Compaction behaviour of plaster of Paris dewatered- and air dried-Nigerian clay

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Abstract. The effects of compaction pressure on the green bulk density and porosity of Nigerian clay were examined over a range of pressure from 47.2 to 157.3 MPa. An exponential behaviour was found between pressed relative density and compaction pressure, the logarithm of relative density increasing with compaction pressure.

An exponential behaviour was also found between compaction pressure and true porosity, the latter decreasing as the logarithm of compaction pressure increased.

Finally, empirical equations relating to true porosity and compaction pressure and also the relationship between relative density and compaction pressure, are presented.

Keywords. Compaction behaviour; plaster of Paris; Nigerian clay.

1. Introduction

The compaction behaviour (Dynys and Halloran 1983) of ceramic powders is strongly influenced by the state of agglomeration of the powder. With increasing applied pressure the density of the powder column will increase, or its porosity will decrease. Several workers (Yu Balshin 1938; Seelig and Wulff 1946; Bockstiegel and Hewing 1965) have studied the relationship between applied pressure and the density or porosity of powder compact, and have attempted to establish mathematical relationships between pressure and average relative density. For dry compaction of nonplastic materials, the agglomerate state of primary industrial relevance involves nonaggregated powder agglomerated into powder free-flowing granules by spray-drying with a binder. Clay in itself has binding characteristics.

The object of this study is to investigate the effect of compaction pressure on the green bulk density and true porosity of Nigerian clay* suitable for refractory brick manufacture.

2. Experimental

The clay used in this study consisted basically of clay substance, vegetable matter and free silica. The as-received clay was wet-sieved to pass 200 mesh. The resulting slip was allowed to settle for 48 h and the supernatant liquid decanted. The slurry was then

dewatered on a plaster of Paris bat and dried in air to a leather-hard condition. The resulting lumps were crushed to powder containing 2.3% moisture.

The clay powder was compacted using a 19 mm internal diameter steel die and punch set. The punch and die were lubricated with engine oil to lessen die-wall friction effects. Compaction was performed on a Buehler Ltd laboratory mounting press at pressures of 47.2, 62.9, 94.4, 110.1, 125.8, 141.5 and 157.3 MPa. Ten clay discs were compacted at each pressure.

The true specific gravity of the clay powder was determined by the evacuation method (Chesters 1974). Three concordant readings were obtained and an average value taken.

The green bulk density and apparent porosity of the clay compacts were determined by evacuation method with kerosene as the liquid medium. The bulk density, D was calculated using the relationship:

$$D = \frac{W_d}{W_s - W_p} \times D_s, \quad (1)$$

where W_d is the dry mass, W_s the soaked mass, W_p the suspended mass and D_s is the density of the liquid medium.

The apparent porosity (AP), was calculated using the relationship:

$$AP = \frac{W_s - W_d}{W_s - W_p}. \quad (2)$$

The true porosity (TP), was also calculated using the relationship:

*Clay is from Afikpo in Abia State of Nigeria.

$$TP = 1 - \frac{D}{D_0}, \quad (3)$$

where D is the bulk density of compact and D_0 the true density of the clay powder.

3. Results and discussion

The specific gravity of the clay as determined by the evacuation method is 2.60.

3.1 Effect of compaction pressure on green bulk density

The green bulk density–compaction pressure relationship exhibits a straight line on a semilogarithmic plot, within

Table 1. Effect of compaction pressure on green bulk density.

Designation	Compaction pressure (MPa)	No. of specimens	Average green bulk density (g cm^{-3})	Standard deviation
P1	47.2	10	1.88	0.0126
P2	62.9	10	1.93	0.0101
P3	94.4	10	1.97	0.0054
P4	110.1	10	2.04	0.0065
P5	125.8	10	2.07	0.0050
P6	141.5	10	2.09	0.0111
P7	157.3	10	2.11	0.0085

the range of compaction pressures used in this investigation. Table 1 lists the average bulk density against the corresponding compaction pressure. Figure 1 shows the semilogarithmic plot of the relative density, D/D_0 , against compaction pressure based on least squares analysis.

3.2 Effect of compaction pressure on green porosity

The relationship between the compaction pressure and green porosity exhibits a straight line on a semilogarithmic plot, within the range of compaction pressures used in this investigation. Table 2 lists the average green porosity as a function of compaction pressure. Figure 2 shows the semilogarithmic plot of compaction pressure against green porosity (volume fraction).

The most prominent features of this investigation are the linear relationships resulting from the semilogarithmic plots of relative density vs compaction pressure and true porosity vs compaction pressure. This means that the bulk of the compaction data, from 72 to 81% theoretical density, can be represented simply by the empirical equation

$$D = D_0 \exp(kP), \quad (4)$$

where k is empirical slope, P the compaction pressure,

Figure 1. Effect of compaction pressure on relative density.

D the density of compact at pressure, P and D_0 the true density of the clay powder.

The D/D_0 and P values obtained in this study were highly correlated. A plot of $\ln D/D_0$ vs P could be fit by a straight line with a regression coefficient of 0.9862. Increasing the compaction pressure from 47.2 to 157.3 MPa increases the bulk density from 72 to 81% of the theoretical density.

Again, increasing the compaction pressure from 47.2 to 157.3 MPa decreases the true porosity, expressed as a volume fraction, from 0.278 to 0.190. This allows the bulk of the compaction data, from 0.278 to 0.190 true porosity, to be represented simply by the empirical equation:

$$P = P_0 \exp(-bp), \quad (5)$$

where P is the compaction pressure, P_0 the compaction pressure at zero porosity, b the empirical slope which is a constant for the material and p the volume fraction porosity. The straight line obtained from a semilogarithmic plot of pressure, P vs volume fraction porosity, P has a regression coefficient of 0.9831. This suggests that the pressure-porosity relationship is well correlated. This is anticipated by the Duckworth (1953) equation in the discussion of Ryshkewitch's paper.

However, it should be noted that the mechanics of dry powder compaction is complex in its details (Broese Van Groenau 1981), and unclear in its foundations (Onoda and Urban 1978), and therefore all equations must be considered empirical rather than based on the principles of mechanics. Nevertheless they are quite useful for the purpose of interpolating green densities and/or porosities as a function of compaction pressure.

The effect on green density and porosity of compaction pressures less than 47.2 MPa and greater than 157.3 MPa, was not investigated in this study. The extrapolated density is 1.79 g cm^{-3} as against the tap density 1.31 g cm^{-3} . It is anticipated that the porosity will increase exponentially with a decrease in compaction pressure.

When semidry powders are pressed, there must be incomplete transmission of pressure because a proportion of the thrust is taken up in overcoming the friction the

Table 2. Effect of compaction pressure on green porosity.

Designation	Compaction pressure (MPa)	No. of specimens	Average green porosity (vol. fraction)	Standard deviation
P1	47.2	10	0.278	0.0049
P2	62.9	10	0.256	0.0039
P3	94.4	10	0.242	0.0021
P4	110.1	10	0.214	0.0025
P5	125.8	10	0.203	0.0020
P6	141.5	10	0.196	0.0044
P7	157.3	10	0.190	0.0033

Figure 2. Effect of compaction pressure on green porosity.

grains exert on each other and on the sides of the die. Shaxby and Evans (1923) have shown that the pressure decreases with the distance from the surface layer at a rate directly proportional to the coefficient of friction of the particles on the walls of the die and to the externally-applied pressure but inversely proportional to the radius of the die (assumed cylindrical).

Consequent on this pressure gradient, the bulk density in the pressed compact must vary with the depth, in accordance with the logarithmic relationship already established.

The apparent porosity of sintered firebricks varies from 9% (very low) to 22.5% while the bulk density varies from 1.96 to 2.36 g cm⁻³. From the compaction data, a suitable compaction pressure corresponding to a given green bulk density or porosity of refractory bricks made from the clay used in this study can be estimated. It should be noted that the porosity of the sintered material will decrease while the bulk density will increase. This means that within the range of compaction pressures used in this study, sintered refractory bricks having porosities between 1.96 and 2.36 g cm⁻³ can be produced from the Nigerian clay used.

4. Conclusion

The effect of compaction pressure on the bulk density and porosity of the Nigerian clay can be described by empirical expressions relating logarithm of relative density to compaction pressure and also relating logarithm of compaction pressure to true porosity before sintering.

The empirical equation describing the effect of compaction pressure on the porosity is similar to the Duckworth equation in the discussion of Ryshkewitch's paper.

The relationship between the bulk density, D and the compaction pressure, P can be represented by

$$D = D_0 \exp(1.07 \times 10^{-3} P),$$

where D_0 is the true density.

The relationship between the compaction pressure, P and the volume fraction of porosity, p can be represented by

$$P = 1816 \exp(-12.94 p).$$

The compaction data for this clay sample has been used to produce refractory bricks by dry pressing prior to sintering.

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