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Compressive strength and durability of fly ash stabilized dolomitic waste as a lightweight construction material

Ikechukwu F. ANEKE[1] and Felix N. OKONTA
Department of Civil Engineering science, University of Johannesburg, P.O Box 524, Auckland Park 2006, South Africa

Abstract. Due to the seriousness of environmental pollution and the production of huge energy consuming building and construction materials, the development of new eco-friendly and energy saving building materials to overcome these issues has been gaining increasing attention. South Africa has largest number of dolomite deposits in southern Africa, if not in the entire Africa. Nonetheless most of the dolomite in South Africa has some impurities of which they are neglected in dumping site (millions of tons). This paper looked at finding alternative use for this dolomitic waste (DW) by stabilizing this waste with another waste called fly ash (FA), introduction of gypsum as an activator will trigger a pozzolanic reaction in presences of water. As a result of this, the product of this reaction will be a useful material in construction and as well solve the difficulties i.e. environmental, social and cost often associated with storing and handling of this waste. This work went as far as providing an alternative for low-cost construction materials that can help deal with South African housing problems.

The waste material was analyzed from geomaterial and geochemistry view point, the chemical reaction between these materials: dolomitic waste and fly ash were illustrated. The XRF, SEM and EDS of the reacted product were looked at, the strength gained by the reaction after sample preparation for 28 days were also shown. However various geotechnical laboratory experiments were conducted ranging from proctor compaction test, compressive strength test and a mathematical model was generated to predict the compressive strength and these results were compared to compressive strength values obtained from the laboratory.

Keywords. Dolomitic waste, fly ash, geochemistry, SEM and compressive strength

Introduction

Generally when a carbonate rock is composed of more than 95% of calcite, it is known as limestone, but otherwise it is called sedimentary rocks [1]. They originate from different natural sources such as dolomitic rocks dust, volcanic rock ([2] and [3]. The mineral dolomite derives its name from Deodat Dolomieu (1750-1801) named after a French engineer and mineralogist.

This dolomitic waste constitute mainly, of a chemical nomenclature (CaMg $(CO_3)_2$), which is an indication that it contains limestone that can be used as a source of calcium oxide (CaO). This calcium oxide is one of the major elements that contribute to pozzolanic reaction between dolomite and fly ash [4]. Although pozzolanic reaction is slow, but can be activated to be more reactive. The large volume of this waste after processing dolomite rock, forms lot of unwanted aggregates which are developed with many features depending on the primary rock properties, this can be used as a

[1]Corresponding author: Frankaneke4@gmail.com

lightweight material [5]. Lots of researchers have looked at the use of dolomite for lightweight construction material, but lightweight materials such as dolomitic waste-stabilized fly ash are gaining increasing interest over past years. Hence these wastes are natural materials and are granular with less bulk density [6]. Furthermore, there are growing interest in the development and utilization of both waste (dolomitic waste and fly ash). The example of this utilization is preparation of a ternary mix known as Dolomite-Fly ash- Gypsum (DO-FA-G) binder, a new cementitious binder based on dolomite, fly ash and gypsum. The hardening of this binder is developed by the means of chemical reactions between the dolomite, silica from the ash (fly ash) and water. The resultant reacted product, produces hydrated calcium silicates (C-S-H), as well as by means of reaction between the calcium sulphates from gypsum, CaO from dolomite and alumina from fly ash also reacts in presences of water to forms ettringite ($3CaO.Al_2O_3.3CaSO_4.32H_2O$). These hydration reactions in dolomite-fly ash-gypsum-water paste are very complex and are dependent on the fly ash mineralogical composition. The solubility of both the crystalline and non-crystalline fractions of the ash depends on the conditions in which the hydration reaction took place.

1. Experimental procedures

The dolomitic waste used in this paper, were collected from lyttelton mine in centurion South Africa and fly ash used for this work, was purchased from ULULA ash South Africa and it is a commercial available class ‘F’ fly ash that has a specific gravity of 2.0. Figure.1 shows the mine where the waste was collected.

Figure 1. Lyttelton dolomite mine

Gypsum was also used for this work and it was purchased from GypsealRhinoborad sealant by BPB GypsumRhino board Division. The chemical compositions of these materials were determined by the use of XRF equipment. In certain cases, additional tests may be required such as XRD test which have been found to be important in the classification of specific material types. Standard procedures exist in most countries (ASTM or SABS) although slight variations might occur.

1.1 Chemical Composition of the materials

Chemical composition of a material is one of the most important indications that a material has a good or bad quality chemical composition for various applications. The detailed chemical compositions of materials used in this research paper are summarized in Table 1 below:

Table 1. Chemical composition of material

Oxide	Gypsum %	Fly ash %	Dolomitic waste %
SiO_2	24	56	2.47
Al_2O_3	0.71	22.5	0.84
Fe_2O_3	0.35	6.8	0.34
CaO	32.3	3.8	31.5
MgO	0.38	2.3	19.12
SO_3	42.8	0.25	<<<<
K_2O	0.1	1.9	0.09
Na_2O	<<<<	0.85	0.11
L.O.I	0.08	0.05	0.45

1.2 Compaction

Standard compaction test was performed in according with ASTM D698 to establish the relationship between the moisture content and dry density of the material. As a result of this, dolomitic waste and fly ash was chosen for some trial mixes and it was mixed with water thoroughly and stored in polythene bag for moisture equilibrium and remixed in accordance with ASTM D 698-91.The fly ash and dolomitic waste are compacted in the mould in three layers, giving an equal taps of 25 blows to each layer. Each trails using standard proctor apparatus, the values of the dry materials and corresponding trials mixes are inferred in Table 2 below. The results of the compaction with their corresponding dry densities and optimum moisture content are shown also in Figure 2. Nonetheless 6% gypsum was only added during sample preparation for casting.

Table 2. First mix of materials for compaction test

Material	Dolomitic waste mass (%)	Fly ash mass (%)	Gypsum (%)
1st Trial	100	0	6
2nd Trial	90	10	6
3rd Trial	70	30	6
4th Trial	60	40	6
5th Trial	50	50	6

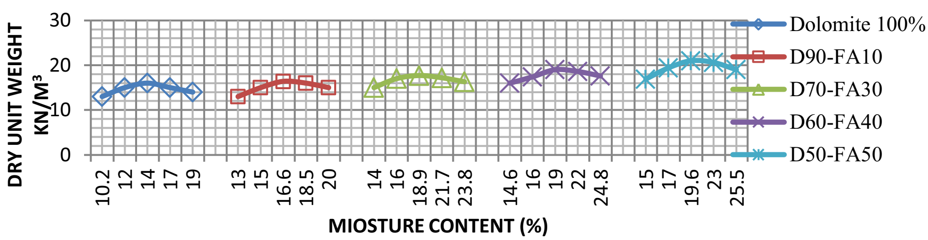

Figure 2. Compaction curves for different varying mixes of dolomitic waste and fly ash samples

The samples were prepared for their maximum densities at optimum water content based on compaction curves obtained as was calculated in Figure 2. 50x50x50 mm cube molds were used. These samples have various curing period for testing i.e. 7, 14 and 28 days. The samples prepared were labeled according to the trial combination chosen. Steam curing method was adopted for this research work. The samples were demolded and covered with plastic bags after 24hours of preparation and was carefully positioned in hydro-autoclave with a constant temperature of 80^{o}C for the curing period of 7, 14, and 28 days.

1.3 Compressive strength test

The compressive strength test were performed on the prepared samples according to ASTM D 695, by using mechanical testing machine, with automated fixtures in order to obtain the ultimate strength of the tested sample with respect to their stress-strain behaviors. The samples were loaded with 50 KN and utilized the speed rate of 5 mm/min. The compressive strength values are determined by the average of three samples tested for each different type of trial mixes. Scanning electron microscopy (SEM) was performed by using SEM Rigaku Ultimate, to study the microstructure of the base material (dolomitic waste) and the resulting samples. The test was carried out using secondary and backscattered electron detectors and a SEM sample was pulverized.

2. Results and discussion

2.1 Chemistry and mechanism of reactions

Fly ash has a reactive silica and aluminum of 22.5% and 56% respectively as presented in Table 1,while the dolomitic waste has 31.5% of free calcium { $(CaMg(CO_3)_2)$} and the samples for the first set was prepared using 6% gypsum. This sample reacts in the presence of water and temperature condition of 80^{o}C as illustrated in the chemical equations below:

$$2Ca + SiO_2 + H_2O \longrightarrow \underset{\text{Dicalcium Silicate}}{Ca_2O\,(SiO_2).H_2O} \text{ Pozzolanic equation} \quad (1)$$

This reaction occurs during the first few days (3days) leading to a very significant strength gain; however the hydration reaction is the same to that of tricalcium silicate. But dicalcium silicate contributes little to the early strength of pozzolans; hence it makes substantial contributions to strength gain in later age.

$$3Ca + SiO_2 + 3[OH] \longrightarrow \underset{\text{Tricalcium Silicate}}{Ca_3O_2\,(SiO_2).H_2O} \text{ Pozzolanic equation} \quad (2)$$

$$3Ca + Al_2O_3 + 6H_2O \longrightarrow \underset{\text{Tricalcium aluminate}}{Ca_3O\,(Al_2O_3).6H_2O} \text{ Pozzolanic equation} \quad (3)$$

$$CaSO_4.2H2O + Al2O3 + \underset{\text{(From Dolomite)}}{\underset{\downarrow}{CaO}} \longrightarrow 4CaOAl2O3.SO.12H2O \text{ Pozzolanic equation} \quad (4)$$

The pozzolanic reaction of aluminate minerals is somewhat more complex than that of the calcium silicates minerals, and it takes place depending on sulfate ions that are present in the pore solution. Tricalcium is soluble, even more so than dicalcium silicate. In reaction that involves gypsum, this actually occurs with unduly reacted ettringite $(Ca_6Al_2(SO_4)_3(OH)_{12}.26(H_2O)$ from C_3A and C_4AF when the gypsum is consumed, the ettringite reacts with the remaining C_3A and C_4AF to form a new lower-sulfate phase known as Monosulphate with little or no ettringite.

2.2 Compaction results

The compaction results of the materials for the trial mixes of the compaction set as reported in Figure 2, when dolomitic waste was compacted the average results obtained shows that dolomitic waste recorded a maximum dry density (MDD) of 16.0 KN/m^3 and corresponding optimum moisture content (OMC) of 14%.for the second trials in Table.2 (D90-FA10), this was done by replacing 10% of dolomitic waste with 10% of fly ash, after 10% of dolomitic waste was subtracted. This resulted in increased (MDD) and (OMC) giving the second trial a value of 16.4 KN/m^3 and 16% respectively which was a clear evidence that fly ash is more denser than dolomite. In the 3^{rd}, 4^{th} and 5^{th} trials when 30, 40 and 50% dolomitic waste was replaced with equal amount of fly ash the results subsequently lead to an increase in MDD and OMC giving value of 17.7 KN/m^3 and 18.9%, 20.5 KN/m^3 and 19%, 22.0 KN/m^3 and 19.6% respectively. This simply shows that both the MDD and OMC are increasing as the mass% of the fly ash is increasing.

2.3 Compressive strength

The results for compressive strength test shows that the first set of mixtures (Table 2) without 6% gypsum have a strength gain in overall, But not as compare to those with 6% gypsum, which demonstrate a very good strength. However fly ash reactions with dolomitic waste enhanced strength development even after 7 days of curing, and the effect of 6%gypsum to compressive strength of the mixture of dolomitic waste and fly ash samples compacted to their respective maximum dry density at corresponding moisture content has been illustrated in (Figure 3 through 5) which shows that the compressive strength of dolomitic waste and fly ash mixtures for all the combination cured for 28 days. The combination of D50%+FA50%+G6% mix recorded strength of 2280 Kpa for 28days curing period from as low as 600Kpa of only dolomitic waste. The effect of pozzolanic reactions dominates strength gain at higher curing periods whereas the effect of density dominates strength gain at lower curing periods.

The dolomitic waste stabilized fly ash mixtures without gypsum have recorded strength up to 2080 Kpa after 28 days curing. The strength of the materials is very much dependent upon the pozzolanic reaction just as stated in equation (1) through equation (4). The addition of water and the method of curing play a critical role, particularly the amount used to prepare the sample. The strength of the materials increases when less water content was used. The pozzolanic reaction itself consumes a specific amount of water, but the water not consumed in the pozzolanic reaction will remain in the microstructure pore space and these pores usually make the end product weaker due to lack of strength–forming calcium silicate pozzolanic bonds. Although the samples were prepared at its OMC, which leads to high strength but low in workability. The perfect graphs of strength were shown for different curing ages, the compressive strength increases with an increase in age but the highest compressive strength were observed at 28 days age for all the different mixes, hence D_o50%+FA50%+G6% recorded a strength up to 2280 Kpa .

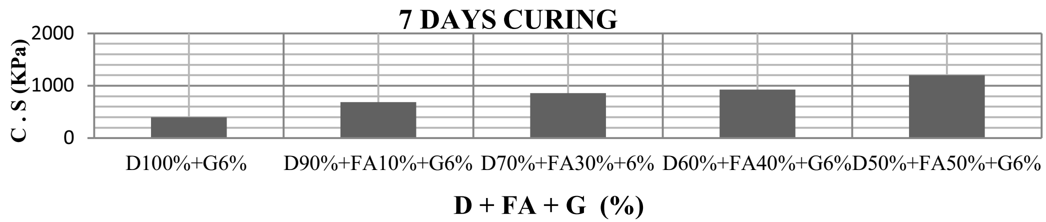

Figure 3. Compressive strength curve versus D_O + Fa + G

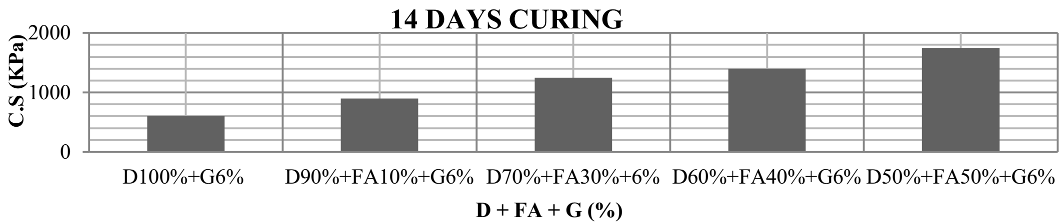

Figure 4. Compressive strength curve versus D + Fa + G

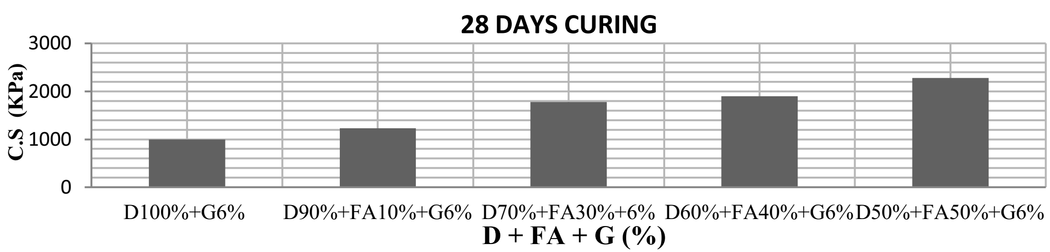

Figure 5. Compressive strength curve versus D + Fa + G

2.4 Stress-strain behavior

Compressive strength test were used to evaluate the stress-strain behavior properties of dolomitic waste, fly ash and gypsum mix propotion.it was seen that the density D, fly ash(FA), OMC, gypsum (G) affects not only the compressive strength, but also affects the stress-strain behavior. With increasing OMC in Figure 2; the specimen becomes stiffer and the stress-strain curves changes from ductile to brittle behavior. Figures 6 and 7 below shows that the mixture of (100% dolomitic D_o waste) + (6% gypsum G) the compressive strength is low and the stress-strain curve is ductile to an extent. The behavior of the specimen at load failure is also shown in Figures 6 and 7 However when mix ratio of D_o50% + FA50% + G6% was tested the compressive strength and stiffness is relatively high.

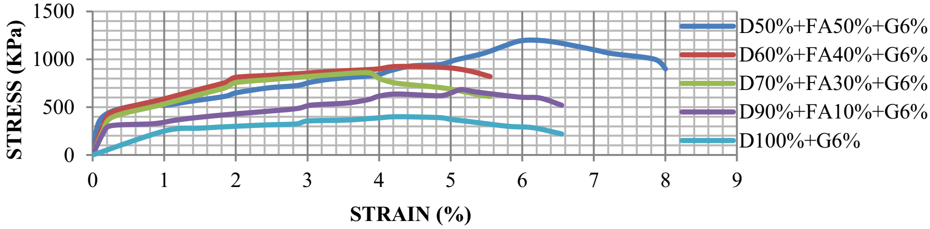

Figure 6. Stress-strain curve for 7 days test

The stress-strain curves become brittle in Figures 6 and 7 suggest that there is a difference between strength and ductility when the compressive strength is high. Its stress-strain behavior is less ductile and starts to be brittle as the level of stress begin to drop. Among mixed components affecting the stress-strain characteristic of dolomitic waste, fly ash, and gypsum of D50% + FA50% + G6% proportion have the most effect.

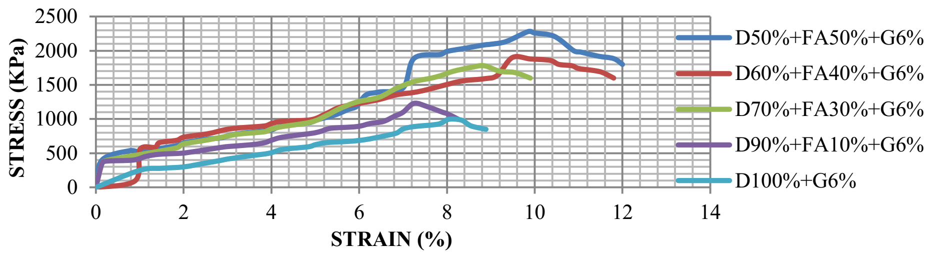

Figure 7. Stress-strain curve for 28 days test

2.5 Microstructure

The microstructure of dolomitic waste stabilized fly ash was analyzed using scanning electron microscope (SEM). In Figure 8, the microstructure of the stabilized material shows the formation of pore heterogonous matrix which does not exist in the original dolomitic waste. The formation of the matrix was due to the pozzolanic reaction occurred after mixing the original dolomitic waste with fly ash and gypsum as an activator.

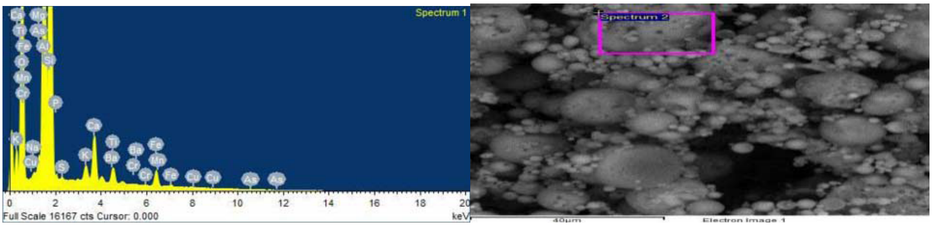

Figure 8. SEM of Do-Fa-G before and after 28days curing

3. Regression analysis

Statistical model were generated and tested to show the relationship between variables for 6% gypsum only with respect to the compressive strength. Input parameters used in this study are based on the experimental result conducted in the laboratory. This includes the values of compressive strength, density, percentages of dolomitic waste, fly ash and finally the weight of water used to the ratio of prepared samples. Equation (5) below shows the regression analysis equation.

$$F = B_0 + B_1 \text{ x } \frac{b}{w} \quad (5)$$

Where F = compressive strength, B_0 and B_1 are the coefficients (Abram's Law). The equation (6) below was used for this study:

$$Y = A_0 + B_{x1} + C_{x2} + D_{x3} \text{ x } \alpha \quad (6)$$

Where Y = Compressive strength, A_0=1, B=Dolomitic waste, C= Fly ash, D = Density of the prepared specimen and α = Mass of H_2O in the specimen (grams). However dolomitic waste, fly ash, density and mass of H_2O are taken as independent variables, where compressive strength is taken as the dependent variables.

Table 3. Variables for 6% gypsum 7 days testing

Dolomite (%) X_1	Fly ash (%) X_2	Density (kN/m^3) X_3	Mass of H_2O (ml) α	C.S Lab values (Kpa) Y	C.S predicted values (kPa) Y
50	50	21.00	760	1200	1203.90
60	40	19.00	745	925	927.59
70	30	17.7	785	860	866.72
90	10	16.40	725	684	696.16
100	<<<	16.00	700	400	397.54

C.S (kPa) = $0.0208_{x1} + 0.01612_{x2} + 0.0751_{x3}$ x 760 = 1203.9 kPa
C.S (kPa) = $0{,}001248_{x1} + 0.0065_{x2} + 0.065_{x3}$ x 745 = 927.59 kPa
C.S (kPa) = $0.00874_{x1} + 0.001944_{x2} + 0.062_{x3}$ x 785 =866.72 kPa
C.S (kPa) = $0.007866_{x1} + 0.0194_{x2} + 0.058_{x3}$ x725 = 696.16 kPa
C.S (kPa) = $0.00791_{x1} + 0.035_{x3}$ x 700 =397.54 kPa

Table 4. Variables for 6% gypsum 28 days testing

Dolomite (%) X_1	Fly ash (%) X_2	Density (kN/m^3) X_3	Mass of H_2O (ml) α	C.S Lab values (kPa) Y	C.S predicted values (kPa) Y
50	50	21.00	776	2280	2291.14
60	40	19.00	736.5	1900	1910.04
70	30	17.7	793	1780	1788.85
90	10	16.40	720	1230	1240.64
100	<<<	16.00	700	1000	1067.50

C.S (kPa) = $0.105_{x1} + 0.275_{x2} + 0.125_{x3}$ x 776 = 2291.14 kPa
C.S (kPa) = $0.107_{x1} + 0.623_{x2}$ + 0.120x3 x 736.5 = 1910.04 kPa
C.S (kPa) = $0.100_{x1} + 0.324_{x2} + 0.118_{x3}$ x 793 =1788.85 kPa
C.S (kPa) = $0.09_{x1} + 0.0211_{x2} + 0.10_{x3}$ x720 = 1240.64 kPa
C.S (kPa) = $0.085_{x1} + 0.090_{x3}$ x 700 = 1067.5 kPa

4. Conclusions

- Dolomitic waste from lyttelton dolomite mine stabilized with fly ash can enhance the mechanical properties of lightweight construction materials. The mixture of D50%+FA50%+6% shows excellent result with highest compressive strength of 2280 Kpa in 28 days testing.
- The microstructure of the optimum strength pozzolanic material appears to be homogeneous and still have some minimum proportion of unreacted fly ash microspheres, with continuous matrices of aluminosilicate.
- The reaction between dolomitic waste and fly ash produces calcium silicate hydrates (C-S-H) which is responsible for strength gain, but the addition of 6% gypsum contributes to development for later age strength again. However the continuous addition of fly ash will be beneficial as the strength continues to increase.
- Some of the predicted values are slightly higher than the laboratory values, Thereby indicating the importance of the influence of mix constituents on the compressive strength of the specimens can be approved.

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