Environmental Research and Technology
https://dergipark.org.tr/en/pub/ert
DOI:https://doi.org/10.35208/ert.1555389

Environmental Research & Technology

Research Article

Integrating biomedical and fly ash waste in concrete: A strength-based comparative study for sustainable construction

Arpita V. BRAHMBHATT[1], Bina Birenkumar PATEL[1*]

[1]*Environmental Engineering Department, L. D. College of Engineering, Ahmedabad, India*

ARTICLE INFO

Article history
Received: 05 September 2024
Revised: 09 December 2024
Accepted: 14 January 2025

Key words:
Sustainable construction, biomedical waste incineration ash, fly ash, leachate analysis, concrete compressive strength, cement replacement

ABSTRACT

This study investigates the feasibility of using biomedical waste incineration ash (BWIA) and fly ash (FA) as partial replacements for cement (0%, 10%, 20%, 30%, and 40%) in M25 grade concrete. Comprehensive testing was conducted to evaluate the compressive strength and weight of concrete with varying percentages of BWIA and FA. A total of 36 concrete cubes were prepared and tested for compressive strength after 7, 14, 28, and 56 days of curing. Leachate analysis was also conducted to assess the environmental impact of the prepared concrete. The results revealed that optimal compressive strength was achieved at 28 days with a 20% replacement of both ashes, yielding strengths of 25.11 MPa for BWIA and 24.57 MPa for FA. Beyond 20% ash replacement, compressive strength declined, and increasing ash percentages led to lighter concrete. Furthermore, leachate analysis confirmed no release of heavy metals, ensuring environmental safety. This research demonstrates the potential for utilization of BWIA and FA as sustainable materials in concrete, addressing waste disposal challenges while contributing to green construction practices. By determining optimal replacement levels and application ranges, the study supports the development of eco-friendly concrete production and promotes sustainability in the construction industry.

Cite this article as: Brahmbhat AV, Patel BB. Integrating biomedical and fly ash waste in concrete: A strength-based comparative study for sustainable construction. Environ Res Tec 2025;8(4) 887-899.

INTRODUCTION

The generation and management of industrial and biomedical waste ashes, particularly fly ash (FA) and biomedical waste incineration ash (BWIA), present significant environmental and sustainability challenges. Fly ash, a by-product of coal combustion in thermal power plants, is one of the largest industrial waste streams globally. India leads FA production with 112 million tons annually, followed by China (100 million tons) and the U.S. (75 million tons). Despite achieving a global utilization rate of 68.72% in 2019, India lags with 38% utilization, and FA generation is expected to reach 600 million tons annually by 2031-32. Unutilized FA occupies vast land areas and poses environmental risks, including water contamination and air pollution [1].

Biomedical waste incineration generates approximately 0.82 million tons of ash annually, with India contributing about 517 tons daily. This ash contains hazardous heavy metals like mercury, lead, and cadmium, which risk leaching into soil and groundwater. Effective management of these ashes is essential for mitigating environmental impacts while addressing global sustainability goals [2].

The construction industry is constantly seeking innovative solutions to address the challenges of waste management, environmental sustainability, and the development of high-performance building materials. In this context, the utilization of waste materials as alternative resources and the incorporation of waste ashes in construction materials have gained significant attention [3]. Waste ashes such as BWIA

***Corresponding author.**
*E-mail address: bina.patel@ldce.ac.in

and FA have proven effective in enhancing concrete's mechanical properties and durability [2, 4, 5]. Initiatives like India's Fly Ash Mission, with its 100% utilization target, promote applications in construction, road embankments, and agriculture, aligning with circular economy goals while reducing environmental impacts and conserving resources. Effective fly ash management globally remains vital for sustainable development and ecological risk mitigation.

Past studies have demonstrated the potential of BWIA and FA in sustainable construction. The utilization of ash as a partial cement replacement has been extensively studied to enhance the sustainability and performance of concrete (Table 1). Nataraja et al. [6] explored the use of BWIA in self-compacting concrete, demonstrating improved strength at replacement levels up to 20%. Similarly, studies on FA replacements have shown significant improvements in compressive strength, with replacement levels reaching 50% (Abushad et al. and R et al. [7, 8]. The inclusion of admixtures, such as ground granulated blast furnace slag and copper tailings, further optimized the mechanical properties of ash-modified concretes (Pandurangan et al., Dandautiya et al. and Nguyen et al. [9–11] highlighted the effectiveness of FA, including standard and substandard varieties with expansive additives, in enhancing concrete properties up to 30% replacement levels. Nagrockienė et al. [12] explored the use of FA with superplasticizers, achieving significant improvements at replacement levels as high as 65%.

Similarly, Kaur et al. [13] reported that BWIA could replace up to 20% of cement without compromising mechanical properties. Al-Mutairi et al. [14] and Genazzini et al. [15] investigated hospital waste ashes, finding their application viable with microsilica admixtures at 10–25% replacement. Other studies done by Akyıldız et al. [16] focused on the environmental safety of using ash, with results indicating negligible leaching of heavy metals.

Moreover, studies on coal bottom ash done by Singh et al. [17] and treated fly ash by Aubert et al. [18] and Al-Rawas et al. [19] further validated the potential of ash for sustainable concrete production, showcasing optimal curing times and replacement levels while ensuring environmental safety.

Manjunath et al. [21] emphasized BWIA's potential in concrete composites, highlighting its mechanical and environmental benefits. Similarly, Al-Biruni et al. [22] explored the use of BWIA in stabilized earth blocks, reinforcing its viability for sustainable construction. Other research by Maschowski et al. [23] explored biomass ash utilization, while Zhuge et al. [24] focused on wood waste ash in green concrete, all demonstrating the versatility of ash as a replacement material.

Studies on FA underline its efficiency in enhancing the mechanical properties of self-compacting concrete [25] and reducing restrained shrinkage cracking expanded on the role of challenging fuel ashes in a circular economy, advocating for their integration into sustainable materials [26]. Moreover, leachate analyses confirm the environmental safety of ash-incorporated concrete, ensuring negligible heavy metal leaching [27].

Sharma et al. [1] detailed FA utilization in India, showcasing government initiatives to promote its application in various sectors. Kumar et al. [2] highlighted BWIA's role in reducing environmental strain while enhancing concrete's mechanical properties. These findings highlight the potential of ash, including BMIA and FA, as sustainable alternatives in concrete production, promoting waste utilization while maintaining structural integrity.

This study investigates the effects of incorporating BWIA and FA into M25 grade concrete, focusing on key parameters such as waste ash percentage (0%, 10%, 20%, 30% and 40%) and curing periods (0, 7, 14, 28 and 56 days). By evaluating mechanical properties, including compressive strength and weight, as well as leaching behaviour, the research aims to assess the structural integrity, load-bearing capacity, and environmental sustainability of waste ash added concrete. Understanding these characteristics will determine the suitability of BWIA and FA for diverse construction and environmental conditions.

The findings contribute to sustainable construction practices by promoting the efficient use of waste materials, addressing waste management challenges, and enhancing concrete performance. This study provides architects, engineers, and construction professionals with insights to develop high-performance, eco-friendly building materials, advancing sustainability in the construction industry.

Table 1. Previous studies on various types of ash utilized in concrete

Sr. no.	Type of cement used	Type of ash used for cement replacement	% of ash replaced	Curing time (days)	Reference
1	M30	BWIA	0-20	7, 14, 28	[6]
2	OPC 53 grade	Class C fly ash from thermal power plant	0-50	7, 14, 28	[7]
3	OPC	Class F fly ash	0- 40	7, 28	[8]
4	-	Class F fly ash Admixture: ground granulated blast furnace slag (GGBS)	70	7, 28	[9]
5	Portland cement	Standard & substandard fly ash Admixture: Expansive additive	0-30	3, 7, 28, 91	[11]
6	OPC 43 grade	Fly ash from thermal power plant Admixture: Copper tailing	0-30	7, 28, 56	[10]
7	Portland cement	Fly ash Admixture: Super plasticizer	0-65	7, 28	[12]
8	OPC 43 grade	Incinerated biomedical waste ash	0-20	7, 28,56	[13]
9	Cement	Incinerated hospital waste ash	0-50		[15]
10	Cement	Hospital waste fly ash Admixture: Microsilica	0-25	28	[14]
11	Cement (CEM I 42.5 R)	Medical waste bottom ash	0-50	7, 28	[16]
12	Portland cement	Incinerated hospital waste ash	0-10	28, 90, 180, 365	[20]
13	OPC	Treated fly ash	12.5,50	28	[18]
14	OPC	Incineration ash	0-40	3, 7, 14, 28	[19]
15	OPC	Coal bottom ash	0-10	28	[17]

MATERIALS AND METHODS

Various international standards are available for concrete, mainly based on British standards or American standards or Indian standards. For the present study, Indian standards are follows for M25 grade concrete preparation and testing. This section highlights the materials and methods used for the entire study.

Materials Used for Concrete

Cement: The cement used in this work was portland pozzolana cement (PPC) of Ambuja Brand. PPC, which is FA based, is an intimately inter-ground mixture of Portland cement clinker or ordinary portland cement and pozzolana, with the possible addition of gypsum (natural or chemical). Alternatively, it may be an intimate and uniform blend of ordinary Portland cement and finely ground pozzolana, with added ground gypsum if required. The standard specifies that the fly ash content should be no less than 15% and no more than 35% by mass of Portland Pozzolana Cement. The physical properties of this cement are presented in Table 2.

Ash: Two different types of ash were used in this study: BWIA, sourced from E-coli Waste Management in Ahmedabad, Gujarat, India (Figure 1a), and FA, obtained from the boiler of a textile industry in Ahmedabad, Gujarat, India (Figure 1b). The physical properties and chemical compositions of both ashes are provided in Table 3. It was observed that the physical and chemical compositions of BWIA and FA were almost similar.

Table 2. Physical properties of Portland Pozzolana Cement

Sr. No.	Physical properties	Test result
1	Normal consistency	32%
2	Setting time: • Initial setting time • Final setting time	 115 minutes 185 minutes
3	Specific gravity	2.97

Figure 1. Types of ashes used for the study (a) BWIA (2) FA

Table 3. Physical and chemical properties of BWIA and FA

Sr. No.	Parameter	Units of parameters	BWIA	FA
	Physical Properties			
1	Specific gravity	--	2.31	2.33
2	Fineness	micron	41	45
3	Density	kg/m^3	1433	1439
4	Water absorption	%	3.40	3.45
	Chemical composition			
1	SiO_2	%	94.30%	97.56%
2	Al_2O_3	%	0.42%	0.40%
3	Fe_2O_3	%	0.023%	0.024%
4	CaO	%	0.75%	0.84%
5	MgO	%	0.20%	0.22%
6	Na_2O	%	0.19%	0.10%
7	K_2O	%	0.11%	0.13%
8	SO_3	mg/gm	0.57 /100	0.62/100
9	Free lime	%	0.0050	0.0052
10	LOI	%	0.0098	0.0090

Fine aggregate: Locally available river sand conforming to Zone II as per Indian Standards IS: 383 (1970) was used as fine aggregate. This sand passed through an IS Sieve of 4.75 mm. The aggregate fraction ranging from 4.75 mm to 150 microns was classified as fine aggregate. Fine aggregates are further categorized as coarse sand, medium sand, and fine sand. The specific gravity, bulk density, fineness modulus, and water absorption of the fine aggregates were measured as 2.64, 1.397 kg/l, 2.81, and 0.80%, respectively.

Coarse aggregate: Gray crushed stone conforming to IS: 383 (1970) with a nominal size of 20 mm was used as coarse aggregate in the concrete mix. Aggregates larger than 4.75 mm in size are classified as coarse aggregates. The shape of the crushed stone plays a critical role in achieving high-strength concrete. Poorly shaped aggregates can result in inferior concrete quality. Generally, the aggregate should have an angular, granular, or crystalline shape with non-powdery surfaces. The specific gravity, bulk density, fineness modulus, and water absorption of the coarse aggregates were recorded as 2.64, 1.320 kg/l, 3.49, and 0.81%, respectively.

Water: Water is essential for the hydration of cement and to ensure workability during mixing and placing. Potable water or tap water is generally considered suitable for this purpose. In this study, tap water (sourced primarily from groundwater) was used for both mixing and curing. The quality of the water used is detailed in Table 4.

M25 Grade Concrete Mix Design Method

The M25 concrete mix was prepared following the recommended guidelines outlined in IS 10262-2009 and IS 456-2000. The detailed steps and design calculations are provided in Annexure 1. Cement was replaced by 0%, 10%, 20%, 30%, and 40% with BWIA and FA, respectively. The required quantities of BWIA and FA are summarized in Table 5.

For the experimental work, a total of 36 concrete cubes, each with dimensions of 150 mm × 150 mm × 150 mm, were cast. Four cubes were cast to determine the compressive strength of normal concrete without ash addition. Similarly, for each replacement level of 10%, 20%, 30%, and 40% with BWIA, a set of four cubes was cast (Figure 2). Likewise, another set of four cubes was cast for each replacement level of 10%, 20%, 30%, and 40% with FA. The cubes were removed from the molds after 24 hours and then placed in a curing tank for 7, 14, 28, and 56 days, as required by the test specifications.

Table 4. Quality of tap water used in concrete preparation

Sr. No.	Parameter	Units	Value
1	pH	--	7.2
2	Total dissolved solids	mg/L	991
3	Chlorides	mg/L	150
4	Fluorides	mg/L	1.1
5	Hardness as $CaCO_3$	mg/L	355
6	Total suspended solids	mg/L	19

Table 5. Quantity of material for mix design

			Quantity (kg)				
Type of ash	Cement replaced (%)	No of Cubes	Ash	Cement	Fine aggregate	Coarse aggregate	Water (litre)
	0%	4	0	1.5690	2.91	4.75	0.8-1
BWIA	10%	4	0.1569	1.4121	2.91	4.75	0.8-1
	20%	4	0.3138	1.2552	2.91	4.75	0.8-1
	30%	4	0.4707	1.0983	2.91	4.75	0.8-1
	40%	4	0.6276	0.9414	2.91	4.75	0.8-1
FA	10%	4	0.1569	1.4121	2.91	4.75	0.8-1
	20%	4	0.3138	1.2552	2.91	4.75	0.8-1
	30%	4	0.4707	1.0983	2.91	4.75	0.8-1
	40%	4	0.6276	0.9414	2.91	4.75	0.8-1

Figure 2. Casted M25 grade concrete cubes

Table 6. Quantity of materials required for concrete specimens for leaching test

Item		Values
Type and dimension of test specimen		M25 concrete, 75mm×75mm×75mm
Material used for preparation of the test specimen and mix proportion of the materials	Water	78 ml
	Cement	125.6 gm
	Fine aggregate	292 gm
	Coarse aggregate	475 gm
	BWIA	31.4 gm
	FA	34.1 gm
Surface area of specimen		421,875 mm^3

Compressive Strength of Concrete Cubes

The compressive strength of the concrete cubes was evaluated using a Compression Testing Machine with a capacity of 200 tons, following the specifications outlined in IS: 516 (1959). During the test, the strength was measured in kilonewtons (KN). The load was applied gradually at a rate of 140 kg/cm^2 per minute until the concrete cube or specimen failed. The compressive strength of the concrete was calculated by dividing the maximum load applied to the cube at failure by its cross-sectional area, with the result expressed in megapascals (MPa). Additionally, the weight of each concrete cube was recorded during the test.

Leachability of Heavy Metals in Concrete Containing BWIA and FA

Both BWIA and FA contain heavy metals. When these ashes are used to partially replace cement in concrete mixes, there is a possibility of heavy metal leaching from the concrete cubes, which can cause environmental issues. Therefore, it is essential to investigate the leachability of heavy metals in concrete cubes containing BWIA and FA. For this purpose, the tank leaching test was employed, as specified in the standard test method for leaching trace elements from hardened concrete (JSCE G575-2005) proposed by the Japan Society of Civil Engineers [28]. This standard outline the requirements for testing trace elements leached from hardened concrete.

The tank leaching test is conducted to determine the quantity of trace elements leached from a concrete specimen that has been immersed in a leachant. During the test, the specimen is kept immersed in the leachant. The leachant refers to the solution used for leaching, while leachate is the solution obtained after the leaching process, with solid particles removed through solid-liquid separation methods such as filtration.

Preparation of concrete specimen: The M25 grade concrete mix was prepared as per IS 10262-2009 and IS 456-2000, as detailed in Table 6. Two sample cubes, each with size of 75 mm x 75 mm x 75 mm, were casted. One concrete cube was cast with 20% replacement of cement with BWI, and second cube was cast with 20% replacement of cement with FA. The weight of the concrete cubes was measured after they were removed from the water. The cubes were ensured to be in a dry condition before weighing.

Weight of concrete specimens: The weight of the concrete cube specimens was measured after they were removed from the water. The cubes were ensured to be in a dry condition before weighing.

Preparation of leachant: To prepare the leachant, 5 ml of distilled water is used per 100 mm^2 of the surface area of a specimen, which is placed into a cylindrical jar. This standard specifies ion-exchanged water or distilled water as the leachant because it is assumed that the environment does not expose concrete structures to significant chemical erosion. Water with lower hardness tends to leach various ions from the concrete. Therefore, distilled water is used as the leachant. The concrete cube is kept in the leachant solution for 10 days. After 10 days, both leachate solutions are collected. The heavy metals in the leachate solutions are determined using Atomic Absorption Spectrometry.

- The surface area of the concrete cube used for leaching analysis is calculated as 75 mm × 75 mm = 5625 mm^2.
- For the leachant, 5 ml of distilled water is used per 100 mm^2 of the surface area of the specimen.
- The quantity of distilled water required is 281.25 ml, approximately 300 ml.

RESULTS AND DISCUSSIONS

Visual Appearance of Concrete with BWIA and FA

The visual appearance of concrete changes with the inclusion of BIWA or FA. These waste ashes can influence the color, texture, and surface finish of the concrete. Concrete with FA tends to exhibit a smoother and more uniform surface finish. The addition of FA often gives the concrete a darker to lighter gray shade, depending on the percentage of waste FA used. Increasing the FA content results in a darker-coloured concrete. This aesthetic can be advantageous in construction where a consistent and clean appearance is desired.

The inclusion of BIWA can result in a different texture and coloration due to its unique chemical composition and granular particle size. BIWA may create a slightly irregular surface or introduce variations in shading. These effects could be subtle but might require adjustments if a highly consistent visual outcome is essential. Both FA and BIWA affect the homogeneity of concrete, which is visible in the casted concrete cubes. While FA generally improves the surface smoothness and produces a darker appearance, BIWA's inclusion might result in a more heterogeneous texture, reflecting its ash composition and particle structure.

Compressive Strength Performance

The study analyzed the compressive strengths of M25 grade concrete cubes with BWIA and FA simultaneously as partial replacements for cement, at replacement levels of i.e. 0%, 10%, 20%, 30%, and 40%, over curing periods of 7, 14, 28, and 56 days. A total of 72 cubes were cast, with 36 cubes for each type of ash. The compressive strength of casted concrete cubes was tested under the compression testing machine. The compressive strength test results were shown in Table 7.

In both cases, the maximum compressive strength was achieved at 20% replacement of cement with ash after curing for 7, 14, 28, and 56 days. For BWIA, the compressive strength was highest at 20% ash replacement, reaching 31.76 MPa after 56 days. Across all curing periods, BWIA mixtures generally exhibited higher compressive strength compared to FA mixtures, except for the 7-day curing period, where both ashes showed similar strengths. FA also achieved its highest compressive strength at 20% replacement, reaching 30.62 MPa after 28 days. Notably, FA mixtures showed a higher initial strength at 7 days for the 40% replacement level (21.64 MPa). However, overall, BWIA consistently outperformed FA in compressive strength, particularly at the optimal 20% replacement level and with extended curing periods.

The maximum compressive strength was obtained with 20% cement replacement in both cases. The maximum compressive strength at 20% replacement of cement by BWIA was 25.11 MPa, and by FA, it was 24.57 MPa, after a 28-day curing period. It is suggested that no more than 20% of cement should be replaced with ashes, as higher replacement levels may lead to a reduction in compressive strength. This trend aligns with previous research studies, indicating that while incorporating BWIA and FA provides benefits like improved waste management, it can adversely affect concrete strength when exceeding the optimal dosage. The study shows a decline in compressive strength as the waste content increases, which is consistent with findings from other studies [6–8, 13, 15, 16]

Overall, the results show that the concrete cube containing BWIA was slightly stronger than the concrete cube containing FA. During the mixing process, the concrete mix containing BWIA required less water compared to the mix containing FA, since BWIA is a granular material, while FA is a very fine material. This suggests that BWIA is a more effective partial replacement for cement in concrete mixes than FA, offering both environmental and structural benefits.

Table 7. Compressive strength of concrete containing BWIA and FA

			BWIA			FA		
Sr. No.	**% of Ash**	**Curing period (Days)**	**Cross-section area (mm× mm)**	**Load (KN)**	**Compressive Strength (MPa)**	**Cross-section area (mm× mm)**	**Load (KN)**	**Compressive Strength (MPa)**
1	0	7 days	150×150	352	15.64	150×149	360	15.64
2	10		150×150	359	15.95	150×150	364	16.10
3	20		150×150	371	16.48	150×149	324	16.17
4	30		149×148	319	14.46	150×148	313	14.49
5	40		149×149	298	13.42	150×150	487	14.09
6	0	14 days	150×150	481	21.37	150×150	498	21.37
7	10		150×150	488	21.68	150×149	452	21.64
8	20		150×149	496	22.19	150×150	445	22.13
9	30		150×149	412	18.43	150×150	548	20.22
10	40		150×148	407	18.33	150×150	553	19.77
11	0	28 days	150×150	547	24.31	150×149	531	24.31
12	10		150×148	551	24.81	150×149	519	24.35
13	20		150×150	565	25.11	150×150	689	24.57
14	30		150×149	483	21.61	150×149	702	23.75
15	40		149×149	469	21.12	150×150	638	23.22
16	0	56 days	150×150	687	30.50	150×149	545	30.05
17	10		150×150	703	31.24	150×149	360	30.62
18	20		150×149	710	31.76	150×150	364	31.41
19	30		150×148	655	29.50	150×149	324	28.35
20	40		149×149	537	24.18	150×148	313	24.38

Assessment of Concrete Weight Variations

It was observed that as the percentage of ash increased, the weight of the concrete cubes decreased by 8% to 13% for both BWIA and FA (Table 8). The concrete cubes containing 0% ash weighed 8.7 kg for both BWIA and FA, whereas at 40% ash weighed 7.6 kg for BWIA and 7.5 kg for FA. This trend suggests that the incorporation of ash into the concrete mix reduces its overall density, leading to lighter concrete cubes. The lower weight concrete offers high heat insulation, reduces the load on structural elements, and enhances seismic resistance, sound absorption, and fire resistance. Additionally, it provides faster construction, easier transportation, and reduced labor time and costs.

The relationship between weight and compressive strength in concrete is crucial for its performance. Generally, denser concrete, with higher weight, tends to have greater compressive strength due to tightly packed particles. However, the inclusion of waste materials like fly ash or polyethylene terephthalate (PET) can reduce weight without compromising, or even enhancing, compressive strength [29–32]. Studies have shown that these additives can maintain structural integrity while optimizing the material's weight, offering a balance between strength and efficiency for construction applications.

The failure mode of concrete cubes containing waste ash differs from the typical failure observed in standard concrete cubes. This variation is attributed to the inclusion of ash in the concrete mix. Figure 3 illustrates the unique mode of failure for these concrete cubes, which differs from the typical failure patterns seen in conventional concrete cubes.

Table 8. Dry weight of concrete cubes after identified curing periods

Sr.No.	% of Ash	Weight of concrete cube containing BWIA (kg)	Weight of concrete cube containing FA (kg)
1	0	8.7	8.7
2	10	8.5	8.1
3	20	8.0	7.9
4	30	7.9	7.8
5	40	7.6	7.5

Figure 3. Mode of failure of casted cubes

Leaching Properties of Concrete

The leaching properties of concrete containing BWIA and FA were assessed to determine potential heavy metal release. Leaching tests showed no heavy metals in the leachate, indicating that the concrete did not release harmful substances (Figure 4). This suggests that BWIA incorporation does not pose a toxicity risk, as cement binds heavy metals, preventing leaching [33, 34]. These results support the safe use of BWIA in concrete, contributing to waste reduction and environmental protection [35].

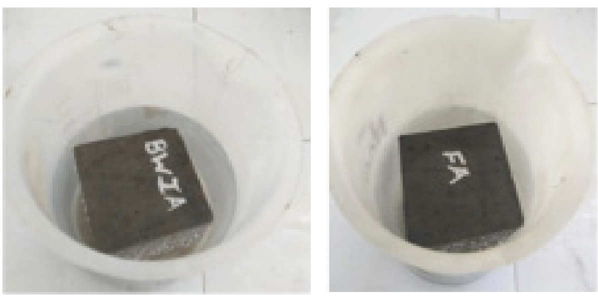

Figure 4. BWIA and FA leachate samples

In India, fly ash utilization has reached 62% [3], but BWIA is still landfilled, causing environmental concerns. Recycling BWIA in concrete can mitigate landfill use and support sustainable construction practices. Similar findings in global studies highlight the benefits of incorporating industrial by-products in concrete [2].

Despite the positive leaching results, further environmental assessments are needed to fully understand the long-term impacts of using BWIA and FA in concrete [36, 37]. Heavy metal leaching into groundwater is a concern due to their non-biodegradable nature and bioaccumulation risks [13, 38]. Traditional disposal methods, like landfilling and incineration, pose secondary pollution risks, underscoring the need for alternative solutions like using BWIA in concrete.

The solidification process in cement traps heavy metals within the matrix, converting them to insoluble forms, which reduces leaching [37, 39]. Thus, using BWIA and FA in concrete offers a sustainable approach to both waste management and building material development.

One-Way ANOVA Analysis for Compressive Strength and Weight of Concrete

ANOVA (Analysis of Variance) is a statistical method used to compare differences between groups and determine if these differences are statistically significant or merely due to random variation. In sustainable concrete research, ANOVA is instrumental in evaluating how various waste-derived materials or methods affect properties like strength and durability, ensuring the reliability of findings. This method is most effective when the data follows a normal distribution [40].

A two-way ANOVA was performed to evaluate the effects of pozzolan content and water-to-cementitious material ratio (w/cm) on two parameters: the slope and intercept of a strength estimation model. The results confirmed that silica fume offered greater strength enhancements due to its pozzolanic activity compared to metakaolin [41]. Another study used ANOVA to analyze the influence of various mix design parameters, such as the type and percentage of industrial by-products like fly ash and GGBS, on compressive strength and durability indices [40]. Additionally, ANOVA was employed to compare the effects of different treated wastewater types on properties like compressive strength, workability, and durability in concrete [42].

In the present study, the performance of concrete incorporating BWIA and FA at varied percentages was analysed in terms of compressive strength and weight using one-way ANOVA at a significance level of $p < 0.05$. For compressive strength across ash percentages, the sum of squares between and within samples was 407.6 and 12,176.4, respectively. For concrete weight, the sum of squares between and within samples was 474.5 and 1,001.6, respectively.

The F-critical values for compressive strength and weight were 2.72 and 3.89, respectively. The sum of squares between the sample and within the sample obtained from the ANOVA analysis for compressive strength and weight are given in Table 9. Based on these F values, compressive strength and weight were found to vary significantly with the percentage of waste ash in the mix.

The ANOVA results clearly indicate that both compressive strength and weight are significantly affected by the percentage of waste ash used in the sustainable concrete mix.

Table 9. Summary of one-way ANOVA for chosen parameter ($p<0.05$)

Parameter (concrete)	Descriptions	Sum of squares (SS)	Degree of freedom (df)	Mean sum of squares (MS)	F value
Compressive strength	Between samples	407.6	3	135.8	2.72
	within the samples	12176.4	76	160.2	
Weight	Between the samples	474.5	2	237.2	3.89
	within the samples	1001.6	12	83.5	

Compressive Strength-Based Comparative Study

The observed curing times and compressive strengths from the present study are compared with those from previous studies using various types of waste ashes as cement replacement in M25 grade concrete. The comparison is presented in Table 10.

The present study evaluated the compressive strength of concrete cubes incorporating BWIA and FA, achieving maximum strengths of 25.11 MPa and 24.57 MPa, respectively, at 28 days of curing with 20% ash replacement. These results are consistent with studies using waste ashes [13, 19]. However, mixes containing advanced admixtures, such as superplasticizers and ground granulated blast furnace slag, have reported significantly higher strengths, reaching up to 57.46 MPa [12] and 43.25 MPa [9]. The performance of this study aligns more closely with studies utilizing biomedical waste ash and coal bottom ash, which achieved strengths ranging from 27.4 MPa to 38.21 MPa [17].

In contrast, some studies reported notably lower compressive strengths, such as 5.87 MPa with BMIA at 5% replacement [6] and 5.10 MPa with Class F fly ash [8]. These variations underscore the impact of factors such as ash type, cement grade, and the use of admixtures on concrete performance. The results of the present study emphasize the potential of BWIA and FA as sustainable partial replacements in concrete, providing moderate strength suitable for certain construction applications. While the strengths achieved are lower than those observed with advanced additives, this study contributes to waste management and sustainable construction by effectively recycling ashes that would otherwise pose disposal challenges.

Table 10. Comparison of maximum compressive strength for different ash types as cement replacements in concrete

Type of cement used	Type of ash used for cement replacement	Maximum compressive strength noted at		Mean sum of squares (MS)	Reference
		Curing time (days)	% Replacement of waste ash		
M30	BMIA	28	5%	5.87	[6]
OPC 53 grade	Class C fly ash from thermal power plant	28	30%	45.28	[7]
OPC	Class F fly ash	28	0%	5.10	[8]
-	Class F fly ash Admixture: ground granulated blast furnace slag (GGBS)	28	70% fly ash & 30% GGBS	43.25	[9]
OPC 53 grade	Fly ash from thermal power plant Admixture: Copper tailing	56	20% fly ash & 5% copper tailing	38	[10]
Portland cement	Fly ash Admixture: Super plasticizer	28	35%	57.46	[12]
OPC 53 grade	Incinerated biomedical waste ash	28	5%	28.7	[13]
Cement	Incinerated hospital waste ash	28	0%	38.8	[15]
Cement (CEM I 42.5 R)	Medical waste bottom ash	7, 28	10%	40-55.8	[16]
Portland cement	Incinerated hospital waste ash	365	10% ash & 15% marble powder	4-65	[20]
OPC	Incineration ash	28	20%	27.4	[19]
OPC	Coal bottom ash	28	30%	34.04-38.21	[17]
PPC	BWIA	28	20%	25.11 N/mm^2	Present Study
	FA			24.57 N/mm^2	

CONCLUSIONS

This study highlights the potential of integrating BWIA and FA as partial replacements for cement (i.e., 0%, 10%, 20%, 30%, and 40%) in M25 grade concrete for sustainable construction. The maximum compressive strength was achieved with a 20% replacement of cement by BWIA (25.11 MPa) and FA (24.57 MPa), exceeding the strength of conventional concrete mixes. Beyond 20%, the strength reduced for both ashes, indicating this as the optimal replacement level. Both ashes reduced the weight of concrete by 8 to 13%, which may offer advantages such as lower dead loads, cost-effective structures, improved seismic resistance, sound absorption, and fire resistance. The ANOVA results show that the percentage of waste ash significantly affects both compressive strength and weight, with F-values of 2.72 and 3.89, respectively, highlighting its acceptability in concrete's performance and sustainability. Leaching tests confirmed no detectable heavy metals in the concrete, demonstrating the environmental safety for utilizing of both ashes for concrete. The integration of BWIA and FA into concrete offers an innovative solution, helping to reduce landfill dependency and address waste management challenges.

SCOPE FOR FUTURE WORK

Future research is encouraged to address challenges related to the use of waste ash particles, including their potential impact on human well-being. This study opens avenues for conducting extensive durability analyses on concrete containing waste ash particles to evaluate their long-term performance under various environmental conditions.

The proposed mix proportions can be validated further for structural applications by assessing their performance in shear, flexure, and compression tests, particularly in the context of brick manufacturing. Additionally, bricks produced using these suggested mix proportions can undergo thorough testing to evaluate their suitability and performance in real-world applications.

Further investigations into the modulus of elasticity and detailed microstructural analysis using scanning electron microscopy are recommended. These studies could provide valuable insights into the mechanical behavior and microstructural properties of concrete and bricks incorporating waste ash, paving the way for their optimized and sustainable use in construction.

NOMENCLATURE

BWIA : Biomedical waste incineration ash

CT : Copper tailing

CTM : Compression testing machine

FA : Fly ash
GGBS : Ground granulated blast furnace
IS : Indian standard
LOI : Loss of ignition
OPC : Ordinary portland cement
PPC : Portland pozzolana cement
UTM : Universal testing machine
w/c ratio : Water-cement ratio

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

1. R. Sharma and R.N. Yadav, "Fly Ash Generation-Utilization, Government Initiatives In India And Other Diverse Applications: A Review," Journal of Advanced Scientific Research, vol. 12(1), pp. 9–20, 2021, doi: 10.55218/JASR.202112102.
2. A. Suresh Kumar, M. Muthukannan, R. Kanniga Devi, K. Arunkumar, and A. Chithambar Ganesh, "Reduction of hazardous incinerated bio-medical waste ash and its environmental strain by utilizing in green concrete," Water Science Technology, vol. 84(10-11), pp. 2780–2792, 2021, doi: 10.2166/wst.2021.239.
3. K.K. Padmanabhan and D. Barik, "Health Hazards of Medical Waste and its Disposal," Energy from Toxic Organic Waste for Heat and Power Generation, pp. 99–118, 2019, doi: 10.1016/B978-0-08-102528-4.00008-0.
4. E.M.R. Fairbairn, B.B. Americano, G.C. Cordeiro, T.P. Paula, R.D. Toledo Filho, and M.M. Silvoso, "Cement replacement by sugar cane bagasse ash: CO2 emissions reduction and potential for carbon credits," Journal of Environmental Management, vol. 91(9), pp. 1864–1871, 2010, doi: 10.1016/j.jenvman.2010.04.008.
5. R.M. Andrew, "Global CO2 emissions from cement production," Earth System Science Data, vol. 10(1), pp. 195–217, 2018, doi: 10.5194/essd-10-195-2018.
6. M.C. Nataraja, N. Chakravarthy H.G., R. Shivaprasad, and S.R. Naganna, "Self-compacting concrete incorporating incinerated biomedical waste ash: a performance assessment," Journal of Engineering and Applied Sciences, vol. 70(1), 2023, doi: 10.1186/s44147-023-00191-y.
7. M. Abushad and M.D. Sabri, "Comparative Study of Compressive Strength of Concrete with Fly Ash Replacement by Cement," International Research Journal of Engineering and Technology, vol. 4(7), pp. 2627–2630, 2017.
8. V.K.S.R, A.M. Arer, B.K. Sangeetha, S.U. Pateela, and S.C. Patil, "Cement Concrete Hollow Blocks To Replacing Cement By Fly Ash," International Research Journal of Engineering and Technology, vol. 5(5), pp. 157–160, 2018.
9. K. Pandurangan, M. Thennavan, and A. Muthadhi, "Studies on Effect of Source of Flyash on the Bond Strength of Geopolymer Concrete," Materials Today: Proceedings, vol. 5(5), pp. 12725–12733, 2018, doi: 10.1016/j.matpr.2018.02.256.
10. R. Dandautiya and A.P. Singh, "Utilization potential of fly ash and copper tailings in concrete as partial replacement of cement along with life cycle assessment," Waste Management, vol. 99, pp. 90–101, 2019, doi: 10.1016/j.wasman.2019.08.036.
11. T.B.T. Nguyen, R. Chatchawan, W. Saengsoy, S. Tangtermsirikul, and T. Sugiyama, "Influences of different types of fly ash and confinement on performances of expansive mortars and concretes," Construction and Building Materials, vol. 209, pp. 176–186, 2019, doi: 10.1016/j.conbuildmat.2019.03.032.
12. D. Nagrockienė and A. Rutkauskas, "The effect of fly ash additive on the resistance of concrete to alkali silica reaction," Construction and Building Materials, vol. 201, pp. 599–609, 2019, doi: 10.1016/j.conbuildmat.2018.12.225.
13. H. Kaur, R. Siddique, and A. Rajor, "Influence of incinerated biomedical waste ash on the properties of concrete," Construction and Building Materials, vol. 226, pp. 428–441, 2019, doi: 10.1016/j.conbuildmat.2019.07.239.
14. N. Al-Mutairi, M. Terro, and A.-L. Al-Khaleefi, "Effect of recycling hospital ash on the compressive properties of concrete: statistical assessment and predicting model," Building and Environment, vol. 39(5), pp. 557–566, 2004, doi: 10.1016/j.buildenv.2003.12.010.
15. C. Genazzini, G. Giaccio, A. Ronco, and R. Zerbino, "Cement-based materials as containment systems for ash from hospital waste incineration," Waste Management, vol. 25(6), pp. 649–654, 2005, doi:

10.1016/j.wasman.2005.01.004.
16. A. Akyıldız, E.T. Köse, and A. Yıldız, "Compressive strength and heavy metal leaching of concrete containing medical waste incineration ash," Construction and Building Materials, vol. 138, pp. 326–332, 2017, doi: 10.1016/j.conbuildmat.2017.02.017.
17. M. Singh and R. Siddique, "Effect of coal bottom ash as partial replacement of sand on workability and strength properties of concrete," Journal of Cleaner Production, vol. 112, pp. 620–630, 2016, doi: 10.1016/j.jclepro.2015.08.001.
18. J. . Aubert, B. Husson, and A. Vaquier, "Use of municipal solid waste incineration fly ash in concrete," Cement and Concrete Research, vol. 34(6), pp. 957–963, 2004, doi: 10.1016/j.cemconres.2003.11.002.
19. A.A. Al-Rawas, A. Wahid Hago, R. Taha, and K. Al-Kharousi, "Use of incinerator ash as a replacement for cement and sand in cement mortars," Building and Environment, vol. 40(9), pp. 1261–1266, 2005, doi: 10.1016/j.buildenv.2004.10.009.
20. T. Aissa, B. Rachid, and F. Kharchi, "Effect of Pharmaceutical Wastes Usage as Partial Replacement of Cement on the Durability of High-Performance Concrete," Procedia Structural Integrity, vol. 13, pp. 218–221, 2018, doi: 10.1016/j.prostr.2018.12.036.
21. B. Manjunath, M. Di Mare, C.M. Ouellet-Plamondon, and C. Bhojaraju, "Exploring the potential use of incinerated biomedical waste ash as an eco-friendly solution in concrete composites: A review," Construction and Building Materials, vol. 387, 2023, doi: 10.1016/j.conbuildmat.2023.131595.
22. M.T. Al Biruni, H.S. Sarker, W.U.S. Charu, and T. Ahmed, "Sustainable use of medical waste incineration fly ash in compressed stabilized earth blocks," Construction and Building Materials, vol. 452, 2024, doi: 10.1016/j.conbuildmat.2024.138886.
23. C. Maschowski, P. Kruspan, A.T. Arif, P. Garra, G. Trouvé, and R. Gieré, "Use of biomass ash from different sources and processes in cement," Journal of Sustainable Cement-Based Materials, vol. 9(6), pp. 350–370, 2020, doi: 10.1080/21650373.2020.1764877.
24. Y. Zhuge, W. Duan, and Y. Liu, "Utilization of wood waste ash in green concrete production," Sustainable Concrete Made with Ashes and Dust from Different Sources, pp. 419–450, 2022, doi: 10.1016/B978-0-12-824050-2.00007-3.
25. S. Altoubat, T.M. Junaid, M. Leblouba, and D. Badran, "Effectiveness of fly ash on the restrained shrinkage cracking resistance of self-compacting concrete," Cement and Concrete Composites, vol. 79, pp. 9–20, 2017, doi: 10.1016/j.cemconcomp.2017.01.010.
26. J. Lehmusto, F. Tesfaye, O. Karlström, and L. Hupa, "Ashes from challenging fuels in the circular economy," Waste Management, vol. 177, pp. 211–231, 2024, doi: 10.1016/j.wasman.2024.01.051.
27. N. A.A. El-Amaireh, H. Al-Zoubi, and O. A. Al-Khashman, "Hospital waste incinerator ash: characteristics, treatment techniques, and applications (A review)," Journal of Water Health, vol. 21(11), pp. 1686–1702, 2023, doi: 10.2166/wh.2023.299.
28. Test method for leaching of trace elements from hardened concrete. Japan Society of Civil Engineers, 2005.
29. S. Tanwani and B.A. Memon, "Trend Line Analysis of Weight Versus Compressive Strength of Concrete," International Journal of Emerging Technology and Innovative Engineering, vol. 2(7), pp. 345–360, 2016.
30. N. Karki, "Compressive Strength Comparison Between Plain Concrete and Polyethylene Terephthalate (PET) Mixed Concrete," KEC Journal of Science and Engineering, vol. 8(1), pp. 48–55, 2024, doi: 10.3126/kjse.v8i1.69265.
31. R. Joshi, "Effect on Compressive Strength of Concrete by Partial Replacement of Cement with Fly ash," International Journal of Engineering Research and Technology, vol. 4(2), pp. 315–318, 2017.
32. S. Hedjazi, "Compressive Strength of Lightweight Concrete," Compressive Strength of Concrete, vol. 11, 2020, doi: 10.5772/intechopen.88057.
33. M.T. Webster and R.C. Loehr, "Long-Term Leaching of Metals from Concrete Products," Journal of Environmental Engineering, vol. 122(8), pp. 714–721, 1996, doi: 10.1061/(ASCE)0733-9372(1996)122:8(714).
34. C. Eckbo, G. Okkenhaug, and S.E. Hale, "The effects of soil organic matter on leaching of hexavalent chromium from concrete waste: Batch and column experiments," Journal of Environmental Management, vol. 309, 2022, doi: 10.1016/j.jenvman.2022.114708.
35. S. Overmann, X. Lin, and A. Vollpracht, "Investigations on the leaching behavior of fresh concrete – A review," Construction and Building Materials, vol. 272, 2021, doi: 10.1016/j.conbuildmat.2020.121390.
36. A. Bardi, Q. Yuan, V. Tigini, F. Spina, G.C. Varese, F. Spennati, S. Becarelli, S. Di Gregorio, G. Petroni, and G. Munz, "Recalcitrant compounds removal in raw leachate and synthetic effluents using the white-rot fungus Bjerkandera adusta," Water, vol. 9(11), pp. 1–14, 2017, doi: 10.3390/w9110824.
37. R.H. Rankers and I. Hohberg, "Leaching Tests for Concrete Containing Fly ASH - Evaluation and Mechanism," Studies in Environmental Science, vol. 48, pp. 275–282, 1991, doi: 10.1016/S0166-1116(08)70411-4.
38. P. Sharma and H. Joshi, "Utilization of electrocoagulation-treated spent wash sludge in making building blocks," International Journal of Environmental Science and Technology, vol. 13(1), pp. 349–358, 2016, doi: 10.1007/s13762-015-0845-7.
39. X. Yuan, "Leaching Behavior of Heavy Metals from Cement Pastes Containing Solid Wastes," IOP Conference Series: Earth and Environmental Science, vol. 186(3), 2018, doi: 10.1088/1755-1315/186/3/012043.

40. V.S. Vairagade, S.S. Uparkar, K.G. Lokhande, A.P. Kedar, S.D. Upadhye, and N.P. Mungle, "A Numerical Analysis of Green Sustainable Concrete Using ANOVA," Turkish Journal of Computer and Mathematics Education, vol. 12(6), pp. 4605–4612, 2021.
41. H. Abdul Razak and H.S. Wong, "Strength estimation model for high-strength concrete incorporating metakaolin and silica fume," Cement and Concrete Research, vol. 35(4), pp. 688–695, 2005, doi: 10.1016/j.cemconres.2004.05.040.
42. A. Raza, S.A.R. Shah, S.N.H. Kazmi, R.Q. Ali, H. Akhtar, S.Fakhar, F.N. Khan, and A. Mahmood, "Performance evaluation of concrete developed using various types of wastewater: A step towards sustainability," Construction and Building Materials, vol. 262, 2020, doi: 10.1016/j.conbuildmat.2020.120608.