Evaluation of Water Absorption and Abrasion Resistance of Binary Waste Binder Based Mortar

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Abstract

This paper presents the durability performance of mortar with respect to water absorption and abrasion resistance using sorghum husk ash (SHA) and calcium carbide waste (CCW) as binder. The study investigates the use of sorghum husk ash (SHA) as silica (SiO_2) source and calcium carbide waste (CCW) as lime (CaO) source. SHA which is an incinerated ash from agricultural by-product of guinea corn husk with major component of amorphous silica (SiO_2) while CCW is an industrial by-product generated from an acetylene gas production process with major component of lime (CaO). The mortar specimen of combination proportion of SHA/CCW of 70/30, 60/40, 50/50, 40/60 and 30/70 binder were examined for water absorption and abrasion resistance at 28, 56 and 90 days curing ages. Paste from different binder combinations of SHA/CCW were studied for setting time, soundness while the mortar samples were used to study the long term strength development, water absorption and abrasion resistance. The study revealed the SHA sample to be of high SiO_2 (84%) and CCW is majorly CaO (66% content). The results obtained showed performance of binders formulated from 70/30 SHA/CCW having 90 days average compressive strength of 8.0 N/mm^2 representing 37% of the control. However, mortars from the various proportion of SHA/CCW combinations satisfied the basic requirements for classes N and O mortar as specified by ASTM C270 2(002). The average water absorption of mortar sample of 70/30 SHA/CCW at 90 days is 13.9% which is about twice that of the control (6.4%). The average abrasion resistance of mortar sample of 70/30 SHA/CCW at 90 days is 88.8% which is about four times higher than control specimen, PCM (20.2%).

Keywords:* *Binder, Mortar, Calcium carbide waste, Sorghum husk ash, Water absorption, Abrasion resistance.

Introduction

Portland Cement (PC) is an essential constituent in the mortar and concrete composite. PC is made by a process known as calcination of calcium carbonate, which has to do with decomposition of limestone resulting in lime (CaO) and CO_2 as the end product (Neville, 2012; Mehta and Monteiro, 2014). In any case, it has been noticed that 5% of CO_2 emission worldwide is from cement production, which imply that cement industry is a major producer of CO_2 (Rubenstein, 2012). The clinker manufacturing process in the cement industry is known to add to the greenhouse effect through the release of CO_2 gas into the atmosphere (Mehta and Monteiro, 2014). Global warming attributed to climate change has become an important worldwide problem due to increasing quantities of greenhouse gases in the atmosphere (Nattapong et al., 2010). In recent years, research and development of alternative binders to PC is constantly in the forefront due to the increased awareness on climate change attributable to global warming. Stratospheric ozone depletion and climate change resulting from emission of greenhouse gases (GHG) due to human and industrial activities with chlorofluorocarbons (CFC) and non-CFC gases such as carbon (IV) oxide (CO_2), adjudged the primary gas emitted (Waterloo News, May, 2013; US National Climate Assessment (NCA), 2014; US Environmental Protection Agency, 2016). This coupled with constant excavation and depletion of lime stone ($CaCO_3$) from their natural sources has resulted in research for alternative materials with focus on re-use and recycling of the abundant agricultural and industrial waste materials.

To address this issue, cement manufacturers have attempted to reduce Portland cement consumption by using supplementary cementitious materials, such as fly ash and natural Pozzolan in producing cement binder (Gartner 2004; Damtoft et al. 2008). Some of agricultural and industrial waste ash which was satisfied the criteria as supplementary cementitious materials are rice husk ash, fly ash and metakoalin etc.

Sorghum husk ash is an agricultural waste acquired from milling of sorghum husk. Incinerated ashes from SHA at controlled temperature have been found to be pozzolanic with major components been amorphous silica which combines with lime in the presence of water to give cementitious properties (Olawuyi*et al.*, 2017).

Calcium carbide waste (CCW) is by-product of acetylene gas generated from calcium carbide used in the production of Polyvinyl Chloride (PVC) and in welding steels especially in the auto industry. The calcium carbide residue is produced by a simple process, which is acquired from the chemical reaction between calcium carbide (CaC_2) and water (H_2O) according to the following equation:

$$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2 \quad (1)$$

CCW in Nigeria is reported to be 70-80% calcium hydroxide ($Ca(OH)_2$) with the impurities in it listed as copper, lead, iron, manganese, nickel and zinc (Chukwudebelu*et al.*, 2013).

Pozzolans by definition are siliceous or siliceous and aluminous materials, which in finely divided form and in the presence of moisture, can react with calcium hydroxide $Ca(OH)_2$ in cement paste to form additional calcium silicate hydrate (C–S–H) (ACI Terminology of Concrete, 2013 in ACI Manual of Concrete, 2016; Neville, 2012). Since calcium carbide residue is rich in $Ca(OH)_2$, it is assumed that it can react with siliceous or siliceous sand aluminous materials in pozzolans containing high silica (SiO_2) resulting in formation of CaO-SiO_2-H_2O – Calcium Silicate Hydrate (C-S-H) which is the final product for strength development.

The idea of Pozzolanic reaction according to Mehta and Monteiro (2014) is based on the fact that Portland cement react using Tricalcium Silicate (C_3S) with water (H) to give Calcium-Silicate-Hydrate (C-S-H) and Calcium Hydroxide (CH)

$$C_3S + H \rightarrow C - S - H + CH \quad (2)$$

and the Portland-Pozzolan cement reaction follows as

$$Pozzolan + CH + H \rightarrow C - S - H \quad (3)$$

Where C = CaO, S = SiO_2 and H = $(OH)^-$

The reaction in Equation 2 is known to be fast and lime producing while the reaction in Equation 3 is rather slow or latent depending on the properties of the pozzolanic material. The pozzolanic reaction in (Equation 3) is basically lime-consuming and does not necessarily require presence of cement but an active source of lime, hence the thought for alternative source of lime to enhance pozzolanic reaction with an agricultural waste ash as Silica source.

Previous studies on the search for alternative binders centred on utilisation of natural Pozzolan such as volcanic ash (Hossain 2003 & 2005; Hassan, 2006; Olawuyi, 2011) or ashes from agricultural wastes (agro-wastes) such as rice husk ash [RHA] (Okpala, 1987; Chaowat, 2001; Abalaka & Okoli, 2013), corn-cob ash [CCA] (Raheem, 2010), sawdust ash [SDA] (Elinwa & Mahmood, 2002), millet husk ash [MHA] (Jimoh et al, 2013;) and palm kernel nut ash [PKNA] (Joshua et al, 2015) amongst others as partial PC replacement in mortar or concrete.

Attempt on total cement replacement in concrete brought about studies into geo-polymer concrete which involve alkali activation of Pozzolanic materials with the use of chemical based hydroxide [NaOH] at elevated temperatures or ambient temperature (Ul. Haqet. al, 2014; Turner and Collins, 2013). Some studies on total cement replacement with Pozzolan in combination with alternative CaO source (calcium carbide waste [CCW]) include the works of Rattanashotinuntet. al. (2013) – baggase ash combined with CCW; Makaratatet. al. (2010) - combining fly ash (FA) and CCW. Joshua et al (2016), combining pulverized calcined clay (PCC) with CCW, both sourced within Nigeria and reported observed hydration reaction with a 28 day strength of 11 MPa without any treatment on the CCW.

Previous attempt reported by Olawuyi et al., (2017) focus on exploratory study of SHA-CCW binder as total replacement of cement but durability properties of SHA-CCW binder were not study. A research into performance of mortar on water absorption and abrasion resistance using SHA and CCW as binder will surely offer contribution towards improving knowledge in concrete technology and infrastructural development.

Materials and Method

2.1 Materials

The materials used in this research were Ordinary Portland cement (OPC) classified as CEM I with 42.5 MPa strength served as the binder for the control in the mortar production. Sorghum hush ash (SHA), calcium carbide waste (CCW), fine aggregate, water and superplasticizer were also components of the materials in this research work.

2.1.1 Sorghum Husk Ash

Sorghum husk was collected from a Bosso Local Government Area, in Niger State, Nigeria. The husks were burnt in open air with a locally fabricated incinerator presented earlier in Abalaka (2013). This was grounded to finer particles in a local mill and sieved with a 75 µm sieve. The final process materials were stored in air-tight polythene bag.

2.1.2 Calcium Carbide Waste

The CCW on the other hand was obtained from a local automobile Welder's (i.e. "Panel-beater" using oxy-acetylene gas) workshop in Minna as sludge form. It was sun-dried and grounded to finer particles in a local mill and sieved with 75 µm sieve. The final process materials stored in air-tight polythene bag.

2.1.3 Fine Aggregate

The fine aggregate used is the simulated reference sand (size range 1.18 mm to 75 µm) sieved out from the available natural sand in consonance with BS EN 196-1:1995 reference sand prescription for strength test on cement (binder).

2.1.4 Water

Potable water available at the Building Laboratory of the Federal University of Technology, Minna was used for mortar production.

2.1.5 Superplasticizer

The superplasticizer used in this study is Master Glenium ACE 456 a high range water reducer.

2.2 Methods

The study involved the determination of physical and chemical properties of the binder materials used in production of the mortar samples. The fresh and long term hardened properties of binder paste were also determined for the mortar samples.

Mortar mix proportion of 1:3 OPC/sand ratio with 0.5 water/cement (w/c) ratio as specified by BS EN 196-1:1995 were used as control and designated as PCM while alternative binders of varied proportion combinations of 70/30, 60/40, 50/50, 40/60 and 30/70 of SHA/CCW, respectively were used as replacement for OPC. These varied proportions were prepared and tested for strength and durability properties at a curing ages of 28, 56 and 90 days.

2.2.1 Particle size distribution of fine aggregate

Particle size distribution of the natural sand was conducted using the dry-sieve approach in accordance to BS EN 933-1:1995. The reference sand required for mortar production in strength determination test specified in the standard (BS EN 196-1:1995) was then extracted using an arrangement of sieve size 1.18 mm and 75 µm. The particles passing the 1.18 mm sieve but retained on the 75 µm sieve was used for the mortar mixture for the strength test. The 1.18 mm sieve was adopted as the upper limit value for the simulated reference sand instead of the 1.6 mm sieve specified by BS EN 196-1:1995 because of non-availability of the 1.6 mm sieve in the laboratory. Figure 1 of Section 3.1 present the particle size distribution of both the natural sand and the simulated reference sand.

2.2.2 Physical properties of binder

The physical properties determined for all the binder materials used in this experiments are specific gravity, which was carried out in accordance with BS EN 1097: 2003 and pH of binders.

2.2.3 Chemical Analysis

X-Ray Fluorescence (XRF) analysis for determination of the oxide composition was conducted on the cementitious materials (OPC, SHA and CCW) at Works Department of Lafarge Cement Company using XRF Analyser connected to a computer system for data acquisition.

2.2.4 Setting time and soundness of binders

The initial and final setting times and the Le Chatelier soundness tests for the OPC binder and the various proportion combinations of SHA/CCW) were determined using neat pastes of standard consistency in accordance with BS EN 196-3:2016. This involved determining the water content of the paste which will produce the desired standard consistency (Neville, 2012). Vicat apparatus was used for measurement of consistency, initial and final setting times. The soundness test was carried out on the respective binders using a Le Chatelier apparatus and results were presented and analysed.

2.2.5 Strength test

The strength of the mortar samples were conducted using 50 mm mortar cubes as specified in BS EN 196-1:1995 standard. The constituent materials were thoroughly mixed before casting into the 50 mm cubes moulds. The samples were left covered with jute bags and cured by water sprinkling until 72 hours before demoulding and water curing by immersion made to continue until testing age.

2.2.6 Water absorption test

The mortar samples were removed from the curing tank and allowed to dried, then placed in the electronic oven to an oven dried at 105 °C for 72 hours. Then the samples were removed from the oven and allowed to cool at room temperature and weighed to determine the initial weights and the values were recorded as *w1*. The final weights were determined after immersing the mortar samples in the curing medium for 30 minutes then removed and clean the surface with cloth, dried and re-weighed again and the value was recorded as *w2*. The values obtained were recorded and the results were calculated to assess the rate of absorption of the mortar specimens in accordance with BS 1881-122 (2011).

$$\text{Water Absorption} = \frac{(w2-w1)}{w1} \times 100 \quad (4)$$

2.2.7 Abrasion resistance test

The mortar samples for the abrasion test were removed from the curing container and allowed to surface dried and clean, then dry it in an oven at 105°C to 110°C weighed and the values were recorded as w1. Then the mortar sample was placed into the Los Angeles abrasion testing machine along with the required steel balls and rotate the steel cylinder at a speed of 30 – 33 revolutions/minute for 500 – 1000 revolutions and sample were removed and pour into 1.7mm sieve and weigh the material that passing through 1.7mm and the value was recorded as w2. The values obtained were recorded and the results were calculated to assess the abrasion resistance of the mortar specimens in accordance with ASTM – C131 (2014) and AASHTO – T96-02 (2015).

$$\text{Abrasion resistance test} = \frac{w2}{w1} \times 100\% \quad (5)$$

$$\text{Or Abrasion resistance test} = 100 - \frac{(w1-w2)}{w1} \times 100 \quad (6)$$

Where; w_1 is the mass weight of the sample
w_2 is the mass weight of fraction passing 1.70mm B.S sieve

3 Results and Discussion

3.1 Characterisation of the Constituent Materials

Figure 1 presents the particle size distribution (PSD) of the natural sand and the simulated reference sand used for the experiment. The PSD revealed the simulated reference sand to have a C_u and C_c values of 2.06 and 0.86 respectively and a Fineness Modulus (FM) of 2.56 indicating a fine sand according to Shetty (2009) classification of fine aggregate.

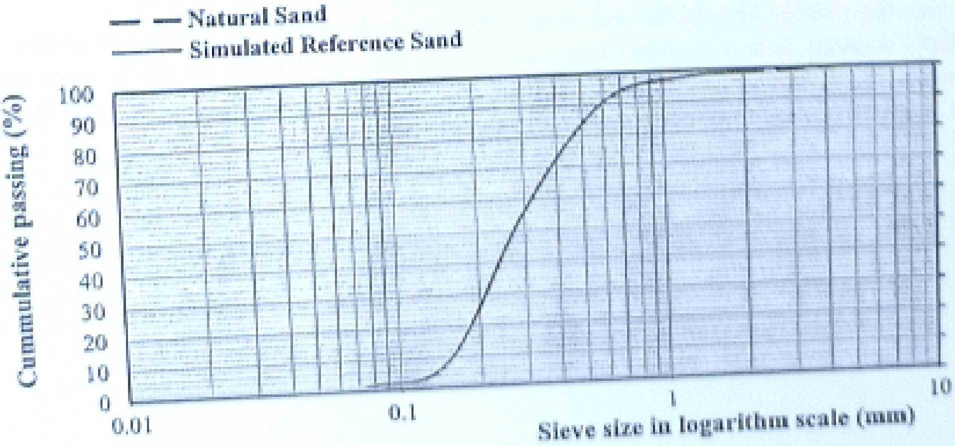

Figure 1: Particle Size

Distribution of Fine Aggregate

Table 1 present PSD of simulated sand in relation to BS EN 196-1:1995 sand for the determination of strength as compared to the simulated reference sand used. It was observed that the simulated reference sand was compliant to three of the six size requirements of the reference sand as prescribed in BS EN 196-1:1995. The simulated reference sand was used for the study despite the shortcomings of not meeting the other three requirements since the study is basically a comparative study on strength development of the alternative binder developed and the Ordinary Portland cement (OPC), but not product validation and certification of the cement. The strength of the mortar samples from OPC used in this study serve purely as a reference to which the strength of the alternative SHA/CCW waste binder was compared.
The specific gravity for the constituent materials is presented in Table 2. The specific gravity of the SHA and CCW are 2.32 and 2.29, respectively. These values were lower than that of OPC and therefore occupies more volume. The pH value for the constituent materials is also presented in table 3. The result indicates that the values for all the binders were alkaline in accordance with Fereshte et al., 2015.

Table 1: Particle size distribution of fine aggregate

Sieve opening (mm)	BS EN 196-1:1995 Reference Sand (%)	Simulated Reference Sand (%)	Remark
2.00	0	0	√
1.60	7 ± 5	0	
1.00	33 ± 5	3	
0.50	67 ± 5	16	
0.16	87 ± 5	92	√
0.08	99 ± 1	99	√

Table 2: Specific Gravity of Constituent Materials (kg/m^3)

Materials	Specific gravity
OPC	3.15
SHA	2.32
CCW	2.29
Sand	2.58

Table 3: pH value of Constituent materials

Materials	pH value
OPC	10.8
SHA	10.29
CCW	11.9

The chemical oxide composition of the various cementitious materials obtained through XRF is presented in Table 4. The SHA samples are majorly silica having 83% SiO_2 contents and classified as Class N Pozzolan as the total oxide I.e. SiO_2+Al_2O_3+Fe_2O_3 is above 70%. The SO_3 for SHA is below 4% and loss on ignition (LOI) is less than 10%. The CCW was observed to contain 66% CaO, while the control specimen, OPC has 64% of CaO content. It was further observed that the SiO_2 and Al_2O_3 for CCW were lower compared to the OPC sample. The LOI of CCW is above the specified 10% maximum, an indication that some heat treatment might be required for more effective performance of the material.

Table 4: Result of XRF Analysis for Oxide Composition of Cementitious Materials

SAMPLE	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	Mn_2O_3	Cr_2O_3	SrO	ZnO	LOI	$SiO_2+Al_2O_3+Fe_2O_3$
SHA	81.1	2.8	2.0	2.0	3.3	0.3	-0.1	5.1	0.6	1.2	0.1	0.0	0.0	0.1	3.3	85.8
CCW	5.6	1.7	0.3	61.4	0.1	0.2	-0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	30.8	7.6
OPC	21.5	5.2	1.2	64.0	2.9	4.5	0.6	0.0	0.1	0.2	0.0	0.0	4.5	3.4	0.0	27.8

3.2 Setting Time and Soundness of Binders

Table 5 presents the result of the consistency and soundness test conducted on the binder combinations and the control (OPC) specimens. The result show that the water demand of the SHA/CCW binders was twice of the control. The SHA/CCW binders reflect a higher water demand trend for similar penetration values. The higher the ash (i.e. SHA) content, the higher the water demands. This could be attributed to the fineness of materials that required higher water demand.

The soundness test presented in Table 5 revealed that all the binder combinations conform to the 10 mm maximum expansion specified by BS EN 197-1:2011. However, the soundness combination of 70/30 SHA/CCW is 3.0 which is higher than OPC. This could be attributed to the high quantities of Magnesia observed in SHA chemical content. Similar observation was reported by Neville, (2012).

Figure 2 present the Results of initial and final Setting time of Binders. The results revealed that the initial setting times of SHA/CCW binder combinations is three times higher than that of OPC. The final setting times of SHA/CCW binders were also about three times higher than the final setting time of OPC. This indicates that Pozzolan are of latent setting in nature and improvement on the binders can be geared towards accelerating the setting times which believed to enhance their strength development trends.

Table 5: Fresh Properties of Binders

Specimen	Consistency			Soundness Expansion (mm)
	Superplasticizer (g)	Water Demand (%)	Penetration (mm)	
OPC	0	36.8	5.0	2.0
SHA/CCW 70/30	3.71	59.2	6.0	3.0
60/40	3.71	56.8	5.0	2.5
50/50	3.71	53.2	5.0	2.5
40/60	3.71	50.4	5.0	1.5
30/70	3.71	49.6	5.0	1.0

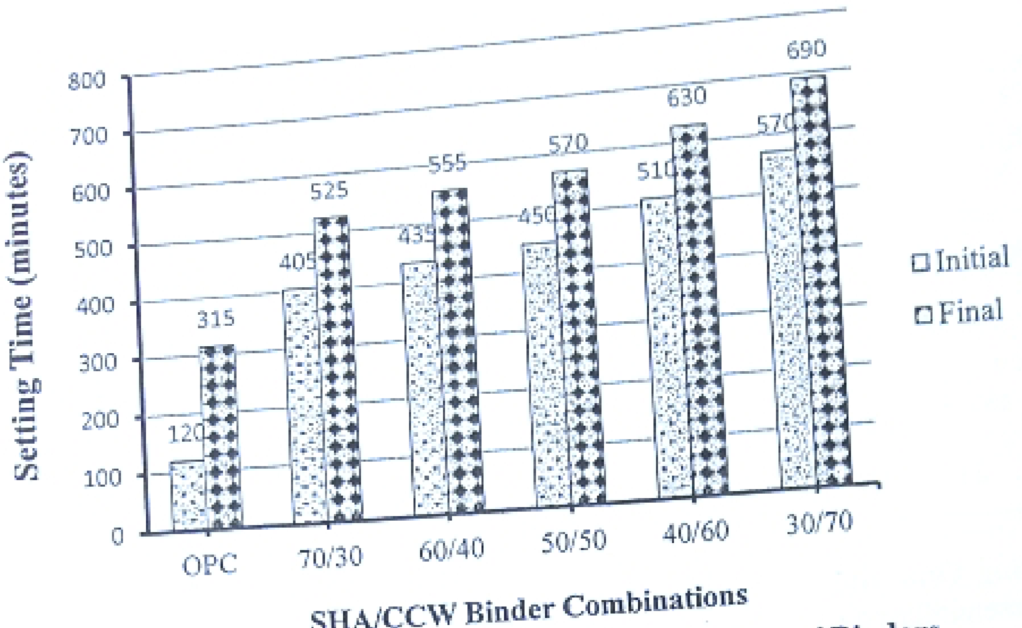

Figure 2: Results of initial and final Setting time of Binders

3.3 Compressive strength of Mortar specimens

Figure 3 present the results of compressive strength of the SHA/CCW binders and the control specimen (PCM). The long term strength (90 days) values for the PCM was observed to be about three time higher than SHA/CCW binders. The 90 days curing age compressive strength for SHA/CCW of 70/30, 60/40 and 50/50 were 8.0, 7.3 and 5.9 N/mm^2, respectively. These values were equivalent to 37%, 34% and 27% compared to PCM. The low strength can be adduced to the additional water used for the binders on basis of the water demand established from the result of the consistency test and the setting rate of SHA/CCW binders. This showed that SHA/CCW binder require improvement in further studies to use water reducers in other to keep the water/binder ratio to be same as for control and also engaging set accelerating mixtures to enhance the setting time.

Despite the low compressive strength of the SHA/CCW binders as observed in this study, the values fall into Type N and O of ASTM C 270 (2002) standard which specified that the mortar can be used in exterior and interior load-bearing walls and non-load bearing partitions.

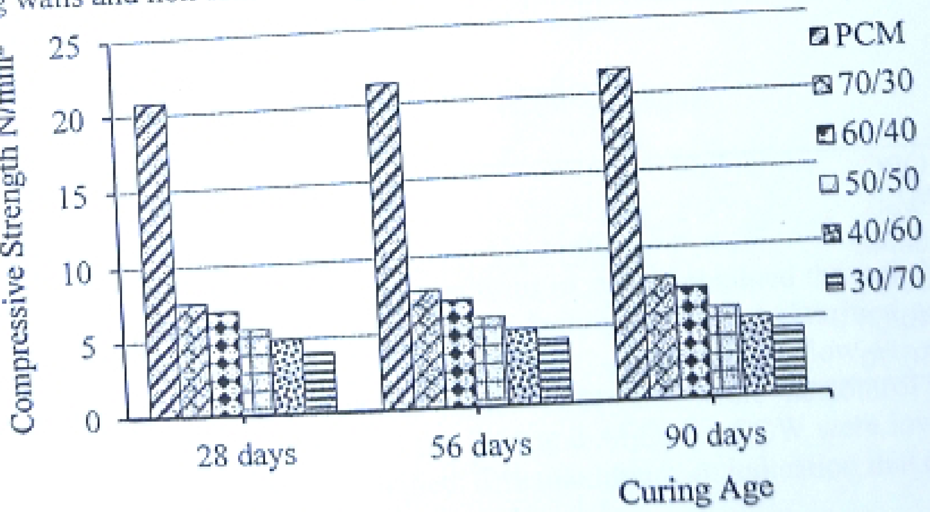

Figure 3: Compressive Strength of SHA/CCW Mortar

3.4 Water absorption

Figure 4 shows the result of water absorption test carried out on mortar made from OPC and SHA/CCW binder combination at respective curing of 28, 56 and 90 days. The results revealed an average value of 6.37% for PCM while 70/30, 60/40 SHA/CCW absorbed 13.92% and 14.21% at 90 days, respectively. The results revealed that both of them were within the limit of 20% specified by Rajput (2006) for building work but higher than 10% specified by Neville, (2012) for concrete water absorption. It was further observed that the quantity of water absorbed by binder combination of SHA/CCW is twice higher than the quantity of water absorbed by PCM. The quantity of water absorbed by binder combination of SHA/CCW decreased as the curing age increased. This could be attributed to the fineness of the materials.

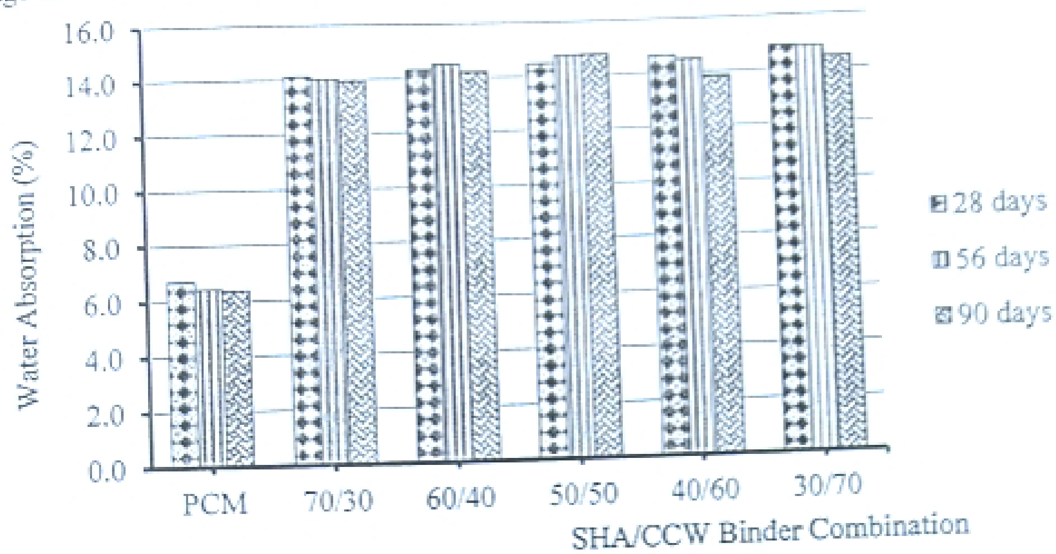

Figure 4. Results of Water Absorption of mortar binder

3.5 Abrasion resistance

Figure 5 represents the result of abrasion resistance test carried out on mortar for control specimen (PCM) and SHA/CCW binder combination specimens cured and tested at 28, 56 and 90 curing days. The results reveals an average mass loss of 20.20% for PCM while 70/30, 60/40 SHA/CCW is 88.83% and 88.99% at 90 days, respectively. It implied that PCM is about 4 times durable against wear effect to abrasion in comparison to SHA/CCW binder combination. This indicated that SHA/CCW binder combinations have higher values of mass loss while PCM exhibited negligible mass loss. It was further observed that there is a slight increase in abrasion resistance of 7% for SHA/CCW binder combination as the curing age increases. Notwithstanding, the durability values for SHA/CCW binder combinations with respect to water absorption and mass loss due to abrasion falls within the limit specified for type N and O mortar classes as prescribed by ASTM C270:2002.

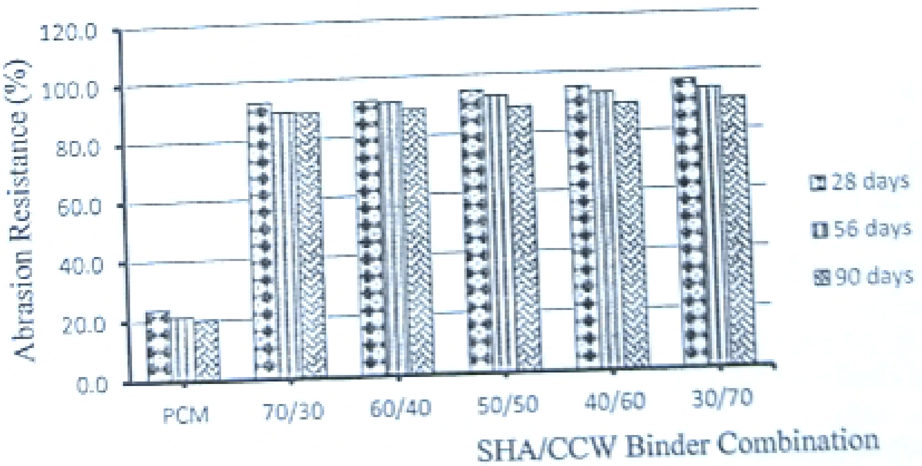

Figure 5. Abrasion resistance mortar binder

4.0 Conclusions

Based on the experimental findings, the following conclusions were highlighted:

1. The results from the study show that alternative binders from the SHA an agricultural waste combined with CCW of industrial waste possesses binding properties.
2. The chemical analysis of SHA indicated that it is classified as Class N Pozzolan with 83% SiO_2 content.
3. The CCW is a good source for CaO with percentage concentration of 66%.

4. The compressive strength of binder formulated from 70/30 SHA/CCW at 90 days is 8.0 N/mm^2 representing 37% of PCM strength, which could be used for Exterior wall mortar.
5. The mortar sample of SHA/CCW combination proportions has low water absorption with a value slightly higher than that of PCM.
6. The average abrasion resistance of mortar sample of SHA/CCW combination proportions is considered low compared to that of PCM.

5.0 Recommendations

The following areas are suggested for further research.

i. Implore the use of set- accelerating admixtures on the SHA/CCW to study if it can improve the setting time.

ii. Studies on heat treatment of CCW is paramount importance due to the high loss of ignition (LOI).

iii. To study the product of hydration through the use of scanning electron microscopy and X-ray diffraction analysis to assess the internal chemical reactions on strength development.

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