Valorization of granite micronized stones wastes for eco-friendly production of fired clay bricks

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Abstract

Construction and mining industries around the globe have been criticized for production of enormous solid wastes that have potential environmental impacts. Therefore, this study presents a feasible approach to recover and utilize granite micronized stones waste for production of eco-friendly bricks. This research work, aimed at substituting a natural clay with granite powder to produce value-added bricks with pronounced physical–mechanical properties. The micronized granite waste stones were crushed and ground to obtain a fine powder sample. Thereafter, different batch compositions containing a varied proportions of granite powder were prepared and fired at different sintering temperatures: 900, 1000 and 1100 °C. The raw materials and bricks were characterized for their chemical compositions, microstructural, mineralogical and physical–mechanical properties. The results showed that, an increase in granite waste powder and sintering temperature enhanced the quality of fired clay bricks in terms of mechanical strength and decreased simultaneously the apparent porosity and water absorption. The final experimental approach showed that, the possibility to produce eco-friendly bricks containing up to 30 wt% of granite powder with enhanced engineering properties fired at 1100 °C is promising.

Graphic abstract

Keywords Granite powder · Clay bricks · Sintering and mechanical strength

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1 Introduction

The industrial ecology is regarded as an evolving integrated instrument which guides industries on the economic utilization of materials and energy in a sustainable way so as to minimize generation of waste on the environment [1]. It emphasizes the establishment of closed loop cycles (recycling and reuse) instead of open loop systems (linear economy) in order to reduce the potential negative impacts of industrial and urban activities on the environment. Explicitly, the industrial ecology approach assumes industrial wastes as by-products and alternative raw materials for another industry [2]. Consequently, management of solid wastes outside mining and processing industries has been considered as a novel and promising alternative method to reduce waste generation and subsequently the potential negative impacts on the environment. The approach is regarded as an eco-friendly and sustainable solution whereby the industrial by-products are transformed into the feedstock of another industry and used as secondary raw materials while minimizing utilization of virgin clay resources which are extensively used. Hence, it is high time that governments, industrial governing bodies and technologists, policy and decision makers come up with the best and novel methods to manage the unceasingly production of wastes to improve environmental performance. The valorisation of industrial wastes can be a promising alternative not only to minimize environmental impacts but also for eco-commercial profit.

Construction and mining industries have been spotted to be responsible for excessive consumption of non-renewable resources while at the same time generate enormous solid wastes which pollute air and contaminate soil and water [3]. It is estimated that, non-renewable resource consumption is 60 billion tons annually, though the value is expected to be twice by 2050 [4]. According to Organization for Economic Cooperation and Development (OECD) and United Nations Environment Program (UNEP), extensive use of natural resources due to rapid population growth and has made nearly ~ 40% of solid wastes to be produced from construction and mining industries which have emitted greenhouse gases and have caused global climate change in the built-up environment [5]. Due to limited resources and environmental issues, there is a need to look for an alternative source of raw materials so as to minimize over-utilization of non-renewable natural raw materials consumption for the benefit of the future generation.

Subsequently, recent studies have reported and demonstrated the potential use of several industrial wastes for different industrial applications. Several works from

literature have reported the incorporation of waste materials into the clay bricks eg. marble and granite sawing powder [6, 7] and waste marble powder [8] that improved greatly the properties of clay bricks. However, there are relatively very limited studies on the incorporation of granite waste in clay-based products [9].

Granite waste results from the crushing, cutting, shaping and polishing of granite rocks to make floor slabs [10, 11]. The process of cutting and polishing granite rocks generate enormous amount of wastes which litter and cause environmental pollution by contaminating air, soil and underground water [11, 12]. The generation of granite fine dust and coarse aggregates in millions of tonnes annually from granite industries is drastically increasing. Thus, managing large amounts of granite wastes which are stored and yet unused is a challenging problem for producers due to environmental pollution [13]. Furthermore, the storage and transportation cost to the disposal sites is considered to be among the world's future environmental problem [14]. To combat such environmental concerns, granite waste is currently utilized as coarse aggregates in the production high performance concrete (HCP) [11, 14, 15] which is regarded as a better environmental solution to reduce health hazards caused by granite wastes while ensuring cleaner production [14]. The construction industries have been found to use limited raw materials such as clay and sand to production purposes. Thus, from an environmental and economic points of view, the utilization of industrial wastes as secondary raw materials which are considered as of no value may lead to reduction of production costs as well as for sustainability purposes. Thus, the incorporation of granite waste into clay-based bricks is considered as an eco-friendly approach and sustainable solution to protect and reduce overexploitation of non-renewable resources for sustainable development.

In this study, the valorisation and the reuse of granite waste is regarded as the best eco-friendly approach to address the granite wastes issues which have adverse environmental impacts. Owing to the high content of alumina silicates and fluxing agents in granite waste, it can therefore be utilized effectively as a feedstock for production of clay-based ceramic materials. The use of granite waste may reduce utilization of limited natural clay resources and environmental footprint. In this perspective, this study explored the feasibility of producing fired clay bricks incorporated with granite waste powder. However, the aim was to characterize the raw materials and bricks in order to determine the optimum batch composition and sintering temperature used in this study. Moreover, the physical-mechanical, microstructural and mineralogical properties of bricks were evaluated. The results of the study may respond to the issue of increased demand building materials which are

expensive in most developing countries by providing construction materials which are both cheap and yet environmental friendly.

2 Experimental procedure

The natural clay sample was obtained from Federal Capital Territory Abuja, in Nigeria and dried at room temperature for 4 days while granite micronized stones were supplied by Abuja Cement Block Company Limited. The clay raw material and granite micronized stones were crushed and milled using grinder and miller Retsch BB-50, 240v, 50 Hz for a duration of 180 min. The natural clay powder was passed through a < 1 mm mesh plate and granite through < 0.425 mm mesh plate size. The chemical composition of the natural clay and granite powder was done using X-ray fluorescence (XRF) Model: Mini-4, PW4030, Rh X-Ray tube, 30 kV, 0.004 mA. The microstructural characterization of raw materials and clay bricks was achieved by Scanning Electron Microscopy (SEM, Scanning Electron Microscope (SEM, Zeiss, EVO, LS10). The mineralogical compositions of clay-soil, granite powder and, clay bricks were determined using Rigaku X-ray diffraction (XRD) Model: Mini-flex-600 W, 2 θ , 100–240 V, 50/60 Hz with Cu K- α radiation. The clay bricks were prepared by varying the amount of raw materials with water as shown in Table 1.

The plastic paste with a mixture of clay and granite powder was cast into a rectangular mold. The prepared clay bricks were air-dried for six days and later were oven-dried at 115 °C for 24 h before the sintering process was performed. The dried clay bricks were sintered in a Cole Parmer Box Furnace Model: CBFM516C, Asheville, NC USA at 900–1100 °C at a ramp rate of 5 °C/min for a duration of 120 min. The physical properties of clay bricks sintered at 900, 1000, and 1100 °C were determined according to (C-373–88, ASTM) guidelines which included apparent porosity, bulk density and water absorption. The determination of the compressive strength of clay bricks was done according to (C-373–72,

ASTM) using the universal testing machine (Model: M, 10,200,10-DS, Prufsyteme, Germany).

3 Results and discussion

The natural clay and granite powder chemical compositions were determined by XRF as shown in the Table 2. The granite waste powder chemical composition comprised of high proportion of silica while other oxides of compounds were in minimum concentration. The main chemical composition of granite powder consisted of high content of silica with other oxides of metals were in low concentration. Besides, the concentration of K₂O and Na₂O as fluxing agents to aid a sintering process were found to be 5.30 and 4.90 wt% respectively. The composition of Fe₂O₃ was below 10 wt% which is a clear indication of good clay material though the presence of both Fe₂O₃ and TiO₂ may impart reddish colour to the clay bricks during a firing process.

3.1 Physical properties of raw materials

The physical properties of the clay sample are shown in Table 3. The aim was to stabilize and reduce the clay's high degree plasticity in presence of water. The addition of granite powder into clay material decreased the original physical properties of the clay sample as shown in the table. The granite powder as a non-plastic material stabilized and reduced the clay soil from high plasticity silt group to low plasticity silt group. The resulting plasticity limits (%) of the clay soil ranged between 15 and 30% which is suitable for the production of clay bricks (Fig. 1).

Table 1 Mixed raw materials compositions in (wt%)

Formulation	Raw materials	
	Granite powder	Natural clay
M-1	0	100
M-2	10	90
M-3	20	80
M-4	30	70

Table 2 Chemical composition of clay and GW (wt%)

Oxides	Natural clay	GW
SiO ₂	66.10	67.15
Al ₂ O ₃	19.36	14.40
Na ₂ O	1.34	4.90
Fe ₂ O ₃	6.78	5.10
K ₂ O	2.10	5.30
CaO	0.15	0.83
MnO	0.14	NA
MgO	1.40	0.70
TiO ₂	1.33	0.42
LOI	1.30	1.20

GW granite waste, LOI loss of ignition, NA not available

Fig. 1 Fired clay bricks production and Characterization methodology

Table 3 Physical properties of the clay soil added with granite powder

Engineering properties (%)	Clay soil in (wt%)	Granite powder in (wt%)		
	100	10	20	30
Liquid limit	40.80	38.6	36.5	34.5
Plastic limit	21.4	20.6	19.9	18.2
Plasticity index	17.60	17.0	16.6	16.2

3.2 Mineralogical and microstructural of raw materials

From the mineralogical point of view, the quartz (SiO_2) peaks were the dominant crystalline phases detected in natural clay while kaolinite, haematite and group of mica known as muscovite were present in minor phases in Fig. 2i. The same trend was observed in granite powder however, the peaks of haematite, calcite, albite and microline were detected in minor phases in Fig. 2ii. Both natural clay and granite powder displayed high peaks of quartz

(SiO_2) as the dominant mineralogical phase. The presence of microline and albite in granite powder acted as fluxing agents to promote vitrification of the clay bricks and thereby reduce the firing temperature. The mineralogical phases of the raw materials were observed to be very essential in influencing the physical–mechanical properties of the clay bricks.

On the other hand, the microstructural characterization using SEM techniques on the raw materials is reported in Fig. 3. The SEM micrograph of a granite powder shows particles which are scattered which confirm the non-plastic nature of granite powder. Nonetheless, the natural clay has fine grained and agglomerated particles which show high plastic nature of the clay as shown in Fig. 3ii.

3.3 Physical Properties Characterization

Figure 4, presents the variation of water absorption values in clay bricks with granite powder and without granite powder fired at different sintering temperatures. The fired clay bricks without granite powder had higher water absorption values compared to clay bricks with 10, 20 and

Fig. 2 The X-ray diffraction patterns of (i) clay sample and (ii) granite powder**Fig. 3** SEM micrographs of raw materials (i) granite powder and (ii) natural clay

Fig. 4 Water absorption of the FCBS fired at 900–1100 °C

30 wt% of granite powder fired at 900–1100 °C for 2 h. The decrease in water absorption values in clay bricks incorporated with 10, 20 and 30% of might be due to vitrification aided by fluxing agents from granite powder as shown in SEM micrographs in Fig. 6v–viii. Therefore, the high amount of granite powder added the lower water absorption values were obtained at 900, 1000 and 1100 °C firing temperatures. The water absorption values between 8 and 12.5% achieved from this work are within the acceptable range of 8–20%.

The apparent porosity data of clay bricks without and with 10, 20, and 30 wt% of granite powder added

Fig. 5 Apparent porosity of fired clay bricks fired at 900, 1000 and 1100 °C

and fired at 900, 1000 and 1100 °C for 2 h are shown in (Fig. 5). The apparent porosity values of clay bricks with 10, 20 and 30 wt% granite powder added were observed to decrease significantly from 900 to 1100 °C. However, high values of apparent porosity values were detected in clay bricks without granite powder which may be due to less liquid phase formed to fill the macro and micro pores embedded in brick matrices. However, the low apparent porosity values in clay bricks with 10, 20, and 30 wt% of granite powder added was due to melting of sintering agents which caused inter-particle cohesion and thereby decreased the amount of macro and micro pores in the clay bricks matrices. The clay bricks with 20 and 30 wt% of granite powder recorded the lowest apparent porosity values compared to other clay bricks.

Figure 6 illustrates the variation of bulk density of clay bricks with and without granite powder fired at different sintering temperatures. Low bulk density data were recorded in clay bricks without granite powder due to less melting and fusion particles to cause densification in the brick matrices. Furthermore, the low bulk density can be influenced by closed pores formed during fabrication and sintering process of clay bricks which reduced the microstructural consolidation. However, the fired clay bricks with 20 and 30 wt% granite powder added and fired at 1100 °C for 2 h recorded the highest bulk density of 2.0 g/cm³ and 2.2 g/cm³ respectively. This mechanism might have been influenced by vitrification and densification processes assisted by fluxing agents from granite powder.

Fig. 6 Bulk density of fired clay bricks fired at 900, 1000 and 1100 °C

Fig. 7 SEM micrographs of clay bricks (i-ii) 0 wt% of granite powder, (iii-iv) 10 wt% of granite powder, (v-vi) 20 wt% of granite powder and (vii-viii) 30 wt% of granite powder fired at 900 °C and 1100 °C for 2 h

3.4 Microstructural and mineralogical characterization of clay bricks

Figure 7, shows the microstructural characterization of the fired samples. In Fig. 7i-ii, there was minimum vitrification process in the clay bricks with 0% of granite powder when sintered at 900 and, 1100 °C. The small amount of fluxing

agents to melt and form enough liquid-phase might be the cause. The clay bricks with 10% of granite powder in Fig. 7iii-iv, showed progressive vitrification on the surface of the bricks when fired from 900 to 1000 °C. However, at the firing temperature of 900 °C, the clay bricks were not vitrified properly because the fluxing agents had not yet melted to form sufficient glassy phase.

Furthermore, in Fig. 7vi-viii, clay bricks with 20 and 30 wt% granite powder added and fired at 900 °C and 1100 °C for 2 h showed extensive vitrification. The mechanism might be influenced by glassy phase formed by the melting of fluxing agents. The SEM micrographs in Fig. 6vi-viii, show formation of glassy phase at 1100 °C which was influenced by the flow of liquid-phase which filled and reduced macro and micro pores in the brick matrices.

Fig. 8 The XRD peak patterns of clay bricks with (i) B-1 with 0 (ii) B-2 with 10 (iii) B-3 with 20 and (iv) B-4 with 30 wt% of granite powder sintered at 1100 °C for 2 h

3.5 Mineralogical characterization of clay bricks

The clay bricks with 0, 10, 20 and 30 wt% of granite powder fired at 1100 °C for 2 h displayed the mineralogical phases of quartz, mullite, and haematite in Fig. 8. Such mineral phases are a result of solid-state sintering which are transformed from the raw materials and are embedded in the glassy phase formed in the clay bricks. However, the formation of mullite depended much on mineralogical phases in the raw materials, firing temperature and the holding/soaking time.

3.6 Colour of the fired clay bricks

The colour of the fired clay bricks is mainly affected by the chemical elements in form of oxides present in the raw materials. The colour of the sintered is among the factors which affect the quality of the bricks. The colour imparted in the fired clay bricks depends significantly in the mass ratio of $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ in calcium rich clay or calcium poor clay, degree of oxidation and the sintering atmosphere. The red colour found in fired clay bricks is due to high concentration of 6.78 wt% of Fe_2O_3 in natural clay and 5.10 wt% of Fe_2O_3 in granite powder. The red colour is mainly influenced by the sintering process, whereby through oxidation reaction the transformation of Fe^{2+} to Fe^{3+} occurs. The visual investigation of the fired clay bricks below in Fig. 9 shows the transformation of the brick colour from light yellow to reddish colour. Therefore, the haematite is generally responsible for the reddish colour enhanced in the fired clay bricks.

3.7 Mechanical properties of clay bricks

The compressive strength data of clay bricks without and with 10, 20 and 30 wt% of granite powder added and fired at 900, 1000 and 1100 °C for 2 h are presented in Fig. 10. The mechanical strength data of clay bricks was observed to be improved with granite powder added due

Fig. 9 Bricks' colour transformation after a sintering process

Fig. 10 Compressive strength of fired clay bricks fired at 900, 1000 and 1100 °C

to vitrification, densification and the formation of mullite phase. Furthermore, reduction in porosity as well as an increase in bulk density due to inter-particle cohesion of the clay bricks influenced high compressive strength. The melting of fluxing agents promoted microstructural consolidation which gave better and high compressive strength values of the clay bricks.

In general, the compressive strength of clay bricks with 10, 20 and 30 wt% of granite powder added improved significantly compared to clay bricks without granite powder. The clay bricks with 30 wt% of granite powder added and fired at 1100 °C for 2 h displayed the best compressive strength of 7.1 MPa which met the acceptable compressive strength value of 7.0 MPa according to (C-373–72, ASTM). Therefore, study shows that, 30 wt% of granite powder is a potential and alternative material that can be used to improve the mechanical strength of eco-friendly fired clay bricks for sustainable building applications.

4 Conclusions

The valorisation of granite powder for eco-friendly production of fired clay bricks to minimize overexploitation of virgin natural clay resources and the adverse environmental impacts of granite waste is demonstrated in this study. From the results of the study the following conclusions can be made.

- Granite powder has high content of alumina silicates and fluxing agents that can effectively be used as a feedstock for production of clay bricks. The approach,

may reduce utilization of limited natural clay resources and negative environmental footprints.

- Addition of granite powder at 10, 20 and 30 wt% in clay bricks and fired at 900, 1000 and 1100 °C for 2 h showed significant improvement in the mechanical strength with simultaneously decrease in the apparent porosity and water absorption values.
- With 30 wt% of granite powder addition gave the highest compressive strength of 7.1. MPa, bulk density of 2.2 g/cm³, and lowest water absorption value of 9.1% due to enhanced vitrification and formation of mullite at the sintering temperature of 1100 °C.
- Nevertheless, the sintering temperature, the holding time at each firing temperature played significant roles towards the formation of glassy phase in the fired clay bricks formed.
- As a result, the production of eco-friendly clay bricks integrated with granite powder can considerably reduce the cost of building materials and subsequently meet our local demand for construction purposes.
- Valorisation of granite waste is thus considered as a better waste management and sustainable solution to transform waste materials into a feedstock of another industry. The approach offers both economic and environmental advantages to provide alternative source of industrial raw material while ensuring safe and clean environment that society desires.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest in this work.

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