Compressive strength and durability properties of pozzolan obtained from co-fired clay and rice husk

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Abstract: This study investigated pozzolan from the co-firing of clay and rice husk. Rice husk was used to replace clay at 1.0%, 1.5% and 2.0% and calcined at 800°C. Pozzolanic strength activity index (PSAI) was performed on the calcined powder materials in accordance with the ASTM C311 standard. The calcined material that obtained the highest PSAI was selected and used to optimize the calcined pozzolan added to Portland cement. The optimum mixture proportions were used for ²⁹Si and ²⁷Al MAS NMR as well as water sorptivity and shrinkage studies which involved autogeneous and drying shrinkages. The results of the study showed that calcined clay that contained 2.0% rice husk had the optimum PSAI whereas 30 wt.% replacement content was the optimum cement replacement. The ²⁹Si and ²⁷Al MAS NMR showed that the superior strength of the optimum mortar mix to the control was due to a stable monosulphate phase formed at the octahedral environment and the formation of extra calcium aluminosilicate phases in the mortar mix. The initial and secondary sorptivity values of the pozzolan were 0.0055 and 0.0022 mm/sec⁰.⁵, respectively, lower than the values of the control, which were 0.0299 and 0.0083 mm/sec⁰.⁵ respectively. The shrinkage performances of the Portland...
cement-pozzolan mix were much enhanced than the unblended mortar mix. The inclusion of the co-fired materials reduced the embodied carbon by approximately 29%. The use of the co-fired material could be a sustainable means to dispose of waste rice husk and also reduce embodied carbon.

**Subjects:** Materials Science; Clean Tech; Civil, Environmental and Geotechnical Engineering

**Keywords:** Co-fired pozzolan; optimum strength; $^{29}$Si/$^{27}$Al MAS NMR; embodied carbon; sorptivity; drying shrinkage

1. **Introduction**

The consumption natural resources of the earth by human beings and the demand for goods and services to meet their needs is a major contributor to the huge amount of waste generation coupled with its disposal into the environment (Sukholthaman & Shirahada, 2015). The quantities of waste generated annually has generally been rising progressively around the globe and this rise is attributed to rapid economic development and urbanization of societies. The generation of waste in developed and emerging countries in the world imposes great economic, social and environmental costs on society through waste collection, treatment and disposal. The increasing waste generation as well as the associated economic, social and environmental impacts have created the opportunity for development and adoption of techniques to reduce waste substantially.

Waste generation from the rice industry has been increasing annually in most West African countries including Ghana, Nigeria, and Togo due to increased consumption resulting from population growth (FAOSTAT Food and Agriculture data, 2015). In 2012, rice production in Ghana was about 0.48 million tonnes (MT), which increased to 0.57MT in 2013 and a further 0.6MT in 2014 (FAOSTAT, 2015). Zerbino et al. (Zerbino et al., 2011) have stated that on the average, a tonne of rice produced generates approximately 200 kg of rice husk. Currently, approximately 0.15 million tonnes of rice husk is produced in Ghana annually. Disposal of rice biomass in most Western African countries is commonly done by open burning (see Figure 1). Uncontrolled or poorly managed burning of rice husk pollutes air quality thereby creating objectionable adverse impact on the environment and on public health and safety. An alternative way to dispose of the waste is for city authorities to collect the waste for proper disposal. The cost of collection of the waste is
approximately 10 USD/tonne. Usually, town folks are unwilling to pay this amount thus leaving city authorities with financial stress. This consequently leaves the waste unattended to and hence posing environmental nuisance.

In some emerging and developing economies, waste from rice cultivation is utilized as a useful resource for the construction industry. Rice husk ash is usually produced and used as a pozzolan for the production of concrete and mortar (de Sensole, 2006; Zerbino et al., 2011). Rice husk has a calorific value between 16 and 17 MJ/kg and could therefore also be used as biofuel. The ashes contain amorphous silica which makes it one of the highly reactive pozzolans (Christopher et al., 2017). Clays can also be processed as a pozzolana (Avet et al., 2018). However, without heating at appropriate temperatures, pozzolanic properties cannot be activated. Using rice husk as a component in clay can serve as both a heating fuel and a source of elemental silica that can further enrich the pozzolanic nature of the clay. The Figure 2 establishes that best pozzolanic activity is attained when calcined at 800°C (Fernandez et al., 2011).

Modern construction has moved from the use of traditional Portland cement to alternative binders. Materials that are commonly used to form alternative binders for construction include fly ash, metakaolins, slag, silica fume and some agricultural waste ashes (Snelling, 2016). Assessment of the suitability of pozzolanic binders can be determined through a variety and several experimental techniques. Strength and durability characteristics of binders are important properties that influence the life cycle design of concrete structures.

The use of compressive strength as a mechanical performance to determine the performance of a pozzolan is described by Donatello et al. (Donatello et al., 2010) as an indirect method of assessment. Mamlouk and Zaniewski (Mamlouk & Zaniewski, 2006) explained that the mechanical behaviour is the material's response to external load. Indirect methods of testing use parameters such as strength, electrical conductivity and heat evolution by conduction calorimetry to determine the influence of the pozzolan (McCarter & Tran, 1996; Paya et al., 2001; Shi et al., 2005). Luxan (Luxan et al., 1989) has indicated that the electrical conductivity and heat evolution methods are less time-consuming. However, the strength activity index determination is more preferable than the other methods. The reason is that the electrical conductivity and heat evolution methods are sensitive to only the pozzolanic effect of powder materials, however, excludes the filler effect whereas Strength Activity Index method is sensitive to both pozzolanic effect and packing effect. Authors including Donatello et al. (Donatello et al., 2010) and Tironi et al. (Tironi et al., 2013) have used strength activity index to explain pozzolanic activity of pozzolans.
Factors that lead to increased strength performance involve the complex transformation of cementitious systems during hydration. Si NMR provides valuable information relating CSH gel, the main hydrated phases of cement whilst Al NMR is useful to probe calcium aluminate hydrates (CAH) and aluminates hydrates such as ettringite and monosulphate hydrates (Mendess et al., 2011). The NMR indicates chemical shifts within ranges and this is a function of bond length and bond valence; all related to polymerization or crystal growth (Mendess et al., 2011).

Durability of a product is its ability to maintain the required performance over a given or long time, under the influence of foreseeable action. Foreseeable actions have been explained as potential degradation factors including temperature, humidity, moisture, UV radiation, abrasion, chemical attack, biological attack, weathering and in temperate environment frost, and freeze-thaw (Anon, 2015). The United States Department of Housing and Urban Planning has stated that using durable materials also means providing affordable, efficient and sustainable homes (J. Liu et al., 2014).

With cement-based materials, moisture penetration through the pores as well as shrinkage effects may prove to be among the significant challenges for concrete and mortar durability. Liu et al. (X. Liu et al., 2011) have indicated that the study of transport of water in cement-based materials such as concrete and mortar means a lot for the analysis of concrete durability. This is because usually aggressive substances are carried along in the pores by water. The ingress of moisture and the transport of ions including chlorides, sulphates and other aggressive chemicals have become the underlying source of many engineering problems such as steel corrosion, carbonation, frost and freeze-thaw actions.

Itim et al. (Itim et al., 2011) mentioned that shrinkage prediction is of very great essence for durability study and the inclination for long term functioning of concrete structures. Drying shrinkage is the loss of moisture (due to drying) from the concrete or mortar to the environment. Aside drying shrinkage, autogenous shrinkage is also a type of shrinkage that is widely gaining attention. Autogenous shrinkage is caused by a reduction in the pore relative humidity as a result of hydration products formation (Jensen & Hansen, 1996). Structural deformation due to shrinkage is well known to be the origin of cracks and even more rarely failure of concrete structures (Hua et al., 2017; Tam et al., 2012). Pozzolans are widely known as a material suitable for all cement-based products including concrete and mortar (Ballim & Graham, 2009; Bediako, Purohit et al., 2017; Fernandez et al., 2011). It has also been used successfully in refining pore structure and restraining shrinkage of cement-based products (Bao-guo et al., 2007; Khatib, 2004; Khatib & Hibbert, 2005).

This study investigated the mechanical and durability properties of co-fired clay and rice husk. The mechanical studies of the work were based on pozzolanic strength activity index (PSAI) prescribed by the ASTM C311 (ASTM, 2002). The PSAI helped in analysing pozzolanic reaction of the co-fired mixtures whereas compressive strength test was used to optimize the co-fired mixture. $^{29}$Si and $^{27}$Al MAS NMR were used to investigate the hydrates formed from the hydration process involving the Portland cement and the cementitious binder pastes. The durability of the cement system containing the calcined pozzolan was based on sorptivity and shrinkage which included autogenous and drying shrinkages. For sorptivity, the pore system of the cement paste in a matrix is the principal feature that relates to transport of water or sorptivity (Dhandapani et al., 2018). Therefore, mortar was formulated and used as a model to understand moisture movement (sorptivity) and shrinkage in concrete. The formulation of mortar was based on the optimum mixture proportion obtained from the results of compressive strength.

2. Materials and methods

2.1. Materials
The materials that were used for the study included Portland cement, clay, water reducer, rice husk, sand and potable water. The Portland cement was an ASTM type 1/11 and was obtained from Ash Grove Cement Company, United States. The clay was obtained from a village, Nyamebekyere in
the Ashanti Region of Ghana. Rice husk was obtained from a rice milling plant at Konongo also in Ashanti Region of Ghana. Grade sand that conformed to ASTM C778 (ASTM, 2006) was used. A polycarboxylate high range water reducer (HRWR) obtained from BASF, United States was also used. Table 1 shows the chemical and mineralogical compositions of the Portland cement.

2.2. Methods

2.2.1. Preparation and calcination of clay-rice husk mixtures

The clay was preconditioned by drying and milling in a hammer mill to sizes ranging between 75 microns and 2 mm. The rice husk was used to replace the powder clay at 2, 1.5 and 1% by weight and mixture used to formulate pellets of sizes ranging between 1 and 3 mm. The pellets containing rice husk content of 2, 1.5 and 1% were labelled as RH1, RH2 and RH3, respectively. The pellets were placed in a ceramic bowl having a diameter of 120 mm and depth of 90 mm and calcined in a laboratory furnace (Barnstead Thermolyne 6000 furnace) at 800°C for 3 h. The 800°C temperature, was used because the clay obtained from this area of Ghana attained maximum Pozzolanic reactivity index at this temperature (Bediako, Kevern et al., 2017). After the 3hrs, the ceramic bowl was removed from the furnace and left to cool on a metallic mesh under room temperature. The calcined materials were milled in a laboratory mill and sieved through 75 microns sieve size using a mechanical sieve shaker. The chemical composition of the calcined material (Clay-RH) is shown in Table 1. Figure 3 shows samples of the calcined clay-rice husk pellets.

2.2.2. Compressive strength and pozzolanic strength activity index

Pozzolanic strength activity index (PSAI) was determined by preparing mortar specimens in accordance with ASTM C109 (ASTM, 2007a) standard. The Pozzolanic Strength Activity Index (PSAI) determination was also guided by the ASTM C311 where replacement of Portland cement is specified at 20% by weight. The standard, ASTM C109 (ASTM, 2007a) specifies the ratio of cementitious binder to sand at 1:2.75 and a water to cementitious binder ratio at 0.485. Mixing of materials was performed in a Hobart mixer in accordance with ASTM C305 (ASTM, 2014a). Flow measurements were performed using the mortar flow table and measurement of the mortar spread by the digital caliper in accordance with ASTM C1437 (ASTM, 2007b). The polycarboxylate-based HRWR was used to achieve the flow of the

| Table 1. Properties of Portland cement |
|--------------------------------------|
| **Property**                     | **PC** | **Calcined Clay-RH** |
|-----------------------------------|--------|-----------------------|
| **Physical**                     |        |                       |
| Fineness (m²/kg)                  | 401.70 | 420.00                |
| Specific gravity                  | 3.13   | 2.61                  |
| **Chemical**                     |        |                       |
| SiO₂ (%)                         | 20.49  | 61.89                 |
| Al₂O₃ (%)                        | 4.26   | 13.51                 |
| Fe₂O₃ (%)                        | 3.14   | 5.84                  |
| CaO (%)                          | 63.48  | 0.21                  |
| MgO (%)                          | 2.11   | 1.74                  |
| SO₃ (%)                          | 2.90   | 0.14                  |
| Na₂O+K₂O (%)                     | 0.49   | 1.21                  |
| LOI (%)                          | 2.20   | 10.00                 |
| **Mineralogy**                   |        |                       |
| C₃S (%)                          | 56.00  |                       |
| C₃S (%)                          | 15.00  |                       |
| C₃A (%)                          | 6.00   |                       |
| C₆AF (%)                         | 9.00   |                       |
mortars that contained the calcined materials. Mortar specimens that attained the desired flow were cast in a 50 mm cube three gang metallic mould. The mould and content were cured under a plastic sheet and a wet burlap cover for 24hrs. After the 24hrs, the mortar specimens were demoulded and cured in water containing lime. PSAI was performed on mortar specimens cured at 7 and 28 days whereas the compressive strength on mortar specimens was measured at 3, 7 and 28 days. Strength determination was taken as the average of three specimens.

2.2.3. Si and $^{27}$Al MAS NMR
Tecnmag Apollo Console (Houston, TX) with 8.45 T magnet and homebuilt, single channel, 4 mm wide-bore NMR probe was used to determine $^{27}$Al and $^{29}$Si spectra. About 90 mg of a sample was taken for each analysis and signal represented as chemical shift value; δ: ppm. The $^{27}$Al and $^{29}$Si Larmor frequencies were 93.074 MHz and 70.958 MHz, respectively. $^{27}$Al spectra were acquired with MAS spinning frequency, last delay and 90º pulse length of 8 KHz, 1s and 2.5 μs respectively. $^{29}$Si spectra were acquired with MAS spinning frequency, last delay and 60º pulse length of 8 kHz, 20s and 5.5 μs respectively. Aluminum nitrate [Al(NO$_3$)$_3$] and Tetramethyl silane (TMS) were used as reference compounds for $^{27}$Al and $^{29}$Si spectra, respectively. All experiments were performed at ambient temperature without any corrections for sample heating.

2.2.4. Sorptivity
Water sorptivity determination was performed in accordance with ASTM C1585 (ASTM, 2014b). The principle behind sorptivity states that if a mortar or concrete surface is exposed to wetting by water, then during the initial absorption period (S), the cumulative water absorption (i) is proportional to the square root of elapsed wetting time (t) (see Equation 1). An average of three mortar specimens were used for the absorption calculations. The ratio of gain in mass per unit area to the density of water was plotted versus the square root of the elapsed time (t). The slope of the line of best fit of these points was taken as the sorptivity value.

$$ i = S \sqrt{t} $$  \hspace{1cm} (1)

2.2.5. Drying and autogenous shrinkage
The shrinkage tests were determined in accordance with ASTM C596 (ASTM, 2017) standard test on mortar specimen. Mortar samples were prepared to achieve a flow of 110 ± 5%. For the cement-blended mortars, the desired flow was achieved with the aid of HRWR (Glenium 7500). Six mortar samples were cast in 25 by 25 by 285 mm prismatic moulds. The specimens were covered with a transparent plastic sheet and a moist burlap to prevent evaporation. After 24 hours of moist curing,
samples were demoulded and cured in a water bath for 48 h. Mortar specimens designated for the drying shrinkage test were placed under curing water for 72 hours after which their dimensions were recorded. On the other hand, specimens designated for autogenous shrinkage were sealed with wax and placed in an environmental chamber maintained at 23°C and 50% relative humidity. The unsealed samples after lime water curing were also exposed to the conditions in the environmental chamber. Length measurement of both the sealed and unsealed mortar prisms were recorded at 4, 7, 11, 18 and 25 days of exposure in the chamber.

2.2.6. Estimation of embodied carbon

The estimation of the embodied carbon emissions considers all the carbon output of the mortar constituents per cubic meter of the control and optimum mortar mix (30RH1). The computation of the embodied carbon was based on Equation (2).

\[ EC = \sum_{i=1}^{n}(CMQ \times EEC) \]  

(2)

Where EC = Embodied energy; CMQ = mass of the ith type material; EEC = Embodied carbon coefficient of the ith material.

This method of computing embodied energy of materials has been used by many researchers including Kumanayake et al. (Kumanayake et al., 2018) and Chau et al. (Chau et al., 2015).

3. Results and discussions

3.1. Pozzolanic strength activity index (PSAI)

Figure 4 shows the strength activity indices of the control and the co-fired pozzolanic incorporated mortars. ASTM C618 (ASTM, 2012) specifies that the activity of mortars containing pozzolans at 7 and 28 days must not fall below 75% represented by the line labelled as minimum (min). The activity of the calcined clay and rice husk were normalized against the control mortar represented by the line labelled as maximum (max). All the pozzolan mortars met the ASTM standard as indicated by the grey line. From the figure, all the co-fired materials attained mortar strength activity indices higher than the control. The maximum strength activity for all the mortars was recorded by RH1 (98% clay and 2% rice husk). The improvement of the strength activity index of RH1 could be attributed to the extra pozzolanic effect imparted on the calcined clay from the rice husk ash.
3.2. Compressive strength

Table 2 presents the mix proportions of the control and the blended mortars. The labelling of the cement and pozzolan mixes were 10RH1, 20RH1, 30RH1 and 40RH1 which represented the replacement of cement with clay by 10 to 40%. The table shows that as the pozzolan content increased from 0 to 40%, the content of the chemical admixture (HRWR) required to achieve the appropriate flow of the mortar also increased. The inclusion of the calcined materials altered the specific gravities of the various mixes. The specific gravities of the control, 10RH1, 20RH1, 30RH1 and 40RH1 of the co-fired material were 3.15, 3.08, 3.01, 2.94 and 2.84, respectively.

Figure 5 shows the results of the compressive strength of mortars; control and the mixtures-10RH1, 20RH1, 30RH1 and 40RH1. The early age strength at 3 and 7 days of 10RH1, 20RH1 and 30RH1 were all higher than the control mortar except 40RH1. However, at 28 days, all the mortar mixture proportions attained compressive strengths which were higher than the control mortar. From Figure 5 it is observed that the 20RH1 and 30RH1 have similar compressive strength at the various curing periods. The student t-test performed between 20RH1 and 30RH1 show a statistically insignificant predictive value (p = 0.67). The preferred replacement content for Portland cement is 30RH1. The reason is that at higher supplementary cementitious content utilization, there are reductions in embodied energy and cost of the binder (ASTM, 2012).

3.3. Al and ²⁹Si MAS NMR

Figure 6 shows the ²⁷Al MAS NMR spectra analysis of the control and the clay-RH binders at 3, 7 and 28 days. The figures show two distinct chemical shift which occurred around 68 ppm and 7.8 ppm. Chemical shift around 68 ppm shows Al substitution in the calcium silicate hydrate (CSH) in the tetrahedral environment of Al, a metastable form of hydrogarnet or calcium aluminosilicate hydrate (CASH) (Andersen et al., 2003; Marceau et al., 2007). The chemical shift around 7.8 ppm corresponds to thermodynamically stable monosulphates (AFm) which occur in the Al(⁴⁶)

Table 2. Mortar mix proportions of control and blended cement mortars

| Material   | Mortar mix proportion |
|------------|-----------------------|
|            | Control 10RH1 20RH1 30RH1 40RH1 |
| Cement (g) | 235.00 211.50 188.00 164.50 141.00 |
| Clay (g)   | 0.00 23.50 47.00 70.50 94.00 |
| Sand (g)   | 646.25 646.25 646.25 646.25 646.25 |
| water (g)  | 113.98 113.98 113.98 113.98 113.98 |
| HRWR (g)   | 0.00 0.57 0.71 1.49 1.59 |

Figure 5. Compressive strength of mortars.
environment (Chenguang et al., 2014; Skibsted et al., 1993). The intensities at the octahedral environment were 94% at 3 days and 99% at both 7 and 28 days. This shows that the hydration progressed from 3 days to 7 and 28 days with an increased aluminium phase in the tetrahedral environment that dissolved in solution into the octahedral environment due to the presence of the
pozzolanic material. The dissolution from the unstable tetrahedral to stable octahedral environment indicates the occurrence of pozzolanic reaction. Anderson et al. (Andersen et al., 2006) have indicated that usually the stable phase formed in the octahedral environment is stratlingite (C₆A₆H₆), a known stable monosulphate phase. The formation of the monosulphate phase in that environment also indicates the substitution of Al³⁺ for Si⁴⁺ to form calcium aluminosilicate hydrates. Chenguang et al. (Andersen et al., 2003) mentioned that Al³⁺ substitution for Si⁴⁺ promotes the stability of calcium silicate hydrates. The increase in stable compound in the aluminophase in the CSH structure explained the reason for the higher strength of clay-RH pozolzan more than the control.

Figure 7 presents the $^{29}$Si MAS NMR of the control and 30RH1 hydrated pastes at 3, 7 and 28 days. The figures (A, B and C) show two spectra representing the hydrated samples. At 3 days, both spectra showed a chemical shift at −89.7 ppm and −109.1 ppm. The shift at −89.7 ppm could indicate partly a Q² and Q³ (1Al) unit similar to the shift found in the studies of Xiaoming et al. (Andersen et al., 2003). At this chemical shift Al³⁺ enters the C-S-H structure forming an aluminium rich compound called gehlenite (Xiamong et al., 2011). The incorporation of 30RH1 in the Portland cement partially responded to pozzolanic reaction after 3 days, which is indicated as a slightly intensified peak on the 30RH1 spectra. At 7 days (Figure B), the two spectra of the control and 30RH1 show a chemical shift at −90.7 ppm and −109.1 ppm. The figure also shows a slight chemical shift from −89.7 ppm at 3 days to −90.1 ppm at 7 days, which is indicative of an increase in polymerization with time. The 30RH1 spectrum shows the formation of an additional peak at −109.1 ppm which could be attributed to the effect of pozzolanic action (C-S-H formation). After 28 days of hydration, there was a slight shift from −90.1 ppm at 7 days back to −89.7 ppm (see Figure C). This indicates a decrease in the crystallinity of the C-S-H content in the Q² and Q³ units. The increase in polymerization was confirmed with the slight shift from −109.1 ppm at 7 days to −109.5 ppm at 28 days on the control spectrum. The chemical shift from −109.1 ppm at 7 days to −112.3 ppm at 28 days as well as the formation of an additional chemical shift at −122.8 ppm (O₄(1Al)) unit confirmed that the addition of calcined clay to cement caused a significantly enhanced polymerized material. This also shows that pozzolanic reaction occurred and caused an increased strength of 30RH1 more than the control.

3.4. Sorptivity
Figure 8 presents the rate of water absorption of the Portland cement (Control) and the clay-rice husk pozolzan (30RH1) mortars. The initial (Si) and the secondary sorptivity (Ss) coefficients of the control mortar were 0.0299 and 0.0083 mm/s$^{1/2}$ respectively. For 30RH1 pozolzan mortars, the Si and Ss are 0.0055 and 0.0022 mm/s$^{1/2}$ respectively. The coefficient of determination ($R^2$) of the linear regression model namely Si (CON), Si (Clay-RH), Ss (CON), Ss (Clay-RH) were approximately 0.96, 0.87, 0.93 and 0.97, respectively. The r-squared values indicate a strong relation between the dependent and independent variables.

The results from Figure 8 show that both the initial and the secondary coefficient values of the 30RH1 mortars were lower than the control mortars. Low sorptivity values of the 30RH1 pozolzan indicate that the binder slows down the rate of ingress of moisture into the mortar and therefore could be used to produce good concrete. This result falls in line with the investigations of Khatib (Khatib, 2004) and Dhandapani et al. (Dhandapani et al., 2018) who also recorded lower sorptivity and absorption on their studies on pozolanzs.

3.5. Drying and autogenous shrinkage
Figure 9 shows the results of the drying shrinkage characteristics of the Control and the 30RH1 mortars. It is a plot of strain (%) versus exposure period in days. A student t-test performed between the two mortar mixes gave a predictive value (p) of 0.33 meaning the difference between the shrinkage values is insignificant. This shows that the inclusion of the pozzolanic material will behave the same way like the Portland cement to restrain shrinkage.
Figure 7. $^{29}$Si MAS NMR spectra of control and 30RH1 paste; A- 3 days, B- 7 days, C- 28 days.

Bediako et al., Cogent Engineering (2020), 7: 1811453
https://doi.org/10.1080/23311916.2020.1811453
Figure 8. Rate of water absorption of Portland cement and clay-RH pozzolan.

Figure 9. Drying shrinkage of Portland cement and Clay-RH pozzolan mortars.

Figure 10 shows the results of the autogenous shrinkage of the Portland cement and blended cement mortars. A student t-test was performed between the values of the control (CON) and the blended (Clay-RH) mortars at a critical value of 0.05. The predictive (p) value was 0.99 meaning the difference between the average values of the two mortar mixes was also insignificant. The results of the autogenous shrinkage performance indicated that the inclusion of the calcined pozzolan could be used in place of Portland cement.

The autogenous and the drying shrinkage performance of the clay-RH pozzolan mortar could be attributed to the formation of adequate hydrates. Gleize et al. (Gleize Philippe et al., 2007) and Itim et al. (Itim et al., 2011) have stated that the formation of extra hydrates usually makes mortars less deformable and hence restrain shrinkage.

3.6. Embodied carbon estimation

Table 3 shows the embodied carbon of the materials contained in the mortars. The bill of activities to produce a cubic meter of the mortar is also shown in Table 4. The table shows that the inclusion of co-fired material in a cubic meter of mortar-reduced cement content by 31% and both water and sand content by 2%.
Figure 10. Autogenous shrinkage of Portland cement and Clay-RH pozzolan mortars.

Table 3. Embodied carbon of concrete constituents

| Material                  | Carbon equivalent (kgCO₂eq/kg) | Reference                      |
|---------------------------|---------------------------------|--------------------------------|
| Portland cement           | 0.9500                          | (Hammond & Jones, 2008)        |
| Sand                      | 0.0021                          | (Hammond & Jones, 2008)        |
| Superplasticiser          | 0.7670                          | (Zhou et al., 2017)            |
| Calcined clay pozzolan    | 0.0700                          | (Zhou et al., 2017)            |
| Water                     | 0.0010                          | (Barcelo et al., 2014)         |

Table 4. Mass content per cubic meter of control and blended mortars

| Material      | Control       | 30RH1   |
|---------------|---------------|---------|
| Cement (g)    | 540.00        | 371.00  |
| 30RH1 (g)     | 0.00          | 159.00  |
| Sand (g)      | 1485.00       | 1457.50 |
| Water (g)     | 261.90        | 257.05  |
| HRWR (g)      | 0.00          | 3.37    |

Table 5. Embodied carbon of control and blended mortars

| Material      | Embodied Carbon (kgCO₂eq) |
|---------------|---------------------------|
|               | Control       | 30RH1   |
| Cement        | 513.00        | 352.45  |
| Clay          | 0.00          | 11.13   |
| Sand          | 3.12          | 3.06    |
| water         | 0.00          | 0.00    |
| HRWR          | 0.00          | 2.58    |
| Total EC      | 516.12        | 369.23  |
Table 5 presents the estimated embodied carbon values per cubic meter of the control and the blended cement mortars. The embodied carbon (EC) content of the control mortar was approximately 516.00 kgCO₂ eq whereas the blended mortar (30RH1) was also approximately 369.23 kgCO₂ eq. The incorporation of 30% content of pozzolan reduced the greenhouse gases by approximately 29%. In essence, the inclusion of the pozzolan could be a means of decarbonizing mortar which could be very beneficial to the environment since it is already known that greenhouse gases are the major cause of global warming.

4. Conclusions
The studies determined the mechanical and durability properties of co-fired clay and rice husk pozzolan. Pozzolanic strength activity index and compressive strength test were used to determine the pozzolanic reactivity and optimum-calcined material, respectively. ²⁹Si and ²⁷Al MAS NMR were used to determine the silicate and aluminic environments of the optimum hydrated paste and compared with the control. The durability studies used in this study were water sorptivity and drying shrinkage. From the results of the study the following conclusions were made:

1. Co-fired material that contained 2% of rice husk content and labelled as RH1 gave an optimum pozzolanic strength activity index of 118% and 116% at 7 and 28 days respectively. The recommended ASTM C618 value at 7 and 28 days is a value greater than 75%.
2. The optimum Portland cement replacement using the co-fired material was at 30%. This could be attributed to the reactivity of the calcined material with Portland cement forming extra cementitious hydrates that enhanced strength properties.
3. The formation of secondary calcium silicate/aluminate hydrate confirmed from the ²⁹Si and ²⁷Al MAS NMR studies was the major contributing factor to the higher strength performance of the 30RH1 mortar than the control.
4. For the clay pozzolan industry, the rice husk biomass could be treated as useful resource since it does not compromise the pozzolanic nature of calcined clay.
5. The sorptivity studies showed that clay-rice husk pozzolan recorded initial and secondary sorptivity values of 0.0055 and 0.0022 mm/sec¹/², which are lower than the Portland cement values of 0.0299 and 0.0083 mm/sec¹/². This shows that the binders prepared using clay-rice husk pozzolan could produce good and an enhanced durable concrete.
6. The shrinkage properties, both drying and autogeneous of the two binders, Portland cement and clay-rice husk pozzolan indicated that there is significant difference between the two binders.
7. The inclusion of the co-fired pozzolan reduced the estimated carbon equivalence from approximately 516.12 kgCO₂ eq to 369.23 kgCO₂ eq which represented about 29% reduction from the control mortar.

Funding
This work was supported by the No fund [No number].

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Citation information
Cite this article as: Compressive strength and durability properties of pozzolan obtained from co-fired clay and rice husk, Mark Bediako, Albert A. Adjaottor, Simon K.Y Gawu & Eric Opoku Amankwah, Cogent Engineering (2020), 7: 1811453.

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