

Characterization and Mechanical Performance of Geopolymer Concrete Incorporating Industrial Waste Materials

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Abstract. This study examines the effect of incorporating incinerated biomedical waste ash (IBWA) as a partial substitute for ground granulated blast furnace slag (GGBS) in geopolymer concrete. The replacement of GGBS with IBWA was carried out at levels of 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50% by weight of the binder. An alkaline activating solution comprising sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) in a ratio of 1:2.5 was employed, with an alkaline-to-binder ratio of 0.61. The fresh properties of the concrete were evaluated using slump and compaction factor tests, while hardened properties were assessed through water absorption, compressive strength, splitting tensile strength, and flexural strength tests. The results showed an improvement in workability up to 20% IBWA replacement, followed by a decline at higher replacement levels. Maximum mechanical performance was achieved at 20% IBWA, with compressive strength, splitting tensile strength, and flexural strength values of 53.62 MPa, 4.81 MPa, and 6.74 MPa, respectively, at 28 days. Water absorption initially decreased and reached its lowest value of 2.46% at 20% IBWA before gradually increasing with further additions. These results demonstrate that IBWA can replace GGBS effectively up to 20% without adversely affecting structural performance, offering a viable and sustainable alternative material for geopolymer concrete production.

1 Introduction

Globalization and Urbanization have led to an increase in the healthcare services at global level, which has resulted into expansion of hospitals, population growth and improved medical laboratory diagnostic services hence leading to increase in generation of BMW. Hospitals and other health care services, medical testing facilities, research centers and

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pharmaceutical manufacturing plants generate significant amounts of hazardous waste that necessitate unique handling before disposal. Though several management methods are available, incineration is still mostly used because of successfully inactivation of pathogenic microorganisms and volume reduction. Nevertheless, incineration generates residual ashes known as the “Incinerated Biomedical Waste Ash” (IBWA), typically comprising 3–10% of mass in input waste and often incorporated to secure sanitary landfill [1]. One of the challenging issues faced by the IBWA is its long-term disposal that has significant environmental implications, as leachable heavy metals, residual toxic compounds and chlorides present in IBWA along with partially combusted matter can pose soil and ground water systems to contamination for long periods of time. In regions with constrained landfill capacity, the continuous accumulation of IBWA places increasing pressure on already burdened waste management systems, underscoring the urgent need for sustainable and value-added reuse strategies [2,3].

At the same time, there is a growing disapproval of the construction sector’s high utilization of ordinary Portland cement (OPC), which production process is energy-intensive and contributes to some 7–8% of worldwide CO₂ release into the atmosphere [4]. In line with governmental and industrial commitments to carbon-neutral development, the reduction of OPC consumption has emerged as an imperative within sustainable construction frameworks, reflecting the growing emphasis on low-carbon building materials and environmentally responsible infrastructure. A possible solution to this problem is presented by means of geopolymer concrete (GPC), a low-carbon process that reportedly provides properties as good as ordinary Portland cement-based (OPC) concretes, with lower environmental impact. Unlike OPC-based systems where clinker hydrates are utilized, geopolymer binders emerge from an alkaline solution with which aluminosilicate-rich precursors, such as GGBS, fly ash (FA), metakaolin (MK) and other industrial wastes are activated. This chemical reaction results in a 3-dimensional aluminosilicate network with the dominate linkage consisting of Si–O–Al, providing dense microstructures as well fast development of strength and improved resistance to chemical and thermal attack [5-8].

Large amount of works revealed the enhanced performance of GGBS and fly ash based geopolymer concretes, however research on non-conventional and hazardous waste materials is still very limited. Especially the use of ashes from biomedical incineration in geopolymer binders has not been properly addressed although their suitability for alkaline activation chemistry can be expected. IBWA is claimed to contain significant amounts of calcium oxide, silica, alumina and iron oxides components that can participate in geopolymerisation reactions. The small particle sizes of IBWA also give rise to a micro-filler effect that would increase particle packing density, decrease pore size structure, and improve early-age strength. However, IBWA is inherently heterogenous as opposed to standardized supplementary cementitious materials due to the different types of waste composition, incineration temperature and combustion efficiency. Such parameters introduce uncertainty about the C-S-H reactivity, homogeneity and long-term behavior, which require systematic experimental investigation before employing it in structural composites [9].

From the sustainability point of view, it is also an interesting circular-economy approach by recycling a hazardous waste such as IBWA into a construction material. This approach simultaneously eases two major problem areas: an environmental concern about the disposal of biomedical waste with a potentially harmful spread, and a dependency on conservative sustaining absorbent materials highly carbon heavy. This double advantage is of particular importance in developing countries where Healthcare Workers management and infrastructure improvements realistically evolve simultaneously. In addition, the construction industry is continuing to explore economic substitutes for high purity industrial binders. In case the IBWA is able to replace GGBS without performance loss, it may have both financially and

environmentally beneficial implications for waste management agencies and concrete producers.

Prior research based upon blended geopolymer systems has shown that the addition of mineral fillers and secondary waste materials can contribute to matrix packing, increasing the rate at which strength develops and thereby enhancing performance provided material limits are not exceeded [10]. However, the excessive substitute may reduce the reactivity of aluminosilicate, accept a small amount of gel material, and decrease strength. Thus, selection of an appropriate replacement threshold is crucial especially for unconventional materials like IBWA which have not been fully investigated when incorporated with geopolymer systems.

Though there are many expected benefits, some issues should be investigated before IBWA could be recommended for incorporation into geopolymer concrete. These aspects comprise the immobilization of heavy metals to retard leaching, the effect of unburnt carbon and chloride residues on workability and durability, and the scarcity of experimental data regarding mechanical as well as durability properties of IBWA-based geopolymer composites. To demonstrate the applicability and performance reliability, it is crucial to examine the full range of fresh and hardened qualities, particularly at different replacement levels.

To address these research gaps, the present work explores the potential of IBWA for replacing a portion of GGBS in geopolymer concrete. Under controlled laboratory conditions, the replacement levels of GGBS were considered from 0% to 50% by weight. To achieve an efficient geopolymerization process, a sodium hydroxide-sodium silicate activator blend (1:2.5) with an alkali-to-binder ratio of 0.61 is adopted. Fresh concrete performance is evaluated by means of the slump, and compaction factor tests; whereas hardened behaviour, at 28 days, is measured in terms of compressive strength, splitting tensile strength, flexural strength and water absorption. The primary objective is to determine the optimum replacement amount of IBWA at which mechanical properties, durability, and workability are harmonized.

Proposed structure for the high-value reutilization of incinerated biomedical waste ash in sustainable construction methodologies, waste valorization, and the production of low-carbon materials as shown in this research. The results are anticipated to facilitate the advancement and use of hazardous healthcare waste in geopolymer technology, while fostering the synergy between environmental conservation and infrastructure development to attain global sustainability objectives.

2 Materials

The geopolymer concretes developed in this study were produced by synergetic mixing of aluminosilicate source materials, alkali-activator and natural aggregates. The ingredients used in the manufacturing of GPC included ground granulated blast furnace slag (GGBS) and incinerated biomedical waste ash (IBWA) as binders, M-sand and coarse aggregate as fine and coarse aggregate. The binder system was activated by blending of NaOH and Na₂SiO₃ alkaline solutions. A brief description for each of the materials including their important physical and chemical properties is provided in subsequent sections.

2.1 Ground Granulated Blast Furnace Slag (GGBS)

The geopolymer matrix was primarily formed using GGBS as the calcium rich aluminosilicate precursor. It is a by-product from hot metal production (iron and steel making) process of blast furnace slag. Material The material is light grey with a vitreous

structure and Blaine fineness of above 385 m²/kg, hence it is very reactive in an alkaline medium. The main chemical composition of GGBS is comprised of CaO, SiO₂ and Al₂O₃, where MgO and Fe₂O₃ are trace elements. The GGBS has high CaO and it could lead to quicker setting properties as well as the better growth strength at the early age due to C-S-H and C-A-S-H gel formed in geopolymer concrete. The image of GGBS employed in this work and SEM image is represented in Figure 1. Table 1 represent the chemical composition of GGBS.

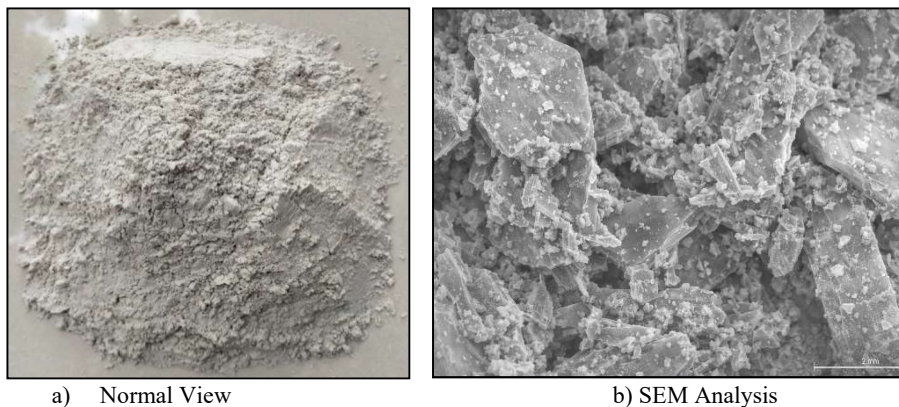


Fig. 1. Ground Granulated Blast Furnace Slag

2.2 Incinerated Biomedical Waste Ash (IBWA)

It was added as a secondary precursor to partly substitute of GGBS. The ash from incineration plant was taken and sieved by means of coarser than GGBS 300- μ m BS sieve, and grounded in for 5–25 minutes in a ball milling process with mills to an average size of about 45 μ m being pointed to have homogeneity (fineness). The ash was ranged from low light brown to dark gray, which depended on the combustion temperature and type of biomedical residue. X-ray fluorescence analyses in the previous research have demonstrated that IBWA commonly includes large percentages of CaO, SiO₂, P₂O₅, Al₂O₃, Fe₂O₃ and trace elements of heavy metals. The oxide composition also suggests that the material is pozzolanically reactive to a significant extent and thus can serve as an active solid phase precursor during geopolymerization when sufficiently stabilised in a high alkalinity environment. A typical photograph of the IBWA used in this work and SEM image is shown in Figure 2. Table 1 represent the chemical composition of IBWA.



Fig. 2. Incinerated Bio-Medical Waste Ash

Table 1: Chemical properties of GGBS and IBWA

Element	Percentage (%)	
	GGBS	IBWA
Ca	23	18.49
Si	12.6	32.80
Al	7.7	15.08
Pb	-	1.98
Cl	-	1.62
Zn	-	1.24
Cd	-	1.58
Cr	-	1.09
C	6.9	-
Ti	0.6	-
Cu	0.7	-
K	0.3	4.23
Mg	4.2	2.28
Mn	0.9	2.12
Fe	0.6	1.21
O	41.9	16.28
MoL	0.8	-

2.3 Sodium Hydroxide (NaOH)

The alkaline activating solution was prepared using sodium hydroxide pellets of laboratory grade. The NaOH ingredient had a purpose to provide the very high pH environment which is required of effective solubilisation of silicon and aluminium species in GGBS and IBWA. A concentration of 12 M was selected as an optimal concentration to balance between strength and workability, consistent with previous reports that higher molar concentrations increase the solution viscosity and have a negative effect on flow properties. The alkaline liquid was mixed 24 h in advance for the dissipation of heat of hydration during dissolution, as well thermal stability before use. A typical image of the sodium pellets used in this work is presented as Figure 3



Fig. 3. Sodium Hydroxide Pellets.

2.4 Sodium Silicate (Na₂SiO₃)

Sodium silicate was mixed together with NaOH to enrich the silica in the activator and improve the degree of polymerization. A commercial admixture employed possessed a SiO₂/Na₂O ratio of 2.5 and a specific gravity of 1.48. The Na₂SiO₃ enhances the gelation and increasing the bond density of reaction products, strengthening mechanical property. For all

mixtures, an alkaline binder ratio of 0.61 and a NaOH:Na₂SiO₃ ratio of 1:2.5 were used in this research work. The photograph of sodium silicate was presented in this work is shown in Figure 4.



Fig. 4. Sodium Silicate Solution.

2.5 Fine Aggregate (Manufactured Sand – M-Sand)

M-sand was adopted as eco-friendly alternative to river sand. The material was classified as Zone II of IS 383 for fineness modulus of 2.6. Its specific gravity was 2.62 and its water sorption is generally not more than 1.8%. Particles of M-sand are angular shaped which provides for particle packing and better interlocking leading to the less porous in geopolymer matrix.

2.6 Coarse Aggregate

Crushed angular CA with a maximum size of 20 mm was utilized for all mixes. Its sp.grade is 2.72 and water absorption comes in the range less than 0.8%. The aggregates satisfied the grading limits specified in IS 383 and free from deleterious materials. The angular shaped aggregates and rough surface of the aggregates bond well with geopolymer binder.

3 Experimental approach

3.1 Mix series and general philosophy

Eleven compositions of geopolymer concrete were prepared to investigate the substitution of Ground Granulated Blast Furnace Slag (GGBS) with Incinerated Biomedical Waste Ash (IBWA). The replacement levels of IBWA were 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45 and 50%), expressed as the percentage by mass of total binder (GGBS + IBWA). Mixes are labeled M0, M5, M10, M15, M20, M25, M30, M35, M40, M45 & M50 as % IBWA replacement increases from 0 to 50%. Alkaline-binder ratio (alkaline activator:total binder mass) was 0.61 constant for all recipes. The ratio of the mass of sodium hydroxide (NaOH) solution to the mass of sodium silicate (Na₂SiO₃) solution was kept at 1:2.5. 12 M (12 mol·L⁻¹) NaOH solution was freshly prepared and allowed to stand for 24 h before it was mixed with sodium silicate.

3.2 Mix proportions

In this research, different materials are mixed according to guidelines for the mix design of geopolymer concrete adopted from the IS 10262-2009. The mix was selected to form a common low-strength (MPa level), geopolymer concrete for testing structural elements, and it would offer laboratory repeatability regarding casting. The mix variations were detailed in Table 2.

Table 2. Mix Proportions of varying IBWA and GGBS in Kg/m³

Mix ID	% of IBWA	IBWA	GGBS	M-Sand	CA	SH	SS
M0	0	-	450	700	1050	78.43	196.07
M5	5	22.5	427.5	700	1050	78.43	196.07
M10	10	45	405	700	1050	78.43	196.07
M15	15	67.5	382.5	700	1050	78.43	196.07
M20	20	90	360	700	1050	78.43	196.07
M25	25	112.5	337.5	700	1050	78.43	196.07
M30	30	135	315	700	1050	78.43	196.07
M35	35	157.5	292.5	700	1050	78.43	196.07
M40	40	180	270	700	1050	78.43	196.07
M45	45	202.5	247.5	700	1050	78.43	196.07
M50	50	225	225	700	1050	78.43	196.07

3.3 Preparation of the alkaline activator

Synthesis of the activator solution was performed using strict safety guidelines (gloves, eye protection, fume hood):

NaOH solutions Commercial NaOH pellets were dissolved in potable water to prepare a 12 M solution. The needed mass of NaOH-pellets was determined using with molarity and solution mass (with the solution-mass of NaOH = 78.43 kg/m³ as mentioned above). Measure and stir the water before slowly adding NaOH pellets (never the other way round) until cooled to ambient temperature. The freshly prepared NaOH solution was capped and allowed to equilibrate for a minimum of 24 h in order to exothermally stabilize and fully dissolve.

Sodium silicate: A commercial sodium silicate solution (the SiO₂/Na₂O ratio and density had been provided by the supplier) was employed as received, and stored at room temperature.

combination: The 185ml NaOH solution and 920g sodium silicate were mixed together slowly to become the final alkaline activators mixture prior to mixing with concrete materials. The resulting activator blending was mixed for 5 min at least to ensure homogeneity and used on the same day it was prepared.

Safety: All activator manipulations were made with chemical-resistant PPE. Waste alkali solution was neutralized and dumped according to local standards.

3.4 Mixing procedure

A common lab pan mixer (60–100 L) or drum tilting mixer were employed. The order of mixing was arranged to obtain uniformly mixed IBWA and binder’s components:

Mixing A good mix of coarse and fine aggregates for 1–2 min was allowed in dry state. The pre-weighed combined binder (GGBS + IBWA for the desired mix) was poured into aggregate blend, and mixed dry for 2–3 min to uniformize color and distribution.

Liquid addition: The dry reactants were initially hydrated with an introduction of 50% of the alkaline activator solution and mixed for 1 minute to allow to all powder constituents

uniformed wetting by the liquid. The rest of the activator was then added and poured while mixing, now for a total time of 3–4 min until homogenous paste was obtained. When superplasticizer was used, it was incorporated with the second half of the activator. If small additional water (0–10 kg) was needed to adjust slum, it was introduced gradually while the concrete continued to be mixed.

Rest & remix: Following the initial mixing, the batch was rested in the mixer without any paddle rotation for 1–2 min and then thoroughly remixed for an additional 1–2 min to achieve uniformity (and expel entrapped air) prior to casting.

Three consecutive sets of slides were prepared for each mix level in order to obtain a set of sufficient samples and to check repeatability.

3.5 Casting and curing

1. Specimen types and quantities

- 150 × 150 × 150 mm cube compressive strength (a minimum of three specimens per age per mix).
- Splitting tensile strength: 150×300 mm cylinders (three specimens for each mix).
- Flexural strength: 100 × 100 × 500 mm beams (three specimens per mix).
- Water absorption: 100 × 100 × 50 mm dried prism or part specimen (three prisms or parts per mixture).
- Workability: The fresh mixes after mixing were tested for the slump cone and compaction factor.

2. Compaction and finishing

Standard table vibration was applied for 15s per layer for the cubes and beams to ensure uniform consolidation without separation of particles. Roding of cylinders was carried out as per standard procedure. The troweling of the Surface finish was executed.

3. De-moulding and curing

- The molds were removed from the specimens at 24 h.
- Methods The procedure for the preparation of other GGBS-rich geopolymer concretes was similar to that employed in our previous work of this kind, and these samples used ambient curing (laboratory environment: $\sim 23 \pm 3$ °C and a relative humidity level of 50–70%) for the rest of the curing period. The specimens were kept in a sealed container (box with plastic lining) to minimize loss of humidity for the first 7 days and then exposed to room conditions for 28 days.
- All the mechanical testing was done at 3, 7, 14 and 28 days.

3.6 Test methods

All of the tests were performed based on the appropriate international standards for geopolymer. Where the national standard differs, the accepted equivalent test method was used.

Slump cone test — conducted as per ASTM C143 / IS 1199 at the time of mixing for consistency and workability. The reading of slump test was taken to the nearest 5 mm.

Compaction factor test — A study based on IS 1199 to assess workability of medium and low-slump mixes. The mean of three determinations was taken as the measurement value for the compaction factor.

Compressive strength — This was determined by testing 150-mm cubes after 28 days using a CTM that had been calibrated to apply load at a rate of 0.6 MPa·s⁻¹ (or as specified by IS 516 / ASTM C39). The mean of the three specimens per mix was considered.

Tensile splitting strength — tested on 150 × 300 mm cylinders at 28 days in accordance to ASTM C496. The maximum recorded load to failure was documented and the tensile strength derived according to the standard mathematical equation. Three samples are averaged.

Flexural strength—3-point loading of 100 mm x 100 mm x 500 mm beams in accordance with ASTM C78 or equivalent. The modulus of rupture was determined and the mean value for three beams is reported.

Water Absorption – tested at 28 days as per ASTM C642 (or IS equivalent). Specimens were oven dried to constant mass, submerged for 24h and increment in mass recorded and absorption by mass percentage calculated.

4 Results and Discussion

4.1 Workability – Slump and Compaction Factor

The workability of eleven geopolymer concrete mixes reduced significantly with increasing IBWA content as observed by the fresh state behaviour. The control (M0) had the highest value for slump and compaction factor which implies that it has good cohesiveness and very easy to place. As the substitution of IBWA for GGBS increased gradually, slump and compaction factor decreased. The decrease was slight for low (up to 10% IBWA) substitution, but after 25% replacement a stronger reduction took place. This pattern is largely attributed to the small particle size and porous surface morphology of IBWA which promote liquid absorption thereby decreasing the free alkaline solution needed for an effective lubrication at the paste/aggregate interface. Similar decreases in workability have been observed for geopolymers based on fine waste-derived ashes which has been ascribed to their higher specific surface area [2,11]. The 50% IBWA replacement paste presented worse workability and more compaction effort to reach a good consolidation. 5 Variation of slump and compaction factor for GPC mix containing IBWA (0%–50%). Although workability studies indicated reduction, no segregation or extensive bleeding was observed in any of the mixtures, thereby suggesting that there was no significant change in paste cohesion for all replacement levels studied. The complete fresh-property results are presented in Table 3 and Figure 5 represent the variation in slump and compaction factor values of geopolymer concrete mixes incorporating incremental IBWA replacement levels ranging from 0% to 50%.

Table 3. Fresh Properties of GPC Mixes

MIX ID	IBWA (%)	Slump (mm)	Compaction Factor
M0	0	92	0.90
M5	5	88	0.89
M10	10	84	0.88
M15	15	81	0.86
M20	20	79	0.85
M25	25	74	0.83
M30	30	69	0.82
M35	35	64	0.80
M40	40	60	0.78
M45	45	56	0.76
M50	50	53	0.75

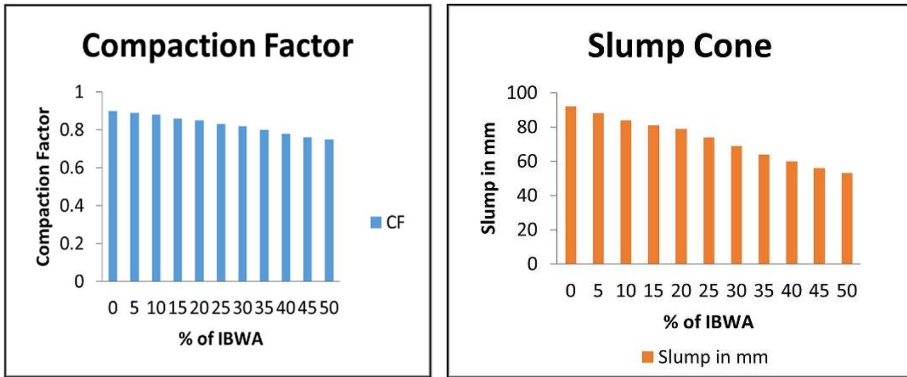


Fig. 5. Variation in slump and compaction factor values of geopolymer concrete mixes incorporating incremental IBWA replacement levels ranging from 0% to 50%.

4.2 Water Absorption

Water sorption showed a continuous rise with the augmentation of the proportion of IBWA within the blend. Specimens with up to 20% IBWA exhibit a slight decrease in water absorption when compared to control mix, implying that the internal microstructure was still relatively dense. On the other hand, mixtures with IBWA content replacement higher than 25% showed sharper rise in absorption and this may be attributed to the presence of inert as well as partially reactive components included in IBWA and this led towards increased development of pores within matrix. Such a behavior is also in agreement with previous observations made on geopolymer concretes containing high contents of nonglassy ash [12]. The higher proximate CaO, SiO₂ and trace heavy metal oxides in IBWA can retard the geopolymerization at high replacement level by preventing the full development of a compact aluminosilicate network [2,13]. The water absorption of GPC with different IBWA is illustrated in Table 4. While the absorption is higher at higher replacement levels, it remained within a reasonable limit for non-structural and construction applications. Figure 6 represents the water absorption in percentage vs IBWA substitution level for GPC hardened specimens.

Table 4. Water Absorption of GPC Mixes with IBWA Replacement

Mix ID	IBWA (%)	Water Absorption (%)	Trend Observation
M0	0	4.20	Baseline (control)
M5	5	3.96	Marginal decrease
M10	10	3.35	Microstructure still dense
M15	15	2.91	Slight decrease
M20	20	2.46	Beginning of moderate decrease
M25	25	4.72	Pore formation more evident
M30	30	4.88	Noticeable increase
M35	35	5.05	Higher unreactive phases affecting matrix
M40	40	5.22	Reduced compactness of network
M45	45	5.38	Continued rise due to delayed geopolymerization
M50	50	5.55	Highest absorption; still usable for nonstructural applications

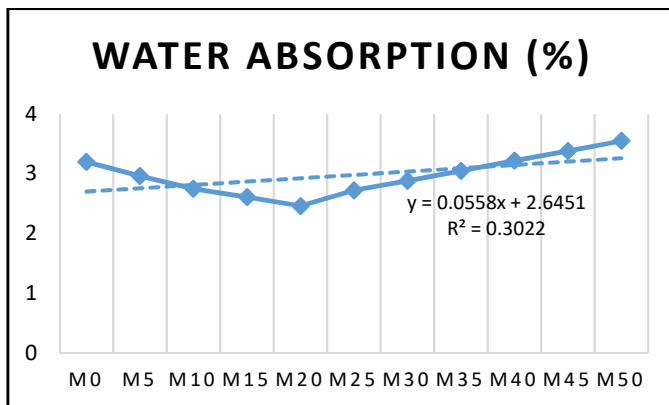


Fig. 6. Water absorption percentage of hardened geopolymers concrete specimens corresponding to varying levels of IBWA replacement.

4.3 Compressive Strength

The variation of the compressive strength results showed an upward U-shape relationship with increasing IBWA incorporation. High strength was manifested in the control mix (M0), due to the as-cast high reactivity of GGBS. The maximum value was generally observed at 20% replacement for mixtures with IBWA. This enhancement is ascribed to the partial incorporation of IBWA which offers more nucleation sites for gel formation, thereby forming a denser matrix and improved interface bonding [14]. The calcium content in GGBS and the siliceous characteristics of IBWA likely enhanced the simultaneous formation of N-A-S-H and C-A-S-H gel phases, resulting in the advancement of early-age geopolymerization. [11].

The compressive strength reduced with increasing the replacement level of IBWA over 20%. This decrease can be attributed to the relatively low inherent reactivity of IBWA compared with GGBS as well as dilution of reactive calcium and aluminosilicate precursors. The high ash amounts might also create micro-voids or weakly bonded interfacial transition zones due to angular geometry of ash particles and low binding gel content [13]. However, even for the 30% IBWA mix strength was up to the level of low-strength geopolymer structural concretes, which means that addition of water bottles to a mixture is still mechanically feasible under certain limit. The compressive strength of the GPC mixes with different IBWA content at 3, 7, 14 & 28 days is demonstrated in Figure 7. Table 5 illustrates the Compressive strength of GPC mixes.

Table 5. Compressive Strength of GPC Mixes at 28 Days

MIX ID	IBWA (%)	Compressive Strength (MPa)			
		3 Days	7 Days	14 Days	28 Days
M0	0	14.74	25.26	31.58	42.10
M5	5	15.62	26.47	32.98	43.40
M10	10	16.95	28.40	35.27	45.80
M15	15	18.73	31.06	38.45	49.30
M20	20	21.45	34.85	42.90	53.62
M25	25	16.73	28.68	35.85	47.80
M30	30	15.44	26.46	33.08	44.10
M35	35	14.11	24.18	30.23	40.30
M40	40	13.16	22.56	28.20	37.60
M45	45	12.22	20.94	26.18	34.90
M50	50	11.34	19.44	24.30	32.40

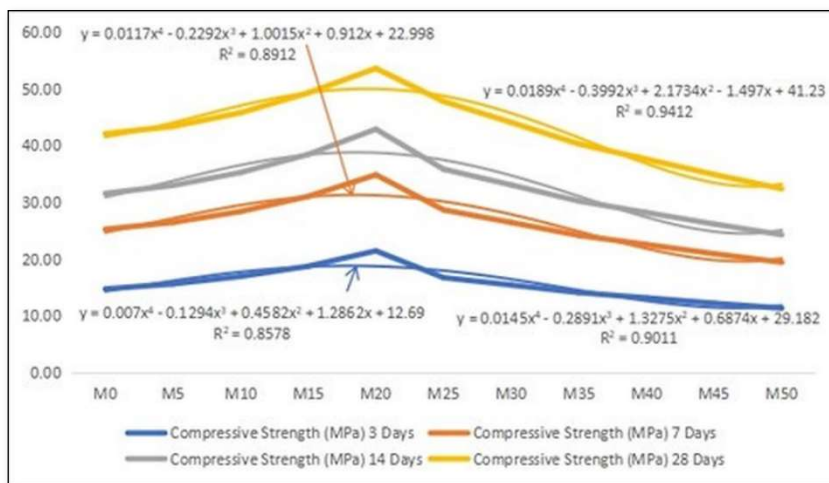


Fig. 7. Compressive strength development of GPC mixes containing varying IBWA content at 28 days.

4.4 Splitting Tensile Strength

Trend for splitting tensile strength followed the similar pattern of compressive strength that is, an enhancement for up to 20% IBWA but a lowering at higher replacement levels. Furthermore, the tensile strength increased with a decrease in IBWA content which suggests that a finer microstructure and better connection between matrix phase and aggregate were obtained by filler effect of IBWA, as well as double-gel reaction phases [15]. But, for the mixes containing from 25% IBWA or more, brittleness increased and tensile strength decreased presumably as the amount of geopolymer gel becomes inadequate to bridge cracks under diametrical compression loading. The reduced tensile strain response at high IBWA contents is consistent with rupture of microstructural cohesion due to over-substitution, which has been observed for other geopolymer systems that contain less-reactive by-products [10]. The development of split tensile strength of GPC mixes with different IBWA content at 3, 7, 14 & 28 days is presented in Figure 8. Table 6 Shows the Split Tensile strength of GPC mixes.

Table 6. Splitting Tensile Strength of GPC Mixes at 28 Days

MIX ID	IBWA (%)	Splitting Tensile Strength (MPa)			
		3 Days	7 Days	14 Days	28 Days
M0	0	1.25	2.14	2.67	3.56
M5	5	1.33	2.25	2.80	3.69
M10	10	1.41	2.36	2.93	3.81
M15	15	1.53	2.53	3.14	4.02
M20	20	1.72	2.80	3.45	4.31
M25	25	1.35	2.31	2.89	3.85
M30	30	1.27	2.17	2.72	3.62
M35	35	1.21	2.07	2.59	3.45
M40	40	1.12	1.93	2.41	3.21
M45	45	1.04	1.79	2.24	2.98
M50	50	0.97	1.66	2.08	2.77

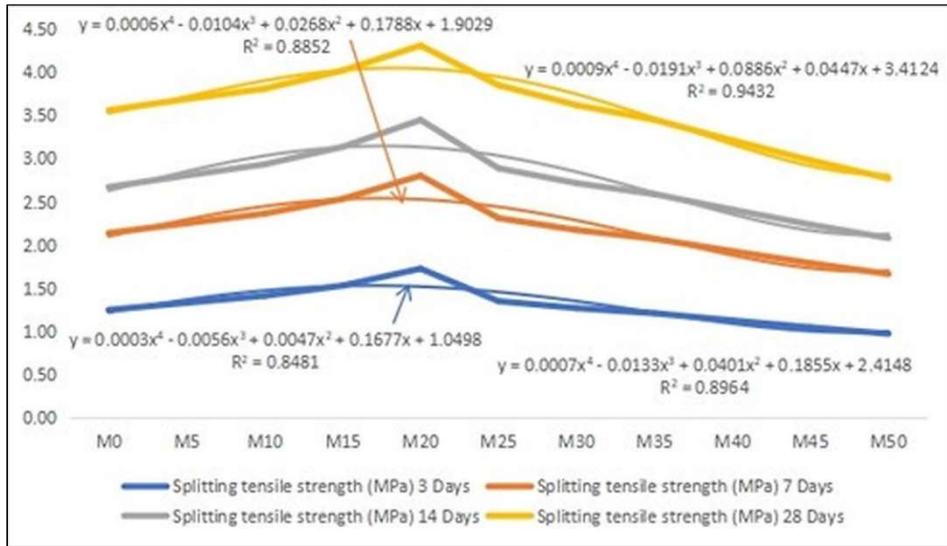


Fig. 8. Split tensile strength of GPC mixes incorporating IBWA at 28 days.

4.5 Flexural Strength

The behaviour of flexural strength reflected that observed for tensile strengths performance; initially higher up to 20% IBWA followed by steady decreases. The highest flexural strength at intermediate IBWA levels indicates increased cracking-arresting ability and better elastic-plastic deformation before fracture. This is because Ca-rich and aluminosilicate gels collaborate to bind the action of fibre-like across microcracks which impede crack propagation [6]. On the other hand, when the contents of IBWA was greater than 30%, the bond damage failed to be alleviated because more pores were connected and less interface micro-bond between reaction-product and coarse aggregate. However, at 25% replacement with IBWA the flexural strength still being similar to that of the reference mix was indicative of IBWA’s potentials for application in moderately loaded structural members. The development of Flexural strength for the GPC mixes with different IBWA content at 3, 7, 14 & 28 days is portrayed in Figure 9. Table 7 Flexural strength of GPC mixes.

Table 7. Flexural Strength of GPC Mixes at 28 Days

MIX ID	IBWA (%)	Flexural Strength (MPa)			
		3 Days	7 Days	14 Days	28 Days
M0	0	1.90	3.26	4.07	5.43
M5	5	2.02	3.42	4.26	5.61
M10	10	2.18	3.65	4.54	5.89
M15	15	2.33	3.86	4.78	6.13
M20	20	2.50	4.07	5.01	6.26
M25	25	2.07	3.54	4.43	5.9
M30	30	1.94	3.32	4.15	5.53
M35	35	1.79	3.07	3.83	5.11
M40	40	1.69	2.90	3.62	4.83
M45	45	1.59	2.73	3.41	4.55
M50	50	1.48	2.54	3.18	4.24

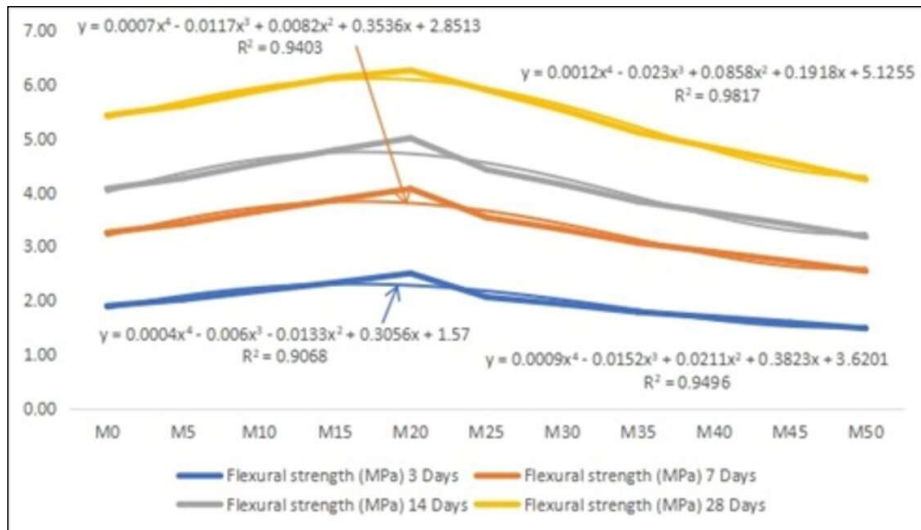


Fig. 9. Flexural strength of GPC mixes incorporating IBWA at 28 days.

4.6 Optimum IBWA Replacement Level

- The best proportion of IBWA in the range of 10-20% can be determined from fresh and hardened properties, where most properties reach their maxima at 20%.
- Under 20% IBWA: enhanced compressive, tensile and flexural strengths, slight reduction in workability and slightly changing in water absorption.
- After 25% IBWA: significantly decreasing trend of mechanical properties and increasing tendency for water absorption.
- The observation also proved that IBWA is actively involved in the geopolymerization process at proper ratios, and not just a passive filler.

5 Conclusion

The experimental work conducted in this programme of research demonstrated that the presence of incinerated biomedical waste ash (IBWA) in GGBS-based geopolymer concrete has a significant effect on fresh and hardened property performances. A total of eleven mixtures were prepared between 0% and 50% Replacement Levels of IBWA, with the following conclusions:

1. Workability decreased progressively with increasing IBWA content. The slump value dropped from 92 mm (0% IBWA) to 53 mm (50% IBWA), representing a 42% reduction. Similarly, the compaction factor decreased from 0.90 to 0.75, indicating stiffer mixes at higher replacement levels.
2. Water absorption increased with IBWA addition. Absorption rise from 4.2% in the control mix to 5.55% at 50% IBWA, reflecting higher porosity and reduced matrix densification at elevated ash contents. Up to 20% IBWA, absorption increase was limited, indicating relatively compact microstructure.
3. Compressive strength exhibited an optimum improvement at moderate IBWA levels.

Strength increased from 42.1 MPa (0% IBWA) to a peak of 52.6 MPa (20% IBWA) a 25% improvement over the control. Beyond 20% replacement, strength declined gradually, reaching 32.4 MPa at 50% IBWA.

4. Splitting tensile strength followed a similar optimum trend.

The tensile strength improved from 3.56 MPa for the reference mix to 4.31 MPa at 20% IBWA, marking a 21% enhancement, before decreasing to 2.77 MPa at 50% replacement.

5. Flexural strength also peaked at moderate IBWA content.

The modulus of rupture increased from 5.43 MPa (0% IBWA) to 6.26 MPa (20% IBWA) a 15% improvement and dropped to 4.24 MPa at 50% IBWA.

6. Overall optimum performance occurred between 20% IBWA.

In this range:

- Compressive strength increased by 21–25%
 - Splitting tensile strength improved by 15–21%
 - Flexural strength improved by 12–15%
 - Workability remained manageable with slump values above 75 mm
7. High IBWA replacement levels ($\geq 20\%$) were found unsuitable for structural-grade GPC, due to reductions of:
- Up to 38% in compressive strength
 - Up to 35% in tensile strength
 - Up to 32% in flexural strength
 - About 30% drop in compaction factor
 - ~80% increase in water absorption compared to optimum mix

Overall, the study concludes that IBWA can effectively replace GGBS up to 20% in geopolymer concrete, delivering improved mechanical performance, enhanced micro-filler benefits, and acceptable durability characteristics while supporting sustainable waste utilization. Replacement levels above 25% negatively affect workability and mechanical properties and are not recommended for structural applications.

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