IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429

Volume 5, Issue 2, May 2025

Impact Factor: 7.67

Enhancing Concrete Performance : A Review of Admixtures

Prerna Jadhav[1], Tejaswini Bhavsar[2], Kirti Bafna[3], Sojwal Solanki[4], Dr. Hiteshkumar Patil[5]
BE Students Department of , Civil Engineering[1,2,3,4]
Assistant Professor, Department of , Civil Engineering[4]
R. C. Patel Institute of Technology, Shirpur
prernajadhav2678@gmail.com, tejaswinibhavsar15@gmail.com, kirtibafna03@gmail.com
sojwalsolanki@gmail.com, hitesh.patil@rcpit.ac.in

Abstract: *This study provides an overview of various mineral admixtures used to modify concrete properties. The research involves partially or fully replacing cement with different mineral admixtures, including fly ash, silica fume, rice husk ash, Ground Granulated Blast Furnace Slag, palm oil fuel ash, and metakaolin. The results show that each admixture yields distinct strength properties when added to concrete. The investigation presents a comprehensive analysis of the effects on concrete characteristics, such as compressive strength, split tensile strength, flexural strength, durability, and workability. This study provides an overview of various mineral admixtures used to modify concrete properties. The research involves partially or fully replacing cement with different mineral admixtures, including fly ash, silica fume, rice husk ash, Ground Granulated Blast Furnace Slag, palm oil fuel ash, and metakaolin. The results show that each admixture yields distinct strength properties when added to concrete. The investigation presents a comprehensive analysis of the effects on concrete characteristics, such as compressive strength, split tensile strength, flexural strength, durability, and workability.*

Keywords: GGBS, Fly ash, Metakaolin, Palm oil fuel ash, Silica fume, Rice husk ash, Marble Dust, OPA, BPA, Aluminium Waste Coconut shell Ash, wheat straw ash, Saw dust

I. INTRODUCTION

The surge in demand for Portland cement in developing countries has led to a growing interest in optimizing concrete performance. Supplementing concrete with mineral admixtures has been found to enhance its compressive strength. Moreover, industrial by-products can be harnessed as eco-friendly alternatives to traditional aggregates or cement. Research has demonstrated the potential of utilizing palm oil shells, a waste product from the agricultural sector, as a lightweight aggregate, while other studies have explored the viability of various mineral admixtures as substitutes for cement.

The quality of concrete can be significantly enhanced by incorporating various mineral admixtures. These include metakaolin, GGBS, Fly Ash, Rice Husk Ash, Palm Oil Fuel Ash, Silica Fume, Marble Dust, OPA, Aluminum Waste, Coconut shell Ash, wheat straw ash, and Sawdust. These admixtures, largely industrial by-products, influence the hardened properties of concrete, allowing for reduced cement content. This not only minimizes environmental impact but also improves concrete properties. Furthermore, utilizing these supplementary cementitious materials can mitigate disposal issues, lead to substantial energy savings, cost reductions, and decreased environmental pollution. The addition of mineral admixtures also affects the fresh concrete, resulting in variations in mechanical and durability properties compared to traditional concrete.

BACKGROUND STUDY:

Firstly, silica fume used in 1969 in Norway but was employed in North America and Europe in Early 1980. The use of silica fume is becoming more popular worldwide because it makes concrete stronger, more durable, and less prone to water damage. Silica fume can replace some or all of the cement in concrete, resulting in better overall quality. Silica

DOI: 10.48175/IJARSCT-26241

fume is a by-product in the decrease of high-purity quartz with coke in electric arc furnaces in the manufacture of silicon and ferrosilicon alloys [1]. In Tables 1 and 2 physical and chemical properties of silica fume are tabulated.

Metakaolin is a non-crystalline, amorphous, and cementitious material. It is used as an admixture to maintain concrete consistency and produce high-strength concrete. Metakaolin is utilized as a substitute material in concrete, offering a more environmentally friendly option. Producing one ton of metakaolin results in a relatively low 175 kg of CO2 emissions, significantly less than those generated by Portland clinker production. In Tables 1 and 2 physical and chemical properties of metakaolin are tabulated.

From agro-waste of palm oil, POFA [2] is obtained. POFA with a finer particle size can improve the compressive strength of concrete. Adding a superplasticizer to POFA can reduce the water to cement ratio and improve compressive strength. In Tables 1 and 2 physical and chemical properties of POFA are tabulated.

Fly ash is a by-product generated from the combustion of coal during electricity production in thermal power plants. The resulting fly ash primarily consists of calcium oxide, silica, and alumina, making it a valuable material for various industrial applications. Fly ash is classified into two main categories: C-type and F-type. C-type fly ash possesses both pozzolanic and cementitious properties, characterized by its high calcium content. In contrast, F-type fly ash exhibits only pozzolanic properties and has a lower calcium content.

Ground Granulated Blast Furnace Slag (GGBS) [3] is produced by rapidly cooling molten slag from a blast furnace using water or steam, resulting in a glassy, granular material. GGBS possesses both pozzolanic and cementitious properties, but requires an activator to initiate the hydration process. This material is then dried and ground into a fine powder. There are four types of GGBS: granulated slag, pelletized slag, expanded/foamed slag, and air-cooled slag. Among these, granulated slag is the most commonly used as a mineral admixture in concrete.

Rice Husk Ash (RHA) is a by-product of rice milling, generated by burning rice husks as fuel. Rich in silica, RHA is a valuable additive in concrete production. Its inclusion enhances concrete's performance by reducing permeability, increasing strength, and providing resistance to sulphate and chloride attacks.

Marble dust, a waste product of the marble industry, can be repurposed as a binding material and admixture in concrete. Its incorporation can significantly enhance the strength and durability of concrete, reducing waste and promoting sustainability.

Bamboo leaf ash (BLA) is a viable supplementary cementitious material that can enhance concrete's performance. Its addition can boost concrete strength while minimizing chloride penetration. Additionally, BLA can be utilized to stabilize soft soils, offering a multifaceted solution for construction applications.

Orange peel ash (OPA) is a promising sustainable material that can be used as a partial replacement for cement in concrete, enhancing its strength while minimizing waste. By utilizing OPA, environmental concerns associated with orange peel waste can be mitigated. Furthermore, OPA can modify the properties of fresh concrete, increasing its setting time and offering potential benefits for construction projects.

Using Aluminium waste in concrete, particularly aluminium dross or dust, can be a sustainable approach, potentially acting as a retarder and reducing concrete's setting time, especially beneficial in hot weather concreting, but it can also reduce workability and strength.

Coconut shell ash (CSA) can be used as a partial replacement for cement in concrete, offering potential benefits like increased strength and durability, while also reducing environmental impact.

Wheat straw ash (WSA), a by-product of burning wheat straw, can be used as a partial substitute for cement or fine aggregate in concrete, offering potential benefits like reduced carbon footprint and improved strength and durability.

Sawdust concrete is a type of lightweight concrete where sawdust, a by-product of wood processing, partially replaces mineral aggregates like sand, offering lower density, better thermal and acoustic insulation, and potential cost savings.

Quartz powder, a fine silica powder, is used in concrete to enhance strength, durability, and aesthetics, serving as a filler and acting as a nucleation point for cement hydration.

Pond ash, a waste product from thermal power plants, can be used as a partial replacement for fine aggregate (sand) in concrete, offering a sustainable and cost-effective solution while potentially improving certain concrete properties.

Using glass powder as a partial replacement for cement or sand in concrete can improve its properties and promote sustainability by reducing CO2 emissions and using recycled materials.

Bottom ash is a coarse, angular material a by-product of burning coal in power plants, can be used in concrete as a partial replacement for fine aggregates or cement, offering a sustainable solution for waste management and potentially improving concrete properties.

Table 1 Chemical Properties of mineral admixtures

	Fly Ash (%)	GGBS (%)	RHA (%)	Silica fume (%)	Metakaolin (%)	POFA (%)	Marble dust	Bamboo leaf Ash	OPA (Orange peel ash)	Aluminum Waste	Coconut Shell ash	Wheat Straw ash	Saw dust	Quartz powder	Pond ash	Glass powder	Bottom ash
SiO_2	25–60	27–38	85.5–95.5	95.75	52	53.5	28.35	78.00	23.3	56.60	37.97	67.34	20.18	97.13	60.57	64.32	32.2 to 50.7
Al_2O_3	10–30	13.24	0–2.5	0.35	46	1.9	0.42	4.96	2.31	15.90	24.12	6.44	1.53	0.47	27.88	2.90	15.5 – 20.3
Fe_2O_3	5–25	0.65	0–1.5	0.21	0.6	1.1	9.70	2.01	2.11	0.30	15.48	4.36	3.5	0.58	3.83	-	4.7–20.8
TiO_2	<1	<1	<1	<1	0.65	0.34	-	0.36	0.32	Trace	-	-	-	-	-	-	0.7–1.5
CaO	<10	34–43	0.51	0.17	0.09	8.3	40.45	4.43	31	18.20	4.99	10.60	3.22	0.75	0.98	18.18	4.2–22.2
MgO	<1	0.15–0.76	0.44	0.09	0.03	4.1	16.25	1.01	3.83	0.50	1.89	-	5.14	-	0.85	-	0.9–4.8
K_2O	<1	0.37	2.91	<1	0.03	6.5	-	3.09	26.26	-	-	-	0.22	-	-	1.53	0.5–2.2
Na_2O	<1	<1	<1	0.51	0.1	-	-	-	0.35	0.36	0.95	0.47	0.20	-	-	13.03	0.5–1.3
LOI	<1	<1	<1	<1	1	6.19	-	1.58	6.54	6.40	11.94	-	61	-	-	-	1.4–33.2
SO_3	<1	<1	<1	0.42	<1	0.93	-	-	0.80	-	0.71	1.85	-	1.07	0.11	-	0.1–0.7
MnO	7–15	<1	<1	<1	<1	0.16	-	-	-	0.60	0.81	-	0.01	-	-	-	-

Chemical Composition of Various Waste Materials for Potential Use in Cement and Concrete Production

The Table 1 presents the chemical composition of various waste materials commonly used as partial replacements or additives in cement and concrete production. The materials listed include Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Rice Husk Ash (RHA), Silica Fume (SF), Metakaolin (MK), Palm Oil Fuel Ash (POFA), and other industrial by-products such as Bamboo Leaf Ash (BLA), Orange Peel Ash (OPA), Rice Husk Powder (RHP), and several others.

The Table 1 categorizes the chemical constituents based on major oxides commonly found in these materials, including:

1. Silicon Dioxide (SiO_2): Silicon dioxide is a key compound for the strength and durability of cement and concrete. The SiO_2 content varies significantly across the materials, with Rice Husk Ash (RHA) exhibiting the highest range of 85.5–95.5%, followed by materials like Bamboo Leaf Ash (78%) and Glass Powder (97.13%). These high SiO_2 levels suggest that these materials could contribute positively to the binding and durability properties of cement and concrete when utilized as supplementary cementitious materials (SCMs).

2. Aluminium Oxide (Al_2O_3): Aluminium oxide plays a role in enhancing the chemical stability and strength of cementitious materials. GGBS, with 13.24% of Al_2O_3, and other materials like Metakaolin (MK) (46%) and Bamboo Leaf Ash (4.96%), present a wide range of Al_2O_3 content. These variations are essential for understanding how each material could potentially improve specific characteristics of concrete, such as early strength development.
3. Iron Oxide (Fe_2O_3): Iron oxide contributes to the colour and specific binding characteristics of cement. Materials such as Saw Dust and Coconut Shell Ash exhibit relatively higher Fe_2O_3 content (15.48% and 15.90%, respectively), suggesting that these materials may also influence the appearance and potentially the mechanical properties of concrete. On the other hand, materials like RHA and Metakaolin exhibit minimal iron oxide content.
4. Calcium Oxide (CaO): Calcium oxide is crucial in cement hydration and the formation of calcium silicate hydrates (C-S-H), the primary bonding phase in concrete. Materials like GGBS (34–43%) and Marble Dust (40.45%) exhibit high CaO content, indicating their potential for high reactivity in cementitious applications. Additionally, materials like POFA (Palm Oil Fuel Ash) (53.5%) and Metakaolin (8.3%) demonstrate varied CaO levels, which can affect their pozzolanic reactivity and influence concrete's long-term strength.
5. Magnesium Oxide (MgO): Magnesium oxide is often a minor component in cement, though high levels can lead to expansion issues in concrete. Materials like POFA (16.25%) and Sawdust (5.14%) show significant amounts of MgO, which may require consideration when used in concrete to avoid undesirable effects such as cracking due to expansion.
6. Potassium Oxide (K_2O) and Sodium Oxide (Na_2O): These alkali oxides are important for the alkali-silica reaction (ASR), which can cause cracking in concrete. The table indicates that Bamboo Leaf Ash (3.09%) and Rice Husk Powder (26.26%) exhibit higher K_2O levels, which may pose a risk of ASR in concrete mixtures. Similarly, materials like Saw Dust and OPA (Orange Peel Ash) show low Na_2O levels, which generally suggest a reduced risk of ASR.
7. Loss on Ignition (LOI): LOI refers to the loss of mass when a material is heated to a high temperature, often representing the content of volatile components like organic matter or water. Materials such as Saw Dust (61%) and Wheat Straw Ash (6.40%) show a higher LOI, which may indicate a greater presence of organic content, affecting their stability and reactivity in cementitious applications.
8. Other Elements: The table also lists minor oxides such as Titanium Oxide (TiO_2), Sulphur Trioxide (SO_3), and Manganese Oxide (MnO), which have lesser but still relevant effects on the material properties. For instance, the presence of sulphur compounds, especially in materials
9. Like Bamboo Leaf Ash (0.93% SO_3), may influence the setting time and strength development in cement.

Table 2 Physical properties of mineral admixtures

	Fly ash	GGBS	RHA	Silica fume	Metakaolin	POFA	Marble dust	Bamboo Leaf Ash	OPA (orange peel ash)	Aluminum waste	Coconut Shell ash	Wheat Straw ash	Saw dust	Quartz powder	Pond ash	Glass powder	Bottom ash
Shape	Spherical	Spherical	Irregular	Spherical	Spherical	Irregular	Granular	Amorphous powder	Irregular, uneven pores	Irregular, Flaky	Solid, Irregular	Irregular	Irregular	Angular	Rounded, subrounded	Irregular, Angular(Sharp edges)	Irregular (rough texture)
Specific	1.9–2.55	2.6	2.3	2.25	2.6	2.22	-	2.64	-	3.39	1.33	2.61	-	2.57	3.03	3.01	2.33

DOI: 10.48175/IJARSCT-26241

gravity															to 2.27		
Average particle size (μm)	0.5–300	4750	<45μ	0.1μ	12 μ	0-160	14.5	-	<90	10-100	37	63-500	4.57	0.1	2000-600	0.1	2000-600
Surface area(cm^2/g)	30-50	30-80	2.5-8	2000-3000	1500-2500	10-50	10-30	10-50	10-40	5-20	20-70	10-40	5-15	1-5	10-30	50-100	10-30
Density (kg/ m^3)	540-860	1200-1300	1000-1300	2000-2200	2600	1000-1500	2700	100-600	150-500	2700	100-400	100-500	100-600	2650	1200-1400	2500-2700	1000-1400
Moisture content (%)	0.5-5	0.1-2	4.5-10.5	0.5-3	0.5-2	5-15	1.59	0.40	18.67	-	5-15	5-15	29.547	0.1-1	10-30	0.1-1.5	20 - 70

Physical Properties of Waste Materials for Cement and Concrete Applications

The Table 2 provides a comprehensive overview of the physical properties of various alternative cementitious and filler materials derived from industrial and agricultural by-products. These materials are increasingly being utilized in concrete and construction due to their eco-friendliness, cost-effectiveness, and potential to improve certain mechanical and durability properties of concrete. The materials listed include Fly Ash, GGBS, RHA, Silica Fume, Metakaolin, POFA, Marble Dust, Bamboo Leaf Ash, Orange Peel Ash (OPA), Aluminum Waste, Coconut Shell Ash, Wheat Straw Ash, Saw Dust, Quartz Powder, Pond Ash, Glass Powder, and Bottom Ash. The physical characteristics considered are particle shape, specific gravity, average particle size, surface area, bulk density, and moisture content

Particle Shape :

The particle shape of these materials plays a significant role in determining their reactivity and workability in concrete mixtures , packing density in concrete .

- Spherical particles (e.g., Fly Ash, GGBS, Silica Fume, and Metakaolin) offer better flow and reduce water demand due to their smooth morphology.
- Irregular particles (e.g., RHA, POFA, Coconut Shell Ash, Wheat Straw Ash, Saw Dust, and Bottom Ash) tend to increase internal friction, affecting workability but enhancing mechanical interlock.
- Granular and angular shapes, seen in Marble Dust and Quartz Powder, improve strength due to increased surface contact.
- OPA has irregular and flaky particles, while Bamboo Leaf Ash exhibits uneven pores, both indicating variable interaction with water and binders.
- Glass Powder is described as rounded to subrounded, suggesting better flow but moderate bonding.

Specific Gravity :

Specific gravity reflects the density of a material compared to water and is essential for concrete mix design.

- Fly Ash (1.9–2.55) and Aluminium Waste (1.33) are relatively light.
- GGBS (2.6), Metakaolin (2.6), and Marble Dust (approx. 2.64) are denser and help in improving the mass density of concrete.
- OPA stands out with a high value of 3.39, making it very dense among organic waste ashes.

DOI: 10.48175/IJARSCT-26241

- Glass Powder (3.01) and Quartz Powder (3.03–2.27) also show high specific gravity, beneficial for structural applications.

Average Particle Size :

Particle size influences reactivity, packing, and surface area.

- Silica Fume and Quartz Powder have the smallest size (~0.1 µm), offering extremely high reactivity.
- Metakaolin (12 µm) and Marble Dust (14.5 µm) are also quite fine, contributing to improved strength and filler effects.
- Fly Ash has a broad range (0.5–300 µm), indicating variability in processing.
- RHA (<45 µm) and OPA (<90 µm) fall in the fine-to-medium range.
- Coarser materials include Wheat Straw Ash (63–500 µm) and Bottom/Pond Ash (2000–600 µm), which may be more suitable as fillers or lightweight aggregates rather than reactive pozzolans.

Surface Area

Surface area relates to the reactivity and bonding capability of materials.

- Silica Fume (2000–3000 cm²/g) and Metakaolin (1500–2500 cm²/g) have extremely high surface areas, promoting pozzolanic reactions and strength gain.
- Fly Ash and GGBS show moderate values (30–80 cm²/g), suitable for cement replacement.
- Organic ashes like POFA, Wheat Straw Ash, and Coconut Shell Ash fall in the range of 10–70 cm²/g, depending on processing.
- Quartz Powder has the lowest surface area (1–5 cm²/g), indicating it behaves more as a filler than a reactive material.

Density :

Density determines the mass per unit volume and affects mix proportions.

- Silica Fume and Metakaolin are relatively dense (2000–2600 kg/m³), contributing to strong, durable mixes.
- Lightweight materials such as Fly Ash (540–860 kg/m³), Bamboo Leaf Ash (100–600 kg/m³), Wheat Straw Ash (100–500 kg/m³), and Saw Dust (100–600 kg/m³) are suited for lightweight concrete or insulation.
- Heavy fillers like Marble Dust (2700 kg/m³) and Quartz Powder (2650 kg/m³) enhance compressive strength and packing.
- Glass Powder and Bottom Ash range from 2500–2700 kg/m³, also contributing to denser mixes.

Moisture Content :

Moisture content affects the handling, storage, and water-cement ratio in concrete mixes.

- Dry materials like Silica Fume, Metakaolin, Fly Ash, and Glass Powder typically have low moisture contents (0.1–5%), ideal for storage and mixing.
- High moisture content is seen in Bottom Ash (20–70%), Saw Dust (up to 29.5%), and OPA (18.67%), requiring pre-treatment or drying before use.
- Organic ashes generally show higher moisture variability due to porosity and storage conditions.

WORKABILITY STUDIES:

The maximum compressive strength of steel fiber-reinforced concrete (FRC) was achieved at an optimal fiber content of 0.3% for both 3-day and 28-day curing periods, while a slightly lower content of 0.2% yielded the highest strength at 7 days. However, partial replacement of cement with fly ash resulted in a decrease in both compressive strength and workability of the FRC. An increase in fly ash content in concrete leads to a significant reduction in compressive strength at 7 days compared to 28 days, indicating a slower early-age strength development with higher fly ash replacement levels. Workability decreases when the percentage of GGBS increases. If GGBS is in higher percentage than SCGB beams shows higher ductility [4]. The workability of Ordinary Portland Cement (OPC) concrete improves with the partial replacement of OPC with Ground Granulated Blast Furnace Slag (GGBS), and this improvement is proportional to the level of GGBS replacement. Hence, the optimum replacement is 40% for structural purposes[5]. The incorporation of Ground Granulated Blast Furnace Slag (GGBS) and marble slurry in M25 grade concrete has yielded notable improvements. Specifically, replacing 20% of cement with GGBS and 40% of fine aggregate with marble slurry has resulted in increased workability, as evidenced by higher slump values. Furthermore, these substitutions have also enhanced the mechanical properties of the concrete, with significant increases observed in split tensile, compressive, and flexural strengths compared to the control concrete. Addition of GGBS reduces water demand and increases workability. For M25 SCC grade strength obtained is maximum at 50% replacement of GGBS to cement and 50% replacement of CRF to river sand [6]. RHA is highly porous material due to this concrete requires increase in water cement ratio. Workability of concrete gets decreased when RHA content is increased[7]. RHA is replaced in OPC at 25% has no effect on workability and strength. 10% replacement of RHA was good for structural concrete[8]. The optimal combination of 10% silica fume (SF) and 30% quarry dust (QD) yielded the highest compressive strength. However, the incorporation of quarry dust and silica fume had a detrimental effect on workability, resulting in a decrease in the concrete's flowability. Max. strength was obtained at 15% of replacement with Silica fume. Workability decreases with increment of silica fume percentage[9]. An increase in metakaolin content leads to a reduction in slump, indicating a decrease in the workability of the concrete. The optimum dose of Silica fume and Metakaolin in combination is found to be 6% and 15% (by weight) respectively at both 7 and 28 day compressive strength[10]. Highest Compressive strength obtained at 15% of replacement at 28 days of curing. Workability decreases with increase in cement replacement[11] .

For the fresh concrete mix, the workability of concrete decreased with increase in the marble dust proportion.5 % replacement results were comparable with the controlled mix results in terms of workability as it showed a difference of few millimetres. However, 10 % replacement showed a considerable amount of declination in the workability[12]. workability of concrete incorporating wheat straw ash (WSA) as a cement replacement generally show a reduction in workability (slump) as WSA content increases. Coconut shell ash (CSA) in concrete show that while it can improve certain properties, its use can also lead to a decrease in workability due to higher water absorption and a rougher surface compared to cement particles.

Workability was found to be reduced while replacing cement partially with bamboo leaf ash[13]. Adding quartz powder to concrete can improve both its workability and mechanical properties. It functions as a filler, helping to reduce porosity and increase strength, while also potentially lowering the water demand. When sand is partially substituted with sawdust in concrete, workability tends to decrease, even if the water-to-cement ratio remains unchanged. As the proportion of fine aggregate replaced by pond ash increases, the workability of concrete tends to decrease. This is primarily due to the higher specific surface area and greater water absorption characteristics of pond ash. The use of glass powder in concrete may initially reduce workability because of its angular shape and larger surface area. However, with adequate mixing and the possible inclusion of a superplasticizer, workability can be maintained or even enhanced.

STRENGTH STUDIES:

The water-to-cement (W/C) ratio has a significant influence on the flexural and compressive strength of concrete, playing a crucial role in determining its overall mechanical properties. The optimum percent replacement is 15% fly ash and 15% metakaolin in cement increases compressive Ness & split tensile strength[14] . It has observed that 10% replacement increases strength and 30% replacement decreases concrete strength on comparison with control concrete[15] . It was observed that a 10% replacement of cement with these materials generally leads to an increase in concrete strength, while a 30% replacement tends to reduce strength when compared to control concrete. Increase in fly ash content in concrete decreases compressive strength in ECC mixes but for FA/C = 1 strength of 25 MPa was achieved. Tensile properties get increased at 1% addition of fibres for FA/C ratio of 0.25. Increase in fly ash content in concrete decreases compressive strength in ECC mixes but for FA/C = 1 strength of 25 MPa was achieved. Tensile properties get increased at 1% addition of fibres for FA/C ratio of 0.25[16]. For M40 grade concrete, a 50% FA replacement results in lower compressive strength, while a 60% replacement provides a higher strength than plain concrete, also enhancing resistance to chloride ion penetration.

Furthermore, fly ash fibre-reinforced concrete demonstrates the highest compressive strength at 20% FA replacement. Incorporating steel fibres into cement with fly ash also increases strength. At 20% and 4% replacement level of GGBS and Nano Silica increases concrete compressive strength. Increase in compressive strength is 37% when compared to conventional mix[17]. In concrete mixes with 80-90% GGBS, 10-20% strength gain was observed in M30 and M40 grades. Optimal results for split tensile strength were achieved with 40% GGBS replacement. Higher GGBS percentages decrease setting time and workability but increase compressive strength[18].

When Recycled Husk Ash (RHA) was used in cement, it improved the compressive strength of pervious concrete, but beyond 10% replacement, the strength began to decrease, especially under aggressive exposure conditions. An optimum RHA replacement of 10% was identified, showing enhanced performance in sulphate environments. At 28 days modified mixture is prepared by replacement of cement with 10% RHA and 100% replacement of aggregates with recycled aggregates gave 2.11% more compressive strength, 3.88% more tensile strength compared to conventional concrete[19]. At 0.25% coir fibre replacement, the highest compressive strength was achieved in concrete with 10% RHA[20].

Regarding other SCMs like silica fume and metakaolin, it was found that 10% replacement of cement with silica fume maximized compressive, flexural, and split tensile strength. Further studies showed that 25% silica fume resulted in higher compressive and split tensile strengths for M30 grade concrete, though tensile and shear properties decreased with higher dosages. Metakaolin, when used as a partial cement replacement, enhanced concrete properties, with 15% replacement yielding the best results in terms of compressive, split tensile, and flexural strength. Fly ash combined with metakaolin also showed an optimal performance with 30% fly ash and 15% metakaolin replacements at 7 and 28 days.

Another focus of the research involved Palm Oil Fuel Ash (POFA), which was used in varying percentages for cement replacement. The results showed that the maximum strength in M40 grade concrete was achieved at 10% POFA replacement. For larger POFA percentages, the strength decreased over time. The maximum compressive and flexural strengths were observed at 30% POFA replacement, while the highest split tensile strength occurred at 5% POFA replacement. The use of POFA was also noted for its cost-reduction potential in concrete production.

Cement can be replaced by coconut shell ash up to 20% to achieve the average target compressive strength as 25 MPa by reducing the environmental impact in global warming potential over 15%[21]. Increasing bamboo leaf ash to more than 20% leads to further reduction in the strength resulting in much lower values in the range of 10- 13 MP[13] . Incorporating marble dust into concrete can improve its strength, especially compressive strength, when used at an optimal replacement level. It also contributes to environmental sustainability by making use of waste materials. Replacing sand with sawdust in concrete can lower compressive strength, particularly at higher replacement levels. However, it can also offer cost savings and environmental advantages.

Incorporating wood ash (WSA) as a partial replacement for cement can enhance the compressive strength of concrete. Optimal performance is typically achieved with 10% to 20% replacement by weight of the binder. This improvement is attributed to the pozzolanic reaction between WSA and calcium hydroxide, which leads to the formation of calcium silicate hydrate (C-S-H) gel, contributing to increased strength. When used as a supplementary material, quartz powder enhances the strength of concrete, often leading to higher compressive strength than conventional concrete. Its nucleation effect accelerates the cement hydration process, further boosting strength.

Incorporating glass powder, particularly as a replacement for cement or fine aggregates, can increase compressive strength, especially at lower replacement levels. Replacing 20% of cement with glass powder has been shown to improve strength. While the compressive strength of concrete with glass powder may decrease in the early curing stages, it increases in later stages.

This research highlights the potential of using alternative materials such as POFA, RHA, silica fume, and fly ash to improve concrete's mechanical properties, reduce costs, and address the increasing demand for construction materials. The findings underscore the importance of optimizing the replacement percentages of these materials to achieve the desired strength and durability in concrete mixes.

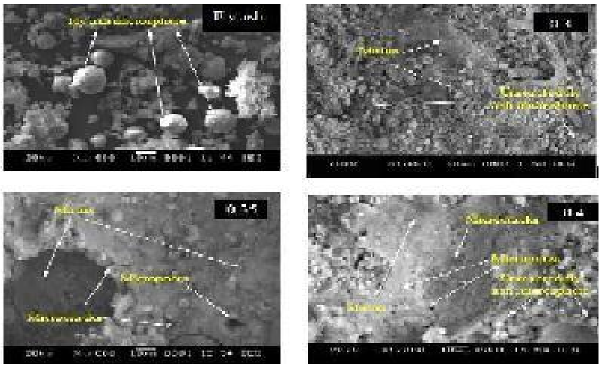
DOI: 10.48175/IJARSCT-26241

DURABILITY STUDIES:

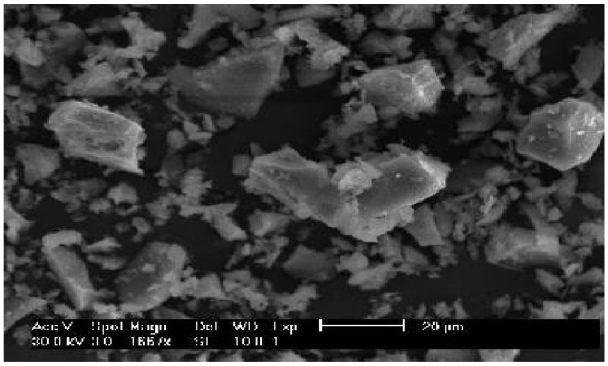
Replacing 30% of cement with Ground Granulated Blast Furnace Slag (GGBS) results in the maximum enhancement of compressive strength, thereby significantly increasing the load-carrying capacity of the concrete. Cement gets maximum compressive strength of 55.82 N/mm2 at 50% replacement of GGBS. Static load showed an increase in 18% fatigueless in HPC compared with conventional concrete[22]. This paper studies of M35 concrete mix with silica fume as a partial replacement of 0, 5,9,12 and 15% by cement weight. The values show usage of silica fume increases durability and strength characteristics at all ages compared to conventional concrete[23] . This paper demonstrates that replaced cement in concrete with metakaolin enhances durability and mechanical properties of concrete included different type of cement under various type of curing in the same time; Metakaolin concrete has a positive effect on compressive strength after exposure to escalated temperature[24]. Fly Ash Enhances durability in harsh environments. RHA Shows improved resistance to sulphate attack, chloride ion penetration, and alkali-silica reaction. Enhances durability in aggressive environments. POFA Enhances durability in tropical environments.

Marble Dust Exhibits improved resistance to sulphate attack and chloride ion penetration. Enhances durability in environments with high sulphate and chloride concentrations. Bamboo Leaf Ash Shows improved resistance to sulphate attack and chloride ion penetration. Enhances durability in tropical environments.

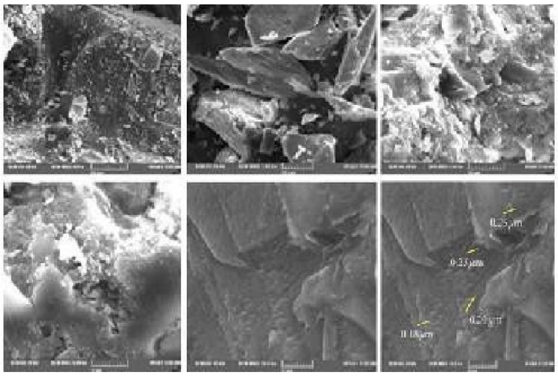
MICROSTRUCTURAL STUDY:



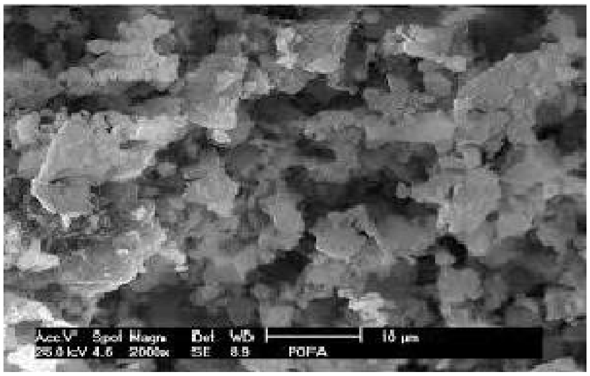
SEM IMG: FLY ASH[25]



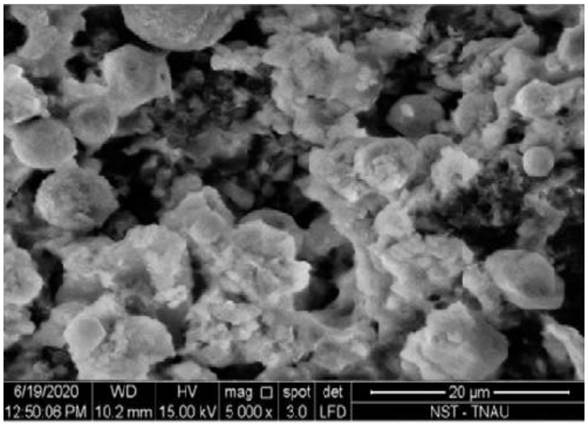
SEM IMG: GGBS[26]



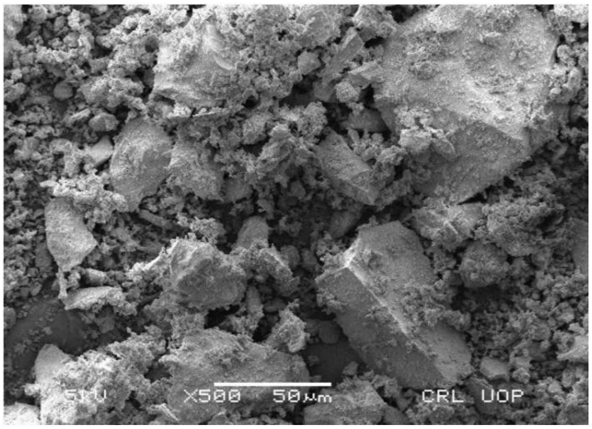
SEM IMG: SILICA FUME[27]



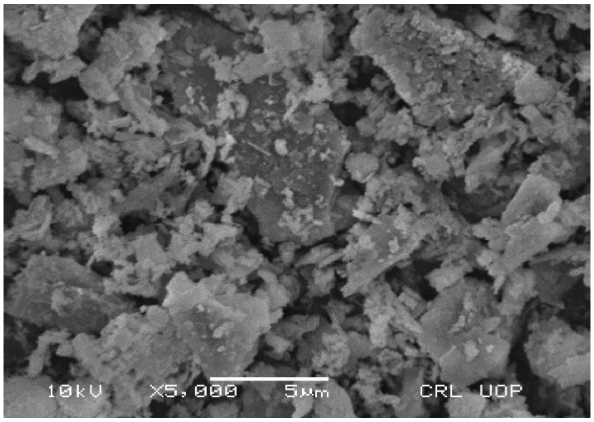
SEM IMG: POFA[28]



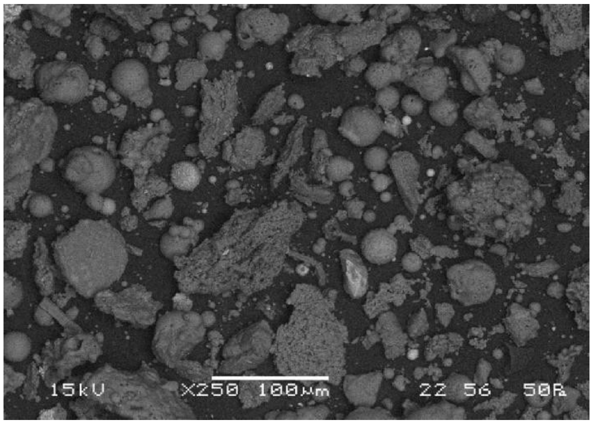
SEM IMG: COCONUT SHELL ASH



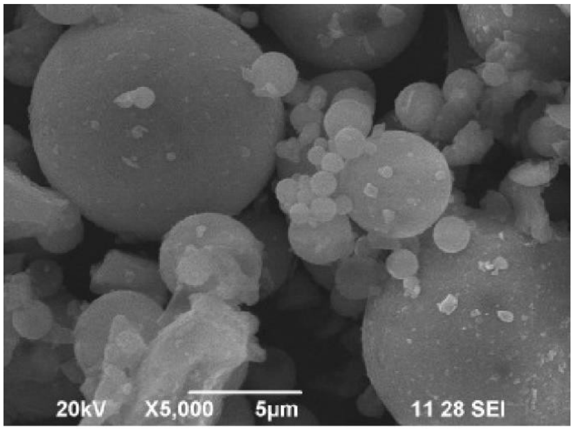
SEM IMG: WHEAT STRAW ASH[29]



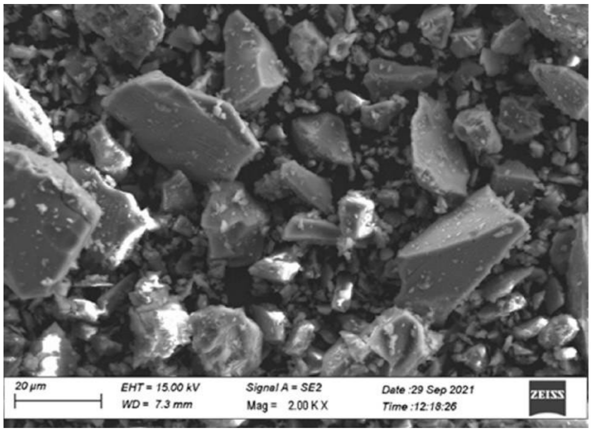
SEM IMG: SAW DUST[30]



SEM IMG: POND ASH[31]



SEM IMG: BOTTOM ASH[32]



SEM IMG: GLASS POWDER[33]

SUMMARY OF ALL ADMIXTURES:

All the mineral admixtures of optimum percentage of replacement with cement with desired conclusions/remarks and Grade of the concrete which is used in the research are listed in Table 3.

DOI: 10.48175/IJARSCT-26241

Table 3 Summary of Admixtures

Mineral Admixture	Author	Grade of concrete	Optimum REPLACEMNT	Conclusion
1. Fly ash	Shiv Kumar et al[34].	M30	35%	Maximum compressive & flexural strength is achieved at w/c-0.4
	Vinay Kumar et al.	M30	30%	Workability increases & strength
	Sri Bhavana et al.[16]	M30	10%	Strength is more with & without bacteria compared to conventional concrete
	Priyanka singh & Niraj[35]	M25	20%	Compressive, Flexural, Split tensile strength increases with added steel fibres.
	Surendra & Rajendra[36]	M40	15% Fly ash + 15% Metakaolin	Increase in compressive & Split tensile strength of concrete
2. GGBS	Lokeshwaran et al.[5]	M30	30%	Workability decreases with increase of GGNS percent. SCGB beams shows higher ductility at higher Percentage.
	Rakesh Kumar et al.[37]	M35	40%	Compressive, Split tensile, Flexural strength increases
	Anand et al.	M30 & M40	40%	Split tensile strength yields better results at 40% replacement
	Naveena & Chaitanya Kumar[38]	M30	30%	Corrosion resistance of finer increases but compressive strength decreases due to acid attack
	Mallesh & Suresh[39]	M20	15% GGBS + 30% Steel Slag	15% GGBS is replaced in cement & 30% steel slag replaced in fine aggregate increases compressive Ness of concrete
	Arvind Singh Gaur et al.[40]	M25	20% GGBS+40% Marble Slurry	Replacing marble slurry in fine aggregate & GGBS in cement, slump, split tensile, flexural strength increases .
	Mani Deep & Jazeb[19]	M60	5% GGBS + 15% Fly ash	Strength & durability of concrete .
	Manjula & Flexikala	M25	50% GGBS + 50% CRF	Water demand is reduced
3. RHA	Godwin et al.	M20	10%	As no effect in workability & strength but flexural, split tensile strength slightly increases
	Talsania et al.[41]	M30-M40	10%	Compressive & flexural strength increases by 10% replacement,
	Salim Khoso et al.[42]	M15	10%	Compressive, tensile strength increases at 10% RHA & 100% recycled aggregate replacement
	Swathika et al.	M20	0.25% Coir Fiber + 10% RHA	Compressive & Split tensile

DOI: 10.48175/IJARSCT-26241

Mineral Admixture	Author	Grade of concrete	Optimum REPLACEMNT	Conclusion
	Nambirajan & Satishbabu	M40	10% RHA + 0.25% Glass fibres	Concrete compressive, split tensile
	Akshay Tandon & Jawalkar	M30, M40, M60	7.5%	Graph shows augment in compressive potency at 7.5% substitution
	Harish et al.	M20	10%	To resist sulfate attack 10%
4. Silica fume	Dilip et al.[43]	M20,M25	10%	optimum at all ages of curing High early strength, good quality
	Arjun kumar[23]	M 30	10%	Compressive Strength increases up to 10% and starts decreasing.
	Kumar & Dhaka	M35	12%	Compressive, flexural strength increases at 12%, split tensile at 9%
	Sesikumar & Tamilvanan[17]	M30	25%	Graph shows increment of strength at 25%
	Akshay suryavanshi	M20, M25, M30	10%	Workability decreases as silica fume increases
	Guru deep Singh	M25	10%SF + 30%QD	SF + QD increases strength due
	Joe Paulson[44]	M20, M25, M30,	13%	ddition of silica fume improves pore structure ,density becomes higher
	Ali M Mansor[45]	M35 and M40	7.5%	se of SF in HPC decreases the tensile and shear strength
	Prabhulal chouhan[1]	M25	15%	orkability decreases with addition of silica fume content
	R.Umamaheswari[46]	M60	10%SF + 10%CSA	For 50% of replacement with the addition of 5% of silica fume the percentage increased for compressive and flexural has shown good percentage of strength increase.
	V.Prakash[47]	M35	Low strength	Pervious concrete has low compressive strength and flexural strength
	R.Selvapriya[48]	OPC M25	5 %, 10 % and 15 %	Compressive strength, Split tensile strength, Flexural strength was increased in silica fume 15% at 7 days and 14 days.
5. Metakaolin	CH Jyothi Nikhila	M70	15%	
	Bindu Biju	M70	10%	With increase in replacement dosage, strength seems to be decreasing
	N.Narmatha[49]	15%	10%	Use of metakaolin increases strength in HPC
	Sunny A. Jagtap	M35	15%	Metakaolin increases the compressive strength, flexural strength

DOI: 10.48175/IJARSCT-26241

Mineral Admixture	Author	Grade of concrete	Optimum REPLACEMNT	Conclusion
	K.Anantha Lakshmi[50]	M25	10%	Graphs shoes increment up to
	O.Hemanth Rama Raju	M35	15%MK + 50% robo sand	10% and then decreases Metakaolin and robo sand
	K.Madhu	M30	10%RHA + 5%MK	Workability decreases because of increased water absorption and strength decreases
	V.Subbamma	M40	30%fly ash +15%MK	Slightly increase in strength by
	Nova John	M30	15%	Use of metakaolin has faster early age strength
6. POFA	Shamed	M25	7.5%	By Usage of POFA cost will be reduced
	Sidek	M30	5%	Using liquidation and powder technique gives optimum percentage of POFA
	Ahmad	M40	15%	Optimum increase up to 15% of replacement
	Subhashini	M30	20%	Use of POFA will reduce environmental problems
7. Bagasse ash	Veeresh Karikatti[3]	OPC M25	5 %, 10 % and 15 %	When compared to OPC mix, GGBS-MP- BAP based binary and ternary mixes have similar properties at ambient temperature. The GGBS-based mix is easy to deal with, with slump values ranging from 100 to 150 mm. AASC mixes are set faster than OPC mixes, with initial and final setting times are 30 and 109 min, respectively
8. Banana and Orange Peel Powder	Shannen Lyka S. Cruz	OPC M25	4 %, 6 %, and 8 %	The incorporation of BPP into cement has exhibited a notable enhancement in compressive strength as compared to OPP. The percentage of OPP substitution in cement rises, it results in a reduction in compressive strength. Days %Comp strength 7days 12% to 29% 14days 26 % to 56% 28days 46% to 110%
9. Coconut Shell	Murthi Palanisamy	OPC M25	25 %	The permeability properties of lightweight self-consolidating concrete containing coconut shell aggregate has been investigated in

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				this study. Based on this experimental investigation, itis practicable to use CSA as aggregate to produce light weight concrete with satisfactory performance.
10. Wheat Straw Ash	Jawad Ahmad[51]	OPC M25	10 % to 20%	The GGBS-based mix is easy to deal with, with slump values ranging from 100 to 150 mm. AASC mixes are set faster than OPC mixes, with initial and final setting times are 30 and 109 min, respectively. Reduction in weight & compressive strength of AASC mixes is observed less under HCl and MgSO4 immersion.

II. CONCLUSION

Fly Ash:

Fly ash enhances compressive, flexural, and split tensile strength. Its inclusion improves workability and chloride resistance, with an optimal replacement range from 10% to 35%, depending on the grade of concrete.

GGBS (Ground Granulated Blast Furnace Slag):

GGBS improves strength and durability, particularly in higher-grade concrete. It can enhance corrosion resistance but may decrease workability with higher replacements (above 30%).

RHA (Rice Husk Ash):

RHA slightly increases compressive and split tensile strength at moderate replacement levels (around 10%) and helps resist sulphate attacks, although excessive use may reduce strength and workability.

Silica Fume:

Silica fume boosts strength, especially at lower percentages (10-12%). It enhances pore structure and increases durability but reduces workability as the replacement level rises.

Metakaolin:

Metakaolin increases compressive strength and improves the early strength of concrete. It can be used at 10-15% replacement without significant loss in workability.

POFA (Palm Oil Fuel Ash):

POFA, when used as a replacement, reduces environmental impact while improving compressive strength up to 15% replacement. It also enhances the sustainability of concrete.

Bagasse Ash:

Bagasse ash, when used with GGBS, shows comparable performance to OPC mixes. It provides similar compressive strength while improving the environmental footprint of concrete.

Banana and Orange Peel Powder:

Banana peel powder improves compressive strength, especially at lower replacement levels (4-6%), while orange peel powder tends to reduce strength as its percentage increases.

Rice Husk Ash (RHA):
Partial replacement with RHA up to 30% provides good concrete strength and functionality, especially at lower levels (10-20%) for better workability.

Coconut Shell:
Coconut shell aggregate can be used in lightweight self-consolidating concrete, offering satisfactory performance in terms of permeability and strength, particularly for reduced weight applications.

Wheat Straw Ash:
Wheat straw ash (10-20% replacement) can reduce the compressive strength of concrete but provides better performance under HCl and MgSO4 immersion, offering environmental benefits in concrete applications.

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