Strength Properties of High-Performance Concrete with Green Banana (Musa acuminata, AAA Group) Peel Ash as Partial Cement Replacement

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Abstract

This study investigated the suitability of using green banana peel ash (GBPA) (AAA group(, which is native to East Africa, as a partial replacement for cement in high-performance concrete (HPC). Green banana peels were collected, dried, and burned at a controlled temperature of 800°C to produce ash, which was then ground and sieved through a 75 μm sieve. The physical and chemical characteristics of GBPA were evaluated through particle size analysis, X-ray fluorescence (XRF), and X-ray diffraction (XRD) analyses. The XRF results showed that GBPA has pozzolanic characteristics, with a SiO_2 content of 47.9%, Al_2O_3 of 16.706%, and Fe_2O_3 of 5.294%. The physical properties revealed a specific gravity of 2.34 and a moisture content of 1.0%. Concrete mixes were prepared with GBPA replacing cement at 0% (control), 5%, 10%, 15%, and 20% by weight, maintaining a constant water-cement ratio of 0.30 and a total binder content of 450 kg/m³. A total of 110 specimens were cast and tested for compressive strength, splitting tensile strength, water absorption, and sorptivity at 7, 14, and 28 days of curing. The control mix achieved a compressive strength of 67.06 MPa at 28 days, while the 5% GBPA replacement exhibited good compressive strength in comparison with the control mix, achieving a maximum of 69.08 MPa at 28 days. Beyond 5%, a decline in compressive strength was observed: 10% substitution achieved 60.167 MPa, 15% achieved 39.55 MPa, and 20% achieved 33.314 MPa after 28 days of curing. Splitting tensile strength followed a similar trend, with the control achieving a maximum of 5.01 MPa at 28 days, while GBPA-modified mixes ranged from a highest of 5.22 MPa at 5% replacement to a lowest of 2.20 MPa at 20%. The durability results demonstrated that 5% GBPA replacement achieved the lowest water absorption (1.07%) and sorptivity (0.000064 mm/min$^{0.5}$), comparable to the control mix. Higher GBPA replacements increased water absorption and sorptivity, reaching 1.47% and 0.0004 mm/min$^{0.5}$ at 20% replacement. This indicates that low GBPA incorporation can maintain satisfactory durability performance while improving sustainability in HPC.The study concludes that 5% GBPA substitution resulted a satisfactory mechanical and durability properties compared to the control mix, and the characterization of GBPA showed pozzolanic properties close to the standard requirements.

1 INTRODUCTION

Concrete is widely used as a construction material due to its versatility, strength, and durability. It has long been a fundamental component of reliable engineering structures. Usually used in most building projects, including foundations, architectural structures, dams, homes, towers, roads, and pavements [1]According to concrete is the second most consumed resource in the world after water, and it has been the most widely used construction material for the past few decades[2].

In civil engineering, the project's progress depends on the appropriate use of building materials. As science and technology advance, more diverse materials will be used in home building to increase efficiency [3]. In order to achieve a compressive strength of 50 MPa (7,250 psi) or above, high-strength concrete is normally mix with additional cementitious materials and admixtures with its simpler mix design and lower compressive strength of 20–40 MPa (2,900–5,800 psi), conventional concrete is the material of choice for standard building applications[4].

High-performance concrete (HPC) has emerged as a promising solution to meet the demand for structures with superior mechanical properties, extended service life, and reduced environmental footprint [4].High-performance concrete is referred to as concrete that meets special efficiency and uniformity requirements that are rarely feasible by using conventional materials and regular mixing, placing, and curing practices[5]. When compared to traditional concrete mixes, HPC shows improved strength, durability, and resilience to a variety of environmental variables.

Chemical and mineral admixtures are the primary means by which high-performance concrete's pore structures are enhanced [6]. Mineral admixtures have been thoroughly researched and used to enhance concrete performance while lowering its environmental effect. Examples of these admixtures include fly ash, silica fume, metakaolin, rice husk ash, and slag. Each of these substances has special properties that have different effects on the properties of concrete [7].

Uganda, regarded as the world's top consumer of green bananas (Mussa acuminata), using 240 kg annually per person, and the world's second-largest producer, with 11.1 million tons produced per year [8]. This banana category locally know as Matooke (*Musa acuminata*, AAA group), is a banana variety indigenous to Uganda and serves as a major staple food for human consumption[9]. And belongs to the East African Highland banana group and is typically characterized by its green color and a thickened midsection[10].Green banana has identified that it possesses pozzolanic properties similar to other mineral admixtures and has the potential to positively influence the engineering properties of concrete when incorporated into its mix design[11] .

To determine green banana peel ash's (GBPA) potential for use in concrete applications, further research into the material's pozzolanic properties is required. Because of their high silica content, pozzolanic materials such as fly ash and silica fume increase strength and durability when they react with calcium hydroxide during cement hydration to form calcium silicate hydrate (C-S-H)[12]. Similar to this, GBPA has a sizable amount of reactive silica and alumina that, when calcined at the right temperatures, enhance its pozzolanic activity [13].

According to, Jarosz-Krzemińska & Gawlicki, (2025) study, GBPA was revealed possossing a chemical composition similar to that of traditional admixtures, with SiO_2, AlO_3, and FeO_3 content required for pozzolanic reactivity[14]. To compare its behavior to well-established materials like fly ash, more research is necessary due to the variability in its composition, which is influenced by variables like banana type and burning temperature [15]. Furthermore, by lowering CO_2 emissions, GBPA may have positive environmental effects, making it a viable substitute for sustainable concrete production [16].

As the construction industry faces significant environmental challenges due to cement production[17], accounting for approximately 8% of global carbon dioxide (CO_2) emissions [16]and traditional mineral admixture such silica fume and fly ash have environmental and health concerns[18], Green banana peels, which are readily available, less costly and biodegradable waste, possess pozzolanic properties could be alternative. Places like Uganda, 61.8 kg of Green Banana peels are generated annually per person and end up as garbage. This enormous volume of garbage puts greenhouse gases into the atmosphere and causes health issues[19] .

Despite extensive studies on banana peel ash, limited research exists on East African Highland bananas (Mussa Acuminata group AAA), which may have different chemical composition. The chemical composition of Banana peels can vary greatly, and this is a significant cause for concern various factors can affect this composition, including the type of banana, growing conditions, and ash production method [18]. According, this variability may have an impact on the consistency of pozzolanic activity, which could result in uneven concrete properties like strength and durability[20].While, its effectiveness of Green Banana, specially Musa Acuminata group AAA, locally know as Matooke as a mineral admixture in high performance concrete (HPC) is not yet to be fully explored. .

This study aimed to utilize agricultural residues generated at the domestic level and integrate them into concrete production for sustainable construction. Specifically, the research focused on developing green banana peel ash (Musa Acuminata, AAA Group) and analyzing its properties to enhance the performance of concrete. To achieve the objectives of this study, the following three specific objectives were followed

1. To characterize the physical properties of green banana peel ash.
2. To characterize the chemical properties of green banana peel ash.
3. To evaluate the effect of green banana peel ash on the compressive and split tensile strength properties of high-performance concrete.
4. To evaluate the effect of green banana peel ash on durability.

2 MATERIAL AND METHODS

2.1 Materials

2.1.1 Cement

Traditional Tororo cement of grade 42.5 was used throughout the experimentation. The cement was obtained from the Tororo Cement Factory in Tororo, Uganda. This complies with US EAS 18 – 1:2017 (Uganda National Bureau of Standards, 2017). The physical and chemical properties of the cement are summarized in Tables 1 and 2

Table 1
Physical Properties of Multipurpose 42.5N Cement (US EAS 18 – 1:2017)

Physical Property	**Standard Requirement (US EAS 18 – 1:2017)**
Bulk (apparent) density	1,000–1,450 kg/m³
Specific gravity	3.15
Blaine specific surface area	330–380 m²/kg

Table 2
Chemical Properties of Multipurpose 42.5N Cement (US EAS 18 – 1:2017)

Chemical Property	Standard Requirement (US EAS 18 – 1:2017)
CaO	58–65%
SiO_2	18–23%
Al_2O_3	3–7%
SO_3	≤ 3.5%
Fe_2O_3	1.5–4%
MgO	0.5–4%
Chloride content	≤ 0.10%

2.1.2 Fine Aggregate

The fine aggregate was obtained from Black company suppliers along Bushenyi Ishaka municipal council. The determination of physical properties such as specific gravity, moisture content and particle size analysis was carried out in accordance with the requirements of ASTM C33/33M, 2022.

2.1.3 Coarse Aggregates

The coarse aggregate is a normal weight aggregate with a size in the range of 10-14mm. It was obtained from Black company suppliers along Bushenyi Ishaka municipal council. The determination of physical characteristics like particle size, specific gravity, aggregate crushing and impact values analysis were carried out in accordance with the requirements of Bs 12620:2002

2.1.4 Green banana Peel Ash (GBPA)

Green banana peels were collected, dried, and burned at a controlled temperature of 800°C to produce ash. The ash is to be ground to a fine powder and then sieved through a 75 μm sieve to achieve a uniform particle size, in accordance to ASTM C618 and BS 8615-1 (2019). Tests to characterize GBPA were carried out accordance with ASTM C618.

2.1.5 Water

Potable water, conforming to US EAS 12: (2014). specifications, was used for mixing, specimen preparation and curing of the blended concrete specimens.

2.1.6 Superplasticizer

The superplasticizer was used for this research work is Sikament NNG KE. No any test is to be carried out on it.

2.2 Area of the study

This research was carried out at Kampala International University Western Campus (KIUWC), Construction Materials Laboratory. Green banana peel ash was obtained from hotels in Ishaka.

2.3 Methods

2.3.1 Experimental Program

The experimental program involves investigating the strength properties of high-performance concrete incorporating green banana peel ash (GBPA) as a partial replacement of cement. Materials selected include OPC, GBPA, water, fine and coarse aggregates and superplasticizer. Concrete mixes included a control mix without GBPA and mixes with GBPA replacing cement at varying percentages ranging from 0–20%. After batching and mixing, specimens was cast and cured under controlled conditions for compressive and splitting tensile tests for 1,2, and 4weeks. Tests of compressive strength were conducted using standard-sized 150 mm x 150 mm x 150 mm cubic specimens. For each mix or test condition 3 cubic specimens were normally casted; thus, 45 cubic specimens were produced overall for the 5 experimental runs. Cylindrical specimens with a standard size of 100 mm in diameter and 200 mm in height was cast for splitting tensile strength tests. Similar to this, each mix or test condition were result in the casting of at 3 cylindrical specimens, for a total of 45 cylindrical specimens for the 5 experimental runs.

2.3.2 Mix Design

For the High-Performance Concrete (HPC) mix design of grade 50, the target compressive strength is set at 50 MPa. A water-cement ratio of 0.30 Extreme exposure is chosen to balance strength and workability IS 456: 2000, with a slump of 75–100 mm to ensure high workability. The cement content for the mix is 450 kg /$m^3$of concrete.

2.3.3 Experimental Design.

Experimental design is an organized methodology utilized to plan, execute and analyze tests aimed at assessing the impact of various variables in an efficient manner. It guarantees that experiments yield significant data while maximizing the use of resources. In this research, the experimental framework is designed to explore the performance of high-performance concrete incorporating green banana peel ash (GBPA) as partial substitute for cement. The mixture design method is used to optimize the proportions of cement and green banana peel ash (GBPA) while keeping the water and aggregate contents constant. This method is chosen because it effectively identifies the ideal mix proportions needed to satisfy specific performance criteria such as the strength. The study includes Five runs that systematically alter the amounts of cement and GBPA, while maintaining consistent levels of water and aggregate. By varying these critical factors, a detailed analysis of their impact on the properties of concrete is conducted. The findings are contrasted with control mixes, confirmed through replication, and illustrated with graphs and charts. This organized approach guarantees a thorough evaluation of high-performance concrete mixtures, offering insights into the ideal proportions of GBPA that improve concrete characteristics while supporting sustainability.

2.3.3.1 Summary of Mix Design Calculation Procedure

Calculation Sample for 5% GBPA Replacement

Total cementitious content = 450 kg/m^3

GBPA (5%) = 0.05 x 450 = 22.5 kg/m^3

Cement = 450 – 22.5 = 427.5 kg/m^3

Water = 0.3 x 450 = 135 kg/m^3

Superplasticizer = 2% x 450 = 9 kg/m^3

Fine and Coarse aggregate quantities remain constant as determined for the control mix based on trial workability and density:

Fine Aggregate = 719.2 kg/m^3

Coarse Aggregate = 1213.13 kg/m^3

This calculation process was followed for mix variations, adjusting the GBPA and cement contents accordingly while maintaining the total binder at 450 kg/m^3. All materials were batched by weight. mixture design is presented in Table 3

Table 3
Mixture Design Table for the Experiments

Mix ID	**W/C**	**Cement (kg/m^3)**	**GBPA (kg/m^3)**	**Water (kg/m^3)**	**Fine Aggregate (kg/m^3)**	**Coarse Aggregate (kg/m^3)**	**SP (kg/m^3)**
Control	0.3	450	0	135	719.2	1213.13	9
5%	0.3	427.5	22.5	135	719.2	1213.13	9
10%	0.3	405	45	135	719.2	1213.13	9
15%	0.3	382.5	67.5	135	719.2	1213.13	9
20%	0.3	360	90	135	719.2	1213.13	9

2.4 Laboratory work

2.4.1 Mixing and Casting

The concrete was prepared by batching the constituent materials cement, fine and coarse aggregates, water, superplasticizer, and Green Banana Peel Ash (GBPA) for the replacement mixes followed by a dry mixing phase for approximately 3 minutes. Water and the superplasticizer were then gradually incorporated during an additional 3 to 5 minutes of wet mixing until a uniform consistency was achieved. The fresh concrete was subsequently placed into oiled molds and compacted to ensure proper consolidation, resulting in the preparation of the following specimens.

- Compressive strength: forty-five (45) of 150mmx150mmx150mm cubes comprising of three samples for each of 5 runs at ages of 7,14 and 28 days respectively,
- Splitting tensile strength: forty-five (45) of 100mmx200mm cylinder comprising of three samples for each of 5 runs at ages of 7, 14, and 28days respectively.
- Water absorption test: Ten (10) of 150mmx150mmx150mm cubes comprising of two samples for each 5 runs.
- Sorptivity test: Ten (10) of 150mmx150mmx150mm cubes comprising of two samples for each 5 runs.

2.4.2 Compressive Strength

The test was performed in relation to the requirements of BS EN 12390-4 (2000). The load was applied gradually until failure, while measuring load and deformation continuously. Compressive strength is calculated by dividing the maximum load by the cross-sectional area of the specimen as in Eq. (1).

$$\textbf{Compressive strength} = \frac{failure\ load\ (p)}{cross\ sectional\ area\ (A)}$$

1

2.4.3 Splitting Tensile Strength

The procedure for determining the splitting tensile strength of concrete involves preparing cylindrical or prismatic specimens with smooth ends, curing them under controlled conditions, and then subjecting them to a compressive load in a testing machine until failure occurs by splitting. Specimens are positioned horizontally on the machine's lower bearing block, ensuring alignment and contact with the loading platens. Until the specimen splits along its diameter, a uniform load is applied at a steady pace. Both the applied load and related deformations are tracked and recorded throughout the test, Following failure. The splitting tensile strength (ft) is computed using Eq. (2) and the maximum load (P) is measured.

Split Tensile strength = $\frac{2p}{\pi \times d \times h}$ (2)

where d is the diameter and h are the height of the specimen. This test is crucial for assessing concrete's resistance to tensile stresses, which is vital for structural applications like beams and pavements.

2.4.4 Water Absorption Test

The durability water absorption test for concrete evaluates its ability to resist water penetration, crucial for assessing its durability in various environmental conditions. Standard cylindrical or prismatic specimens are prepared and cured according to specified procedures. Initially, the specimens' masses are recorded (M_1), followed by full immersion in water at controlled excess water allowed to drain, and their final masses (M_2) are measured. The water absorption percentage is then calculated using Eq. (3):

$$\text{Water absorption} = \left(\frac{M_{2-M_1}}{M_1}\right) \times 100$$

3

indicating the quantity of water absorbed relative to the initial mass. This test provides insights into the concrete's porosity and resistance to water ingress, essential for evaluating its long-term performance and durability in construction applications.

2.4.5 Sorptivity Test

The sorptivity test for concrete measures the rate at which the material absorbs water through capillary action, which is critical for assessing its durability and porosity in various environmental conditions. Standard cylindrical or prismatic specimens are prepared and cured according to specified procedures. Initially, the specimens' sides are sealed to ensure water ingress occurs only through the exposed surface. The specimens' initial masses (M0) are recorded. The bottom surface of each specimen is then placed in contact with water at controlled temperatures. At predetermined time intervals, from 5 to 120 minutes), the specimens are removed, surface water is wiped off, and their masses (Mt) are measured. The sorptivity (S) is calculated using Eq. (4):

$$S = \frac{\Delta\,\mathrm{Mt}}{A.\sqrt{t}}$$

4

where ΔMt is the increase in mass due to water absorption at time t, A is the cross-sectional area of the specimen exposed to water, and t is the time.

3 RESULT AND DISCUSSION

This section was presented the results obtained from the various tests conducted on High-performance concrete incorporated green banana peel ash (GBPA) as partial replacement of cement. These results are encompassing the results of characterization tests carried out on the GBPA and other materials, as obtained using ASTM C 618 (2012) specifications, and the results of performance evaluation tests of the mineral admixtures in HPC. The section covered the characteristics of GBPA, Tests on fresh properties of HPC and tests on harden properties of HPC. Graphs and tables are used to illustrate the variations in performance due to the replacement levels of GBPA.

3.1 Result of GBPA on Fresh Properties of HPC

The results of the slump test showed that adding Green Banana Peel Ash (GBPA) affects how workable the concrete is. A 5% replacement slightly increased the slump to 79 mm, indicating a slight lubricating effect, whereas the control mix (0% GBPA) recorded a slump of 76 mm. But as the GBPA content rose above 5%, the slump progressively lessened, reaching 77 mm at 20% GBPA replacement, suggesting a mild decline in workability. This decrease is explained by GBPA's greater surface area, higher water absorption, and decreased cementitious material, which restricts the amount of free water available. According to the findings, workability is maintained or improved by 5% GBPA replacement. The results are summarized in As Table 4. Similarly, a study conducted by Kumar et al.(2025) into bamboo leaf ash and ground granulated blast furnace slag as cement replacements have revealed analogous trends, where lower replacement percentages can initially improve workability, but increasing the ash content beyond a certain threshold consistently leads to a reduction in slump due to increased surface area and water absorption

3.2 Characterization Results

This section presents results of physical and chemical characterization of GBPA in accordance with ASTM C 618 – 12, as shown Table 4.

3.2.1 Green Banana Peel Ash

The physical properties of Green Banana Peel Ash (GBPA) are presented in Table 4. GBPA has a specific gravity of 2.34, a moisture content of 1.0%, and a light gray color. The specific gravity of GBPA is lower than that of ordinary Portland cement (approximately 3.15), indicating lower density. The moisture content of 1.0% complies with the maximum limit of 3.0% specified by ASTM C618 (2022). These factors contribute to increased water demand and reduced free water content at higher replacement levels. Consequently, as GBPA content increases beyond 5%, slump decreases from 79 mm (at 5% replacement) to 71 mm (at 20% replacement), as previously discussed.

Table 4
Particle size distribution of GBPA

Sieve sizes	Weight retained (g)	Percentage of total weight retained (%)	Cumulative percentage of total weight retained (%)	Percentage passing (%)
1.18 mm	0.0	0.0	0.0	100
600 μm	0.0	0.0	0.0	100
300 μm	0.2	0.2	0.2	99.8
212 μm	2.5	2.5	2.7	97.0
150 μm	4.2	4.2	7.1	92.7
75 μm	10.6	10.6	17.7	82.1
Pan	82.0	82.0	99.7	0.0

3.3 X-ray fluorescence Analysis

The chemical composition of the GBPA shows variation when compared with standard requirements for conventional cement and pozzolanic materials. According to US EAS 18 – 1:2017 and ASTM C150/C150M-22, the CaO content (4.928%) is lower than that typically associated with Portland cement. The SiO_2 content (47.900%) represents the major oxide component, although the combined proportions of SiO_2, Al_2O_3, and Fe_2O_3 (approximately 69.9%) are slightly below the threshold commonly specified for pozzolanic materials under ASTM C150/C150M-22, this can be associated with calcination temperature, which range between 600–800 degree Celsius[22]. The presence of alkali oxides, particularly K_2O (7.88%), the moderate potassium oxide (K_2O) content observed in the material indicates alkali presence, which may influence the chemical behavior of the binder system. alkali levels are known to contribute to the total alkali content of cementitious systems and may potentially promote alkali silica reaction (ASR) when reactive silica is present in aggregates under moisture exposure. other studies on Banana Peel Ash (BPA), GBPA shows similar trends but slightly lower K2O levels[23]. These discrepancies could be attributable to burning circumstances and raw material makeup. While GBPA has nearly acceptable pozzolanic potential, careful mix optimization and possibly blending with other pozzolans are preferable for optimal performance in concrete applications. These observations provide a baseline chemical characterization of the material and form an important reference for interpreting its behavior when incorporated into concrete mixtures. XRF results were presented in Table 6

Table 5
Oxide Composition of GBPA from XRF Test

S/N	Component	Percentage composition
1	SiO_2	47.900
2	Al_2O_3	16.706
3	Fe_2O_3	5.294
4	CaO	4.928
5	MgO	7.022
6	SO_3	1.977
7	MnO	0.225
8	K_2O	7.88
9	TiO_2	0.268
10	P_2O_5	1.368
11	Cl	0.2036
12	ZnO	0.138
13	Others	3.578
14	LOI	2.512

3.4 X- Ray diffraction analysis

This analysis was conducted to identify the mineralogical phases—whether amorphous or crystalline present in the Green Banana Peel Ash (GBPA). Figure 1 presents the X-ray diffraction (XRD) patterns for six distinct materials: (a) raw GBPA, (b) heated (calcined) GBPA, (c) a cement blend with partial ash replacement, (d) pure cement, (e) hydrated cement containing GBPA, and (f) a standard reference showing crystalline phases. The diffraction patterns are displayed in different colors to distinguish the material compositions related to the Green Banana Peel Ash and the various cementitious mixtures.

The XRD pattern displayed the major spectrum with sharp and distinct peaks, indicating the presence of crystalline phases such as silica (SiO_2) that occurred $2\theta = 40.6^o$, Potassium oxides (K_2O) at $2\theta = 28.5^o$, and Calcium Oxide (CaO) at 29.8^o. The XRD pattern al so displayed the minor spectrum with peaks, indicating the presence of crystalline phases such as aluminum oxide (Al_2O_3) that occurred $2\theta = 66.5^o$, Iron oxides (Fe_2O_3) at $2\theta = 33.5^o$.

The peaks of heated or Calcined Green Banana Peel Ash (GBPA), indicate the decomposition of organic matter and the formation of reactive silica which is an essential for pozzolanic behavior.

The diffraction peaks of GBPA-Cement Blend (Ash Partial Replacement) is a combination of GBPA and cementitious materials and the presence of calcium silicate hydrates and a reduction in portlandite ($Ca(OH)_2$) peaks indicate pozzolanic activity. In Pure Cement, the characteristic peaks of common cement phases such as alite, belite, aluminate, and ferrite are observed and intensity of these peaks are comparable to the GBPA-cement blend for reactivity analysis. The XRD patterns of hydrated cement with GBPA show a reduction in peak intensity, particularly for calcium hydroxide, suggesting the occurrence of a pozzolanic reaction. This reduction indicates the consumption of calcium hydroxide and the formation of additional amorphous phases, which may contribute to strength development over time, consistent with findings reported by Christopher et al. (2020).Standard Reference (Crystalline Phases) acted as a reference standard used to compare phase identification in the other spectra. The sharp and distinct peaks served as a baseline to match the crystalline compounds present in GBPA and cementitious materials. The presence of silica content contributed to pozzolanic activity by reacting with calcium hydroxide ($Ca(OH)_2$) in cement hydration, improving strength and durability (Ferraro and Nanni,2012).

3.5 Results of Fine Aggregate

The results of tests carried out to establish the physical properties of the fine aggregate is presented in Table7.The fine aggregate has specific gravity of 2.62, water absorption value of 1.63%, moisture content of 1.0% and fineness modulus of 2.85. Table 6 shows Particle size Distribution of Fine Aggregate.

Table 6
Particle Size Distribution for Fine Aggregate

Sieve sizes (mm)	**Average weight Retained (g)**	**Percentage Retained (%)**	**Cumulative percentage retained (%)**	**Percentage Passing (%)**	**Permissible percentage passing as per Bs 12620:2002**
10	0	0	0	100	100
5.00	14.3	1.43	1.43	98.57	90–100
2.36	24.1	2.41	3.84	96.16	75–100
1.18	129.8	12.98	16.82	83.18	55–90
0.6	603.9	60.39	77.21	22.79	15–30
0.3	131.6	13.16	90.37	9.63	0–10
0.15	53	5.3	95.67	4.33	0–5
0.075	27.1	2.71	98.38	1.62	
Pan	15.2	1.5	99.88	0	
FM = 2.85					

The results of particle size analysis presented in Table 7, used 1000g of aggregate sample. The maximum percentage of fine aggregate was retained on sieve size 600 µm, followed by sieve size 300 µm, then sieve size 150 µm, then sieve size 1.18 mm. the minimum percentages retained on sieve sizes 5.0 mm, 2.36 mm and 75 µm respectively. As per BS EN 12620:2002 + AI:2008 specification, the fine aggregate falls within zone 2 classification. this finding supported by several studies conducted before, such us Christopher et al., (2020) found that it is good for concrete works.

3.6 Physical Assessment of the Coarse Aggregate

The results of tests carried out to establish the physical properties of coarse aggregate. The coarse aggregate has a specific gravity of 2.65, water absorption of 0.81%, moisture content of 1.5% and particle size distribution of coarse aggregate as shown in Table 2.

The results of particle size analysis are used 1000g of coarse aggregate for the test. The maximum percentage of coarse aggregate was retained on sieve of size 10mm, followed by sieve size 6.3mm, then sieve size 14mm, and then sieve size 5 mm. the least percentage retained was on 2.3 mm and 20 mm respectively. As per BS EN 12620:2002 + AI:2008 specification, the coarse aggregate classifies as 14 mm single size.

3.7 Results for Compressive Strength of HPC

Compressive strength tests were conducted at 7,14 and 28 days. Table 4.6 presents the results obtained for different GBPA replacement levels.

Table 7
Results of Compressive Strength

Run	7days of strength	14days of strength	28days of strength
Control	64.185	65.87	67.06
1	63.96	66.18	69.08
2	58.16	59.00	60.167
3	32.62	33.10	39.55
4	27.36	29.80	33.314

The results indicate a gradual decrease in compressive strength as the proportion of Green Banana Peel Ash (GBPA) increases as it can be observed from Table 6. The 5% replacement demonstrated the greatest strength throughout all curing periods, reaching 65.16MPa after 7days, 66.18MPa after 14days, and 69.08MPa at 28days, suggesting that a low level of GBPA substitution permitted a satisfactory retention of strength. In contrast, mixtures containing large amount of GBPA exhibited a reduction in strength, with Run 2 (10%GBPA) measuring 58.16MPa after 7days, 59.00MPa at 14days, and 60.167MPa at 28days, suggesting that a as the amount of GBPA substitution increased from 5% reduction of strength is encountered. Run 3 (15%GBPA) showed values of 32.62MPa, 33.10MPa, and 39.55MPa, respectively. The most considerable strength decline was seen in Run 4 (20% GBPA), which only measured 27.36MPa at 7days, 29.80MPa at 14days, and 33.314MPa at 28days, reinforcing the idea that excessive GBPA beyond 5% substitution compromises the integrity of the cement matrix. These results suggest that the ideal cement substitution is limited below 5% .

3.8 Results of Splitting Tensile Strength of HPC

Splitting tensile strength tests were conducted at 7,14 and 28 days. Table 7 presents the results obtained for different GBPA replacement levels.

Table 8
Splitting Tensile Strength Results

Run	7days of Strength	14days of Strength	28days of Strength
control	4.26	4.67	5.01
1	4.21	4.81	5.22
2	3.99	4.01	4.22
3	2.22	3.32	3.33
4	2.00	2.11	2.20

The results indicate the percentage of Green Banana Peel Ash (GBPA) replacement rises the splitting tensile strength findings show a progressive loss in strength. Among all Runs 5% replacement demonstrated high strength with values of 4.26MPa at 7days, 4.67MPa at 14days, and 5.01MPa at 28days, the control mix showed the equal tensile strength to first Run, proving the better bonding and cohesion of regular Portland cement (OPC) in HPC. The tensile strength progressively decreased as the GBPA content rose. Once GBPA replacement reached 10% the decline becomes more noticeable. At 7,14, and 28days, run 2 (10% GBPA) showed values of 3.99MPa, 4.01MPa, and 4.22MPa, demonstrating that too much cement replacement weakens the concrete matrix and decreases aggregate cohesiveness, while Run 3 (15% GBPA) produced even lower values of 2.22MPa, 3.32MPa, and 3.33 MPa. Run 4 (20% GBPA) had the lowest tensile strength, measuring just 2.00MPa, at 7days, 2.11MPa at 14 days, and 2.20 MPa at 28days. This indicates that HPC's resistance to tensile pressure is diminished by excessive replacement. The decrease is explained by the reduced calcium silicate hydrate (CSH) production, which is essential for the development of tensile strength, and GBPA's worse binding capacity in comparison to cement. The results indicate that while higher replacements result in a more noticeable loss in performance, GBPA can be utilized in HPC up to an ideal limit of 5% without appreciably reducing tensile strength. Fiber reinforcing, more pozzolanic materials, or improved GBPA processing (such finer griding) might all be used to increase tensile strength at greater GBPA levels. The mixtures with a 5% replacement of banana peel ash demonstrated similar performance to those made with ordinary Portland cement, while specimens with a 20% replacement showed significant reduction in the strength of the interfacial transition zone.

4.5.4 Results of Water Absorption Test of HPC

Water absorption serves as a crucial measure of both the porosity and longevity of concrete.in high-performance concrete (HPC), a reduced water absorption usually indicates a more compact microstructure and enhanced resistance to external factors like moisture penetration and chemical degradation. This section provides an analysis of the findings from the water absorption tests performed on various concrete mixtures as shown Table 4.9, to assess the impact of green banana peel ash (GBPA) on permeability and durability properties of HPC.

Table 9
Water Absorption Test of HPC

Mix ID	Wet Weight of Specimen (kg)	Dry weight Of Specimen (kg)	Saturated Water Absorption (%)
Control	8.08	7.99	1.1
1	8.12	8.03	1.07
2	8.08	7.99	1.15
3	8.09	7.98	1.38
4	8.15	8.03	1.47

The findings of the water absorption test show a distinct trend, generally as the amount of Green Banana Peel Ash (GBPA) replaced rises, HPC's absorption capacity rises as well. The lowest water absorption (1.07% increase in weight) was found in the 5% replacement, while the control secured the second with 1.1% in weight, indicating that 5% replacement (Run 1) has a denser microstructure with fewer pore spaces. Water absorption progressively increased for the GBPA containing mixtures. The absorption increased little to 1.14% Run 2 of 10% replacement of the cement, suggesting that minor GBPA addition has no discernible effect on the pore structure. However, the absorption rose to 1.384% at 15% GBPA (Run 3), indicating more pronounced effect on water uptake. The absorption measurement showed an increased trend as the GBPA content rose further. at 20% GBPA (Run 4), the greatest absorption was 1.47%. there are probably two main causes for this increase in water absorption. Firstly, GBPA contributes less to the creation of hydrated compounds that fill holes in concrete matrix because it has a lower binding capacity than cement. Second, GBPA particles might create larger interior spaces, which would increase permeability and enable the absorption more water. According to these findings, GBPA can be utilized in HPC with good outcomes, although larger replacement levels (over 10%) may impact long term performance by increasing permeability. Nonetheless, HPC performance can be improved while taking advantage of the environmental benefits of GBPA inclusion with the use of supplemental pozzolanic materials, controlled GBPA fineness, and appropriate mix design modifications.

4.6.2 Results of Sorptivity Test of HPC

Sorptivity refers to the capacity of concrete to absorb and convey water via capillary action, which is essential for evaluating its durability. For high-performance concrete (HPC), lower sorptivity values enhanced resistance to moisture penetration and diminished risk of degradation. This section details the findings of the sorptivity test conducted on different HPC mixtures as shown Table 4.10, emphasizing the impact of adding green banana peel ash (GBPA) on the capillary water absorption characteristics of the concrete.

Table 10
Sorptivity Test of HPC

Mix ID	Initial weight specimen (g)	weight of after 60min (g)	sorptivity in mm/min$^{0.5}$
Control	8012.0	8023.3	0.000064
1	8012.0	8023.3	0.000064
2	8029.7	8072.8	0.00025
3	7968.0	8019.6	0.0003
4	7952.7	8014.2	0.0004

The results of the sorptivity test show that when the GBPA level rises, so does water absorption. The control mix and the first Run (5% replacement(had the lowest sorptivity (0.000064 mm/min^{05}), suggesting a lower permeability and denser microstructure. Sorptivity readings progressively increased with increasing GBPA replacement, reaching 0.0004 mm/min^{05}, at 20% GBPA. According to this pattern, capillary porosity rises with increasing GBPA levels, facilitating greater water penetration. In order to balance durability and permeability, moderate GBPA replacement (5%) maintained comparatively low sorptivity. Nevertheless, extensive replacement (> 5%) led to noticeably greater sorptivity, which would have compromised HPC's ability to withstand moisture intrusion. As a result, maximizing GBPA dosage is essential to attaining increased durability while preserving sufficient strength.

the results of water absorption and soprtivity indicate that the incorporation of green banana peel ash (GBPA) influences the permeability characteristics of high-performance concrete. Lower GBPA replacement levels maintained good durability performance, whereas higher replacement levels increased water ingress through greater pore connectivity. Therefore, GBPA is more suitable at lower replacement levels, where it can enhance sustainability while maintaining satisfactory durability.

4 CONCLUSIONS

The research studied the suitability of using green banana peel ash (GBPA) in replacement of cement in High-performance concrete (HPC). The performance of GBPA in HPC mixtures was assessed in terms of compressive strength, splitting tensile strength. As well as the physical and chemical characteristics of GBPA were thoroughly investigated and described. The influence of GBPA on these properties were analyzed, and its performance was correlated with its chemical composition and pozzolanic activity to establish meaningful relationships between its characteristics and concrete performance. On the basis of the results obtained from this study, the following conclusions were reached after analyzing the laboratory test results. Characterization of green banana peel ash (GBPA) has shown that it possesses some pozzolanic properties which is lower than the standard requirements.

Compressive strength results of 5% replacement demonstrated that early-age strength (7 days) were lower than the control mix, However, the curing days indicated a slower strength gain due to the pozzolanic reaction taking time to develop. whereas, at 28 days, GBPA-modified HPC exhibited significant strength improvements ,with some replacement levels achieving values somehow comparable to the control mix, confirming its long-term strength contribution. The highest compressive strength recorded was 69.08MPa at 28 days with 5% replacement.

Splitting tensile strength followed a similar trend, with initial reductions at 7 days but improved performance at 28days in each age. The control mix achieved 5.01MPa at 28 days, while the GBPA-modified mixes showed values ranging from 5.22MPa at 5% replacement to 2.20MPa at 20% substitution, indicating that there was a reduction.

Overall, the water absorption and sorptivity results demonstrate that the incorporation of green banana peel ash (GBPA) influences the permeability characteristics of high-performance concrete. Low GBPA replacement levels-maintained durability properties comparable to the control mix, indicating that the concrete retained a relatively dense and less permeable microstructure. However, increasing the GBPA replacement level resulted in progressively higher water absorption and sorptivity, suggesting an increase in pore connectivity and capillary water movement within the concrete matrix. These findings indicate that while GBPA has potential as a sustainable supplementary cementitious material, excessive replacement levels may adversely affect the durability performance of high-performance concrete by increasing its susceptibility to moisture ingress. Therefore, maintaining GBPA at lower replacement levels appears to provide a better balance between sustainability and long-term concrete performance.

5 Recommendations

Based on the research findings the following suggestions are put forth to further investigation the potential of Green Banana Peel Ash (GBPA) in High-performance concrete (HPC):

1. Verification of the Optimal GBPA Dosage in Various Mix Designs: Further research should concentrate on verifying this dosage in various HPC mix designs under various cement compositions, aggregate types, and curing conditions in order to guarantee its adaptability for a range of concrete applications, as this study was successful in determining the ideal GBPA replacement level.
2. Long-term durability studies : in order to ascertain the long-term sustainability of GBPA-modified HPC in various structural applications, extensive research on the durability of GBPA-modified HPC under various environmental conditions is needed, including sulfate attack, carbonation resistance, freeze-thaw cycles, and chloride exposure, should be conducted.

Declarations

Conflict of Interest

The authors declare no conflict of interest.

Ethical Approval

This study was conducted in accordance with Kampala International University and national ethical guidelines of Uganda.

Consent to Publish

Not applicable.

Clinical Trial Declaration

Not applicable.

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Author Contribution

Abdirashid Abdulahi Mohamed ; conceptualization, methodology, data analysis, data collection, interpretation of the result and preparation of the original draft. Ahmed Abdirizak Dirie ; literature review and data collection. Dr. Sani Aliyu Abubakar and Dr Paul Yohanna supervised the work. Farhan Adan Nuur, manuscript review, technical support .

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Data Availability

All data generated or analyzed during this study are included in this article.

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Figures

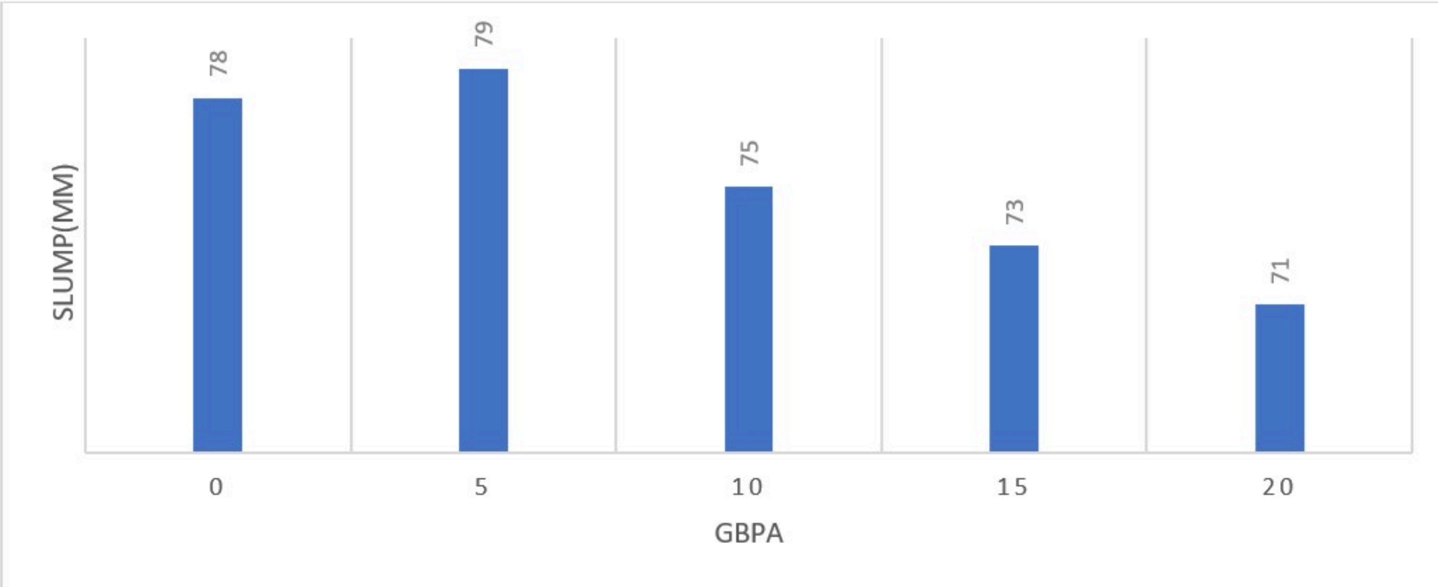

Figure 1

Slump test result

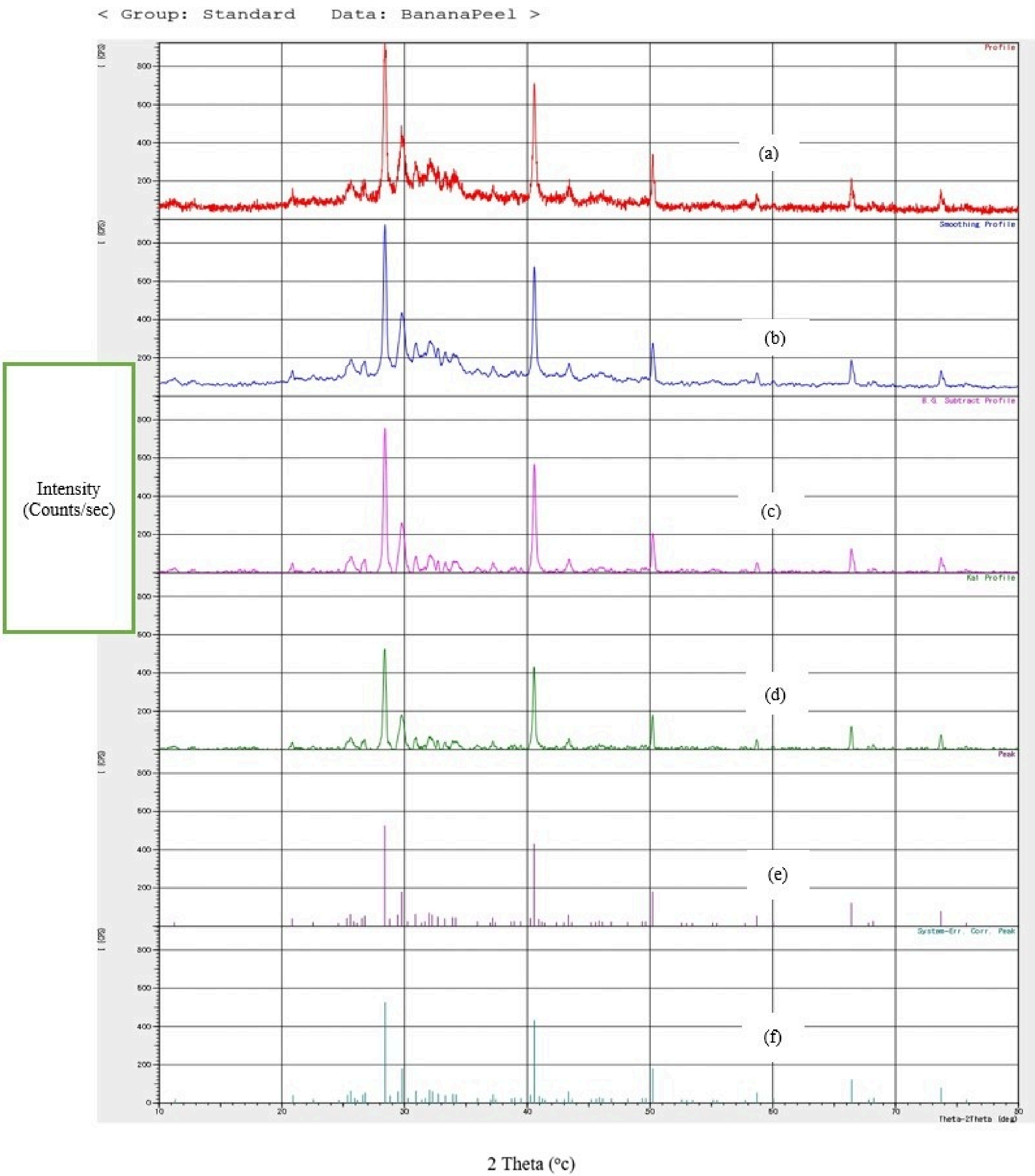

Figure 2

Figure 1 Shows the pattern of XRD for GBPA.

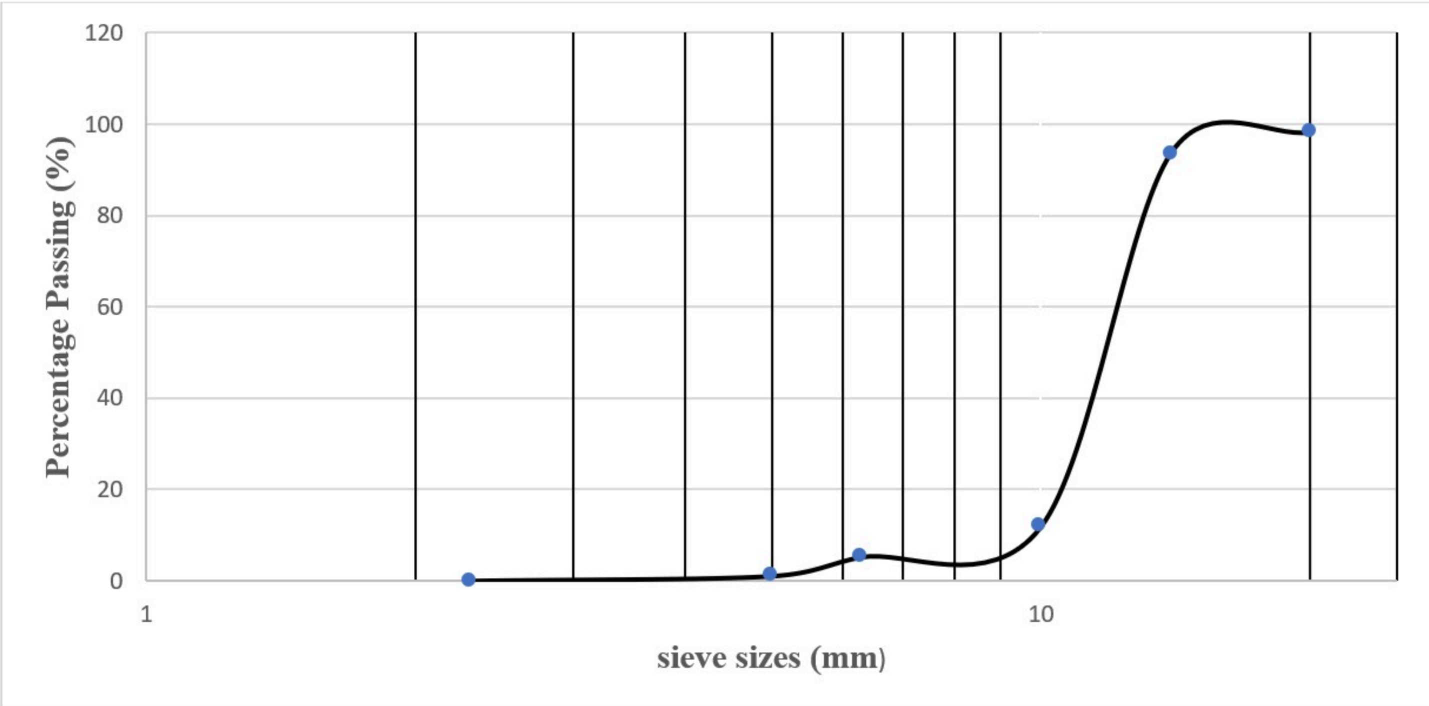

Figure 3

Figure 2 Particle Size Distribution for Coarse Aggregate

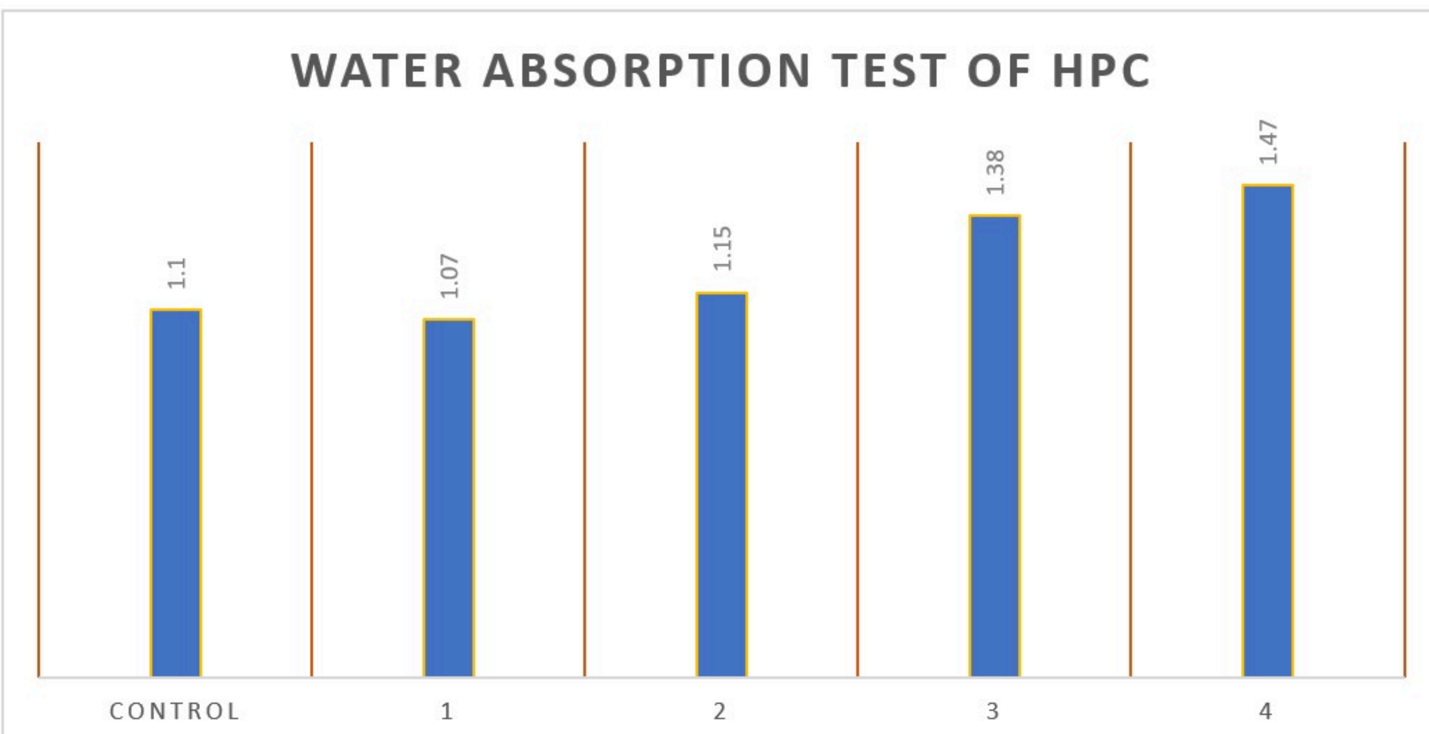

Figure 4

Figure 4. 9 Variation of Water Absorption with GBPA for HPC

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