBFS (G) at 20%, 30%, and 40% replacement levels.
- Polycarboxylate Ether (PCE) superplasticizer was added for enhanced workability.

Curing:

- Cubes were cured in water at 27 ± 2°C as per the standard curing method.

Testing:

- Compressive strength was tested at 7 days and 28 days using a Universal Testing Machine (UTM) as per IS 4031 (Part 6): 1988.
- The load was applied uniformly at 140 kg/cm² per minute until failure.

7-Day Compressive Strength Results:

Design Mix	Compressive Strength (MPa)	Observation
C	**10.0**	Standard mix used as a control.
F20	**9.2**	Slight reduction due to slower fly ash hydration.
F30	**12.4**	Optimum mix with enhanced early strength.
F40	**6.0**	Significant reduction due to excess replacement.
S20	**7.2**	Moderate improvement over higher silica mixes.
S30	**5.5**	Lower strength due to delayed pozzolanic action.
S40	**3.1**	Minimal early strength, insufficient bonding.
G20	**5.8**	Slow strength gain due to latent hydraulic action.
G30	**6.3**	Slightly better strength but below control mix.
G40	**5.3**	Reduced performance with excessive replacement.

Table.3

28-Day Compressive Strength Results:

Design Mix	Compressive Strength (MPa)	Observation
C	**14.3**	Standard control with expected performance.
F20	**14.4**	Comparable to control, indicating good results.
F30	**15.0**	Maximum strength, confirming it as the best mix.
F40	**10.8**	Decline due to excessive fly ash content.
S20	**6.0**	Minimal improvement from 7-day strength.
S30	**10.3**	Significant improvement due to better hydration.
S40	**4.2**	Poor long-term strength indicating low bonding.
G20	**7.3**	Gradual improvement, suggesting steady hydration.
G30	**9.2**	Moderate gain over 7 days, still below control.
G40	**5.8**	Consistent but lower than expected strength.

Table.4

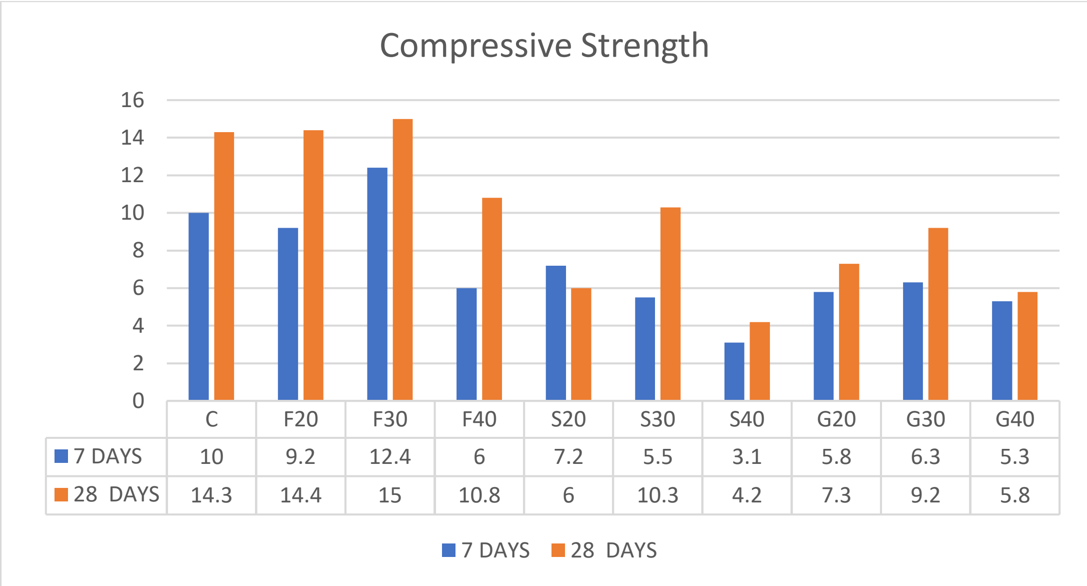

Fig.1

Fig.2

Detailed Discussion:

The compressive strength results align with IS 4031 (Part 6): 1988 requirements, highlighting the influence of industrial by-products on performance:

Fly Ash (F):

- The F30 mix outperformed the control mix with a 15.0 MPa result at 28 days, indicating optimal pozzolanic reaction.
- F40 showed reduced strength due to excess fly ash, slowing hydration.

Silica Fume (S):

- S30 showed significant improvement at 28 days (10.3 Mpa), suggesting better microstructure densification over time.
- S40 had the lowest strength due to poor particle bonding at higher replacement levels.

GGBFS (G):

- The strength gain was gradual but steady. G30 reached 9.2 Mpa at 28 days, reflecting better long-term performance.
- Higher replacement (G40) reduced strength due to insufficient hydration at early stages.

Conclusion:

- **F30 (Fly Ash 30%)** was identified as the **optimum mix**, offering superior compressive strength at both **7 and 28 days**, surpassing the control mix.
- **Silica Fume** and **GGBFS** mixes demonstrated moderate performance, emphasizing the need for optimal dosage.
- These findings confirm that partial replacement with **industrial by-products**, as per **IS 4031 (Part 6): 1988**, can enhance **eco-friendliness** while maintaining compressive strength.

Water Absorption

The **water absorption test** is a crucial assessment to determine the durability and porosity of hardened mortar. It measures the amount of water absorbed by concrete specimens when immersed in water for a specific duration. This property is essential for evaluating how well the material can resist water ingress, which significantly affects its long-term performance and durability. According to **IS 12330** and **IS 516**, lower water absorption indicates better durability, making it a key parameter for sustainable construction.

Design mix	Water Absorption %
C	9.2
F20	10.3
F30	10.8
F40	11.2
S20	15.5
S30	21.5
S40	30.5

Table.5

Results and Discussion:

The results indicated that the control mix (C) had the lowest water absorption at 9.2%, reflecting a denser microstructure with minimal porosity. Among the by-product mixes, fly ash at 30% replacement (F30) showed relatively low water absorption (10.8%), maintaining structural integrity. However, higher fly ash content (F40) exhibited increased porosity with 11.2% absorption. Silica fume mixes, particularly S30 and S40, demonstrated significantly higher absorption rates at 21.5% and 30.5%, respectively, indicating poor packing density and increased pore structure. These results suggest that excessive silica fume negatively impacts durability due to micro-crack formation.

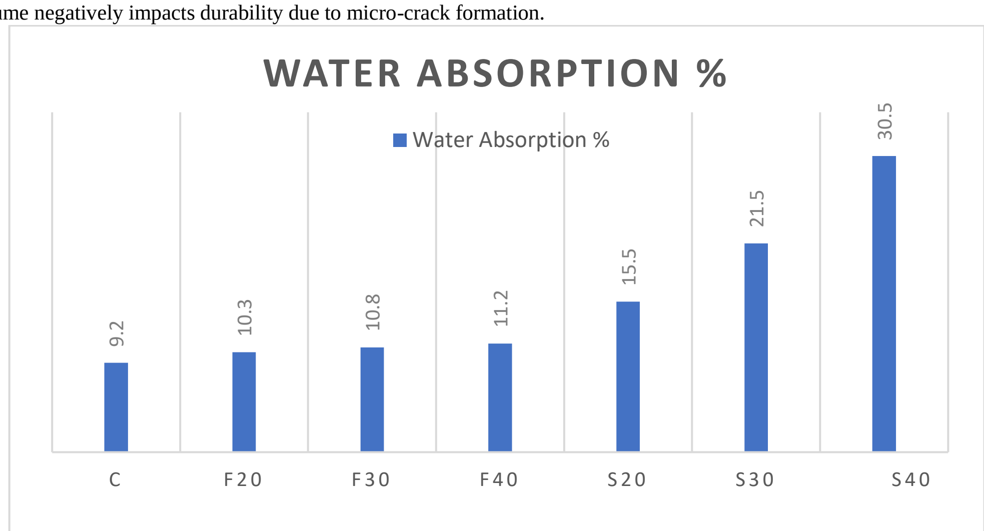

Fig.3

Heat Resistant

The test was conducted using 70.6 mm mortar cubes prepared with OPC 53 grade cement, partially replaced by industrial by-products such as Fly Ash (F), Silica Fume (S), and GGBFS (G) at 20%, 30%, and 40% replacement levels. The cubes were cured for 28 days, as specified by IS 456, and subsequently exposed to elevated temperatures between 300–600°C in a muffle furnace for 2 hours. Post-heating, the cubes were allowed to cool naturally to room temperature. The compressive strength was tested as per IS 516, and the percentage strength loss was calculated using the formula:

Design mix	28 days strength	Strength loss	Strength loss %
C	14.3	12.5	12.58
F20	14.4	10.33	28.2
F30	15	8.5	43.3
F40	10.8	8.6	20.3
S20	6	5.1	15
S30	10.3	8.6	16.5
S40	4.2	2	52.3

Table.6

Detailed Discussion:

The results indicate that the control mix (C) had the least strength loss (12.58%), reflecting superior heat resistance. Among the by-product mixes:

Fly Ash (F) mixes showed a notable increase in strength loss with higher replacement percentages. F30 had the highest loss (43.3%) due to increased porosity at elevated temperatures. Silica Fume (S) mixes showed moderate heat resistance at lower replacement levels. However, S40 had a severe strength loss of 52.3%, indicating poor performance under thermal conditions. Optimal performance was observed in F20 and S20, with strength losses of 28.2% and 15%, respectively, suggesting they are better suited for heat-resistant applications.

Results and conclusion:

The experimental study demonstrated that partially replacing OPC 53 grade cement with fly ash, silica fume, and GGBFS significantly influences the mechanical and durability properties of mortar. The compressive strength results showed that F30 achieved the highest strength (15 MPa) at 28 days, indicating improved performance at moderate fly ash replacement. The water absorption test revealed increasing absorption with higher replacement levels, with S40 showing the highest value (30.5%), suggesting reduced density. In the heat resistance test, the control mix (C) exhibited the least strength loss (12.58%), while S40 had the highest (52.3%), indicating poor thermal stability. Optimal performance was observed at 20–30% replacement levels for both fly ash and silica fume. Overall, this study highlights the potential of industrial by-products to enhance sustainability by reducing cement usage while maintaining acceptable mechanical and durability properties.

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