Development of Light-weight Geopolymeric Materials using Fly Ash and Waste Paper

Natali MS. Nyabanga, Leslie F. Petrik and Tunde V. Ojumu

***Abstract*—** The aim of this paper is to utilize coal fly ash and waste paper which are currently causing disposal problems, for the production of lightweight materials which might find application in construction industry. The view is to investigate the effects of waste-paper to fly ash ratio on the properties of lightweight, high strength geopolymeric materials produced from these wastes. The results of this study show that decreases in weight, compressive strength and tensile strength as the waste paper content increases. It can be shown that with up to 50% decrease in weight of geopolymeric material with a comparative compressive strength of 4.51 MPa, similar to commercially available construction materials can be achieved by using 20% waste paper with coal fly ash. The capillary water absorption revealed that the material absorbs water at a fast rate suggesting its suitability for indoor applications. The results of this study would provide an alternative and cost-effective approach to manufacturing of non-load bearing construction materials from waste.

***Keywords*—** Coal Fly Ash, Light-weight, Geopolymer, Waste Paper.

I. INTRODUCTION

THE exponential population growth coupled with prevalent industrialisation results in the intensification of coal combustion for power generation. 38% of global electricity is from coal-fuelled power plants. Ahmaruzzam [1] reported that an estimate of 600 million tonnes of coal ash is being produced annually worldwide. In South Africa, coal fuels approximately 85% of its electricity [2]-[3]. Coal fly ash (CFA) is a coal power plant by-product that is extracted/captured by electrostatic precipitators from exhaust gases in power plants [2]. CFA is composed of fine glass-like particles that are highly susceptible to distribution by wind, and thus may pollute the air and cause airborne diseases such as chronic bronchitis, asthma, etc.[4]. The salts and the toxic elements such as As, Hg, B, Pb, Ni, Se, Sr, V and Zn in CFA have a potential to leach into the soil, contaminating surface and ground waters. [4]-[5].

The re-use of waste materials to avert an increasing toxic threat to the environment is also an economically viable solution of waste materials rather than land disposal [6],[7]. Researchers have found that CFA can be used for many applications such as an adsorbent for treatment of acid mine water, zeolites manufacturing, construction applications and recently it has been mostly used to make geopolymer[8]. The activation of aluminosilicate material by alkali silicate forming three dimensional aluminosilicate binder is called geopolymerisation and the three-dimensional binder formed is called a geopolymer [9].

To improve mechanical properties such as fire resistance characteristics, flexibility and ductability in geopolymers reinforcement of different fibres (synthetic and natural) from waste materials has been introduced [9] [10]. Waste paper has drawn interest as a reinforcement material for geopolymer to due to its properties such as low density, low cost, desirable strength to weight ratio and high availability[11]. Disposal of waste paper on open dump landfills leads to environmental problems such as the pollution of soil, surface and water [12]. Waste paper has attracted the construction industry and has been employed for various purposes such as, fibre cement board[13], block [14], low density board[15] and papercrete [16]. As waste paper has been used extensively in the production of light weight construction material, its application as a light-weight filler for non-load bearing geopolymer synthesis in this report is viable.

Papercrete has been widely used for non-load bearing construction material and the composition has included ordinary portland cement and other aggregates. The following studies have been done by various researchers on waste paper as a construction material to develop papercrete using cementious material such as bottom and fly ash as well as granulated blast-furnace slag. Akhtar et al, [18] reported that six different mix proportions were computed by utilising paper pulp and fly ash. The weight of the brick reduced by approximately 50%.

Anuara. (2015) studied the effect of incinerated waste paper on geopolymer strength. Different percentages of waste paper (0%, 25%, 50%, 75% and 100%) were tested. Experimental results showed the highest compressive strength 6.788 MPa was obtained with the use of 12M NaOH.

Momin & Sayyad. [20] investigated the papercrete brick with cement as the binder and the optimised mix was 1:1.5:4: 2 (cement: fly ash: sand: paper) resulting in a compressive strength of 3.24 MPa which is higher than conventional clay bricks and satisfies the IS code recommendation.

Pachamutu & Thangaraju. [21] studied the effect of incinerated paper sludge ash content on fly ash based geopolymer concrete. The paper sludge ash content varied from

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(0%- 20%) of fly ash replaced by paper sludge under different curing regimes. At 20% the maximum compressive strength was 20 MPa.

Most of the researchers used incenerated paper before mixing with the aluminosilicte binder. These studies are the basis of the current project.

Yan et al, [19] and Momin & Sayaan [20] did not incinerate paper but used additives such as sand and cement and achieved 23 MPa and 3.2 MPa compressive strength for 20 % waste paper content with aggregates such as cement and sand. This study coal fly ash and waste cardboard paper are being used without the aid of sand and cement to achieve the same properties required for a non-load bearing material construction material. Addition of chemical and aggregates will result in a costly geopolymer. To achieve a low cost and lightweight geopolymer only waste paper and fly ash will be the raw materials without the addition of aggregates..

II. Materials

A. South African Coal Fly Ash

The coal fly ash (CFA is obtained from Lethabo Coal Power Station (LPS), located close to the Vaal River near Vereeniging in the Free State province in South Africa.

B. Waste Cardboard Paper Pulp (WCP)

In this study, post-consumer wastepaper pulp (WP) (i.e. cardboard boxes) which was obtained from a recycling company in Montague Gardens, Cape Town, South Africa was used for the light weight filler. The compacted value of density for cardboard pulp is 683 kg/m3. The waste cardboard paper pulp is brown in colour. Fig 1 shows the SEM image of the waste cardboard paper pulp.

C. Alkali Silicate Activators

The alkali silicate used for the activation of CFA consisted of sodium hydroxide (NaOH) and sodium silicate (Na2SiO3). The ratio of CFA/ Alkali Activator was kept constant at 2.5. NaOH solution of 10 M was prepared by diluting NaOH pellets of 99 % purity in water. The ratio of Na2SiO3/NaOH was kept as 2.

III. Experimental

A. Mix Composition

The mixture composition consisted of 0%, 10%, 20%, 30% and 40% wastepaper. The pulp used in this study had 75% water. The solid to liquid ratio was varied, all the composition proportions were shown in table 1.

B. Specimen Preparation

NaOH solution was prepared 24 hours prior to the geopolymer synthesis to allow the reaction to cool down. The NaOH solution was mixed with Na2SiO3 to make an aqueous solution and it was mixed for 5 minutes. The wet ingredients were added to the dry (fly ash) and mixed in a mechanical mixer for 25 minutes to produce a homogeneous paste. The waste paper cardboard pulp was then added and mixed for another 25 minutes to allow the paste to blend well with the pulp. The paste was then transferred into metallic cubic molds (100mm×100mm×150 mm) and hydraulic press was used as casting method. Paper is a fibrous material therefore to reduce any voids the pressure used was 4 MPa and the specimen after hydraulic press size became (100mm x 100mm x 100 mm) for all compressive strength and split tensile strength test samples. The specimen was de-moulded after 24 hours and wrapped in plastics to avoid moisture loss. An oven was used to cure the specimen at 80˚C for 60 h. The specimens were unwrapped and there after left for 7 days at room temperature before all the analysis tests such as XRD, SEM, compressive strength tests, water absorption tests and split tensile strength test. Reference Geopolymer was prepared by mixing coal fly ash and alkali activator for 30 minutes and cured in the oven for 24 hours at 80oC.

TABLE I: Mixture Proportions

Code	CFA (kg)	WP (kg)	WP %wt of CFA	NaOH (kg)	Na_2SiO_3 (kg)	H_2O (kg)	S/l*
A1	2.7	0.3	10	0.36	0.72	0.9	3.33
B1	2.4	0.6	20	0.32	0.64	0.9	3.33
C1	2.1	0.9	30	0.28	0.56	0.9	3.33
D1	1.8	1.2	40	0.24	0.48	0.9	3.33
A2	2.7	0.3	10	0.36	0.72	1.8	1.67
B2	2.4	0.6	20	0.32	0.64	1.8	1.67
C2	2.1	0.9	30	0.28	0.56	1.8	1.67
D2	1.8	1.2	40	0.24	0.48	1.8	1.67
A3	2.7	0.3	10	0.36	0.72	2.7	1.11
B3	2.4	0.6	20	0.32	0.64	2.7	1.11
C3	2.1	0.9	30	0.28	0.56	2.7	1.11
D3	1.8	1.2	40	0.24	0.48	2.7	1.11
A4	2.7	0.3	10	0.36	0.72	3.6	0.83
B4	2.4	0.6	20	0.32	0.64	3.6	0.83
C4	2.1	0.9	30	0.28	0.56	3.6	0.83
D4	1.8	1.2	40	0.24	0.48	3.6	0.83
Ref	3	0	0	0.40	0.80	-	-

* All the compositions in table 1 are in kilograms
*s/l ratio is (CFA + WP)/H2O

C. CFA, WCP and Geopolymer Analysis

X-ray diffraction (XRD) and scanning electron microscopy (SEM) were used as morphology and mineralogy analysis on coal fly ash as well as fly ash based geopolymeric materials. The analysis was done using a Philips PANalytical instrument with a pw3830 X-ray generator operated at 25 mA and 40 kV. The scale used for samples was from 10o to 90o at 0.02o intervals.

X-ray fluorescent Philips 1404 Wavelength Dispersive spectrometer was used for elemental analysis of coal fly ash.. The spectrometer was fitted with a Rhodium Tube and with the following analysis crystals: LIF200, LIF220, LIF420, PE, TLAP and PX1.

Compressive strength tests were performed using SANS method 5863:2006 standard procedure. The equipment used was (PTL-10 model) using cubic samples. Instrument: MTS CriterionTM Series 60 (60 ton) Standard: Modified ASTM 370 Rate: 10 mm/min. Split Tensile test was performed in order to ensure material specifications to determine the quality of the geopolymer blocks. Blocks were placed in the testing machine with the required pieces and then blocks were subjected to tension until they failed (SANS 1058).

The water absorption test was performed using the ASTM

D570 C98 standard procedure.

IV. Results

The synthesis of lightweight geopolymeric material is similar to the synthesis of ordinary geopolymer. For this study the effect of waste paper content on compressive strength, tensile strength, water absorption and weight will be investigated.

A. Analysis and Characterisation

Table 2 shows chemical properties of CFA done by X-ray Fluorescence. The table shows that the CFA has relatively low calcium content which classifies the fly ash as class F based on literature.

TABLE II: XRF RESULTS FOR LETHABO CFA

Major Oxides	CFA 1 (%)	CFA 2 (%)	CFA 3 (%)	Average (%)
SiO_2	56.46	56.10	56.28	56.28±0.18
Al_2O_3	29.86	30.53	30.85	30.41±0.51
Fe_2O_3	3.59	3.61	3.60	3.60±0.01
CaO	4.44	4.50	4.39	4.44±0.06
TiO_2	1.59	1.59	1.58	1.59±0.00
MgO	1.10	1.09	1.11	1.10±0.01
K_2O	0.70	0.71	0.67	0.69±0.02
P2O5	0.50	0.49	0.50	0.49±0.01
MnO	0.03	0.02	0.03	0.03±0.01
Cr_2O_3	0.04	0.04	0.03	0.04±0.00
Na_2O	0.41	0.27	0.35	0.34±0.07
V2O5	0.03	0.02	0.03	0.03±0.01
Total	99.73	100.96	102.43	101.04±1.35
SiO_2/Al_2O_3	1.89	1.84	1.82	1.85±0.36
Si/Al	2.41	2.34	2.33	2.36±0.45

Table 1 shows the elemental composition of Lethabo coal fly ash, the results show that Lethabo coal fly ash is class F. The CFA was concluded to be class F as the total amount of SiO2, Al2O3 and, Fe2O3 is 89.84% while the composition of calcium oxide is 4.44±0.06%. This observation is in agreement with published results on the composition of Matla CFA (Petrik et al., 2003). The Lethabo coal fly ash scanning electron microscope is shown in Fig 1. The SEM image shows different spherical sizes of LPS fly ash. Fig. 2 shows the coal fly ash mineralogical composition done by the X-ray Diffraction (XRD) analysis technique. Quartz and mullite were the major phases identified in LPS fly ash. Between 20° and 38° 2θ a broad hump was noticed which was due to the amorphous glassy phase with high percentage of quartz and mullite contained in fly ash.

B. The effect of water ratio on compressive strength

This section involved the study of the impact of water on the geopolymerisation process upon the compressive strength of the dried lightweight geopolymer. Four levels of the ratio of solids to water were used in this study; 3.33, 1.67, 1.11, 0.83. Fig 2 shows the compressive strength obtained for each waste paper content. As the ratio decreases the water content is increasing.

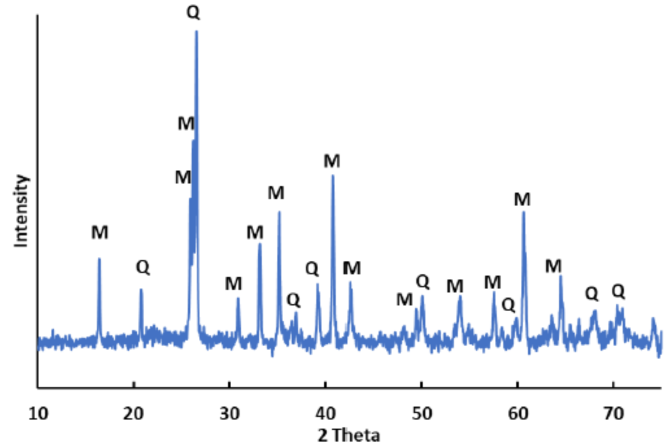

Fig 1: XRD for coal fly ash

Fig 2 shows the geopolymer with 10% waste paper content which had the highest compressive strength at all water content ratios whilst 40% waste paper content attained the lowest compressive strength. It is shown in Fig 2 that as the solid to liquid ratio decreased the compressive strength decreased linearly up to a ratio of 1.11. Based on the trend observed in Fig 2 it can be deduced that as the amount of additional water is increasing the compressive strength decreases with an optimum ratio of 1.67

However, from 1.11 a slight decrease in compressive strength is observed and this sudden change in trend is attributed to the high water in the geopolymer paste. During geopolymerisation process it is necessarily relevant to have sufficient water content otherwise coal fly ash will not be completely wet considering that there is also waste paper being added and paper is known for its ability to absorb water which will have an impact on the workability of the paste, making it difficult to mould the samples. Difficulty in moulding results in voids and would reduce the mechanical properties of the geopolymer. Further, the increase of water content negatively affected the compressive strength of the geopolymer. The geopolymerisation reaction releases water therefore it is vital to maintain the additional water at minimal.

The results obtained in Fig 2 agree with the observation reported by Yan et al. [19], Hardjito et al. [22]; and Patankar et al.[23]. The authors also found that the flow of the geopolymer increased with an increase in the water to geopolymer ratio whilst compressive strength of the geopolymer decreased with an increase in water to geopolymer binder ratio. In this section, the amount of water was proven to be very significant and effective for the development of strengths of the final geopolymers.

As Fig.3 shows the geopolymer weight reduced as the waste paper content increased. The graph indicates that the weight significantly decreased as the waste paper content increased. The reference geopolymer (100mm3) from the study had an average weight of 1.72 kg which makes the sample with 20% waste paper content more than 50% lighter at 0.69 kg.

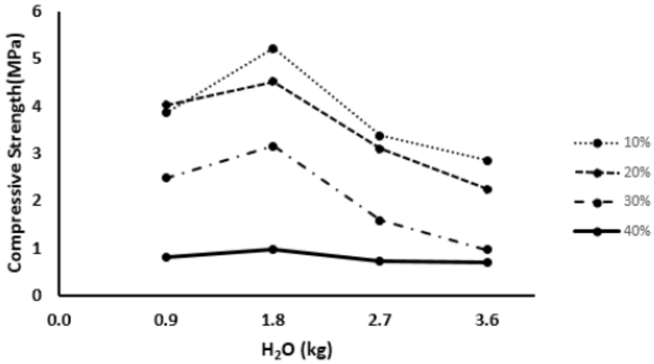

Fig. 2: Effect of water on geopolymer compressive strength

C. Effect of Waste Paper Content on Geopolymer Weight

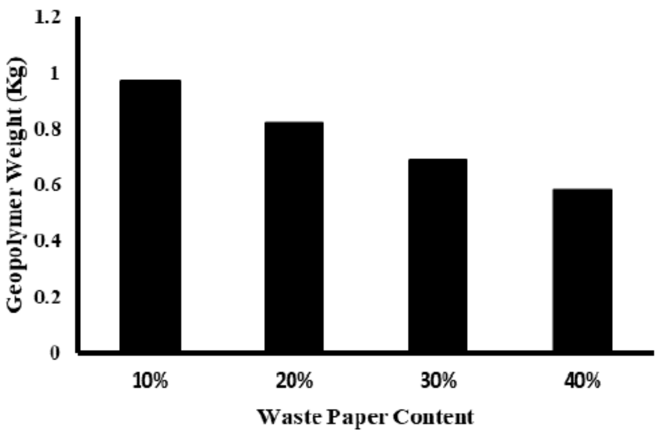

Fig 3: Effect of waste paper content on geopolymer weight

D. The Effect of Waste Paper Content on Geopolymer Compressive Strength

The effect of waste paper content/ waste paper ratio on compressive strength was studied and the results are shown in Fig 4. The waste paper percentages were 10%, 20%, 30% and 40% by weight of CFA. As depicted in Fig 4 the compressive strength decreases with increase in wastepaper content. The trend observed in Fig 4 can be attributed to the paper properties, although paper is known for its light weight properties however paper does not have desirable strength properties. The compressive strength decreased with a significant increase in waste paper content. At high waste paper content, the geopolymer becomes brittle and this can be attributed to the voids in the specimen which are caused by increasing cellulose fibre pulp which is of low strength in the geopolymer. There is poor bonding between cellulose particles and geopolymer particles which increases tiny voids. The required standard of ASTM C129 for non-load bearing materials is more than 1.5 and based on the results of this study waste paper content of 20% and 30% pass the required standards of ASTM. For SANS only 20% waste paper content passes the requirement 3.5 MPa for non-load bearing materials.

As all the studies showed Anuara (2015) produced 6.8 MPa, Momin & Sayyad.[20] produced 3.24 and Pachamutu & Thangaraju. [21] produced quite high compressive strength of 20 MPa and 20% waste paper. These studies did not use fly ash and incinerated waste paper only they all had aggregates such as cement and sand. However, for the current study waste paper was not incinerated as this would have consumed energy as the process requires oven to be used at higher temperatures of 120oC for longer periods such as 80 hours. This current study used waste paper as the only aggregate of the experiments and still managed to obtain the minimal required strength by ASTM 1.5 MPa and SANS 2.8 MPa. Based on the current study it can safely be concluded that CFA and waste paper (no incineration) are able to produce geopolymeric material that meets specifications without extra aggregates.

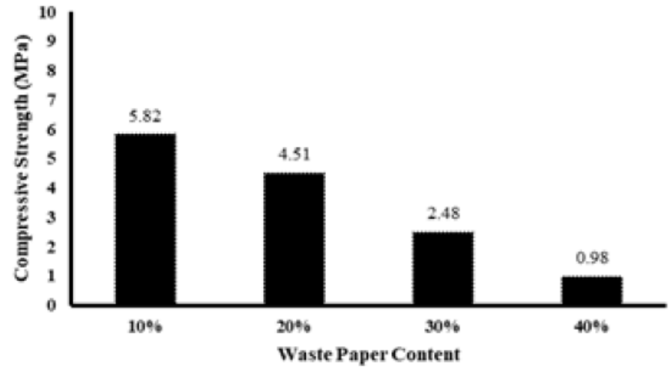

Fig 4: Effect of waste paper content on geopolymer compressive strength

Fig 4 shows that at 20% the strength is above the minimum compressive strength required by ASTM and SANS standards. Fig 2 shows 40 % waste paper content as the geopolymer with least weight of 0.58 kg. Although the main aim was to develop light-weight geopolymeric materials, 40 % waste paper content has 0.98 MPa compressive strength which is below the SANS, IS and ASTM. Based on the Figs 3 and 4, 20% waste paper content is the optimum content in geopolymer as it weighed 0.69 kg and has 4.51 MPa compressive strength which is above the required standard compressive strength.

E. The effect of waste paper content on tensile strength

This section involved the study of the impact that the amount of waste paper had on geopolymer split tensile strength. There four levels of waste paper content that were tested, 10%, 20%, 30% and 40%. Fig 5 shows the tensile strength obtained for each waste paper content. It can be observed that there was an increase when waste paper content increases from 10% waste paper content to 20% and there was a decrease in split tensile strength from 30% waste paper.

The results of splitting tensile of the lightweight geopolymer material at 7 days aging are given in Fig 4 above. The tensile strength increased by 32% when 20% waste paper was utilized. Further increase of the waste paper content led to a decrease of the tensile strength. The observed decrease in strength is attributed to the poor bonding of geopolymeric molecules and waste paper strands. The excess amount of waste cardboard paper limits the geopolymerisation process which will result in tiny voids that create weak geopolymer. Similar trends were also reported by Mansur and Aziz [30] for the jute fibre-reinforced cement paste. The enhanced ductility comes from the debonding and pull-out of fibres that bridge across the cracks.

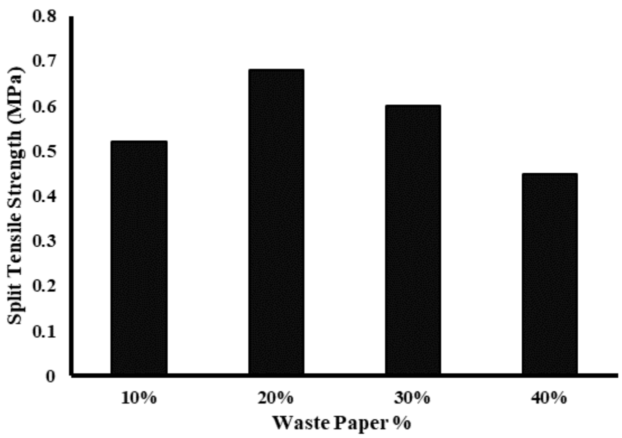

Fig 5: Effect of waste paper content on split tensile strength

F. The effect of waste paper content on water absorption

One of the important factors to be analyzed or characterized on a building material before its application is determining the water absorption or rather hydrometric properties. Karagiannis et al., (2016) discussed that determining moisture related problems in building materials will assist the designers to take adequate preventive measure at the design stage. The light weight geopolymer developed in this study is not expected to be exposed to the weather since it is designed to be used for non-load bearing in door application. Investigating the water absorption rate is of importance to determine the appropriate applications in the non-load bearing construction sector.

The quantity of water absorbed per 0.001 m3 cube cured at 80oC and aged for 7 days is shown in Fig 6. The average of 3 blocks was calculated and used to simulate the graph.

Fig 7 shows that from time 0 the geopolymer absorbs water gradually but from 25 minutes of immersion in water the water uptake becomes constant. For 10% waste paper content the water absorbed within 30 minutes is the lowest among the four waste paper compositions. 10% waste paper geopolymer has the least amount of waste paper which makes the geopolymerisation process and the polycondensation stage effective allowing the geopolymer network to form leaving minimal voids and air bubbles when moulding the paste. 30% and 40% waste paper absorbed the most amount of water as waste paper creates larger voids that disrupts the geopolymerisation process.

Based on Stevulova. [24] study it was reported that waste paper based construction material (papercrete) absorbs water rapidly with an increased time of water immersion. Stevulova. [24] further reported that papercrete absorbs water immediately it encounters water due to its cellulosic characteristic with high porosity.

It should be noted that the geopolymer contains wastepaper fibre only (without any aggregates) which a highly hygroscopic material, therefore its absorption is of will be different from the reaction of other materials (like masonry or concrete blocks) to water. As shown in Fig 6 the geopolymer absorbed a considerable amount of water after 15 minutes of exposure depending on paper. This finding generally indicates that light weight geopolymeric material in this study absorbs water at a higher rate than samples with lower paper content.

Fig 7 shows the rate at which each waste paper content absorbs water. For all waste paper compositions between 0 minutes and 5 minutes the geopolymer initially absorbs water at a faster rate and as the time increases the rate of absorption decreases. The behaviour of this light weight construction material when in contact with water is attributed to the high porosity of waste paper. Considering the material under study contains waste paper too with high water absorption rate the moment the geopolymer is in contact with water, water fills the small voids and cracks caused by waste paper during curing. Akinwumi et al.,[14], [17] has reported similar observations for most waste paper based blocks/ construction materials.

It is therefore recommended that light weight geopolymeric material should be used for partitioning walls but kept at least 1m from the ground and used for only interior walls due to the high water absorption rate. These recommendations are similar to the ones suggested by Akinwumi. [14] for the papercrete.

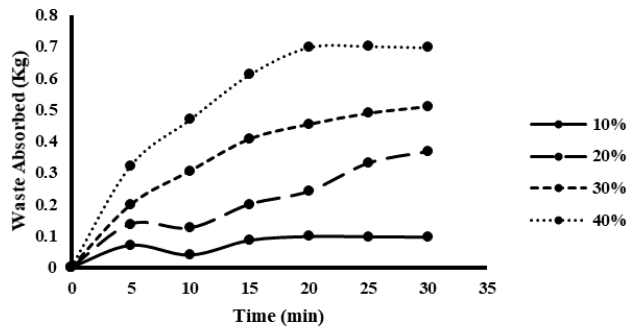

Fig 6: Effect of waste paper on water absorption

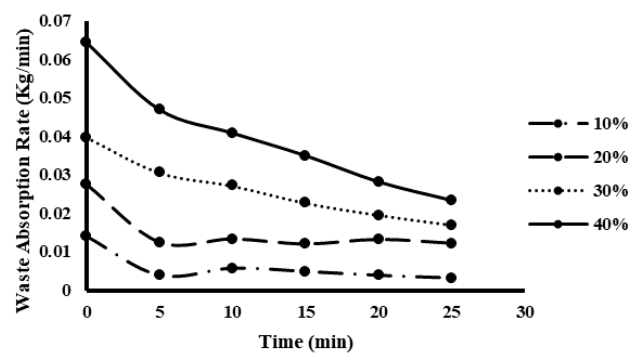

Fig 7: Water absorption rate of each waste paper content

V. Conclusion

This study showed that the weight of the geopolymer brick manufactured in this study ranged from 0.98 to 1.1 kg which is lower compared to 2.2 kg geopolymeric bricks without added paper. The waste paper accounted for 20% content of the materials of construction. 20% waste paper content geopolymer has the highest strength of 4.51 MPa. 40% waste paper content weighed the least with less than 0.6kg. However, 40% WP content cannot be used as it was proven in figure 4 that it has the least compressive strength and highest water absorption rate in figure 7. This type of prefabricated building blocks may be used for the speedy construction of interior walls. Light weight geopolymeric material is recommended for dry wall applications with at least 1 m above ground level and with a plastering or damp-proof membrane to avoid capillary rise of water from the ground into the microstructure. It is evidently concluded that the fly ash based building bricks with waste paper reinforcement can be used for the construction of lightweight partition walls, infilled walls and ceilings.

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