Potential of Anthill Soil as a Pozzolan in Concrete

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Abstract: Cement is the most utilised construction material and the second most consumed commodity in the world after water. It has been reported that the heavily energy-intensive processes that are involved in its production account for about 7 to 10 % of the total global anthropogenic carbon dioxide (CO_2), which is the main cause of climate change; and are also expensive economically. Energy and cost efficiency can however be achieved by reducing on the amount of clinker, and in its place utilising pozzolans, which require less process heating and emit lower levels of CO_2. This research aimed to provide an original contribution to the body of knowledge by investigating Anthill Soil (AHS) for pozzolanic properties. Cement was replaced in concrete with AHS by weight using 5% increments by weight, from 0 to 30% at the point of need. Durability was investigated using the water absorption and sulfate tests. Results of the chemical analysis by X-Ray Diffraction (XRD) showed that AHS contained the chemical composition required for pozzolans, and the compressive strengths achieved were for classes that are listed by standards as being durable and suitable for structural applications. The behaviour of AHS in workability, density, gain in compressive strength over time, water absorption and sulfate tests were also consistent with the characteristics of pozzolans, leading to a conclusion that it may be suitable for use as a pozzolan to improve the properties of concrete, reduce on the harmful effects of cement production to the environment and lower the overall cost of concrete, allowing for the construction of low cost buildings.

Key words: Anthill soil, cement replacements, pozzolans, sustainability of concrete.

1. Introduction

Literature has reported that alongside contributing to the sustainability of concrete, pozzolans result in more durable and affordable concrete [1]. It has been further argued that cement is one of the most notorious contributors to global anthropogenic carbon dioxide (CO_2) [2]. Cement was described by Zhou *et al*. [3] as the most utilised construction material, its global consumption only seconding that of water, and it is the main ingredient of concrete, constituting between 7 to 15% of the total mass of concrete [4]. The yearly global production of cement is about 1.6 billion tonnes, and accounts for approximately 7% of the total global CO_2 emissions [3]. Surprising, global emissions that amount from aviation were estimated at 2% by Johnson & Gonzalez [5], which is substantially lower than those from cement. More so, it has also been claimed that cement is the most energy intensive material produced after steel and aluminium, since it has been estimated that the production of a ton of cement emits approximately a corresponding ton of CO_2 [3]. In concurrence with Zhou *et al*. [3], research by the Mineral Products Association [6] reported that the Embodied Carbon Dioxide (ECO_2) of cement from cradle to factory gate was 930kg CO_2 per ton on

average.

The CO_2 that is emitted by the production of cement has been attributed to the raw materials, fossil fuels and electrical power that is used up by the production processes as is shown in (1) below [7]. The calcination of raw materials to produce cement requires temperatures of above 1450^0C [8].

$$CO_{2\ total} = CO_{2\ raw\ materials} + CO_{2\ fuels} + CO_{2\ electric\ power} \qquad (1)$$

Further arguments in literature have been raised in relation to the cost of cement. It has been opined that cement is the most expensive constituent of concrete, its price bearing an astronomical increase annually, and thereby becoming a major hindrance to the delivery of affordable housing and other infrastructure [8]. With these price increases, the basic need for low-cost but functional materials for construction cannot be emphasised enough [9]. In the wake of a global warming threat and skyrocketing prices of cement, and with a heavy demand for concrete in the developing world and other major and equally populous economies such as China and India predicted, cement producing companies have not anticipated in the foreseeable future any major changes in production that will reduce on emissions and cost [1]. However, energy and cost efficiency can be achieved by reducing on the amount of clinker, and in its place utilising pozzolans that require less process heating, emit fewer levels of CO_2 and are less expensive [10].

Anthills are soil grains coated with sticky hardening secretions from the recta and mouths of ants, and are very cohesive in nature [11]. Subsequently, Nene & Parihar [12], Odumodu [13] and Olaniyi & Umoh [11] opined that AHS must have a high plasticity index, and should therefore be superior to ordinary clay. AHS has been observed to endure extremely hot daytime and low night time tropical temperatures with no evidence of stress. AHS has also been observed to withstand heavy rainfall without disintegrating. Further, people have been observed to use AHS on paths that carry heavy human traffic as well as constructing traditional huts, and at the same time on plinths of the huts as additional mountings or footings. The authors observed a substantial quantity of AHS in tropical Africa, and using it in concrete could have a significant impact on reducing the amount of cement in concrete mixes and subsequently the cost. According to Olaniyi & Umoh [11], anthills are available all over the world, with the distribution depending on the soil and vegetation, climatic features and the presence of water.

This research aimed at exploring the suitability of Anthill Soil (AHS) as a pozzolan following these two objectives:

1) Investigating the feasibility of using AHS in concrete through analysing its chemical composition, workability, density and compressive and tensile strengths of the resultant concrete.
2) Examining the durability of concrete made using AHS in terms of water absorption and sulfate resistance.

So as to gain an in-depth knowledge on the performance of AHS in concrete, the fundamental quantitative method was used, with validity and reliability based on empirical data that was obtained from laboratory experiments, which by and large were cross-referenced with those of 100% cement. Kothari [14] argues that the findings of the empirical study are capable of being verified by experiments, and that evidence gathered by this method is the most powerful.

2. Why Use Pozzolans in Concrete?

Pozzolans are defined by Bapat [1] as aluminosiliceous or siliceous materials in finely divided form. They do not contain enough calcium to form cementitious materials, and need to combine with calcium hydroxide [$Ca(OH)_2$], also known as lime, from the hydration of cement [1]. As they are not hydraulic, they do not harden by themselves when they come into contact with water, but in amorphous state, and

through secondary hydration react with the lime that is released by the initial hydration in the presence of water to form further calcium silicate and calcium aluminate compounds, which are strength developing and less permeable [1].

Pozzolans mainly consist of reactive silicon dioxide (SiO_2) or glass, and aluminium oxide (Al_2O_3), with the remainder being iron oxide (Fe_2O_3) and other chemicals [15]. Calcium oxide (CaO) is essential for early strength development, whereas SiO_2 and Al_2O_3 are vital for latter age strength development, also known as the secondary hydration phase [16]. Due to low levels of CaO, pozzolans do not contribute to the early age strength gain during the early hydration phase, but only act as inert fillers. As a result, Nehdi *et al.* [17] opined that pozzolans may not be an alternative to admixtures where early age is of importance, even though Shetty [8] argued that consideration should also be taken with pozzolans as their gain in strength after 28 days is usually substantial.

During this early period, pozzolans are still beneficial because they increase the reactivity of cement by promoting early hydration due to increased space for the growth of hydrates that results from an increase in effective water cement ratio (WCR) as the water to solid ratio is kept constant [1]. The reactivity of cement is also enhanced by Pozzolans in the early age through the seeding effect that results from the addition of nucleation sites on the filler surface for hydrates from cement, as well as the change on the packing of particles [1]. The latter age strength that is associated with Pozzolans is due to the reaction of SiO_2 with free lime from cement hydration through the secondary reaction over time to form strength giving compounds such as Calcium Silicate Hydrate (C-S-H) as is shown in (2) after Bapat [1].

$$Pozzolans + Ca(OH)_2 \text{ (free lime)} + H_2O \text{ (water)} = \text{Calcium-Silicate-Hydrate (C-S-H)} \quad (2)$$
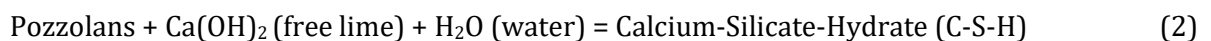
The C-S-H that is formed as a result of cement being replaced with Pozzolans changes from fibrillary to foil-like, resulting in a less well-interconnected capillary pore structure, thereby inhibiting bleeding by filling capillary channels and voids which were occupied by water and water-soluble lime, leading to lower permeability and consequently enhanced durability [18]. This secondary C-S-H is also less dense than the cement components from which it is generated [19]. Pozzolans also improve durability by absorbing alkalis due to their low ratio of CaO/SiO_2 [1]. The finely divided particles of Pozzolans micro-fill the voids that are found in the transition zone of plain concrete [1]. This transition zone is the interfacial region between coarse aggregate and hardened cement, where the cement paste is of poor quality due to internal bleeding, and aggregates are large and flaky, both of which weaken the bond between the cement paste and aggregates. Pozzolans reduce the width of the transition zone, porosity and the amount of free lime between cement and aggregates, thereby contributing to enhanced strength and durability [1].

Sulfate attack due to sodium sulfate (Na_2SO_4) is characterised by expansion due to the presence of $Ca(OH)_2$, which reacts with sulfates to form gypsum [$CaSO_4.2(H_2O)$], and/or with unhydrated aluminate (C_3A) and alumina-bearing hydration products, to form ettringite, whereas attack due to magnesium sulfate ($MgSO_4$) is characterised by the loss of strength from formation of the non-cementitious insoluble brucite [$Mg(OH)_2$], which destroys the C-S-H gel to form Magnesium Silicate Hydrate (M-S-H), that is not cementitious [1]. Due to the packing effect by unreacted particles, pozzolans reduce alite (C_3S) that otherwise promotes attack by sulfates and consume lime, the product of hydration, thereby hindering further production of gypsum during sulfate attack [1].

Pozzolans reduce the heat of hydration of wet concrete by 60%, aid pumpability and provide a better finish to freshly placed concrete [20]. Fologbade [21] in agreement with Kosmatka *et al.* [20] posited that the use of Pozzolans would be suitable for mass concreting and concrete works in hot climates by virtue of their slow strength development that is facilitated by their low heat of hydration, which reduces thermal

stresses. The use of Pozzolans also helps in preserving the environment by adding sustainability to concrete through the reduction of CO_2 that is emitted during the production of cement, optimising on the amount of concrete consumed by reducing the mass per unit volume of mixes due to their lower particle specific gravity and improving the properties of both fresh and hardened concrete; thereby enhancing the service life of structures [1] and [22]. Pozzolans also improve the workability of mixes, with high slumps being attributed to their lower density compared with that of cement, which increases the volume of mixes, prevents block formation of cement particles, and by the filler effect of their finer particles between aggregates and cement grains, reduce friction, thereby facilitating a better flow of concrete [23].

3. Research Significance

Abundantly observed in North Eastern Kenya by the authors, and could be by extension in many other hot climates, the potential of using AHS as a pozzolan to replace cement is high, but it has been remotely studied, and its use as such is currently non-existent. There is also debate as to its pozzolanity, with Olaniyi *et al.* [11] and Otieno *et al.* [24] reporting that it could have pozzolanic properties, but Sanguansub [25] claiming that it may not have any cementation other than suction, and attributing its good condition to rapid repairs by ants. Limited work was found on the performance of AHS in water absorption or sulfate aggressive environments, which has been found to be a major durability issue for concrete [1].

Among the parameters tested were the chemical composition of AHS by exploring minimum chemical composition requirements against the recommendations of the American Society for Testing and Materials [26] and British Standards Institution [15] and [27], and the density of AHS concrete, which, according to Shetty [8] should fall within 2000 and 2600 kg/m^3 for concrete. Compressive strength, which according to Arya [28] is the most important parameter in the design of structural concrete, since it can influence the long term serviceability of concrete, its ability to carry load and resist chemical infiltration as well as the cost of design and that of the overall project was also investigated. Other parameters considered were the gain in strength over time, which is an important characteristic of pozzolans, and performance in water absorption and resistance to sulfate attack, both of which count towards the durability of concrete [1]. In fact, Neville & Brooks [29] attached a higher importance to permeability over the chemical composition of a cement paste when it comes to durability, and argued that the ingress of harmful chemicals is the main cause of the corrosion of steel in concrete. Mehta [30] on the other hand posited that the diffusivity of sulfate ions, which is the main cause and control of the rate of degradation by sulfate attack varies by several orders of magnitude, compared with aluminate (C_3A), which only varies between 1% and 12%.

4. Experimental Programme

Anthill Soil (AHS) was harvested from the Eastern province of Kenya and transported to the UK for tests under licence. The qualitative chemical composition of AHS was obtained using X-Ray Diffraction (XRD). Well graded washed concrete sand of between 0 to 4.75 mm was used for fine aggregates, whereas for coarse aggregates, crushed limestone graded between 4.75 to 16mm was used conforming to BS EN 12620 [31]. This grading, according to Shetty [8] aids in achieving a better interlocking effect in concrete. Cement used was 52.5N snowcrete ordinary Portland cement, in accordance to BS EN 197-1 [15].

BS 5328 [32] gives methods of specifying concrete mixes using mix proportions for Standard mixes (ST). From Table 5 of BS 5328-2 [32], it is possible to target a slump based on the weight of cement and aggregate proportions, with total free water, which is specified in Table 14 of BS 5328-1 [33]. However, as this work also aimed at investigating the effect of AHS on the workability of concrete, the ST5 mix from Table 5 of British Standards [32], which is expected to have a slump of 125 mm at 370kg of cement, 1770kg of total

aggregates and a maximum Water Cement Ratio (WCR) of 0.45 to achieve a concrete of strength grade C50, was deliberately manipulated with more cement and aggregates than those specified by BS 5328 [32], and a WCR of 0.5 in a bid to achieve the lowest slumps possible for the control mix.

The quantities of cement, fine aggregates, coarse aggregates and water used were 380kg, 760kg, 1140kg and 180 litres per cubic meter respectively or a mix proportion of 1: 2: 3. AHS was dried and sieved using a 45 μm sieve conforming to BS 410-1 [34], to achieve a degree of fineness of not more than 63μm [35]. Cement was then replaced by weight using AHS at replacements of 0% to 30%, at 5% steps. The 0% replacement, also known as the control in this research, was used as the reference to which all performances were compared [36]. Concrete mixing conformed to ASTM C192 [37]. Aggregates, cement and water were introduced into a concrete mixer. The top of the mixer was covered to prevent evaporation and the mixer was run for a total of eight minutes with a three-minute rest in between the mixing. To determine workability, a slump test conforming to BS EN 12350 [38] was carried out, and the measurement was taken as is shown in Fig. 1.
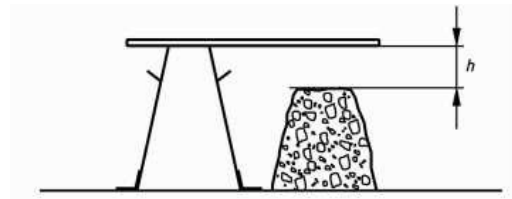

Fig. 1. Measurement of slump [38].

Cubes measuring $100 \times 100 \times 100$ mm were then cast for compressive strength tests, and at the same time cylinders of 300 height and 150 mm diameter were made for the splitting tensile strength tests to BS EN 12390-2 [39]. The specimens were stripped after 24 hours and kept submerged in water in a curing tank whose temperature was maintained at $20^0C \pm 2$, and a pH of 7 until their ages of testing conforming to BS EN 12390-2 [39]. Compressive tests were carried out at 7, 28, 56, and 90 days, following the rationale already discussed that the strength development due to pozzolanic reaction is slower compared to that of cement. BS EN 12390-3 [40] requires that at least three specimens be made for each test in order to ensure repeatability. For this study, ten identical specimens were cast for each test and a standard deviation was calculated.

The density of specimens was calculated by dividing mass / volume after weighing them in air and also while submerged in water and was reported in kilograms per cubic meter (Kg/m^3) [41]. Compressive tests were conducted to BS EN 12390-3 [40], whereby the strength (stress) is calculated by dividing maximum load at failure (Newtons) / cross sectional area (mm^2) and reported in Newtons per square millimetre (N/mm^2). The results reported for compressive strength were converted from mean strengths (f_{cm}) to characteristic strengths (f_{cu}) using equation (3) after Arya [28]. Tensile strength (splitting tensile) tests were conducted to BS EN 12390-6 [42] utilisng 150mm diameter cylinders.

$$f_{cu} = f_{cm} - 1.64 \text{ s.d } (N/mm^2) \tag{3}$$

where s.d is the standard deviation of the data collected

The water absorption test was carried out on the replacement that was found to have achieved the highest compressive strength from the strength tests described above, with the rationale based on Arya's [28] argument that durability is directly proportional to the compressive strength of concrete, and was conducted to BS EN 772-11 [43]. Test cubes were oven dried and weighed after curing before being immersed in water to a depth of 5 mm for a total of 10 minutes, after which they were re-weighed and the coefficient for water absorption ($C_{w.s}$) determined as specified in BS EN 772-11 [43].

Sulfate elongation tests conformed to ASTM C1012 [44], which specifies the test method for length change of hydraulic cement mortars exposed to sulfate solutions. Mortar bar prism samples of size 160 mm $\times$ 40 mm $\times$ 40 mm and 100 mm $\times$ 100 mm $\times$ 100 mm cubes were cast for the 5% replacement level (found to have achieved the highest compressive strength from the tests above). Two cubes were crushed to ensure that the mortar had achieved compressive strengths of not less than 20.0 ± 1.0 N/mm². The lengths of the bars were taken before immersion in 5% sodium sulfate (Na_2SO_4), 5% magnesium sulfate ($MgSO_4$) and 2.5% + 2.5% Na_2SO_4 and $MgSO_4$ solutions at laboratory temperatures of 23± 2⁰C. A pH of 6 to 8 was maintained on the sulfate solutions throughout the testing period. Lengths were measured at weeks 1, 2, 3, 4, and 8, and at 4, 8, and 9 months using a comparator. Readings were taken as an average of ten prisms. Length changes were calculated by using (4).

$$\Delta L = \frac{L_x - L_i}{L_g} x100$$

(4)

where:

Δ_L = percentage change in length at age of measuring,

L_x = Comparator reading at age of measuring (mm),

L_i = Comparator reading on immersion (mm),

L_g = 160 mm (nominal length between the innermost ends of the molds used).

Compressive strength deterioration was assessed using the method taken from Moon *et al.* [22], who studied deterioration from sulfate attack on cube specimens by measuring the Strength Deterioration Factor (SDF), which was calculated by using (5).

$$SDF = (f_{cw'} - f_{cs'}/f_{cw'}) \text{ x } 100$$

(5)

where $f_{cw'}$ is the compressive strength of cube specimens immersed in the control solution (N/mm²) and $f_{cs'}$ is the compressive strength of cube specimens immersed in the sulfate solutions (N/mm²). Visual observations for surface deterioration were made at the end of the 270 days immersion period.

5. Results and Discussions

5.1. Chemical Analysis

The American Society for Testing and Materials [26] and British Standards [15], [27] recommendations for natural pozzolans suitable for concrete are that the chemical composition should constitute of a sum of at least 70% Silicon dioxide (SiO_2), Aluminium oxide (Al_2O_3), and Iron oxide (Fe_2O_3); a maximum of 10% Calcium oxide (CaO) and a Loss On Ignition (LOI) of not more than 10%. The values in Table 1, obtained by X-Ray Diffraction (XRD) on the sample of AHS that was used for this study show a combination of SiO_2, Al_2O_3, and Fe_2O_3 of more than 70%, LOI of less than 10% and a CaO content of less than 10%, satisfying the requirements of these standards for natural pozzolans.

Table 1. Chemical Composition of AHS Used

Chemical	Percentage composition
Calcium oxide (CaO)	2.3
Silicon dioxide (SiO_2)	58.3
Aluminium oxide (Al_2O_3)	20.4
Ferric oxide (Fe_2O_3)	6.8
Magnesium oxide (MgO)	2.7
Potassium oxide (K_2O)	1.4
Sodium oxide (Na_2O)	0.6
Sulphur trioxide (SO_3)	0.3
Loss on ignition (LOI)	8.4

5.2. Workability

Fig. 2 shows the slumps of AHS replaced concrete over the seven replacement levels. According to literature, pozzolans improve the workability of concrete mixes due to their lower densities compared with that of cement, which increases the volume of mixes, prevents block formation of cement particles, and by the filler effect of their finer particles between aggregates and cement grains, reduce friction between particles, facilitating a better flow of concrete [23]. The density of AHS as a clay, being 1800kg/m³ is lower than that reported for cement (3100 kg/m³) [45] and [48]. AHS was observed to behave like a pozzolan by improving workability of the concrete studied, with workability increasing with further replacement.
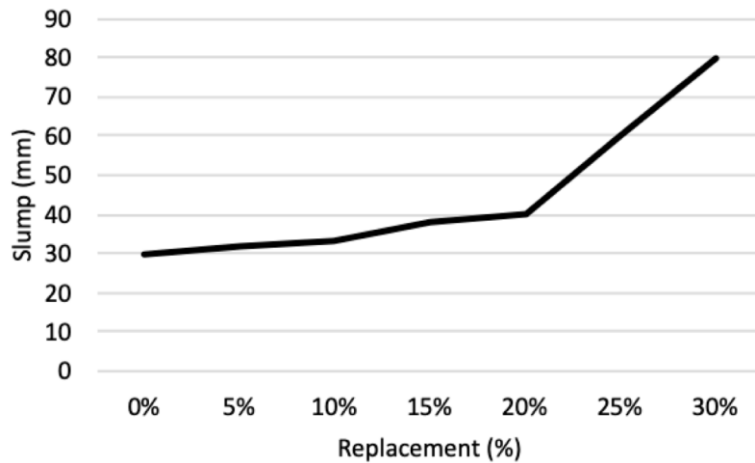

Fig. 2. Workability of AHS replaced concrete.

5.3. Density

Table 2 shows the standard deviation of the cube density data, whereas Fig. 3 shows the densities of AHS replaced specimens over 90 days of curing. Whereas the density of the control specimens increased with time due to the production of $Ca(OH)_2$, a product of the hydration of cement [1], those of the AHS-replaced specimens were observed to decrease with curing age, a characteristic which was explained by Bapat [1] as being a result of the eventual consumption of $Ca(OH)_2$ by the reaction that involves pozzolans during the secondary hydration to form the less dense C-S-H. AHS's behaviour in density is consistent with literature that the strength giving C-S-H produced as a result of the pozzolanic reaction is less dense than the cement components from which it is generated [19].
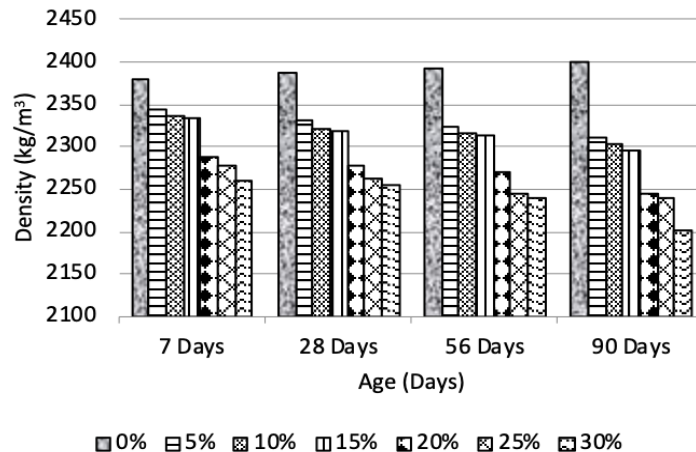

Fig. 3. Densities of AHS replaced specimens over 91 days (kg/m³).

Table 2. Standard Deviation (σ) of Cube Densities
(Kg/m³)

	7 days	28 days	56 days	90 days
0%	8.9	8.3	7.4	9.2
5%	8.1	10.9	11.2	9.5
10%	7.9	8.1	6.9	11.4
15%	11.2	9.6	9.2	11.0
20%	8.1	8.4	10.7	10.1
25%	7.7	11.3	8.3	9.8
30%	9.3	9.5	8.7	10.6

5.4. Compressive Strengths (f$_{cu}$)

Table 3 shows the standard deviations calculated from compressive test results achieved for the ten results per test of AHS replacements, whereas in Fig. 4 are the average characteristic compressive strengths (*f$_{cu}$*) achieved by the specimens over 90 days of curing. British Standards Institution (BSI) BS 8500 [46] lists concrete class C25 as the lowest strength grade that could be termed as durable and suitable to be used for structural applications. From the results, whereas only the 5% and 10% replacements achieved strengths that were above this grade at 28 days, all replacements were above this strength grade at 90 days. Compared with the control specimens, the gain in strength of the AHS specimens between 28 and 90 days was considerably high as is shown in Table 4. This is consistent with literature that the strength development of pozzolans is slow in the first 28 days, as their SiO$_2$ has to wait for Ca(OH)$_2$, the product of initial hydration of cement, with which it then reacts in the secondary hydration to form the further strength giving C-S-H [1].

Table 3. Standard Deviation (σ) of Cube Compressive Strengths
(N/mm²)

	7 days	28 days	56 days	90 days
0%	2.0	2.1	2.8	2.1
5%	2.2	1.5	2.3	2.0
10%	1.8	3.0	1.7	1.9
15%	2.1	1.6	1.9	2.2
20%	2.3	1.3	1.4	1.9
25%	1.4	1.7	2.3	1.3
30%	1.1	1.2	2.8	1.8
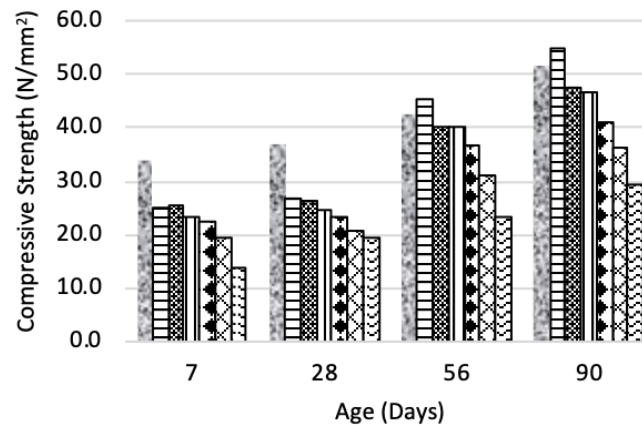
Fig. 4. Compressive strengths of AHS replaced specimens (N/mm²).

Table 4. Percentage Increase in Compressive Strength of AHS Replaced Specimens

0%	5%	10%	15%	20%	25%	30%
14.7	28.1	21.1	21.8	18.0	15.5	9.8

5.5. Tensile Strength

Table 5 shows the standard deviation of the splitting tensile strength data collected. The tensile strength of concrete has been reported to be approximately 10% of its compressive strength [29]. This fact was consistent throughout all replacements as can be seen in Fig. 5, with the tensile strengths of all replacements not falling far below those of the control. Tensile strengths are not very critical with structural concrete due to its weakness in tension, and for this reason steel bars, which are strong in tension are used to reinforce its tensile zone [28].

Table 5. Standard deviation (σ) of cube splitting tensile strengths (N/mm^2)

0%	0.5
5%	0.6
10%	1.1
15%	0.9
20%	0.4
25%	1.3
30%	0.7
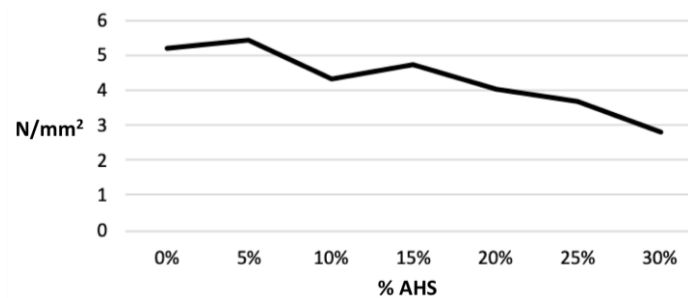
Fig. 5. Splitting tensile strengths of AHS replaced specimens at 90 days (N/mm^2).

5.6. Water Absorption

As discussed, Neville & Brooks [29] claimed that permeability is the most important aspect of durability and service life of structures. The work of pozzolans in reducing permeability through the filling up of pores using the secondary C-S-H gel was also discussed by Bapat [1]. Table 6 and Table 7 show the standard deviations and coefficients of water absorption of the 5% AHS replaced specimens (found to have achieved the highest compressive strength from the compressive strength tests) respectively against those of the control specimens.

Table 6. Standard Deviation (σ) of Cube Water Absorption

Specimens	[$C_{w.s}$ (g/m^2.s)]
Control	0.043
5% AHS	0.089

Table 7. Coefficients of water absorption of 5% AHS replacement [$C_{w.s}$ (g/m^2.s)]

Specimens	$C_{w.s}$ (g/m^2.s)
Control	0.5788
5% AHS	0.4402
Difference	0.1386

The results show that AHS was able to reduce the coefficient of water absorption by 0.1386 $C_{w.s}$ (g/m^2.s) or 24% from that of the control specimens, spelling lower permeability, and therefore could improve durability [29]. The ability of AHS to reduce water absorption can be related to the discussion before, whereby the hydration products of AHS precipitate in the small spaces between cement particles, blocking pores, thereby resulting in a refined pore structure, with a reduced number of pores [1]. It was also discussed that by pozzolanic activity, SiO_2 in pozzolans reacts with water and $Ca(OH)_2$ in the secondary hydration to form C-S-H, that inhibits bleeding by filling capillary channels and voids which were occupied by water and water-soluble lime, resulting in a denser concrete with low permeability [1].

5.7.   Sulfate Tests

Table 8 shows the Standard deviation of prism elongation data, whereas Figure 6 shows the average percentage elongation of AHS specimens at the 5% replacement after 270 days of immersion in the Na_2SO_4, $MgSO_4$ and mixed sulfate solutions. Consistent with literature, AHS specimens showed less elongation in the Na_2SO_4 solution. Bapat [1] posited that the pozzolanic reaction helps in resisting the Na_2SO_4 attack as they refine pores, dilute C_3A and remove $Ca(OH)_2$ by converting it into Calcium Silicate Hydrate (C-S-H), which is cementitious, thereby reducing the quantities of gypsum formed. Shetty [8], in agreement with Bapat [1] argued that the precipitation of $Ca(OH)_2$ between the grains of pozzolans, the consumption of $Ca(OH)_2$ and aluminate hydrate (C_xAH_y) by the pozzolanic reaction to form C-S-H, thereby reducing permeability; and the filler effect by unreacted particles of pozzolans limit gypsum and the secondary formation of ettringite in Na_2SO_4 environments.

Table 8. Standard Deviation (σ) of Prism Elongation Measurements

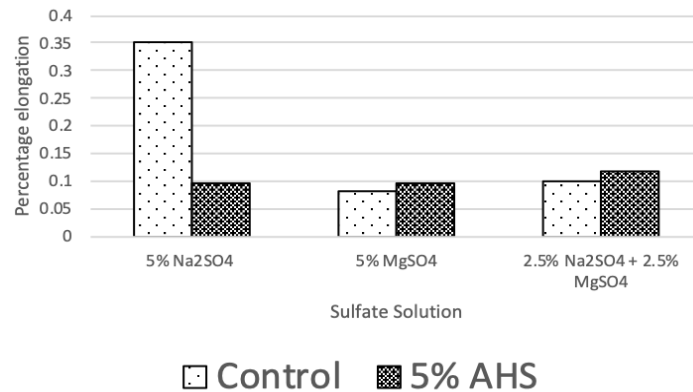| Specimens	Na_2SO_4	$MgSO_4$	Na_2SO_4 + Mg SO_4
Control	0.0019	0.0068	0.0014
5% AHS	0.0092	0.0026	0.0091

Fig. 6. Percentage elongations in sulfate solutions at 9 months for 5% AHS-replaced specimens.

Consistent with literature, the control specimens showed a marginally better performance than the AHS specimens in the $MgSO_4$ solution, even though according to Mehta [30], the loss of strength and adhesion rather than expansion and cracking should be the main manifestation of $MgSO_4$ attack. As discussed, the reaction between $MgSO_4$ and $Ca(OH)_2$ produces the insoluble brucite, which blocks capillary pores, forming a sulfate impermeable layer [22]. However, since pozzolans contain less $Ca(OH)_2$ and more C-S-H, $MgSO_4$ readily reacts with the secondary C-S-H gel to form Magnesium Silicate Hydrate (M-S-H) gel once the combined layer of gypsum and brucite has peeled off, explaining the perceived superiority of the control specimens over pozzolans in solutions that contained $MgSO_4$ for Moon *et al's* [22] work. The performance of

AHS in the mixed sulfate solution was consistent with literature. Pozzolanic specimens immersed in the mixed sulfate solution by Moon *et al* [22] were either similar or inferior to those that were immersed in the Na_2SO_4 solution, spelling the predominance of the more aggressive $MgSO_4$ attack over Na_2SO_4 attack, especially when the pH of pore water solution is low in the hydrated cement [1].

Table 9 shows the standard deviation of the Strength Deterioration Factors (SDFs) of the 5% AHS replaced specimens, whereas Fig. 7 shows the average SDFs of the specimens. AHS's behaviour was consistent with literature in the Na_2SO_4, $MgSO_4$ and the mixed sulfate solutions, whereby SDFs were lower in both the Na_2SO_4 and mixed sulfate solutions, but slightly higher in the $MgSO_4$ solution. Moon *et al* [22] observed higher SDFs for Silica Fume (SF) specimens immersed in the $MgSO_4$ solution. As discussed, the loss of strength is associated with decalcification of cement hydrates, mainly C-S-H [1]. Bapat [1] and Moon *et al* [22] attributed the low performances of pozzolans in the $MgSO_4$ solution to the formation of insoluble brucite [$Mg(OH)_2$], which destabilises and destroys the C-S-H gel to form the non-cementitious M-S-H, which causes softening of the cement matrix. The alteration of C-S-H to M-S-H was termed as the major process and probably the final stage of $MgSO_4$ attack by Al-Amoudi *et al* [47] and Bapat [1]. $MgSO_4$ attack on the secondary C-S-H to form M-S-H gel explains the similarity in behaviour of the control and pozzolanic specimens in solutions that contain $MgSO_4$ [22]. The strength deterioration in the $MgSO_4$ solution was consistent with literature that $MgSO_4$ attack is manifested through the loss of strength [1].

As also discussed, ettringite and gypsum are the compounds that cause expansion and cracking of hardened concrete in Na_2SO_4 environments, with ettringite being associated with expansion and gypsum with the loss of stiffness, adhesion and strength [48]. It was also discussed that pozzolanic reactions refine pores, dilute C_3A and remove $Ca(OH)_2$ by converting it into a cementitious material, thereby reducing the quantities of gypsum formed. The secondary C-S-H densifies the pore structure and transition zone, and as a result reduces the permeability and diffusion of sulfate ions into hardened concrete, thereby limiting gypsum and secondary formation of ettringite [1]. This is reinforced by the fact that the permeability of AHS specimens reported in Table 7 above was lower than that of the control specimens, and may have therefore hindered the ingress of sulfate ions in the Na_2SO_4 solution.

Table 9. Standard Deviation (σ) of Cube Strength Deterioration Factors (SDFs)

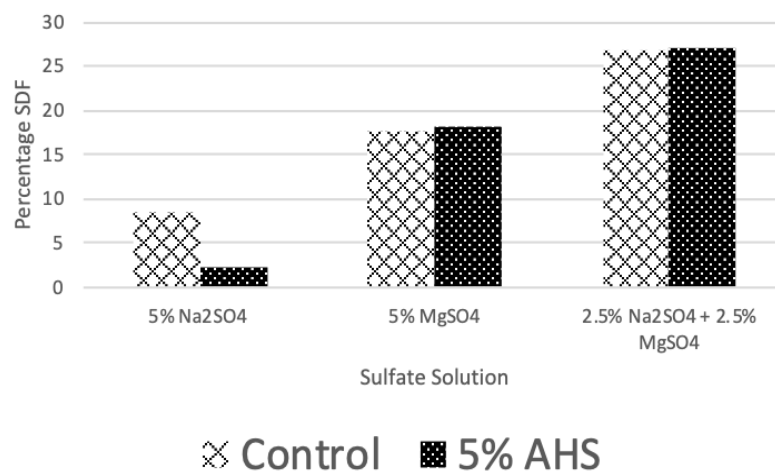| Specimens	Na_2SO_4	$MgSO_4$	Na_2SO_4 + Mg SO_4
Control	0.7	1.3	1.1
5% AHS	0.3	1.5	1.2

Fig. 7. Strength Deterioration Factors (SDFs) of specimens immersed in sulfate solutions.

Consistent with the results of this study, Bapat [1] in agreement with Mehta [30] posited that the reaction between Na_2SO_4 and C-S-H is negligible and as such, Na_2SO_4 attack is manifested and evaluated through expansion due to the presence of gypsum and ettringite. The findings agree with Moon *et al* [22] who reported higher SDFs for the control specimens in the Na_2SO_4 solution compared with those of SF replaced specimens.

| MgSO₄ | Na₂SO₄ | Na₂SO₄ +MgSO₄ |

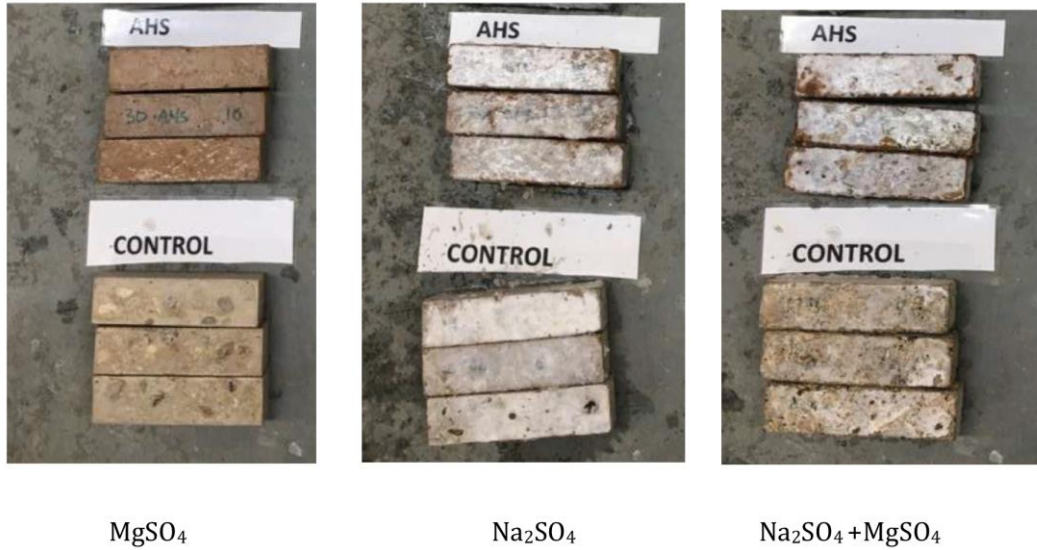$MgSO_4$ Na_2SO_4 $Na_2SO_4 + MgSO_4$

Fig. 8. Surface deterioration of specimens immersed in sulfate solutions at 270 days.

Fig. 8 shows the extent of surface deterioration of the control and 5% AHS specimens immersed in the three sulfate solutions at 270 days. From the results, no surface deterioration was observed on all specimens that were immersed in the Na_2SO_4 solution, whereas extensive surface deterioration which included cracking, mass loss and some disintegration were observed on specimens that were immersed in the $MgSO_4$ solution. For the mixed sulfate solution, visible wider cracks, mass loss, spalling and some disintegration were observed on the control specimens, whereas for the AHS specimens, a mass loss and some disintegration was observed. Moon *et al* [22] attributed the good performance of the control specimens in the $MgSO_4$ solution to the pore blocking effect by the formation of the less permeable brucite. Consistent with literature, the most severe effects of sulfate attack were observed in solutions that contained $MgSO_4$ [1]. Also consistent with literature, the inferiority of specimens that were immersed in the mixed sulfate solution to those that were immersed in the Na_2SO_4 solution spelled the predominance of the more aggressive $MgSO_4$ attack over the Na_2SO_4 attack, which is also highly soluble in water at room temperature (20^0C) compared to Na_2SO_4 [1] and [22]. For Moon *et al's* [22] work, sulfate ions diffused more rapidly in the mixed sulfate solution compared with the individual sulfate solutions, and reacted with the $Ca(OH)_2$ to form gypsum of softening sulfate attack. Moon *et al* [22] further posited that the presence of brucite and gypsum for specimens that were immersed in the $MgSO_4$ solution was the cause of surface deterioration. Unlike Moon *et al* [22] who reported that the control specimens showed visible cracks and spalling in the Na_2SO_4 solution, little surface deterioration was observed on the control specimens in the Na_2SO_4 solution.

6. Inference

The standard deviations calculated for the densities, compressive and tensile strengths, water absorption, sulfate elongation and strength deterioration tests show a small spread of data from the means, and as a result signify a good repeatability, and consequently a high level of confidence in the results obtained. The fact that AHS improved workability of the concrete tested, reduced its density, did not undermine its

compressive and tensile strengths, and that it showed a trend of increasing compressive strength over time, reduced water absorption and gave advantage in sulfate solutions consistent with the properties of pozzolans points towards a conclusion that it could possess pozzolanic properties, and that there is a great potential of introducing it in concrete with benefits of improving its properties in both fresh and hardened states. Using AHS in concrete could also work towards sustainability by reducing the amount of cement consumed and lowering the overall cost of concrete, thereby allowing for the construction of low cost buildings. The findings challenge Sanguansub's [25] claims that AHS may not have any cementation other than suction, and that their good conditions are just but a result of the rapid repairs by ants. Moreover, the chemical composition of AHS in Table 1 shows that it possesses the required chemical composition as is recommended by the American Society for Testing and Materials [26] and British Standards Institution [27] for natural pozzolans.

7. Conclusion

This work investigated the pozzolanic properties of Anthill Soil (AHS) in concrete. Cement was supplemented in concrete with AHS by weight from 0% to 30% replacements using 5% steps at the point of need. Durability was investigated using water absorption and sulfate tests. Results of the chemical analysis by X-Ray Diffraction (XRD) showed that AHS contained the required chemical composition for pozzolans, and the compressive strengths achieved were for those classes that are listed as being durable and suitable for structural applications. The behaviour of AHS in workability, density, and gain in compressive strength over time, sulfate tests and water absorption were also consistent with the characteristics of pozzolans. This evidence, coupled with evidence of the abundance of AHS in warm climates points towards the conclusion that AHS may qualify to be added to the pozzolanic family of materials, to improve the properties of concrete, reduce on the harmful effects of cement production processes to the environment and lower the overall cost of concrete to facilitate low cost buildings.

Acknowledgment

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

John Kamau conducted the research, analyzed the data, wrote the paper; Ash Ahmed analyzed the data, wrote the paper; Joseph Kangwa wrote the paper. Ash Ahmed also hereby confirms all authors approve the final version.

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