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CERAMIC WASTE REUSABILITY: EFFECT OF AGGREGATE GRAIN SIZE AND MIX RATIO ON LIGHTWEIGHT DENSE MASONRY UNIT PRODUCTION

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Abstract: Ceramic ware waste generation is becoming a global concern because of its high volume, hazardous nature, limited reusability, and poor waste management practices. This study examined the feasibility and efficacy of the inclusion of this waste as complementary aggregate in solid masonry unit production with bias interest on the compressive strength and water absorbability. Three particle sizes (1.4, 1.7, and 2.0 mm) of crushed ceramic ware waste were blended with natural fine aggregate under three different mix ratios (10, 20, and 30%) to produce the masonry units cured for 7, 14, 21, and 28 days prior to compressive tests analysis. Afterwards, some of the categories cured for 28-days were subjected to water absorption test. Morphology and elemental composition of the aggregates were also inspected using SEM-EDM machine. Also investigated were some of the aggregates' physical properties. Results indicated that most of the waste-modified solid masonry units not only had water absorption capacity within required standard. The values were equally better than the unmodified dense block (control), the values were lower by 27 - 50%. Of the eighteen different categories produced, all M20T14, M20T21, and M30T28 modified dense masonry unit series with P1.7 (1.7 mm) and P2.0 (2.0 mm) particle sizes had high crushing force, compressive strength, and modulus range relative to the controls, which were 57 - 70 kN, 57 - 61 kN, 59 - 76 kN; 5.1 - 5.2 MPa, 5.1 - 5.5 MPa, 5.3 – 6.8 MPa; and 400 – 441 MPa, 411 – 419 MPa, 468 – 480 MPa respectively. Hence, modified masonry units with particle sizes P1.7 and P2.0 under the M20T14, M20T21, and M30T28 series are suitable masonry units for non-loading construction purposes. Interestingly, modified masonry unit (M30P2.0T7) cured under 7 days could also fit into this category. Hence, utilization of ceramic ware waste as co-aggregate in dense masonry units with M20 and M30 series production were established in this study for non-loading construction purposes.

Keywords: Ceramic ware waste; dense modified masonry unit; compressive strength; water absorption capacity

INTRODUCTION

Elevated solid waste generation over the last 30 decades has spurred aggressive solid waste management practices globally. Main concerns emanating from the waste volume are health hazards and environmental pollution, these concerns are caused by greenhouse gases emission generated from the biodegradable fraction of the waste. The teeming waste volume calls for pragmatic management practices. While combustible fraction of the waste has several established management practices; such as heat energy fuel, the non-combustible portion has been reused, recycled, or landfilled. However, best management practices strongly depend on the composition of the waste stream.

The construction and demolition waste, an example of non-combustible waste, has grown with development, accident, natural disaster, and wars. The waste contribution to the waste stream globally is about 75% (Daniyal and Ahmad, 2015). Though in the European union-28, construction and demolition waste only accounted for about 35% of the total waste generated by economic activities and household (Eurostat, 2014). The highest constituent of this waste is ceramic waste; about 54% (Daniyal and Ahmad, 2015). Ceramic tile industry is another major source of ceramic waste. The industry generates about one-third ceramic waste from every daily operational activity (Senthamarai and Manoharan, 2005). As at 2012, the global ceramic tiles production was close to 12 billion square meters. Hence, the estimated waste volume will translate to about 4 billion square meters (Daniyal and Ahmad, 2015). The major challenge with the huge volume of ceramic waste include its potential to increase competition for land if managed by open dumping or the use of sacrificial land. Hence, good management practice of the waste is germane and has therefore attracted a lot of attention. Management options that have been harnessed include reuse as fillers, production of storage tank for nuclear waste, and as aggregate and binders in concrete production (Devanathan et al., 2011; Halicka et al., 2013; Jay et al., 2014; Medina et al., 2012). The latter application is due to the pozzolanic property of ceramic ware waste, which makes it act as a cementitious material. This observation is documented in several literatures (Pacheco and Jalili, 2011; Kenna and Archbold, 2014). This gives an insight into why it could be applied in masonry unit production.

Masonry unit are blocks or mortars that are utilized for building structures. They are made from mixture of aggregate, binder, and water. Compressive strength and water absorbability of masonry units are vital properties that are easily influenced by the production process and materials utilized. Another important parameter is the cost incurred from the binder and cement usage. More inclusion of binder often results in improved masonry unit compressive strength, this however elevates the production cost. Furthermore, high water absorbability and low compressive strength with regard to standards are not desirable in solid masonry unit production. Every profit-oriented manufacturer will also want to keep the production cost to the minimum.

In some studies, conducted to improve these masonry unit properties, solid waste was included in the concrete mix at various proportions. Some of the outcomes had improved water absorbability and compressive strength with reduced production cost. For instance, Patel and Pitroda (2013) reported that the inclusion of fly ash from glass fiber in masonry unit production enhanced both compressive strength and reduced water absorption. In another study, introduction of rice husk mixed with slaked lime into the concrete mix resulted in higher compressive strength (Chukwudebelu et al., 2015). These studies are good indicators of the positive impact of solid waste in masonry unit production. Hence, this study investigates the potential and effect of utilizing 10, 20, and 30% ceramic ware waste as complementary aggregate to natural fine aggregate in the production of solid masonry units with respect to the aforementioned properties.

METHODOLOGY

Ceramics ware wastes were collected from various dumpsites in Ilorin Metropolis, Nigeria. Initial size reduction of this waste was carried out by milling to about 2 – 5 cm with the use of sledge hammer before further reduction into desired particle sizes was carried out with motorized hammer mill. Thereafter, the grain size distribution was investigated with mechanical sieving machine. Grain sizes of ceramic ware wastes that were of importance in this study were 1.4, 1.7, and 2.0 mm. The choice of these grain sizes was based on a preliminary experiment we conducted which indicated that grain sizes within this range (1.4 - 2.0mm) are suitable for solid masonry unit construction. Under this grain size range, masonry units barely had surface cracks and retained its form after demoulding. Milled ceramic ware waste from these processes was stored in polythene bags placed in dry area safe from the advent of rain or direct sunlight. The co-aggregate used with ceramic ware waste in this experiment was natural fine aggregate. This was collected from a flowing river in Ilorin, Nigeria. The reason behind this choice as source was both to reduce clay content that might add to the intended cementitious property of the mix and to minimize the production cost. The collected river bed sand was dried in open air, sieved of any large size particles above 1.0 mm including biological materials, before storage under a dry and cool environment.

Physical and chemical properties of the aggregates were examined using standard protocols. The morphological structure and elemental composition of these aggregates were carried out with a SEM-EDX. For the EDX, energy-dispersive X-ray piece of information for the aggregate samples were collected at an accelerating voltage of 15 kV using a Thermo Scientific UltraDry Premium silicon drift detector with NORVAR light element window and Noran System Six imaging system (ThermoFisher Scientific, Madison WI, USA). For the SEM, aggregate samples were attached to cylindrical aluminum mounts with double-stick carbon tape (Ted Pella, Redding, California, USA), and measurable surplus was blown off with nitrogen gas. The specimens were sputter coated (Cressington 108auto, Ted Pella, Redding, California, USA) with a conductive layer of gold. Images were acquired with a JEOL JSM-6490LV scanning electron microscope (JEOL USA, Inc., Peabody MA, USA).

Furthermore, ordinary Portland cement with Dangote trade name, was the binder used for this experiment. This met the BS EN 197 CEM II standard. The other ingredient for the masonry unit production was tap water. Both aggregates for this study, natural fine aggregate and milled ceramic ware waste, were mixed in three ratios; 90:10, 80:20, and 70:30. Particle sizes of this ceramic ware waste were varied among 1.4, 1.7, and 2.0 mm as earlier stated.

Hence, the mix contained the aggregates, the cement, and tap water in the ratio of 7:1:0.5. The choice of water-to-cement ratio was based on Mehta and Monteiro (2006) study which reported that 0.3 – 0.5 water-to-cement ratio does not negatively impact compressive strength. The mix was prepared by generously and thoroughly mixing both aggregates in the appropriate ratio before the introduction of the right proportion of the binder and subsequently drinking water. This was followed by another sufficient blending to ensure homogenized mix paste. The paste was introduced into a slightly lubricated 105 mm stainless steel cubed mold with one of the ends opened, then it was manually ram-compacted and then carefully demolded on approximately 8 cm by 10 cm smooth surface wooden pallet. This fresh mold was carefully labeled with oil-based paint and placed under shed from the advent of rain and sunlight for a period of 24 hrs before curing. Curing was carried out by submerging the molds in water for a period of 7, 14, 21, and 28 days (**Fig. 1**).

Fig. 1 Cured masonry units.

Fig. 2 Stored masonry units after curing.

For ease of understanding in this study, samples cured for 28 days without the inclusion of ceramic ware waste, the control, was denoted as M0T28; samples containing 30% ceramic ware waste with 1.7 mm particle size and cured for 7 days was denoted as M30P1.7T7; samples containing 10% ceramic ware waste with 1.4 mm particle size and cured for 14 days was denoted as M10P1.4T14;samples containing 20% ceramic ware waste with 2.0 mm particle size and cured for 21 days was denoted as M20P2.0T21. These label patterns were followed for other solid masonry units based on the aggregates proportion, particle size of the ceramic waste, and period-based curing condition of the masonry units.

The cured samples were stored in a dry and shaded environment (Figure 2) from the advent of rain or excessive sun radiation for 15 days before some of the samples, with 28 days curing time, were subjected to water absorption test ensuring procedure documented by Manasseh and Adie (2015). While others irrespective of curing time were subjected to compressive strength test. The mechanical assays were inspected using Testometric (M500) universal testing machine set at a test speed of 5 mm/min following procedure stated by Villarmizar *et al.*, (2012) and in accordance to ASTM D 2166-00e1. The equipment automatically records all the parameters in terms of yield, break, and peak, except Young's modulus which was not reported in terms of yield, peak, and break. However, out of these three stages (yield, peak, and break), the mean values for the break stages were considered for results presentation except for stress and force, where the mean values of the peak stages were considered. The experiment was at least duplicated. Statistical tool employed for the compressive indices analyses was SAS 9.4. Furthermore, weight loss due to the solid block handling was also considered.

RESULTS AND DISCUSSION

Physical properties of aggregates

The natural fine aggregate obtained from river bed shows obvious dissimilarities with ceramic ware waste in terms of the specific gravity, porosity, and bulk density. This is understandably based on material nature, pore size, and weight. The result in Table 1 shows that as the particle size of ceramic ware waste decreases, specific gravity increases. Furthermore, the specific gravity of the waste was less than the value documented by Amitkumar *et al.,* (2013). Difference in particle size was the reason for these variations. This study considered granular ceramic ware waste, while Amitkumar *et al.,* (2013) focused on powered ceramic waste. The specific gravity for the natural fine aggregate was close to the value reported by Manasseh and Adie (2015). The authors obtained a specific gravity of 2.6. The slight variation could be as a result of difference in the parent material composition. Natural fine aggregate had the least porosity which was about 2 – 65 % less than the ceramic ware waste. However, the bulk density was higher than any of the ceramic (1.4, 1.7, and 2.0 mm) by at least 40 - 60 % (Table 1). Pictorial views of the crushed ceramic ware waste are printed in Figures 3 - 5. Interestingly, the natural fine aggregate had some level of clay content (about 7 %) which might enhance bindability of mix. It also contains close to 90 % sand content (Table 1). This cementitious property is also observed in ceramic ware waste and often denoted as the pozzolanic property. Additionally, the low organic content in natural fine sand is a strong indicator that this aggregate is suitable for masonry unit production.

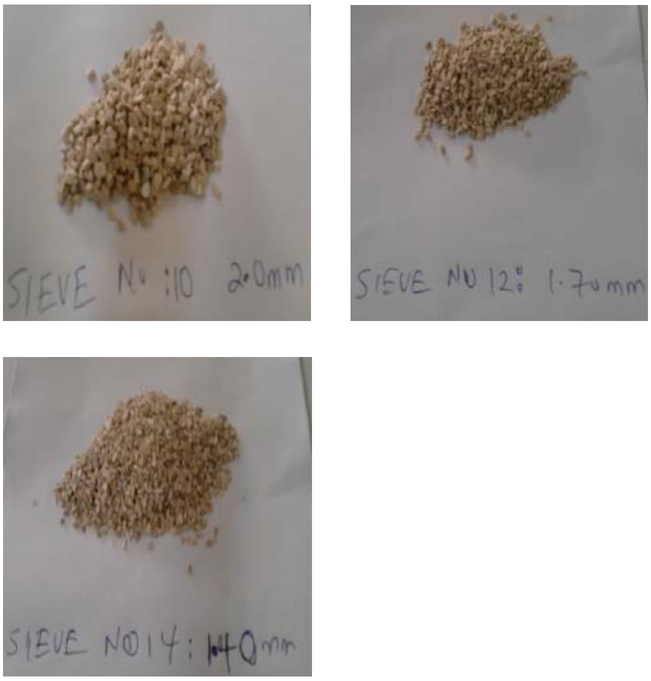
Structural morphology and chemical composition of aggregates

The structural and chemical composition from the SEM-EDX test gave a better understanding of the peculiarities between the two aggregates considered in this study. An observation worth mentioning is the similarities in the chemical constituents of the two aggregates, though ceramic waste seems to have a higher elemental concentration in comparison to natural fine aggregate. Elements observed in both aggregates were oxygen, carbon, aluminum, silicon, sodium, potassium. Another element resident in ceramic ware wastes was magnesium while natural fine aggregate contained additionally iron and titanium (**Figs. 6–7**). However, the major constitutes for both aggregates were oxygen,

Table 1. Natural fine aggregate and ceramic properties.

Property	Natural fine aggregate	Ceramic ware waste		
Particle size	≤ 0.3 mm	2.0 mm	1.7 mm	1.4 mm
Specific gravity	2.87±0.0	1.26±0.1	1.90±0.1	2.03±0.3
Porosity (%)	8.16±0.0	8.33±0.0	10.3±0.1	13.4±0.3
Bulk Density (g/cm3)	1.65±0.0	0.97±0.1	0.93±0.1	0.65±0.0
Clay Content (%)	6.48	NA	NA	NA
Organic Content (%)	1.90	NA	NA	NA
Carbon Content (%)	1.10	NA	NA	NA
Silt Content (%)	2.00	NA	NA	NA

*NA – Not available



Figs. 3-5 Ceramic ware waste of the three particle sizes considered in this study.

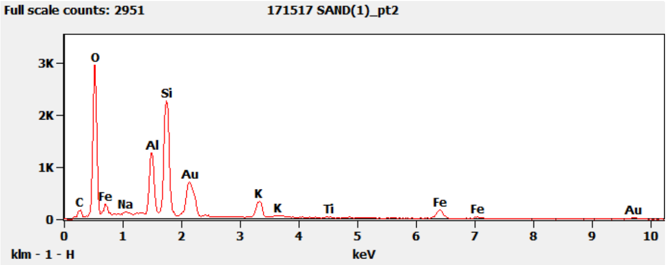


Fig. 6 Elemental composition of the natural fine aggregate.

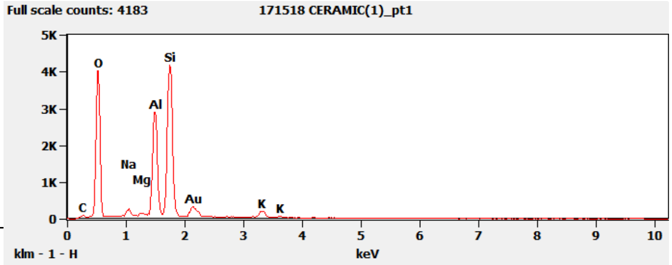


Fig. 7 Elemental composition of the ceramic ware waste aggregate.

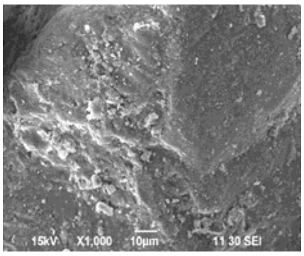


Fig. 8 Natural fine aggregate

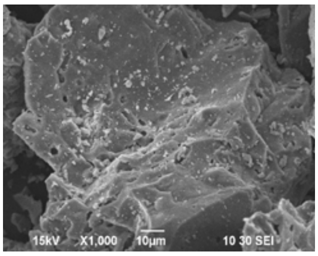


Fig. 9 Ceramic ware waste

silicon, and aluminum; forming over 90 % of the composition. Morphologically, structures of both aggregates were obviously different. Ceramic ware waste had some evident pore spaces at 10μm and ×1000 magnification. This feature might enhance it adherence to other composition of the masonry unit mix (Figures 8 & 9).

Water absorption capacity

During curing, there was drastic reduction in the level of water the blocks were submerged in within the first 7 days. Afterward, this water level became relatively stable. This huge reduction in the water level was due to water absorption by the submerged masonry units in order to complete the hydration process. This phenomenon is different from water abasorption capacityof the masonry unit.

Typical challenge with sand masonry unit is its relatively high water absorption capacity. According to Villarmizar *et al.,* (2012), water absorption capacity in an indicator of the resistance behaviour of masonry unit to immersion. In this study, water absorption capacity for all the dense masonry units considered after 28 days curing time were less than that of 100% sand solid masonry unit (M0T28 - control) by 27 - 51 % except for M30P1.4T28 which was the same with the control. The least water absorption capacity (5.2%) was found with M10P1.4T28 and M10P2.0T28 masonry units (Figure 10). These masonry units with water absorption capacity ≤ 7% could indicate their suitability for construction purposes, especially in wetlands or regions with high yearly rainfall. This is because the masonry units have water absorption capacities (5.2 - 7.6%) that were relatively close to the recommended British standard (BS, 1970) for such wet condition. In comparison with the water absorption capacity documented in a study on compressed earth block blended with of coal-ash and cassava peel, the values obtained in this study were 5 – 6 times lesser than the ones Villarmizar *et al.,* (2012) reported. This suggest that masonry units considered in this study are more suitable for construction purposes in regions of partial wetlands relative to earth block units. Other parameters were investigated to substantiate the usability of these co-aggregate-masonry units for construction purposes.

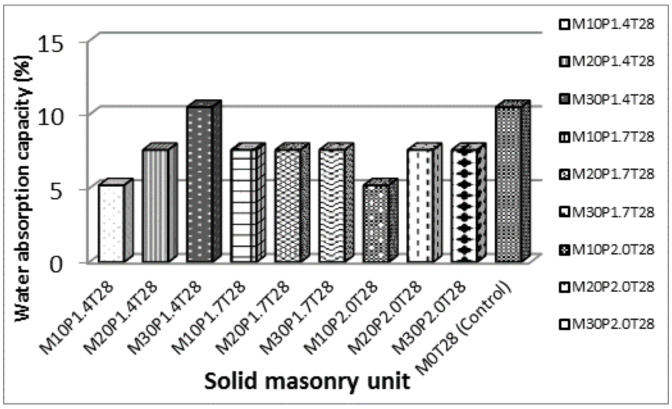


Fig. 10 Water absorption capacity of various masonry units after 28 days curing time.

Compressive Indices

Energy required to crush masonry unit

Energy required to crush the modified dense masonry units' range between 39 - 113 kN (Figures 11 &12). This range is lower when compared to the range (41 - 187 kN) documented in a study on hollow masonry unit modified with ceramic ware waste (Ajayi-Banji *et al.*, 2018). However, aside being a hollow masonry unit, particle size of the ceramic ware waste was 0.075mm. This might have influenced the crushing energy of the hollow masonry unit. Energy at break required to crush the modified solid masonry units regardless of the categories was higher than the respective controls except for M10P1.7M7 masonry unit and some other solid masonry units subjected to 28 days curing time. For instance, the energies required to crush the modified masonry unit after 7, 14, and 21 days were greater than the respective controls by 2 - 77 %, 27 - 212 %, and 17 - 109 % correspondingly (Figures 11 & 12). These were suspected to indicate that the inclusion of ceramic ware waste in solid masonry unit production cured prior to 28 days enhanced masonry unit strength largely. Despite the inconsistency in energies required to crush the modified solid masonry unit categories after 28 days, modified masonry unit M10P1.4T28 required the highest crushing energy (125 Nm), while M10P1.7T14 required the least crushing energy (39 Nm). Furthermore, there was no obvious consistent trend to describe this parameter for all the considered modified categories. However, the crushing energies in this study were 3 – 10 times greater than the ones reported by Chukwudedelu *et al.,* (2015). The basic difference was the aggregates used. While this study considered ceramic waste as aggregate, Chukwededelu *et al.,* (2015) focused on rice husk for the same purpose. Other compressive strength indices were also considered to understand these patterns.

Statistically, mix ratio, curing time, and particle size had significant individual and interactive effect ($P < 0.05$) on the energy at break required to crush the solid masonry units for all the categories. The only exception to this result was the masonry units with same mix ratio; M20 series or M10 series or M30 series, ($P > 0.05$). This result was not presented in this manuscript.

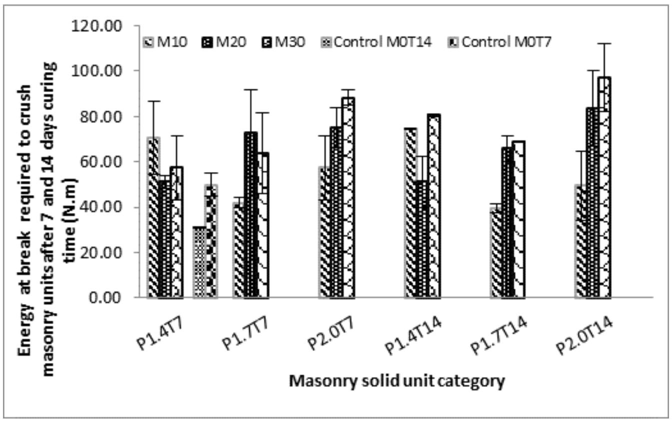


Fig. 11 Energy required to crush the masonry units after 7- and 14-days curing time.

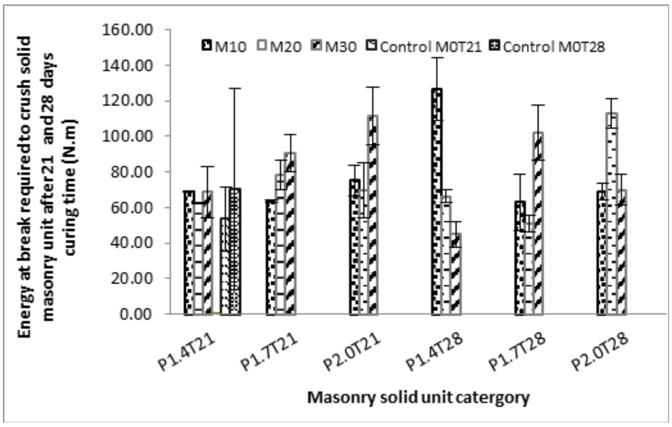


Fig. 12 Energy required to crush the masonry units after 21- and 28-days curing time.

Force required to crush solid masonry unit

Force required to crush the masonry units were between 31.5 – 79.2 kN. This is higher than the crushing force (2.4 – 4.2 kN) reported by Chukwededelu *et al.,* (2015) in a dense masonry unit study produced from blend of rice husk and slaked lime. The obvious reason for the low crushing force from this literature was the biological material used for masonry unit. Unlike energy required to crush the various dense masonry unit, force at peak required to crush the solid modified masonry unit gave a consistent trend. Modified masonry units with M10 (10% ceramic ware waste blended with 90 % natural fine aggregate) required the least crushing force (31.5 – 47.5 kN) except for the masonry unit (M10) under P1.4T28 category (66.5 kN). However, all the modified categories required higher crushing force than the respective control. Modified masonry unit required 2.4 – 82.0 %, 9.6 – 106.0 %, 22.3 – 71.7 %, and 0.0 – 65.0 % higher forces to crush the modified masonry units compared with the control after 7, 14, 21, and 28 days curing time in that order (Figures 13 & 14). This gives a better information on the improved strength from blending the ceramic ware waste with natural fine aggregate than the required crushing energy in solid masonry unit production. Also, from Figures 13 and 14, M30P1.7T28 (30% ceramic ware waste with 1.7 mm particle size blended with 70 % natural fine aggregate to produce solid masonry unit cured in water for 28 days) required the highest crushing force (75.2 kN) while the lowest crushing force (31.3 kN) required by the modified masonry unit was found with M10P2.0T7 masonry unit.

Also noteworthy is the impact of particle size and curing time on forces required to crush the modified masonry units. Considering a crushing force threshold of 50 kN, most M10 categories were less than 50 kN except M10P1.4T28 as earlier stated. Hence, subsequent focus of discussion on this parameter was on modified solid masonry units with M20 and M30 mix ratios. Interestingly, all modified solid masonry unit categories with combined 1.7 mm and 2.0 mm particle sizes with M20 and M30 mix ratios (M20P1.7, M30P1.7, M20P2.0, and M30P2.0 series) irrespective of their curing time required crushing forces at least equal to the threshold (≥ 50 kN) compared to other categories. The only exceptions to these were M20P2.0T7, M30P1.7T7, and M20P1.7T28. Furthermore, P1.4 dense masonry unit series seem not to have a consistent trend, particularly with P1.4T28, hence was not further considered. Based on these observations, M20P1.7, M20P2.0, M30P1.7, and M30P2.0 solid masonry unit series subjected to 14, 21, and 28 days curing time showed some additional strength that could be beneficial in high quality dense masonry unit production.

Another important observation was the vital effect curing time seems to impact on crushing force. For instance, crushing force slightly increase with curing time for the P1.7 solid masonry unit series (P1.7T7, P1.7T14, P1.7T21, and P1.7T28) and P2.0 series (P2.0T7, P2.0T14, P2.0T21, and P2.0T28) except for M20P1.7T28 and M30P2.0T28 masonry units. For instance, crushing force for masonry unit P1.7T7 with M30 mix ratio value was 42.9 kN after 7 days and 75.2 kN after 28 days curing time respectively. This was about 75 % increment (Figures 13 & 14). The P1.4 series also followed the same trend except for some inconsistencies with the P1.4T28 series and the reason for these is not precisely understood. Nevertheless, curing time seems to enhance the force at peak required to crush modified solid masonry units under this study.

The mix ratio, particle size, and curing time significantly affect ($P < 0.05$) the force required to crush the dense masonry units. Furthermore, all the interactive effects between these parameters were significant ($P < 0.05$) except for the interactive effects between mix ratio and curing time and the one between particle size and curing time (Result not shown).

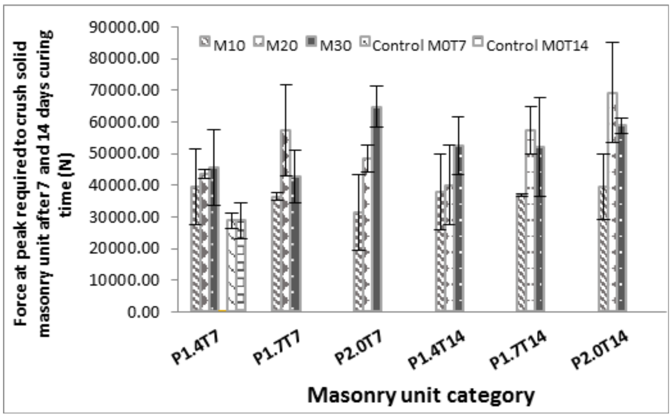


Fig. 13 Force required to crush the masonry units after 7 and 14 days curing time.

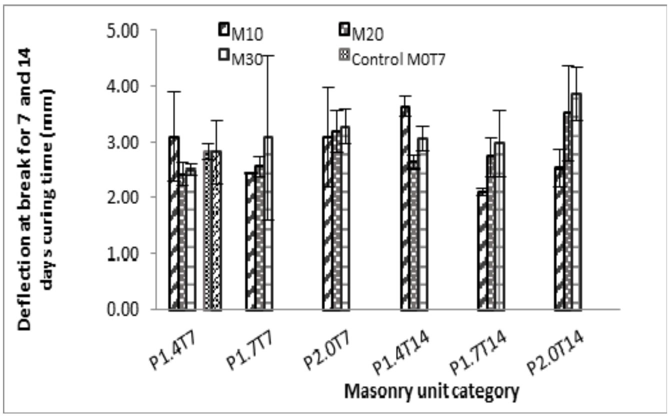


Fig. 15 Deflection in masonry units after 7- and 14-days curing time.

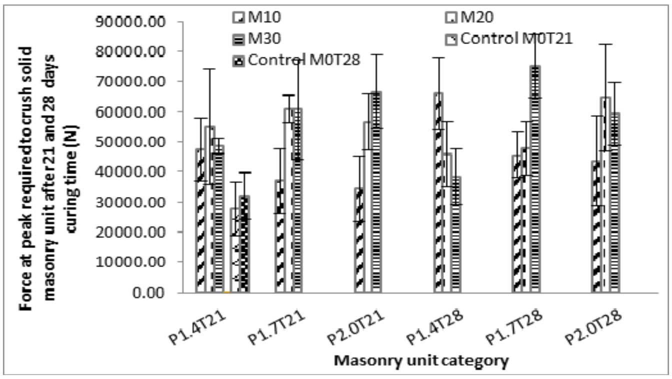


Fig. 14 Force required to crush the masonry units after 21- and 28-days curing time.

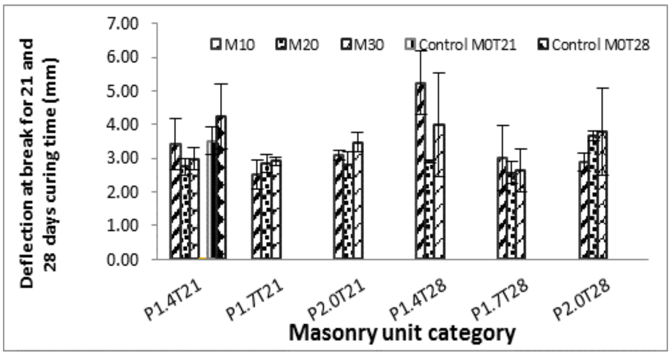


Fig. 16 Deflection in masonry units after 21- and 28-days curing time.

Deflection

The values for masonry units' deflection in this study were between 2.1 and 5.3 mm. This range was lower than the range (6.0 – 7.3 mm) observed by Chukwededelu *et al.,* (2015) in a study on the prospect of using rice husk for hollow and dense masonry unit production. In our study, deflections at break for modified masonry unit categories cured for 7 and 14 days were relatively close to the respective controls except for M10P1.4T14, M20P2.0T14, and M30P2.0T14. For instance, the deflection for T7 and T14 days series ranges between 2.41 - 3.29 mm and 2.08 – 3.08 mm in that order, while the respective control had 2.82 and 2.81 mm deflection respectively. Deflection pattern also seems consistent from 7 to 21 days curing time only when the M10P1.4 masonry unit series (M10P1.4T7, M10P1.4T14, and M10P1.4T21) were exempted. Considering the T7 series (P1.4T7, P1.7T7, and P2.0T7), particle size increased as deflection increased (Figure 15). The masonry units under T14 and T21 series also had similar trend. However, this was not the case for T28 series, where there was initial decrease in deflection as particle size increased from P1.4T28 to P1.7T28 before subsequent increase in particle size from P1.7T28 to P2.0T28 (**Figs. 15–16**). For instance, in Figure 16, 12.9 % decrease in deflection was noted as particle size changes from 1.4 mm (M20P1.4T28 dense block) to 1.7 mm (M20P1.7T28 solid block) and then a 42 % increase from 1.7 mm (M20P1.7T28 masonry unit) to 2.0 mm (M20P2.0T28 solid block). The reason behind this behaviour is not clear.

The effects of curing time and particle size on the deflection that occurred during the compressive test of the solid masonry units were significant ($P < 0.05$). There were also significant interactive effects ($P < 0.05$) when mix ratio and particle size were considered and from curing time and particle size interaction (Result not shown).

Stress

This is a very important parameter for quality masonry unit consideration. The compressive stress values at peak for the modified blocks cured for 7, 14, and 21 days were relatively steady and greater than the respective controls under all conditions except for M10P2.0T21. The compressive strength for these modified dense masonry units after 7, 14, and 21 days were in the range of 3.31 - 5.87, 3.34 - 5.33, and 3.81 - 6.04 MPa respectively and for the matching controls were 3.23, 3.25, and 3.52 MPa. This could infer that the modified solid masonry units produced from the blend of ceramic ware waste with natural fine aggregate had about 2.5 - 82 %, 3.4 - 65 %, and 8.2 – 72 % compressive strength increase based on curing period. This is suspected to indicate improved strength in the modified masonry units. The compressive strength values obtained in this study for modified masonry units were all higher than the ones Villarmizar *et al.*, (2012) reported in a compressed earth masonry unit study. Villarmizar *et al.,* (2012) values for the best blend category was between 3.26 – 3.37 MPa. However, compressive strength from this study was lower than some of the values (5.8 – 12.2 MPa) reported for concrete pavement block by Ling *et al.*, (2012). The obvious reasons for this remarkably large difference was the cement to aggregate mix ratio. Ling *et al.*, (2012) used a lower cement to aggregate ratio (1: 5.7) compared to 1:7 used in this study. Furthermore, the concrete pavement block had some blend of tyre waste which was used to replace coarse sand. This was also suspected to have enhanced the compressive strength.

Furthermore, on the modified masonry units, several compressive strengths for the dense masonry units subjected to 28 days curing period had greater values compared to the control (4.14 MPa), though the trend for the series, T28, was not consistent (Figures 17 & 18). Notwithstanding, the highest average compressive strength or stress of 6.82 MPa was obtained from this T28 series (M30P1.7T28) of solid masonry unit. On the contrary, the least compressive strength value (3.31 MPa) was observed for the T7 series (M10P1.7T7) solid masonry unit (Figures 17 & 18). Hence, curing time might have imparted the compressive strength. This is in line with previous studies that opined that time and humidity affect hydration process and hence concluded that blocks cured for 28 days should give the highest compressive strength compared with lesser curing times. In this study, the 28 days masonry units had the highest compressive strength, however, mix ratio and particle size seems to play major roles in the values of the compressive strengths even after 28 days curing time. In general, modified masonry units with compressive strength ≥ 4.1 MPa is an indication that they meet the non-loading concrete masonry unit standard (ASTM C129).

In contrast to previous statistical data from this study, only mix ratio and curing time had significant effects ($P < 0.05$) on the compressive strength of the masonry units. This also confirms the previous suggestion that curing time impacted compressive strength. However, there was significant interactive effect ($P < 0.05$) on the compressive strength of the masonry units between the three variables under consideration in this study. Also, the interactive effect between mix ratio and particle size based on compressive strength was significant ($P < 0.05$). This result was not presented in this manuscript.

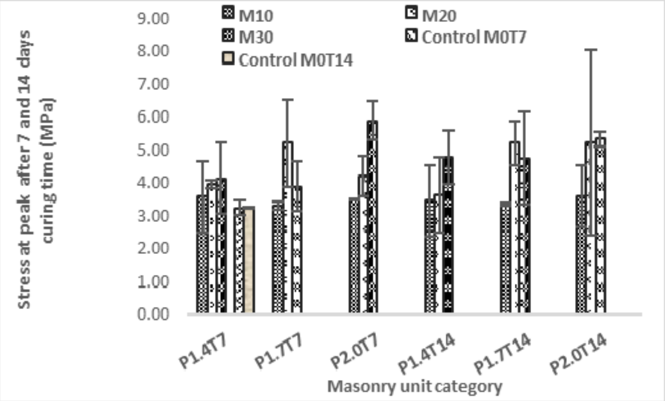


Fig. 17 Stress for masonry units after 7- and 14-days curing time.

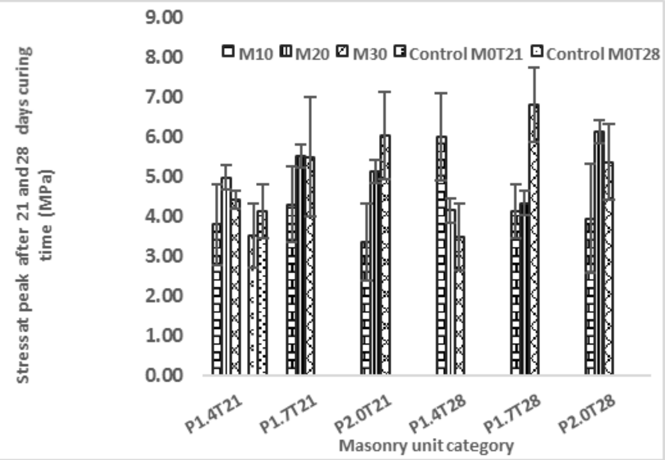


Fig. 18 Stress for masonry units after 21- and 28-days curing time.

Strain

The values of strain at break obtained in the study for the modified dense masonry unit ranges between 1.98 – 5.00 % (Figures 19 & 20). These are better than the strain range (1.50 – 23.00 %) documented for the various blend of coal ash, cassava peel waste and earth in a compressed earth block production study (Villarmizar *et al.*, 2012). Interestingly, only the block category with no cassava peel waste inclusion had closely related strain with this study. This is an indication that masonry constituent and the respective quantity influences value of strain obtained from masonry unit compression. With respect to other views, the trend of the strain obtained from the masonry unit seems consistent except with P1.4 masonry unit series. Furthermore, the strains for other masonry unit in our study increased with rise in mix ratio except for P1.4 series, P2.0T21, and P1.7T28 masonry units. Compared with the control, the strain increased by 2.7 - 43.0 %, 5.4 - 60.0 %, 0.0 - 37.9 %, and 0.0 – 73.5 % after 7, 14, 21, and 28 days curing time respectively. However, some of the strains for the modified masonry units were less than the respective control (M10P1.7T14, M10P2.0T28, M20P1.4T28, M20P1.7T28, and

M30P1.7T28). The reason for this different trend is not fully understood.

Particle size of the ceramic ware waste, the mix ratio of ceramic ware waste to sand aggregate, and curing time for the masonry unit, all had significant effect ($P < 0.05$) on the strain obtained when the masonry units were subjected to load. Similarly, there was significant effect ($P < 0.05$) on strain from the interaction of mix ratio and particle size, as well as, curing time and particle size. However, there was no significant effect from the interaction of the three parameters (Result was not presented).

Young's modulus

Modulus obtained in this study was between 188 - 481 MPa. This was higher than the modulus (33.7 MPa) Chukwededelu *et al.,* (2015) obtained in a study on the feasibility of using rice husk in dense and hollow masonry unit production. Furthermore, Young modulus in this study was negatively affected by strain. Most of the masonry units with lower modulus than the respective controls have higher strain than the controls (Figures 21 - 22). Relatively, the M10 series masonry unit has the lowest range of modulus. Also noteworthy is the obvious effect of the masonry unit variables (particle size, mix ratio and curing time) on the modulus. Dense masonry units under M20T14, M20T21, and M30T28 series had modulus above 400 MPa, except for M20P1.4T14 and M30P1.4T28. These might confirm previous observations about the limitation from P1.4 masonry unit series (Figures 21 - 22). Also, of interest is the high modulus (421 MPa) after 7 days curing time for M30P2.0T7 masonry unit. This implies that despite low curing time; particle size and mix ratio could enhance solid masonry unit quality.

Statistically, mix ratio and curing time has significant effect ($P < 0.05$) on the Young's modulus obtained in this study. Also, there was significant interactive effect ($P < 0.05$) from these three variables on Young's modulus (Result not shown).

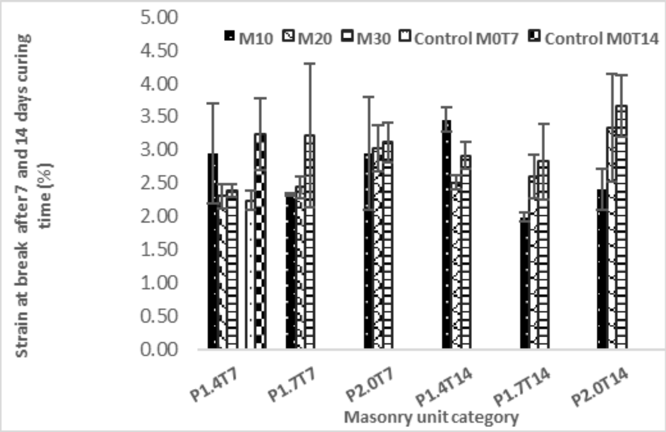


Fig. 19 Strain for masonry units after 7- and 14-days curing time.

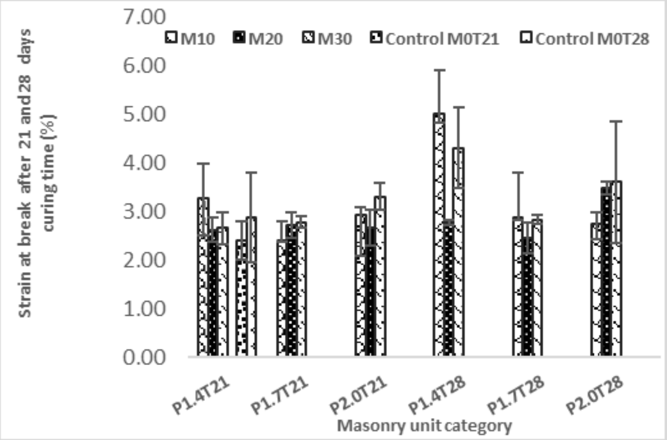


Fig. 20 Strain for masonry units after 21- and 28-days curing time.

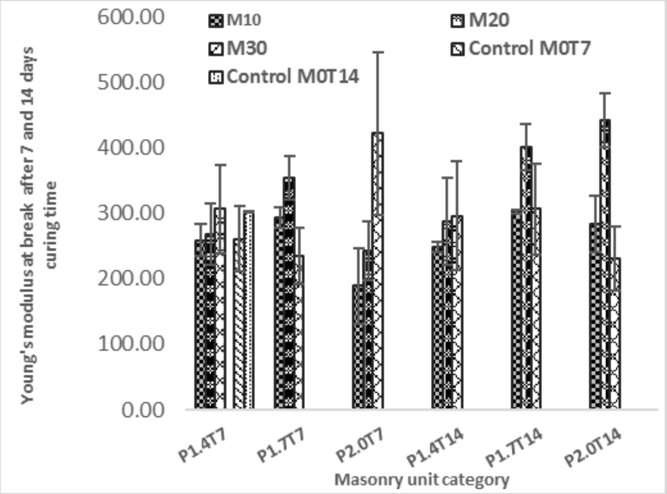


Fig. 21 Young's modulus for masonry units after 7- and 14-days curing time.

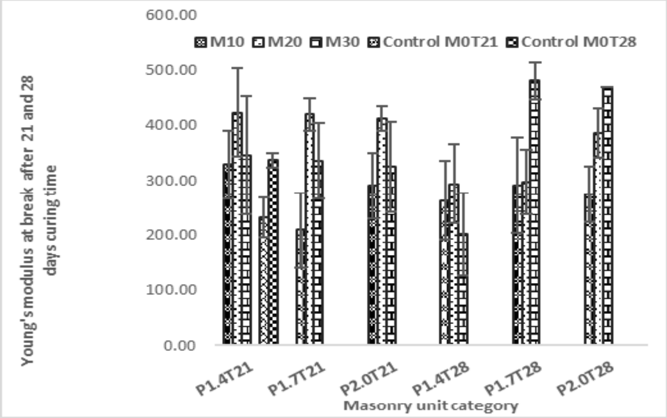


Fig. 22 Young's modulus for masonry units after 21- and 28-days curing time.

CONCLUSION

The feasibility of utilizing ceramic ware waste mainly generated from construction and demolition waste or from ceramic industries, which was partly blended with natural fine aggregate, was considered in this study for dense masonry unit production. Eighteen different class of these modified solid blocks were produced after being subjected to some combined conditions that includes particle sizes (1.4, 1.7, and 2.0 mm) mix ratios (M10, M20, and M30), and curing time (7, 14, 21, and 28 days).

The results show that most of the M20 and M30 (20% and 30% ceramic waste) modified masonry unit series gave suitable construction quality as the crushing forces (> 50 kN) and moduli (> 400 MPa) were higher compared with other categories and the compressive strengths met standard (≥ 4.1 MPa) for non-loading dense masonry unit. The water absorption capacity of these masonry unit series cured for 28 days were relatively close to the required standard (< 7%). Interestingly, these stated and desirable qualities were also found with M30P2.0T7 masonry unit. This is an indication that suitable masonry unit for non-loading structural purposes can be produced under 7 days curing time with the consideration of 30 % (2.0 mm particle size) ceramic ware waste to 70 % natural fine aggregate mix ratio.

The applicability of ceramic ware waste as co-aggregate in dense non-loading masonry units' production was established in this study.

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