EUROPEAN JOURNAL OF MATERIALS SCIENCE AND ENGINEERING
Volume 9, Issue 3, 2024: 209-230 | www.ejmse.ro | ISSN: 2537-4338

EJMSE

DOI: 10.36868/ejmse.2024.09.03.209

INVESTIGATING THE POZZOLANICITY OF BAGASSE ASH

Daniel Alemayehu CHEKOL[1*], Esayas Gebreyouhannes FTWI[2]

[1]Ethiopian Public Health Institute, Arbegnoch Street, Addis Ababa, Ethiopia.
[2]School of Civil and Environmental Engineering, Addis Ababa Institute of Technology, Addis Ababa University, King George IV Street, Addis Ababa Ethiopia.

Abstract

This study aims to investigate the pozzolanic reactivity of bagasse ash while partially replacing cement. Rapid, reliable, and relevant (R^3) testing techniques were employed. This was done by measuring the heat of hydration and by determining the amount of bound water. The blending of cement made the paste require more water, to enhance the setting time, have more peaks in a narrower range position of °2θ and with Aluminum containing compounds, to have a lower average crystallite size (16.46ηm) and lower diffraction angle. The cumulative heat flow in the blended samples decreased to 275.18J/g at 170hours and the maximum rate of heat flow decreased to 69.41J/gh which was found delayed at 5 minutes and 13 seconds. The difference in heat of hydration between the reference and blended sample increases as time increases starting from 3J/g on the 1st day to 9J/g on the 3rd day. Blended samples were found to have lower bound water(gram) (2.58%) content on day 1 than the reference. Compressive strength at an early age (≤ 1 day) is lower in the bagasse ash (BA) blended mortar cubes and during later days compressive strength of BA blended mortar cubes were the highest and quartz blended mortar cubes were the lowest. Besides, the pozzolanic activity of bagasse ash (PABA) was found to be 346.08mg of $Ca(OH)_2$ per gram of bagasse ash. Results were compared with the strength development and pozzolanic activity determination test. The presence of pozzolanic reactivity of the bagasse ash was confirmed, and results were found to be coherent and in agreement with each other.

Keywords: *Pozzolanic activity, Reactivity test, Heat of hydration, Bound water, Modified Chapelle test, Isothermal calorimeter, Cumulative heat flow, Compressive strength*

Introduction

To cope with the increasing need for construction materials of good quality, the utilization of alternative materials that are renewable, cheaper, and eco-friendly is important. Studies on partial and full replacement of the most widely used materials, such as cement, by renewable alternative construction materials are important to secure the sustainability of production. Bagasse ash is one of these materials that have the potential to partially replace cement which results in improvement in the concrete properties. However, the cause of this property improvement has not been well investigated and properly addressed in previous studies. Investigating this gap is the focus of this study by examining the pozzolanic reactivity of bagasse ash in concrete at a 10% level of replacement of cement.

Partially or fully replacing cement with bagasse ash will save a significant amount of virgin material, cost, and production energy [1],[2]; improve the properties of concrete [3]; play an important role in the reduction of Carbon emission and other environmental impacts [2]; and assists in waste management and green concrete production by ensuring sustainability [1]. However, these need a careful and detailed study since the utilization of replacing materials has

*Corresponding author: danielalemayehuch@gmail.com

its own limitations and constraints. For efficient and effective utilization of bagasse ash as a replacement material, determining the replacement level and studying the mechanisms formed during hydration is mandatory. In this study, mechanisms formed during hydration are investigated by developing and selecting appropriate characterizing and testing methods.

Sugar cane bagasse is an agro-fibrous waste after the extraction of juice from the sugar cane. The major by-products of sugar are molasses, ethanol, and bagasse. Bagasse ash is found after burning the bagasse in the open air. Jahanzaib Khalil, Aslam [3] found 55.05-78.34 percent of Silica in bagasse ash in different studies which is responsible for the pozzolanic property. The chemical composition of bagasse ash depends on the plantation area. According to Jahanzaib Khalil, Aslam [3], the bagasse ash chemical composition is affected by the incineration temperature, method, time, temperature, and grinding mechanism.

The amount of sugar cane produced in 2022 was 1,922.06 million tons worldwide [4] and 1 ton of sugar cane will generate 270 Kg of sugar cane bagasse [5]. Ethiopia will have a potential of 1.17 million tons of bagasse ash per year when factories run at full capacity [6]. Meanwhile, the annual cement consumption of Ethiopia in 2025 was estimated to be 19.97 million tons [7]. This shows that the utilization of bagasse ash as a cement replacing material can save a significant amount of cement every year.

The partial replacement of cement with bagasse ash was found to have an improvement in workability [8]; increment in compressive strength [9],[10]; increment in flexural strength [11],[12]; increment in splitting tensile strength [13]; improvement in durability [11]; increment in resistance to chloride ions, acid and sulfate attacks, and the alkali–silica reaction [2]; reduction in the heat of hydration [14],[15]; and strengthen the interfacial transition zone between cement matrix and the aggregates [16]. However, these property improvements were achieved up to a certain level of replacement of cement with bagasse ash. Optimum property improvement in terms of mechanical performance and durability was achieved at a 10% level of replacement of cement by bagasse ash [3].

In addition to the above benefits, replacing some parts of cement will reduce the water, air, and land degradation and pollution caused by the production of that amount of cement [17]. To produce 1 ton of cement, 0.85 tons of CO_2 will be produced and released into the air contributing to global carbon emissions [18]. Conversion of waste materials, which were supposed to pollute the environment, into useful materials will contribute to waste management in keeping the environment clean.

SCMs (Supplementary Cementitious Materials) are materials used to partially replace Portland clinker without affecting early strength development [19]. Berodier [20] indicates limitations on the utilization of SCMs as good quality SCMs have limited availability; SCMs have a maximal replacement level beyond which the strength decreases; and SCMs have a slow strength development at an early age caused by slow reactivity. Having a better understanding of the hydration process and reaction mechanism helps to solve their limitation [20],[21].

Results obtained from previous pozzolanic reactivity studies using different methods were not in agreement with compressive strength development. This makes the methodology employed to investigate the problem unreliable. The pozzolanic reactivity can be determined by measuring the consumption of portlandite, the reaction degree of SCM, the amount of bound water, the heat released during the reaction, or the volume change over the reaction. The compressive strength tests were correlated to these SCM screening tests [22].

Thus, this study investigated the pozzolanic reactivity of bagasse ash while replacing cement partially by measuring heat flow using an Isothermal calorimeter and with a bound water determination test using oven treatment. Results were compared with the compressive strength and the determined amount of pozzolanic activity of bagasse ash (PABA). This study attempts to fill the gap by using a rapid, relevant, and reliable (R^3) testing approach.

Mode of Action of SCMs

Different possible reasons were given for the improvement in the concrete property when it is blended with SCMs. These are due to the filler effect and pozzolanic reaction of SCMs. The filler effect is the physical presence of SCMs or even an inert material that impacts the reaction of the clinker phases. The filler effect impacts the reactivity by providing relatively more space for the formation of clinker hydrates since the portion of the clinker is replaced by SCMs (dilution effect) and by making the surfaces of the SCM act as nucleation sites for hydrates [23], [20]. Both of them have a significant acceleration effect on the hydration of the clinker [20]. Fillers used at different amounts of replacement and particle size distribution show improvement in concrete properties and microstructure [24].

The second reason for property improvement is due to the pozzolanic reaction of SCMs with cement. SCMs contribute to the development of compressive strength by reacting with the Portland cement hydration products and filling the pore space previously occupied by the water [22]. SCMs hydrate with the hydration products of cement or in the presence of cement to produce additional CSH and other hydration products [25]. Therefore, the pozzolanic activity can be assessed by the extent and rate of the pozzolanic reaction.

When SCMs are blended with cement, the performance of the reaction will be complex. The complication is due to the physical presence of SCMs that affects the extent and rate of reaction of the clinker component; SCMs are usually amorphous with complex and varied mineralogy, which makes them difficult to quantify by many classical techniques; and the rate of reaction of SCM in a cement blend may be quite different from the rate of reaction of the same SCM in systems containing simply alkali or lime [23].

Many studies have been done on blended systems with SCMs from different views. However, the generic microstructural development of blended systems is still not clearly understood. This is due to, first, difficulty in identifying the mechanisms controlling the hydration of Portland cement in a more complex system; second, most authors described the effect of a specific SCM regarding the changes of the microstructure, compressive strength, and evolution of the phase assemblage but have not established generic knowledge; third, although the SCMs have a slower reaction, they contribute to cement hydration from the very beginning [20]. Most of the studies reported long-term changes caused by the introduction of SCM. However, early hydration is a very important step for later properties. It is of interest to investigate bagasse ash's mode of action in the totality of the hydration process.

R^3 Testing

The hydration of cement is a complex process and has not been fully understood until now. When SCMs are added, the process will be more complex and require more techniques to assess reactivity. To evaluate the reactivity of SCMs thoroughly, a range of test methods has been proposed in the literature, mostly based on portlandite consumption. However, these tests often do not correlate well with compressive strength development [26], [27], [28].

Besides, conventional reactive test methods such as Chapelle's and modified Chapelle's test have certain drawbacks caused by the very accelerated settings and the high degree of divergence from the actual conditions since there is high water content and the solution solely comprises $Ca(OH)_2$ [29]. To avoid these problems a better method called R^3 has been developed.

Testing methods should be efficient and accurate to measure the reactivity of SCMs. According to Snellings and Scrivener [22], a suitable test method should be practical and simple in terms of use and cost, give results rapidly, be repeatable and reproducible, be generally applicable to all SCM types, and finally enable easy comparison between the test result and the quality criterion (usually the compressive strength).

Compressive strength is considered a reliable indicator for the presence of a reaction [30], [26]. Jhatial, Nováková [29] and Londono-Zuluaga, Gholizadeh-Vayghan [31] also found a strong linear correlation between the R^3 test(bound water and heat of hydration) and the relative compressive strength at 28 days for conventional SCMs.

The R^3 test was first developed by Avet, Snellings [27] and set as a standard by ASTM-C1897 [32] in 2020 and then improved by Avet, Li [33] as a novel rapid, relevant, and reliable (R^3) testing approach to evaluate the reactivity. Londono-Zuluaga, Gholizadeh-Vayghan [31] found that the R^3 test results showed very good reproducibility in different samples and very small interlaboratory variations at different laboratories on heat of hydration and bound water tests.

Materials

Materials Used for the Study

The Messobo OPC which complies with the requirements of Ethiopian standards ES-EN-197-1 [34], Sable Normalise standard sand that fulfills requirements given by the European code as reference sand[35], quartz powder, bagasse ash from Wonji sugar factory, water from Addis Ababa Water and Urban Sewerage Authority (AAWUSA) were used in this study. The gradation of the standard sand in cumulative passing percentage is shown in Fig. 1 below.

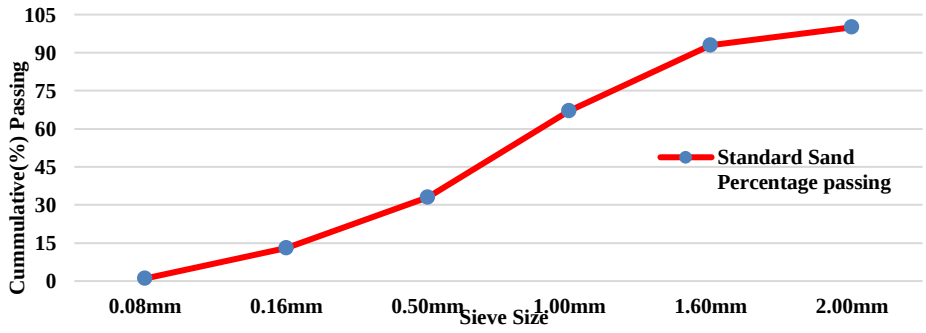

Fig. 1. Grain size distribution of standard sand

The fresh bagasse ash released from the furnace and cooled in the air was collected. It was not treated with any chemicals. The bagasse ash and quartz were sieved, and those grain sizes that pass through 125µm and smaller sieve sizes were used, and their gradation was made to be similar to cement as shown in Fig. 2 below.

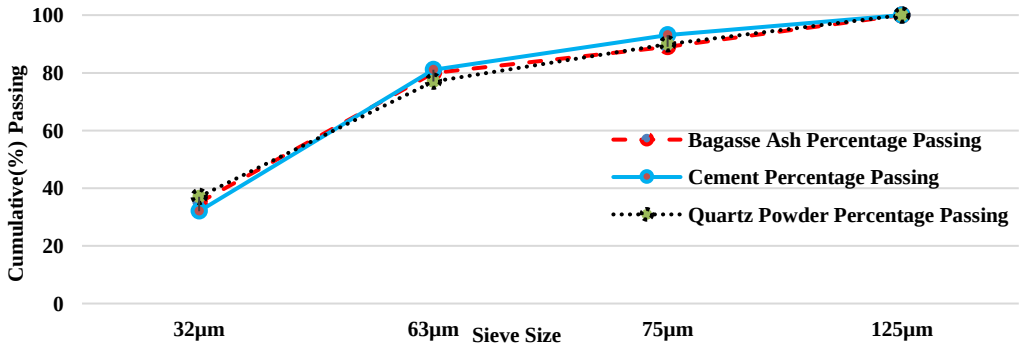

Fig. 2. Grain size distribution of cement, bagasse ash and quartz powder

Physical and Chemical Properties of Materials

Physical Property of Materials

The fineness of bagasse ash, quartz powder, and cement was determined using the Blaine air permeability test as per ASTM-C204 [36]. Results showed that the bagasse ash was found to have the lowest density and highest surface area as compared to quartz powder and OPC while having similar particle sizes, as shown in Table 1 below.

Table 1. The physical properties of the raw materials

Material	Density (g/cm^3)	Blaine air (cm^2/gm)	Average sieve size (μm) in which half of the particles pass
Bagasse ash	2.03	4,546	42.33
Quartz powder	2.50	3,980	42.08
OPC	3.15	3,601	43.39

Replacement of the bagasse ash was made by volume to keep the volume of cementitious material per unit volume of the mix constant. The volume equivalency of the bagasse ash was computed according to ACI-211.1-91 [37] and found to be 0.6481%. This implies that replacing 1% volume of cement with an equal volume of bagasse ash is equivalent to replacing 0.65% weight of cement with bagasse ash to account for the lower density of bagasse ash. Similarly, the volume equivalency for quartz was found to be 0.8%.

Chemical Property of Materials

The chemical properties of bagasse ash and cement were investigated using X-Ray Fluorescence (XRF) and chemicals (Gravimetric and Complex metric method). More or less similar results were obtained, as shown in Table 2 below and the XRF result was considered since it is the most reliable one.

Table 2 Chemical Composition of Cement and Bagasse Ash

Chemical Composition (%)	Messebo OPC Cement**	Bagasse Ash*	Bagasse Ash**
SiO_2	23.20	75.98	70.18
Al_2O_3	5.08	11.54	5.66
Fe_2O_3	3.60	2.28	3.42
CaO	61.82	1.12	1.26
MgO	1.93	0.60	1.63
Na_2O	0.29	0.64	-
K_2O	0.21	1.92	-
MnO	-	<0.01	-
P_2O_5	-	0.42	-
TiO_2	-	0.09	-
H_2O	-	1.10	-
SO_3	2.58	-	-
LOI	0.94	5.81	-
$SiO_2 + Al_2O_3 + Fe_2O_3$	-	89.80	79.18

* The Chemical composition was done using the XRF method.
**The Chemical composition was done using chemicals.

Based on the chemical composition of bagasse ash result: $SiO_2 + Al_2O_3 + Fe_2O_3 = 89.80\%$. This value is greater than 70%, and the Loss on Ignition (LOI) value of the bagasse ash was found to be less than 10% (5.81%). Thus, based on these results, the material is classified as pozzolanic in Class N [38].

Fresh Properties of Mortar Pastes

The fresh properties of mortar pastes with and without bagasse ash were measured by standard consistency and setting time tests according to ASTM-C187 [39] and ASTM-C191 [40] methods, respectively. Three 500g each from the reference and blended sample (10% of bagasse ash by volume) were prepared and tested. Results for the standard consistency and setting time test are given in Table 3 below.

Table 3 Standard consistency and setting time test results

Sample	Standard Consistency		Setting Time (min)	
	Standard Consistency (gm)	W/C (%)	Initial Setting Time(min)	Final Setting Time(min)
Reference	139	27.8	120	385
Blended 1	169	33.8	155	410
Blended 2	167	33.4	150	465
Blended 3	168	33.6	150	420

From Table 3 above, it can be inferred that the water demand and setting time of the blended mixes were higher than the reference mixes. This is in line with the findings of Amin [41], Ganesan, Rajagopal [42], and Hailu and Dinku [43] in their study of bagasse ash as cement replacement material. All the findings on the water to cement ratio for normal consistency and the initial and final setting time of cement were within the standard range [44]. The increase in water demand enhances the initial and final setting time. Blending makes the initial setting time increase by 32 minutes and the final setting time by 47 minutes as compared to the reference sample.

Experimental Program

In this study, the pozzolanic reactivity of bagasse ash was investigated with microstructure characterization using XRD analysis, heat flow measurements using an isothermal calorimeter, bound water determination using oven thermal treatment, determination of the PABA using modified Chapelle test, by measuring the compressive strength of mortar cubes, and finally by creating a correlation between these tests and the strength development.

Characterization of the Hardened Paste

Characterization of the hardened pastes was made using XRD Analysis in the CuKα radiation diffractometer. XRD analysis is advantageous due to its ease and speed of measurement and accuracy as compared to traditional quantitative phase analysis methods such as Bogue calculations and optical microscopy [45]. It has also advantages of accessibility, rapidity, multiple phase identification, and quantification capacity with limitations in the quantitative analysis that requires extensive knowledge and the amorphous phase which gives diffuse signals and requires complex analysis [46].

Samples from the same batch were cast for XRD and cured at 25°C. XRD was used to characterize the crystalline phases formed and the crystallite size and to follow the portlandite consumption. According to Feret [47], and Varin, Bystrzycki [48], crystallite size is calculated using Scherrer's equation. Measurements were carried out on independently cast pastes on day 1. The hardened pastes of SCMs were ground with agate and prepared in powder form.

Heat of Hydration Measurement

Heat flow of the SCM blended and reference cement mixes are carried out using calorimetry experiments. Among the calorimetry tests, an isothermal calorimeter test is used in this study. According to Sedaghat [49], Sedaghat, Zayed [50], Wadsö [51], and Wang, Ge [52], an isothermal calorimeter has advantages in measuring the instantaneous and total heat flow at different ages; operating at a wide range of temperatures; able to study the hydration stages from

the recorded heat flow curve at the desired hydration age; performing well with blended cement; do not depend on the knowledge of compound composition.

The heat production rate per mass of cement is quite similar for cement pastes and cement mortars (and then probably also for concretes) of the same water to cement ratio [51]. Also, the way that a cement paste is mixed does not much influence the reaction rate. The heat of hydration for hydraulic Portland cement is measured according to ASTM-C1702 [53] and ASTM-C186 [54].

The cumulative heat of the reaction was measured using a ToniCAL isothermal calorimeter over 7 days (170 hours) at 25°C. Paste ingredients, including the mixing solutions, were stored overnight at the same temperature as the test. About 10g of blended and reference cement samples each were prepared in triplicate and poured one after the other into a test tube. Water was injected using a syringe and needle. Samples were placed in the calorimeter and tested one by one.

Bound Water Determination

Water in the hardened cement paste can be in a constitutive (chemically bound) or free (chemically unbound) state. The chemically combined water is the water that combines chemically with the cement in the hydrate phases [55], and separation can be made only by calcining the material at high temperatures or by chemical reactions. Taylor [56] defines chemically bound water as the water present in interlayer spaces or more firmly bound but not that present in pores larger than this. According to Li, Snellings [26], the weight loss due to heating is proportional to the amount of water present in the hydration products of CSH and CASH and this water is used to define the SCM reactivity.

Reference and blended samples were prepared and cast on plastic sheets in triplicate with 4mm thickness and put in a 25°C enclosed environment for 24 hours. This was done to create similar conditions with the heat of hydration test. Samples were dried at 110°C in an oven. According to ASTM-C642 [57], samples were considered dry when the mass change within 1 day did not exceed 0.5%. In this study, the condition was fulfilled after 2 days of drying. Then samples were heated at 350°C for 2 hours and cooled down to 100°C. The thermal treatment was limited to 350°C since higher temperatures resulted in portlandite dehydroxylation, which is not desired in this study. Finally, the bound water was determined by calculating the mass change after heating the samples.

Determination of the PABA

To define the pozzolanic activity of materials, measuring the fixed quantity of calcium hydroxide is one method. The amount of $Ca(OH)_2$ produced from the reaction of CaO with bagasse ash was evaluated using the Modified Chapelle test. This test was preferred because of its quick indication of pozzolanic reactivity (within a day) compared to the Frattini test [27].

For this test, 1g of bagasse ash was mixed with 2g of calcium oxide and 250ml of deionized water. Similarly, reference samples were also prepared without bagasse ash and run in parallel to the bagasse ash blended samples. The mix was heated at 90°C for 16 hours with continuous stirring. Water loss was prevented by a reflux condenser. After cooling down to 20°C, a solution of 60g sucrose in 250ml of deionized water was added to complex the calcium ions in the solution and to dissolve the unreacted portlandite. The suspension was filtered through a filter paper, and the liquid was titrated with a 0.1M solution of HCl using phenolphthalein as a PH indicator. According to Avet, Snellings [27], Ferraz, Andrejkovicová [58], and Scrivener, Lothenbach [23], the amount of bound portlandite, meaning that the PABA is determined using Eq. 1 given below.

$$PABA = \text{mg CH/g Bagasse Ash} = 2\left(\frac{V_1 - V_2}{V_1}\right) * \frac{74}{56} * 1000 \quad (1)$$

where: V_1 = Volume of HCl added for the titration of the reference sample and
V_2 = Volume of HCl added for the titration of the sample with bagasse ash.

Compressive Strength Determination

Standard mortar cubes were cast to determine the strength development of the bagasse blended, quartz blended, and reference samples over time. The blending was made at 10% replacement by volume of OPC.

Mix proportions were made with 1 part of cement to 3 parts of sand with a water to cement ratio of 0.5 as per EN-196-1 [59]. Mortar cubes were unmolded after 24 hours and cured in a water pond until tested. The compressive strength measurements were carried out on mortar cubes of 50*50*50 mm at 1, 3, 7, 28, 56, and 90 days of age.

Research Framework

The research framework for the study is given in Fig. 3 below.

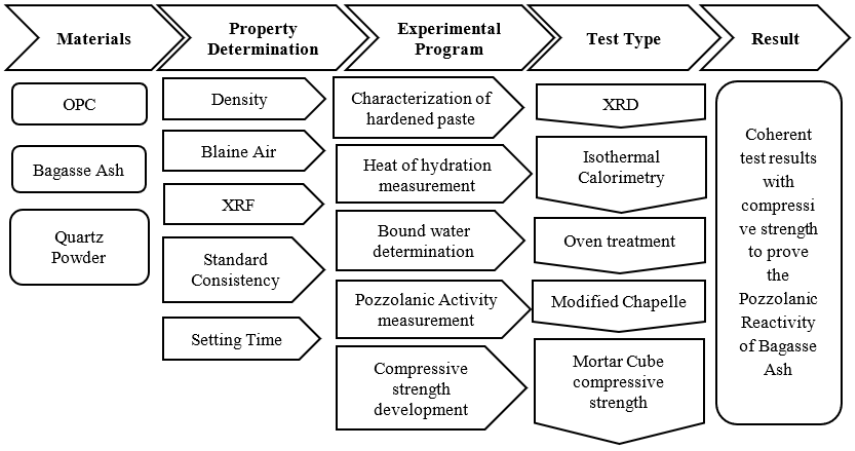

Fig. 3. Research Framework for the Study

Results and Discussion

Characterization of the Hardened Paste

The samples were analyzed, compounds were identified, and XRD patterns were drawn. The analysis result is given in Fig. 4 and 5 and pattern lists for each sample are shown in Tables 4 and 5 below.

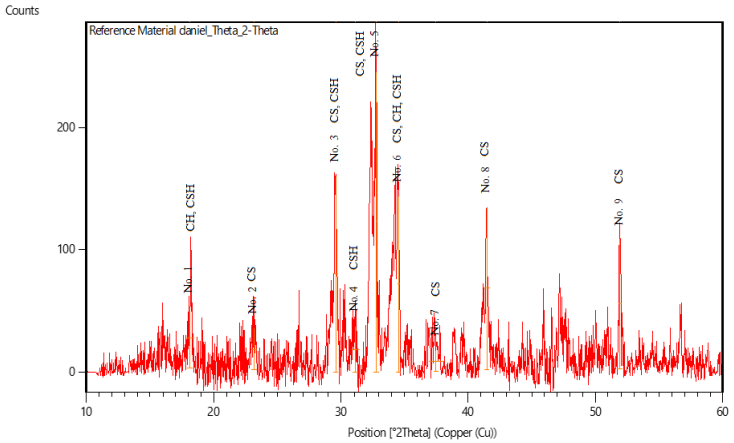

Fig. 4. Chemical compounds detected in reference sample on day 1

Table 4. Pattern list of the reference sample

Number	Ref. Code	Score	Compound Name	Displacement [°2Th.]	Scale Factor	Chemical Formula	Abbreviation
1	00-042-0551	43	Calcium Silicate	0.000	0.759	$Ca_3 Si O_5$	CS
2	00-004-0733	17	Calcium Hydroxide	0.000	0.336	$Ca (O H)_2$	CH
3	00-040-0513	16	Calcium Silicate Hydrate	0.000	0.401	$Ca_4 Si_3 O_{10}$!2 $H_2 O$	CSH

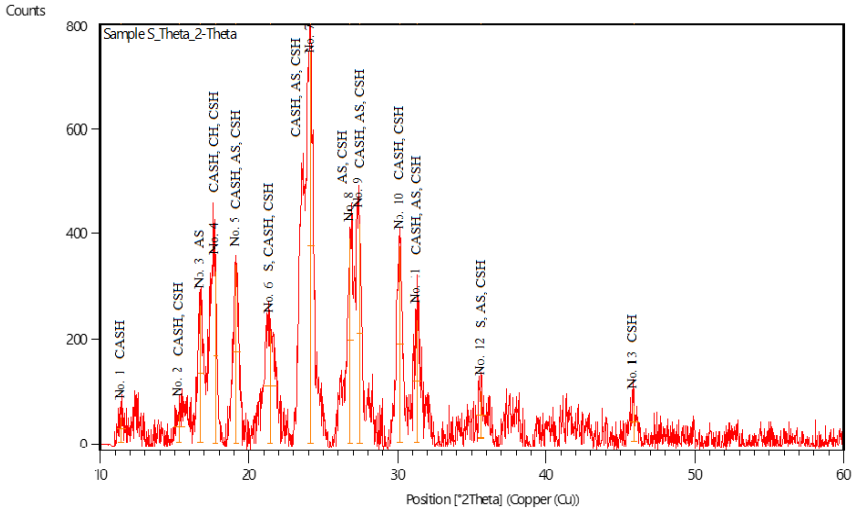

Fig. 5. Chemical compounds detected in blended sample on day 1

Table 5. Pattern list of the blended sample

No	Ref. Code	Score	Compound Name	Displacement [°2Th.]	Scale Factor	Chemical Formula	Abbreviation
1	00-027-0605	31	Silicon Oxide	0	0.253	$Si O_2$	S
2	00-029-0286	28	Calcium Aluminum Silicate Hydrate	0	0.894	$Ca Al_2 Si_3 O_{10}$!6 $H_2 O$	CASH
3	00-022-0018	7	Aluminum Silicate	0	0.2	$Al_2 Si O_5$	AS
4	00-044-1481	2	Calcium Hydroxide	0	0.057	$Ca (O H)_2$	CH
5	00-019-0250	10	Calcium Silicate Hydrate	0	0.165	$Ca_3 Si_3 O_9$! $H_2 O$	CSH

From the above XRD results, the peaks in the reference sample were C_3S, CH, and CSH, whereas in the blended sample were S, CASH, AS, CH, and CSH. More peaks with unreacted C_3S in the reference sample and more peaks with unreacted SiO_2 in the blended sample were observed. The presence of unreacted SiO_2 and CH shows the unfinished pozzolanic reaction in the blended sample. The reaction between SiO_2 and CH is pozzolanic. In later days, these compounds will react and form additional CSH, which improves the microstructure and strength of the blended sample furthermore. This is consistent with the findings of Qing, Tao [60], Maldonado-García, Hernández-Toledo [61] and the compressive strength of mortar cubes in this study. The formation of CH, AS, CASH, and CSH indicates the occurrence of a pozzolanic reaction in the blended sample. Besides, in the reference sample, most of the cementitious

compounds detected are CSH phases which are major contributors to strength. This makes the reference sample to get more strength than the blended samples on day 1.

More peaks (9 out of 13) in less than 28° positions of 2Θ with a narrower range (11.396 - 45.921° of 2θ) and Compounds with Aluminum elements were found in the blended sample. Fewer peaks with a wider range (18.13 - 51.93° of 2θ) were observed in the reference sample showing the presence of more reaction than the one with more peaks [62]. This indicates the reaction retarding effect of blending and is consistent with the results of the heat of hydration in this study. The cumulative heat of hydration evolved on day 1 by the blended sample was lower than the reference sample. According to Snellings, Salze [45], the extent of reaction measured by XRD is related to the amount of cumulative heat of hydration that evolved.

Besides, the crystal size is found to be 24.49ηm in the reference and 16.46ηm in the blended sample. These are thicknesses of particles that are perpendicular to the crystal plane. This shows that the reference sample has a larger crystallite size. This implies that the reference sample diffracts at a larger angle than the blended. This is consistent with the XRD analysis pattern shown in Fig. 4 and 5 above.

Heat of Hydration Measurement

Results on the instantaneous and cumulative heat evolved in both reference and blended (with bagasse ash) pastes at 170 hours and 24 hours are shown in Fig. 6 and 7 below respectively. An average value of the three samples from each group was taken for comparison.

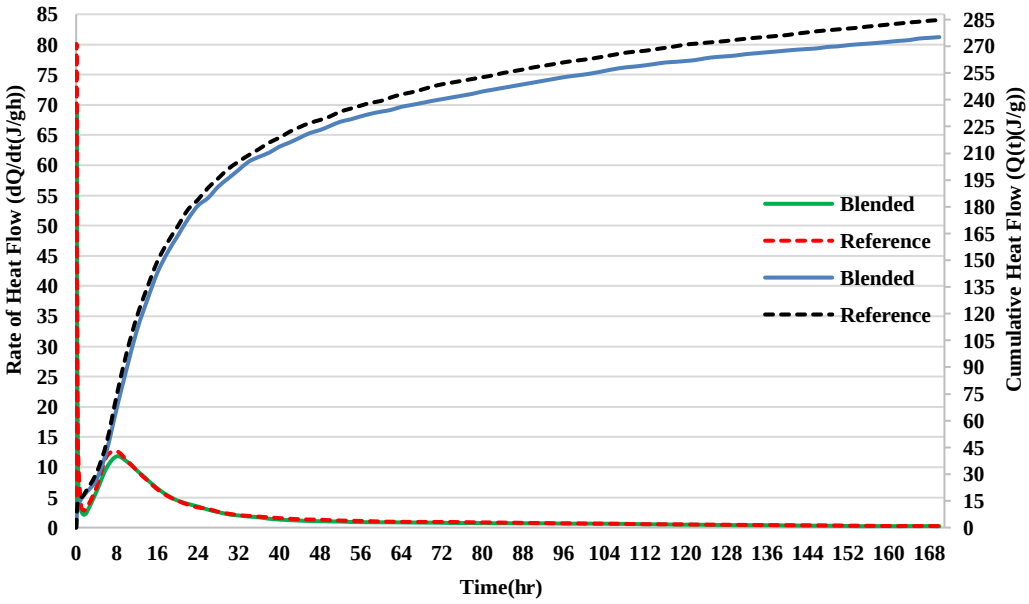

Fig. 6. Average rate of heat flow and cumulative heat evolved during 170 hours (7 days)

From Fig. 6 above and Fig. 7 below, it can be inferred that the addition of bagasse ash was found to have a decreasing effect on the instantaneous and total heat evolved. This is consistent with the findings by Chusilp, Jaturapitakkul [63] in their study of the utilization of bagasse ash in concrete. According to Feng, Zhang [64], the reduction in cumulative heat of hydration helps to reduce the autogenous shrinkage of cement and concrete products.

The exothermic nature of the reaction resulted in a rapid rise in the rate of heat evolution up to the first 5 minutes. A dense layer is formed during this time, which leads to a relatively slow reaction period from 30 to 90 minutes. This is the time in which the paste remains plastic and

workable. This period is followed by a new increase in the rate of heat liberation, which lasts for about less than 8 hours. At the beginning of this period, the paste loses its plasticity and acquires a certain degree of firmness, and becomes unworkable. This is related to the initial setting time, and during the later time in this period, the paste loses its plasticity and becomes a rigid mass. This is followed by the last stage, during which a gradual decrease to 3J/gh within 24 hours in the heat of hydration and to still further lower rates after that. This indicates a slow rate of hydration by diffusion through the solid hydration products. In comparison, the rate of hydration in blended samples is lower. The optimum values of heat flow in each sample are given in Table 6 below.

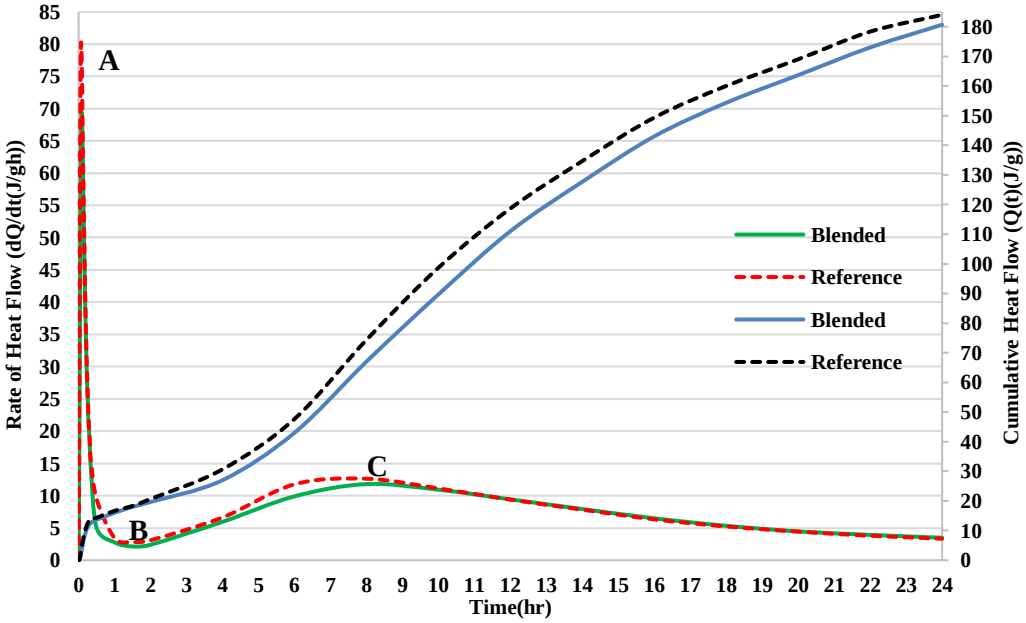

Fig. 7. Average rate of heat flow and cumulative heat evolved during 24 hours (1 day)

Table 6. The maximum rate of heat flow and cumulative heat flow of test samples

Sample	Time for Maximum Rate of Heat Flow (Minute: Second)	Maximum Rate of Heat Flow(J/gh)	Cumulative Heat Flow(J/g)	Minimum Rate of Heat Flow at 2nd Minimum (B) (J/gh)	Maximum Rate of Heat Flow at 2nd Peak (C) (J/gh)
Reference 1	0:04:14	82.22	287.07	2.80	12.90
Reference 2	0:04:04	78.37	285.61	2.90	12.40
Reference 3	0:04:25	79.65	281.62	2.80	12.60
Average	**0:04:14**	**80.08**	**284.77**	**2.83**	**12.63**
Blended 1	0:05:16	67.35	270.87	2.00	11.50
Blended 2	0:05:07	69.88	277.26	2.10	12.10
Blended 3	0:05:16	70.99	277.42	2.30	11.80
Average	**0:05:13**	**69.41**	**275.18**	**2.13**	**11.80**

From Table 6 above, it can be inferred that blending reduces the maximum rate of heat flow by an average of 10.67J/gh, delays the time for the maximum rate of heat flow by an average of 59 seconds, and declines the cumulative heat flow by an average of 9.59J/g. It also decreases the second minimum rate of heat flow(B) by 0.70J/gh and decreases the second peak rate of heat flow(C) by 0.83J/gh.

Besides, blending increases the length of the induction period and reduces the intensity of the main hydration peak. This will help in lowering the thermal cracking potential of massive concrete at an early age. Similar results were found by Sedaghat [49].

According to Snellings, Salze [45], the heat released on different days is assumed to be directly proportional to the degree of reaction. However, this will work for materials with similar chemical compositions. Similarly, the heat released from the reference sample on day 2 is more than on day 1, which implies that the degree of reaction on day 2 is more than on day 1. It is true for the pozzolanic reactivity of the blended samples as well. This is consistent with the trend in compressive strength development results in this study. Alujas, Fernández [65] also found similar results. The cumulative heat flow of both reference and blended samples is shown in Figure 8 below.

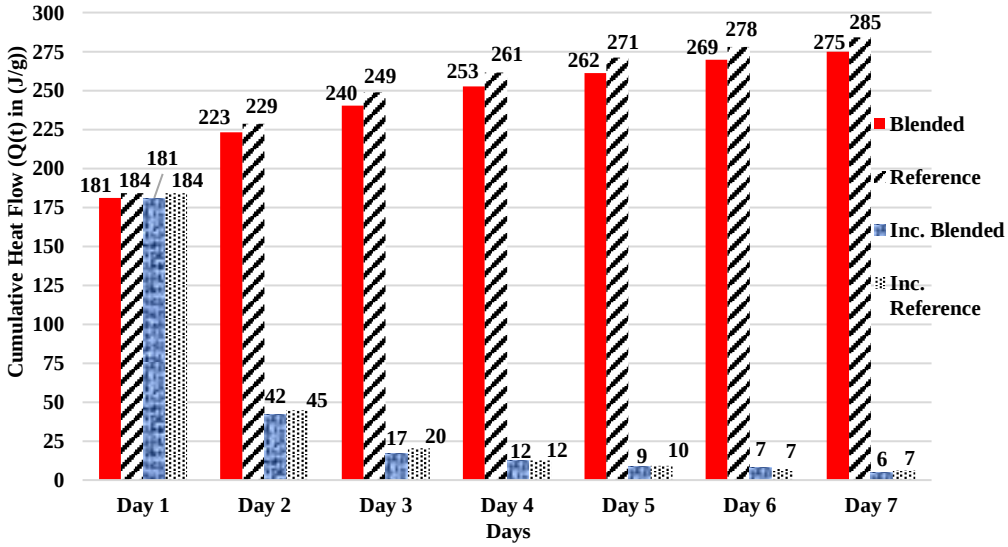

Fig. 8. Average cumulative heat evolved and its daily increment in each sample

In blended samples, 65.9%, 81.3%, and 87.5%, and in reference samples, 64.56%, 80.35%, and 87.37% of the heat of hydration from the total (at 170 hours) are released during the first, second, and third day respectively. This implies that the majority (88%) of the heat is released within the first three days. Increments after the third day are minimal and become very small after the sixth day. This is consistent with the findings of Avet, Snellings [27].

The difference in the heat of hydration between the reference and blended sample rises as time increases. The difference starts from 3J/g and ends up at 10J/g on the seventh day. This implies that developments in the evolved heat between the two consecutive corresponding samples are consistent with the compressive strength development.

Bound Water Determination

Results of the bound water determination experiment showed that the reference samples and the blended samples were found to have 2.89% and 2.58% bound water (gm) on average on day 1, respectively, as shown in Table 7 below.

The blended samples had a lower amount of bound water. Similarly, Massazza [66] found lower bound water content on day 1 and an increase afterward in the fly ash blended cement. This implies that there is more hydration reaction (CSH formation) in reference samples on day 1 and an improvement in pozzolanic reactivity that causes a further increase in the CSH formation

during later days. This will improve the compressive strength of the blended sample after day 1, and it is consistent with the findings of compressive strength. Likewise, Li, Snellings [26] found a strong linear correlation between bound water and compressive strength.

Table 7. Bound water determination test results

Sample	Mass after 2 days in Oven(gm) at 110℃	Mass after furnace for 2hrs (gm) at 350℃ and Cool to 100℃	Bound Water (gm)	Bound Water (gm)%	Average
Reference 1	27.5659	26.7774	0.028604181	2.860418125	
Reference 2	30.6527	29.7771	0.028565183	2.856518349	2.887622185
Reference 3	37.3091	36.21	0.029459301	2.945930081	
Blended 1	45.5632	44.4011	0.025505232	2.550523229	
Blended 2	35.7722	34.8751	0.025078133	2.50781333	2.579049192
Blended 3	45.8375	44.6096	0.026788110	2.678811017	

According to Prochońa and Piotrowskia [67], specimens with a higher content of Al_2O_3 and SiO_2 show lower values of bound water amount. Since the bagasse ash has a higher content of Al_2O_3 and SiO_2, the experimental samples show a lower amount of bound water than the reference one.

Determination of the PABA

The PABA was determined using the Modified Chapelle test in duplicates and found to have an average value of 346.08mg $Ca(OH)_2$/g bagasse ash, as shown in Table 8 below. This shows the presence of a pozzolanic reaction. According to this test, the reference sample must verify $V_1 * \frac{56}{2} < 1{,}000$, and all the reference sample measurements satisfy this condition.

Table 8. Amount of PABA per gram of Bagasse Ash

Experiment	Measurement	Volume of HCl in Blank Sample(V_1)	Volume of HCl in Blended Sample(V_2)	PABA (mg $Ca(OH)_2$/ g Bagasse Ash)
	Measurement 1	25.9	22.6	336.73
1	Measurement 2	25.9	22.5	346.94
	Average	**25.9**	**22.55**	**341.84**
	Measurement 1	25.6	22.3	340.68
2	Measurement 2	25.7	22.2	359.92
	Average	**25.65**	**22.25**	**350.32**
	Grand Average	**25.775**	**22.40**	**346.08**

In a similar study on Brazilian bagasse ash, Cordeiro, Toledo Filho [68] found a minimum of 36mg CaO/g bagasse ash and a maximum of 298mg CaO/g bagasse ash. In another study, Quarcioni, Chotoli [69] found a minimum of 146mg $Ca(OH)_2$/g bagasse ash and a maximum of 468mg $Ca(OH)_2$/g bagasse ash using Chapelle's method.

Compressive Strength Test

The workability of the mortar was checked using a flow table test and showed a slight reduction in the blended mixes. This is due to the high surface area of the bagasse ash. The compressive strength values used are averages of three specimens prepared from all mixes. According to Ahmad, Adekunle [70] variation in compressive strength of the individual specimens should be within the acceptable range (with a standard deviation within 3 MPa). All test results fall within this range.

The compressive strength results in Fig. 9 below indicate an increment while the cement is partially replaced by bagasse ash throughout the test period. Bagasse ash blended mortars show reduced compressive strength at day 1 of age due to retarding effect of the ash. At early ages, filler effects dominate, leading to increased and sometimes also a faster reaction of the clinker

phases due to more space relative to the amount of clinker and increased nucleation rates [71], [65], [72]. Berodier [20] also found that the slower reaction of SCMs makes the SCM only contribute significantly after the main clinker reactions. The pozzolanic reaction starts to become significant between 1 and 3 days, as can be observed by the evolution of compressive strength for blended mortars. After 3 days, significant gains in compressive strength were observed.

Besides, the quartz blended mortars show comparable strength development on day 1 and lower strength then after as compared to others. Lin, Wang [73] found that the addition of quartz powder does not change the type of hydration product but has a dilution effect and crystal nucleation effect. This shows that the filler effect plays a role up to strengths developed by quartz replacement, and the remaining increment in strength beyond the reference sample is due to the pozzolanic reactivity of the bagasse ash.

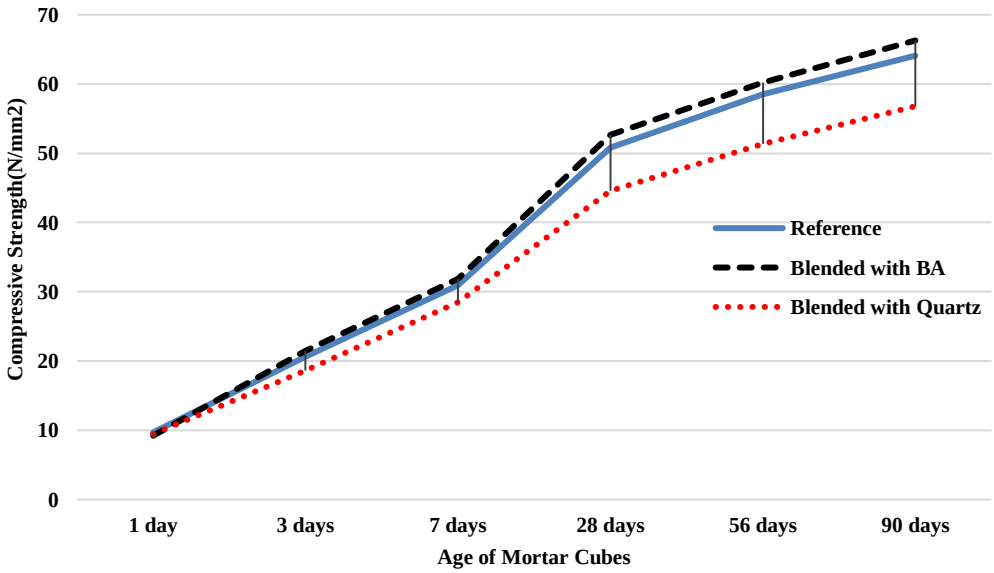

Fig. 9. Compressive strength development of mortar cubes at different ages

Snellings and Scrivener [22] in their study of SCMs blended system found that all blended cement shows lower strengths at day 1 of hydration than the reference OPC. However, all blended cement except the quartz filler surpassed the OPC reference over the long term. The timing at which the reference is surpassed depends on the reactivity of the SCM. Similar results were found, as shown above in Fig. 9.

Correlation Between Tests and Compressive Strength Development

Four different SCM screening tests were applied to a representative sample of bagasse ash blended and reference mixes. The results of each test were compared with compressive strength. A correlation was found between tests and compressive strength development.

A microstructure study using XRD analysis showed fewer peaks in the reference sample than the blended at an early age. This indicates the presence of more reactions in the reference sample. Besides, more compounds that contribute to strength were observed in the reference sample. All these make the reference sample have better compressive strength on day 1. Similar results were found in compressive strength measurement on day 1.

High bound water was found in the reference samples showing the presence of higher reactivity than the blended sample on day 1. Having higher reactivity implies more strength.

Likewise, at an early age (≤ 1 day), a slightly higher compressive strength was found in reference samples showing higher reactivity.

At an early age, more or less similar cumulative heat of hydration (181J/g and 184J/g) between the blended and reference samples were observed and increased during later days. Similarly, compressive strength development of the blended and reference mortar cubes (9.22 and 9.69MPa) show a similar increment on day 1 and a significant increment then after. The difference in heat of hydration between the two samples increased in later days. Similarly, the difference in compressive strength development between the two samples increased in later days.

A strong linear correlation was found between the heat of hydration and compressive strength on days 1, 3, and 7 in blended (R^2 = 0.9869) and reference samples (R^2 = 0.9734). This is consistent with the findings by Li, Snellings [26] on supplementary cementitious materials. Londono-Zuluaga, Gholizadeh-Vayghan [31] also found a strong correlation value of 0.87 for natural pozzolana (fly ash and slags) with compressive strength. The relationship between Compressive Strength Development and Cumulative Heat of Hydration on Days 1, 3 and 7 is shown in Fig. 10 below.

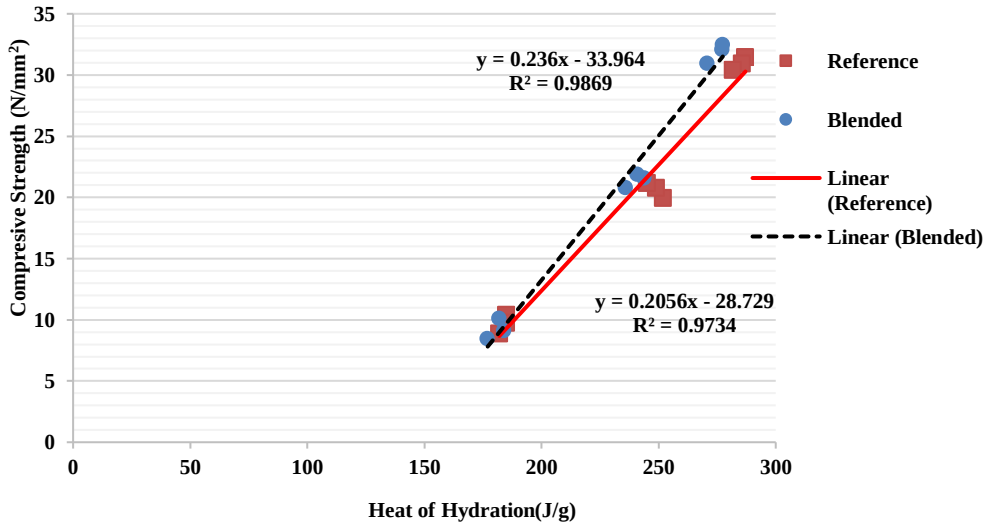

Fig. 10. Relationship between compressive strength development and cumulative heat of hydration on days 1, 3 and 7

Results from the determination of PABA also strengthen the above findings and confirm the presence of pozzolanic reactivity of the bagasse ash. The above results correspond to the findings of other researchers. They also correlated well with compressive strength development and were coherent with each other.

Conclusion

The demand for construction materials increases while resources are limited. Production of those materials causes environmental pollution and requires much energy. This triggers the need for alternative construction materials that are economically, technically, and environmentally feasible. A detailed study is mandatory to achieve this goal. This study was conceived with those objectives and investigated the pozzolanic reactivity of bagasse ash thoroughly.

The proposed method met all the criteria of the SCM screening test. It was also in agreement with the findings of PABA and correlated well with compressive strength development. Results were achieved rapidly, and the findings were reliable. The testing methods were also relevant and found to give a coherent result.

Findings show that blending made the paste require more water; to enhance the setting time; to have more peaks in a narrower range position of °2θ (11.396 - 45.921° of 2θ) and with Aluminum containing compounds; to have a lower average crystallite size (16.46ηm) and lower diffraction angle; lower cumulative heat flow (275.18J/g) and lower maximum rate of heat flow (69.41J/gh) within 170hrs; lower bound water content (2.58% (gram)) on day 1; and higher compressive strength after day 1 than the reference sample. The PABA was also found to be 346.08mg of $Ca(OH)_2$ per gram of bagasse ash.

Results obtained in this study clearly show the existence of pozzolanic reactivity of the bagasse ash while partially replacing cement. Due to this, the bagasse ash as cement replacing material provides additional improvements in strength and reduction in the heat of hydration properties.

The findings of this study are consistent with the findings of other similar studies conducted. The abundance of bagasse ash as industrial waste, the pozzolanic reactivity, and the technical advantages that the bagasse ash showed during the studies are promising findings that support an effort made to utilize this material in a standardized form.

Therefore, further studies need to be done on the scale-up practical implementations on site and Life Cycle Assessment (LCA) to evaluate the environmental impact of using bagasse ash thoroughly with accounting for all stages of the production process, transportation, and end-of-life scenarios need to be encouraged to reinforce this effort and to optimize utilization and compatibility of the material. Promotion on the use of bagasse ash in concrete need to be done and codes and specifications need to be updated to reflect the latest knowledge on their performance and environmental benefits. Moreover, continuous research and policy support can facilitate the widespread adoption of bagasse ash in the construction industry.

However, there are certain limitations associated with the use of bagasse ash in concrete, such as the variability of their chemical composition and availability in different regions. Besides, the interaction of bagasse ash with other concrete ingredients may require careful consideration and adequate quality control measures during concrete production. In spite of these limitations, the prospects for the use of bagasse ash in concrete appear promising.

Acknowledgments

Messobo Cement Factory and the Ethiopian Public Health Institute are acknowledged for their cooperation.

References

[1] Zaheer, M.M. and M. Tabish, *The durability of concrete made up of sugar cane bagasse ash (SCBA) as a partial replacement of cement: a review.* **Arabian Journal for Science and Engineering**, 2023. **48**(4): p. 4195-4225. https://doi.org/10.1007/s13369-023-07698-9.

[2] Li, Y., et al., *Utilization of sugarcane bagasse ash (SCBA) in construction technology: A state-of-the-art review.* **Journal of Building Engineering**, 2022. **56**: p. 104774. https://doi.org/10.1016/j.jobe.2022.104774.

[3] Jahanzaib Khalil, M., M. Aslam, and S. Ahmad, *Utilization of sugarcane bagasse ash as cement replacement for the production of sustainable concrete – A review.* **Construction and Building Materials,** 2021. **270**(121371): p. 14. https://doi.org/10.1016/j.conbuildmat.2020.121371.

[4] Knoema. *World - Sugar cane production quantity in 2022*. 2024 March 13, 2024]; Available from: https://knoema.com/atlas/World/topics/Agriculture/Crops-Production-Quantity-tonnes/Sugar-cane-production.

[5] Miranda, N.T., et al., *Sugarcane bagasse pyrolysis: A review of operating conditions and products properties.* **Renewable and Sustainable Energy Reviews**, 2021. **149**: p. 111394. https://doi.org/10.1016/j.rser.2021.111394.

[6] Ethiopian-Sugar-Corporation, *Ethiopian Sugar Corporation*, in *Ethiopian Sugar Industry Profile*, **Corporate-Communication-Executive-Office**, Editor 2019, Ethiopian Sugar Corporation: Addis Ababa. https://www.slideshare.net/meresaf/ethiopian-sugar-industry-profile-166554323 Accessed on May 25, 2024

[7] FDRE, M.o.I., *Ethiopian Cement Industry Development Strategy 2015-2025*, **M.o. Industry**, Editor 2015: Addis Ababa, Ethiopia. p. 161.

[8] Rajasekar, A., et al., *Durability characteristics of Ultra High Strength Concrete with treated sugarcane bagasse ash.* **Construction and Building Materials**, 2018. **171**: p. 350-356. https://doi.org/10.1016/j.conbuildmat.2018.03.140.

[9] Praveenkumar, S., G. Sankarasubramanian, and S. Sindhu, *Strength, permeability and microstructure characterization of pulverized bagasse ash in cement mortars.* **Construction and building materials**, 2020. **238**: p. 117691. https://doi.org/10.1016/j.conbuildmat.2019.117691.

[10] Shafiq, N., et al. *Effects of sugarcane bagasse ash on the properties of concrete*. in ***Proceedings of the Institution of Civil engineers-engineering Sustainability***. 2016. Thomas Telford Ltd. https://doi.org/10.1680/jensu.15.00014.

[11] Memon, S.A., et al., *Use of processed sugarcane bagasse ash in concrete as partial replacement of cement: mechanical and durability properties.* **Buildings**, 2022. **12**(10): p. 1769. https://doi.org/10.3390/buildings12101769.

[12] Setayesh Gar, P., N. Suresh, and V. Bindiganavile, *Sugar cane bagasse ash as a pozzolanic admixture in concrete for resistance to sustained elevated temperatures.* **Construction and Building Materials**, 2017. **153**: p. 929–936. http://dx.doi.org/10.1016/j.conbuildmat.2017.07.107.

[13] Batool, F., A. Masood, and M. Ali, *Characterization of sugarcane bagasse ash as pozzolan and influence on concrete properties.* **Arabian Journal for Science and Engineering**, 2020. **45**: p. 3891-3900. https://doi.org/10.1007/s13369-019-04301-y.

[14] Cordeiro, G.C., P.V. Andreao, and L.M. Tavares, *Pozzolanic properties of ultrafine sugar cane bagasse ash produced by controlled burning.* **Heliyon**, 2019(5): p. 6. https://doi.org/10.1016/j.heliyon.2019.e02566.

[15] Andreão, P.V., et al., *Sustainable use of sugarcane bagasse ash in cement-based materials.* **Green Materials**, 2019. **7**(2): p. 61-70. https://doi.org/10.1680/jgrma.18.00016.

[16] Rossignolo, J.A., et al., *Improved interfacial transition zone between aggregate-cementitious matrix by addition sugarcane industrial ash.* **Cement and Concrete Composites**, 2017. **80**: p. 157-167. https://doi.org/10.1016/j.cemconcomp.2017.03.011.

[17] Kolawole, J.T., et al., *State-of-the-art review on the use of sugarcane bagasse ash in cementitious materials.* **Cement and Concrete Composites**, 2021. **118**(103975): p. 25. https://doi.org/10.1016/j.cemconcomp.2021.103975.

[18] Wi, K., et al., *Use of an agricultural by-product, nano sized Palm Oil Fuel Ash as a supplementary cementitious material.* **Construction and Building Materials**, 2018. **183**: p. 139-149. https://doi.org/10.1016/j.conbuildmat.2018.06.156.

[19] Snellings, R., *Solution-Controlled Dissolution of Supplementary Cementitious Material Glasses at pH 13: The Effect of Solution Composition on Glass Dissolution Rates.* **Journal of the American Ceramic Society**, 2013. **96**(8): p. 2467–2475. https://doi.org/10.1111/jace.12480.

[20] Berodier, E.M.J., *Impact of the supplementary cementitious materials on the kinetics and microstructural development of cement hydration*, in *À LA FACULTÉ DES SCIENCES ET TECHNIQUES DE L'INGÉNIEUR, LABORATOIRE DES MATÉRIAUX DE CONSTRUCTION*, 2015, ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE: Suissie. https://infoscience.epfl.ch/record/204690?v=pdf

[21] Snellings, R., *Assessing, understanding and unlocking supplementary cementitious materials.* **RILEM Technical Letters**, 2016. **1**: p. 50-55. https://doi.org/10.21809/rilemtechlett.2016.12.

[22] Snellings, R. and K.L. Scrivener, *Rapid screening tests for supplementary cementitious materials: past and future.* **Materials and Structures**, 2016. **49**(8): p. 3265-3279. https://doi.org/10.1617/s11527-015-0718-z.

[23] Scrivener, K.L., et al., *TC 238-SCM: hydration and microstructure of concrete with SCMs.* **Materials and Structures**, 2015. **48**(4): p. 835-862. https://doi.org/10.1617/s11527-015-0527-4.

[24] Moosberg-Bustnes, H., B. Lagerblad, and E. Forssberg, *The function of fillers in concrete.* **Materials and Structures**, 2004. **37**(74). https://link.springer.com/article/10.1007/BF02486602.

[25] Kaur, A., *The effect of properties of fly ash on strength and microstructure development of mortars*, in *Department of Civil Engineering*, 2016, Indian Institute of Technology Delhi.

[26] Li, X., et al., *Reactivity tests for supplementary cementitious materials: RILEM TC 267-TRM phase 1.* **Materials and Structures**, 2018. **51**(151): p. 14. https://doi.org/10.1617/s11527-018-1269-x.

[27] Avet, F., et al., *Development of a new rapid, relevant and reliable (R3) test method to evaluate the pozzolanic reactivity of calcined kaolinitic clays.* **Cement and Concrete Research**, 2016. **85**: p. 1-11. http://dx.doi.org/10.1016/j.cemconres.2016.02.015.

[28] Avet, F.H., *Investigation of the grade of calcined clays used as clinker substitute in Limestone Calcined Clay Cement (LC3)*, in *LABORATOIRE DES MATÉRIAUX DE CONSTRUCTION*, 2017, ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE: Suisse. p. 169. https://core.ac.uk/download/pdf/148034255.pdf

[29] Jhatial, A.A., I. Nováková, and E. Gjerløw, *A review on emerging cementitious materials, reactivity evaluation and treatment methods.* **Buildings**, 2023. **13**(2): p. 526.

https://doi.org/10.3390/buildings13020526.

[30] Martirena, F., B. Middendorf, and H. Budelman, *use of wastes of the sugar industry in lime-pozzolana binder. A study of the reaction.* **Cement & Concrete Research**, 1998(11): p. 1525-1536. https://doi.org/10.1016/S0008-8846(98)00130-6

[31] Londono-Zuluaga, D., et al., *Report of RILEM TC 267-TRM phase 3: validation of the R3 reactivity test across a wide range of materials.* **Materials and structures**, 2022. **55**(5): p. 142. https://doi.org/10.1617/s11527-022-01947-3.

[32] ASTM-C1897, *Standard Test Methods for Measuring the Reactivity of Supplementary Cementitious Materials by Isothermal Calorimetry and Bound Water Measurements*, in **Annual Book of ASTM Standards,** 2020, ASTM International: West Conshohocken, PA. p. 5. https://doi.org/10.1520/C1897-20.

[33] Avet, F., et al., *Report of RILEM TC 267-TRM phase 2: optimization and testing of the robustness of the R3 reactivity tests for supplementary cementitious materials.* **Materials and Structures**, 2022. **55**(3): p. 1-14. https://doi.org/10.1617/s11527-022-01928-6.

[34] ES-EN-197-1, *Cement - Part 1: Composition, specifications and conformity criteria for common cements*, in **Ethiopian Standard**, 2013, Ethiopian Standards Agency(ESA): Addis Ababa, Ethiopia. p. 37.

[35] Société-Nouvelle-du-Littoral-S.N.L., *Safety Data Sheet For Siliceous Standard Sand*, S.N.d. Littoral, Editor 2019, Société Nouvelle du Littoral (S.N.L.): Leucate, France. http://www.standard-sand.com/wp-content/uploads/2019/07/1309-Safety-data-Sheet-for-S.N.L-silica-Standard-Sands-March-2019.pdf

[36] ASTM-C204, *Standard Test Method for Heat of Hydration of Hydraulic Cement*, in **Annual Book of ASTM Standards,** 2011E1, ASTM International: West Conshohocken, PA. p. 10. https://doi.org/10.1520/C0204-11E01.

[37] ACI-211.1-91, *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*, in **ACI Committee Report 211,** 2002, American Concrete Institute: USA. p. 10.

[38] ASTM-C618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, in **Annual Book of ASTM Standards,** 2012a, ASTM International: West Conshohocken, PA. p. 5. https://doi.org/10.1520/C0618–12a.

[39] ASTM-C187, *Standard Test Method for Amount of Water Required for Normal Consistency of Hydraulic Cement Paste*, in **Annual Book of ASTM Standards,** 2011, ASTM International: West Conshohocken, PA. p. 3. https://doi.org/10.1520/C0187-11.

[40] ASTM-C191, *Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle*, in **Annual Book of ASTM Standards,** 2013, ASTM International: West Conshohocken, PA. p. 8. https://doi.org/10.1520/C0191-13.

[41] Amin, N.-u., *Use of Bagasse Ash in Concrete and Its Impact on the Strength and Chloride Resistivity.* **Journal of Materials in Civil Engineering** @ ASCE, Technical Note, 2011. **23**(5). http://doi:10.1061/(ASCE)MT.1943-5533.0000227

[42] Ganesan, K., K. Rajagopal, and K. Thangavel, *Evaluation of bagasse ash as supplementary cementitious material.* **Cement & Concrete Composites**, 2007. **29**: p. 515–524. https://doi.org/10.1016/j.cemconcomp.2007.03.001.

[43] Hailu, B. and A. Dinku, *Application of sugarcane bagasse ash as a partial cement replacement material.* **Journal of EEA**, 2012. **29**(1): p. 1-12.

[44] EN-196-3, *Methods of testing cement — Part 3: Determination of setting times and soundness*, in **European Standard**, 2005, European Committee for Standardization (CEN).

[45] Snellings, R., A. Salze, and K. Scrivener, *Use of X-ray diffraction to quantify amorphous supplementary cementitious materials in anhydrous and hydrated blended cements.* **Cement and Concrete Research**, 2014. **64**: p. 89-98. http://dx.doi.org/10.1016/j.cemconres.2014.06.011.

[46] Juenger, M.C., R. Snellings, and S.A. Bernal, *Supplementary cementitious materials: New sources, characterization, and performance insights.* **Cement and Concrete Research**, 2019. **122**: p. 257-273. https://doi.org/10.1016/j.cemconres.2019.05.008.

[47] Feret, F.R., *Determination of the crystallinity of calcined and graphitic cokes by X-ray diffraction.* **Analyst**, 1998. **123**(4): p. 595-600. https://doi.org/10.1039/A707845E

[48] Varin, R.A., J. Bystrzycki, and A. Calkab, *Effect of annealing on the microstructure, ordering and microhardness of ball milled cubic (L12) titanium trialuminide intermetallic powder.* **Intermetallics**, 1999. **7**(7): p. 785-796. https://www.academia.edu/42975579/Effect_of_annealing_on_the_microstructure_ordering_and_microhardness_of_ball_milled_cubic_L12_titanium_trialuminide_intermetallic_powder

[49] Sedaghat, A., *Cement Heat of Hydration and Thermal Control*, in *Department of Civil and Environmental Engineering, College of Engineering, University of South Florida,* 2016, University of South Florida, Scholar Commons. p. 143. http://scholarcommons.usf.edu/etd/6142.

[50] Sedaghat, A., A. Zayed, and P. Sandberg, *Measurement and Prediction of Heat of Hydration of Portland Cement Using Isothermal Conduction Calorimetry.* **Journal of Testing and Evaluation**, 2013. **41**(6): p. 943-950. https://doi.org/10.1520/JTE20120272.

[51] Wadsö, L., *Isothermal calorimetry for the study of cement hydration. (Report TVBM (Intern 7000-rapport);*, 2001, Division of Building Materials, LTH, Lund Institute of Technology, Lund University.: Lund University. p. 37. https://lucris.lub.lu.se/ws/files/4471618/4388332.pdf

[52] Wang, K., et al., *Developing a Simple and Rapid Test for Monitoring the Heat Evolution of Concrete Mixtures for Both Laboratory and Field Applications*, 2007, Center for Transportation Research and Education Iowa State University. p. 62. https://cdn-wordpress.webspec.cloud/intrans.iastate.edu/uploads/2018/03/calorimeter.pdf

[53] ASTM-C1702, *Standard Test Method for Measurement of Heat of Hydration of Hydraulic Cementitious Materials Using Isothermal Conduction Calorimetry*, in **Annual Book of ASTM Standards,** 2015a, ASTM International: West Conshohocken, PA. p. 8. https://doi.org/10.1520/C1702-15A.

[54] ASTM-C186, *Standard Test Method for Heat of Hydration of Hydraulic Cement*, in **Annual Book of ASTM Standards**, 2015a, ASTM International: West Conshohocken, PA. p. 7. https://doi.org/10.1520/C0186-15A.

[55] Lura, P., F. Winnefeld, and X. Fang, *A simple method for determining the total amount of physically and chemically bound water of different cements.* **Journal of Thermal Analysis and Calorimetry**, 2017. **130**(2): p. 653-660. https://doi.org/10.1007/s10973-017-6513-z.

[56] Taylor, H.F., **Cement Chemistry**. 1997: Thomas Telford.
[57] ASTM-C642, *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*, in **Annual Book of ASTM Standards,** 2013, ASTM International: West Conshohocken, PA. p. 3. https://doi.org/10.1520/C0642-13.
[58] Ferraz, E., et al., *Pozzolanic Activity of Metakaolins By The French Standard of the Modified Chapelle Test: A Direct Methodology.* **Acta Geodyn. Geomater.**, 2015. **12**(3(179)): p. 289-298. http://doi:10.13168/AGG.2015.0026.
[59] EN-196-1, *Methods of testing cement — Part 1: Determination of Strength*, in **European Standard**, 2005, European Committee for Standardization (CEN). p. 36.
[60] Qing, X., et al., *Characteristics and Applications of Sugar Cane Bagasse Ash Waste in Cementitious Materials.* **Materials**, 2019. **12**(39). https://doi.org/10.3390/ma12010039.
[61] Maldonado-García, M.A., et al., *The influence of untreated sugarcane bagasse ash on the microstructural and mechanical properties of mortars.* **Materiales de Construcción**, 2018. **68**(329): p. 15. https://doi.org/10.3989/mc.2018.13716.
[62] Fekadu, L., *Increasing Compressive Strength Property of Bagasse Ash Blended Concrete by Using Chemical Activator (NaSO4)*, in *School of Civil and Environmental Engineering*, 2019, Addis Ababa University, Addis Ababa Institute of Technology: Addis Ababa.
[63] Chusilp, N., C. Jaturapitakkul, and K. Kiattikomol, *Utilization of bagasse ash as a pozzolanic material in concrete.* **Construction and Building Materials,** 2009. **23**(11): p. 3352-3358. https://doi.org/10.1016/j.conbuildmat.2009.06.030.
[64] Feng, Y., et al., *Hydration and strength development in blended cement with ultrafine granulated copper slag.* **PLOS ONE**, 2019. **14**(4). https://doi.org/10.1371/journal.pone.0215677.
[65] Alujas, A., et al., *Pozzolanic reactivity of low grade kaolinitic clays: Influence of calcination temperature and impact of calcination products on OPC hydration.* **Applied Clay Science**, 2015. **108**: p. 94-101. http://dx.doi.org/10.1016/j.clay.2015.01.028.
[66] Massazza, F., *Pozzolana and Pozzolanic cements*, in **Lea's chemistry of cement and concrete**, 3rd, Editor. 1998. p. 471–635. https://doi:10.1016/b978-075066256-7/50022-9
[67] Prochońa, P. and T. Piotrowskia, *Bound water content measurement in cement pastes by stoichiometric and gravimetric analyses.* **Journal of Building Chemistry**, 2016. **1**: p. 18-25. http://dx.doi.org/10.17461/j.buildchem.2016.103.
[68] Cordeiro, G., et al., *Pozzolanic activity and filler effect of sugar cane bagasse ash in Portland cement and lime mortars.* **Cement and Concrete Composites**, 2008. **30**(5): p. 410-418. https://doi.org/10.1016/j.cemconcomp.2008.01.001.
[69] Quarcioni, V.A., et al., *Indirect and direct Chapelle's methods for the determination of lime consumption in pozzolanic materials.* **IBRACON Structures and Materials Journal**, 2015. **8**(1): p. 1-7. http://dx.doi.org/10.1590/S1983-41952015000100002
[70] Ahmad, S., et al., *Properties of self-consolidating concrete made utilizing alternative mineral fillers.* **Construction and Building Materials**, 2014. **68**: p. 268-276. http://dx.doi.org/10.1016/j.conbuildmat.2014.06.096.
[71] Lothenbach, B., K. Scrivener, and R.D. Hooton, *Supplementary cementitious materials.* **Cement and Concrete Research**, 2011. **41**: p. 1244–1256. https://doi.org/10.1016/j.cemconres.2010.12.001.

[72] Cyr, M., P. Lawrence, and E. Ringot, *Efficiency of mineral admixtures in mortars: Quantification of the physical and chemical effects of fine admixtures in relation with compressive strength.* **Cement and Concrete Research**, 2006. **36**: p. 264–277. https://doi.org/10.1016/j.cemconres.2005.07.001.

[73] Lin, R.-S., X.-Y. Wang, and G.-Y. Zhang, *Effects of Quartz Powder on the Microstructure and Key Properties of Cement Paste.* **Sustainability**, 2018. **10**(10): p. 3369.
https://doi.org/10.3390/su10103369.

Received: February 15, 2024
Accepted: July 10, 2024