



Supplementary Cementitious Materials for Sustainable Construction: An Analysis on Industrial by Products in 2025

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Abstract - In India, awareness is increasing regarding the substantial accumulation of garbage in several sectors, including industrial facilities, power plants, and demolition sites, which has become a significant environmental, economic, and social issue. Industry by-products are materials that stay unused, unwanted, and deemed to possess no economic worth to society as a whole. By-products like fly ash, silica fume, industrial slags, mining refuse as well as sludge from the dimensional stone industry are being employed in concrete by various researchers. These non-biodegradable pollutants can be inhaled by humans and animals, posing a threat to the ecosystem. The appropriate disposal of by-products produced by industrial activity has become a significant concern. The incorporation of these wastes into concrete offers a viable solution for both the generating industry and the concrete sector. This research integrated multiple investigations concerning the use of industrial wastes as supplementary cementitious materials (SCM) in concrete. Characterization of diverse industrial by-products is essential as the initial stage for their usage. Based on characterization behaviour of the particular waste in concrete can be understood. It has been shown that these wastes can potentially substitute 5% to 30% of conventional cement based on their characteristics.

I. INTRODUCTION

The use of waste substances in concrete construction has won increasing interest in recent years due to its capacity to address urgent environmental demanding situations, beautify economic performance, and power innovation in the construction area. the technical benefits of incorporating industrial by-products in concrete are similarly noteworthy. the increasing environmental concerns associated with the excessive use of ordinary portland cement (opc) and depletion of natural resources have accelerated research into alternative supplementary cementitious materials (scms). several industrial by-products such as fly ash, silica fume, wood ash, phosphogypsum, quarry dust, and red mud have demonstrated promising potential as partial cement replacements in concrete, leading to improved sustainability and performance. fly ash, a widely studied by-product of coal combustion, has shown significant enhancement in fresh concrete properties, long-term performance, and strength characteristics of concrete. partial substitution of opc with fly ash up to 40% has exhibited ecological and structural advantages [5], while swamy et al. (1983) confirmed comparable performance up to 30% substitution. high-volume fly ash concrete with 70% fly ash and ground granulated blast furnace slag (ggbs) also offered economic and environmental benefits, although depending on source-specific properties [6]. silica fume, when used as a 10–15% partial substitution of cement in m35 concrete, significantly optimizes strength and long-term performance, making it a desirable scm for high-performance concrete work [7]. similarly, wood ash, derived from combustion of wood and wood-based materials, displays pozzolanic characteristics and improves compressive strength at optimal replacement levels (particularly wa1 at 10%) [11]. however, its variable composition and increased water needs necessitate careful assessment. phosphogypsum, in combination with fly ash up to 30% replacement, improves mechanical performance in m25 concrete, while also presenting a sustainable approach for industrial waste disposal [12]. pozzolanic agro-wastes such as sawdust ash (sda), maize cob ash (mca), and sugarcane bagasse ash (scba) have also been investigated. optimal cement replacement levels of 10% (sda, mca) and 25% (scba) yielded desirable strength while decreasing environmental footprints and construction costs [13]. marble slurry waste (msw) and granite waste are rich in calcium content and have been found suitable for use in non-load-bearing concrete structures. while marble slurry provides improved compressive and tensile strength [1], granite waste contributes to environmental preservation by mitigating air pollution chances and disposal issues. similarly, red mud, a residue from aluminum production, showed promising



results in m50 concrete at up to 15% cement replacement, although further research is required for higher replacement levels [2].

brick dust, a byproduct of the brick and tile manufacturing plants, has been successfully used to replace up to 20% of cement, offering enhanced resistance to acid attack and reducing heat during hydration [3]. additionally, ceramic waste powder (cwp) and marble dust powder (mdp), when incorporated in m20 concrete, offer an impressive waste management strategy while maintaining desired strength [4]. other notable industrial by-products include milled waste glass, which has a proven potential for up to 20% cement replacement with cost and emission control benefits, though durability and alkali-silica reaction (asr) aspects warrant more study [8], and waste paper sludge ash, which enhances compressive strength at 5% substitution while reducing concrete self-weight [9]. past studies have consistently indicated that the integration of scms such as fly ash, quarry dust, recycled water, and silica fume contributes to betterment in concrete strength and environmental performance [10]. these materials facilitate reduced production costs and consumption of natural resources while addressing industrial waste disposal concerns. the use of recycled aggregates, bottle caps in fiber-reinforced concrete, and other innovative materials further supports sustainable practices by enhancing mechanical properties. in substance, the literature affirms that utilizing industrial by-products as scms in concrete promotes sustainability, minimizes environmental degradation, and ensures economic construction practices in alignment with modern development goals. in this research paper, a cumulative study on these types of industry by-products when utilized as a scm in concrete have been presented and discussed thoroughly.

II. INDUSTRY BY-PRODUCTS AND THEIR PROCESSING FOR THEIR USE AS SCM

Supplementary Cementitious Materials (SCMs) are materials used in concrete to replace a significant portion of cement present in concrete. When engineered, can enhance concrete properties and reduce environmental impact. The use of industrial by-products as SCMs is a key strategy for sustainable concrete production. Proper processing ensures their optimal performance in cementitious systems.

Researchers have adopted following processing methods:

A. Drying:

The drying method is a physical preprocessing process used to reduce the moisture content of industrial by-products before their use as (SCMs). Drying is usually carried out in oven or by directly exposing the material to solar radiations. It ensures a material without volatile substances and maintain the water in the mix.

B. Crushing:

Crushing is a mechanical process used to reduce the size of industrial by-products to make them suitable for use as SCMs. It helps improve the reactivity, surface area, and uniformity of the material.

Table 1: Preprocessing on Various Industrial by products to be utilized as Cement Replacement

Sr. No	Waste	Method of Preprocessing	Reference
A.	Marble Slurry Wastes (MSW)	Material is dried in open air and then oven dried for 24 hrs. & crushed	[1]
B.	Red Mud	Pulverization	[2]
C.	Waste Glass Powder	Pulverization and color	[3]
D.	Brick Dust	Grinding & Pulverization	[4]
E.	Marble Dust and Ceramic Waste	Pulverization	[5]
F.	Waste Paper Sludge Ash	Sun dried and incinerated	[6]
G.	Granite Waste	Pulverization	[7]
H.	Wood Ash	Pulverization	[8]
I.	Phosphogypsum and Flyash	Burning	[9]
J.	Plant Solid Waste Ash	Burning and Pulverization	[10]
K.	Flyash and GGBS	Steam, then dried and Pulverization	[11]

**C. Pulverization:**

Pulverization is a mechanical preprocessing method in which Crushing and grinding industrial by-products into fine particles to improve their properties for use as (SCMs). Grinding is a physical preprocessing method. Increases surface area for better pozzolanic or hydraulic reaction. Improves uniformity and particle distribution. Enhances the strength and durability of concrete.

D. Burning:

The burning method is a thermal preprocessing used to convert industrial by-products into (SCMs) to removes volatile matter, reduces carbon content, and increases the amorphous (reactive) silica or alumina content by improving their chemical reactivity.

E. Steam Processing:

The steam processing preprocessing method is used to enhance the reactivity of certain industrial by-products by exposing them to high-temperature steam under controlled conditions to Removes residual moisture or volatile substances and can modify microstructure to increase surface area or reactivity.

F. Alkali Activation:

The alkali activation method is a chemical pretreatment used to activate aluminosilicate-rich materials, such as - products fly ash, slag, metakaolin), to form geopolymers or alkali-activated binders. This method serves as a sustainable option to ordinary Portland cement (OPC).

1. Properties of Different Materials

The **properties of materials** are the characteristics that define its behaviour. These properties play a critical role in determining the suitability of a material for its specific applications.

a. Physical Properties: - The physical properties of various Industry by products, such as fineness and specific gravity; make them suitable for different applications in the construction industry. These properties highlight the potential of this Industry by products to be repurposed and utilized effectively in various construction applications.

- **Fineness:** - Fineness is a measure of how small or pure a material is. Fineness is defined in terms of specific surface area. It influences water demands of a cementitious system.
- **Specific gravity:** - Specific gravity of any material is the ratio of its density to the density of water. It will govern the packing of the particles in a mix.

b. Chemical properties: - A specific characteristic of a substance like an element or a compound, relating to how it can change because of a reaction. The chemical composition of various. Industry by product s provides valuable insights into their reactivity and potential applications. Understanding these chemical properties is crucial for determining the reactivity and potential uses of these Industry by products in various industrial and construction applications.

Cement Paste Properties: - Cement paste is a thick, sticky mixture of water and cements that hardens over time. Cement paste is formed by combining water and cement, creating a thick, sticky mixture that hardens 3over time. The addition of various Industries by product s can significantly modify the properties of the cement paste. Resulting in changes to its consistency, fineness, and setting times. These variations in properties highlight the importance of understanding the influence of Industry by products on cement paste to optimize its performance for different applications.

c. Mortar Properties: - Mortar is a binding material used in construction to join building blocks like bricks, stones, and tiles. It is made from a mixture of water, a binder, and an aggregate. When certain Industry by products is added to cement, they can significantly influence its compressive strength over time. Understanding the impact of this Industry by products on mortar's compressive strength is crucial for optimizing their use in sustainable construction practices. The compressive strength of concrete is the maximum load that a concrete sample can withstand before failing when subjected to compression.

Mortar is a basic component of concrete construction, which plays an important role in stability, durability and general structural integrity of wall and solid elements. It is a practical paste made of a binding machine, such as Cement or lime, sand and water mixed with fine sets. Sometimes additives or Adamics are introduced to Improve specific properties such as usability, setting time or resistance to environmental factors. The mortar acts as a binding agent in masonry, providing harmony between bricks, stones or concrete blocks, ensuring their adjustment and stability. Its Primary Function is to distribute the load equally in masonry elements, increasing the overall Strength of the Structure. The versatility of the mortar allows it to be used in different applications, including plaster, beeping and rendering, making it an indispensable material in modern construction.



Table 2: Properties of Cement paste with different industry by product.

Sr. no	Industry by product	Consistency	Fineness	Initial setting time(M)	Final setting time(M)	Source
A.	Red mud	33%	294 m ² /kg	183	289	[2]
B.	Marble Dust And Ceramic Waste	26.75	—	80	190	[5]
C.	Wood Ash	31%	96%	55	535	[8]
D.	Phosphogypsum and Fly ash	32%	2.33%	48	—	[9]
E.	Flyash and GGBS	—	303 m ² /Kg	50	275	[11]
F.	Silica Fume	32%	5%	45	—	[13]

One of the most important aspects of mortar in concrete construction is its setting and preprocessing process. Mortar setting time depends on environmental conditions such as temperature, humidity and air, as well as the types of binder used. Proper preprocessing is important to achieve the desired power and durability, as insufficient preprocessing can reduce cracks and structural performance. Water retention capacity is another important factor in ensuring that the mortar still works during sufficient period before it is strict. To improve the performance of the mortar, different entries are used, for example to increase the softener's work ability, accelerator to speed up the accelerator time and to postpone the setting in warm weather conditions. These changes help to adapt mortar performance under different environmental and structural conditions.

- In Red mud 7 days compressive strength they get 42, as standard value should not be less than 33. And 28 days compressive strength they get 54, as standard value should not be less than 43.
- In Phosphogypsum and Fly ash 7 days compressive strength they get 37.76, as standard value should not be less than 33. And 28 days compressive strength they get 54.67, as standard value should not be less than 43.
- In Flyash 7 days compressive strength they get 140, as standard value should not be less than 33. And 28 days compressive strength they get 142.5, as standard value should not be less than 43.
- In Flyash and GGBS 7 days compressive strength they get 51.6, as standard value should not be less than 33. And 28 days compressive strength they get 71.3, as standard value should not be less than 43.

Table 3: Properties of Mortar with different industry by product

Sr. No	Industry by product	Fineness	Sp. Gravity	Source
A.	Marble Slurry Wastes (MSW)	360 μm	2.85	[1]
B.	Red mud	120 μm	2.93	[2]
C.	Waste Glass Powder	200 μm	3.01	[3]
D.	Brick dust	200 μm	2.6	[4]
E.	Marble Dust And Ceramic Waste	90 μm	2.64	[5]
F.	Waste Paper Sludge Ash	90μm	2.6	[6]
G.	Granite Waste	90 μm	2.53	[7]
H.	Wood Ash	150 μm	—	[8]
I.	Phosphogypsum and Flyash	—	2.89	[9]
J.	Plant Solid Waste Ash	75μm	—	[10]
K.	Flyash and GGBS	—	2.78	[11]
L.	Fly Ash	45 μm	3.30	[12]



Table 4: Chemical Composition table comparing different industrial by-products and waste materials

Source	LOI	SO ₃	Na ₂ O	K ₂ O	P ₂ O ₅	MgO	CaO	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	Chemical Composition
						1.217	97.78	0.40		0.33	Marble Slurry Wastes (MSW)
A.	10 %		5 %				3 %	35 %	19 %	8 %	Red mud
B.		00.40	012.2	00.80		01.80	14.5	0.6	00.90	68.10	Waste Glass Powder
C.	01.10	00.39	00.08	00.25		02.46	2.12	7.99	01.99	67.43	Brick dust
D.	43.63	00.07	00.90	00.60		02.70	43.20	1.90	02.50	13.80	Marble Dust And Ceramic Waste
	01.61	00.10	00.75	02.18	00.16	00.72	4.46	4.32	18.29	63.29	
E.		01.07	00.22	00.16		03.59	14.94	0.92	02.06	60.57	Waste Paper Sludge Ash
F.						07.30	47.60	1.43	03.09	20.55	Wood Ash
G.	04.62	01.00		01.90		01.40	6.9		21.00	59.00	PhoSpho- Gypsum and Flyash
H.	04.41	00.46	00.12	00.15	01.56	05.60	4.50	4.21	05.96	65.22	Plant Solid Waste Ash
	06.21	01.55	00.25	06.41	01.80	04.31	11.2	3.2	06.64	66.80	
	10.32	01.84	01.10	04.96	01.26	00.95	1.63	4.35	06.05	69.82	
	00.15	01.72		00.30		06.41	35.17	1.23	17.11	34.26	GGBS
	00.80	00.14	01.10			00.91	1.4	3.6	30.80	60.50	Fly Ash
									00.65	93.00	Silica Fume



2. Concrete Properties

Concrete is one of the most widely used construction materials in the world. Its properties are essential for ensuring durability, strength, and performance in various structural applications. The properties of concrete can be categorized into **fresh** and **hardened** properties, each affecting how it behaves during and after the curing process.

A. Fresh Concrete: - Workability is measured using different tests depending on the type of concrete and its application.

- **Slump Test:** - 0-25 mm (Very Low Workability), 25-75 mm (Low Workability), 75-125 mm (Medium Workability), 125-175 mm (High Workability).
- **Compacting Factor Test:** - Compacting Factor ranges from **0.7 to 0.95** (higher value = better workability).
- **Vee-Bee Consistometer Test:** - Time taken for concrete to change shape due to vibration.

a. **Wood Ash:** - In the experiment the detected slump was shear in the replaced wood ash concrete changed when compared with control mix due to the roughness of mixture because of the lack of binding material like cement in the mixture as the proportion of wood ash in the two types of wood ash with cement increased. Additionally, if two types of wood ash were mixed, the moisture absorption in the mix increased as the proportion of wood ash increased. Different percentages of plasticizer additives were used for cement replacement to achieve the desired slump of about 50 mm. Our research has shown that you can achieve the desired slump by incrementing the moisture quantity of the mixture.

b. **Plant Solid Waste Ash:** - Slump test and Compaction factor results for SDA (saw dust ash), MCA (maize cob ash), and SCBA (sugarcane bagasse ash) at 0%, 5%, 10%, 15%, 20%, 25%, and 30% cement replacement. The results indicate that the slump and compaction factor for SDA and MCA decreases with increase in cement replacement. This could be due to decreased formation of the cementitious matrix attributed to insufficient water for workability and hydration. However, slump and compaction factor for SCBA increased with increase in cement replacement. This could be due to high surface area of SCBA that required less water for wetting the cement particles as more cement is being replaced.

c. **Silica Fume:** - Workability of concrete for 33, 43 and 53 OPC varies from 25, 20 and 16 mm respectively for concrete with 40% fly ash. The high value of the workability is achieved for concrete with cement with 33 grades and the lowest for 53 grade cement. This behavior can be because the greater the cement degree the greater. Fine cement requires more water to wet surface particles.

d. **Phosphogypsum and Fly ash:** - The results Slump Test conducted on the concrete batches designed with different cement: Phosphogypsum and Fly ash ratios. It indicates that samples with 0% 5% 10% 15% and 20% replacement of cement with Phosphogypsum and Fly ash have a slump value 19, 30, 55, 70 and 25. The results Slump Test conducted on the concrete batches designed with different cement: Phosphogypsum and Fly ash ratios. It indicates that samples with 0% 5% 10% 15% and 20% replacement of cement with Phosphogypsum and Fly ash have a Compaction factor value 0.81, 0.86, 0.89, 0.93 and 0.91. The results of slump tests conducted on concrete batches with varying ratios of cement and Industry by product s indicate that the replacement of cement with Marble Slurry Wastes (MSW) reduces the workability of concrete, with higher MSW content leading to a lower slump value. Waste Paper Sludge Ash (WPSA) showed a decrease in workability with increasing ash content, as WPSA particles absorbed more water. In the case of Wood Ash, the slump decreased due to the roughness of the mixture and increased moisture absorption. However, the desired slump could be achieved by incrementing the moisture quantity of the mix

Plant Solid Waste Ash, including sawdust ash, maize cob ash, and sugarcane bagasse ash, showed varying effects on the slump and compaction factor. While SDA and MCA reduced workability with increased cement replacement, SCBA improved workability due to its high surface area and lower water requirements.

3. Hard Concrete: - The mechanical properties of concrete determine its strength, durability, and behaviour under different loading conditions. These properties are crucial for designing safe and long-lasting structures.

- a. **Compressive Strength:** - The ability of concrete to resist axial compressive forces.
- b. **Tensile Strength:** - The resistance of concrete to tension forces.
- c. **Flexural Strength:** - The ability of concrete to resist bending.

4. Marble Slurry Wastes (MSW): - Based on the results of 7th, 14th and 28th day compressive strength, the optimum and permissible usage sample percentage replacement of cement with MSW is 7%, which give 1821psi, 2304psi and 3036psi of compressive strength on 7th, 14th and 28th day, respectively. The concrete with 7% partial replacement of cement with MSW can provide a compressive strength and tensile splitting strength of more than 3000psi and 28tones, respectively. Though the



workability of concrete will slightly decrease, but still it can be used safely in the concrete of non-load bearing structures.

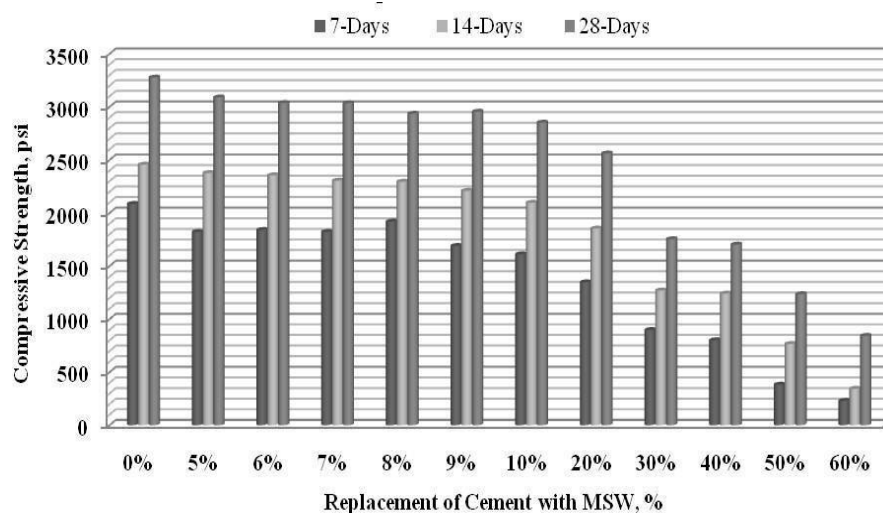


Fig 1. Variation of compressive strength of concrete with different percentages of marble slurry waste (MSW) used as partial replacement of cement at 7, 14, and 28 days of curing.

- a. **Waste Paper Sludge Ash:** - The maximum compressive strength measured was 15% more than that of reference mix at 28 days corresponding to concrete mix containing 0% waste paper sludge ash in place of cement. Splitting tensile strength was found to be more than that for reference mix at 5% cement replacement. Splitting tensile strength decreased with increasing waste paper sludge ash content.
- b. **Granite Waste:** - In the present investigation granite waste has been used as replacement of cement up to a maximum of 20%. However, 10% can be taken as optimum dosage which can be mixed in cement concrete for giving optimum possible compressive strength at any stage. The specimens were tested for split tensile strength using a calibrated compression testing machine of 2000kN capacity. It can be observed that at a 10% replacement of granite powder, an optimum of 3.43 N/mm² split tensile strength was obtained. The results of flexural strength obtained on different percentage substitutions of granite powder with cement. On mediation of the results, it can be observed that at 10% partial substitution, a maximum of 4.62N/mm² flexural strength was obtained.
- c. **Brick dust:** - For cement concrete specimen, replacement of 20 to 30 percent of cement with BDMA gives almost the same or slightly higher compressive strengths compared to control specimen.
- d. **Red mud:** - For each percentage replacement 2.5% to 5% increase in compressive strength is observed. But beyond 20% replacement of red mud the strength decreases. Split tensile strength of Red mud concrete at 7days and 28 days gradually decreases with increase in percentage replacement. At each replacement level of cement with Red mud an increase in strength was observed with increase in age may be due to pozzolanic reaction of Red mud. Because of higher percentage of finer material, concrete obtained is more compact with smaller quantity of voids leading to higher strength.
- e. **Waste Glass Powder:** - The results show that compressive strength gain in glass added concrete occurs at a lower rate than that in controlled concrete, but in long-term recycled glass concrete has the potential to exceed control concrete strength.
- f. **Marble Dust and Ceramic Waste:** - Due to higher part of silica oxide in ceramic waste its core compressive strength is attained at 30% replacement of ceramic waste concrete. By more than 30% of replacement, the compressive strength is decreasing. Due to lower percentage of silica oxide in marble dust powder its compressive strength decreases continuously. The rate of fall shows the reduction in adhesive strength between the surface of marble powder and cement. Its core compressive strength is attained at 20% replacement of marble dust concrete. On further replacement of Cement with marble dust powder, decreases the Compressive Strength.
- g. **Wood Ash:** - The outcomes show that there are differences in the test results for the two types of concrete samples replaced with wood ash. This may be mainly due to the difference in chemical composition of wood ash, calcareous wood ash (CaO), silica (SiO₂) and alumina (Al₂O₃), which greatly contributes to the bonding function of the concrete mixture. As mentioned in segment 1 overhead, there may be several minor constraints that can also affect bonding characteristics such as the occurrence



of unburned carbon and the water to cement proportion.

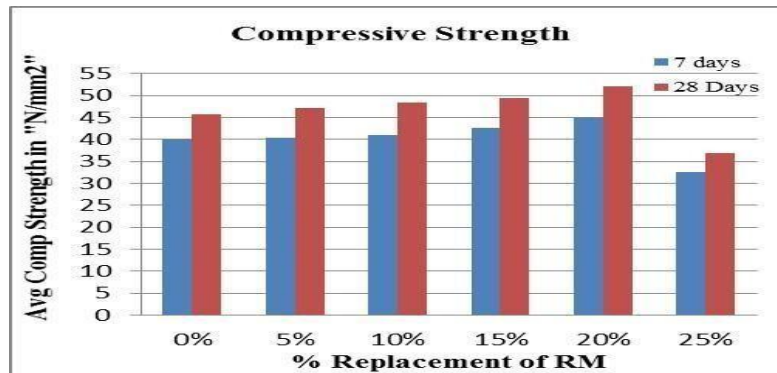


Fig 2. Variation of compressive strength of concrete with different percentages of red mud (RM) used as partial replacement of cement at 7 and 28 days of curing.

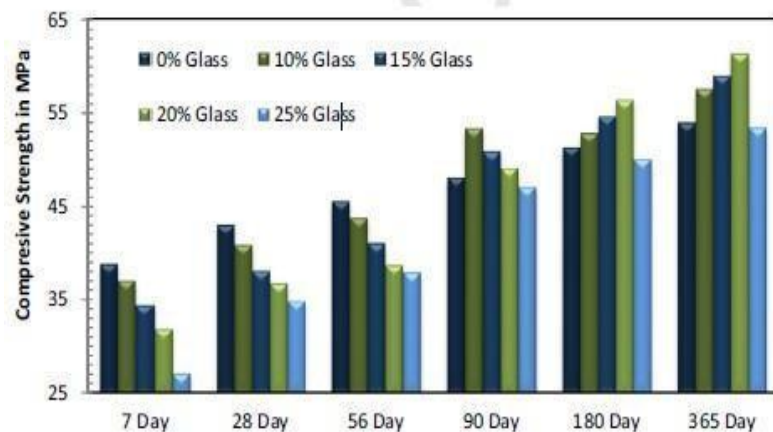


Fig 3. Variation of compressive strength of concrete with different percentages of waste glass powder used as partial replacement of cement at various curing ages (7, 28, 56, 90, 180, and 365 days).

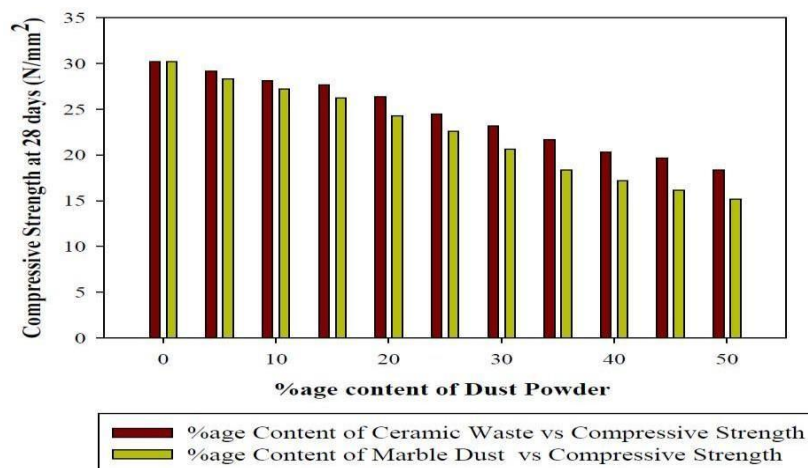


Fig 4. Comparison of compressive strength of concrete incorporating different percentages of ceramic waste and marble dust at 28 days of curing.



III. CONCLUSION

1. Drying, crushing, pulverization, burning and steam preprocessing are necessary procedures to improve industrial by-products for use as SCMs, making sure they fulfill the reactivity, consistency and performance requirements of the study.
2. The study shows that an increase in the fineness of the SCM material results in enhanced water absorption in the mixture.
3. A judicious mix design effectively compensates for the changes in mix qualities resulted from the substitution of cement with waste as SCM.
4. Compounds with high silica oxide, iron oxides, and calcium oxide content are deemed advantageous for use as supplementary cementitious materials in concrete.
5. The workability of fresh concrete appears to decrease with elevated levels of most waste items utilized as cement substitutes.
6. The study revealed that increased SCM content could reduce early strength, whereas long-term strength and durability usually enhance due to ongoing pozzolanic reactions.
7. The ideal replacement percentages of waste materials as supplementary cementitious materials (SCM) in concrete typically range from 5% to 30%, dependent upon the physical, chemical, and mineralogical properties of the material.
8. Exceeding the ideal replacement percentage typically decreases the strength of the mixtures, underscoring the necessity for comprehensive material characterization.

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