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Assessing the Engineering Potentials of Alkali - Activated Geopolymer for Enhancement of Expansive Soil for Road Construction.

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Abstract - This study investigates the potential of utilizing geopolymer as an alternative soil stabilizer for enhancement of expansive soil for road construction. The soil was treated with different concentrations of geopolymer and was compacted using three compaction energies, British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH). Geopolymer treatment resulted in the reduction of plasticity index and linear shrinkage from 23% to 8% and 18% to 3% respectively, which is an indication of soil improvement. Combining the soil with geopolymer significantly improved the soil's dry density and compressive strength. The specimens exhibited a general trend of increasing Maximum Dry Density (MDD) and decreasing Optimum Moisture Content (OMC) with increase in geopolymer content and compaction effort. An increase in MDD from (1.69 -1.77) Mg/m^3, (1.71-1.79) Mg/m^3 and 1.73-1.93) Mg/m^3 for BSL, WAS and BSH respectively was recorded at 25% geopolymer concentration. The Unconfined Compressive Strength (UCS) values increased with increase in geopolymer content, age of curing and compaction energy. The seven days cured UCS values of 785kN/m^2 and 875kN/m^2 geopolymer/expansive soil blend compacted using WAS and BSH effort falls within the range of 750–1500kN/m^2 UCS value specified by the Nigerian General Specifications for sub-base materials. Likewise, the soaked CBR values of 56% and 73% recorded using WAS and BSH respectively met the 30% requirement for sub-base materials specified by the Nigerian General Specifications. While the highest geopolymer dosage yields the best outcomes, the intermediate geopolymer dosage of 15% was found to be adequate for enhancement of relevant engineering properties. Additionally, expansive soil treated with lime and tested for UCS, 1-D swell, and durability properties were compared with geopolymer-treated soil. The comparative analysis shows that geopolymer and lime treatment yield comparable results. Overall, geopolymer was found to be an excellent sole soil stabilizer and can be employed in improving the engineering properties of expansive soil to meet practical applications.

Key words: ***Expansive soil; Geopolymer; Stabilizer; Alkali; Metakaolin.***

1.0 INTRODUCTION

Expansive soils also known as swell-shrink soils are widespread in different parts of the world and are also found largely in the North-Eastern region of Nigeria, where they occupy an estimated area of 104,000 km^2[1].These soils show excessive swelling and shrinking characteristics with moisture variations, which causes adverse effects on structures, particularly light buildings and pavements, those that cannot counteract the upward thrust posed by them [2]. These soils are poor materials to use for highway or air field construction because they contain high percentages of plastic clay. In areas where they occur, usually there is no suitable natural gravel or aggregate and most deposits cover significantly large areas such that avoiding them is not possible. These soils are a very common cause of foundation problems Foundation soils which are expansive will "heave" and can cause lifting of buildings or other structures during periods of high moisture. Conversely during periods of falling soil moisture, expansive soil will collapse and can result in building settlement either way, damage can be extensive[3].

Over the last several decades, several types of stabilization techniques–including physical, mechanical, and chemical methods were developed to treat expansive soils. Among these methods, chemical stabilization, particularly using calcium-based stabilizers, proved to be more reliable and capable of stabilizing soils effectively[4]. Characteristically, traditional calcium (Ca)-based stabilizers, cement and lime, effectively mitigates the problems associated with such problematic soils by reducing their plasticity, swell-shrink potential and improving their strength properties. However, the conventional stabilizers present some disadvantages; high energy cost, high emissions of carbon dioxide (CO_2) and environmental pollution in their manufacturing

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process[5,6,7]. In the light of the foregoing, the use of aluminosilicate materials such as metakaolin through alkali activated type of cement known as geopolymer have been hailed as an eco-friendly and sustainable alternative to (Ca)-based stabilizers.

Geopolymer is a term for a binder produced from the chemical reactions of a precursor containing silica with alumina material by the presence of alkaline activators. The main components are the source materials which should be rich in major constituents, such as silicon (Si) and aluminum (Al), from either natural or waste and by-product materials, such as clays, kaolinite, etc. or red mud, fly ashes, slags, etc. The liquid is usually based on sodium hydroxide or silicate or potassium hydroxide or silicate [8]. Thus, this study intends to investigate the effect of treating expansive soil with geopolymer for road construction.

2.0 MATERIALS

2.1 Expansive Soil (ES)

Deposits of expansive soil in the field show a general pattern of cracks during the dry season as shown in Plate 1. Cracks measuring 70 mm wide and over 1m deep have been observed and may extend up to 3m or more in case of high deposits[4]. The expansive soil used in this study is the black cotton soil obtained along Gombe-Biu Road (latitude $10^0$13N and longitude $11^0$23E) 30km from Gombe town in Gombe state, North–Eastern Nigeria. The top soil was first removed before the soil samples were taken at depths of 1-1.5m below the ground surface by disturbed sampling. All samples were collected and investigated in their natural states.



Plate 1. Desiccation cracks in soil caused by drying [4]

2.2 Metakaolin (MK)

The processed metakaolin sample shown in Plate 2 was obtained through the calcination of kaolinite clay, sourced locally from Alkareli (10°15′58″N 10°20′07″E) in Bauchi State, Nigeria. Kaolin powder was sieved under dry conditions with a mesh to obtain a uniform particle size of <0.75μm. The dried kaolin powder was then calcined at a temperature of 600-800^{0}C for 6 hours to form metakaolin. After the metakaolin had cool down to room temperature, it was sieved through 75μm sieve for use.



Plate 2. Processed Metakaolin

2.3. Sodium hydroxide (NaOH)

A sample of sodium hydroxide is shown in Plate 3. It is one of the most important components of an alkali activator used in geopolymer production, particularly for metakaolin-based geopolymers[9]. Its main function is to provide a highly alkaline environment that activates the aluminosilicate precursor. It was purchased from a chemical laboratory shop in Jos, Plateau State, Nigeria.



Plate 3. Sample of Sodium Hydroxide

2.4 Sodium Silicate (Na_2SO_3)

Sodium Silicate is one of the most commonly used alkaline activators in geopolymer production. It plays an important role in supplying soluble silica and promoting geopolymerization. The Sodium silicate solution (vitrosol D-A53) shown in Plate 4 was obtained locally from M.Y and CO. in Jos, Plateau State, Nigeria.



Plate 4. Sodium Silicate

3.0 EXPERIMENTAL PROGRAM

The study was conducted in two phases. Phase one was the determination of the index and engineering properties of the untreated expansive soil, while the second phase involved adding varying proportions (5%,10%,15%,20% and 25%) of geopolymer to the soil to determine its properties when it was used as a stabilizing agent. Geopolymer preparation was performed as a two-step process. The initial step involves the

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mixing of the relevant ingredients to create the alkali activated solution (AAS) with a specific mix proportion. The second and final step involves the process of mixing the AAS and metakaolin in the required proportions to prepare the geopolymer slurry. A simplified diagram of the geopolymer synthesis process is shown in Figure 1.

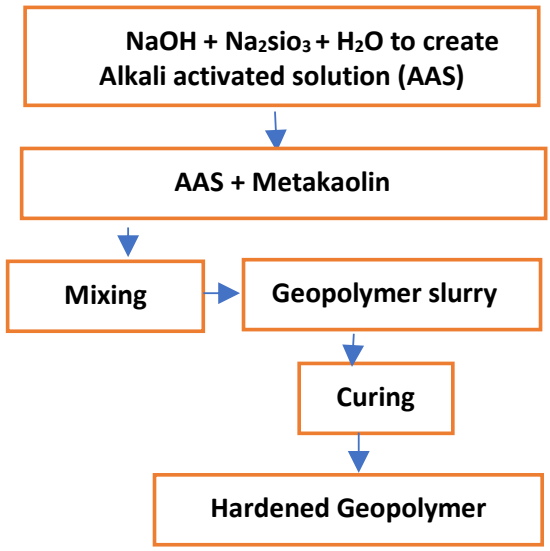

Figure 1: Simplified diagram of geopolymer synthesis

4.0 RESULTS AND DISCUSSION

4.1 Effect of Geopolymer on Moisture content- Content – Dry Density Relationship

The moisture content–dry density relationship curves shown in Figure 2 were determined for both control soil and geopolymer-treated soil at the specific dosages (5%, 10%,15%,20% and 25%). These curves provided the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of the geopolymer treated soil for each dosage, which are of utmost importance for specimen preparation for all further testing procedures.

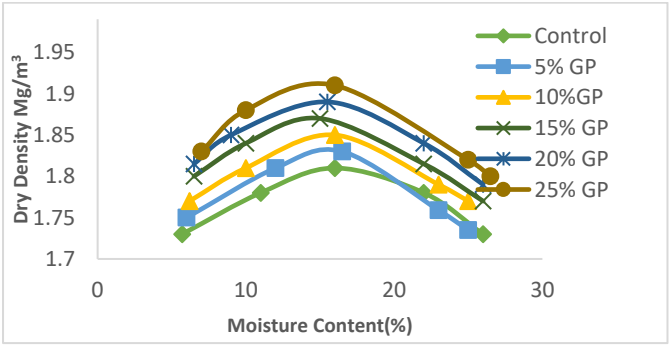

Figure 2 Moisture content–dry density curves for control and geopolymer-treated soil

The mixing of the geopolymer slurry with the soil causes cluster and flocculation of soil particles, resulting in a geopolymer-soil mixture with reduced dry density and higher water holding capacity than the control soil. The increased geopolymer dosages were observed to significantly reduce the water holding capacity of the soil due to chemical or morphological changes in the mixture, thereby lowering the OMC of the soil - geopolymer mix. This is one of the primary objectives of stabilizing high plasticity soils, where the OMC reduces and the MDD increases. The result aligns with the findings of other researchers[10,11,12].

4.2 Effect of Geopolymer on Atterberg limits

The Atterberg limits or consistency limits: liquid limit (w_l), plastic limit (w_p) and plasticity index (I_p) furnish information on the ability of the soil to retain water, as well as its ability to swell. The results of Atterberg limits, L_S and f_S tests of the untreated and geopolymer treated soil after 24 hours are presented in Table 1.

Table1: Variations in soil properties due to addition of GP

Property	0 %	5% GP	10% GP	15% GP	20% GP	25% GP
Liquid limit (%)	68	57	45	36	31	23
Plastic limit (%)	38	34	26	20	18	15
Plasticity Index (%)	30	23	19	16	13	8
Linear shrinkage	21	14	12	10	7	5
Free swell (%)	90	78	72	67	58	42

It was observed that geopolymer treatment significantly reduced the plasticity index of the expansive soil from 30%-8%. The results showed a decreasing trend in the liquid limit from 68% to 23%, increasing geopolymer content from 0 to 25% as shown in Figure 3.

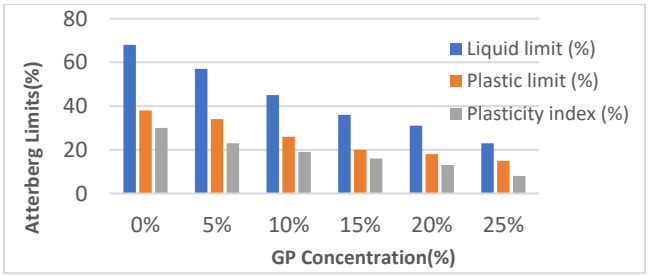

Figure 3. Variation of Atterberg limits with Geopolymer content

The gradual reduction in liquid limit could be associated with the collection and flocculation of clay particles, which is a result of ion exchange at the surface of the particles. Plastic limit generally decreased with higher geopolymer contents, from a value of 38 to 15% at 25% geopolymer content. The reduction in liquid and plastic limits resulted in a general decrease in the plasticity index value of the expansive soil/geopolymer blend. A plasticity index (I_p) value of 30%

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recorded for the untreated soil was reduced to 8 % at 25 % geopolymer addition as shown in Figure 4. Similar reduction in the I_p was observed when a predetermined dosage of lime was added to the native soil. The result agrees with the findings of several researchers [8,13. 24].

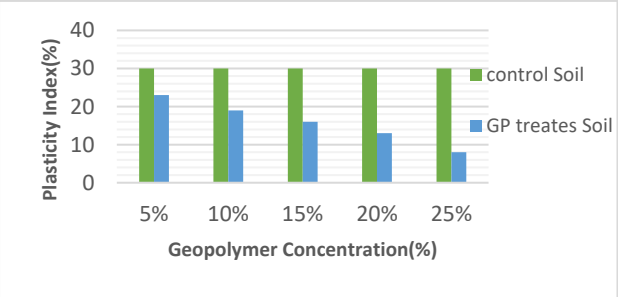

Figure 4. Variation of I_p due to addition of Geopolymer

4.3 Effect of Geopolymer (GP) on pH

It is known that a high alkaline environment is necessary to activate the reactive alumina and silica of the raw materials to form geopolymers. The Alkali Activated Solution (AAS) used in this study was found to have a pH of 13.5, thereby establishing the high alkaline reaction setting. The control soil was tested for its initial pH and was found to be 7.0. The change in pH of the soil-geopolymer mixture is an indicator of a progressive chemical reaction, in addition to giving insight into the environmental impact of the geopolymer on soil.

4.4 Effect of Geopolymer on Linear Shrinkage

Both geopolymer and lime treated soils were tested for linear shrinkage for five dosages (5%, 10%, 15% 20 and 25%). All specimens were cured for a period of 24 hours prior to testing. Both treatments were observed to have lowered the shrinkage ability of the expansive soil virtually to a negligible level. The addition of lime to the soil specimens reduced the soil shrinkage ability of the soil. A similar trend was observed for the geopolymer treated specimens. Addition of geopolymer in the proportion by weight of 5%, 10%, 15%, 20% and 25%% reduced the shrinkage potential by 86%, 88%, 90% ,93% and 95% respectively. The shrinkage became virtually negligible following the addition of the 25% geopolymer. The results of the shrinkage test for geopolymer treated soil presented in Figure 5 align with the findings of other researchers [14,15,16].

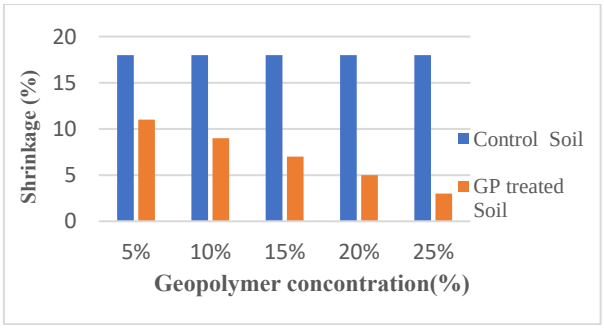

Figure 5. Variation of linear shrinkage with geopolymer content.

4.5 Effect of Geopolymer on Swell Potential of Expansive Soil

The control and geopolymer treated soil samples were both tested for 1-D swell tests in keeping with ASTM D4546-08. A single predetermined dosage of lime treated and three different dosages of geopolymer (5%, 10%, and 15%) treated soil were tested after curing periods of 24 hours. Results obtained from the swell test are shown in Figure 6. The swell potential of the soil reduced after its treatment with geopolymer and lime.

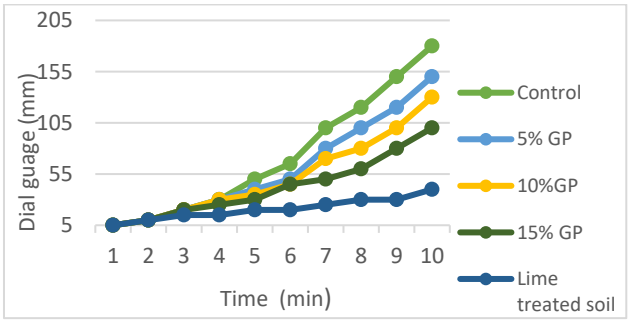

Figure 6. Time swell curve of varying geopolymer dosage

For geopolymer, the reduction was incremental as the concentration of the geopolymer increases. The swell potential of the control soil was observed to have reduced by about 50%, 75% and 87.5% with corresponding dosage of 5%, 10% and 15% geopolymer. It is assumed, therefore, that the swell would have become insignificant with longer curing time and geopolymer content. It is likely that the fast reduction in swell is due to a swift exchange of cations between the geopolymer and lime on one hand and the clay minerals on another hand. This process weakens the capacity of clay minerals to absorb water. The result aligns with other researchers, [3,17,18].

4.6 Effect of Geopolymer on Durability Characteristics

Durability characteristics are the properties of a material that determine its ability to maintain its strength, integrity, and performance over time when exposed to environmental conditions and service loads. The durability test results for

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the relevant lime and geopolymer combinations considered in evaluating the admixture stabilization of black cotton soil are presented in Table 2.

The highest resistance to loss in strength of 92% (i.e. 8% loss in strength) with respect to the lime-

Table 2. Effect of immersion in water on UCS Soil Geopolymer mixtures

	10%GP			15%GP			20%GP			25%GP		
Lime (%)	p_d	p_c	R	p_d	p_c	R	p_d	p_c	R	p_d	p_c	R
0	195	230	0.85	680	780	0.87	845	1001	0.84	945	1040	0.91
1	325	360	0.90	815	945	0.86	980	1075	0.91	1170	1335	0.87
2	425	455	0.93	1040	1140	0.91	1270	1495	0.85	1430	1625	0.88
3	650	685	0.95	1140	1270	0.90	1400	1660	0.84	1660	2015	0.82
4	780	845	0.92	1560	1690	0.92	1725	1920	0.90	1950	2275	0.86

p_d UCS (kN/m^2) of specimens cured dry for 7days and soaked in water for another 7days; p_c UCS (kN/m^2) of specimens cured dry for 1days **R-** resistance to loss in strength (i.e ratio of p_d to p_c

geopolymer mixtures that yielded very high UCS values was recorded for 4% lime and 15% geopolymer. The minimum resistance to loss in strength of 82% (i.e.18% loss in strength) was recorded for 3% lime and 25% geopolymer combinations. Consequently, judging from the high durability recorded (i.e. 18% loss in strength) for UCS value of 2015kN/m^2 a concentration of 25% geopolymer can be said to be adequate for this form of stabilization. A similar assertion was made by [19]

4.7. Effect of Geopolymer on Unconfined Compressive Strength (UCS)

The result of the variation of geopolymer content and curing age on unconfined compressive strength is presented in Figure 7. Combining the soil with geopolymer improved the soil's compressive strength. The UCS values increased with increase in geopolymer content, age of curing and compaction energy. The peak values of 875,1438 and 1600kN/m^2 were respectively recorded at 25% geopolymer concentration for 7, 14- and 28-days curing.

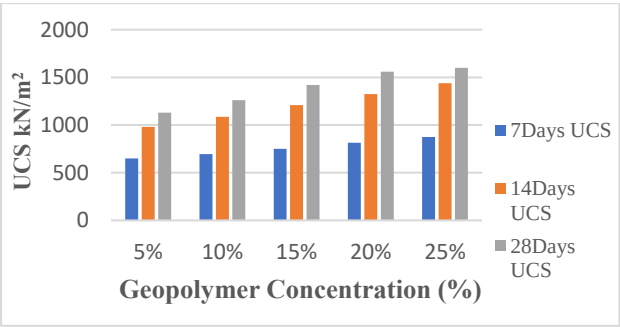

Figure 7. Variation of UCS with geopolymer content and curing age.

4.8 Effect of Geopolymer on California Bearing Ratio (CBR)

The results of the effect of geopolymer treatment on California Bearing ratio (CBR) are shown in Figure 8. Generally, CBR values with higher compaction effort were observed in the order BSL, WAS and BSH compaction. There was significant improvement in strength of the soil samples treated with geopolymer. The CBR value of the natural soil increased from 13% to a highest value of 73% at 25% geopolymer content. The general trend was that of increase in CBR values with increase in geopolymer content and compaction effort. The trend conforms with the results reported by [15,20,21].

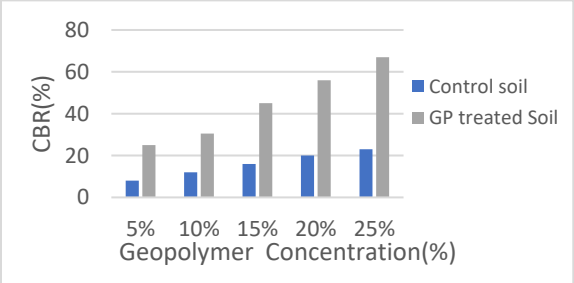

Figure 8. Variation of CBR with geopolymer content

4.9 Comparison of Geopolymer and Lime Treatment of Expansive Soil

A comparison of the effect of geopolymer and lime treatment on plasticity index (I_p) of the expansive soil is shown in Figure 9. It was observed that both stabilizers effectively reduced the I_p of the soil, however, the reduction in geopolymer treated soil was higher than that of lime treated soil. Geopolymer treatment resulted in reduction of I_p from 30% to 5% while lime treatment reduced the I_p from 30% to 7%, both at 25% concentrations.

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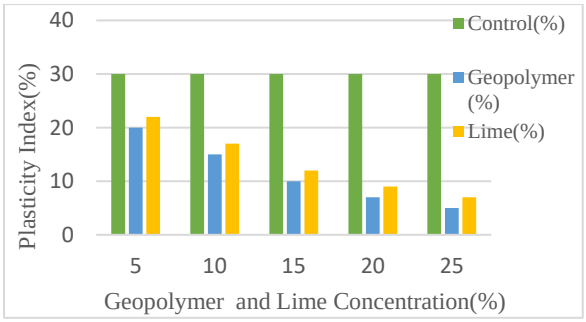

Figure 9. Comparison of I_p of Geopolymer treated and Lime Soil

A similar trend was observed in the linear shrinkage of both treatments as shown in Figure 10. The comparative analysis of I_p, L_s and CBR
shows that geopolymer and lime treatment yield comparable results. The result is consistent with those reported by [22,23, 24s]

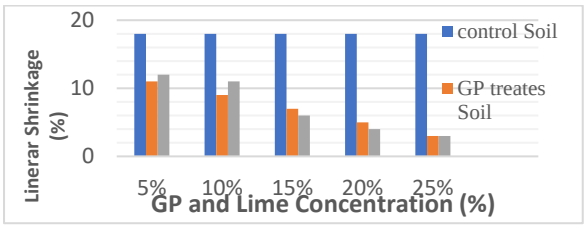

Figure 10. Comparison of LS of Geopolymer treated and Lime treated Soil

A demonstration of the comparison between geopolymer treated and lime treated soil on CBR of the expansive soil is shown in Figure 11. The
comparative analysis revealed that geopolymer and lime treatment yield comparable results.

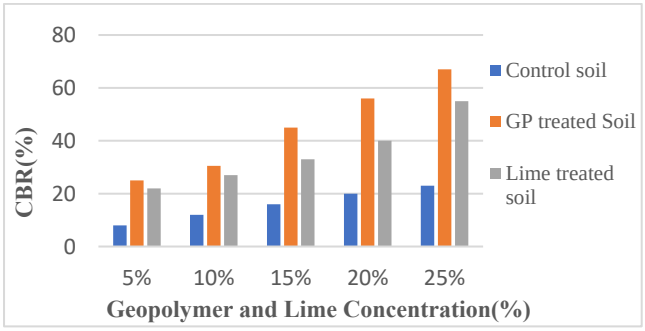

Figure 11. Comparison of CBR of Geopolymer treated and Lime treated Soil

5.0 CONCLUSIONS

Based on the results of the study conducted the following conclusions are drawn:

1.There was notable improvement in the index properties of geopolymer treated soil: w_l (23%), I_p(8%), L_s (5%) andf_s (42%). The soil's dry density (1.93Mg/m^3) confirmed the significant development.

2. The study clearly demonstrates the potential of metakaolin-based geopolymer as sole binder for stabilization of expansive soil. Geopolymer treatment shows significant improvement in strength: UCS (1600kN/m^2), CBR (67%), stiffness, volume change, and long-term performance characteristics of expansive soil.

3. A comparison of lime-treated soil with geopolymer-treated soil shows that their plasticity index (7%vs5%), Maximum dry density (1.90Mg/m^3 vs1.93Mg/m^3, strength: CBR (65% vs 67%), UCS (1590kN/m^{2}vs 1600kN/m^2), swell, and durability characteristics are comparable**.**

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