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The Structural Behavior of Pozzolan-lime Cement as a Potential Substitute to Portland Cement in Low-strength Construction Applications

Dans N. Naturinda
(PdD Fellow, Makerere University, Kampala, Uganda)

Anthony G. Kerali
(Associate Professor, Makerere University, Kampala, Uganda)

Dan Tindiwensi
(Senior Lecturer, Makerere University, Kampala, Uganda)

Abstract

Construction materials constitute a significant component of construction cost. Portland cement is one of the costly materials used even in applications that do not require its high strength grades. The use of alternative materials such as pozzolan-lime cement that can substitute or supplement Portland cement to reduce the cost is hindered by limited information on their performance and cost-saving benefits. This research examined the structural behaviour of natural pozzolans mixed with lime as a potential substitute to Portland cement in low-strength construction applications. The research approach was experimental. Trial mixes were prepared for different pozzolan particle sizes, and different pozzolan contents. Strength development was monitored over a period of ninety days and compressive strength tests performed at 7 days, 28 days and 90 days. The optimum pozzolan content that gave peak compressive strength development was predicted to be between 54% and 60% irrespective of the pozzolan particle size. Similarly, the most consistent effect was established with predominant pozzolan particle size of at least 125µm. The peak compressive strength values attained from the pozzolan–lime system are adequate for many low-strength applications but can be enhanced by addition of small quantities of Portland cement.

Keywords

Natural pozzolan, pozzolan-lime cement

1. Introduction

A number of studies (Berhane, 1987; Day, 1990; Habitat, 1985) have indicated that construction materials constitute a high proportion of construction cost. This is bound to be higher for remote areas where most of the materials have to be transported for longer distances. Traditionally, Portland cement has been a major construction material in most forms of building construction, mainly as a binding agent in concrete, mortar, renders, walling blocks, roofing tiles and pavers. However, it is a relatively expensive material mainly due to high production energy requirements, transportation costs, and artificial price fixing. When used for small buildings and low-strength applications, Portland cement makes construction unnecessarily more expensive than it ought to be. Habitat (1985) estimates that up to 80% of the world-wide use of cement does not require strength levels of Portland cement. According to Spence (1980), the continued demand for OPC, even where unnecessary, can be attributed to its high 'status value' and limited knowledge of viable alternatives.

been tried as an alternative or supplement to Portland cement. However, their use is not widespread because of being associated with inferior products and low social-status. Day (1990) attributes the little confidence in the use of such alternative binders to lack of sufficient information on their qualities that influence their performance.

There are vast deposits of natural pozzolans in Uganda especially in form of volcanic soils and other natural earth deposits of similar origin in rift valley areas (Department of Geological Surveys and Mines 1992). Rudimentary methods have been tried to exploit and use pozzolans in rural areas. However, their extensive use has been hindered by the suspect quality of their products and lack of adequate information about their performance.

2. Problem Statement and Research Aim

Whereas there is a vast potential for natural pozzolans in several parts of Uganda with good qualities for use in construction, there has been no rigorous examination of such qualities in relation to their potential to substitute OPC in low-strength applications to reduce the cost of housing. As a result, there is lack of confidence in extensive use of the pozzolan materials because of limited knowledge to demonstrate their structural performance. There is also limited demand for their appropriate application in construction due to lack of information on cost saving possibilities and other economic benefits.

This research was carried out to examine the structural behaviour of natural pozzolans mixed with lime as a potential substitute to Portland cement in low-strength construction applications. This, it is believed, would reduce the cost of housing construction to address the problem if inadequate housing in rural Uganda. The exploitation of natural pozzolans is also bound to empower the rural communities with the required skills to process and utilise the material. It can be a stimulant for local micro-industrial developments and employment opportunities, for the betterment of the quality of life and living standards of the local communities.

3. Materials and Methods

The key materials used include volcanic ash, hydrated lime (to BS 890/1972), and stone dust. The volcanic ash was pulverized to nine different grades of particle size, i.e. 45µm, 63µm, 75µm, 90µm, 106µm, 125µm, 150µm, 180µm and 212µm. Each grade was used to prepare five different blends with lime, containing 10%, 30%, 50%, 70% and 90% of the volcanic ash. For each of these blends, nine 50mm mortar cubes were prepared. Each treated portion was mixed thoroughly in a motorised mixer, and the same quantity of water added to each.

The moulds were made of nine compartment gangs and hence, nine replicates of experimental units (50mm mortar cubes) were made out of each blended portion and labelled accordingly. All the cubes were subjected to the same humid environment for curing at room temperature. Three cubes were picked randomly without replacement from each batch of 9 cubes and tested for compressive strength after 7 days. This was also done from the remaining six, after 28 days of curing. The remainder were tested after 90 days of curing. This procedure was aimed at achieving pre-treatment equality of the sample portions by random assignment. The compressive tests were guided by the test procedure prescribed in ASTM311 detailed under Test Method C109/C109M.

4. Data Analysis and Discussion

The effect of pozzolan grade was assessed to determine whether the changes in the pozzolan particle size 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. Single factor ANOVA was performed to explain variability based on the degrees of freedom (F-statistic), and the plausibility value (P-Value) of the various pozzolan grades and fixed blends. The F statistic for all combinations was much greater than critical F-value. Similarly, the P-value was found to be 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. This is given in Figure 1 below.

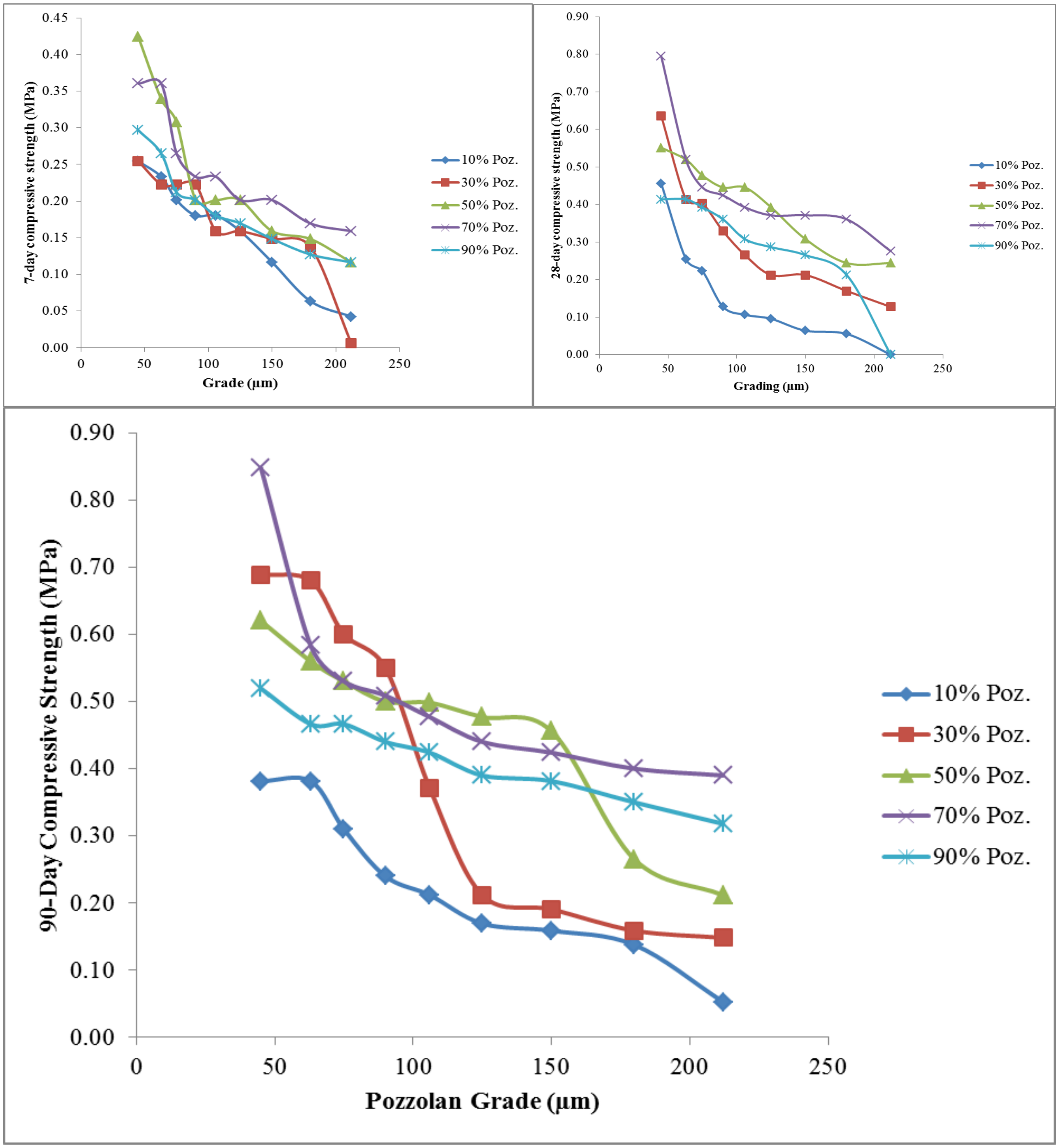

Figure 1 Variation of compressive strength with pozzolan particle size

The results 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 indicate 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. The functions for the various experiments were used to determine the rates of strength development from which the optimum values were derived. The 50% and 70% experiments exhibited the highest possible 7-day and 28-day compressive strength attainable of any of the experimental units under consideration. The 30% pozzolan mixes performed better than other experiments with the finest grades at 90 days.

The 50% experiment had the highest negative gradient, while the 70% experiment had the smallest at 7 days. 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. At 28 days, the gradient is smallest for the 50% experiment followed by the 70% experiment. This is also the case for the 90-day experiments. As such, the two sets of experiments exhibit the highest stability and least sensitivity to changes in pozzolan grade.

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 was established by examining the variation of compressive strength with respect to the pozzolan content in the mix. The findings are presented in Figure 2 below.

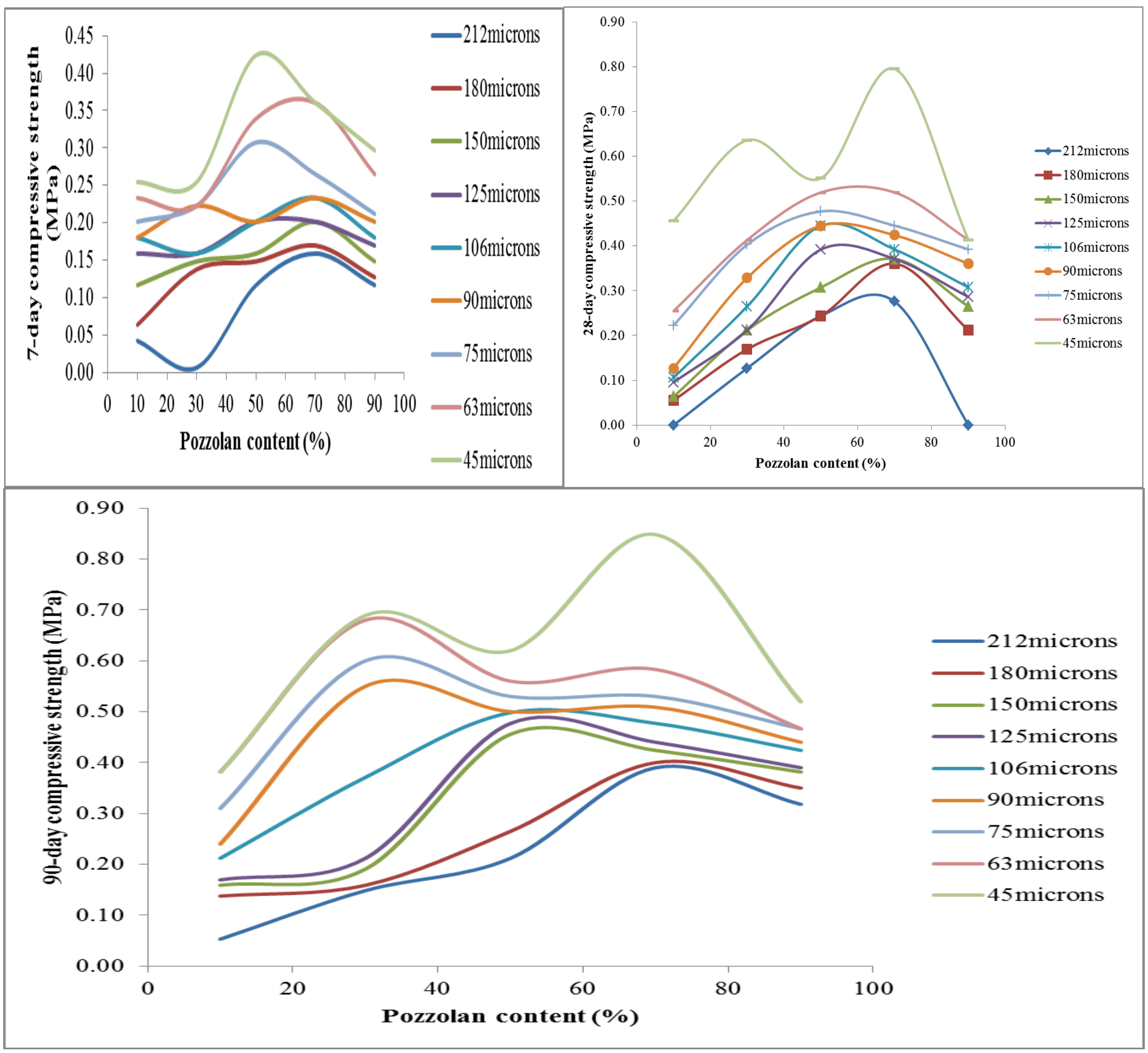

Figure 2 Variation of compressive strength with pozzolan:lime content

The trend of variations in compressive strength with pozzolan content exhibited peaks and valleys for the three sets of experiments as shown in the plots. The peaks imply that the compressive strength increases with the pozzolan content up to a certain point, beyond which it begins to reduce. The existence of valleys for low pozzolan contents could be an indication of the dilution effect of pozzolan to the latent strength properties of lime until such a point when the contribution to strength values by the pozzolan-lime reaction outweighs the dilution effect. The existence of peaks and valleys suggests polynomial relations between compressive strength and pozzolan blend. As such, polynomial functions were assumed for data from the various experiments, which were then adjusted using computer software to attain a fitting relation.

The peaks for the 7-day experiments are skewed to the right, implying that the highest achievable strength is influenced more by the pozzolan content than the lime content. However, the experiment that exhibits the highest compressive strength achievement has its peak close to the 50% pozzolan blend. This indicates the need for both pozzolans and lime almost in equal measure, for the best results. At 28 days, apart from the 45μm experiment, all the observed trends are smooth curves with virtually no valleys. This could be a result of prolonged exposure of the pozzolan/lime blend under favourable curing conditions by which most of the reactive material yielded more strength countering the dilution effect observed for the 7-day experiments. Similar trends are exhibited after 90 days of curing.

The derived polynomial functions were adjusted as much as possible to maintain the same maximum peak attained with the observed data. The absolute critical values of the independent variables were determined from the first derivative of the derived functions at which the derivative is equivalent to zero. The critical points were checked using the second derivative to confirm whether the turning point is the required absolute maximum critical point. The results indicate that for all pozzolan grades, the maximum attainable compressive strength at 7 days of curing is attainable for higher pozzolan contents, in this case above 50%. The values did not seem to follow any particular trend, probably suggesting no clear link between the blend that gives maximum strength values and the grade of the pozzolans. The results of the 28-day and 90-day experiments were consistent with the findings for the 7-day experiments with the critical blends are all above 50% of pozzolans, and there is no clear trend between the critical values and the grade of the pozzolan.

The maximum blending values attainable did not indicate a clear bearing of varying pozzolan blends on the actual strength attained. This comparison was revealed by working out the actual strength attained by substituting the absolute critical values in the derived polynomial expressions for each experiment. The values obtained are presented in Table 1.

Table 1 Critical pozzolan/lime blends and attainable maximum strength

	7-Day		**28-Day**		***90-Day***	
Experiment	*Critical Blend Values(%)*	*Max. Strength (MPa)*	*Critical Blend Values (%)*	*Max. Strength (MPa)*	*Critical Blend Values (%)*	*Peak Strength (MPa)*
45μm	54.602	0.4315	62.793	0.723	61.452	0.779
63μm	62.838	0.3687	59.993	0.534	39.385	0.653
75μm	53.621	0.3102	52.606	0.478	29.462	0.600
90μm	78.146	0.2435	56.014	0.451	30.934	0.550
106μm	70.415	0.2332	55.046	0.454	56.420	0.506
125μm	59.579	0.2077	57.597	0.409	57.176	0.501
150μm	75.523	0.0841	71.827	0.372	57.468	0.482
180μm	74.522	0.1726	68.753	0.338	76.816	0.402
212μm	62.658	0.1349	64.404	0.286	76.670	0.370

The comparison between critical blends and attainable maximum strength reveals that while the strength increases as the grade reduces, the critical blends do not seem to follow the same trend. This could be a suggestion of greater stability for the pozzolan content in the variation of attainable compressive strength. On this basis, it can therefore be assumed that provided the pozzolans are available in adequate but not excessive quantities, the compressive strength will be less sensitive to variations in the actual pozzolan content. The derived critical blend and maximum strength values are comparable with the observed values. Therefore, the derived mathematical functions can be considered to predict the trend of compressive strength variation with pozzolan content close enough to the expected real values. The mid-range grades of 106μm, 125μm and 150μm exhibited more stability and predictability in strength development which was attributed to an ideal balance between the filler effect and the reaction between pozzolans and lime for these grades. Hence, while the finest grades could give high compressive strength values, the mid-range grades presented the most stable materials that can be used with consistent results.

The comparison shows that for the finest grades, the pozzolan content yielding peak strength values for the various pozzolan grades decreases with time. While this shows a greater significance of lime in strength development over time, it also depicts a high level of sensitivity and instability of pozzolan-lime mix designs for the finest pozzolan grades. The wider range of pozzolan contents that give peak strength values after 28 days and 90 days makes it difficult to design an appropriate mix for these grades, which will yield predictable and consistent strength results.

The medium to the least fine grades examined depicted more stability with less variability between pozzolan content that gives peak early age compressive strength and that giving the peak ultimate strength values after 90 days. Therefore a design mix based on these experiments is more predictable and reliable, and is expected to give consistent results. The most stable of these blends can be observed through strength development prediction by applying the peak values to each of the derived mathematical models for 7-day, 28-day, and 90-day experiments as shown in Table 2.

Table 2 Strength development predictions

Experiment	Pozz. Content with Peak Strength (%)	7-day Strength MPa	28-day Strength MPa	90-day Strength MPa
106μm	70.4	0.23	0.39	0.47
	55.0	0.21	0.45	0.51
	56.4	0.22	0.45	0.51
125μm	59.6	0.21	0.41	0.50
	57.6	0.21	0.41	0.50
	57.2	0.21	0.41	0.50
150μm	75.5	0.08	0.37	0.38
	71.8	0.09	0.37	0.41
	57.5	0.10	0.34	0.48
180μm	74.5	0.17	0.33	0.40
	68.8	0.17	0.34	0.39
	76.8	0.17	0.32	0.40

The 106μmgrade showed consistent results for the 55.0% and 56.4% contents, registering the highest values of 0.51MPa after 90 days. The higher content of 70.4% did not register as much increase in strength over the 90-day period. Hence, it would not be recommended in practice. The 125μmgrade exhibited the highest level of stability with all the three derived pozzolan contents registering the same compressive strength values for each relationship. The ultimate strength is also comparable to that of 106μm, at 0.50MPa. While the higher grades also depicted some level of consistence, they are not as stable as the 125μmgrade, and registered much lower strength values. The 125μm grade seems to present a strong balance between early age strength and ultimate strength. It would therefore be recommended as the most versatile grade that gives consistent results, and least sensitive to changes in pozzolan content. This further confirms the findings from the interaction analysis by which the 125m blend was found to be the optimum blend to enable effective reaction of pozzolans and lime within a 50% to 70% pozzolan content range.

The derived mathematical functions were used to predict the range within which interaction consistence is maintained. The pozzolan content was varied between 0% and 100% in the functions for the 7-day, 28-day, and 90-day experiments with the 125µmgrade to obtain the resultant illustrations given in Figure 3 which are adjusted within the range of 21% to 84% that exhibited reliable results.

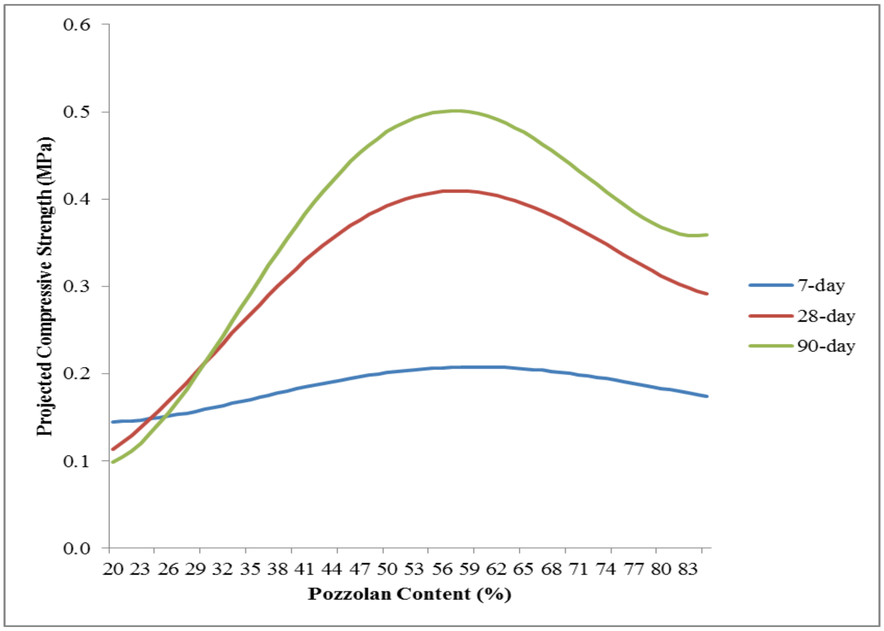

Figure 3 Strength development prediction for the optimum grade

From the illustrated comparison, it can be observed that the range of pozzolan content that gives the same strength values for the same duration irrespective of the pozzolan content is 47% to 68%. It is in this region that there is noticeable increase in compressive strength values between 7-day, 28-day, and 90-day experiments, irrespective of the pozzolan content. The best results are however obtained in the range of 54% to 60% pozzolan content.

5. Conclusions and Recommendations

The research generated strong evidence of strength development with varying proportions of natural pozzolans and lime. The results also confirmed that in addition to pozzolan content, the pozzolan grade also has influence on the strength development process of the pozzolan – lime system. It can also safely be deduced that the best results of compressive strength values can be obtained in the pozzolan-lime system if the predominant pozzolan particle size is in the range of 125µm, and the pozzolan content between 54% and 60%. As such, the pozzolan grade has maximum effect on strength development when the pozzolan content is between 54% and 60%. Similarly, the pozzolan content has maximum effect on strength development when the predominant pozzolan grade (particle size) is in the range of 125µm. It can also be suggested that any deviation outside the 54% to 60% range that does not fall below 47% or above 68% pozzolan content will still register good and comparable peak compressive strength values.

The compressive strength values registered by natural pozzolans with lime in the presence of water were too low for use in structure elements of housing construction. The highest observed value was 0.9MPa, while the most likely value generated from the developed mathematical models is 0.5MPa. However, there is a wide range of low-strength applications where such compressive strength values may be acceptable. These include mass concrete for small structures, masonry mortar, plasters, renders, light weight bricks, and soil stabilisation. These applications may constitute a substantial portion of materials used in small housing structures. Hence, the use of pozzolans can significantly reduce the construction cost of such houses. Addition of limited quantities of Portland cement may be considered to enhance the structural performance of the material.

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