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Mechanical And Microstructural Performance of Concrete Incorporating Bio-Medical Waste Ash As A Partial Replacement of Cement

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Abstract
This study examines the potential of Biomedical Waste Ash (BMWA) as a sustainable and eco-friendly partial replacement for cement in M30 grade concrete. Concrete mixes were produced with 0%, 10%, 20%, and 30% BMWA at a constant water–cement ratio of 0.45, and their fresh, mechanical, and microstructural properties were evaluated. The fresh concrete tests indicated that the slump value and overall workability decreased slightly as BMWA content increased, yet these reductions remained within acceptable limits for practical applications. Mechanical testing revealed that BMWA replacement at 10–20% provided the most significant improvement in compressive, split tensile, and flexural strength, particularly at later ages, owing to enhanced pozzolanic activity. However, higher replacement levels, such as 30%, resulted in a slight decrease in strength because of reduced cementitious material. Microstructural investigations supported these findings: SEM analysis showed effective bonding between BMWA particles and the cement paste, forming a denser and less porous matrix. Energy-dispersive spectroscopy (EDS) confirmed the presence of essential oxides responsible for pozzolanic reactions. Additionally, X-ray diffraction (XRD) analysis identified the formation of major cementitious compounds, including calcium silicate hydrate (C-S-H) and portlandite, indicating that BMWA actively participates in hydration. Overall, the study demonstrates that BMWA can serve as a viable partial replacement for cement, improving key properties of M30 concrete at optimum levels while promoting sustainable waste management and lowering environmental impact without compromising performance.
Keywords: *Bio-Medical Waste Ash, Compressive Strength Test, Flexural Strength Test, Split Tensile Strength Test, SEM, XRD.*

1. Introduction
Concrete is one of the most widely used construction materials globally due to its strength, durability, and versatility. It is produced by mixing cement, sand, aggregates (gravel or crushed stone), and water to form a paste that hardens over time and gains strength. Concrete is used in diverse applications such as buildings, bridges, roads, and dams, and its performance can be modified by altering the mix proportions. The overall quality of concrete depends on the characteristics of the raw materials and the mixing process. In recent years, growing environmental concerns have encouraged the development of eco-friendly concrete by incorporating waste materials such as fly ash and biomedical waste ash (BMWA) as partial replacements for cement. This approach reduces environmental pollution and conserves natural resources. Biomedical waste, generated from hospitals, clinics, and laboratories during diagnosis, treatment, or research, can pose serious health and environmental risks if improperly managed. Incineration is commonly used to treat this waste, producing biomedical waste ash (BMW ash) as a by-product. Instead of disposing of this ash, studies have

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revealed that BMW ash possesses properties comparable to cement, making it a potential partial replacement material in concrete. Utilizing BMW ash not only reduces the reliance on cement—which is energy-intensive and contributes significantly to pollution—but also lowers construction costs and promotes sustainable waste recycling. However, before application, the ash must be adequately treated and tested to ensure its safety and environmental compatibility. [1]

1.1.Source of Bio-Medical Waste

The sources of biomedical waste are the various locations and activities where medical or healthcare-related procedures generate materials that may be infectious, hazardous, or require specialized handling. These sources are generally classified into major and minor categories. Major sources include hospitals, clinics and nursing homes, pathology and diagnostic laboratories, medical and dental offices, veterinary hospitals and animal research facilities, medical research institutions and universities, as well as blood banks and dialysis centers. Minor sources of biomedical waste consist of pharmaceutical companies, home healthcare activities, mortuaries and autopsy centers, cosmetic surgery and tattoo clinics, veterinary clinics and pet care centers, and non-governmental organizations (NGOs) or relief camps that generate waste during vaccination drives or health campaigns.

1.2.Classification of Bio-Medical Waste

Biomedical waste is generally categorized into hazardous and non-hazardous waste based on the level of risk it poses to human health and the environment. Hazardous biomedical waste refers specifically to waste that presents a potential risk of infection, injury, or harm due to its infectious, toxic, or radioactive nature. Non-Hazardous biomedical waste refers specifically to waste that does not presents any biological, chemical or radiological threat and is similar to domestic waste.

2. Methodology

An experimental investigation was carried out to evaluate the influence of Biomedical Waste Ash (BMWA) as a partial replacement for cement on the mechanical and microstructural properties of M30 grade concrete. The study methodology encompassed the selection and characterization of constituent materials, mix design formulation, specimen casting, curing, and subsequent testing in accordance with the relevant IS standards. [2]

2.1. Materials

The materials used in this study included Ordinary Portland Cement (OPC) of 43 grade conforming to IS 8112:2013. Manufactured sand (M-sand) classified under Zone II as per IS 383:2016 was employed as the fine aggregate, while crushed granite with a nominal maximum size of 20 mm, also conforming to IS 383:2016, served as the coarse aggregate. Potable tap water, free from organic impurities, oils, and acids and meeting the requirements of IS 456:2000, was used for both mixing and curing to ensure consistent hydration and strength development. Biomedical Waste Ash (BMWA) was sourced from a certified hospital incineration facility. The ash primarily comprised oxides of calcium, silica, and alumina, indicating its pozzolanic potential. Prior to use, it was oven-dried, sieved through a 90 µm sieve, and stored in airtight containers. The incorporation of BMWA contributed to secondary hydration by reacting with $Ca(OH)_2$ released during cement hydration, leading to the formation of additional calcium silicate hydrate (C–S–H) gel, thereby enhancing the strength and durability characteristics of the concrete. Figure 1 shows Process Of Biomedical Wast Ash Formation

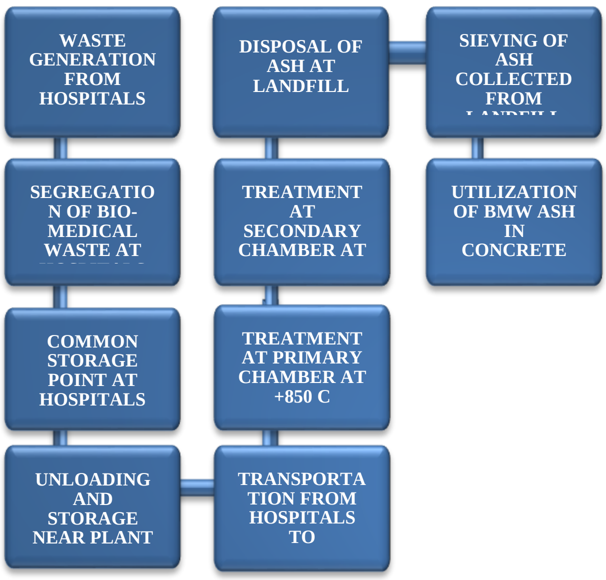

Figure 1 Process of Biomedical Wast Ash Formation

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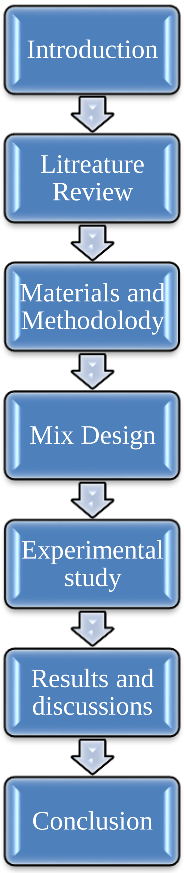

Figure 2 Detailed Methodology

2.2. Mix Design

The concrete mix for M30 grade was designed in accordance with IS 10262:2019 and IS 456:2000. A target mean strength of 38.25 MPa was established, considering a standard deviation of 5 MPa. A constant water–cement ratio of 0.45 was adopted to evaluate the effect of BMWA replacement levels of 0%, 10%, 20%, and 30%. The water content was maintained at 152 L/m³, and a polycarboxylate-based superplasticizer at 0.5% of the binder content was added to obtain the required workability. The cementitious material content was adjusted based on the selected water–cement ratio, and aggregates were proportioned using the absolute volume method to ensure the desired strength and durability characteristics. Figure 2 shows Detailed Methodology Table 1 shows Concrete Mix Proportions for 1m³ at 0.45 Water-Cement Ratio Figure 3 shows Slump Variations with BMWA Content for 0.45 W/C Ratio

Table 1 Concrete Mix Proportions for 1m³ at 0.45 Water-Cement Ratio

Materials	Calculations			
W/C Ratio	0.45			
Materials (kg/m³)	0% BMWA	10% BMWA	20% BMWA	30% BMWA
Coarse Aggregate	1255	1255	1255	1255
Fine Aggregate (M-Sand)	713	713	713	713
Cement	338	304.2	270.4	236.6
Bio-Medical Waste Ash (BMWA)	0	33.8	67.6	101.4
Water	152	152	152	152
Superplasticizer (%)	0.77	0.77	0.77	0.77

3. Results and Discussion

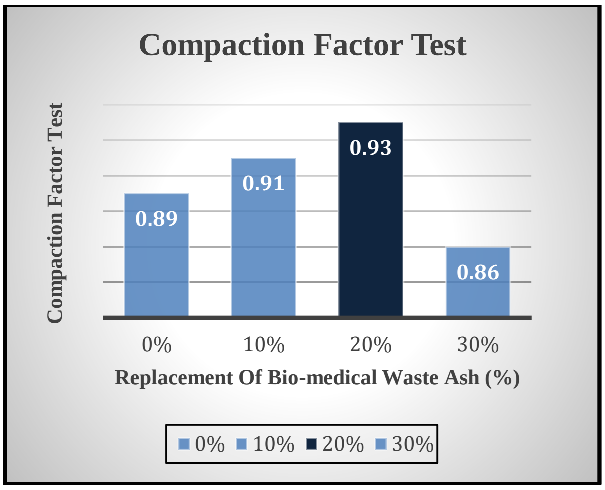

Figure 3 Slump Variations with BMWA Content for 0.45 W/C Ratio

3.1. Results

This section discusses the influence of Biomedical Waste Ash (BMWA) as a partial replacement for cement on the mechanical and microstructural properties of M30 grade concrete at a constant water–cement ratio of 0.45. All tests were performed after curing durations of 7, 14, 28, 56, and 90 days, and the corresponding results are presented and analyzed in the following subsections

3.1.1. Workability

The workability of concrete was observed to decrease with increasing BMWA content, primarily due to the higher surface area and porous nature of the ash, which increased the overall water demand. Table 2 presents the corresponding slump and compaction factor values for the mixes prepared at a water–cement ratio of 0.45. Table 2 shows Workability Results Figure 4 shows Compaction Factor Variations with BMWA Content for 0.45 W/C Ratio

Table 2 Workability Results

Contents	Readings			
W/C Ratio	0.45			
BMWA (%)	0	10	20	30
Slump (mm)	80	88	95	72
Compaction Factor	0.89	0.91	0.93	0.86

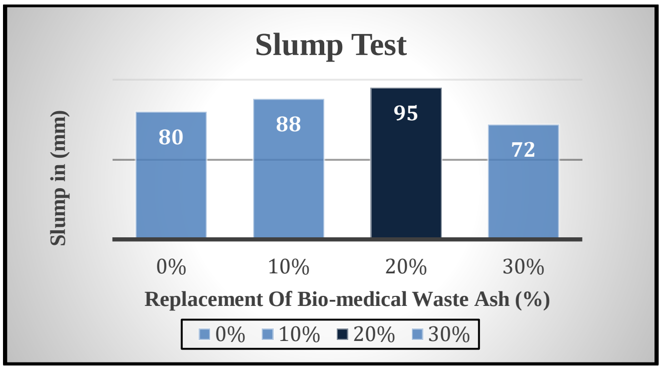

Figure 4 Compaction Factor Variations with BMWA Content for 0.45 W/C Ration

3.1.2. Compressive Strength Test

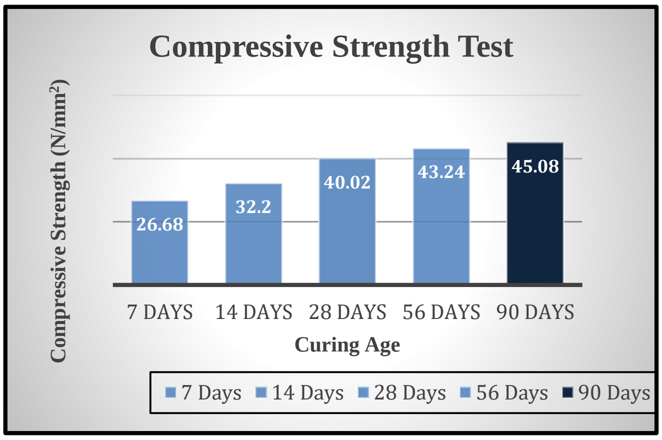

Figure 5 Compressive Strength for 0.45 W/C Ratio (20% BMWA)

Table 3 Compressive Strength Result

W/C	BM WA (%)	7 Days	14 Days	28 Days	56 Days	90 Days
0.45	0	25.30	30.82	37.72	40.94	43.06
0.45	10	23.55	28.52	34.96	37.90	39.65
0.45	20	26.68	32.20	40.02	43.24	45.08
0.45	30	22.08	27.60	33.12	35.88	36.80

3.1.3. Split Tensile Strength Test

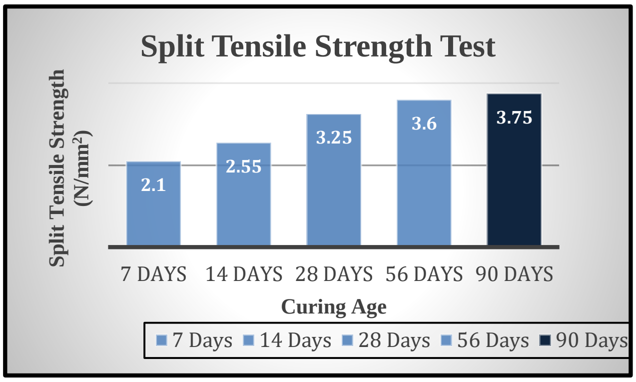

Figure 6 Split Tensile Strength for 0.45 W/C Ratio (20% BMWA)

Table 4 Split Tensile Strength Result

W/C	BM WA (%)	7 Days	14 Days	28 Days	56 Days	90 Days
0.45	0	2.0	2.35	3.0	3.25	3.40
0.45	10	1.90	2.25	2.90	3.15	3.35
0.45	20	2.10	2.55	3.25	3.60	3.75
0.45	30	1.75	2.10	2.70	2.95	3.10

3.1.4. Flexural Strength Test

Table 5 Flexural Strength Result

W/C	BM WA (%)	7 Days	14 Days	28 Days	56 Days	90 Days
0.45	0	3.32	3.63	3.84	4.03	4.14
0.45	10	3.36	3.67	3.91	4.08	4.20
0.45	20	3.43	3.74	3.99	4.17	4.28
0.45	30	3.13	3.35	3.63	3.83	3.95

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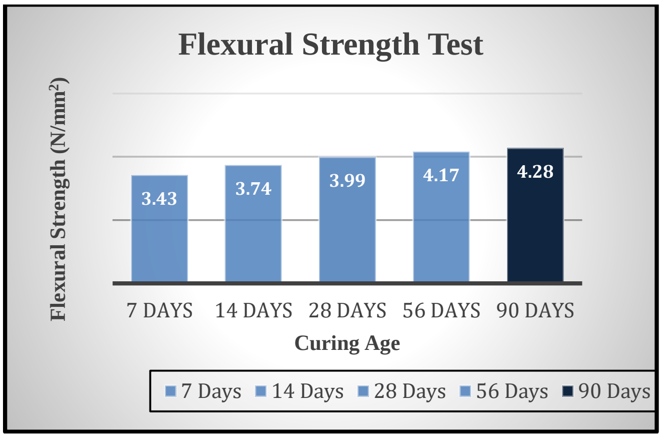

Figure 6 Split Tensile Strength for 0.45 W/C Ratio (20% BMWA)

3.1.5. Microstructural Analysis (20% BMWA Concrete at 0.45 W/C Ratio)

Microstructural analysis of the 20% BMWA mixes, conducted using SEM and XRD, revealed that a water–cement ratio of 0.45 significantly enhanced matrix densification, reduced porosity, and improved overall hydration. The mix with W/C = 0.45 exhibited a more uniform and compact microstructure, characterized by increased formation of C–S–H gel and a noticeable reduction in Ca $(OH)_2$ peaks, confirming the strong pozzolanic reactivity of BMWA. Both SEM and XRD results indicated that the incorporation of BMWA promotes secondary hydration, leading to a refined microstructure and improved strength performance. Figure 7 shows SEM Pattern of 20% BMWA Replacement Concrete with W/C Ratio 0.45 [3]

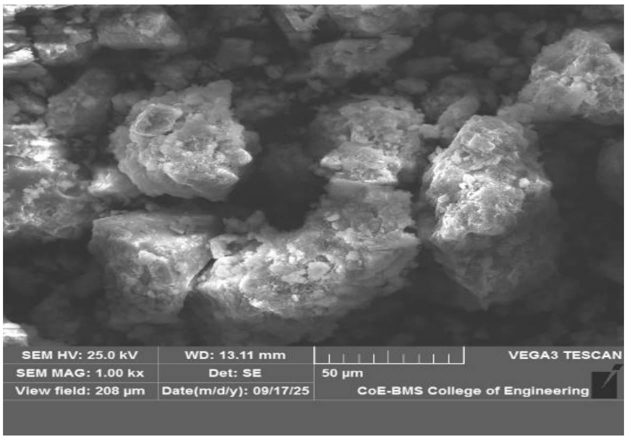

Figure 7 SEM Pattern of 20% BMWA Replacement Concrete with W/C Ratio 0.45

3.2. Discussion

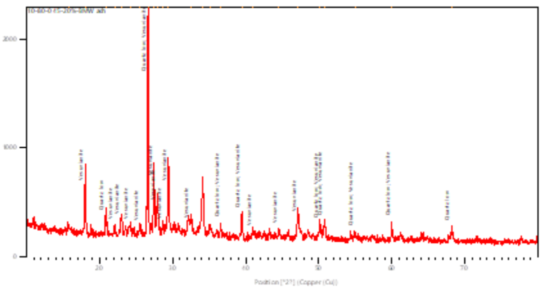

FIGURE 8. XRD pattern of 20% BMWA Replacement Concrete with W/C Ratio 0.45

- **Workability:** The workability results, evaluated through slump and compaction factor tests, showed that the highest slump value of 95 mm was obtained for the 20% BMWA mix at a water–cement ratio of 0.45. Similarly, the maximum compaction factor of 0.93 was recorded for the same W/C ratio, indicating improved workability.
- **Compressive Strength:** Compressive strength increased with curing age due to enhanced hydration and the pozzolanic contribution of BMWA. The mix containing 20% BMWA at a W/C ratio of 0.45 achieved the highest 90-day compressive strength of 45.08 N/mm².
- **Split Tensile Strength:** A progressive improvement in split tensile strength was observed with longer curing periods. The 20% BMWA mix at a W/C ratio of 0.45 achieved the maximum value of 3.75 N/mm².
- **Flexural Strength:** Flexural strength exhibited a steady increase with curing age, with the 20% BMWA mix at a W/C ratio of 0.45 attaining the highest value of 4.28 N/mm².
- **Microstructural Characteristics:** SEM and XRD analysis of the 20% BMWA mixes confirmed that a W/C ratio of 0.45 resulted in improved matrix densification, reduced porosity, and enhanced hydration. Both techniques demonstrated that BMWA facilitates secondary hydration, contributing to a refined microstructure and improved overall strength performance

Conclusion

- **Feasibility of BMWA Utilization:** Biomedical Waste Ash (BMWA) demonstrated its potential as an effective partial cement replacement material, offering a cost-efficient and environmentally sustainable alternative for concrete production. [4]
- **Workability Performance:** All concrete mixes exhibited medium workability. The mix containing 20% BMWA showed marginally improved workability due to better particle packing, whereas the 30% replacement level resulted in a slight reduction in slump values.
- **Compressive Strength Development:** Compressive strength increased consistently with curing age. The mix with 20% BMWA at a W/C Ratio of 0.45 achieved the highest 90-day compressive strength of 45.08 N/mm², while the 30% replacement showed comparatively lower strength.
- **Split Tensile Strength:** The highest split tensile strength was also recorded for the 20% BMWA mix, reaching 3.75 N/mm² at 90 days for the 0.45 water–cement ratio, following the same performance trend observed in compressive strength. [5]
- **Flexural Strength:** Flexural strength improved with curing age, with the 20% BMWA mix at a W/C Ratio of 0.45 attaining the highest value of 4.28 N/mm² exhibiting the highest bending resistance. A slight reduction in flexural performance was observed at the 30% replacement level.
- **Microstructural Findings:** SEM and XRD analysis indicated a denser and more refined matrix for the 20% BMWA mix with a W/C Ratio of 0.45. In contrast, the 30% replacement mix displayed more unreacted ash particles and noticeable micro voids.
- **Optimum Replacement Level:** Considering both mechanical and microstructural outcomes, a 20% BMWA replacement was identified as the optimum level, ensuring enhanced strength characteristics, acceptable workability, and improved sustainability compared to conventional concrete.

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