Aquatic Weed for Concrete Sustainability

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Abstract: Ordinary Portland cement (OPC) is the primary binder of concrete, accounting for approximately 5% to 7% of greenhouse gas (GHG) and carbon dioxide (CO₂) emissions with an annual production rate of more than 4 billion tons. It is critical to reduce the carbon footprint of concrete without sacrificing its performance. To this end, this study focuses on the use of water hyacinth ash (WHA) as a pozzolanic binder in the production of concrete as a partial replacement for cement. Four mixes are designed to achieve C-25-grade concrete with varying proportions of cement replacement with WHA of 0%, 5%, 10%, and 15% of the cement weight. Extensive experiments are performed to examine the workability, strength, durability, and microstructure of concrete specimens. The test results confirm that incorporating WHA in concrete improved its workability, strength, and durability. The optimal results are obtained at the maximum OPC replacement level, with 10% WHA. The use of WHA as a partial replacement for cement greatly reduces the energy required for cement production and preserves natural resources. More research is needed to use WHA on a large scale to achieve greater sustainability in the concrete industry.

Keywords: water hyacinth ash; concrete; fresh properties; compressive properties; microstructure properties; durability

1. Introduction

The development of any country is primarily characterized and measured by improvements in living conditions and the growth of its built infrastructure. Concrete is one of the most prevalent and widely consumed building materials utilized in the construction of megastructures and infrastructures, and it is important to the world that it is a highly versatile, all-around material, one that is used every year in development [1–5]. Despite its significant contribution to built infrastructure, concrete is responsible for the extensive use of natural resources in its production. Cement is a well-known, essential component in the production of concrete. The manufacturing of cement affects nonrenewable natural resources, the atmospheric environment, and costs, as well as engineering and durability behavior aspects [6–10]. Manufacturing 1 ton of Portland cement requires quarrying 1.5 tons of limestone and clay [6,11,12]. It has been reported that, throughout the world, 4.40 billion tons of cement are produced yearly, contributing to 5%–7% of GHG and CO₂ emissions [6,13–16].

On the other hand, generating 1 ton of clinker requires an enormous amount of energy (850 Kcal/kg) and raw materials (1.7 tons on average) [17–19]. The world has seen global climate changes as a result of these interrelated issues, which ultimately led to the depletion
of the ozone layer. Because of the loss of ozone, the sun’s infrared rays will reach the ground directly, drying up plants and exposing people and animals to several dangerous diseases.

Creating a sustainable system loop that can transform resources that are sent to landfills as waste into useful products for the construction sector would be the ideal goal to partially address the aforementioned situation. This would save natural resources, similar to how finding locally accessible, sustainable, eco-efficient, appropriate, cheap, and low-energy alternative agricultural and industrial waste materials to partially or completely replace cement has become mandatory and necessary to ease this global issue. Since plant extracts contain a variety of organic components, there has been a lot of research on replacing some of the cement with various plant wastes [6]. Numerous studies on cement auxiliary materials, such as silica fume, fly ash, rice husk ash, coffee husk ash, ground nut ash, bamboo leaves ash, banana leaves ash, sugarcane bagasse, corn cob ash, animal bone powder, tobacco waste, and eggshell, have been conducted in the last two decades. Unexpectedly, these materials proved successful in meeting the needs of cement concrete solid development.

Water hyacinth (Eichhornia crassipes) is a free-gliding and -floating aquatic weed that grows in still or moderately mobile crisp water bodies, and it inhabits bodies of water in such quantities that these bodies either start to interfere with human usage or become a health hazard by serving as insect breeding areas [20]. It poses the risk of oxygen depletion, water quality degradation, biodiversity loss, water loss, and waterway blockage, all of which impede agriculture, fisheries, recreation, and hydropower. Water hyacinth has been referred to as a noxious weed and an invasive aquatic plant [12]. In less than two weeks, it grows dynamically and richly to produce large biomass and double its population. It consists of long and fibrous roots that may be up to 3 m in length and has a fibrous stem. The average length of the fiber is 1.604 mm and the average diameter is 5.5 microns [1,6]. It is a completely free source of biomass that is currently being underutilized as a supplementary cementitious material [1,6,21,22].

Ethiopia is one of the nations fighting against the presence of water hyacinth in its water bodies despite having abundant water resources and wetland ecosystems [23–26]. Due to the rapid growth of the water hyacinth, there is a risk that these waters will be infested by it if the situation persists. Water hyacinth, also known as “Imboch” in the local Amharic language, was first discovered in Ethiopia in 1956 in Koka Lake and the Awash River (Stroud, 1994), referenced in [17]. From late 1956 to late 2011, the weed’s presence in water bodies decreased [27–32]. The lack of natural enemies for the weed has been largely blamed for the water hyacinth’s rapid proliferation in Ethiopia over the past 30 years, according to the United Nations Environmental Programme (UNEP). Due to its ability to quickly blanket entire streams, water hyacinth is one of the most invasive and widely dispersed plants in Ethiopia [25]. It invaded Lake Tana in Bahir Dar, Ethiopia, affecting not only the aquatic life in the lake but also the socioeconomic activities of the local populace, whose livelihoods rely directly or indirectly on the lake’s ecosystem services [33]. Dersseh et al. [33] stated that Lake Tana’s invaded area was 20,000 ha, 50,000 ha, and 34,000 ha, respectively, in 2012, 2014, and 2015, compared with official agency estimates of less than 5000 ha during the peak growing season. According to a survey conducted from 4 to 14 October 2018 and excluding the infestation region in the floodplain, 2279.4 hectares of Lake Tana were projected to be covered by water hyacinth [33]. It cost an average of about USD 100,000 to control and remove water hyacinth from the invaded areas in Ethiopia between 2000 and 2013 [28]. Figure 1 shows the removal of invasive water hyacinth from Lake Tana. As it covers a large portion of the lake, anyone could imagine the adverse impact it will have on water quality, biodiversity, waterway flow, agriculture, fisheries, and recreation.

Previous studies have been conducted on the possible use of water hyacinth ash (WHA) as a partial replacement cement in concrete production [1,6–8,15,16], and they proved that workability improved with the addition of WHA; the concrete compressive strength and split tensile strengths decreased with 20% WHA content, and up to 10% WHA could replace
cement. Damtoft et al. [7] investigated the mechanical performance of concrete that was increased with 15% WHA, including microsilica admixtures; the workability improved incrementally with the addition of WHA. Turner and Collins [16] identified that WHA has a lower specific gravity than cement (2.44 times lower than cement), and its fineness is twice as high as that of cement; additionally, consistency, slump, and setting time improved with the addition of WHA compared with normal cement; 10% WHA was the most optimal dosage for the partial replacement of cement. Vieira et al. [15] discovered that the water absorption of concrete containing 10% WHA was lower, and the chloride resistance was 3.5% higher when compared with control concrete, indicating greater durability.

In the present experimental research work, cement is substituted with WHA by 5%, 10%, and 15%, and it is utilized in concrete production to evaluate the workability, mechanical strength, and microstructures with thermogravimetric and Fourier-transformed infrared spectroscopy analyses. Finally, the effect of using WHA as a supplementary replacement material for cement in concrete durability properties is investigated.

2. Materials and Methods

2.1. Materials Used

2.1.1. Binders

In this work, ordinary Portland cement (OPC) and water hyacinth ash were used as binders. The adopted cement was OPC 42.5R, produced by Derba MIDROC Cement PLC. The cement quality was tested as per ASTM C1084–19 [34]. The grading and physical properties met the requirements of ASTM C 150–19 [35].

2.1.2. Coarse Aggregates

Locally available crushed stones, sieved and retained on sieves with sizes of 4.75 mm and above, were used as coarse aggregates. The coarse aggregate was also tested for various properties, such as unit weight, specific gravity, moisture content, water absorption capacity, and nominal aggregate size to ensure its suitability for the experiment. All physical tests were performed as per ASTM standards and conformed to all necessary standard requirements. Table 1 lists the appropriate test methods used and the corresponding physical properties gained as a result of the coarse aggregate.

2.1.3. Fine Aggregates

In this work, natural river sand from the city of Bahir Dar that passed through a 4.75 mm sieve was used as a fine aggregate. Table 2 shows the adopted test methods and
physical properties for sand, and based on the result attained, it conforms to all ASTM standard requirements.

Table 1. Coarse aggregate test results.

| No. | Property                        | Test Method | Result  | Unit       |
|-----|---------------------------------|-------------|---------|------------|
| 1   | Unit weight                     | ASTM C 29   | 1594.56 | kg/m$^3$   |
| 3   | Specific gravity                | ASTM C 128  | 2.75    | -          |
| 4   | Moisture content                | ASTM C128   | 1.01    | %          |
| 5   | Water absorption capacity       | ASTM C128   | 1.41    | %          |
| 6   | Nominal aggregate size          | -           | 25      | mm         |

Table 2. Fine aggregate test results.

| No. | Property                        | Test Method | Result  | Unit |
|-----|---------------------------------|-------------|---------|------|
| 1   | Fineness modulus                | ASTM C117   | 2.68    | -    |
| 2   | Specific gravity                | ASTM C 136  | 2.71    | -    |
| 3   | Moisture content                | ASTM C 128  | 1.8     | %    |
| 4   | Water absorption capacity       | ASTM C128   | 2.45    | %    |

2.1.4. Water Hyacinth

Figure 2 shows the main steps of the WHA production process. Firstly, water hyacinth was manually collected from Lake Tana in Bahir Dar, Amhara National Regional State, Ethiopia, because the use of machinery was prohibitively expensive. It is important to note that the manual collection method is a time-consuming and labor-intensive activity. Then, the collected samples were washed and cleaned with potable water to remove dirt and impurities. Thereafter, the washed samples were cut uniformly into smaller pieces and sundried for over a week. Finally, the WHA was found after the dried water hyacinth samples were burned in a Muffle Furnace at 800 °C for 6 h and cooled at room temperature for 24 h to convert the organic matter into an inorganic substance. The samples were then ground using a milling machine and sieved down to 150 µm. WHA samples passed through a 150 µm sieve were used as a cement replacement material [1].

2.2. Mix Proportions and Sample Preparation

The mix design was performed based on the physical test results of aggregates, as in the ACI 211.1 [36] mix design procedure for normal concrete. All concrete mixes were designed to achieve C-25-grade concrete with a target mean strength of 33.5 MPa. A cement content of 360 kg/m$^3$, a constant water–cement ratio of 0.49, and a slump of 25 to 50 mm were used to achieve the specified target mean strength. The designed mix proportion of the concrete was 1:2:3 (binder:fine aggregates:coarse aggregates). All mixes were batched with 0%, 5%, 10%, and 15% WHA by weight to replace cement. The mix proportion of cement to WHA and the mix designation are provided in Table 3.

Table 3. Mix designation.

| No. | Mix Designation | Percentage of Cement | Percentage of WHA |
|-----|-----------------|----------------------|-------------------|
| 1   | 0% WHA          | 100                  | 0                 |
| 2   | 5% WHA          | 95                   | 5                 |
| 3   | 10% WHA         | 90                   | 10                |
| 4   | 15% WHA         | 85                   | 15                |
A mechanical mixer was used to obtain a uniform mixture of ingredients. The mixing process entailed first dry mixing the binder and aggregates for three minutes followed by the slow addition of water as mixing continued. After all of the water was added, the mixing was continued for an additional three minutes in order to achieve a homogeneous mixture. Immediately after mixing, the slump of the mixture was evaluated, followed by pouring the fresh mixtures into pre-oiled molds to evaluate mechanical and durability properties.

2.3. Test Methods

Following various tests on the material qualities of cement, fine aggregates, coarse aggregates, and WHA, the fresh property of all concrete samples was determined in terms of the concrete’s workability. The ASTM C143-12 [37] slump test was used to examine the workability of concrete in a new concrete mix. The short-term water absorption capacity test came before the compressive strength test. The amount of water absorption—measured as residual water left in concrete interfaces—that determines how durable or fragile it is. Following a 72 h water curing period and a drying phase in an oven at 105 °C, the weights of the specimens were properly measured to determine the percentage of water absorption. The specimens were subsequently submerged in cold water for an additional hour before being properly weighed [33].

The water absorption of each concrete mixture was evaluated after 7 and 28 days of curing in accordance with ASTM C 642 [38]. For the compressive strength test, concrete cube specimens were cast in 150 mm × 150 mm × 150 mm and cured for 3, 7, 28, 56, and 91 days. After casting, the cubes were wrapped in plastic sheets and kept at room temperature for 24 h. The cubes were removed from the molds after 24 h of casting and submerged in water for curing until the time of the test. The compressive strength tests were performed on the samples in accordance with ASTM C 109 [39].

To study the behavior of WHA concrete in different environments, e.g., dampness, salts, acids, etc., different chemical solutions were prepared. The experimental work for chemical resistance was carried out according to ASTM C722 [40]. The resistance to sulfate attack was conducted on the compressive strength of the concrete cubes by immersing the samples in a 5% Na₂SO₄ solution. Fourier-transformed infrared (FTIR) spectroscopy tests were conducted on the selected mixes to identify the chemical compounds present in the hardened WHA samples using a DIGILAB FTS3500 with a transmittance wavelength range of 500–4000 cm⁻¹ [41–45]. The consumption and amount of calcium hydroxide in the sample were determined by thermogravimetric analysis (TGA). The TGA enables the
determination of fixed calcium hydroxide. To perform the TGA tests, the samples were prepared for 5% and 10% WHA at curing ages of 7 and 28 days.

3. Results and Discussion

3.1. Fresh Properties of WHA

The slump of concrete containing varying percentages of WHA is shown in Figure 3. As can be seen in Figure 3, as the percentage of WHA increases, the workability of the concrete improves. The slump of fresh concrete with 0% WHA was 35, whereas the slump with 5% WHA was 48, representing a 37.14% improvement in workability. The higher the percentage of WHA in the cement replacement, the better the workability of the concrete. Because WHA has a smooth surface and spherical shape, it lowers the specific surface area more than ordinary Portland cement [42]. The same effects were observed by [1,7,16].

![Figure 3. Workability of concrete for various percentages of WHA.](image)

3.2. Water Absorption Capacity

The water absorption of each concrete mixture was evaluated after 7 and 28 days of curing according to ASTM C 642 [38]. As shown in Figure 4, the water absorption of concrete significantly reduced as the age of the concrete increased. On the other hand, as the percentage of WHA cement replacement increases, the concrete absorbs slightly less water. This demonstrates that voids in WHA-replaced concrete are fewer and nonporous when compared with the control-mix concrete. The increase in mass expressed as a percentage of dry mass was used to analyze water absorption. It is evident that the cover concrete rapidly lost water while curing due to hydration. For concrete with a control mix, surface water absorption was 7.48% and 4.5% after 7 and 28 days, respectively. This higher water absorption could be attributed to the higher porosity of the concrete preserved on the surface due to air [38]. The amorphous phase of WHA may facilitate the hydration reaction and result in fewer unhydrated WHA particles, decreasing water absorption in the concrete samples [42].
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![Figure 4](image-url). Water absorption of concrete with different percentages of WHA.

3.3. Compressive Strength Development

To test the compressive strength of the hardened concrete, first, the concrete cube samples were immersed in a water tank containing clean water at a normal temperature of 25 ± 2 °C for curing ages of 3, 7, 28, 56, and 91 days, then they were dried for 24 h in the open air. The result of the test for each sample in all curing periods is shown in Figure 5. From the figure, it can be seen that, except for the 15% WHA-containing samples, the compressive strength of all concrete cubes increased incrementally with the WHA replacement level with respect to the normal (0% WHA) concrete. The figure also reveals that all samples, including the 15% WHA, achieved both the designed (25 MPA) and mean target (33.5 MPa) compressive strength at the later age of 28 days, and the result is supported by [1,13,25]. Compared with the 0% WHA, at 28 days, the strengths were improved by 1.4 MPa (4.23%) and 2.6 MPa (7.85%) for 5% WHA and 10% WHA, respectively, whereas the 15% WHA samples decreased by 1.10 MPa (3.23%). It can also be seen that the strength increased with curing age for all of the samples. Among the 56-day strength enhancements obtained above for concrete containing 10% WHA, a remarkable enhancement of (42%) was obtained with respect to the reference control mix. This enhancement could be related to a higher amount of calcium-silicate-hydrate (C–S–H) formed as a consequence of WHA addition. The main reason for the improvement in concrete compressive strength is the pozzolanic reaction from WHA and calcium hydroxide, which promotes the formation of hydrated calcium silicate. However, concrete without WHA can only rely on cement to hydrate into a small amount of C–S–H. Hydrated calcium silicate is one of the most important elements that provide strength. Therefore, the compressive strength of concrete with 10% WHA achieved maximum strength and was the optimum replacement level; the result is in agreement with previous findings [8]. According to [1,16], the incorporation of more than 10% WHA in cement concrete continuously decreased the compressive strength because increasing WHA content would greatly accelerate the rate of hydration in the concrete, resulting in the early evaporation of water from the mix before the full reaction could occur, resulting in a reduction in compressive strength.
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Figure 5. Compressive strength of concrete for different curing ages.

3.4. Thermogravimetric Analysis

In the TGA technique, the sample is first heated, and the mass change due to heating is recorded as a derivative thermogravimetric (DTG) curve. In studies on cementitious samples, the most significant mass changes are the mass loss due to H₂O release (dehydration, dehydroxylation) until they reach 550 °C and above 550 °C due to CO₂ release (decarbonation). In a sample that was treated with isopropanol and left in a vacuum to remove the free water, the mass loss until it reached 550 °C corresponded to the amount of bound water in the hydrate phases [46]. Between 450 and 550 °C, the main thermal transition (endothermic) was seen. The mass loss at this temperature range can be used to determine the amount of calcium hydroxide in the sample [46]. This peak indicates that Ca(OH)₂ or C–H breakdown occurs during heating, resulting in a considerable mass loss in the sample. Between 550 and 850 °C, a slight second peak was noticed, which is thought to be caused by the dissolution of CaCO₃ and the loss of water from the C–S–H gel. A low Ca/Si ratio suggests that C–A–S–H gel crystallinity reduces with increasing Al concentration and that increased Al-absorbed content results in more C–A–S–H phases. The following list of chemical reactions can be used to characterize the breakdown processes [46].

Dehydration of C–H:

\[
\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O} \uparrow \tag{1}
\]

Carbonation of CaCO₃:

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \uparrow \tag{2}
\]

Dehydroxylation of C–S–H:

\[
\text{C} - \text{S} - \text{H} \rightarrow \text{C} - \text{A} - \text{S} - \text{H} + \text{HO}_2 \uparrow \tag{3}
\]

In this study, TGA investigations were performed for the concrete samples containing 5% WHA after the 7th day of curing and for the 10% WHA samples after the 7th and 28th days of curing (Figures 6–8). As shown in the figures, to level the weight loss, we
subtracted the upper dotted line $Y$-axis value from the lower dotted line $Y$-axis value to obtain the weight loss (%) value for each portion. Figures 6 and 7 show the TGA results for 5% WHA and 10% WHA seventh-day curing samples, respectively. On day 7, the 5% WHA samples decomposed into an average of 27% C–H from the concrete mixes after an approximate heating temperature of 450 °C; it lost 10% after 50 °C (500 °C), and no decompositions occurred until the temperature reached 600 °C (Figure 6). Beyond 600 °C, water decomposed from C–S–H, and decarbonation (the release of CO$_2$ from CaCO$_3$) occurred. Together they lost 23% of their mass at 750 °C; after which, it remained constant. The thermal stability of the sample linearly decreased in terms of dehydration, dehydroxylation, and decarbonation for the 10% WHA content (Figure 7); compared with the 5% WHA mixes, it decomposed an equivalent amount of water and CO$_2$ (23%); a continuous heating temperature of more than 750 °C was required. This corroborates that the 5% WHA samples complete dehydration at a 750 °C heating temperature. As shown in Figure 8, a TGA examination of the 28th-day sample of concrete incorporating 10% WHA revealed that the Ca(OH)$_2$ dehydrated and lost about 0.30% of its mass at a temperature of 500 °C, and the figure indicates that there was no mass loss for C–H and other components of the concrete until the heating temperature rose above 600 °C. Then, after reaching 600 °C, the C–S–H gel and CaCO$_3$ released water and CO$_2$, respectively; they lost about 11% of their mass at a temperature of 700 °C, and further continuous reductions were observed up to 800 °C. This suggests that adding more WHA to the cement results in a pozzolanic reaction in the C–S–H gel produced by the cement and silica after the initial addition of WHA, and this also increases the heat of hydration; hence, the water within the C–S–H and the CO$_2$ present in the CaCO$_3$ evaporated rapidly, resulting in a large amount of dehydroxylation and decarbonation. This implies that the 5% WHA concrete sample contained more water than the 10% WHA concrete sample, and it takes more time (curing age) to achieve strength at early ages, as evidenced by the compressive strength result.

Figure 6. TGA curve for 5% WHA for 7 days of curing.
3.5. Fourier Transformed Infrared Spectroscopy Analysis

Figures 9 and 10 show the infrared spectra of selected WHA mixes (0% WHA, 5% WHA, 10% WHA, 15% WHA) at curing ages of 7 and 28 days (with main bands marked). The results show that the wavenumbers and curves of the 7- and 28-day pastes...
were essentially the same, indicating that the hydration products did not change with the
development of the hydration process, with the exception of the 7th-day samples, in which
the number of hydrated quartz particles was higher than that of the 28th-day samples,
where the wavelength stretched for the 10% WHA mixes. In the sample with the highest
percentage of 10% WHA samples, the unreacted particles displayed a sharply intensified
peak at wave numbers 470, 600, and 770 cm\(^{-1}\). This indicates an incomplete activation
reaction, which increased the amount of partially reacted and unreacted particles in the
sample and decreased its mechanical strength. This is consistent with the earlier discoveries
of [45].

![Figure 9. FTIR spectra of concrete with WHA for the 7th day.](image)

![Figure 10. FTIR spectra of concrete with WHA for the 28th day.](image)

Several past studies have revealed that mortar and concrete produced with
pozzolans with OPC performed better against sulfate attacks than plain OPC mortar and
concrete. The deterioration of concrete due to sulfate attack is mostly measured in terms
of weight loss, strength change, spalling, cracking, and expansion [48]. The changes in
compressive strength loss in the percentage of hardened concrete made with 5%, 10%, and
Figure 9 shows the infrared spectra of all 7-day samples, with spectra ranging from 500 to 4000 cm$^{-1}$ for the characteristic wavenumber and the associated functional groups of cement paste. From the result of the FTIR spectrum analysis of WHA, the major peaks were as follows: 3650, 3720, 2350, 2290, 1500, 920, 889, and 680 cm$^{-1}$. Due to the presence of calcium in the sample, a low wavenumber band can be observed at 684 cm$^{-1}$. H–O–H band vibrations were found at the peak value of 1500 cm$^{-1}$. The peak value of 684.15 cm$^{-1}$ indicates asymmetric stretching vibrations in Al–O bonds due to anhydrous WHA. Other researchers have observed T–O bond-stretching at the peak values of 966 cm$^{-1}$ and 1635 cm$^{-1}$, which correspond to H–O–H bonds and Al–O bonds at a wavenumber of 688 cm$^{-1}$ [47].

At the age of 28 days (Figure 10), the material became sharper at a peak of 960.80 cm$^{-1}$ due to the presence of activated alkali; this shift represents the gel component of the WHA material reacting with alkali activators. Because of this reaction, a new product, aluminosilicate hydrate gel, is formed. This study demonstrates the formation of chain links such as Si–O–Al. The extending vibrations related to O–H twisting vibrations and H–O–H extending vibrations (3600 to 1600 cm$^{-1}$) represent free water and provided proof of a soluble base initiation response in the concrete [38], revealing that the expansion of H–O–H extending vibrations could be observed at 3500 cm$^{-1}$. During the hydration reaction, 1030 to 1170 cm$^{-1}$ is attributed to the Ca-modified silica gel (C–S–H). The band area detail of 4000–3500 cm$^{-1}$ indicates the loss of Ca(OH)$_2$, 3500–1600 cm$^{-1}$ indicates the stretching of the –OH bond and bending of the H–O–H vibrations, and 1000–800 cm$^{-1}$ indicates the loss of the CaCO$_3$ gel [15].

3.6. Sulphate Attack Resistance

Several past studies have revealed that mortar and concrete produced with pozzolans with OPC performed better against sulfate attacks than plain OPC mortar and concrete. The deterioration of concrete due to sulfate attack is mostly measured in terms of weight loss, strength change, spalling, cracking, and expansion [48]. The changes in compressive strength loss in the percentage of hardened concrete made with 5%, 10%, and 15% WHA compared with the control mix (0% WHA) immersed in 5% Na$_2$SO$_4$ solution for 3, 7, 28, 56, and 91 days are plotted as a function of immersed curing time in Figure 11. A higher negative relative percentage indicates greater resistance to sulfate attack and higher positive results for lower resistance and vice versa [49]. The result in the figure shows that, for 5% and 10% WHA replacement levels for OPC, the concrete samples had better resistance to sulfate attack for all immersed curing times. Notably, after 56 days of curing time, both the 5% and 10% WHA samples outperformed 100% OPC concrete samples in terms of sulfate resistance, with 7.31% and 3.51%, respectively. On the other hand, they achieved 8.37% and 4.54% after 91 days of immersed time. However, a deterioration in compressive strength due to sulfate attack was observed when the cement was replaced with 15% WHA for all immersing periods. For instance, its compressive strength decreased by 6.21% (1 MPa) and 4.1% (1.7 MPa) for 3- and 91-day immersions, respectively. In addition, for all concrete samples, the sulfate attack resistances decreased when the samples were kept in sulfate solution for up to 28 days and gradually improved at the later age of 91 days. The ettringite and expansive gypsum that are formed as a result of sulfate attack are most likely the cause of degradation, cracking, spalling, and expansion in 100% OPC concrete. When OPC paste is submerged in sulfate solutions, the stiffness of the material reduces, and the water absorption values of ettringite increase, resulting in the formation of gypsum and ettringite [47,50]. Another problem is that by lowering cohesion in the hydrated OPC paste, as well as reducing adhesion among the aggregate particles, the expansion and cracking caused by sulfate attack enhances the compressive strength loss of concrete specimens [50]. Therefore, WHA plays a major role in OPC concrete by improving its sulfate resistance; 5% WHA is the maximum replacement level to resist any effects on the concrete and provides better resistance to sulfate attacks.
15% WHA compared with the control mix (0% WHA) immersed in 5% Na₂SO₄ solution for 3, 7, 28, 56, and 91 days are plotted as a function of immersed curing time in Figure 11. A higher negative relative percentage indicates greater resistance to sulfate attack and higher positive results for lower resistance and vice versa [49]. The result in the figure shows that, for 5% and 10% WHA replacement levels for OPC, the concrete samples had better resistance to sulfate attack for all immersed curing times. Notably, after 56 days of curing time, both the 5% and 10% WHA samples outperformed 100% OPC concrete samples in terms of sulfate resistance, with 7.31% and 3.51%, respectively. On the other hand, they achieved 8.37% and 4.54% after 91 days of immersed time. However, a deterioration in compressive strength due to sulfate attack was observed when the cement was replaced with 15% WHA for all immersion periods. For instance, its compressive strength decreased by 6.21% (1 MPa) and 4.1% (1.7 MPa) for 3- and 91-day immersions, respectively. In addition, for all concrete samples, the sulfate attack resistances decreased when the samples were kept in sulfate solution for up to 28 days and gradually improved at the later age of 91 days. The ettringite and expansive gypsum that are formed as a result of sulfate attack are most likely the cause of degradation, cracking, spalling, and expansion in 100% OPC concrete. When OPC paste is submerged in sulfate solutions, the stiffness of the material reduces, and the water absorption values of ettringite increase, resulting in the formation of gypsum and ettringite [47,50]. Another problem is that by lowering cohesion in the hydrated OPC paste, as well as reducing adhesion among the aggregate particles, the expansion and cracking caused by sulfate attack enhances the compressive strength loss of concrete specimens [50]. Therefore, WHA plays a major role in OPC concrete by improving its sulfate resistance; 5% WHA is the maximum replacement level to resist any effects on the concrete and provides better resistance to sulfate attacks.

Figure 11. Resistance of concrete to sulfate attacks.

All of the experimental results confirmed that replacing cement with WHA of up to 10% improves the engineering and microstructure properties of concrete. The use of WHA has significant environmental and socioeconomic implications. It helps to reduce the amount of ordinary Portland cement used in the production of concrete, which eventually reduces the energy required for cement production and preserves natural resources. Aside from improving the engineering and microstructural properties of concrete, the use of WHA in concrete could also reduce the negative impact of this invasive aquatic weed on human health, water quality, biodiversity, waterway flow, agriculture, fisheries, and recreation. All of these have significant economic and health consequences for society.

The use of WHA with only OPC is a limitation of this work. It is critical to conduct several experimental studies with WHA and other supplementary cementitious materials, with or without an alkali-activator, to examine its impact on several engineering and durability properties of concrete. Such experiments enable the identification of the best combinations to yield better mechanical and durability properties, as well as sustainability. In the future, the authors intend to conduct relevant experimental research with the inclusion of ground-granulated blast-furnace slag (GGBFS) in geopolymers, concrete, or mortar.

This study examined the impact of WHA on the workability, strength, durability, and microstructure properties of concrete to make use of an invasive aquatic weed, water hyacinth, removed from Lake Tana. The results corroborated that water hyacinth in the form of ash improved the performance of concrete. To achieve greater sustainability in the concrete industry, a thorough study of how to scale up the use of WHA is required. Indeed, because water hyacinth has several negative effects on natural waterbodies, the research should focus on planting and harvesting it in controlled artificial waterbodies to avoid the associated environmental and socioeconomic impacts. As a result, the authors encourage agricultural and environmental researchers to investigate the safe cultivation of water hyacinth. A lifecycle assessment of WHA will then be used to determine the long-term impact on concrete sustainability.
4. Conclusions

This work investigated the fresh, mechanical, and durability properties, as well as the microstructural performance, of concrete with WHA partially replacing ordinary Portland cement. An extensive literature review on this additive (WHA) was conducted, experiments were carried out, and test results were discussed. Based on the obtained results, the following conclusions can be drawn:

- Burning water hyacinth at 800 °C for 6 h yields a good pozzolanic property, suitable for use as a supplementary cementitious material in concrete.
- The slump values of concrete are highly dependent on the proportion of WHA. High levels of WHA increase slump results and, hence, the workability of the concrete mix.
- The concrete specimens exhibited a reduction in water absorption with curing time, which can be attributed to the minimal voids and pores in the concrete samples.
- The concrete specimens with the highest percentage of WHA exhibited the greatest durability.
- Adding 5% to 10% WHA to concrete improves its compressive strength. However, further increasing the WHA replacement level results in a decrease in the compressive strength of the concrete, with a 10% replacement of cement with WHA yielding the optimal results.
- A microstructure analysis confirmed that the structure of C–S–H gels changes in samples when WHA is added, which contributes to compressive strength. The decomposition of Ca(OH)₂ and the formation of CaO, as well as the release of H₂O, reduce the porosity of concrete.
- Replacing OPC with WHA in concrete by up to 10% would improve the sulfate attack resistance of the concrete.
- Further research is recommended to improve the use of WHA in concrete on a large scale in order to achieve greater sustainability without adverse environmental and socioeconomic impacts.

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