Establishing an optimal content of treated wastewater sludge ash as cementitious addition in concrete

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***Abstract*—The paper investigated the application of pulverised wastewater treatment sludge as a replacement for cement in concrete production. The physico-chemical properties of the sludge obtained from 90 Ml/day capacity treatment plant and burnt to 1000°C were determined. The influence of sewage sludge ash (SSA) blended in partial replacement for cement in concrete was investigated for workability, tensile and compressive strength and water absorption. The chemical composition of the sludge ash conducted by x-ray fluorescence (XRF) analysis showed that silica and alumina contents accounted for 50.7% with high content of hematite (>10%). The burnt sludge was then introduced as replacement for cement in the ratio 0, 10, 20 and 30% for concrete mix ratio 1:1.5:3 at water-cement ratio of 0.5. The workability, measured via slump and compaction factor, mildly decreased linearly with SSA content, though within acceptable standard limits. The irregular morphology of SSA particles produced a decrease of slight decrease of concrete workability. The split tensile and compressive strength relationships with respect to SSA content were parabolic at an optimum SSA content of 18%. The water absorption decreased with curing age of concrete and increased linearly with SSA content.**

***Keywords*—Blended cement concrete, sewage sludge ash, cementitious addition, workability, compressive strength, tensile strength, water absorption.**

I. Introduction

The construction industry is a vast consumer of natural resources and among the largest greenhouse gases emission sources, which makes it one of the major threats to non-renewable natural resources. The integrated waste management strategy demands for reduction, recycling and reuse of wastes for a sustainable and cleaner environment. Recycling and reuse of wastes have found tremendous application in building and construction materials. There is a strong demand for environmentally safe reuse and effective disposal methods for sludge due to the increasing quantity of sludge generated by the water and wastewater treatment plants in major cities of the world. Although sanitary landfills are the conventional method of disposal of sewage sludge, rapid urbanization has made it increasingly difficult to find suitable landfill sites in densely populated cities. Moreover, rapid decrease in both the capacity and residual service life of existing landfill facilities are of great concerns to built environment professionals especially the urban and regional planners. Therefore, incineration has become one of the few alternatives available for disposal of sewage sludge. These ashes are a serious problem, so their valorization in a sector like construction, with a high demand for resources, would be of a great advantage from an economic and environmental perspective. Sewage sludge ash, a fine-size silty material, is the by-product produced during the combustion of dewatered sewage sludge in an incinerator [1].

Recently, Adewuyi & Ola [2] investigated the applicability of water supply treatment sludge ash as cementitious addition or supplements for building and infrastructure construction to mitigate the disposal problems. A number of feasibility studies have been conducted on usefulness of sludge as construction materials, namely cementitious material substitutes, building bricks and lightweight fine aggregates [3-7]. The utilization of digested sludge blended with limestone to produce a ‘‘biocement’’ was among the successful outcomes of such investigations [8]. Several studies have shown that sludge or sludge ash could blend with clay to produce brick [4, 9-11]. In furtherance to Tay [3], Lin & Weng [12] found that the pulverized sewage sludge ash content and firing temperature were the two key factors determining the quality of brick. They found 20 to 40% of ash content (fired at 1000°C for 6 h) most appropriate for producing quality bricks with corresponding optimum moisture content of 13-15%. However, 10% ash content produced clay bricks with higher compressive strength than normal clay bricks.

Baeza-Brotons et al. [13] studied the viability of using sewage sludge ash (SSA) as 5, 10, 15 and 20% partial replacement of ordinary Portland cement in concrete. It was found that the addition of SSA in concrete blocks cured for 28 days gave densities and strengths similar to the control sample (0% SSA) with significant reduction of water absorption. Smol et al. [14] presented a nice review of potential applications of SSA in the production of construction of materials production. The most important utilization of SSA in construction industry include cementitious additions, production of bricks, ceramic and glass, stabilizing agents and binding materials for pavement layers in road constructions.

Adewuyi et al. [15] investigated the physical, chemical and mineralogical properties sludge ash produced from a 90 Ml/day capacity Glen Valley Wastewater Treatment Plant in Gaborone, Botswana to establish the feasibility of utilizing SSA in partial replacement of cement in concretes and mortars. However, the physical chemical and mineralogical properties of SSA vary with the source and the treatment processes of wastewater, and the temperature and duration of the pulverization process ([2], [15]). The primary purpose of this paper was to investigate the influence of varying content of SSA in partial replacement of Portland cement on the properties of fresh and hardened concrete.

II. Description of the Study Area

Glen Valley wastewater treatment plant is a 90 Ml/day capacity facility comprising the old and new plants of capacity 40 Ml/day and 50 Ml/day respectively which serves Gaborone municipality and the surrounding settlements. Gaborone is the capital city of Botswana. The treatment plant which started operation in 2009 was designed to treat incoming streams of both domestic and industrial wastewater as well as substantial amount of evacuated wastes pit latrines around the city. Glen Valley is now run by Water Utility Corporation. It is located at Broudhurst in the northeastern part of Gaborone. Although Gaborone is not a heavily industrialized city, it accounts for major industries such as breweries, abattoirs, paper and pulp, pharmaceutical, paints and chemical industries which discharge their wastewater into the sewer networks. The wastewater undergoes both primary and secondary (biological) treatment where both primary sludge and secondary sludge are formed. The treated sludge is stored in piles for the use of local farmers and individuals as manure for agriculture purpose. Typical treatment processes employed at Glen Valley treatment plant includes primary settlement, secondary settlement, aerobic digestion and anaerobic digestion.

III. Experimental Programme

A. Materials

Grade 32.5 ordinary Portland cement was used in this study. Coarse aggregate was crushed granite of maximum nominal size of 19 mm. Fine aggregate was natural coarse sand collected from Notwane River of maximum nominal size of 4.75 mm. The particle size distribution curves of the aggregates are plotted in Figure 1. The properties of cement such as consistency, setting times, soundness and compressive strength are summarized in Table 1. The aggregates were free from deleterious materials and the physical properties were carried out in accordance with BS 812 [16]. The properties of fine and coarse aggregates are presented in Table 2. It is obvious that the fine and coarse aggregates employed as constituents of the concrete in the study are well-graded. Potable water of pH of 7.1 which conformed to the requirements of BS 3148 [17] was used in mixing the aggregates and cement.

Notwane river sand as fine aggregate

Crushed granite as coarse aggregate

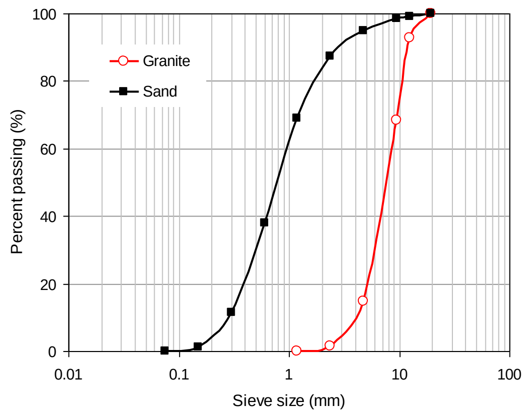

Fig. 1: Samples of particle size distribution of fine and coarse aggregates

TABLE 1: PHYSICAL PROPERTIES OF CEMENT

Standard Consistency (%)	30
Specific gravity	3.15
Initial setting time (min)	290
Final setting time (min)	450
Soundness (mm)	1.0
Compressive strength (N/mm^2)	
3 days	24.5
7 days	30.8

TABLE 2: PROPERTIES OF AGGREGATES

	Sand	Crushed granite
Specific Gravity	2.64	2.70
Bulk Density (kg/m^3)	1240	1464
Moisture content	4.09	0.6
Fineness modulus	3.00	6.15
Aggregate Crushing Value (%)		12.9
Impact Value (%)		7.13

B. *Physical properties of sewage sludge ash*

The dried sewage sludge was collected from the GVWTP. The colour of the sundried sludge was deep gray and subsequently changed to reddish brown after incineration to a temperature of 1000°C for 2 hours. The loose bulk density of sludge ash was 810 kg/m^3. The pH of the sludge ash was 7.1, the specific gravity was 2.45 g/cm^3 and the BET surface area was 6.7 m^2/g. The results agreed with the findings of Donatello *et al*. [18]. It is obvious from the particle size distribution of the sludge ash in Figure 2 that over 60% of the material was finer than 50 µm.The texture of sun-dried sludge was rough, while the smoothness of the sieved sludge ash was comparable to cement as shown in Figure 3.

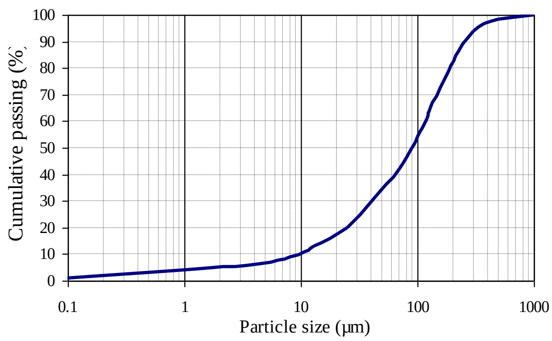

Fig. 2: Cumulative particle size distribution of sludge ash from Glenn Valley Plant

Sun-dried raw sludge

Sludge ash ≤ 50 µm

Fig. 3: The texture of raw sludge and sludge ash ≤ 50 µm sludge.

C. *Preparation and analysis of sludge ash*

The specific gravity of sludge ash was determined by pycnometer. The particle size distribution was analyzed by laser diffraction over the size range 0.4–900 µm using Beckman Coulter LS-100. The specific surface area and pore size distribution of sludge ash was determined by a single port Gas Sorption Analyzer Coulter Omnisorp 100 using the Brunauer–Emmett–Teller (BET) test method. The pH was determined by preparing a 1:5 sludge ash to liquid ratio suspension using deionized water. The mixture was shaken for 5 min and left for 3 hours to equilibrate before measuring the pH in accordance with BS 7755 [18].

The chemical composition of the sludge ash was determined by X-ray fluorescence (XRF) using dispersive energy spectrophotometer. The elemental oxide contents in the sludge especially the silicon oxide (SiO_2) or silica present was a principal criterion for a good pozzolan. Loss on ignition (LOI), which is a measure of percentage of organic content (carbon) in the material, was determined by oven drying 2–3 g of material at 105°C to constant mass before calcining at 1000°C for 2 hours, cooling and re-weighing. The loss in weight is expressed as a percentage of the original sample

D. Chemical composition of SSA

The chemical constituents of the sludge ash produced from the Glen Valley wastewater treatment plant as analyzed by XRF is tabulated in Table 3. It can be observed silica and alumina contents accounted for 50.7% of the constituents of the sludge ash. The sum of SiO_2, Al_2O_3 and Fe_2O_3 was 64%. Also, high content of Fe_2O_3 (> 10%), which is a reactive oxides as the previous two, qualified the ash as an active mineral addition in partial replacement of cement in concretes and mortars. With the CaO content (> 10%), the ash is expected to behave as an inert mineral residue. The 8.5% content of phosphorus, indicated by P_2O_5, explained why farmers collect the treated sludge as a phosphate fertilizer for agricultural purposes. The combination of reactive oxides, inert mineral and phosphate oxide in a significant level is an indication of varieties sources of waste discharged into Glen Valley treatment plant. The low value of LOI (< 10%) shows that organic content in the sludge is relatively low, thereby enhancing the binding properties of the sludge ash when mixed with cement.

TABLE 3: CHEMICAL COMPOSITION OF SSA

Constituents	% by weight of dry sample (average of three samples)
SiO_2	40.3
Al_2O_3	10.4
Fe_2O_3	13.3
CaO	13.1
MgO	1.7
K_2O	0.9
Na_2O	2.9
MnO	0.1
TiO_2	0.5
P_2O_5	8.5
SO_3	3.6
Cl	0.1
LOI	4.6

E. Mix proportioning and casting of concrete specimens

Four different concrete mix proportions designated C_0, C_1, C_2 and C_3 with a fixed water-cement ratio of 0.5 were considered for the study. The cementitious materials, fine and coarse aggregates were kept constant at 410 kg/m^3, 615 kg/m^3 and 1230 kg/m^3 respectively representing a concrete mix ratio of 1:1.5:3 in proportion of cement, fine and coarse aggregates. The only difference in the concrete mix proportions C_0, C_1, C_2 and C_3 is the percentage SSA content corresponding to 0, 10, 20 and 30% of the mass of cement. Each concrete mix proportion was prepared in a rotating drum mixer. The aggregates and cement were placed in the drum and mixed in parts with water to ensure a better bond between the cement paste and the aggregates. All mixing and sampling of concrete were carried out in accordance with the procedures given in BS 1881. The mix proportioning computed using arbitrary volume method is presented in Table 4.

TABLE 4: CONCRETE MIX PROPORTION

Mix proportions	C_0	C_1	C_2	C_3
Cement (kg/m^3)	410	369	328	287
SSA (kg/m^3)	0	41	82	123
SSA/cement ratio (%)	0	10	20	30
Water (kg/m^3)	205	205	205	205
Water/cement ratio	0.50	0.50	0.50	0.50
Fine aggregate (kg/m^3)	615	615	615	615
Coarse aggregate (kg/m^3)	1230	1230	1230	1230
All constituents (kg/m^3)	2460	2460	2460	2460
Average Slump (mm)	65	51	45	35

Three concrete cylinders of 100 mm diameter × 200 mm length each of 0, 10, 20 and 30% SSA contents were cast, cured and tested for split tensile strength at 28 days. Also, a total of forty-eight 150 mm concrete cube specimens (representing 12 cubes of 0, 10, 20 and 30% SSA contents) were cast, cured and tested for compressive strength according to BS 1881. The compressive strengths of the specimens were determined from average crushing load of 150 mm cubes at 7, 14, 21 and 28 days. Concrete specimens were cast and then covered with thin polythene membrane to minimize moisture loss. The concretes were stored and tested in the laboratory under mean air temperature of 26 ± 1˚C. The specimens were demoulded after 24 ± ½ hours and then transferred into a water-curing tank for the test periods.

IV. RESULTS AND DISCUSSION

A. Setting times of cementitious materials

The binding quality of portland cement paste is due to the chemical reaction between the cement and water, called hydration. Portland cement is not a simple chemical compound, it is a mixture of many compounds. Four of these make up 90% or more of the weight of portland cement: tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite. The purpose of the setting time test is to determine the time that elapses from the moment water is added until the paste ceases to be fluid and plastic (called initial set) and the time required for the paste to acquire a certain degree of hardness (called final set). The initial and final sets of the SSA-blended cement showed linear trends for both the initial and final sets as shown in Figure 4.

The set times increased as the SSA content increased. The difference between the initial and final set times decreased between 0 and 10% SSA, and later widened up as the SSA content increased. The rate of the final set time increased more highly with SSA content than the trend of the initial set time.

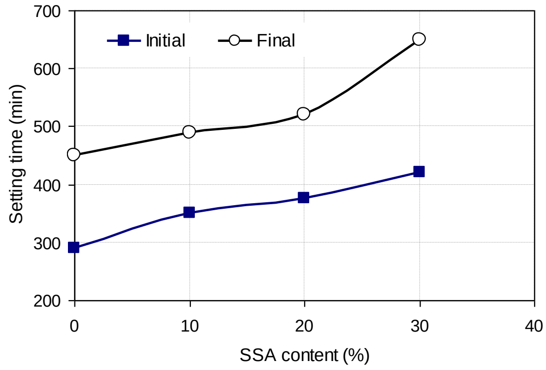

Fig. 4: Initial and final set times for SSA-blended cement.

B. Properties of fresh SSA-blended cement concrete

Concrete must always be made with a workability, consistency, and plasticity suitable for job conditions. Workability is a measure of how easy or difficult it is to place, consolidate, and finish concrete. This study assessed the workability of the mix proportions using slump and compaction factor tests. Figure 5 shows the test results of workability of the four concrete mixtures. The slump of the concrete mixes decreased linearly with increase in SSA content. The control specimen C_0 had the highest slump of 65 mm, while C_3 had the lowest slump value of 35 mm. It is evident from the test results that slump fell within the recommended range for plain and reinforced concrete. The relationship between slump and SSA content is almost perfectly linear with $s = -0.96c + 63.4$ ($R^2 = 0.98$), where s and c are the slump value and SSA content respectively.

The slump of C_1, C_2 and C_3 represent 21.5%, 30.8% and 46.2% difference with respect to the control C_0. This shows that there is a steep loss of workability as the SSA content in the mix increased from 0 to 30%. Likewise, the relationship between the compaction factor and the SSA content was also perfectly linear with $cf = -0.0026c + 0.924$ ($R^2 = 0.97$), where cf and c are the compaction factor and SSA content respectively. The slump of concrete mixes C_1, C_2 and C_3 represent 4.3%, 6.5% and 8.6% difference with respect to the control C_0. It is apparent that SSA content did not have much effect on the compaction factor of the mixes.

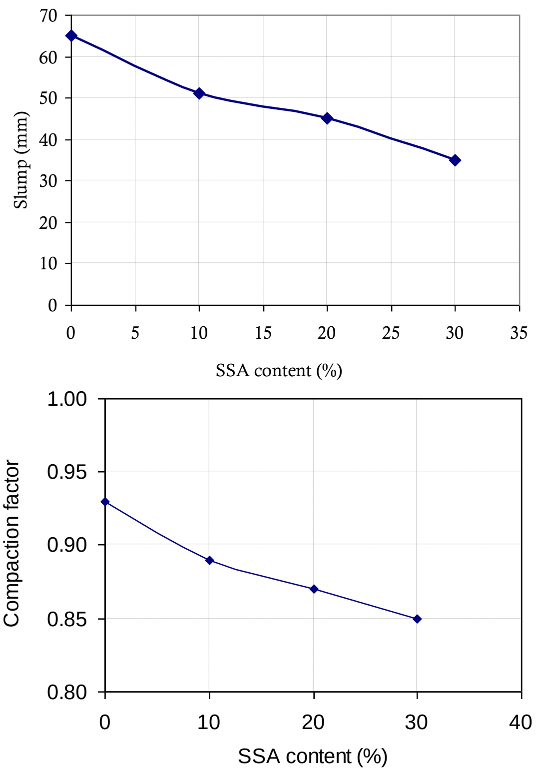

Fig. 5: Workability of SSA-blended cement concrete

C. Split tensile strength of SSA-blended cement concrete

The tensile strength of concrete is conventionally about one-tenth of the compressive strength. It is determined by loading a concrete cylinder across a diameter in accordance with BS EN 12390:6 [19]. The relationship between the split tensile strength of the concrete mixes and the SSA content was simply quadratic or more perfectly cubic as shown in Figure 6.

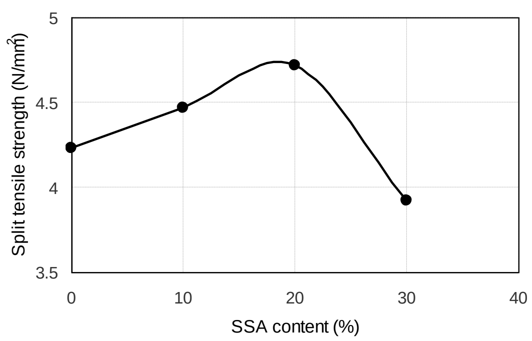

Fig. 6: Split tensile strength for SSA-blended cement concrete

The 28th day tensile strength of concrete increased steadily until it reached its peak at 20% SSA content and thereafter declined. The tensile strength as the percentage of the compressive strength showed that C_0, C_1, C_2 and C_3 were 13.1%, 11.5%, 11.8% and 15.1%. The direct tensile strength of normal concrete is usually between 8 and 12% of the compressive strength and is often estimated as 0.4 to 0.7 times the square root of the compressive strength in MPa [20]. However, the tensile/compressive strength ratios for C_0 and C_3 mixtures fell out of the normal range, while C_1 and C_2 were within the specified range. The findings gave an optimal SSA content of 18% for split tensile strength.

D. Compressive strength of SSA-blended cement concrete

Compressive strength is the measured maximum resistance of a concrete specimen to axial loading. The 7th day strengths of concrete are often estimated to be about 75% of the 28th day strength ([20], [21]). As shown in Figure 7, the 7th day strengths of C_0, C_1, C_2 and C_3 were 52%, 62%, 64.6% and 59.2% of the 28th strength which fell below the conventional prediction. The compressive strength of concrete specimens with respect to the SSA-blended cement concrete is parabolic. The optimal SSA content for maximum compressive strength was also 18%. Concrete mixes C_1 and C_2 (corresponding to 10% and 20% SSA) had 20.4% and 24.1% compressive strength higher than the control mix, C_0, while mix C_3 was 19.5% less than that of mix C_0.

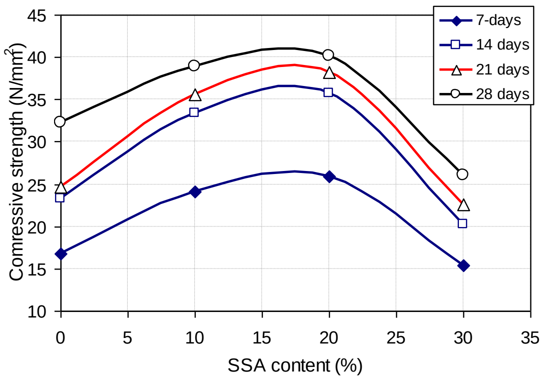

Fig. 7: Compressive strength of SSA-blended cement concrete

E. Water absorption

The absorption of fly-ash concrete was comparable with that of concrete without ash, although some ashes can reduce absorption by 20% or more [21]. Water absorption for 7 days and 28 days were perfectly linear with respect to the SSA content in the mixes as shown in Figure 8. However, the rate of increase in water absorption decreased with the age of concrete. It is evident from the study that SSA increased the water absorption of the concrete specimens of mixes C_0, C_1, C_2 and C_3.

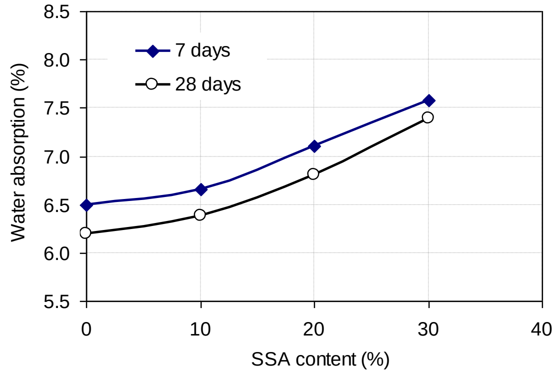

Fig. 7: Water absorption of SSA-blended cement concrete

V. CONCLUSION

This work has confirmed the potentials of SSA from multi-purpose wastewater treatment plant in Gaborone as supplementary cementitious material in partial replacement of cement in concrete production. Different SSA content between 0 and 30% at equal interval of 10% was investigated to evaluate the factors that could enhance the performance concretes. The following conclusions can be drawn from the experimental study conducted on the suitability of SSA as cementitious addition in concrete.

1. The pulverized treated sludge ash from wastewater treatment plant is pozzolanic (combined contents of SiO_2, Al_2O_3, Fe_2O_3, and CaO is in excess of 70%).
2. The set times for the hydration of cement is comparative provided are linear, but seems to be widening.
3. The workability of concrete with SSA-blended from 0-30% was found to be within the specification plain and reinforced concrete.
4. The optimal SSA content for split tensile and compressive strength is 18%. The water absorption of concrete at 7th day and 28th show that water absorption decrease with the curing age.

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