Applied Clay Science, 5 (1990) 165–181
Elsevier Science Publishers B.V., Amsterdam

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Effects of variation in water content, clay fraction and sodium carbonate additions on the synthetic moulding properties of Igbokoda clay and silica sand

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(Received January 23, 1989; accepted after revision Feburary 9, 1990)

ABSTRACT

Loto, C.A. and Adebayo, H., 1990. Effects of variation in water content, clay fraction and sodium carbonate additions on the synthetic moulding properties of Igbokoda clay and silica sand. Appl. Clay Sci., 5: 165–181.

In this investigation, the Igbokoda pure silica sand is characterised and used as a base sand for the Igbokoda clay–sand mixture in an attempt to develop an efficient synthetic moulding sand. The mechanical properties of the clay–sand–water mixture were determined. The effect of additions of Na_2CO_3 to the moulding sand was examined with particular attention to its influence on mechanical properties of the synthetic moulding sand. The fineness number, screen bulk fraction, total coarse fraction and the total fine fraction of Igbokoda silica sand were found to be within the range that could give good mouldable properties. The values obtained for the green compressive strength, the dry compressive strength, the green and dry shear strengths, collapsibility and toughness indicate that Igbokoda clay has good values as a binder for synthetic moulding sand. In general, the addition of Na_2CO_3 gives improved properties to the moulding sand though with a tendency towards impaired collapsibility values.

INTRODUCTION

Development of moulding sand and techniques of its testing has been a subject of investigation for a very long time. Clays from different deposits have been characterised and also the base silica sands used in synthetic moulding sands. Comprehensive investigations have been carried out on various aspects of moulding sand development and testing (Grim and Cuthbert, 1945; Schubert, 1958; Lawrence, 1961).

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0169-1317/90/$03.50

The various work of Sanders and Doelman (1967, 1968, 1969) on durability of bonding clays are particularly significant in this respect. The individual research work of these investigators could not be separately reviewed here due to lack of space.

In a previous study (Loto and Omotosho, 1990), clay obtained from the Igbokoda deposit was characterised and its synthetic moulding sand properties when subangular lagoon sand was used as the base sand were determined. The present work is a continuation of the previous one and is undertaken to look into the effect of sodium carbonate additions on the synthetic moulding sand properties, using a high-quality pure white base silica sand ($\approx 98\%$ pure). The Igbokoda silica sand used as the base sand in this investigation is currently being used for large-scale glass manufacturing. An attempt to further utilise the sand in the foundry industry is one of the aims of this work.

Sodium carbonate addition to this moulding sand is undertaken as an activation treatment for the clay (Sanders and Doelman, 1967, 1968, 1969). It has been previously shown that Igbokoda clay is kaolinitic in structure and its water retention or swelling capacity is low. This contributed to its lower green and dry compressive strengths when compared with a bentonite clay. An activation process which will involve the replacement of Ca in the clay with Na ions is expected to enhance more free water adsorption of the clay and hence gives improved strength properties. In addition, Igbokoda clay is acidic (pH 4.2). There is therefore a tendency towards flocculation of the clay platelets due to its high viscosity when mixed with water (Flinn, 1963). Addition of sodium carbonate will provide Na^+ which is expected to make the clay at least slightly alkaline. This will enhance optimum distribution of clay in the sand mixture and thus gives improved moulding properties.

EXPERIMENTAL PROCEDURES

Separation of clay from sand

The as-received untreated clay contained a lot of coarse grain particles, mainly sand. The separation of the raw clay into two fractions, above and below 4 mesh size (clay and silt will pass through a 4-mesh screen while the silica sand will not) was therefore considered necessary. Gravity sedimentation was used to separate the quartz coarse particles from the clay.

The as-received wet clay was mixed with water and thoroughly dispersed with 1.5 g/dm^3 calgon (sodium hexametaphosphate). After stirring for about 20 min, the jar's content was allowed to settle for about 5 min. The sand sediment and the clay particles in suspension were separated by decantation. The sediment consisting of quartz was discarded while the clay suspension was retained for subsequent separation treatment.

Due to the finess of the clay particles, a faster sedimentation technique,

TABLE I

Chemical composition of Igbokoda clay

	Igbokoda clay
K^+ (ppm)	300
(%)	0.03
Na^+ (ppm)	1710
(%)	0.171
Ca^{2+} ppm)	1120
(%)	0.112
Fe (ppm)	8080
(%)	0.808

"centrifugal separation", was used. This is an extension of gravity separation, as the settling rates of particles are increased under the influence of centrifugal force. A laboratory centrifuge consisting of four 55-cm^3 tubes radially arranged and traces of 70 mm radius when rotating was used for the separation. The tubes were filled with the slurry obtained from the gravity separation suspension, and allowed to rotate under the centrifugal force of 1.9 KN at 15,000 r.p.m. for 30 min. The clear water suspension obtained was discarded and the clay sediment removed for further use. The composition of the clay (Table I) has earlier been determined (Loto and Omotosho, 1990).

The obtained fine clay sediment was oven-dried using a laboratory Gallenkamp oven at a temperature of 50°C for 15 h.

pH measurement. 10 g of the fine clay material was dissolved in 50 cm^3 of distilled water contained in a beaker and thoroughly stirred. Its pH was measured by a pH meter and recorded as 4.2.

S.E.M. analysis. A scanning electron microscope (SEM) equipped with an energy dispersive spectrophotometer (EDS) was used to analyse qualitatively the chemical composition of the clay (Fig. 1) and a micrograph of the clay particle (Fig. 2) was made.

Preparation of the base silica sand

The base silica sand used was washed several times with water and dried in the sun for ten days. The size and distribution of the sand grains was determined by the sieve analysis test method of the A.F.S. (American Foundryman Society). A dried 50-g sample of the sand was used. The sample was placed on top of a series of BSS 410 sieves and shaken with the vibrating sieve shaker for 15 min. The sand retained on each sieve after shaking and that on the bottom pan was weighed. Its percentage of the total sample was determined (Table II).

Additive. The additive used was sodium carbonate ($Na_2CO_3 \cdot 10H_2O$).

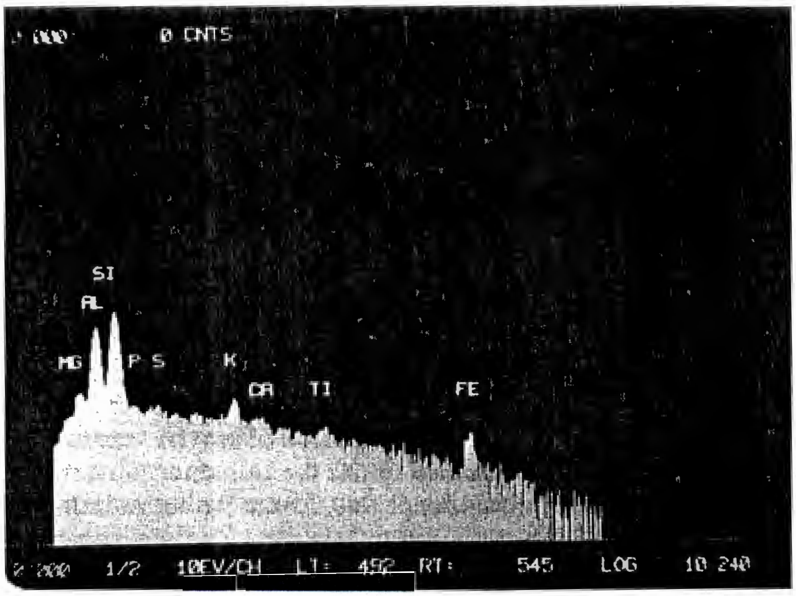

Fig. 1. SEM/EDS qualitative chemical analysis of Igbokoda Clay: *MG*=magnesium; *AL*=aluminium; *SI*=silicon; *P*=phosphorus; *S*=sulphur; *K*=potassium *CA*=calcium; *TI*=titanium; *FE*=iron.

Preparation of test samples

The base silica sand, varying amounts of clay by dry weight percent and known amounts of tempering water were mechanically mixed by a mulling apparatus. After mixing, the sample was stored in polyethylene bags to prevent air-drying.

Cylindrical test specimens conforming to A.F.S. standard specimens were prepared and used for the mechanical tests. An amount of sand mixtures adequate to form standard 50-mm diameter and 50-mm high test specimens after three rams were determined and measured out. In all the experiments, the dry sample weight used ranged from 150 to 170 g depending on the dry sand–clay ratio. The ramming device was securely mounted, the sand poured into the specimen tube and rammed by impact with three blows of 6,500 g weight. By the manually operated ramming device the weight was dropped from a height of 50 mm ± 0.125. Three rams normally produce a specimen of 50 mm ± 0.79 in height provided the proper weight of sand was put in the specimen tube. Gauge marks are shown at the top of the rammer rod to measure the specimen height. The specimen was removed from the tube by means of a stripping post.

Fig. 2. SEM micrograph of Igbokoda clay particle showing the surface structure and the particle shape (× 1000).

Green compression test

The green compression test was carried out to determine the compressive stress in kN/m^2 necessary to cause rupture of the standard cylindrical specimen using a Universal sand strength testing machine. Green compressive strength tests were performed immediately after the specimen was stripped from the tube to prevent any increase in green strength due to air-drying with increase in exposure time. The compressive strength was determined by axially loading the cylindrical specimen through the flat faced holders of the compression testing machine. The rate of loading was standardised by keeping it constant to prevent or minimise creep of green sand under loading. The results obtained are presented in Figs. 3 and 8. Details of the tests, testing

TABLE II

AFS sieve analysis of Igbokoda silica sand

Sieve number	Amount of 50-g sample retained on sieve		Multiplier	Product
	(g)	(%)		
8	0.00	0.00	–	–
16	0.12	0.24	8	1.92
22	1.24	2.48	16	39.68
30	8.81	17.62	22	387.64
52	24.85	49.72	30	1491.60
60	7.29	14.58	52	758.16
100	5.29	10.58	60	634.80
200	1.19	2.38	100	238.00
300	0.00	0.00	200	0.00
PAN	0.00	0.00	–	0.00
Total	48.79	97.58	–	3551.18

Average grain fineness: $\frac{3551.18}{97.58}=36.40$

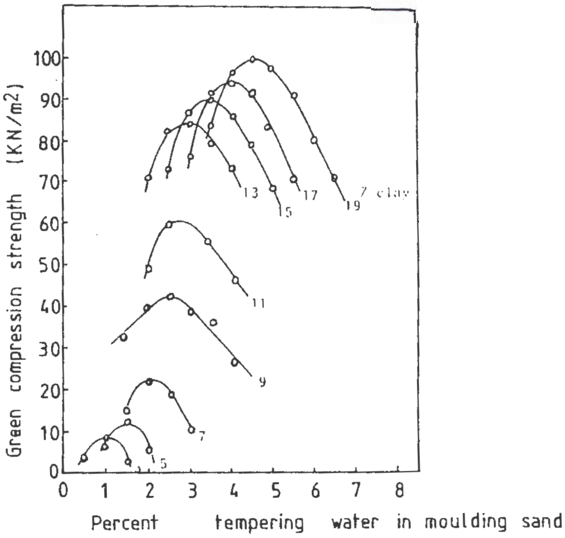

Fig. 3. Variation of green strength with clay and percent of tempering water for Igbokoda-clay-bonded silica sand.

procedures and equipment are given in the Foundry Sand Handbook (American Foundrymen Society, 1963).

Green shear test

The green shear test was carried out on the universal testing machine. This was achieved by changing the loading surfaces on the testing machine from compression to shear plates. The specimen then ruptured in shear along its longitudinal axis when sufficiently loaded.

Dry compression and shear tests

These tests followed the same procedures as for the green compression and green shear tests (American Foundrymen Society, 1963).

The dry compression and shear tests were carried out by drying the specimen in an oven at 100–110°C for 2 h before testing. Since dry compression strength is usually much greater than green strength, higher loads were required on the universal test machine.

Shatter index tests

The shatter index tests were carried out in a shatter index tester which is designed to drop a rammed specimen of mould sand from a height of 1.85 m onto a steel anvil. To determine the shatter index of the moulding sand, an A.F.S. standard test specimen was prepared without stripping. The tube containing the rammed specimen was seated in position in the top casing below the plunger. The specimen was ejected from its tubular mould by gently pulling down the handle. The fragments were collected in a 12.5-mm mesh sieve.

Basically, the shatter index value was used to determine the toughness and collapsibility of the moulding sand.

For toughness determination:

$$\text{Shatter index} = \frac{W_1}{W} \times 100$$

For collapsibility:

$$\text{Shatter index} \doteq W / W_1$$

where W is weight of specimen, and W_1 is weight of sand remaining on the sieve.

Additions of sodium carbonate

Sodium carbonate ($Na_2CO_3 \cdot 10H_2O$) was added to the dry silica sand/clay mixture. The effects of this additive on the properties of the synthetic moulding sand were determined by adding varied amounts of it to the silica sand–clay–water system. 13% by dry weight of clay content and 3 wt% of tempering water were used.

The various tests earlier described in this work were carried out on the moulding sand with varied amounts of added sodium carbonate. The amounts of sodium carbonate added to the dry moulding sand ranged from 0.5 to 3 wt%.

RESULTS AND DISCUSSION

Sieve analysis

Table II gives the results of sieve analysis (A.F.S. standard) of the base silica sand used for the synthetic moulding sand. Sieving is done to determine the fineness number of the sand grains. The finess number is essentially the average grain size of the silica sand and it corresponds to the sieve number whose openings could just let pass all the sand grains if all were of the same size. The second column of Table II shows both the number of grams and percentages of the 50-g sand sample retained on each sieve. The percentage retained on each sieve was multiplied by a factor given in column 3 of Table II. The factor is the size of the preceding sieve. Column 4 gives the product obtained by multiplication of each percentage retained on each sieve and the factor.

The average grain fineness was determined by dividing the total sum of the aforementioned products by the total percentage of sand grains retained in the sieve set and pan. Table II also gives the average grain fineness.

Sieve analysis of the Igbokoda white silica sand gave its average grain fineness number as 36 (36.40).

The bulk fraction of the silica sand is represented by the value in the middle portion of Table II. The sieve analysis indicated that the Igbokoda silica sand is a 4-screen bulk fraction sand. A screen fraction is arbitrarily defined as retaining more than 10% of the sand; that is, it is one of four succeeding screens on which the bulk of the sand is retained, each screen having more than 10% retained on it. In green sand moulding, 3-, 4-, 5- and 6-screen bulk fractions are being commonly used, but the 4-screen type seems to be most versatile over a wide range of conditions.

The coarse fraction of the sieve analysis is composed of the total percentage of sand grains retained on the screens, coarser than those of the bulk fraction and in amounts of less than 10%. The sieve analysis result (Table II) indicated that the total coarse fraction by dry weight of Igbokoda silica sand is 3.00 (2.72)%. The total coarse fraction must be limited to amounts usually less than 4% for sand of the 4-screen distribution type. This limitation is necessary since an excess of coarse particles contributes to a poor casting surface finish.

The fine fraction of the sieve analysis is composed of the total percentage of sand grains retained on screens finer than those of the bulk fraction and in amounts of less than 10%. The result of the sieve analysis showed that the total fine fraction (by weight) of Igbokoda silica sand is 2.38%. The total fine fraction must be limited in amount, usually to less than about 5% by weight for a sand of the 4-screen type. This limitation is necessary since an excess of fine particles causes balling to occur during mulling.

Moulding properties of test samples without sodium carbonate additions

Figs. 3–7 show the results of tests obtained for the moulding properties of the Igbokoda-clay-bonded silica sand. The effect of various percentages of clay and tempering water on the green compression strength of the moulding sand is presented in Fig. 3. The curve for the green shear strengths also follows the same trend. It is shown in Fig. 3 that for each of the various percentages of clay content, and with increasing percent of tempering water, green compression strength increased steadily from a relatively low value to an optimum value. After reaching the optimum value, the strength decreased to a minimum value as the tempering water increased. This phenomenon is apparently due to the fact that inadequate water fails to develop adequate strength and that too much water causes excessive plasticity and weakness in the clay–silica–water bond strength. The polar characteristics of clay enable it to adsorb strong polar molecules such as water, and the adsorption results in the formation of a thin water layer around the clay particles, thus enhancing the clay's plasticity.

Fig. 4 shows the influence of the clay binder content on the strength of the synthetic moulding sand. The curve of Fig. 4a was obtained by plotting the peak (optimum) points of curves in Fig. 3 against their corresponding percent clay content. This curve was used to determine the optimum clay content for the moulding sand and it shows that the green strength of the moulding sand increased gradually from 3% clay content up to 7% clay content by weight, after which the situation changes to a rapid increase of the green strength from 7% clay up to 13% clay content by weight. After reaching 13% clay content, the increase in green strength became relatively very small with further increase in clay content. Since the strength of the clay–silica–water bond is partly a function of the number and area of contacts of sand grains (Lawrence, 1968; Draper, 1968), this behaviour was not unexpected. As the binder layers become continuous and then progressively thicken, proportionately less

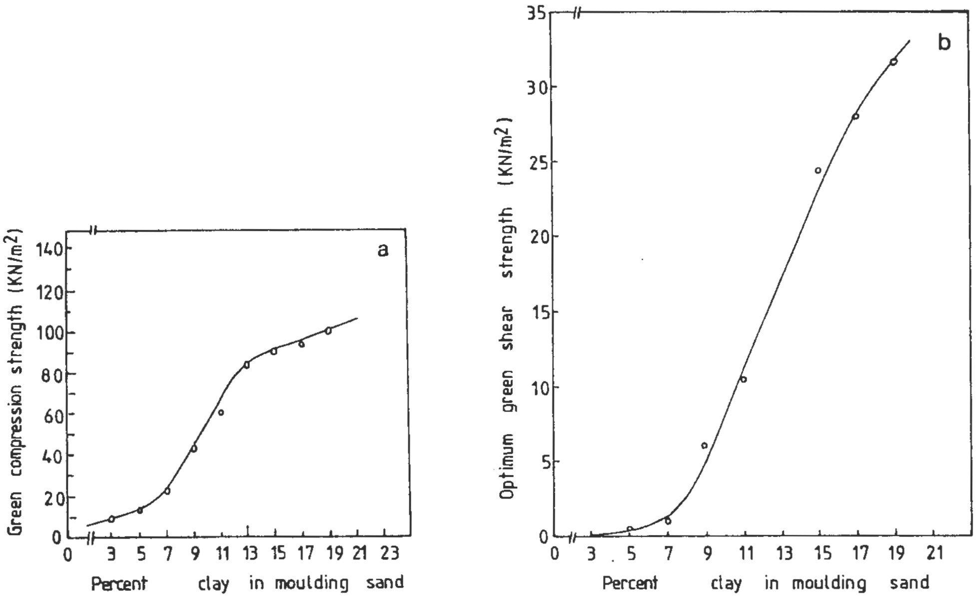

Fig. 4a. Variation of optimum green compression strength with percent clay content for the Igbokoda-clay-bonded silica sand.
b. Variation of optimum green shear strength with percent clay content for the Igbokoda-clay-bonded silica sand.

advantage is to be gained from further binder layer addition (Flinn, 1963). At a particular clay content the green sand is considered to be clay-saturated. A clay-saturated green sand is one containing a high enough percentage of clay so that any further increase in clay content will not cause an increase in maximum green compression strength of the aggregate. Fig. 4 shows that the Igbokoda-clay-bonded Igbokoda silica sand, did not become clay saturated within the percentage of clay content used in the experiment. There was an increase in green compression strength with increase in clay content up to the 21 wt% limit of clay used. This suggests that at least up to 21% clay can still be used to give an increase in green compression strength. A clay-saturated sand has about the same compressive strength as the clay by itself. The specific percentage of clay required for saturation depends on the purity and the type of clay, base sand, and on the additives. It is known that in most cases about 8 to 12 wt% of bentonites (either sodium or calcium bentonites) and about 20 to 25 wt% of fire clay are sufficient to produce a saturated mixture with a sand fineness AFS number of 60 to 100 (Heine et al., 1977). The average fineness number for Igbokoda silica sand is determined to be 36.40.

The effects of increasing the percentage of clay content on the dry strength

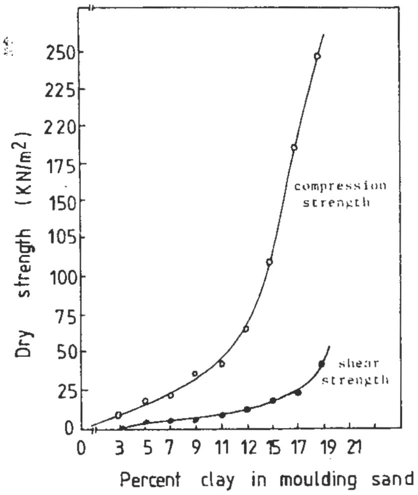

Fig. 5. Dry strength (compression and shear) at points of optimum green compression strength vs. percent clay content.

of the moulding sand is shown in Fig. 5. The curves were obtained by plotting the respective value of dry compression and shear strengths (obtained for varying percentage of tempering water with maximum values of green strength) against the corresponding percentage of clay content. It can be seen from Fig. 5 that both the dry compressive and the shear strengths increase gradually with increasing clay content from 3 to 13% by weight. This is followed by sharp increase with further increasing clay content. This trend will be due to the attainment of an improved binder distribution and higher bulk densities. It could also be due to the effect of the surface tension of the water surrounding the clay and sand–clay particles and filling the capillary interstices, particularly interstices of the clay particles. The surface tension is caused by the surface layers of water acting on a stretched membrane, forcing the particles together. As the water layer becomes thinner by drying, the forces holding the particles together increase (Taylor et al., 1966).

Fig. 6 shows the effects of a varying percentage of clay contents on the collapsibility of the moulding sand, and it was obtained by plotting the values of collapsibility (obtained with various percentages of tempering water that developed maximum green compression strength) against percentage of clay contents. It is also shown in Fig. 6 that collapsibility of the moulding sand decreases steadily from a maximum value at 3 wt% of clay to a relatively low value at 11 wt% with increasing clay content from 11 to 15 wt% the decrease in collapsibility is slow and small.

Fig. 7 shows the effect of a changing amount of clay on the toughness of the moulding sand. The curve shows that the toughness (of the synthetic mould-

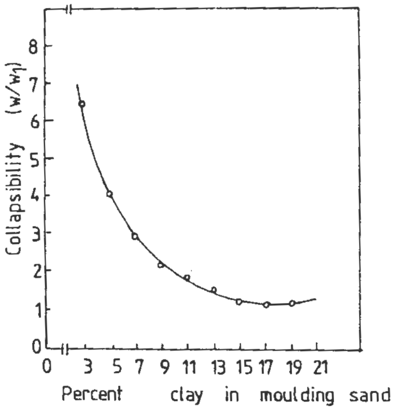

Fig. 6. Collapsibility at point of optimum green compression strength vs. percent clay content.

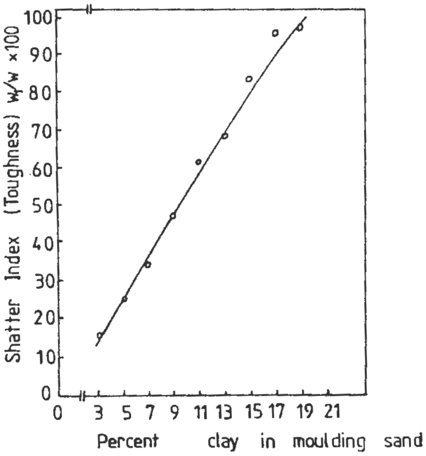

Fig. 7. Toughness at points of optimum green compression strength vs. percent clay content.

ing sand) follows an increasing trend as the clay content increases. With a clay content between 3 and 19 wt% the increase in toughness gives an almost linear relationship.

Figs. 6 and 7 together are a measure of deformation or plasticity of a moulding sand. Deformation during the green compression test gives evidence of the "toughness" of a sand. It is determined from the decrease in length of the cylindrical specimen during the green compression test and can be measured by means of a dial gauge attached to the green sand testing head. The product of deformation and green strength is used as an index of toughness (Beely, 1982). Moulding sand toughness is calculated by $d \times s \times 100$, where d=deformation (μm) and s=green compression strength (kN/m).

A low toughness value indicates friability in pattern withdrawal and subsequent handling operations. Too high a value may indicate unsatisfactory moulding qualities resulting from excessive clay or water content. Values of 50–85 have been quoted by Davies (1950) as representing a mouldable range. The Igbokoda-clay-bonded Igbokoda silica sand, with 13 wt% clay content and 3 wt% tempering water, gave a toughness value of 64, which falls within the mouldable range.

Effects of sodium carbonate additions

The effects of sodium carbonate additions on the green compression and shear strengths of the synthetic moulding sand are presented in Fig. 8. Both strengths increased by addition of up to 0.5 wt% sodium carbonate. Beyond this 0.5 wt% the green compression and shear strengths began to decrease. The fall in both green compression and shear strengths continued steadily as the sodium carbonate content was further increased.

Fig. 9 shows the effects of sodium carbonate addition on the dry compression and shear strengths of the synthetic moulding sand. The dry compression strength increased proportionally with increasing sodium carbonate addition. The dry shear strength also increased steadily with increasing sodium carbonate addition but not proportionally.

Fig. 10 shows the effects of sodium carbonate addition on the collapsibility of the synthetic moulding sand. The collapsibility decreased steadily with sodium carbonate addition of up to 2.0 wt%. Beyond this 2% addition the collapsibility became fairly constant.

The effects of sodium carbonate addition on the toughness of the synthetic

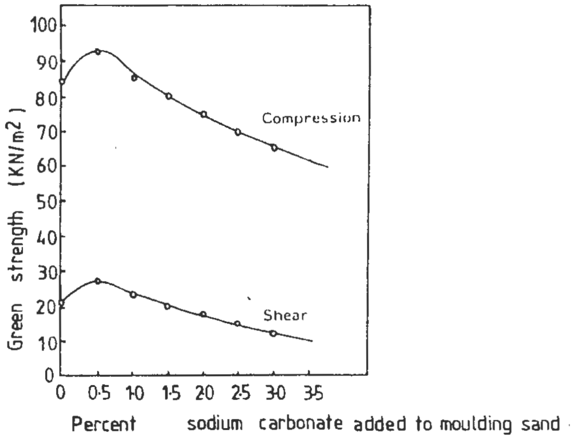

Fig. 8. Variation of green strength with percent sodium carbonate content for the Igbokoda-clay-bonded silica sand.

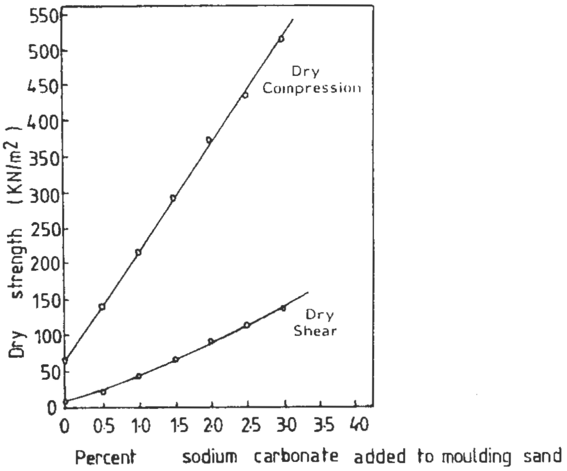

Fig. 9. Dry strength (compression and shear) vs. percent sodium carbonate content for the Igbokoda-clay-bonded silica sand.

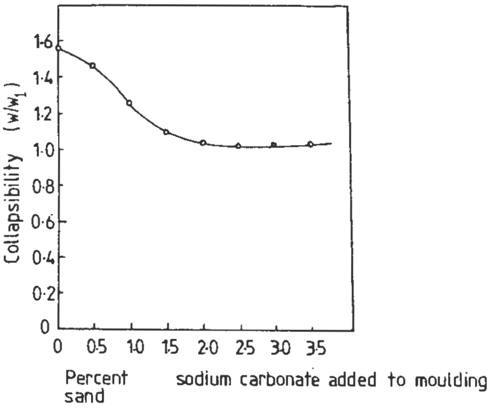

Fig. 10. Collapsibility vs. percent sodium carbonate content for the Igbokoda-clay-bonded silica sand.

moulding sand is shown in Fig. 11. The toughness increased steadily with increasing sodium carbonate addition of up to 2 wt%. The toughness became almost constant when the sodium carbonate addition further increased beyond 2.0%.

All the above results show, in general, an improvement of the properties of the synthetic moulding sand up to certain amounts of sodium carbonate addition, except for the dry compression strength, which increased proportionally with increasing sodium carbonate addition, the same as for the dry shear strength, though this increase was not proportional.

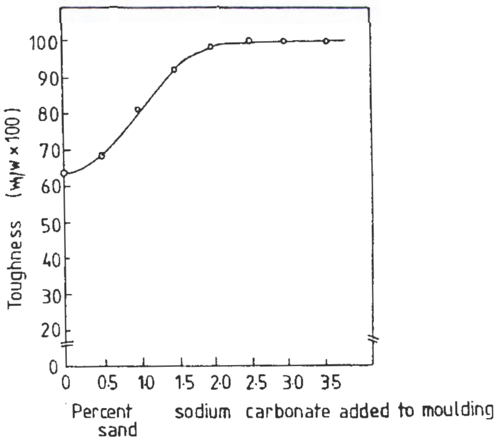

Fig. 11. Toughness vs. percent sodium carbonate content for the Igbokoda-clay-bonded silica sand.

The addition of Na_2CO_3 to the synthetic moulding sand is an activation process. It has been explained that by mass action the sodium displaces the calcium (content of clay) which combines with the carbonate to form $CaCO_3$ (Sanders and Doelman, 1967, 1968). In the base exchange chemistry the Na^+ is increased and the Ca^{2+} reduced. The resultant $CaCO_3$ is almost insoluble in water and is not involved further in the base exchange chemistry but is present as an accessory mineral (Sanders and Doelman, 1968, 1969), i.e., it precipitates as a calcium salt (Flinn, 1963). The nature of the precipitate was not determined.

This treatment has altered the structure of the clay mineral and it has various effects on the properties of the synthetic moulding sand. First, the adsorption of Na^+ by base exchange has made the clay more alkaline, increasing its pH from its original 4.2 to a basic condition (not measured) and thus enhancing optimum distribution of clay in the sand mixture (Flinn, 1963). The Na^+ gets adsorbed to the broken bonds at the edge of kaolinite crystal layers. A mechanism explaining how the adsorption makes the mixture more alkaline (Flinn, 1963) is that at low pH the excess H^+ or other ions are bonded to the clay. Under acid conditions (low pH) such as with the clay used here, the viscosity is high. This is because the attractive forces between the clay particle are apparently higher at a low pH, thus leading to flocculation of the clay platelets (Flinn, 1963). Optimum clay distribution in the sand mixture will enhance the improved properties of the green and dry compressive strengths, green and dry shear strengths, collapsibility and toughness such as obtained by Na_2CO_3 addition in this work.

Igbokoda clay contains Na^+ and Ca^{2+} as indicated by chemical analysis. It also contains some montmorillonite minerals, though the mineral content seems to be dominated by kaolinite as indicated by X-ray diffraction analysis (Loto and Omotosho, 1990). The results (Fig. 8) show that an addition of about 0.5 wt% of Na_2CO_3 gave the Igbokoda clay an optimum green strength. This addition is substantial when compared with the 0.17 wt% of the ion in the clay or the 0.02 wt% in about 13 wt% of the sand.

A steady and continued fall in both green compression and shear strengths with increasing sodium carbonate content was observed (Fig. 8) beyond the optimum value of 0.5% Na_2CO_3 addition to the moulding sand. The reason for this is difficult to explain. However, it could be attributed to a reduction in plasticity or rigidity of the clay resulting from too much water adsorption caused by the Na^+ exchange. Free water can be more easily adsorbed when the weaker monovalent Na^+ predominates over the divalent Ca^{2+} cation (Sanders and Doelman, 1967). With increasing Na_2CO_3 addition, more free water will be adsorbed, which beyond the optimum limit, that is beyond the liquid limit of the clay (Sanders and Doelman, 1967), could cause the weakening of the bond strength. Liquid limit measures the water-holding capacity of a clay.

The linear increase in dry compressive strength was not unexpected. The loosely bonded "mechanically held" water has been eliminated and only the tightly bonded water in the clay–water–silica bond remains. Under basic conditions, Na^+ ions are bonded to the clay; at low pH values, the excess H^+ ions are bonded to the clay particles instead. The residual bonding forces of the Na^+-to-water combination (for the dry bonds) are evidently quite high. The optimum distribution of clay due to its basic nature by the addition of Na_2CO_3 has an enormous effect on its dry compressive and shear strengths.

CONCLUSIONS

(1) Igbokoda silica sand is a 4-screen bulk fraction sand. It possesses moderate amounts of coarse and fine fractions as is evident from the result of sieve analysis of the sand. The coarse fraction is 2.72% and fine fraction is 2.38% by weight. The purity of the silica sand ($\approx$98%) and its average fineness number of 36.40 suggest that it could be very suitable in situations where maximum refractoriness is required, for example in steel moulding sands.

(2) The Igbokoda-clay-bonded Igbokoda silica sand exhibits optimum green compression and shear strengths at the addition of 13 wt% clay and 3 wt% tempering water. The dry compression and shear strengths values of the synthetic moulding sand are also reasonably good though relatively lower than the typical dry compression and shear strengths of typical green sands (the western and southern bentonites of the U.S.A.).

(3) The clay-bonded silica sand with an optimum clay content at 3 wt% of tempering water exhibits a moderate toughness and collapsibility values which fall within the mouldable range.

(4) The green compression and shear strengths of the synthetic moulding sand are improved by addition of upto 0.5 wt% of sodium carbonate.

(5) The dry compressive strengths of the synthetic moulding sand increased proportionally with increasing sodium carbonate addition, while the dry shear strength also improves considerably.

(6) The toughness of the synthetic moulding sand is improved by sodium carbonate addition, while the collapsibility is impaired.

(7) Igbokoda clay demonstrates reasonable cation exchange with sodium ion in the activation treatment with sodium carbonate, as evidenced by the improved properties obtained.

ACKNOWLEDGEMENTS

The authors acknowledge the co-operation of the Department of Metallurgical and Materials Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria and the Department of Mechanical Engineering, University of Lagos, Nigeria, for making available the research facilities used in this investigation. Permission to use the SEM/EDS equipment for the qualitative analysis of the clay by the Department of Engineering Metals, Chalmers University of Technology, Gothenburg, Sweden, is also acknowledged.

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