An Examination of Compressive Strength Variation of Pozzolan-Lime Cement with Pozzolan Particle Size

Dans N. Naturinda¹, Anthony G. Kerali², and Dan Tindiwensi³

Abstract—Uganda has vast deposits of natural pozzolans, mainly of volcanic origin, which can be beneficial in construction of affordable housing for low-income earners. While pozzolan–lime cement has been used over the years as a low-cost binder in construction, the need for finely ground pozzolans for adequate strength development usually has a reverse effect of increasing the cost. This research examined the variation of compressive strength values with pozzolan particle sizes in pozzolan-lime cement. It was aimed at establishing whether the changes in pozzolan particle size would produce respective significant changes in compressive strength of pozzolan-lime cement, and the nature and extent of this effect. Experimental tests were carried out on various trial mixes of hydrated lime with volcanic ash ground to different sizes and tested for compressive strength. The results indicated a strong inverse relationship between the pozzolan particle size and compressive strength. Adequate interaction between the lime and pozzolan particles was realized for particles not exceeding 125µm, with consistent compressive strength results achieved with 50% to 70% pozzolan content. The peak compressive strength values of 0.9MPa attained are suitable for several low-strength construction applications like mortars, renders and plasters. The achievable strength values can be enhanced with addition of limited quantities of Portland cement.

Keywords—Natural pozzolans, hydrated lime, compressive strength, pozzolan-lime cement.

I. INTRODUCTION

POZZOLAN is defined by the American Society for Testing and Materials (ASTM C125) as “a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value, but will, in finely divided form and in the presence of moisture, chemically react with lime at ordinary temperatures to form compounds possessing cementitious properties”. The pozzolan–lime mixture used this way in construction applications is referred to as pozzolan-lime cement. Pozzolanicity is a measure of the content of reactive silica or alumina in the pozzolan. Materials whose pozzolanicity does not need any induction are categorized as natural pozzolans. Artificial pozzolans are the ones that require calcination to induce pozzolanicity.

Uganda has vast deposits of natural pozzolans, mainly of volcanic origin, which can be beneficial in construction of affordable housing for low-income earners. Currently, the pozzolans are used by cement manufacturers to blend OPC. Rudimentary methods have been tried to exploit the pozzolans for use in construction in rural areas. However, their extensive use has been hindered by limited information about their performance and quality properties.

Day [1] contends that the choice of a pozzolan to be exploited depends so much on economics, as the quality of the material can be controlled by tailoring the particle size to obtain sufficient reactivity. Kerali et al [2] showed that the pozzolan activity and their filler effect depend on their particle size. Yetgin and Chavdar [3] established that the degree of reaction and subsequent strength of a hydrated mixture of lime and pozzolans cannot be deduced only from the chemical composition, but also from other characteristics like fineness and the crystalline structure of the pozzolan.

While the chemical composition and crystalline structure are fixed for any given pozzolan, the fineness can be customised by grinding the material to the required level. However, the higher the level of grinding required the more the energy used, and hence the higher the cost of production. As such, the most appropriate grade is the one that gives the required performance to satisfy the functional requirements while optimising the cost of production. Hence, there is need to determine the optimum particle size that would provide adequate structural performance.

II. PROBLEM AND OBJECTIVES

While the pozzolan-lime cement has been used over the years as a low-cost binder in construction, the need for finely ground pozzolans for adequate strength development usually has a reverse effect of increasing the cost. The lack of information about the optimal particle size that would give adequate compressive strength with lime has been a limitation for full exploitation of natural pozzolans for economic housing construction. As a result challenges of inadequate housing

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prevail in rural communities with abundant natural pozzolan deposits that can be used to ameliorate the situation.

This research examined the variation of compressive strength values with pozzolan particle sizes in pozzolan-lime cement. It was aimed at establishing whether the changes in pozzolan particle size would produce respective significant changes in compressive strength of pozzolan-lime cement, and the nature and extent of this effect. The understanding of the compressive strength variation trends with changing particle size would help to predict the optimum particle size that can produce adequate strength for low-strength applications to reduce the cost of construction.

III. METHODOLOGY

The compressive tests were guided by the test procedure prescribed in ASTM311 detailed under Test Method C109/C109M. The raw material was pulverized to nine different particle sizes, i.e. 45µm, 63µm, 75µm, 90µm, 106µm, 125µm, 150µm, 180µm and 212µm. Each grade was used to prepare five different blends with hydrated lime, containing 10%, 30%, 50%, 70% and 90% of the pozzolan material. For each of these blends, nine 50mm mortar cubes were prepared. Respective proportions of lime and pozzolan by volume were measured using a standard laboratory burette of 100cm³.

The lime and pozzolans were dry-mixed for two minutes in a paddle mixer. The same quantity of water initially determined to give a workable mixture was added and mixed for two minutes. Two parts of the fine aggregate (stone dust) were then added and mixed for one minute. The moulds were filled in three approximately equal layers, each layer tamped thirty times with a 1 cm² rod, and the surface levelled with a trowel. The cubes were then cured in a curing bath with thermostatic control and circulation pump to maintain a constant curing temperature. Compression testing was carried out on a strain controlled testing machine applying uniaxial compression with a constant strain rate of 1mm per minute.

IV. FINDINGS AND DISCUSSION

The one-value-at-a-time (OVAT) effect of pozzolan grade was assessed to determine whether the changes in the pozzolan grade would produce respective significant changes in compressive strength of the pozzolan – lime system for a given level of lime content. The assessment also examined the nature and extent of this effect by performing a single factor (one-way) ANOVA to determine the $F$ statistic to explain variability based on the degrees of freedom, and the plausibility value ($P$-Value) of the various pozzolan grades and fixed blends. The $F$ statistic for all combinations was much greater than $F_{crit}$. Similarly, the $P$-value was very small for all combinations. This is a clear reflection of variability in the sample means, and hence a strong indication that the compressive strength changes with the pozzolan grade.

The nature of the effect was determined by observing the trend of compressive strength with grade variations for the different experiments. Figure 1 presents the scatter plot for the 7-day experiments.

![Fig. 1 compressive strength variation with pozzolan grade](image1)

The plots for all the categories of experiments show an inverse relationship between the compressive strength and pozzolan grade. It can therefore be postulated that the finer the pozzolan, the higher the compressive strength for a given content of pozzolan/lime, and curing duration. The observations also indicated that the highest strength values are obtained for both the finest pozzolan grades and longer curing durations.

The plots indicate a relatively linear relationship between strength development and pozzolan grade. As such, a linear regression model was used to determine a mathematical function that relates the two variables and gives the best fit possible between them. The mathematical relationships of the linear equivalents were derived by linear regression methods and used to determine the sensitivity of each experimental set. Figure 2 shows the 7-day variation of mean compressive strength values with pozzolan grade for the given pozzolan grades, alongside their lines of best fit derived from linear regression models.

![Fig. 2 linear models for strength variation with pozzolan grade](image2)
the closest the given observations can be linearly related. To examine how good this linear relationship is, in representing the actual relationship, the correlation coefficient R and coefficient of determination R² were derived. The R values and R² values, together with the 7-day coefficients for the linear relationships are summarised in Table 1 below.

### Table 1

**Coefficients for Strength Variation with Pozzolan Grade Models at 7 Days**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>a</th>
<th>b</th>
<th>R</th>
<th>R²</th>
<th>Rank</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>0.30838</td>
<td>-0.00129</td>
<td>-0.9912</td>
<td>0.9825</td>
<td>4</td>
<td>-3</td>
</tr>
<tr>
<td>30%</td>
<td>0.31432</td>
<td>-0.00124</td>
<td>-0.9319</td>
<td>0.8684</td>
<td>2</td>
<td>-3</td>
</tr>
<tr>
<td>50%</td>
<td>0.42254</td>
<td>-0.00163</td>
<td>-0.8943</td>
<td>0.7998</td>
<td>2</td>
<td>-3</td>
</tr>
<tr>
<td>70%</td>
<td>0.38129</td>
<td>-0.00119</td>
<td>-0.8953</td>
<td>0.8016</td>
<td>1</td>
<td>-3</td>
</tr>
<tr>
<td>90%</td>
<td>0.30921</td>
<td>-0.00163</td>
<td>-0.9398</td>
<td>0.8832</td>
<td>4</td>
<td>-3</td>
</tr>
</tbody>
</table>

The negative values of R are a confirmation of the inverse relationship between compressive strength and pozzolan grade. In all experiments, the value of R² is very close to 1, which is a confirmation of an almost perfect relation between the derived linear function and the actual observations. The a values reflect the theoretical maximum compressive strength attainable for an infinitely small pozzolan grade. In this case the 50% and 70% experiments exhibit the highest possible 7-day compressive strength attainable of any of the experimental units under consideration.

The sensitivity of the compressive strength with change in pozzolan grade is reflected from the b coefficients, which effectively represent the gradient of each of the linear relationships. The 50% gradient has the biggest negative gradient, while the 70% experiment has the lowest. In this case the 70% experiment exhibits the most stable treatment that is least sensitive to changes in pozzolan grade, while the 50% experiment presents the most sensitive, hence least stable.

The ranking considers both the maximum attainable compressive strength and the sensitivity to variations in pozzolan grades, given that the linear relationships are all a close representation of the observed data. In this case, the 70% experiment gives the best ranked material of the 5 experiments, while the 10% and 90% experiments exist at the periphery of the desirable outcome.

The 28-day and 90-day experiments exhibited similar behaviors. The 50% and 70% experiments exhibited the highest possible 28-day compressive strength attainable of any of the experimental units under consideration. The b coefficients for the 28-day experiments are lowest for the 50% experiment followed by the 70% experiment. As such, the two sets of experiments exhibit the highest stability and least sensitivity to changes in pozzolan grade. The 50% experiment gives the best ranked material closely followed by the 70% experiment. Among the mid-range experiments for 90-day, the 50% shows the closest relation followed by the 70% blend. Looking at the implications of these factors in practice favours the 50% blend followed by the 70% blend against all the others. This is premised on the consistence exhibited over the duration of the experiments than the ultimate values registered at the end of the experiments.

Since finer grades would be associated with higher grinding requirements and hence higher production costs, it was important to identify the pozzolan – lime mix that would yield relatively high compressive strength values that are least sensitive to changes in pozzolan fineness. This was done by extrapolating the derived linear experimental models to establish their y-intercepts, which would represent the highest possible compressive strength values for infinitely small pozzolan particles. The sensitivity to changes in pozzolan grades was established from the first derivatives of the models; in which case the x-coefficient represents the gradient, which is an indication of the rate at which the compressive strength changes with pozzolan grade.

The 50% pozzolan – lime mix was found to yield the highest possible early compressive strength values for the finest pozzolan grade. However, the 70% mix, which presented the second highest values exhibited the highest stability, and hence the lowest sensitivity to changes in pozzolan grade with changes in compressive strength values.

The 28-day experiments registered better stability for the 50% mix than for the 70% mix. However, the 70% mix registered the highest possible compressive strength values, a clear interchange of performance over time. Similar to the early strength experiments, the two mixes presented the best performance values (compressive strength values and sensitivity to changes in grade) of all the experiments performed, though interchanged. It can therefore be suggested that the design mix that presents the optimum performance in terms of stability and wet compressive strength lies between the 50% and 50% mixes.

The long-term (90-day) experiments yielded mixed results in terms of mixes that present maximum attained compressive strength and sensitivity to grade variations. However, while the 50% and 70% mixes did not register the best performance values, they were still among the top ranked mixes. On the basis of this consistence, the two mixes are considered to be the most stable and more reliable in performance prediction.

The interchange in performance between 50% and 70% mixes with respect to maximum attainable compressive strength and stability against changes in grade over time implies that in between the two mixes lies the mix that would yield optimum performance in terms of functionality and cost. This mix can be established by examining the variation of compressive strength with respect to the pozzolan content in the mix. Observations from the interaction plots revealed significant interaction of the pozzolan content and pozzolan grade in influencing compressive strength for the 50% and 70% blends. This interaction was consistent for the entire duration of the experiments as opposed to other blends that exhibited interaction only for ultimate strength tests.

Interaction was also observed for the fine grades up to...
125µm. This is upper limit of pozzolan grade that would enable effective reaction of pozzolan and lime as any finer grades would be more expensive to produce, while less fine grades would be less effective in registering sustainable compressive strength development. The optimum strength registered was 0.50MPa.

V. CONCLUSIONS AND RECOMMENDATIONS

The 125µm grade exhibited the highest level of stability registering the same compressive strength values for each mathematical relationship. While the higher grades depicted some level of consistence, they were not as stable as the 125µm grade, and registered much lower strength values. Hanna and Ajify, 1976 (as quoted in Day 1990) established that the finest grades had a predominant effect on the early age strength, while less fine grades had more influence on ultimate strength. The 125µm grade presented with a strong balance between early age strength and ultimate strength. It is therefore recommended as the most versatile grade that gives consistent results, and least sensitive to changes in pozzolan content.

The findings further confirmed that 125m blend was the optimum blend to enable effective reaction of pozzolans and lime within a 50% to 70% pozzolan content range. The ultimate compressive strength consistently registered within the optimum range of pozzolan blends and grade was 0.5MPa. However, a peak value of 0.9MPa was registered in one of the experiments.

ASTM C618-89 prescribes a minimum of 5.5MPa for pozzolan-lime mortars with Portland cement. Hammond [4] recommended a minimum of 4.1MPa based on the Indian System (IS:1727, 1967). Day (ibid) observes that most of these requirements may be too high placing inappropriate restrictions upon pozzolans which can provide adequate performance for low-cost construction. The Indian Standard (IS 4098, 1967) [5] prescribes a minimum of 0.7MPa 28-day compressive strength for low grade pozzolan-lime mortars and mass concretes. This seems to be attainable from the system models developed under this research. It is suitable for several low-strength construction applications like mortars, renders, soli stabilisation and plasters.

The realisable strength values are too close to the minimum edge. This is an indication the Portland cement may not be indispensable, but limited amounts which would not grossly impact on the cost may be necessary to enhance the performance of the pozzolan – lime material in the low-strength construction applications. Trials performed by the Department of Geological Surveys and Mines [6] registered up to 6.2MPa with 10% Portland cement in a 75% pozzolan – lime system. Extensive trials would be needed to establish the most economic Portland cement blend in the pozzolan – lime system for low-strength applications.

REFERENCES