Evaluation of clay soils from Manjacazi district (Mozambique) as potential raw material for the ceramic industry

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ABSTRACT

The Manjacazi district is composed of vast alluvial plains with aplenty clay soils in their numerous valleys. Regardless of its high proportion, clay soils from Manjacazi are only exploited for conventional pottery and local ceramic bricks. This is basically because the potentialities of these clay soil have not been evaluated. Up to the present moment, no study that evaluates the potential applications of these clay soils is available. This study aims to evaluate the suitability of the Manjacazi clay soils as industrial mineral resources for the ceramics industry by studying their ceramic properties as well as drying and firing behaviours. The ceramic properties of the fired clay briquettes of Manjacazi were interpreted by linear shrinkage, compressive strength, and water absorption. The Manjacazi clays are distributed in loam, clay loam, clay, sandy clay loam, and sandy loam in the grain size distribution diagram. Besides, they are low plastic organic silts with low compressibility, medium plastic inorganic silts with low compressibility, and high plastic inorganic silts with high compressibility. Linear shrinkage was generally high and increased slightly with firing temperature. In contrary, their water absorption and compressive strength decrease with firing temperature. Therefore, these clays have ceramic suitability for the manufacture of walled floor blocks, clay roofing tiles, checker bricks, and solid bricks.

1. Introduction

All over the world, clay soils are used as the main raw materials for the ceramics industry because of their thermal conductivity and strength (Vieira et al., 2008; Gualtieri et al., 2010; Fadil-Djenabou et al., 2015). Natural clays normally occur together with other soil fractions like silt and sand.

The Manjacazi district is composed of extensive alluvial plains with aplenty clay soils in their numerous valleys. Regardless of its high proportion, clay soils from Manjacazi are only exploited for conventional pottery and local ceramic bricks. This is basically because the potential applications of these clay soils have not been evaluated. It is then obvious that the physical and technological properties of the Manjacazi clay soils need to be analysed to ameliorate their use as ceramic raw material and to open ways for other potential industrial applications.

In Manjacazi district, for economic reasons, the ceramics industry is controlled by the artisanal and small-scale miners and depends on clay soils from nearby deposits. Artisanal and small-scale mining of these clay soils are made without any prior study and originates various problems during the manufacturing process, such as deformations and breakage of the final products. This study aims to evaluate the suitability of the Manjacazi clays as an industrial mineral for the ceramics industry by studying their physical and technological properties.

2. Background geology

The Manjacazi area is located at the Mozambique sedimentary basin (Figure 1). According to Salman and Abdula (1995), the Mozambique sedimentary basin takes up both central and southern parts of the coastal plain of Mozambique, extending onto the continental shelf and slope. For Salman and Abdula, the sedimentary fill is composed of upper Jurassic, Cretaceous and Cenozoic rocks which discordantly overly the Karoo basalts and rhyolites of Stormberg series (early Jurassic). The upper Jurassic occur as continental red beds, usually scattered within buried grabens. Cretaceous rocks occur as terrigenous sediments of Stromberg series (early Jurassic). The upper Jurassic occur as continental red beds, usually scattered within buried grabens. Cretaceous rocks occur as terrigenous sediments of continental and marine provenance. The Cenozoic deposits are predominantly of marine and deltaic environment.

The Manjacazi area is composed of recent alluvial and internal dune deposits (GTK, 2006) (Figure 2). The recent alluvial deposits comprise gravel, sand, silt, and clay in interdunes valleys. The internal dune
deposits contain reddish, brownish and yellowish aeolian sands consolidated by vegetation. These internal dunes are positioned inland, near the present shoreline. The geomorphological pattern of the area, comprising alternating internal dunes and elongated lakes, has preserved the orientation of the original palaeo-dune system. The elongated hills are not derived from dune migration, but rather from consecutive dune formation along a migrating shoreline. This is confirmed by the existence of many small lakes and lagoons with salty water, which means that these intra-dune depressions are regarded as abandoned sea channels. According to fossils of *Gerithium*, *Tapes* and *Tellina* found in similar sands in Inhambane, southern Mozambique, the age of the internal dunes is intra-Pleistocene. Migration of the shoreline denotes a regressive movement.

3. Material

The studied clay soils were collected in the Manjacazi district, Southern Mozambique. The Manjacazi clay soils are located in southern Mozambique a few kilometres from the town of Xai-Xai (Gaza Province) in the Mozambique sedimentary basin *Salman and Abdula* (1995). A total of twenty clay samples were collected in this area (Table 1). The samples were collected from the exploited quarries, labelled according to their

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**Figure 1.** Detailed map showing the sedimentary basins of Mozambique. Modified after Lächelt (2004).
soil horizons and their colours were determined using the Munsell Soil Color Book.

4. Analytical methods

Particle size distribution (PSD) was evaluated by sieving for the coarse and fine sand fractions using sieves of 200 and 50 μm, respectively. The silt- and clay-sized fractions were determined by sedimentometry using Robinson’s pipette method (Jackson and Saeger, 1935).

Colours of the clay soil samples were determined using the Munsell (1994) organised in “hue, value, and chroma.” The “hue” notation indicates its relation to red, yellow, green, blue, and purple. The “value” notation indicates its lightness. The “chroma” notation indicates its strength (intensity). The colours displayed on the individual soil colour chart are of constant hue designated by a symbol in the upper right-hand corner of the card. Vertically, the colours become successively lighter from the bottom of the card to the top by visually equal steps—their value increases from the bottom upward. Horizontally, they increase in chroma to the right and become greyer to the left. The value notation of each chip is indicated by the horizontal scale across the bottom of the chart.

The liquid limit (LL) and plastic limit (PL) were measured using the Casagrande apparatus (Casagrande, 1947). According to the NP-143 (1969) norm, the liquid limit of a clay sample is the water content corresponding to 25 strokes, obtained by interpolation on a curve relating the water content of each of the 5 specimens of the sample with several strokes for which the lower edges of a groove opened on a specimen are joined to an extent of 1 cm when the test was done in Casagrande apparatus. The plastic limit of a clay sample is the moisture content, expressed as a percentage of the weight of the oven-dry soil, at the boundary between the plastic and semisolid states of consistency. It is the moisture content at which a soil will just begin to crumble when rolled into a thread. The liquid limit (LL) and plastic limit (PL) were used to calculate the plasticity index (PI) which is a range of moisture in which a clay sample remains in a plastic state while passing from a semi-solid state to liquid state. This was calculated as follows:

\[
PI = LL - PL
\]

In the Engineering Laboratory of Mozambique, the clay samples were dried outdoors, then crushed in the agate ball mill and sieved in a 1 mm aperture sieve. Then they were humidified using current drinking water and manually kneaded. The added water, for humidification, was in a weight percentage of 10–15%, for the clay material. The clay paste obtained was stored in impermeable plastic bags for at least 24 h for the homogenization and degradation of the organic matter to improve the plasticity and eliminate adsorbed water. The ceramic properties were determined on test briquettes (150 mm × 10 mm × 10 mm) manually made in a cubic metallic mould.

The wet briquettes were initially dried in the open air for one week and then in the electric oven at 105 °C until a constant weight was obtained. After oven drying, the briquettes in sets of 5 elements were cooked sequentially in the electric oven at 850 °C, 900 °C and 950 °C. Each sample is left to equilibrate for 2 h, before the following heating sequence. After soaking for 30 min at each final temperature, the briquettes were furnace-cooled to room temperature. The ceramic properties of the fired briquettes were accessed by measuring linear shrinkage, water absorption capacity, and Compressive strength. In the clay samples, during the phases from moulding to the firing of briquettes, the following ceramic properties were determined:

- Linear shrinkage (LS) - the percentages of Shrinkage were determined by measuring the length of the briquettes before (L0) and after firing (L) using the formula (2). This is used to evaluate the plasticity of the material.

\[
LS (\%) = \frac{[(L_0 - L)/L_0]}{100}
\]

- Water absorption (Wa) – The fired briquettes were dried in the oven at 110 °C until constant weight and then immersed in distilled water for 24 h. The mass of each wet briquette was then weighed for the calculation of the percentage of water absorption (formula 3). This is used to evaluate the degree of porosity and the sintering of the material.

\[
WA (\%) = \frac{[(W - MF)/MF]}{100}
\]
### Table 1. Physical properties of the Manjacazi clays.

| Physical properties | NG-01-A | NG-01-B | NG-02-A | NG-03-A | NG-03-B | NG-04-A | NG-05-A | NG-05-B1 | NG-05-B2 | NG-06-A |
|---------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| **Munsell code**    | 2.5Y 7/1| 2.5Y 5/4| 2.5Y 5/3| 2.5Y 7/2| 2.5Y 5/4| 5Y 6/3  | 2.5Y 7/1| 2.5Y 7/2| 2.5Y 5/2| 2.5Y 2/1|
| **Sample color**    | Light grey| Light olive brown| Light olive brown| Light grey| Light olive brown| Light yellowish brown| Light grey| Light grey| Greyish brown| Black |
| **Particle size distribution (%)** | | | | | | | | | | |
| Clay (<2 m)         | 41.99 | 33.31 | 22.82 | 24.18 | 29.55 | 20.16 | 22.02 | 18.52 | 51.01 | 21.54 |
| Silt (2-50 m)       | 38.35 | 18.42 | 46.89 | 59.31 | 49.38 | 38.25 | 39.42 | 47.19 | 33.61 | 45.13 |
| Sand (>50 m)        | 19.66 | 48.27 | 30.29 | 16.51 | 21.06 | 41.06 | 38.56 | 54.29 | 15.39 | 33.33 |
| **Atterberg limits** | | | | | | | | | | |
| Liquid limit (LL)   | 40    | 63    | 60    | 40    | 47    | 58    | 27    | 29    | 31    | 47    |
| Plastic limit (PL)  | 31    | 38    | 38    | 28    | 32    | 37    | 24    | 27    | 29    | 33    |
| Plastic index (PI)  | 9     | 25    | 22    | 12    | 15    | 21    | 3     | 2     | 2     | 14    |
| **Physical properties** | | | | | | | | | | |
| Munsell code        | 2.5Y 5/2| 2.5Y 7/1| 2.5Y 4/4| 2.5Y 7/1| 2.5Y 4/3| 2.5Y 8/1| 2.5Y 7/3| 2.5Y 5/3| 2.5Y 4/3| 2.5Y 6/3|
| Sample color        | Greyish brown| Light grey| Olive brown| Light grey| Olive brown| White| Pale yellow| Light olive brown| Olive brown| Light yellowish brown |
| **Particle size distribution (%)** | | | | | | | | | | |
| Clay (<2 m)         | 21.31 | 28.55 | 23.75 | 24.6  | 19.35 | 28.92 | 28.77 | 21.77 | 22.28 | 20.65 |
| Silt (2-50 m)       | 31.07 | 37.1  | 17.95 | 44.7  | 16.87 | 44.38 | 44.13 | 36.42 | 37.54 | 36.2  |
| Sand (>50 m)        | 47.62 | 34.35 | 58.3 | 30.7  | 64.8 | 26.7 | 27.1  | 41.8 | 40.19 | 43.15 |
| **Atterberg limits** | | | | | | | | | | |
| Liquid limit (LL)   | 59    | 36    | 46    | 36    | 46    | 42    | 37    | 33    | 38    | 47    |
| Plastic limit (PL)  | 34    | 26    | 31    | 28    | 30    | 34    | 31    | 23    | 26    | 34    |
| Plastic index (PI)  | 25    | 10    | 15    | 8     | 16    | 8     | 6     | 10    | 12    | 13    |
Where $W$ is the mass of wet briquette after 24 h soaking in water and $M_f$ is the mass of the fired briquette.

- Compressive strength ($C_s$) - was evaluated determining the maximum compressive stress that under gradually applied load a given briquette will sustain without fracture. This is used to evaluate the application of the material and the degree of sintering.

Diagrams were made using MS-Excel 2013 and GCDkit (Janoušek et al., 2006) and edited for image quality in CorelDraw X3.

5. Results

5.1. Physical properties

The results of the Manjacazi clays physical properties are presented in Table 1. These results include soil colour, texture and Atterberg limits.

5.1.1. Soil colour and relative proportions

The soil exhibits a wide range of colour from Greyish brown, Light grey, Olive brown, Light grey, Olive brown, White, Pale yellow, Light grey, Olive brown, Light grey, Olive brown, White, Pale yellow, Light grey.
olive-brown, Light yellowish-brown, and Black also described more technically by using Munsell soil colour codes (Table 1). The relative proportions for A horizon are 20.16 – 41.99% clays, 36.42 – 59.31% silts and 16.51 – 41.8% sands while for the B horizon are 18.35 – 51.01% clays, 18.87 – 49.38% silts and 15.39 – 64.78% sands. These relative proportions belong to loam, clay loam, clay, sandy clay loam, and sandy loam in the ternary soil textures diagram (Figure 3). In the Winkler diagram of grain size classification of clay raw materials, the samples fall in the fields of thin-walled floor blocks, clay roofing tiles, checker bricks, and solid bricks (Figure 4).

5.1.2. Atterberg limits

The data of Atterberg limits are presented in Table 1. The plasticity of the Manjacazi clays is mostly influenced by the silt and sand fractions. Hence, the Manjacazi clays show plastic index varying from 3 - 25. They are composed of plastic (clay), fluxing (silt) and inert (sand) components. On the plasticity chart (Figure 5), the Manjacazi clays plot bellow the A-line and within the zones of (3) inorganic clays, low compressibility and low plasticity, (5) inorganic silts and organic silts and organic clays, medium plasticity, (6) inorganic clay, high plasticity, (7) inorganic silt and organic clays, high compressibility.

| Samples     | Temperature (°C) | Linear shrinkage (%) | Water absorption (%) | Compressive strength (MPa) |
|-------------|------------------|----------------------|----------------------|---------------------------|
| NG-01-A     | 850 900 950      | 4.57 4.70 4.85       | 8.697782 7.9874 8.819228 | 16.8732 19.54152 19.77696 |
| NG-03-A     | 850 900 950      | 6.16 6.33 6.34       | 5.559603 5.77037 7.777539 | 18.17478 19.77696 19.34532 |
| NG-05-A     | 850 900 950      | 6.34 1.73 1.47       | 21.09687 20.61749 20.41159 |

| Samples     | Temperature (°C) | Linear shrinkage (%) | Water absorption (%) | Compressive strength (MPa) |
|-------------|------------------|----------------------|----------------------|---------------------------|
| NG-06-A     | 850 900 950      | 7.25 7.13 7.82       | 7.703367 5.909296 4.428877 | 17.14788 16.95168 14.47956 |
| NG-07-A     | 850 900 950      | 11.00 12.00 5.47     | 18.70534 18.34626 17.52768 | 20.03202 20.3858 21.43485 |
| NG-07-B     | 850 900 950      | 5.47 5.87 7.33       | 18.89406 16.03935 16.65046 | 21.64086 20.46366 15.27908 |

| Samples     | Temperature (°C) | Linear shrinkage (%) | Water absorption (%) | Compressive strength (MPa) |
|-------------|------------------|----------------------|----------------------|---------------------------|
| NG-08-A     | 850 900 950      | 5.60 6.67 7.47       | 21.56558 21.94274 21.56558 | 18.34778 17.48142 17.79534 |
| NG-09-A     | 850 900 950      | 6.98 7.41 7.96       | 8.818804 7.615212 6.973359 | 20.44404 18.42318 21.11112 |
| NG-09-B     | 850 900 950      | 7.41 7.96 4.53       | 16.03935 16.65046 15.27908 |

| Samples     | Temperature (°C) | Linear shrinkage (%) | Water absorption (%) | Compressive strength (MPa) |
|-------------|------------------|----------------------|----------------------|---------------------------|
| NG-10-A     | 850 900 950      | 5.33 5.60 5.87       | 23.65805 23.67 23.52108 | 18.67824 18.5409 17.8542 |
| NG-10-B     | 850 900 950      | 4.80 5.20 5.53       | 17.79534 16.677 15.71562 | 21.44466 19.26684 15.95106 |
| NG-10-B1    | 850 900 950      | 5.73 6.27 6.84       | 16.69626 16.51713 16.11622 | 18.20736 18.56762 13.4397 |
| NG-10-B2    | 850 900 950      | 7.13 7.56 5.33       | 16.11622 15.95073 11.04535 |

Table 2. Technological properties of the Manjacazi clays.
5.2. Technological properties of the fired clay briquettes

The technological properties of the clay briquettes fired at 850, 900, and 950 °C are presented in Table 2. These properties include compressive strength, linear shrinkage, and water absorption. The compressive strength slightly increased as the firing temperature gradually increased from 850 to 900 °C, and the increase in strength became more pronounced as the temperature was increased further up to around 950 °C (Figure 6). The linear shrinkage for the Manjacazi clays was found to increase with firing temperature as shown in Figure 7. Water absorption decreases with firing temperature (Figure 8).

6. Discussions

The clay horizons were delineated based on physical properties differentiations observed on a profile wall or in a pedon in the Field. These physical properties included colour and texture differentiation. Colour is an important indicator of mineral content and texture has to do with grain size (clay, silt and sand) distribution in soil. The clay horizons exhibit a wide range of colour from greyish brown, light grey, olive-brown, light grey, olive-brown, white, pale yellow, light olive-brown, light yellowish-brown, and black. The yellowish, reddish and brownish colours are associated with the clay content as well as the goethite, jarosite, hematite, lepidocrocite, ferrhydrite and gypsum occurrence in the soils. On the other hand, the blackish and greyish colours are associated with the silt, humus and sand content. These colours are indicative of pyrite, iron sulphide, glauconite and quartz occurrence in soil. A deeper discussion on the clay mineralogical composition is beyond the scope of this paper.

The Manjacazi clays consist of organic and inorganic clays and silts with lower and higher compressibility as well as low, medium and high plasticity. These clays plot below the A-line and do not fit the correlation.
well on the plasticity chart. The greater the plasticity of the clayey soil, the greater the soil compressibility. The majority of the samples are medium plasticity clay loam. The other groups are low plasticity sand or silt and high plasticity silty clay. These interpretations are following the plots of loam, clay loam, clay, sandy clay loam, and sandy loam in the ternary soil textures diagram. The difference in water content between plastic and the liquid limit is called the plasticity index. The plastic limit of a soil is the moisture content at which soil begins to behave as a plastic material. The liquid limit of a soil is the moisture content at and above which clay particles are effectively suspended in water, providing sufficient lubrication for the mass to flow. High liquid limit normally indicates high compressibility and a high shrinkage/swelling potential. Plasticity generally increases with higher clay content (Wagner, 2013). The plasticity of the clayey soil is affected by the particle size distribution and organic material. The greater the plasticity, the greater is the shrinkage on drying.

The firing temperature has a positive correlation with the linear shrinkage and the compressive strength and negative correlation with water absorption. The increase in firing temperature produced the increase in the linear shrinkage and the compressive strength. However, the increase in the firing temperature leads to the reduction of water absorption in the test specimens of the Manjacazi clay. The decrease in water absorption with firing temperature is associated with the vitrification or the melt content increase with the rise of temperature and consequent reduction of the open porosity (Pinheiro and Holanda, 2010). The firing temperature highly affects the linear shrinkage and the compressive strength (Karaman et al., 2006; Khan et al., 2014).

7. Conclusion
The ceramic properties of the fired clay briquettes of Manjacazi were interpreted by linear shrinkage, compressive strength, and water absorption. The Manjacazi clays are characterized by an increase of linear shrinkage with the increase of firing temperature as well as the decrease of water absorption and compressive strength with firing temperature. These clays are classified as loam, clay loam, clay, sandy clay loam, and sandy loam. Their plasticity, after Casagrande chart, indicates low plastic organic silts with low compressibility, medium plastic inorganic silts with low compressibility, and high plastic inorganic silts with high compressibility. Therefore, these clays have ceramic suitability for the manufacture of walled floor blocks, clay roofing tiles, checker bricks, and solid bricks. It should be quoted that the processability may need an addition of fluxing agents and the enrichment of clay content by sifting for sand content reduction.

Declarations

Author contribution statement

Vicente Albino Manjate: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Zaquir Issufo: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Anastacia Mangenge: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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Figure 8. Compressive strength with firing temperature for Manjacazi clays.
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