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Abstract

The need for alternative cementing materials to replace ordinary Portland cement (OPC) has promoted characterization research on pozzolana as an important ingredient in cement production. In Uganda, natural pozzolana application in cement production is done by only two producers of Portland cement and on a small scale due to capacity constraints. These capacity constraints, together with other technological issues, continue to hinder the cost reduction and improved quality benefits attributed to the use of pozzolana as a mineral admixture in Portland cement concrete. There is a high abundance of natural pozzolana in Uganda in the form of volcanic ash/tuffs which, if adequately characterized, can facilitate the production of different cementing materials and increase output from the various players in the cement production industry in Uganda. This paper reviews methods of pozzolana characterization and presents preliminary research findings on the application of natural pozzolana sourced from Uganda in the development of Portland cement mortars. Samples collected from two different deposits in the western region of Uganda were prepared and subjected to chemical analysis and tests on compressive strength, flexural strength and flowability. The preliminary findings are indicative of good quality pozzolanic materials that can be applied as mineral addition in the production of Portland cement concrete.

Keywords: Characterization, Portland pozzolana cement, volcanic ash, natural pozzolana, Uganda

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1. Introduction

Pyroprocessing limestone and clay to produce clinker in the manufacture of Portland cement is an energy-intensive process, but a partial replacement of cement with pozzolanic material presents significant benefits [1, 2] and moderate challenges. General benefits that have been documented in various studies include the low cost of the pozzolana raw material, reduced environmental pollution, resistance to alkali attack of concrete, and improvement of other performance and rheological properties of concrete. The challenges are due to delayed setting and slow rate of early strength development [2, 3]. Mitigative measures that can be applied in the activation of reactivity of natural pozzolana to overcome these challenges are documented [2]. Pozzolana is a non-cementitious material whose major mineral constituents are silica and alumina. The material reacts with calcium hydroxide under moist conditions and at ordinary temperature to exhibit cementitious properties. Its characteristic reaction with the free calcium hydroxide in lime and Portland cement makes it an important ingredient in the production of alternative concrete binders to ordinary Portland cement. Pozzolana exists in natural form (volcanic ash, clay etc) and artificial form (calcinated clays, pulverized fly ash, rice husks, etc). The availability of natural pozzolana in Uganda is mainly manifested as volcanic ash or tuff and is largely deposited along the boundaries of the great rift valleys of Eastern Africa. Geological maps obtained from the Uganda Geological Surveys and Mines Department reveal the high abundance of volcanic material that covers much of the eastern and western parts of the country.

The scale of application of pozzolana in Portland cement production in Uganda is limited in comparison with its application in the more evolved European economies. Produced under the single application classification "multipurpose cement", it poses a technological challenge of optimizing binder properties to meet all the requirements for the varied applications. Market dynamics of demand and supply have also contributed to keeping the price of cement very high, hence failing efforts to achieve low cost housing in Uganda. The use of natural pozzolana in the production of Portland-based hydraulic cement in Uganda is largely motivated by process costs reduction, but pozzolanic cement is not applied in structural concrete. Hima cement ltd, a subsidiary of the French Lafarge group, and Tororo cement Company ltd are the current producers of Portland cement in Uganda. According to the 2012 Statistical Abstract published by the Uganda Bureau of Statistics (UBoS), there has been a consistent growth in the net domestic supply of cement binders since 2008. The net domestic supply of cement increased from 1.15 million tons in 2008 to 1.67 million tons in 2011. The UBoS results are faulted in proportions of imported cement compared to net domestic supply as the local manufacturers heavily import clinker from Pakistan and China, which enters the country as a raw material. The nature of construction ongoing is largely non-storied residential houses that are targeting the growing middle class, hence the high demand of the multipurpose pozzolana cement. The cost of pozzolana cement in Uganda ranges from USD 13.00 to USD 15.00 per 50 Kilogram bag compared to the global rate of less than USD 4.50.

The characterization of natural pozzolana in Uganda will establish a basis for the formulation and production of alternative cementing materials that enhance different properties for varied applications. Characterization will also establish the viability of the pozzolana deposits and production quality control. An effective characterization of pozzolanic material requires sophisticated laboratory equipment and strict quality control methods. The scarcity of these factors in Uganda has acted as a deterrent for mid-size investors and the informal sector to participate in cement production.

2. Requirements for pozzolanic mineral additions to hydraulic cement

The successful application of natural pozzolana as a mineral admixture in Portland cement concrete depends on the ability of the pozzolanic material to modify the fresh and hardened properties of concrete. This is achieved through establishing proper chemical compositions, physical properties and the right quantity proportions of the pozzolanic material. Understanding the characterization test methods is paramount for their application in testing for conformity of the binder material to established specifications and in implementing quality control.
The requirements of good pozzolanic admixtures for use in hydraulic cement can be classified as chemical or physical. Chemical characterization seeks to establish the presence of principal elements that form the pozzolanic sample material and also available alkali and levels of resistance to chemical attack. Physical characterization includes tests such as strength, fineness, microstructure, density, permeability, durability, and setting behavior. The European Standard EN 196 – Part 2 series and ASTM C311 provide the procedures of characterization of natural pozzolana cement material applied in Portland cement concrete. These standards present minimum requirements for laboratory and equipment. The standards also provide different test methods that are applied for material characterization, quality control, performance prediction, development of new material blends, and establishment of influence of the binder material on physical, chemical and durability characteristics of composites [5].

2.1 Chemical Characterization

The chemical characteristics of interest include oxides content (silica, alumina and ferrous oxide), sulfate, chlorides, insoluble residues and loss on ignition (L.O.I.) [5, 6]. ASTM C618 states a minimum composition of 70% for the sum of Silica, Alumina and Iron oxides for characterizing a material as a natural pozzolana. The chemical characterization of natural pozzolana is a complicated process because the composition of the pozzolana materials varies with both time and space. A generalization of chemical characteristics can be made if the established parameters are within the acceptable range of variance and meet the requirement of ASTM C618. Advances in research are seeing a shift from the classical wet chemistry towards instrumental analysis techniques in the determination of chemical properties in cement samples [6]. These techniques apply tools such as X-ray fluorescence, atomic absorption and plasma spectroscopy. These tools are preferred to the conventional wet chemistry method because of the benefit of being less time consuming and having a higher reproducibility. Instrumental techniques require half an hour compared to wet methods which require several days to conclusively perform chemical characterization tests [5].

2.2 Physical Characterization

The main indicators of physical/mechanical properties of cement binders are strength, fineness, air content, soundness, setting behavior, heat of hydration, sulfate expansion, alkali-silica reaction, and water content [6]. Most of these properties impact on each other, e.g. water content and setting behavior directly impact the final strength of concrete. ASTM C311, ASTM C618 and EN 196 series give minimum requirements and detailed procedures on sampling and testing of different pozzolana classes to assess their influence on the key mechanical properties of mortar and concrete. Test methods use X-ray diffraction, scanning electron microscopy (SEM), isothermal conduction calorimetry and other tools in assessing the effectiveness of pozzolanic materials on improving key mechanical properties of cement and concrete. These test methods will be applied on sample blends of Portland based clinker and natural pozzolana from Uganda in the design of cement recipes.

3. Experimental Procedure

3.1 Materials

Natural pozzolana samples used were sourced from two sites in the western part of Uganda. Sample group A was sourced from Mudege village, Kisoro District. Sample A occurs naturally as a volcanic ash. Sample group B was sourced from Kataara village II, Rubirizi District. Sample B manifests as tuffs. Samples were milled and graded in two fineness groups, i.e., 100% passing 75µm sieve and 150µm sieve. The fine samples were blended with Portland cement type CEM I 42.5 N (EN 197-1:2005) and applied in mortar samples preparation. Tap water and standardized sand (DIN EN 196-1 and ISO 679) were used.

3.2 Determination of chemical properties of natural pozzolana samples

Three analytical techniques were applied in the chemical characterization of the pozzolana samples. These included instrumental UV, titration and gravimetric analysis techniques. The instrumental technique applied a UV Spectrophotometer 20D+ to determine Iron (Fe) content. Titration and gravimetric analysis techniques were applied to determine CaO and MgO, and Al_2O_3, SiO_2, SO_3, loss on ignition (LOI) and moisture content (MC). The tests were done according to EN 196-2. Chemical characterization results are shown in Table 1.

3.3 Determination of Physical properties of pozzolana blended Portland cement.

Testing for Flexural and Compressive Strength

This was performed in accordance with EN 196-1 guidelines. Mortar prisms 40 mm x 40 mm x 160 mm were made with standard sand (as described by EN 196-1) and a binder material that comprised of OPC type CEM I with its content partially replaced with natural pozzolana. Two fineness levels (100% passing 75 µm sieve and 150 µm sieve) were applied in the experiment and replacements of 20%, 30% and 40% natural pozzolana on binder content of the composite materials were chosen. 36 mortar prisms were cast out of 12 mix batches. The prisms were tested for flexural and compressive strength at 28, 56 and 90 days.

Flowability

Flow properties of the 12 mortar batches used in casting the mortar prisms above were evaluated. A flow table test was done according to EN 1015-3 where a cone shaped mould was placed on a flow table and filled with fresh mortar in two layers. 15 strokes were applied on each sample after removing the mould and two diameter measurements of horizontal spread were taken on the mortar spread at sections perpendicular to each other.

4. Results and discussion

4.1 Chemical Properties

Table 1 shows the characteristic oxide composition of the pozzolana samples and their loss on ignition. Results of both samples A and B meet the ASTM C618 requirement for a minimum composition of 70% of the sum of silica, alumina and iron oxides for characterizing a material as a good natural pozzolana. EN 197-1:2005 allows the replacement of clinker with pozzolana up to a maximum of 50%. This pozzolana provides extra silica, alumina and iron oxides that react with the excess reactive calcium hydroxide during the hydration process to produce more cement hydration compounds.

Table 1: Oxide composition and LOI of the natural pozzolana samples

Sample No.	% CaO	% MgO	% Al_2O_3	% Fe_2O_3	% SO_3	% SiO_2	% LOI @960 °C	Total $SiO_2 + Al_2O_3 + Fe_2O_3$
A	4.13	3.11	16.10	12.71	<0.01	64.00	0.25	92.81
B	10.20	5.78	14.85	12.68	<0.01	52.48	12.03	80.01

The loss on ignition (LOI) results show that sample B has a high level of either organic compounds or carbonates. Organic compounds are known to negatively influence the binding properties of cement.

4.2 Compressive Strength

The results in Figures 1 to 4 reveal that the compressive strength decreased with the increase in pozzolana content. The rate of decrease in strength also decreased with the increase in pozzolana content.

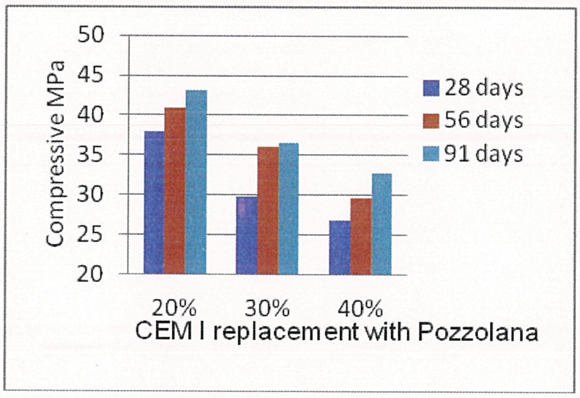

Figure 1: Sample B – 75 µm fineness (100%passing)

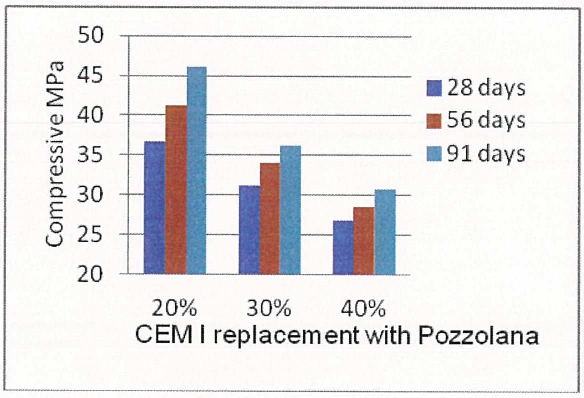

Figure 2: Sample B – 150 µm fineness (100%passing)

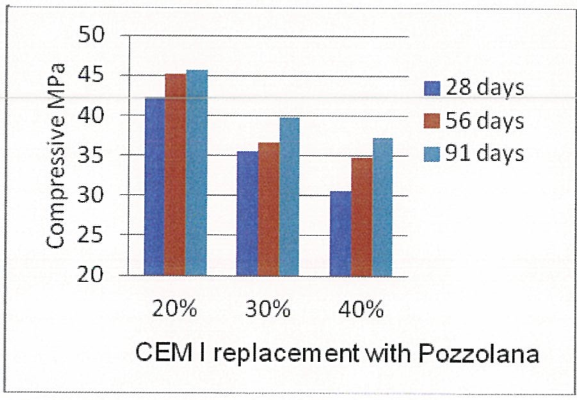

Figure 3: Sample A – 75 µm (100% passing)

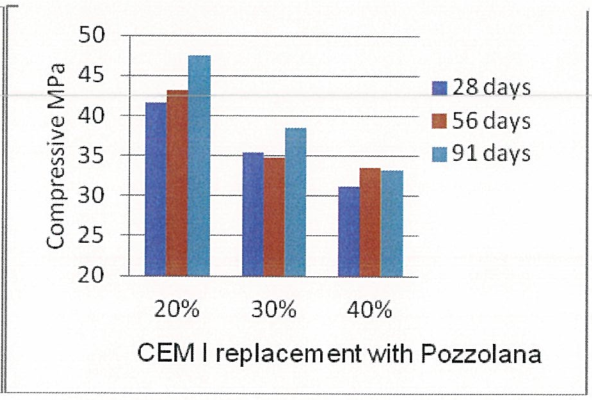

Figure 4: Sample A – 150 µm (100% passing)

The process of hydration is dependent on the fineness of cement particles. However, the compressive strength results were not influenced to a large extent by particle size. Research has shown that cement hydration can only be completed if the fineness of cement particles is less than 50 µm [7]. However, the CEM I 42.5 N used for the mortars in this study has 90% of particles under the size of 75 µm. The sample from the Kisoro District (Sample A) exhibited superior strength properties than that from the Rubirizi District (Sample B). Sample A was able to achieve 28 days strength (42.3MPa) at 20% displacement that was slightly below the 42.5 MPa of pure OPC cement mortars, which is a good indicator that the sample can be applied in the production of structural cement. The minimum 28 days strength achieved by all samples at 40% replacement with pozzolana was much higher than the 12 MPa recommended by the European Standard EN 998 for masonry cement.

4.3 Flexural Strength

Figures 5-8 present the flexural strength results of the mortar prisms. Results show that the

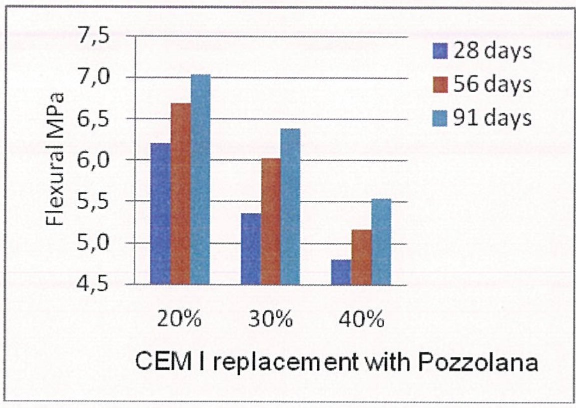

Figure 5: Sample B – 75 µm (100% passing)

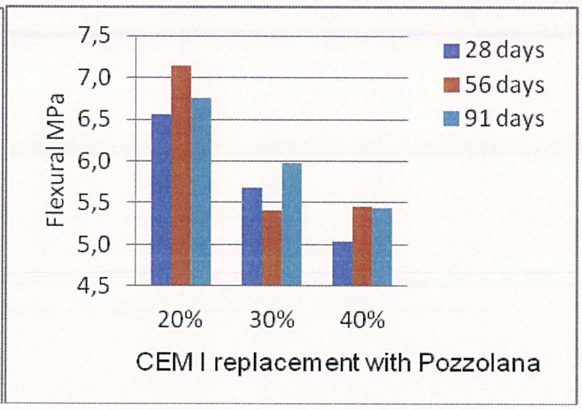

Figure 6: Sample B – 150 µm (100% passing)

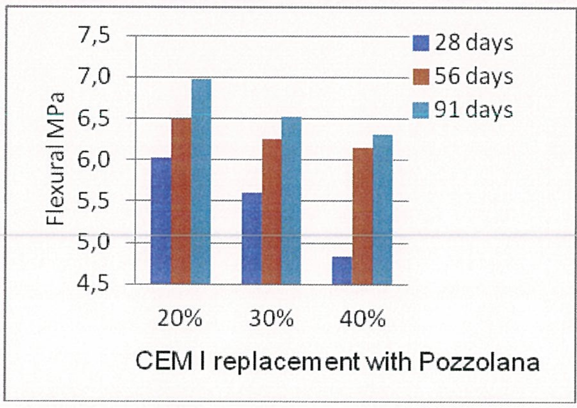

Figure 7: Sample A – 75 µm (100% passing)

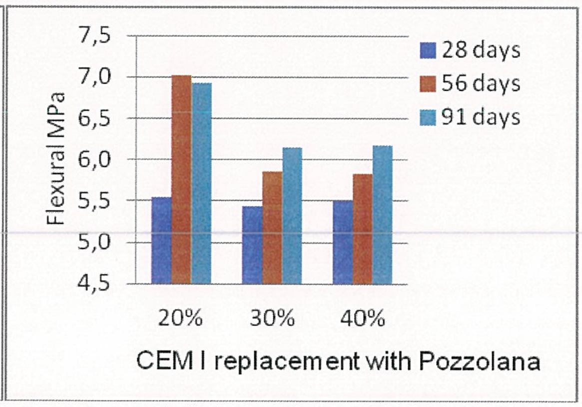

Figure 8: Sample A – 150 µm (100% passing)

flexural strength increased with the increase of the curing period and decreased with the increase in pozzolana content. The results are more consistent for the samples that used the 100% passing 75 µm sieve fineness of natural pozzolana than those of the 150µm size. This is likely because finer binders are known to improve workability [7] and hence ensure a more uniform mix. On the contrary to compressive strength results, particle size had a larger influence on the flexural strength of the mortar samples.

Table 2 shows the values of flexural and compressive strength for reference mortars made with 100% CEM I 42.5 N as binder and with 20% and 30% replacement by commercial fly ash, respectively. The fly ash has a comparable PSD to the employed cement.

Table 2. Flexural and compressive strength of reference samples after 28 days

Binder	Flexural strength (MPa)	Compressive strength (MPa)
100% CEM I 42.5 N	8.19	49.94
80% CEM I 42.5 N + 20% fly ash	7.20	41.03
70% CEM I 42.5 N+ 30% fly ash	6.00	28.95

In the case of both flexural and compressive strengths, all 20% pozzolana samples have a lower flexural strength than the corresponding fly ash replacement, as well as a higher decrease in strength than the replacement level. However, for the 30% replacement, the pozzolana A samples have the same compressive strength as 70% of the pure CEM I mortar samples, and higher compressive strength than the corresponding fly ash sample. In the case of 30% pozzolana B mortars, the compressive strength remains higher than the 30% fly ash sample, but drops below the one of 70% of the pure CEM I mortar samples. These results indicate that both pozzolanas can be successfully used as cement replacement.

4.4 Flowability

Results of the flowability tests on fresh mortar (DIN EN 1015-3) showed an increase for the various natural pozzolana replacement ratios applied in casting the mortar prisms. Flowability properties did not increase with the increase in pozzolana content beyond 30%. The exploratory tests did not establish any relationship linking fineness to flow properties. The research, however, realized flow-abilities of up to 17.0 x 17.5cm at 40% replacement for sample A (Kisoro) compared to a standard 14.0 x 14.0cm flowability achieved by cement type CEM I 42.5 N. This implies that the application of pozzolana samples in Portland cement concrete will reduce the water cement ratio or increase workability of fresh concrete which both are desirable properties of concrete. Sample B (Kataara) achieved spreads of up to 16.5 x 16cm at 40% displacement of cement CEM I with natural pozzolana. The research will, at a later stage, develop a statistical model to predict the influence of mix proportions and particle size of the pozzolana cement binder on the flowability of mortars.

5. Conclusion and Recommendations

The exploratory experiments indicate the following research concerns and conclusions:

I. The chemical characterization revealed that both samples met the minimum requirement to be characterized as pozzolanic. Sample A had a low value of LOI (0.25%) while sample B had a very high LOI value (12.03%). The LOI value is an indication of the presence of either organic compounds or carbonates. Organic compounds negatively influence the binding properties of cement. Sample A had a very high percentage of silica, alumina and iron oxides, characteristic of a good pozzolana material for use in Portland cement concrete.

II. Compressive strength analysis for sample A at 20% replacement of CEM I with pozzolana showed a compressive strength of 42.3 MPa. This is slightly less than the minimum limit of 42.5MPa at 28 days for CEM I 42.5 N. This is an indicator that slightly lower replacement ratios can be applied in the production of cement for structural purposes. The analysis of sample A at 30% and 40% replacement of CEM I with pozzolana also produced compressive strength results above the minimum requirements for varied applications such as masonry work and other non structural applications. The analysis of sample B at all replacement ratios showed that the pozzolana sample can be applied mainly for non structural purposes. All samples reveal that the process of strength generation is continuous at a significant rate.

III. The flexural strength analysis showed acceptable values that increased with the curing period.

IV. The flowability analysis revealed that application of the pozzolana samples in cement mortar production significantly increased the spread of the samples without loss of mechanical properties.

In conclusion, a detailed characterization of Uganda's pozzolana for application in Portland cement based binders is important for both improved concrete properties and reduction in the cost of housing in the region. The process of characterization will provide the necessary information that will enable participation of mid-size enterprises and informal sector in cement production process.

6. Acknowledgement

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7. References

[1]. Abdelaziz G. E., Abdelalim A. M. K., Ghorab H. Y., and Elsayed M. S., (2010) "Characterisation of OPC Matrix Containing Dealuminated Kaolin", Concrete Research Letters, Vol. 1 (4), Page 131-141, Cairo – Egypt.

[2]. Shi Caijun(2001), "An Overview of Reactivity of Natural Pozzolans", Canadian Journal of Civil Engineering, Vol. 28, Canada.

[3]. Adepegba Dotun, (1992), "Pozzolana – The Cheap Alternative to Portland Cement", Journal of the Network of African Countries on Local Building Materials and Technologies; Vol. 2, No. 1; United Nations Centre for Human Settlements (Habitat); Nairobi, Kenya ISSN 1012-9812.

[4]. 2012 Statistical Abstract, Uganda Bureau of Statistics, www.ubos.go.ug.

[5]. Ramachandran V. S. and Beaudoin James J. (2001), "Handbook of Analytical Techniques in Concrete Science and Technology; Techniques, Principles and Applications", William Andrew Publishing, LLC, Norwich, New York, U.S.A.

[6]. ACI Committee E-701 Materials for Concrete Construction (2001), "Cementitious Materials for Concrete", ACI Educational Bulleting E3-01, American Concrete Institute, Farmington Hills.

[7]. Neville A. M., (2004) "Properties of Concrete", 4th Ed, Pearson Education Limited, England.