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ORIGINAL RESEARCH ARTICLE

EFFECTS OF CRUSHED AND POWDERED BRICK PARTICLES ON LIGHTWEIGHT PAPERCRETE

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ABSTRACT

This paper studied a light weight paper and mortar composite called papercrete which was produced using brick particles as aggregate and as pozzolan. Papercrete samples were produced with crushed brick particles to completely substitute sand as fine aggregate and labelled Sample BAP. Another set of samples were produced using crushed brick particles as aggregate and powdered brick particles as pozzolan to partially replace 10% of the cement content. These were labelled Sample BCP. Additional samples labelled Sample SP were produced with sand as aggregate and with no cement replacement to serve as controls. Initially, an X-ray diffraction analysis was performed on powdered brick particles to assess their chemical composition in line with ASTM 618. A total of 135 test samples were cast and tested for density, water absorption, compressive strength and tensile strength at 14 and 28 days. Similarly, samples were subjected to thermal conductivity and fire reaction tests. The results show an increase in density, compressive and tensile strength of Samples BAP and BCP over Sample SP. Additionally, all samples recorded low thermal conduction and a good reaction to fire as none of the samples ignited when subjected to fire. However, all samples had high water absorption values. It was concluded that using crushed and powdered brick particles to produce papercrete increases its density and strength and can be used as aggregate and pozzolan in producing papercrete.

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1.0 Introduction

Several factors are pushing the demand for alternative materials to substitute or supplement concrete. One of such is the need for low-cost construction materials. Secondly, as sustainability has come forth as the most dangerous environmental issue at present, the movement is now towards the utilization of materials that aid ecological sustainability. Moriconi (2007) traced the current construction practice as unsustainable remarking that it goes to wasteful use of cement and mineral resources which are restricted. As an example, aggregate which constitutes the biggest ingredient of concrete is being quickly consumed as it is estimated that close to eleven billion tonnes of aggregate is used annually (Smith, 2009). Of this amount, roughly eight billion tonnes of aggregate comprising sand, gravel and crushed rock is used in concrete (Mehta, 2001; Naik and Moriconi, 2005). Also, Moriconi (2007) showed that in summation to the enormous amounts of crushed rock, sand and drinking water consumed, two billion tonnes of Portland cement is also consumed, which is not an environmentally-friendly material considering that it uses up a great deal of energy during manufacture and releases greenhouse gases (GHG) which contributes to global warming.

One key effort towards ensuring sustainability is the usage of reused materials in concrete and concrete based systems. Lately, there has been much interest in a concrete based system called papercrete. Papercrete is produced by mixing recycled paper, Portland cement and sand (Chung et al., 2015; Lyons, 2007; Mohammed, 2009 and Titzman, 2006). When these materials are mixed and cured, they raise a material like concrete. The benefit of this material is multi-fold. First, it provides an environmentally favourable and fertile means of throwing out wastepaper which makes a significant component of environmental waste. The Bureau of International Recycling (BIR) in 2012 estimate that over 400 million tons of paper is created and consumed annually with only around 50% recovered. In Nigeria, the Food and Agriculture Organization (FAO) (2012) estimate that 19,000 tons of paper and paperboard was produced and a further 570,000 tons imported with only 8000 tonnes recovered.

Even before the advent of papercrete, other recycled materials have been widely applied to supplement or substitute some ingredients in concrete based systems. One such endeavour is the usage of waste brick. Waste bricks are byproducts of brickmaking and construction demolishing which are crushed to appropriate sizes for use as pozzolan or as aggregates. As aggregates, CBB is mostly used to replace coarse aggregate. When applied as fine aggregate, it significantly increases the water taken in a mix (Bektas, 2007). However, Khatib (2005) reported comparable strength properties with concrete containing normal fine aggregate when CBB was used as fine aggregate, hence suggesting the feasibility of using CBB as fine aggregate.

Being a comparatively new material, most studies on papercrete have focused on measuring its properties. Sangrutsamee et al. (2012) examined the properties of papercrete containing different paper types and content and obtained compressive strength as high as 6.14N/mm^2 and thermal conductivity as low as 0.28910W/mK. Titzman (2006) studied a papercrete-concrete composite with acceptable results for compressive strength (143.6psi-0.99N/mm^2), tensile strength (28.3psi-0.19N/mm^2), thermal conductivity (0.10W/mK); while samples subjected to flammability test did not inflame. Primarily, papercrete is produced by shuffling in mortar with paper fibres. This investigation on the other hand assessed the viability of utilizing other materials as constituents in papercrete by producing papercrete using CBB as fine aggregate.

1.1 Papercrete

Papercrete also called fibrous concrete or fibercrete is a generic term applied to identify a mixture of cement, sand, paper and water (Chung et al., 2015; Mohammed, 2009 and Titzman, 2006). Papercrete is primarily made by mixing shredded paper with cement, sand and water to make a paper-mache slurry that can be cast into block units and also used as mortar in binding the blocks (Lyons, 2007). When papercrete dries, the resulting fabric is gray in colour and is highly water-absorbent (Titzman, 2006). Nevertheless, due to its light weight, it has good insulating properties and the cement content significantly increases its resistance to fire (Lyons, 2007). Each of the ingredients in papercrete contributes a different property in the admixture. The cement is responsible for the strength of the material as it binds other ingredients together (Kokkinos, 2010). Sand adds thermal mass, makes the mix stronger and less water absorbent (Kokkinos, 2010). The fibres on the other hand, are responsible for low density, low strength and low thermal conductivity (Sangrutsamee et al., 2012).

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Surveys on the utilization of wastepaper–mortar composites indicate varying strengths of papercrete. In the study by Sangrutsamee et al. (2012), compressive strength of over 6N/mm2 was achieved by varying the pulp content. Mohammed (2009) obtained a 28-day compressive and flexural strength of 5.56N/mm^2 and 1.43N/mm^2 respectively at a papercrete density of 650kg/m^b. Papercrete also has sound insulation properties. Kokkinos (2010) reported that papercrete has a low thermal conductivity coefficient and high thermal diffusivity which means even though papercrete changes temperature quickly, it does not transfer much heat. This has been noted by other researchers. Studies by Masjuki et al. (2008) obtained a thermal conductivity K, for papercrete of 0.85W/mK. Sangrutsamee et al. (2012) carried out a study to assess the thermal conductivity of papercrete containing different paper types and varying pulp content, and obtained values ranging between 0.2890 and 0.6250W/mK. Titzman (2006) obtained thermal conductivity as low as 0.10 W/mK. Papercrete however absorbs water easily, behaving like a sponge when exposed to water (Titzman, 2006). Also, in a study of Suganya (2012), water absorption values as high as 74% were obtained.

1.2 Crushed Brick as Concrete Ingredient

Recycled clay bricks are waste materials obtained either from building demolitions or discarded products that do not adapt to standard during manufacture (Bektas, 2007). These materials are crushed to smaller sizes to get the shape of material involved (0.075mm-50mm for aggregate or ground to powder fineness for pozzolan) (Bektas, 2007). Crushed brick is mainly used as coarse aggregate in construction. Bektas (2007) attributed the averseness to its use as fine aggregate to the increased water demand when used as fine aggregate. According to Schultz and Hendricks (1992), using waste brick as aggregate helps to get rid of the large amount of masonry rubble generated and serves to meet aggregate demand for novel building. In addition, Khalaf and DeVenny (2004) reported that crushed brick tends to increase tensile and flexural strength when used as aggregate as a result of improved bonding between brick aggregate and cement paste. The same view is held by Khatib (2005) who reported that when broken brick or concrete is used as aggregate, cementation continues beyond 28 days hence the rate of strength development is higher when fine crushed concrete or crushed brick is used.

Raw clay in itself, has no pozzolanic property. However, when clay is fired during the brick making process, it acquires the possibility to undergo a pozzolanic reaction with lime in the presence of water (Roger, 2011). When excited to temperatures between 600-950°C, the structure of clay minerals undergoes an alteration that allows them to react with calcium hydroxide. When calcined, the loss of water in clay causes the collapse of the crystalline structure of alumino-silicates, leaving alumina and silica in an unstructured (amorphous) state. It is in this unstructured state that silica and alumina have the potential to combine with and reduce calcium hydroxide. This is, however, not possible in clays that are mixed with high quantities of very crystalline minerals like quartz and feldspar (Pinheiro et al., 2010). Also, if calcination temperature exceeds certain limit, the disordered silica and alumina will recrystallize and form other unchanging composites like mullite (A3S2) that will not react with lime.

2. Materials and Methods

Binder: Dangote Portland cement obtained from local dealers in Zaria and conforming to BS 12 (1996) was used.

River sand was also obtained from local dealers in Zaria. The sieves used were 4.75mm, 2.36mm, 1.18mm, 600μm, 300μm, 150μm and conformed to BS 410 (1986).

CBB: waste bricks were obtained from a local dealer in PZ Zaria and were manually crushed to smaller sizes. The bricks were also screened using a 5mm sieve in order to get rid of large particles and to obtain particles within the fine aggregate limit (4.75mm to 600μm) pozzolans (75μm and below). Grading of the crushed burnt brick was carried out based on the result of the sieve analysis conducted i.e. the percentage by weight of particles retained on each sieve in the sieve analysis of the river sand was used to grade the crushed brick. This was done in order to enable comparison between samples containing crushed brick with samples containing river sand.

Paper sludge: the preparation of the paper sludge involves soaking the paper in water and then grinding. Newspapers were soaked in water until they were indulgent enough to mash. The soaked newspapers were then ground until the desired consistency was obtained. The ground paper was left in slurry form until it is needed. Before usage, water was drained from the ground paper thus leaving it in a saturated surface dry (SSD) condition. This was done in order to apply the same measure of water for all the mixes.

Casting of samples: The experiment started with the determination of the quantity of water to ensure a workable mix. A mix ratio of 1:1:3 as suggested by Lyons (2007) was employed with varying quantities of water. The trials established that 2.5g of water per 1g of ground paper at saturated surface dry condition was suitable. Three samples 'SP', 'BAP' and 'BCP' were prepared. Sample SP contained cement, sand as fine aggregate and paper. Sample BAP contained cement, CBB as fine aggregate and paper. Sample BCP contained cement, CBB as fine aggregate, CBB replacing 10% of cement and paper. The moulds used were 72mm x 72mm x 72mm cube moulds for density, water absorption, compression, and thermal conductivity tests. Cylinder moulds 100mm x 200mm (ASTM C42, 1990; BS 1881-120, 1983) were used for tensile test and 250mm x 90mm x 25mm rectangular moulds (BS EN 11925-2, 2010) were used for fire reaction test. Three samples each were produced per batch for the compressive strength, tensile strength and water absorption tests. A sample per batch was used for the thermal conductivity test. Six samples per batch were used for the reaction to fire test. A total of 135 specimens were cast. The samples for strength tests were also used to assess the density of the materials.

Curing: As papercrete is highly water absorbent and takes a significant time to dry, the samples were cured for 7 days by covering with polythene sheets and then, allowed to get air-dried.

Density test: the density of the papercrete samples was determined in accordance with BS EN 12390-7 (2009). The samples for each mix were weighed and their volume determined in accordance with section 5.5.5 of the standard.

Water absorption test: this was determined by total immersion in accordance with ASTM C642 (1997). The oven dry mass (A) and saturated mass (B) after immersion in water was determined for all the samples. The oven dry mass was determined by weighing the samples and drying in an oven at a temperature of 100°C for 24 hr. The saturated mass was determined by immersing the samples in water until they achieved a constant mass. This took up to 48 hours. The absorption percentage was then calculated using the Eqn (1) due to ASTM C642 (1997):

$$\text{Absorption after immersion (\%)} = \frac{B-A}{A} \times 100 \qquad (1)$$

Strength tests: the compression test was conducted in accordance with BS EN 12390-3 (2009). The cubes were placed, trowelled face sideways, in the testing machine and loaded. The loading was stopped once the sample became fractured. The tensile strength was also determined using the same compression machine as in the compression test.

Thermal conductivity test: the test was carried out at the laboratory of the Department of Chemical Engineering, Kaduna Polytechnic. The parameters for determining the thermal conductivity were measured using the standard method for thermal conductivity described by Ashraful (2005). A free and forced heat transfer apparatus was used. The apparatus consists of a controller and a hot plate. The power supply is set from the controller. The temperature of the hot plate was then recorded after the readings reached a steady state. The temperature at two points on a sample was then recorded. The thermal conductivity was then computed using Fourier's law as stated by Incropera and Dewitt (2002) and presented in Eqn (2):

$$Q = \frac{K \times A \times \Delta T}{L} \quad (2)$$

where: Q = heat transfer (W); k = thermal conductivity (W/mK); A = area of the specimen (m^2); ΔT = difference in temperature (K) between two sections (of area A) at a distance L (m); L = distance between two sections (of area A) at which temperature is taken.

Fire reaction test: the reaction of papercrete to fire was assessed using Single Flame Ignitability (SFI test) in accordance with BS EN 11925-2 (2010). The samples were fixed in a horizontal position and a filter paper placed underneath the sample. Flame was placed on the edge and surface of three samples each per mix for 30 seconds. The time to ignition and the time until the flames spread up and reach 150mm above the flame application point are recorded. Also, the ignition or otherwise of the filter paper was noted.

3. Results and Discussion

3.1 Chemical Analysis of CBB

Table 1 presents the composition of major oxides in powdered brick while Table 2 presents the composition of oxides in the CBB used in relation to the requirements for class N pozzolana. Table 2 shows that the sum of silica, alumina and iron oxide in CBB exceeds the 70% minimum recommended by ASTM C618. The sulphur trioxide (SO3) content was also less than the maximum 4% required by the standard. Also, the analysis revealed no traces of magnesia (MgO) while the sum of minor oxides was less than 5%. Hence based on the oxide composition the CBB used in the study has the potential to undergo pozzolanic reaction.

Table 1: Chemical Composition of CBB and Pumice

	Concentration, %							
Compound	Al_2O_3	SiO_2	Fe_2O_3	CaO	SO_3	MgO	Na_2O	K_2O
CBB	16.10	65.20	10.66	1.69	0.12	—	—	2.80

Table 2: Chemical Requirements of Class N Pozzolana

S/No.	Properties	Recommendation for Class N Pozzolana	CBB
1	Silica (SiO_2) + Alumina (Al_2O_3) + Iron oxide (Fe_2O_3)	70 (min %)	91.96%
2	Sulphur trioxide (SO_3)	4 (max %)	0.12
3	Magnesia (MgO) +		—
4	Free alkali e.g. Na_2O, K_2O	5 (max %)	2.80

3.2 Bulk Density and Water absorption

Figure 1 presents the density of the papercrete samples at 14 and 28 days. Samples BAP and BCP containing brick particles had higher densities than the control sample, SP at both ages. This increase in density could be as a result of the pozzolanic effect of very fine CBB particles which reduce the amount of $CaOH_2$ thus improving densification. Also, Joy (2005) pointed that regardless of the reactivity of pozzolanic particles, if very fine, it will be able to fit into cement grains thus resulting in more efficient paste packing. This lowers the mean capillary size and reduces bleeding and hence results in a denser microstructure (Joy, 2005). Even with the increase in density of samples BAP and BCP over sample SP, papercrete containing crushed and powdered brick still meets the requirement of ASTM C332 (1999) which requires the density of lightweight concrete to be lower than 1440 Kg/m3. Figure 2 indicates that all samples are highly water absorbent. This could be due to the high content of paper (60%) used in the mixes just like Titzman (2006) acknowledged that unless special treatments are applied to papercrete, it behaves like a sponge soaking in water. Sangrutsamee et al. (2012) also obtained water absorption values as high as 58% using different types of recycled paper at varying contents.

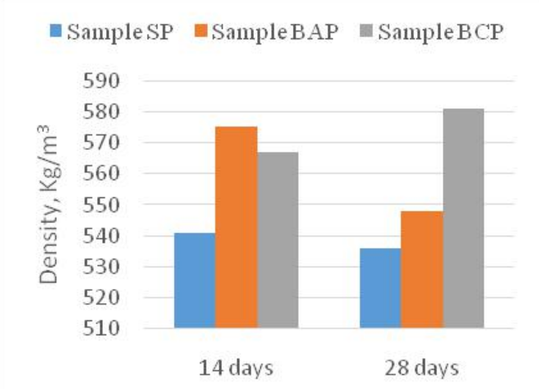

Figure 1: Bulk Density of *Papercrete* Samples

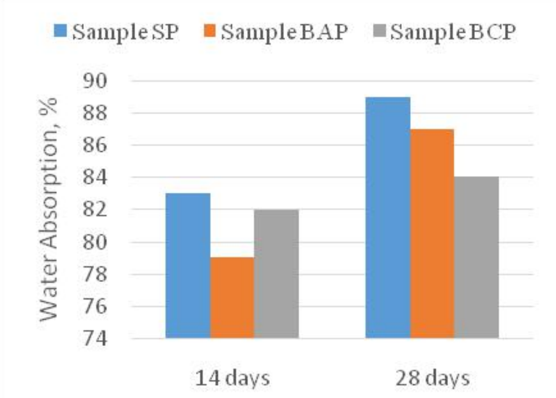

Figure 2: Water Absorption of *Papercrete* Samples

3.3 Strength of Papercrete

The results of the compressive and tensile strength tests are also presented in figure 3. At 14 days, samples BAP and BCP containing brick particles gained 9% in strength over the control sample, SP. At 28 days, Sample BAP containing crushed brick particles as fines gained 3% in strength over the Sample SP. In an earlier study by Khatib (2005), strength results similar to the control mixture containing normal fine aggregate were obtained using crushed brick as fine aggregate to produce concrete. Sample BCP containing crushed and powdered brick particles gained 39% increase in strength over Sample SP and 36% over Sample BAP. This significant increase in strength could be attributed to the pozzolanic action of the powdered brick particles as Rogers (2011), indicated that burnt brick if fine enough will undergo pozzolanic reaction when combined with lime in the presence of water. Lin et al. (2010) pointed that pozzolans reduce calcium hydroxide $CaOH_2$ from the hydrating cement paste resulting in additional cement gel thus improving strength. Additionally, the compressive strength of all the samples fall within the range 0.7 N/mm^2 – 7.0 N/mm^2 required by ASTM C332 (1992). Results of the tensile strength test in figure 4 were in tandem with those of the compressive strength with samples BAP and BCP containing crushed and powdered brick particles recording similar or higher values than the control at both ages.

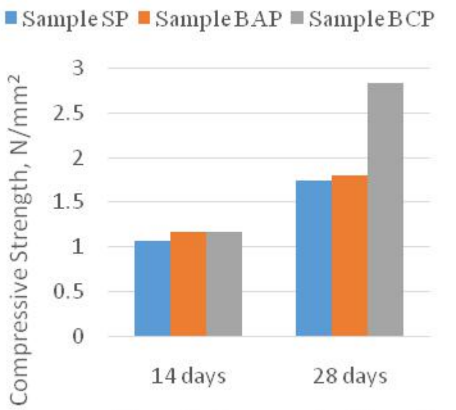

Figure 3: Compressive Strength o *Papercrete* Samples

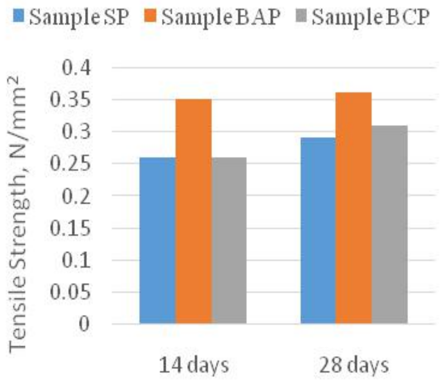

Figure 4: Tensile Strength of *Papercrete* Samples

3.4 Thermal Properties

Figure 5 presents the thermal conductivity of the papercrete samples. Sample BAP (0.641 W/mK) containing crushed brick particles recorded a lower thermal conductivity than the control (0.657W/mK). However, Sample BCP (0.663W/mK) containing crushed and powdered brick particles increased in thermal conductivity over the control. These differences in thermal conductivity could be attributed to variations in porosity and density of the samples. However, the values obtained by all the samples were more than the maximum 0.43 W/mK prescribed in ASTM C332 (1999). Still, the thermal conductivity of the samples are very low when compared to other materials such as concrete (1.25W/mK). Also, in an earlier study, Sangrutsamee et al. (2012) assessed the thermal conductivity of papercrete containing different paper types and obtained values ranging from 0.289W/mK to 0.625 W/mK for different mixes of papercrete. Just as with the thermal conductivity test, all the samples reacted well upon impingement with flame. None of the samples ignited upon application of flame as there were no flaming droplets nor ignition of the filter papers used in the test.

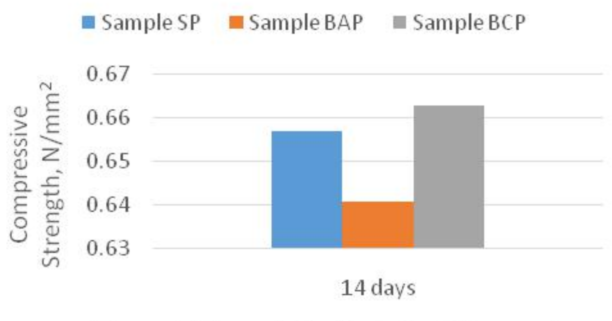

Figure 5: Thermal Conductivity of *Papercrete* Samples

4. Conclusion

This study assessed the effect of using crushed and powdered brick particles as aggregate and as pozzolan in producing papercrete. An initial XRD analysis on powdered brick particles reveal the presence of major oxides – silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3) above the minimum recommended in ASTM 618 thus signifying its suitability as a pozzolan. Density and strength tests show an increase for samples containing crushed brick particles over ordinary papercrete and even greater increases in samples containing both crushed and powdered brick particles. In addition, all samples met the density and strength requirements for lightweight insulation concrete outlined in ASTM C332 (1999). The thermal conductivity values of the samples were above the limit recommended by the standard but significantly low when compared to other widely used materials like concrete and steel. Furthermore, all the samples responded well to the fire reaction test as there was no ignition in any of the samples. Conversely, all the samples were highly water absorbent. Overall, brick particles increase the density and strength of papercrete with no significant adverse effect on water absorption, thermal conductivity and fire reaction.

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