

EVALUATION OF BACTERIAL CONCRETE FOR CO₂ ARRESTATION USING WATER HYACINTH ASH AS SUSTAINABLE ADDITIVE

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Abstract

India, the world's second-largest cement producer, stands to gain substantially from growth in construction and infrastructure. However, the cement industry contributes 8% of global carbon dioxide emissions, releasing nearly one tonne of greenhouse gases per tonne of cement. Nowadays, the government is taking a number of steps to reduce pollution emissions in an effort to lessen the negative environmental effects of the concrete sector. Promoting the manufacturing of "green concrete" is one of the most practical and scalable ways to lower CO₂ emissions in the cement sector. This study explores the use of water hyacinth ash (WHA) as a partial replacement for cement in concrete. The goal is to reduce greenhouse gases from cement production. The study replaces cement with WHA at levels of 10%, 20%, 30%, 40%, and 50% in the production of concrete pavers. Furthermore, the study incorporates microbial cultures capable of self-healing cracks via calcium carbonate (CaCO₃) precipitation. This dual mechanism of carbon capture and crack repair represents an innovative approach to sustainable building materials. Test results indicate that WHA is a stable and effective material that enhances concrete's mechanical properties, making it viable for construction. Using WHA as a substitute could significantly reduce the nation's cement demand and lower the industry's carbon footprint.

Keywords: CO₂emissions; Concrete paver; Mechanical properties; Microbial culture; Self-healing properties; Water hyacinth ash (WHA)

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Introduction

Air pollution is a critical global issue with profound implications for environmental sustainability and public health (Faheem *et al.*, 2021). The degradation of air quality, driven by physical, chemical, and biological alterations in the atmosphere, has far-reaching consequences, including approximately seven million premature deaths annually, (Kaur and Pandey, 2021). Among the industrial contributors to environmental degradation, the cement industry stands out due to its substantial carbon dioxide (CO₂) emissions, which account for nearly 8% of global CO₂ emissions (Ali *et al.*, 2015). This sector's expansion, particularly in rapidly industrializing economies like India, has exacerbated environmental challenges, emphasizing the need for effective pollution mitigation strategies (Barcelo *et al.*, 2014; Suhendro, 2014). The cement industry, while integral to India's economic development, poses significant environmental challenges (Sonu *et al.*, 2023). The primary source of CO₂ emissions in this sector is clinker production, a crucial component in cement manufacturing (Koul *et al.*, 2022). These emissions contribute to climate change and the proliferation of greenhouse gases, which negatively impact ecosystems and human health (Obi *et al.*, 2016). Recognizing the urgent need to address these issues, governments and industries worldwide have prioritized the adoption of sustainable practices in construction (Sivakrishna *et al.*, 2020). One such approach is the development of "green concrete," a revolutionary material designed to reduce carbon emissions while conserving natural resources (Gaurav *et al.*, 2020). Green concrete incorporates secondary cementitious materials (SCMs) as partial substitutes for traditional cement (Gupta and Yadav, 2020). This innovation offers dual benefits: reducing the carbon footprint associated with cement production and promoting the utilization of alternative raw materials (Sindhu *et al.*, 2017). One of the most promising avenues within this framework is agro-waste incorporation, which addresses the twin challenges of managing agricultural by-products and mitigating the environmental impacts of cement production (Boban *et al.*, 2017).

Agro-waste is a significant contributor to global pollution primarily because of its improper disposal, which leads to environmental degradation (Chen *et al.*, 2016). The agricultural sector generates vast quantities of by-products, including crop residues, husks, and other organic materials, much of which remains underutilized (Javeed *et al.*, 2024). If not managed, these wastes cause air and soil pollution either through open burning or

decomposition, which releases harmful gases and particulate matter into the atmosphere (Lee and Park, 2018). However, the transformation of agro-waste into value-added recycled applications represents a paradigm shift in waste management and resource utilization (Abana *et al.*, 2021). By repurposing agricultural by-products as raw materials in industries such as construction, it is possible to mitigate environmental pollution while simultaneously reducing the reliance on non-renewable resources (Gebru *et al.*, 2021). For example, agro-waste such as rice husk ash, sugarcane bagasse, and wheat straw has shown immense potential as supplementary materials in concrete production (Lucas *et al.*, 2018). Green concrete is an innovative idea that has provided a great way to respond to all the environmental challenges associated with traditionally based construction activities (Molyneux, 2020). Green concrete mainly consists of alternative raw material contents in addition to conventional cements; therefore, by replacing the required proportion of conventional cements with SCMs or agricultural wastes, it can effectively reduce the level of carbon emissions and meet the strength requirement or, in some cases, have the same strength (Tittelboom *et al.*, 2010).

This study discusses the feasibility of incorporating WHA into concrete as a partial replacement for cement. An innovative application of agricultural waste in the cement industry is water hyacinth (*Eichhornia crassipes*) ash (WHA). Water hyacinth is a highly invasive aquatic plant; its rapid growth and obstruction of waterways pose an environmental challenge (Rezania *et al.*, 2015). Traditional control methods such as manual removal of water hyacinth or chemical control are only effective to a limited extent and can worsen environmental problems on a large scale (Jahagirdar *et al.*, 2019). But, if this biomass is converted into ash and partially used instead of cement in concrete, not only the environment but also the economy brings an innovation to the new circular economy concept by using waste as a valuable construction material (Tziviloglou *et al.*, 2016; Wei *et al.*, 2024).

The integration of micro cultures into concrete increases the autogenic healing capacity of concrete, which ensures longer life and less maintenance compared to conventional cement mortar (Varghese and Vasudev, 2023). Furthermore, alternative materials help to reduce the production of cement from natural sources, thus reducing the environmental impact of cement production (Krishnan and Nagan, 2025). This research presents

water hyacinth ash (WHA) as an emerging bio-based material that helps to decrease the use of cement and aid in sustainable construction. As demand for construction materials continues to grow, it is imperative to adopt eco-friendly alternatives that balance economic growth with environmental responsibility (Muruges and Balasundaram, 2017). Incorporating WHA and microbial culture in concrete production addresses the urgent need to reduce carbon emissions and provides scalable solutions for cleaner, sustainable construction practices (Krishnan and Nagan, 2022). In conclusion, green concrete represents a transformative innovation in the construction industry. This study illustrates the ability to develop high-performance, eco-friendly building materials based on WHA and microbial culture. Such innovations will open up a green future, where the construction industry can positively contribute toward global sustainability goals while striving to meet the increasing demands of modern infrastructure.

In this investigation, the concrete pavers were manufactured with different percentages of WHA, namely 10%, 20%, 30%, 40%, and 50%, to determine their mechanical properties and environmental effects. The results indicate that WHA not only reduces the amount of cement but also helps to reduce the emission of greenhouse gases. This finds expression in the global drive for sustainable development and a built environment with a reduced environmental footprint by the construction sector. In addition to incorporating WHA, this study further develops the integration of microbial culture into concrete as a self-healing mechanism. A specific process called microbial-induced calcite precipitation (MICP) involves certain bacteria promoting the growth of calcium carbonate crystals, filling micro cracks in the concrete, thereby increasing its durability and service life (Mohammadi and Ramezaniapour, 2023). Furthermore, MICP has the added benefit of absorbing atmospheric CO₂, making the material more sustainable. The novelty of this research is the synergistic combination of WHA and microbial culture (*Bacillus subtilis*) for creating a sustainable concrete system with double functionality: CO₂ capture and self-healing capability via calcium carbonate precipitation while improving the performance properties of concrete (Rezania *et al.*, 2015). Therefore, the use of WHA and microbial culture in concrete production is a significant step forward towards sustainable construction practices (Jahagirdar *et al.*, 2019). This study highlights bio-waste's potential in sustainable construction, offering India's cement sector a valuable pathway to meet global sustainability goals.

Materials and Methods

The materials used in this study are Ordinary Portland cement, fine aggregate, water, SP500 Superplasticizer, and Water Hyacinth ash were used.

Cement

Ordinary Portland Cement (OPC) was used for making paver blocks. The cement was bought from Sivakasi and tested for fineness and loss of ignition, as well as its specific gravity. The physical properties of cement are displayed in Table 1.

Table 1. Physical Properties of Cement

Test	Result
Fineness	90 μ
Loss of Ignition	7.5g in 10g
Specific Gravity	3.15

Water Hyacinth Ash

Water hyacinth (*Eichhornia crassipes*) remains were collected from the local area in Sivakasi. Water hyacinth grows very rapidly to occupy a large area of water within a short time. The dried biomass was burned at 700°C in the muffle furnace. WHA is dried, pre-ground, and finely ground to reduce particle size, then sieved to meet specific fineness requirements, typically targeting particles that pass through a 90-micron sieve, comparable to cement standards. Similarly, the ignition test was conducted. In this study, water hyacinth ash (WHA) was used as the sustainable additive in the paver block production. The physical properties of WHA are displayed in Table 2. Figure 1 describes the water hyacinth residues, dried biomass, and ash. Figure 2 describes the tests conducted for WHA-like fineness, ignition, and specific gravity.



Figure 1. a) Water Hyacinth Residues, b) Dried Biomass, and c) Biomass Ash



Figure 2. d) Fineness, e) Ignition, and f) Specific Gravity

Table 2. Physical Properties of Water Hyacinth Ash

Test	Result
Fineness	90 Micron
Loss of Ignition	6.9g in 10g
Specific Gravity	2.85

Fine Aggregate

Fine aggregate that has a fineness modulus of 2.7 and specific gravity of 2.65 and passes through an IS sieve is referred to as fine aggregate. The quality of the fine aggregate was checked to make sure it was free of organic contaminants prior to casting concrete samples for this investigation. It falls under Zone II and complies with IS 383 1970.

Superplasticizer

In this investigation, SP500 Superplasticizer, a high-range water-reducing admixture (HRWR), was used in concrete to improve its workability without increasing the water-cement ratio. Due to lower water content, it contributes to higher early and final compressive strength.

Microbial Culture

Bacterial addition to concrete is a potential approach for the improvement of durability, sustainability, and self-healing ability. *Bacillus subtilis*, a gram-positive, rod-shaped, non-pathogenic bacterium, has been reported to initiate precipitation of calcium carbonate (CaCO₃) by biomineralization (Leema *et al.*, 2024). This process allows for microcrack sealing in concrete, and hence it is a candidate microorganism for self-healing applications. In this research, *Bacillus subtilis* (MTCC No. 1427) was procured from the Microbial Type Culture Collection (MTCC), India. The culture was kept in aseptic conditions according to Bio-safety Level 1 (BSL-1) standards. All microbial manipulation was done within a laminar airflow chamber with standard personal protective gear (PPE), such as gloves and lab coats.

Preparation of Bacterial Medium

A nutrient broth medium was made by dissolving 13 g/L of nutrient broth (1.0 g meat extract and 5.0 g peptone) in 100 mL of distilled water in 250 mL sterile conical flasks. The flasks were plugged using cotton plugs and aluminum foil and sterilized in an autoclave at 121°C for 30 minutes. Upon reaching the ambient temperature, 1 mL of *Bacillus subtilis* inoculum was added aseptically to every flask and incubated at 37°C for 24 hours. Turbidity and a light-yellow coloration were signs of bacterial growth. Cultures were preserved under ambient temperature and used within 20 days. All the procedures were in accordance with BSL-1 bio safety guidelines, such as sterilization, waste disposal, and the use of PPE to ensure that there was no contamination or health hazard. To maintain microbial viability in mixing and curing, the bacterial culture was introduced at the final mixing step with a calcium lactate solution as a carrier of nutrients. Mixing was done at room temperature, and curing at ambient conditions was avoided to prevent heat stress, thereby maintaining maximum bacterial activity for precipitation of CaCO₃.

Experimental Work

Cement is a versatile material that binds various substances together, hardening and setting over time (Indhumathi *et al.*, 2023). It has excellent adhesive properties, making it ideal for combining with materials like sand, stone, and gravel to form solid masses. Cement is commonly used in making mortar and concrete, both of which are essential in construction (Vishnuram *et al.*, 2023). Paver block, created by mixing cement with sand and water, is used for bonding bricks and stones. Concrete, made by mixing cement with aggregates, is a stronger material used for foundations, floors, and other structural components. A granular material that passes through a 4.75 mm IS sieve includes substances like sand, gravel, crushed stone, or aggregates, known as fine aggregates. These fine aggregates play a key role in improving the workability of the mixture (Paithankar *et al.*, 2023). They fill the gaps between coarse aggregates, helping to create a more compact structure (Dhanalakshmi *et al.*, 2023). The use of fine aggregates is important for enhancing the overall strength and durability of concrete (Win *et al.*, 2023a). Their presence ensures better cohesion and stability in the final product. The paver blocks are made with WHA as a component. Table 3 describes the chemical properties of WHA through the EDX mapping.

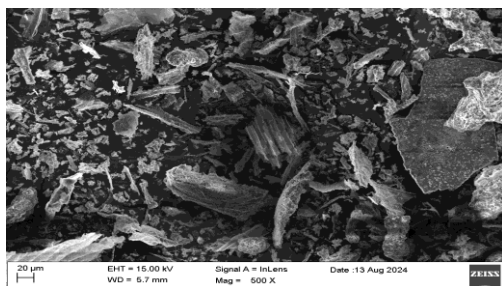
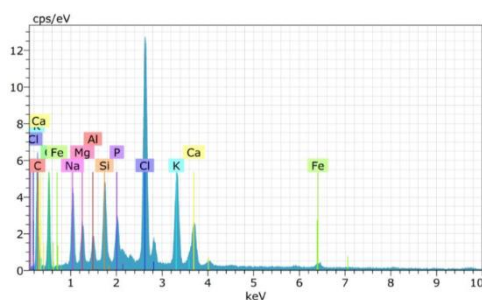
Table 3. Chemical Properties of WHA

Element	Symbol	Content (wt.%)
Oxygen	O	30.46
Calcium	Ca	4.29
Chlorine	Cl	2.87
Silicon	Si	3.14
Potassium	K	3.48
Iron	Fe	3.26
Phosphorus	P	1.36
Magnesium	Mg	1.02
Sodium	Na	1.12
Aluminum	Al	0.94

Figure 3 is an SEM photo of WHA. Scanning electron microscopy (SEM) (Carl Zeiss (Sigma) model analysis) is a method whereby a focused beam of electrons is used to create high-resolution images of a sample surface. Water hyacinth ash (Eichhornia crassipes) is applied for this test. It clearly displays a microporous surface with honeycomb-shaped pores. It also Figure 4 illustrates the elemental composition of the ash determined by EDX analysis. Table 4 presents the different percentages of WHA used, which are 0%, 10%, 20%, 30%, 40%, and 50% by weight of cement. The mixes were prepared as per the Indian standard IS

Table 4. Mix Proportion

Mix Proportion of WHA	Mix Id
Control Mix	WHA 0
10% of WHA by using weight of cement	WHA 10
20% of WHA by using weight of cement	WHA 20
30% of WHA by using weight of cement	WHA 30
40% of WHA by using weight of cement	WHA 40
50% of WHA by using weight of cement	WHA 50

**Figure 3. SEM Analysis of WHA****Figure 4. EDX Analysis of WHA**

456:2000. Prior to placing the mixes in the cube molds. WHA has been incorporated into pavers to enhance their strength. M25 grade concrete. The proportion of 1:1:2 and the water-cement ratio of 0.4 were employed. Concrete mix designs in this research were designed according to the guidelines in the Indian Standards (IS). All mixes were designed to develop a specified compressive strength of 25 MPa upon curing for 28 days.

Mechanical Properties of concrete

Determination of Compressive Strength Test

Compressive strength determines resistance to axial compressive loads of concrete or paver blocks. It is a primary indicator of structural performance in concrete (Kaliraj *et al.*, 2023). The most common test for Paver's specimen cube or cylinder - involves constantly increasing a compressive force on the specimen until it fails. Compressive strength is expressed as the ratio of the greatest supported load to the cross-sectional area of the specimen. A material is guaranteed to be able to sustain a great load without breaking. But the load-bearing capacity increases with time as the cement hydrates, and so standard tests are conducted after 28 days (Win *et al.*, 2023b). Figure 5 shows the image of Compressive strength test for the paver block.

**Figure 5. Compressive strength test Image**

Determination of Split Tensile Strength Test

The split tensile test, which involves applying a diametric compressive load to a specimen to induce tension along the vertical plane, is frequently used to measure tensile strength (Yehualaw *et al.*, 2022). This characteristic is crucial in situations like shrinkage or thermal expansion where tensile tensions could occur. This test is crucial for comprehending fracture formation and guaranteeing compatibility with reinforcing, even if concrete is naturally weak in stress. Pavers' or concretes' cracking behaviour's greatly influenced by tensile strength, which is normally 15% of compressive strength. Figure 6 shows the tensile strength test for the paver block.



Figure 6. Split Tensile test Image

Determination of Absorption Test

A water absorption test was conducted to investigate some of the durability properties of bricks, including the extent of burning of bricks, quality, weathering behaviour of bricks, etc. It is a test used to find out the extent of closeness of the bricks because water is absorbed in the pores of the paver blocks. Paver block samples were left at room temperature for balancing them. Following immersion of the totally dry specimen in clean water at $27\pm 2^\circ\text{C}$ for twenty-four hours, it was immersed (Mohammadi and Ramezani pour, 2023). Remove the specimen from the water, and with the aid of a damp cloth, wipe away any excess water; thereafter, weigh the specimen. Figure 7 indicates the picture for the test for water absorption of the paver block.



Figure 7. Water Absorption Test

Acid Resistance Test

An acid resistance test was conducted to evaluate the durability characteristics of paver blocks, including resistance to chemical attack, material integrity, and long-term performance under aggressive environmental conditions. This test helps to assess the compactness and pore structure of the paver blocks, as acidic solutions can penetrate

through pores and affect the internal matrix (Jena *et al.*, 2020). Prior to testing, the paver block specimens were conditioned at room temperature to achieve equilibrium. The completely dried specimens were then immersed in an acid solution maintained at $27\pm 2^\circ\text{C}$ for a period of 24 hours, following standard testing procedures (Vijay *et al.*, 2017). After immersion, the specimens were removed from the solution, surface moisture was gently wiped off using a damp cloth, and the specimens were weighed to determine the effect of acid exposure. Figure 8 shows the experimental setup used for the acid resistance test of the paver blocks.



Figure 8. Test on Acid Resistance

Determination of Efflorescence Test

When soluble salts, frequently from the cement, aggregate, or water, are drawn to the surface by moisture, a white, powdery deposit known as efflorescence forms on the surface of concrete or masonry. It can be ugly and occasionally a sign of more serious structural moisture-related problems. Concrete bricks can be tested for efflorescence to see if there are too many soluble salts in the material, which could lead to problems with long-term durability (Pachaivannan *et al.*, 2020). The brick was submerged in water for a full day before being removed and allowed to dry fully. If there is no visible or white deposit on the paver bricks' surface during this test, it means that there are no dissolving salts (Bandyopadhyay *et al.*, 2023). Figure 9 shows the image for the Efflorescence test for the paver block.



Figure 9. Efflorescence test

Results and Discussion

Compressive Strength

The compressive strength is carried by paver blocks incorporating water hyacinth ash (WHA) as a partial cement replacement, along with microbial culture for self-healing and CO₂ sequestration. Table 5 shows the compressive strength test for the paver block. As a filler material, WHA, due to its fine particle size, reduces the voids between the cement particles and increases the density of the concrete matrix (Achal *et al.*, 2011). The pozzolanic reaction of WHA with Ca(OH)₂ during cement hydration results in additional C-S-H gels that improve strength (Kumar and Biabie, 2020). Compressive strengths achieved by the control mix (0% WHA, no microbial culture) were 15.3 MPa at 7 days and 25.3 MPa at 28 days. Water hyacinth ash may contain amorphous silica and alumina. These react with Calcium Hydroxide (Ca(OH)₂) released during cement hydration. C-S-H is the main strength-giving compound in concrete. This reaction improves the long-term strength and durability of the concrete (Lee *et al.*, 2025). WHA particles can act as micro fillers, filling the voids between cement and aggregate particles (Tziviloglou *et al.*, 2016). This improves packing density and reduces porosity, contributing to better strength. The incorporation of microbial culture in the control mix marginally enhanced durability and self-healing characteristics, while the compressive strength reached 15.8 MPa at both 7 and 28 days. WHA replacement at 10% combined with microbial culture enhanced compressive strength. Incorporating WHA in concrete mixtures has shown

significant improvements in workability and compressive strength, particularly at a 10% replacement level of cement. Results achieved a value of 16.2 MPa at 7 days and 26.2 MPa at 28 days. At 20% replacement, the strengths continue to advance at 16.66 MPa at 7 days and 26.7 MPa at 28 days. It is due to the WHA's pozzolanic activity and refined microstructure. Optimum strength was at 30% replacement by WHA; the compressive strengths reached up to 17.33 MPa at the 7th day and to 27.3 MPa at the end of the 28th day as compared with the control mix. Strength fell below this optimum. At 40% WHA, compressive strength decreased to 14.00 MPa at 7 days and 24.1 MPa at 28 days, whereas at 50% WHA, strengths decreased further to 8.33 MPa at 7 days and 23.5 MPa at 28 days, mainly because of slower pozzolanic reactions and higher voids. the use of calcite-precipitating bacteria to enhance concrete's compressive strength and reduce permeability through bio-mineralization processes (Denneman *et al.*, 2011). A graphical illustration of compressive strength results is shown in Figure 10.

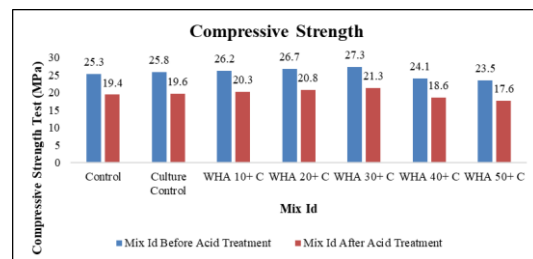


Figure 10. Graphical illustrations of compressive strength

Table 5. Compressive Strength Test

Mix Id	Compressive Strength (N/mm ²)	Compressive Strength (N/mm ²)
	7 Days	28 Days
Control	15.3	25.3
Culture Control	15.8	25.8
WHA 10+ Culture	16.2	26.2
WHA 20+ Culture	16.6	26.7
WHA 30+ Culture	17.3	27.3
WHA 40+ Culture	14.1	24.1
WHA 50+ Culture	13.3	23.5

Table 6. Split Tensile Strength Test

Mix Id	Tensile Strength (N/mm ²)	Split Tensile Strength (N/mm ²)
	7 Days	28 Days
Control	2.74	3.52
Culture Control	2.78	3.55
WHA 10+ Culture	2.80	3.58
WHA 20+ Culture	2.85	3.61
WHA 30+ Culture	2.91	3.65
WHA 40+ Culture	2.62	3.40
WHA 50+ Culture	2.55	3.39

Split Tensile Strength

The split tensile strength of paver blocks in which water hyacinth ash (WHA) was used as a partial replacement for cement and microbial culture for self-healing and CO₂ sequestration. Table 6 shows the split tensile strength test for the paver block. Results show that the tensile strength increases with 30% WHA replacement to a peak value of 2.91 MPa at 7 days and 3.65 MPa at 28 days, attributed to the pozzolanic activity of WHA, which fills the voids and thus increases the density of the matrix. At higher percentages above 30%, there is less cement available to form C-S-H gel. WHA lacks sufficient pozzolanic activity; it acts as an inert material, weakening the matrix. This results in lower split tensile strength due to the reduced cementitious phase (Zhuang *et al.*, 2022). Tensile strength drops with WHA above 30% because of reduced cement content, slower pozzolanic reactions, and higher porosity, which resulted in 3.40 MPa and 3.39 MPa for 40% and 50% WHA replacement at 28 days, respectively. These results indicate that WHA is a suitable and sustainable cement replacement up to 30%, with microbial culture improving performance and supporting eco-friendly paver block production. A graphical illustration of split tensile strength is shown in Figure 11.

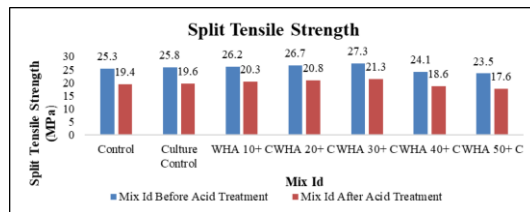


Figure 11. Graphical illustrations of split tensile strength

Water Absorption Test

A water absorption test was performed on paver blocks to determine the effect of replacing cement with water hyacinth ash. Weights before and after the blocks were measured, and the percentage of water absorption was calculated. Table 7 shows the water absorption test results. Bacterial concrete

showed reduced water absorption due to calcium carbonate precipitation, which fills microcracks and pores. At 10% WHA, water absorption is lowest, likely due to the combined filler effect of WHA and pore-sealing by bacteria. Water absorption increased at 20-50% WHA, possibly due to excess ash reducing the cementitious matrix and increasing porosity.

The results show that the water absorption increases with increased levels of WHA replacement. For the control and cultured control samples, the water absorption was at 1.27% and 1.21%, meaning that the microstructure was dense with minimal porosity. The addition of WHA started increasing the water absorption gradually, from 1.43% at 10% WHA up to 1.51% at 50% WHA. This trend can be attributed to the reduction of cement content and the porous character of WHA, which is slightly increasing the permeability of the mixture. In addition, microbial culture contributed towards crack healing and densification via calcium carbonate precipitation, as proved by the minimal increase in water absorption compared to what was expected without the action of the microorganisms (Pernicova, 2014). However, at higher WHA replacement levels, reduced cement content dominated, resulting in slightly higher absorption rates due to increased void spaces. A graphical illustration of the water absorption test is shown in Figure 12.

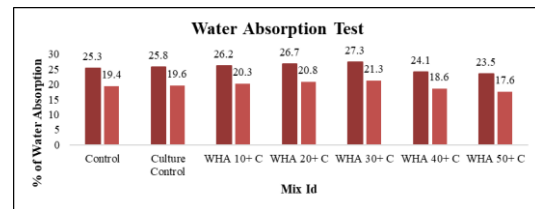


Figure 12. Graphical illustrations of Water Absorption Test

Acid Resistance

Compressive strength of acid-treated and untreated samples was measured to observe the effects of acid on compressive strength of the block. Effects of acid treatments on compressive strength

Table 7. Water Absorption Test

Mix Id	Before immersion (Kg)	After Immersion (Kg)	Percentage of Water Absorption (%)
Control	4.635	4.670	1.27
Culture Control	4.635	4.670	1.21
10% WHA + Culture	4.515	4.580	1.43
20% WHA + Culture	4.460	4.525	1.45
30% WHA + Culture	4.400	4.465	1.47
40% WHA + Culture	4.355	4.420	1.49
50% WHA + Culture	4.296	4.361	1.51

of all samples are clearly seen in Figure 13. Compressive strength of the control specimen decreased from 25.3 MPa to 19.4 MPa with about 23% loss. On the other hand, the compressive strength of WHA 30 with culture medium decreased from 27.3 MPa to 21.3 MPa with around 22% loss. The bacterial product (CaCO_3) reduces the porosity of concrete, and therefore the concrete is more resistant to environmental conditions. The bacterial addition in the paver block prevented the acid from penetrating into the microstructure and thus preserved the compressive strength of the block (Tziviloglou *et al.*, 2016). The main reason for the difference is that the concrete pore was filled with calcium carbonate by bacteria Table 8 shows the Acid Resistance Test results.

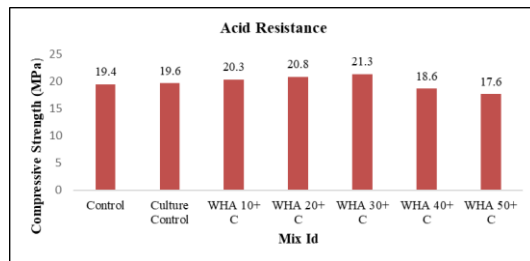


Figure 13. Effects of acid treatments on compressive strength

Efflorescence Test

An efflorescence test on paver blocks made using water hyacinth ash as a partial substitution for cement and microbial culture for self-healing shows varied levels of efflorescence at different mix proportions. The control mix and the culture control mix showed almost negligible efflorescence with no distinct deposits of soluble salts on the surface. The mixes with 10%, 20%, 30%, and 40% WHA replacement, mixed with microbial culture, showed very minor efflorescence, as the pozzolanic reaction of WHA combined with the precipitation of calcium carbonate due to microbes prevented salt from migrating to the surface. It was found that these mixes presented a clean surface with no evident salt deposits; hence, no risk of efflorescence was present in these mixes. However, the mix with 50% WHA replacement and microbial culture showed slight

efflorescence, with minimal white deposits forming on the surface. This increase in efflorescence is likely due to the higher alkali content in WHA at higher replacement levels, which may introduce more soluble salts into the mix, coupled with the reduction in cement content. Although this slightly increases the efflorescence, the presence of microbial culture also reduced the total permeability of the system, which contributed to crack healing. These results reveal that WHA is an efficient and sustainable partial replacement for cement with minimal effect on efflorescence up to 40% replacement. Figure 14 shows the image for the efflorescence of the paver block.



Figure 14. Efflorescence the paver block (WHA 50%)

Visual Indicators of Microbial Activity

Visual surface variations were detected in microbial concrete specimens during and post curing. Figure 15 shows the visual indicators of microbial activity in microbial concrete paver blocks. During the initial curing stage, the formation of gas bubbles on the paver surface (Fig. 15X) suggested possible microbial metabolic activity, in accordance with CO_2 interaction. On the 28th day of curing, there was a white layer formation on the surface of bacterial concrete specimens (Fig. 15Y). Although this layer looks like salt-migration-induced efflorescence, the presence of *Bacillus subtilis* and increased compressive strength point toward the prospect of biologically induced deposition of calcium-based minerals. Further, the ultimate paver surfaces were denser and optically sealed (Fig. 15Z), which is likely to be a result of microbial action in sealing the cracks. Yet, additional microscopic and compositional

Table 8. Acid Resistance Test

Mix Id	Compressive Strength (N/mm^2) at 28 Days	
	Before Acid Treatment	After Acid Treatment
Control	25.3	19.4
Culture Control	25.8	19.6
WHA 10+ Culture	26.2	20.3
WHA 20+ Culture	26.7	20.8
WHA 30+ Culture	27.3	21.3
WHA 40+ Culture	24.1	18.6
WHA 50+ Culture	23.5	17.6

examinations are required to establish the character of these deposits and the contributions to self-healing and carbon sequestration.



Figure 15. Visual Indicators of Microbial Activity

Figure X Gas bubble formation during early curing, indicating microbial activity.

Figure Y White surface layer observed on cured microbial concrete; possible mineral deposit or efflorescence.

Figure Z Final paver block showing smoother surface, potentially due to microbial crack healing.

Conclusion

Being a pozzolanic material, WHA can replace cement up to an optimum percentage of 30%. Its fine particle size enhances the compressive and tensile strengths because of filling pores and improving microstructure. Beyond 30% replacement, the mechanical properties are diminished because of low cement content and increased porosity, thus demanding a balanced mix design. This facilitates the paver blocks to be highly durable by way of microbial-induced calcite precipitation. This enables the self-healing of the microorganism system through the restoration of some structure, increased impermeability, and potentially lengthened lifetime. Second, the biochemical reactions of microbial cultures, such as *Bacillus subtilis*, sequester CO₂ as CaCO₃ to reduce anthropogenic carbon dioxide emissions. The partial substitution of cement by water hyacinth ash (WHA) in paver blocks, supplemented with microbial culture for self-healing and CO₂ sequestration, can be a very sustainable and innovative solution for modern construction. In synergy, WHA and microbial culture create environmentally responsive paver blocks with enhanced functionality. The following points are the benefits and findings related to WHA in concrete applications.

- WHA influence the mechanical qualities of concrete when used as a partial substitute 30% replacement for cement.
- Significant increases in workability and compressive strength have been observed when WHA is added to concrete mixtures, especially when 10% of the cement is replaced.
- The use of WHA reduces the energy required for cement production, thus lowering the carbon footprint of concrete. WHA reacts with calcium hydroxide (Ca(OH)₂) to form additional C-S-H gel, which contributes to long-term strength.
- Water hyacinth, being a rapidly growing biomass, provides a sustainable source of material that can mitigate environmental pollution caused by its overgrowth.
- Finer ash particles fill voids in the cement matrix, reducing porosity and improving strength.

WHA successfully utilizes wasted agricultural products through the reduction in cement usage along with the minimum environmental footprint, while microbial culture significantly enhances durability and sustainability, hence overcoming the paramount challenges in construction. This sustainable approach provides less expensive yet durable and sustainable infrastructure solutions through the potential synthesis of waste by-products and biological technology for achieving sustainable and resistant building materials. This method helps to address several environmental concerns: reduced CO₂ emissions, use of agricultural waste, increased strength, and resource conservation. The conversion of water hyacinth to ash not only manages invasive species but also serves as a resource for the circular economy, turning waste into a resource.

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