

**ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL
ENGINEERING**



**INVESTIGATION OF THE POZZOLANIC REACTIVITY OF
BAGASSE ASH VIA COMPRESSIVE STRENGTH
DEVELOPMENT**

A Thesis in Structural Engineering

By **DANIEL ALEMAYEHU CHEKOL**

October 16, 2020

Addis Ababa

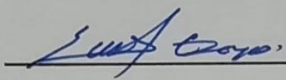
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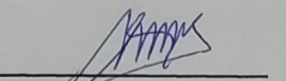
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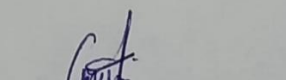
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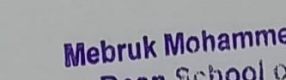
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UNDERTAKING

I certify that research work titled “Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged/referred.

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ABSTRACT

Currently, the construction sector demands more materials with good quality than ever. On the contrary, materials are scarce and depleting. So, the need for alternative construction materials that are renewable, cheaper, and eco-friendly is increasing. Studies on partial and full replacement of the most widely used materials are timely. The general objective of this study is to investigate the pozzolanic reactivity of bagasse ash via compressive strength development while partially replacing cement at 10% by volume.

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. Test results were compared with the strength development and with the pozzolanic activity determination test. Furthermore, the characterization of pastes was also done.

The blending of cement made the paste to require more water and enhance the initial and final setting time. In reference samples, the cumulative heat flow was 284.02J/g at 170hrs and the maximum rate of heat flow was 80.08J/gh which was found at 4 minutes and 14 seconds. Whereas in blended samples the cumulative heat flow decreased to 275.18J/g at 170hours and the maximum rate of heat flow decreased to 69.41J/gh which was found delayed to 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 2.58% bound water(gram) content whereas the reference samples were found to have 2.89% bound water(gram) content on day 1. Compressive strength at an early age (≤ 1 day) is lower in the bagasse ash (BA) blended mortar cubes. But, during later days compressive strength of BA blended mortar cubes were the highest and quartz blended mortar cubes were the lowest. In addition to this, the pozzolanic activity of bagasse ash (PABA) was found to be 346.08mg of Ca(OH)_2 per gram of bagasse ash. The proposed R^3 method meets all the criteria of SCM screening tests and well correlated to the compressive strength development. Results of the R^3 test were also in accordance with the findings of the PABA.

All these confirmed the presence of pozzolanic reactivity of the bagasse ash and results were found to be coherent and in agreement with each other. Therefore, improvements in the concrete property while bagasse ash is used as a partial replacing material is partly due to the pozzolanic reaction of the bagasse ash.

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ACRONYMS

AA	Addis Ababa
AAiT	Addis Ababa Institute of Technology
ACI	American Concrete Institute
AFNOR	Association Française de Normalisation
ASTM	American Society for Testing and Materials
BA	Bagasse Ash
BS	British Standard
CEN	Commission for European Normalization
CH	Portlandite or Calcium Hydroxide
Cu α	Copper Radiation Source
EN	European Standard
ES	Ethiopian Standard
ISO	International Organization for Standardization
LEMVP	Laboratoire des Essais des Matériaux de la Ville de Paris
LOI	Loss on Ignition
NMR	Nuclear Magnetic Resonance
OPC	Ordinary Portland Cement
PABA	Pozzolanic Activity of Bagasse Ash
SCBA	Sugar cane Bagasse Ash
SCM	Supplementary Cementitious Material

SEM	Scanning Electron Microscopy
SNL	Société Nouvelle du Littoral
TGA	Thermogravimetric Analysis
UK	United Kingdom
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

Chemical Formula

C ₃ S	Tricalcium Silicate
C ₂ S	Dicalcium Silicate
C ₃ A	Tricalcium Aluminate
C ₄ AF	Tetracalcium Aluminoferrite
C-S-H	Calcium Silicate Hydrate
C-A-S-H	Calcium–Alumino–Silicate–Hydrate
C\$H ₂	Gypsum
Aft	Ettringite (Ett)
AFm	Monosulfate (Ms)
Hg	Hydrogarnet

CHAPTER 1 INTRODUCTION

1.1 Background

The rapidly increasing construction sector demands more construction materials with good quality than ever. In the process of satisfying this need, the environment is degrading and resources are depleting from time to time. To cope up with the increasing need, the utilization of alternative construction 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 material are important to secure the sustainability of production. In this study, partial replacement of cement with bagasse ash is investigated. Partial replacement of cement with bagasse ash brings additional benefit to the concrete (Hailu and Dinku 2012), (Amin 2011), (Rajasekar, Arunachalam et al. 2018). But the cause of this property improvement is not well investigated. Investigating this gap is the focus of this study by examining the pozzolanic reactivity of bagasse ash in concrete.

According to Snellings and Scrivener (2016), studies on pozzolanic reactivity need a suitable test method that is practical and simple in terms of use and cost which gives rapid, repeatable, and reproducible results. The method should also be generally applicable to all SCM types and enable easy comparison between the test result and the quality criterion mostly compressive strength development (Snellings and Scrivener 2016).

Sugar cane bagasse is a by-product of the sugar factories obtained after extracting economical sugar from sugar cane. Bagasse ash is produced by burning the bagasse at high temperatures. The bagasse ash has a lower density, larger specific surface area, and lower price than cement (Hailu and Dinku 2012).

In previous studies, it was found that partially replacing cement with bagasse ash improves the property of concrete. Optimum improvements were achieved in compressive strength, flexural strength, split tensile strength, and resistance to Chloride ion penetration at a 10%

level of replacement (Hailu and Dinku 2012), (Amin 2011), (Rajasekar, Arunachalam et al. 2018).

In addition to this, cement production takes an immense amount of energy and releases a significant amount of CO₂ during production. On the contrary, bagasse ash does not need energy for production and has no release of CO₂. It is environment-friendly and can be supplied sustainably. In the meantime, utilizing bagasse ash as a replacement material plays an important role in managing industrial wastes.

According to Snellings and Scrivener (2016), supplementary cementitious materials (SCMs) contribute to the development of compressive strength by reacting with the Portland cement hydration products and fill the pore space previously occupied by the water. 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 SCMs screening tests (Snellings and Scrivener 2016).

Thus, this study investigated the pozzolanic reactivity of bagasse ash via compressive strength development. It was done by measuring heat flow using an Isothermal calorimeter and with bound water determination test using oven treatment. Results were compared with compressive strength development of mortar cubes and with the determined amount of pozzolanic activity of bagasse ash (PABA). Characterization of the hydration products was also made using X-Ray Diffraction (XRD) analysis for a better understanding of the reactivity of bagasse ash.

1.2 Statement of the Problem

Many studies have been done on blended systems with SCMs from different views. But the generic microstructural development of blended systems is still not clearly understood. Researchers give different explanations for this. Among the many explanations, Berodier (2015) gives the following as:

- the mechanisms controlling the hydration of Portland cement are not totally understood. So, it is difficult to identify the changes in a more complex system.

- 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.
- although the SCMs have a slower reaction, they contribute to cement hydration from the very beginning. Most of the studies reported long-term changes caused by the introduction of SCM. However, the early hydration is a very important step for the later properties. So, bagasse ash being one of the SCMs, it is mandatory to study its effect on the totality of the hydration process.

Partially replacing clinker with SCMs helps to reduce both costs and CO₂ emissions related to cement production. The cement industry contributes 5-8% of the global CO₂ emissions and in 2050 the share might rise beyond 25% if no further action is taken (Snellings 2016). So, there is a clear challenge on how emissions will be kept at this point or even lower.

This study contributes to strengthening the link between waste management and construction material production. According to Snellings (2016), there is a high need to have less carbon-intensive and more circular economies which sets the scene for a diversified future of localized sustainable binders. So, identification of new research, advancing characterization methods, and a more generalized understanding of reaction mechanisms for cementitious binders are important (Snellings 2016).

In previous studies, it was found that replacing some portions of cement with sugar cane bagasse ash brought improvement in compressive strength, flexural strength, workability, resistance to chloride ion penetration and decreases the rate of water absorption property of concrete (Amin 2011), (Hailu and Dinku 2012), (Shruthi, Eramma et al. 2014), (Aishwarya, Dakshayini et al. 2016), (Rajasekar, Arunachalam et al. 2018), (Setayesh Gar, Suresh et al. 2017), (Ganesan, Rajagopal et al. 2007). All these improvements were obtained up to a 10% level of replacement.

The chemical composition of bagasse ash depends on the area of the sugar cane plantation farm. In the Ethiopian study, the bagasse ash produced locally by Wonji sugar factory was shown optimum improvement on the property of concrete at a 10% replacement level (Hailu 2011).

However, it is not clearly known how this improvement in concrete property is achieved. It may be due to the filler effect or pozzolanic reactivity of the bagasse ash. Acting as a filler implies that the bagasse ash may fill the voids created due to cement reaction or may create a nucleation site for the reaction. Pozzolanic reactivity is explained by forming a hydration product. Characterization of the hydration product needs to be done to investigate the reactivity of the bagasse ash. Therefore, this study investigated the causes of concrete property improvement via compressive strength development using more powerful and reliable characterization techniques which help to better understand and exploit bagasse ash reactivity.

1.3 Objective

1.3.1 General Objective

The general objective of this study is to investigate the pozzolanic reactivity of bagasse ash via compressive strength development while partially replacing cement.

1.3.2 Specific Objectives

The specific objectives of this study are:

- To measure consistency and setting time in reference and blended cement pastes.
- To characterize the microstructure of hardened cement paste in reference and blended samples.
- To measure the heat of hydration development in reference and blended cement mix.
- To determine the amount of bound water in hardened reference and blended cement pastes.
- To determine the pozzolanic activity of bagasse ash.
- To determine the compressive strength development in reference, bagasse ash blended, and quartz blended mortar cubes at different ages.
- To establish a correlation between tests and relative strength development.

1.4 Research Questions

The research questions for the study are:

- How much water needed and setting time taken by reference and blended cement mix?
- What does the microstructure of hardened cement paste comprise in reference and blended samples?
- How much heat is evolved from the hydration of reference and blended cement samples?
- How much bound water is found in the hardened paste samples?
- How much is the pozzolanic activity of bagasse ash?
- How much is the compressive strength development in reference, bagasse ash blended, and quartz blended mortar cubes at different ages?
- Do tests correlate with compressive strength development on mortar cubes?

1.5 Significance of the Study

Partially or fully replacing cement with renewable materials like bagasse ash will save a significant amount of virgin material and production energy, improve the property of concrete, and play an important role in waste management. But this needs a careful and detailed study since the utilization of replacing materials have their own limitations and constraints. For efficient and effective utilization of the bagasse ash as a replacement material, determination of the replacement level and studying the mechanisms formed during hydration is mandatory. In this study, mechanisms formed during hydration are covered. Thus, this study contributes to the full utilization of the material and thus to add a significant amount of benefit to the construction industry.

This study also hopes to add knowledge on the subject matter and create interest in researchers to undertake a further investigation of bagasse ash and other SCMs. The findings and recommendations of the research can be used by those who need to use pozzolanic material.

1.6 Scope of the Study

Though there is a slight difference in chemical composition between the bagasse ash produced at different cultivation areas, results are more or less similar. In this study, the bagasse ash produced by Wonji-Shoa Sugar Factory is used.

In this study 10% level of replacement of cement is used since the optimal level of property improvement of concrete is achieved at this point. To investigate reactivity a detailed study was made at this point of replacement level.

1.7 Organization of the Paper

This paper is organized into six chapters. The first chapter deals with the introduction part reflecting on the background of the study, statement of the problem, objectives of the study, research questions, significance of the study, and scope of the study. The second chapter discusses the review of related literature. Chapter three explains the materials and experimental program used in the research. The fourth chapter describes the results and discussion of the findings of the study by relating to previous works. Finally, conclusions and recommendations are given in chapter five.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

In this chapter, previous researches related to this study were reviewed. To give a good background for the study topics on Supplementary Cementitious Materials, Pozzolanic reactivity, methods of assessing pozzolanic reactivity, bagasse ash, availability of bagasse ash, and its significance for structural members was discussed. The literature on testing methods and methodology employed in this study, a summary of previously done studies related to the topic, and finally research gap was also discussed in this section.

2.2 Supplementary Cementitious Materials (SCMs)

SCMs are materials that have properties similar to cement and are widely used to partially replace Portland clinker in blended cement. When the clinker contents are further reduced without compromising the development of early strength, it necessitates a better assessment and enhancement of the reactivity of the available SCMs (Snellings 2013). Mostly they are by-products of industries or other natural processes.

The majority of SCMs are silicate-based materials. They are either latent hydraulic or pozzolanic. A latent hydraulic material can sustain its reaction with water without additional reagents upon activation. Whereas, a pozzolanic material requires additional portlandite (Snellings and Scrivener 2016).

When SCMs are blended with cement the performance of the reaction will be complex. According to Scrivener, Lothenbach et al. (2015), the complication is due to:

1. The physical presence of SCMs affects the extent and rate of reaction of the clinker component (discussed in the next section).
2. SCMs are usually amorphous with complex and varied mineralogy which makes them difficult to quantify by many classical techniques.

3. 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.

The utilization of SCMs in concrete is advantageous in many ways. According to Owaid, Hamid et al. (2012), the benefits of using SCMs in concrete are:

i - improve and increase:

- Rheological/flowability properties, making concrete easier to pump, place and finish;
- the strength of concrete; and
- the resistance to chloride ions and sulfate attack.

ii - reduce:

- the permeability to water and other fluids,
- the corrosion rate of embedded steel,
- the risk of delayed ettringite formation, and
- deleterious expansion due to the alkali-silica reaction.

On the other hand, there are also limitations on the utilization of SCMs. Berodier (2015) indicate limitations on the utilization of SCMs as:

- limited availability of good quality SCMs,
- has a maximal replacement level beyond which the strength decreases,
- has a slow strength development at an early age caused by slow reactivity.

Having a better understanding of the hydration process of SCMs helps to solve problems related to their limitation (Berodier 2015).

The utilization of SCMs has the above benefits and limitations and is still under study. The physical presence of SCMs has a filler effect and is discussed in the next section.

2.2.1 Filler Effect of SCMs

The filler effect is the physical presence of SCMs or even an inert material that impacts the reaction of the clinker phases. According to Scrivener, Lothenbach et al. (2015) and Berodier (2015), this effect has the following two components:

- (a) Dilution effect - the substitution of clinker by SCM makes the clinker grains fewer and this gives relatively more space for the formation of clinker hydrates and

therefore the degree of reaction of the clinker component will be significantly higher in the unsubstituted material.

- (b) Being a nucleation site - the surfaces of the SCM may act as nucleation sites for hydrates. This effect would have relatively minor for SCMs with a similar particle size distribution to that of Portland cement, but it can be important for fine materials such as silica fume, which has a significant acceleration effect on the hydration of the clinker (Berodier 2015).

2.3 Bagasse Ash

Sugar cane bagasse is an agro-fibrous waste after extraction of juice from the sugar cane. The major by-products of sugar are molasses, ethanol, and bagasse. Bagasse ash is found after burning this waste in an open-air. It exhibits pozzolanic property due to its large amount of Silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3) content.

The bagasse ash used by Hailu (2011) in his study of partial replacement of cement by bagasse ash was found to have a density of 2.16g/cm^3 and a Blain surface area of $4,716\text{cm}^2/\text{g}$ whereas the cement was found to have a density of 3.15g/cm^3 and a Blain surface area of $2,910\text{cm}^2/\text{g}$. This implies that bagasse ash replacement creates a better surface reaction area during mixing and lower weight concrete after casting. It also has a high percentage of Silica (65.58%) which is responsible for the pozzolanic property. Assuming that Silica reacts with components of cement during hydration which would be proved in this study later on.

2.3.1 Availability of Bagasse Ash

Bagasse ash is abundantly available in Ethiopia. A number of sugar factories are operating and many more are under construction in the country. These factories are producing bagasse ash as a by-product and dumping it as a waste. The potential production of bagasse ash by sugar factories is shown in Table 2.1 below.

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The currently operating sugar factories are Wonji Shoa, Metahara, Finchaa, Kessem, Tendaho, Arjo-Dedessa, Omo Kuraz 2, and Omo Kuraz 3. They have a total annual crushing capacity of 12,240,000 tons of sugarcane and 443,700 tons of bagasse ash.

Factories that are under construction are Omo Kuraz 1, Omo Kuraz 5, Tana Beles 1, Tana Beles 2, and Wolkayit. After completion, these factories are expected to have a total annual crushing capacity of 20,160,000 tons of sugarcane and 730,800 tons of Bagasse ash. After the completion of all factories, the country will have a total annual crushing potential of 32,400,000 tons of sugarcane and 1,174,500 tons of bagasse ash.

Table 2.1 Annual Sugar Cane Crushing Capacity and Expected Bagasse Ash Production By Factories When They Work at Full Capacity (Ethiopian-Sugar-Corporation 2019)

i. Currently Operating Sugar Factories with Crushing Capacity					
Factory	Location	Crushing Capacity per day (TCD)	Annual Crushing Capacity (Ton)	Bagasse (Ton)	Bagasse Ash (Ton)
Wonji Shoa	Oromia	6,250	1,500,000	435,000	54,375
Metehara	Oromia	5,372	1,289,280	373,891	46,736
Fincha	Oromia	12,000	2,880,000	835,200	104,400
Tendaho	Afar	13,000	3,120,000	904,800	113,100
Kessem	Afar	6,000	1,440,000	417,600	52,200
Arjo Dedessa	Oromia	8,000	1,920,000	556,800	69,600
Omo Kuraz 2	SNNPR	12,000	2,880,000	835,200	104,400
Omo Kuraz 3	SNNPR	12,000	2,880,000	835,200	104,400
Total		51,000	12,240,000	3,549,600	443,700
ii. Currently Under Construction Sugar Factories with Crushing Potential					
Omo Kuraz 1	SNNPR	12,000	2,880,000	835,200	104,400
Omo Kuraz 5	SNNPR	24,000	5,760,000	1,670,400	208,800
Beles 1	Amhara	12,000	2,880,000	835,200	104,400
Beles 2	Amhara	12,000	2,880,000	835,200	104,400
Wolkayit	Tigray	24,000	5,760,000	1,670,400	208,800
Total		84,000	20,160,000	5,846,400	730,800
Over All Total		135,000	32,400,000	9,396,000	1,174,500

According to Geremew (2017) from the total crushed sugarcane 28-30% will be bagasse and from this 11-14% estimated to be bagasse ash. Calculations were made based on these average percentages with an annual operational period of 240days in the above table.

From Table 2.1 it can be inferred that the country will have the potential of producing 1.17 Million tons of bagasse ash per year when factories run at full capacity. This shows that the utilization of bagasse ash as a cement replacing material can save a significant amount of cement every year. It can also be seen that bagasse ash is abundantly available.

2.3.2 Significance of Bagasse Ash as a Cement Replacing Material for Structural Members

Optimum property improvement on concrete was found at a 10% cement replacement level by bagasse ash. At this replacement level compressive, flexural, and split tensile strength increases (Hailu and Dinku 2012), (Shruthi, Eramma et al. 2014), (Aishwarya, Dakshayini et al. 2016), (Amin 2011), (Setayesh Gar, Suresh et al. 2017).

Based on the experimental study carried out by Aishwarya, Dakshayini et al. (2016) at 10% cement replacement level by bagasse ash, the compressive strength improved by 1.21 times and the splitting tensile strength improved by 1.04 times. The concrete also shows less permeability to chloride ions and thus improves durability. Improvements were also found on the ultimate load-carrying capacity of the beam by 1.075 times and on the maximum axial load carrying capacity of the column by 1.097 times.

Geremew (2017) also found similar results while cement is replaced by bagasse ash up to 10% in concrete production. The enhancement was made on compressive strength by 1.0123 times, flexural tensile strength by 1.0865 times at 28 days, flexural strength by 1.31 times.

Rajasekar, Arunachalam et al. (2018) also made experimental investigation using treated bagasse ash and found improvement in workability, compressive strength, resistance to chloride ion penetration, and also decrement in the rate of water absorption. So, they concluded that it is possible to use treated bagasse ash in the production of ultra-high-strength concrete with superior performance due to the pozzolanic action of treated bagasse ash.

Fly ash, natural pozzolans, and ground slag have lower heat of hydration than Portland cement. Using them will reduce the amount of heat built up in a concrete structure. Some pozzolans have a heat of hydration of only 40% that of Type I Portland cement. The reduction in temperature rise is especially beneficial in concrete used for massive structures. (PCA-Committee 2002).

In addition to controlling heat rise, natural pozzolans were used to improve resistance to sulfate attack and were among the first materials to be found to mitigate alkali-silica reaction (PCA-Committee 2002). Note that bagasse ash is one of the pozzolans.

Bagasse ash as a cement replacing material gives all these benefits to construction in general and structural members in particular than using Portland cement only as a binding material.

2.4 Quartz

Quartz is available in nature as raw material and as an industrial by-product. It is used in this study as a filler by replacing cement partially. According to Moosberg-Bustnes, Lagerblad et al. (2004) fillers used at different amounts of replacement and particle size distribution, show improvement in concrete property and microstructure. It helps to evaluate concrete property improvement due to the filler effect.

2.5 Pozzolanic Reactivity

SCMs contribute to the development of compressive strength by reacting with Portland cement hydration products and water to form hydration products that have low solubility and that fills the pore space previously occupied by the water (Snellings and Scrivener 2016).

SCMs hydrate with the hydration products of cement or in the presence of cement to produce additional CSH and other hydration products. This reaction is generally known as the pozzolanic reaction and such materials are also known as pozzolans. (Kaur 2016)

A pozzolanic material may be defined by its ability to react with calcium hydroxide. Therefore, the pozzolanic activity can be assessed by the extent and rate of the pozzolanic reaction. Before discussing pozzolanic reactivity, understanding the hydration of cement is important.

2.5.1 Hydration of Cement

Hydration of cement is a complex process and has not been fully understood until now. Researchers have been studying and made much progress through time. When cement and water reacted crystalline and semi-crystalline hydration products, capillary pores, air voids from incomplete compaction, and deliberate entrainment and remaining unreacted cement will be formed. It is assumed that the volume of entrapped and entrained air is expected to vary with time and the hydration products are expected to occupy the water-filled capillary pores (Wong and Buenfeld 2009). The schematic representation of the process is shown in Figure 2.1 below.

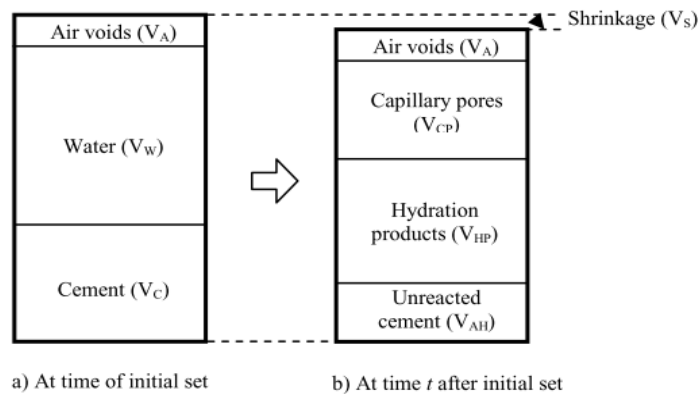


Figure 2.1 Schematic Representation of the Volumetric Proportions of the Main Components in Hardened Cement Paste (a) at the time of initial set and (b) at time t after setting. (Wong and Buenfeld 2009).

Portland cement reacts with water to form CSH (gel-like structure) and CH(portlandite). The portlandite reacts with pozzolana to form additional CSH. The simplified hydration progress of Portland cement is given in Table 2.2 below.

Table 2.2 Simplified Hydration Progress of Portland Cement Phases (Czarnecki, Broniewski et al. 1994) as cited by (Prochoña and Piotrowskia 2016).

Portland Cement	
Phases	Hydration
$C_3S = 3CaO \cdot 2SiO_2$	$2C_3S + 6H \rightarrow C_3S_2H_3 + 3Ca(OH)_2$
$C_2S = 2CaO \cdot SiO_2$	$2C_2S + 4H \rightarrow C_3S_2H_3 + Ca(OH)_2$
	Without gypsum: $C_3A + 6H \rightarrow C_3AH_6$ (hydrogarnet)
	With gypsum (when $C\hat{S}H_2/C_3A = 3$): $C_3A + 3C\hat{S}H_2 + 26H \rightarrow C_6A\hat{S}_3H_{32}$ (Ettringite)
$C_3A = 3CaO \cdot Al_2O_3$	With gypsum (when $C\hat{S}H_2/C_3A = 1$): $2C_3A + C_6A\hat{S}_3H_{32} + 4H \rightarrow 3C_4A\hat{S}H_{12}$ (Monosulfoaluminate) Or $C_3A + C\hat{S}H_2 + 10H \rightarrow C_4A\hat{S}H_{12}$
	With gypsum (when $C\hat{S}H_2/C_3A < 1$): $C_3A + C_4A\hat{S}H_{12} + CH + 12H \rightarrow 2C_3A(C\hat{S}, CH)H_{12}$
	Without gypsum: $C_4AF + 7H \rightarrow C_3(A,F)H_6 + C(A,F)H^*$
$C_4AF = 4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	With gypsum: $C_4AF + 3C\hat{S}H_2 + 27H \rightarrow C_6(A,F)\hat{S}_3H_{32} + C(A,F)H^*$
	After depleting gypsum: $C_4AF + C_6(A,F)\hat{S}_3H_{32} + 2CH + 2H \rightarrow 3C_4(A,F)\hat{S}H_{12}^*$

*(A, F) indicates aluminum with variable substitution of iron

2.5.2 Methods of Assessing Pozzolanic Reactivity

Pozzolanic reactivity of SCMs can be assessed by direct and indirect methods. The two methods are discussed in the following section.

2.5.2.1 Direct Methods

Direct methods are used to assess pozzolanic reactivity by measuring the amount of unreacted SCM remaining and then the amount reacted. The common measuring methods used are XRD analysis, Selective dissolution, Back Scattered Electron (BSE) image analysis obtained in Scan Electron Microscopy (SEM), and Nuclear Magnetic Resonance (NMR) (Scrivener, Lothenbach et al. 2015).

2.5.2.2 Indirect Methods

Indirect methods are used to assess pozzolanic reactivity by quantifying phases in the microstructure and thereby enabling back-calculation of the degree of reaction of the SCM based on hypotheses about the reaction products of the SCMs. Quantification is made using thermogravimetric methods through the measurement of bound water, portlandite consumption, calorimetry, and chemical shrinkage.

2.6 Pozzolanic Reactivity Assessment Techniques Used in This Study

In this study, 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 Chappelle test, by measuring the compressive strength of mortar cubes, and finally by creating a correlation between these tests and the strength development.

According to Snellings and Scrivener (2016), the pozzolanic reactivity of SCM can be determined by measuring the heat released during the reaction, the amount of bound water, the consumption of portlandite, the reaction degree of the SCM, or the volume change over the reaction. The literature on the above methods is discussed in the next topics.

2.6.1 X-Ray Diffraction (XRD) Analysis

XRD analysis is the conventional view of the use of quantitative diffraction methods used to determine the crystalline phases of the substance. This is done using powder or slice form of the substance depending on the type of the machine used for analysis.

The main advantages of XRD analysis are the ease of measurement, speed of measurement, and accuracy compared to traditional quantitative phases analysis methods such as Bogue calculations and optical microscopy (Snellings, Salze et al. 2014).

The XRD technique is based on the scattering of the x-ray beam caused by the crystalline arrangement in the bulk specimen. Consequently, only the crystalline phase can easily be identified. Rietveld analysis can be done to quantify the phases of the sample with the external standard method (Berodier 2015).

A hydrating cement is a combination of complex materials consisting of numerous coexisting phases, both residual anhydrous phases and hydration products that can each have variable composition and crystallinity. In a typical hydrating Portland cement at least around 10 different phases can be expected to be present simultaneously, while hydrating blended cement show an additional level of complexity (Scrivener, Lothenbach et al. 2015).

According to Scrivener, Lothenbach et al. (2015), the most important problem that needs to be dealt with is the significant overlap of the contributions of the peaks from the various phases. A particular difficulty is to correctly assign the contributions of amorphous or nanocrystalline phases such as blast furnace slag or CSH, which appear as diffuse, broad peaks in the XRD data.

The Crystallite size of particles in pastes can be determined using Scherrer's equation based on XRD data. According to Feret (1998), and Varin, Bystrzycki et al. (1999) Scherrer equation is given as:

$$D = \frac{K * \lambda}{\beta * \cos \theta} \dots\dots\dots \text{Eq. 2.1}$$

Where: -

D = Crystallites Size(nm)

K = Scherrer's Constant

λ = Wavelength of X-ray Sources

β = FWHM (Full Width at Half Maximum of XRD Peak) (radians)

θ = XRD peak position(radians)

2.6.2 Heat Flow Measurement

Heat flow of the SCM blended and reference cement mixes are carried out using calorimetry experiments. The mix should satisfy the following conditions:

- the SCM is the reaction limiting reagent in the system, all other reagents are added in excess,
- the systems are designed to produce similar reaction products.

Scrivener, Lothenbach et al. (2015) suggested that if both of the above conditions are met, the heat flow is expected to be more comparable to the strength development.

2.6.2.1 Heat Flow Measurement Methods

There are four types of heat flow measurement methods. According to Sedaghat, Zayed et al. (2013) the first two heat flow measurement methods were solution calorimetry and isothermal conduction calorimetry methods. Later, the adiabatic and semi-adiabatic methods were developed. A brief description of these methods is given by Sedaghat

(2016); Sedaghat, Zayed et al. (2013); Wadsö (2001), and Wang, Ge et al. (2007) and summarized as shown below.

- **Solution calorimetry** - in this method the blended and reference samples with fully hydrated cement are dissolved in a mixture of hydrofluoric and nitric acid. Dissolution is carried out in a Dewar vessel (semi-adiabatic conditions), and the temperature rise is measured during the dissolution process. The amount of heat evolved is calculated based on the registered temperature in a similar manner as in the semi-adiabatic method. The difference between heat released by the blended and reference sample is an examined heat of hydration. The potential chemical energy in a material can be measured by the heat liberated when the material is decomposed into the basic chemical components.
- **Isothermal conduction calorimetry** - in this method measurement of heat takes place under constant temperature and the heat generated from the hydration reaction of cement is removed by the absorbent element. The thermocouple sensor disposed between the test sample and the absorption element records the amount of heat generated, which is proportional to the degree of reaction of the test sample.
- **Adiabatic calorimetry** - in this method the temperature evolution at the center of the sample is measured. Based on the known heat capacity the evolved heat is calculated. An essential element of the adiabatic calorimeter is a cooling and heating system that maintains the environment around the sample at that same temperature so that there is no heat transfer from the sample.
- **Semi-adiabatic calorimetry** - this method is similar to adiabatic calorimetry and the internal temperature of the sample is measured as well. However, in semi-adiabatic calorimetry, there is no control system of the ambient temperature of the sample and true adiabatic conditions are not provided. Instead, very good thermal insulation is used to maintain a condition close to adiabatic, so that heat loss to the environment is as small as possible. The output is a temperature versus time similar to as in the adiabatic test. The evolved heat is calculated based on data of temperature evolution, the known heat capacity of the sample, and the amount of heat loss to the environment during the test.

From the above heat flow measurement tests, an isothermal calorimetry test is used to determine the heat of hydration in this study. The benefits of using an Isothermal calorimetry test are discussed in the next section.

2.6.2.2 Isothermal Calorimetry Test

Isothermal heat conduction calorimetry is a useful method for determining the heat production rate and the developed heat during cement hydration. It is used for the following purposes:

- to determine the total heat of hydration,
- to determine the rate of heat production in concretes,
- as a general tool to investigate the hydration process.

From previous studies, it was concluded that 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 (Wadsö 2001). Also, the way that a cement paste is mixed does not much influence the reaction rate.

The two ASTM standards used to measure the heat of hydration for hydraulic Portland cement are ASTM C1702 (isothermal conduction calorimetry) (ASTM-C1702 2017) and ASTM C186 (heat of solution calorimetry) (ASTM-C186 1998).

The advantages of using Isothermal conduction calorimetry cited by Sedaghat (2016); Sedaghat, Zayed et al. (2013); Wadsö (2001) and Wang, Ge et al. (2007) are summarized as:

- measures the heat of hydration instantly from the time of mixing of cement with water.
- a useful technique in studying the effects of admixtures on cement hydration.
- can be executed with low labor input and with better precision as compared to the heat of the solution method.
- can typically operate at a wide range of temperatures and using different water to cement ratios.
- measures the total heat and records the thermal power or heat flow at different ages.

- provides the user the ability to study the hydration stages from the recorded heat flow curve at the desired hydration age.
- sample preparation and operation of the instrument are fairly easy, though its use requires some basic training.
- the cumulative heat at any age can be calculated by the integration of the area under the heat flow curve versus time.
- performs well with blended cement while the solution calorimetry is less suited.
- offers simplicity in the procedure and availability of commercial equipment to conduct the test.
- calibration coefficients are remarkably stable over time as long as there is no hardware or bath temperature change contrary to the systems in adiabatic conditions in which the temperature change due to cement hydration process may affect the heat of hydration development mechanism.
- it is noteworthy that the ASTM C1702 method is not dependent on knowledge of compound composition, which makes it much more useful for analysis of non-Portland cement.

2.6.2.3 Heat of Hydration Measuring Device

Even though there are many types of isothermal calorimetry test measuring devices, in this study ToniCAL calorimeter which is situated in Messobo cement factory at Mekele is used. It is a computer-controlled isothermal heat flow measuring calorimeter and works continuously to determine the total evolved heat of hydration of binding materials mainly cement according to ASTM C1702. This device allows to directly determine the heat development rate (J/g) independent of the elapsed time. It helps as an alternative method for rational quality control methods for ASTM C186 and DIN EN 196-8 (Toni-Technik-Baustoffprufsysteme-GmbH 2020). The device is shown in Figure 4.5 in the analysis section.

2.6.3 Bound Water Determination

Water in the hardened cement paste can be in a constitutive (chemically bound) or free (unbound chemically) state. The chemically combined water is the water that combines chemically with the cement in the hydrate phases and separation can be made only by calcining the material at high temperatures or by chemical reactions. Taylor (1997) defines

chemically bound water as the water present in interlayer spaces, or more firmly bound, but not that present in pores larger than this. Free water is the water that remains from the saturated paste, which occupies the larger capillary pores. However evaporable water is the sum of free water and physically adsorbed water. The unbound chemically water includes water vapor, physicochemical, and physicochemically bound water (pellicular, sorption). Pellicular water occurs on the surface of the developed pores or in cement paste capillaries and with fixed water vapor relative humidity in the pores, it remains at a constant level (Prochońa and Piotrowskia 2016), (Lura, Winnefeld et al. 2017).

Evaporable water would be released after heating the sample at +105°C in an oven for 24 hours. Samples should be heated for an additional 24 hours if mass change within 1 day didn't exceed 0.5% according to ASTM-C642 (1997). Bound water would be determined by heating the samples at 400°C for 2 hours in the furnace and cooling down to 100°C (Avet, Snellings et al. 2016). The temperature is limited to 400°C because after this point dehydroxylation of the portlandite will occur and the critical temperature for water achieved. Changes occur in heating the concrete at different temperatures. The changes are given in Table 2.3 below. From the table, it can be seen that after 400°C dehydroxylations of portlandite occur. Because of this sample heating is limited at this point.

Table 2.3 Changes Which Take Place In Concrete During Heating (Hager 2013)

Temperature Range	Changes
20 - 200°C	Slow capillary water loss and reduction in cohesive forces as the water expands; 80 – 150°C ettringite dehydration; C-S-H gel dehydration; 150 – 170°C gypsum decomposition ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$); Physically bound water loss;
300 - 400°C	Approximately 350°C break up of some siliceous aggregates(flint); 374°C critical temperature of water;
400 - 500°C	460 – 540°C Portlandite decomposition $\text{Ca}(\text{OH})_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$;
500 - 600°C	573°C quartz phase change $\beta - \alpha$ in aggregates and sands;
600 - 800°C	The second phase of the C-S-H decomposition, formation of $\beta\text{-C}_2\text{S}$;
800 - 1,000°C	840°C dolomite decomposition; 930 - 960°C calcite decomposition $\text{CaCO}_3 \rightarrow \text{CaO} + \text{C}_2\text{O}$, carbon dioxide release; Ceramic binding initiation which replaces hydraulic bonds;
1,000 - 1,200°C	1,050°C basalt melting;
1,300°C	Total decomposition of concrete, melting.

Adding more water causes more hydration. This will make the concrete to release more water during heating. Bound water found by ignition is used to determine the degree of hydration in the mix. It was also found that a direct proportionality between the amount of chemically bound water and the amount of cement that has reacted but the direct proportionality will be changed when the cement is blended with SCMs (Fagerlund 2009).

According to Bougara, Lynsdale et al. (2010), bound water account for most of the water in the calcium silicate hydrate which influences strength development. The one with a higher amount of bound water will show higher strength.

2.6.4 Determination of the Pozzolanic Activity of Bagasse Ash (PABA)

Different methods were considered to determine the rate at which portlandite is consumed by the SCM as a direct measure of the reactivity of the SCM. In these methods specified amounts of SCM and portlandite are mixed with water and the portlandite content of the mix is measured at defined ages. The consumption of portlandite is typically tested in dilute suspensions (Snellings and Scrivener 2016).

Fratini (1950) developed a laboratory methodology to assess pozzolanic activity. It was based on the evaluation of the OH^- and Ca^{2+} concentrations presented in a mixture of Portland cement and pozzolan. This becomes the basis for the actual EN 196-5 standard. In contrary to Fratini's methodology, Chapelle (1958) developed a pseudo-dynamic test to evaluate the pozzolanic activity of a material, based on the consumption of $\text{Ca}(\text{OH})_2$ in a saturated water medium. After a decade time, Benoit (1967) improved the Chapelle methodology, particularly in terms of temperature at 90°C and for a duration of 16 hours of the test, using 1g of pozzolan, 1g of calcium oxide, and 100ml of distilled water and gave the denomination "Chapelle test" to this methodology (Ferraz, Andrejkovicová et al. 2015).

Besides Largent (1978) also criticizes the Fratini test, because the system does not reach equilibrium and is performed in a static environment, introduced modifications to the Chapelle test, namely the continuous stirring during the duration of the test, and renamed the methodology to "modified Chapelle test" (Ferraz, Andrejkovicová et al. 2015), (Scrivener, Lothenbach et al. 2015).

Thus, to compare the new test with the existing method, in this study modified Chapelle test was run on CaO and blended (CaO + Bagasse Ash) samples according to the NF P18-513 standard. This test was preferred because of its quick indication of pozzolanic reactivity (within a day) as compared to the Frattini test (Avet, Snellings et al. 2016).

The test allows the quantification of $\text{Ca}(\text{OH})_2$ fixed (consumed) by 1g of bagasse ash when mixed with 2g of CaO and 250ml of distilled CO_2 free water. The test was done using the following setup shown in Figure 2.2 below.

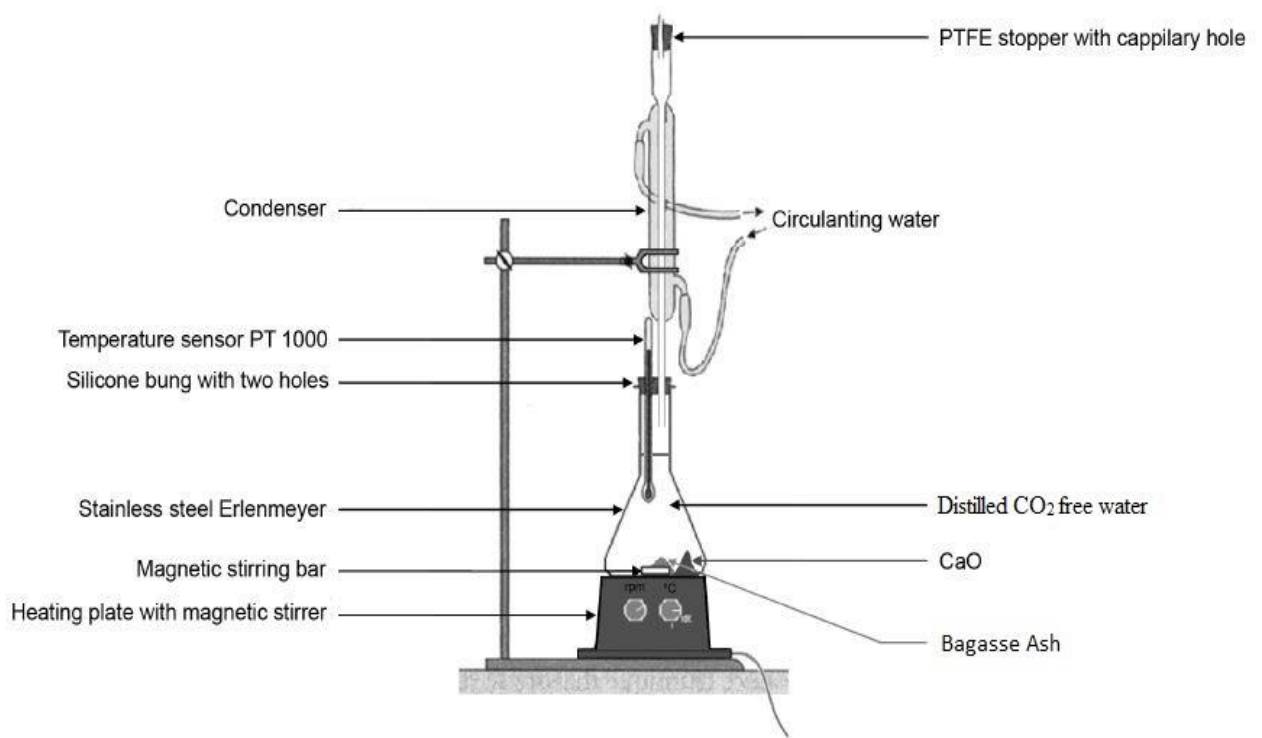
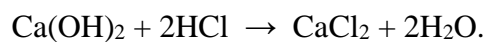
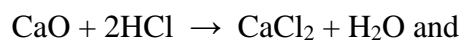


Figure 2.2 Modified Chapelle Test Setup (adapted from NF P18-513, 2010: association Française de Normalisation, La Plaine Saint-Denis, (in French)) (Ferraz, Andrejkovicová et al. 2015).

The result is determined by titrimetry with HCl and the titration reactions are given as:



The PABA is calculated using the following equation:

$$\text{PABA (in mg Ca(OH)}_2 \text{ fixed/g bagasse ash)} = 2 * \frac{V_1 - V_2}{V_1} * \frac{74}{56} * 1000 \dots \text{Eq. 2.2}$$

Where:

PABA - Pozzolanic Activity of Bagasse Ash, expressed in mg Ca(OH)₂ fixed/g bagasse ash;

V₁ - Volume of HCl added to the solution obtained from without bagasse ash (blank test);

V₂ - Volume of HCl added to the solution obtained with bagasse ash.

The blank test (without bagasse ash) must verify $V_1 * \frac{56}{2} < 1,000$ and the repeatability of the modified Chapelle test is 10% (Ferraz, Andrejkovicová et al. 2015), (Scrivener, Lothenbach et al. 2015), (Avet, Snellings et al. 2016). The Chapelle tests were carried out in duplicate, standard errors were below 3% portlandite consumption (Scrivener, Lothenbach et al. 2015).

2.6.5 Compressive Strength Determination

Compressive strength is considered a reliable indicator for the presence of reaction (Martirena, Middendorf et al. 1998). The change in microstructure due to the formation of new products makes the material denser and stronger. The addition of SCMs contributes to the development of compressive strength by reacting with the Portland cement hydration products and water to form hydration products (Snellings and Scrivener 2016).

Standard mortar cubes were used to determine the strength development of the reference, bagasse ash blended and quartz blended samples over time. Three groups of mortars, the first is at 0% substitution level (reference), the second is at 10% substitution level of cement by bagasse ash and the third is at 10% substitution level of cement by quartz were studied.

According to ES-1176-1 (2005) (EN 196-1) for the compressive strength of mortar cube test, mixes should be prepared at 1:3 cement to sand ratio with 0.5 water to cement ratio. The sand is recommended to be standard sand that fulfills requirements given by the Euro code as reference sand.

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 50x50x50 mm at 1, 3, 7, 28, 56, and 90 days of age.

2.7 Rapid, Relevant and Reliable Testing (R³)

To evaluate the pozzolanic reactivity of SCMs, 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 (Avet, Snellings et al. 2016); (Avet 2017). Thus, in this study, a novel rapid, relevant, and reliable (R³) testing approach

which was developed by Avet, Snellings et al. (2016) to evaluate the reactivity of kaolinitic clays was used to assess bagasse ash reactivity.

Testing methods should be efficient and accurate to measure the reactivity of SCMs. According to Snellings and Scrivener (2016), 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 development through time).

Reactivity in this study was assessed by measuring the heat released during hydration by Isothermal calorimetry. This is supplemented by a simple thermogravimetric method that can be used to determine the bound water content in the range of 110°C to 400°C with an oven.

The R^3 test results were compared to relative strength development based on standard compressive strength on mortar cubes. Finally, the modified Chapelle test was run to compare the R^3 test to a commonly used existing test method.

2.8 Previous Research Works Related to This Study

In this section previous research works that were done related to the bagasse ash as a partial cement replacing material and its reactivity during hydration are summarized. Papers and theses are reviewed and summarized in Table 2.4 below for ease of comparison. The reviewed papers were done by Hailu and Dinku (2012); Bahurudeen, Kanraj et al. (2015); Cordeiro, Toledo Filho et al. (2008); Kramar and Ducman (2018); Martirena, Middendorf et al. (1998); Chusilp, Jaturapitakkul et al. (2009); Geremew (2017); Cordeiro and Kurtis (2017); Joshaghani and Moeini (2017); Cordeiro, Andreao et al. (2019); Amin (2011); Sales and Lima (2010); Bersisa (2019) and Fekadu (2019).

Table 2.4 Summary of Previously Done Related Researches

S.N.	Title	Author	Journal Name	Year of Publication	Summary of Major Findings	Limitations
1	Application of sugarcane bagasse ash as a partial cement replacement material	Hailu, B. and A. Dinku	Zede Journal	2012	Bagasse ash replacement was found to be optimal at 10%. Up to this point, the property of concrete improved and decline then after.	Didn't investigate the reason of concrete property improvement.
2	Performance evaluation of sugarcane bagasse ash blended cement in concrete	A. Bahurudeen, Deepak Kanraj, V. Gokul Dev, Manu Santhanam	Cement and Concrete Composites	2015	A comprehensive evaluation of mechanical and durability characteristics suggested that sugarcane bagasse ash replacement produces good quality concrete in blends up to 25%.	The study didn't investigate the reason behind concrete property increment.
3	Pozzolanic activity and filler effect of sugar cane bagasse ash in Portland cement and lime mortars	G.C. Cordeiro, R.D. Toledo Filho, L.M. Tavares, E.M.R. Fairbairn	Cement and Concrete Composites	2008	SCBA may be classified as a pozzolanic material, but that its activity depends significantly on its particle size and fineness	A discrepancy was observed in pozzolanic activity results. Findings were not coherent with each other.
4	Evaluation of Ash Pozzolanic Activity by Means of the Strength Activity Index Test, Frattini Test and DTA/TG Analysis	Sabina KRAMAR, Vilma DUCMAN	Tehnički vjesni	2018	Different ashes were found to have different pozzolanic reactivity. This was confirmed by the amount of lime that they chemically react to.	As most tests are limited to the analysis of compositions recognized as standard, the results obtained refer only to a specific mixture and thus cannot fully confirm material pozzolanicity.
5	Use of Wastes of the Sugar Industry as Pozzolana in Lime-Pozzolana Binders: Study of the Reaction	J.F. Martirena Herna ́ndez, B. Middendorf, M. Gehrke, and H. Budelmann	Cement and Concrete Research	1998	Results show that sugar cane bagasse ash does not act as a reactive pozzolana, mainly due to the presence of unburned material and carbon, whereas sugar cane straw ash shows good pozzolanic activity comparable to that of rice husk ash.	It is difficult to prove reactivity by pore structure. An appropriate methodology was not used.

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S.N.	Title	Author	Journal Name	Year of Publication	Summary of Major Findings	Limitations
6	Utilization of bagasse ash as a pozzolanic material in concrete	Nuntachai Chusilp, Chai Jaturapitakkul, Kraiwood Kiattikomol	Construction and Building Materials	2009	The optimum cement replacement by ground bagasse ash was 20wt% of the binder. At 30% replacement water permeability and compressive strength decrease.	The reason for increment or decrement in the concrete property was not investigated.
7	Bagasse Ash as a Partial Substitute of Cement on Concrete Rigid Pavement	Miheret Geremew Advisor Dr. Esayas Gebre Youhannis	MSc. Thesis at AAiT	2017	Up to 10% replacement in concrete enhancement in compressive strength, flexural tensile strength at 28 days, flexural strength, and reduction heat of hydration was found.	The reason for concrete property improvement was not investigated.
8	Effect of mechanical processing on sugar cane bagasse ash pozzolanicity	Guilherme C. Cordeiro, Kimberly E.Kurtis	Cement and Concrete Research	2017	Increasing the SCBA specific surface area and the soluble fraction was found to increase pozzolanic reactivity. The increment was achieved because of physical effects and portlandite consumption.	Though it compares SCBA and Rice Husk ash, it didn't investigate the reason for concrete property improvement.
9	Evaluating the effects of sugar cane bagasse ash (SCBA) and nano silica on the mechanical and durability properties of mortar	Alireza Joshaghani, Mohammad Amin Moeini	Construction and Building Materials	2017	Addition of SCBA in nano silica containing mixtures were found to decrease the compressive strength at 3 and 7 days of age but showed improvement in the long term.	Didn't investigate the reason why the mechanical and durability property of mortar improved.
10	Pozzolanic properties of ultrafine sugar cane bagasse ash produced by controlled burning	Guilherme Chagas Cordeiro, Pryscila Vinco Andreao, Luís Marcelo Tavares	Heliyon	2019	The addition of SCBA600 as replacing material reduces the total accumulated heat and portlandite content. It also refines pore structure and significantly increases compressive strength after 3 days of age.	The study didn't explore the reason for how these improvements were achieved.

S.N.	Title	Author	Journal Name	Year of Publication	Summary of Major Findings	Limitations
11	Use of Bagasse Ash in Concrete and Its Impact on the Strength and Chloride Resistivity	Noor-ul Amin	Journal of Materials in Civil Engineering © ASCE	2011	Bagasse ash is found to be an effective mineral admixture and pozzolan with an optimal replacement level of 20% cement. It also reduces the chloride diffusion by more than 50% without any adverse effects on other properties of the hardened concrete.	Property improvements were investigated but not how this is achieved.
12	Use of Brazilian sugarcane bagasse ash in concrete as sand replacement	Almir Sales, Sofia Araújo Lima	Waste Management	2010	Samples with 20% and 30% of SCBA replacement of sand showed higher compressive strength.	The mechanism and reason behind this improvement are not investigated using different methods.
13	Early Age Thermal Behavior of Bagasse Ash Concrete Under Different Ambient Temperatures	Amanuel Bersisa Advisor Dr.- Ing. Adil Zekaria	MSc. Thesis at AAiT	2019	The study found that early age cracking risk is determined by the strength development and the heat evolution of concrete.	The study didn't find out how strength improvement is achieved while bagasse ash is used as a replacement material.
14	Increasing compressive strength property of bagasse ash blended concrete by using chemical activator (NaSO ₄)	Lidya Fekadu Advisor Dr. Esayas Gebre Youhannis	MSc. Thesis at AAiT	2019	In this study, Sodium Sulfate was found to be an appropriate chemical activator on bagasse ash blended concrete and favor compressive strength at an early age.	The role of bagasse ash in strength development was not investigated.

2.9 Research Gap

Even though partially replacing cement with bagasse ash brought an improvement on the property of concrete, it is not clearly known how this is achieved. Different possible reasons were given for the improvement in the concrete property. The first possible reason is due to the chemical reaction of the bagasse ash by forming hydration products. The second possible reason is that due to the dilution effect and creating a nucleation site for the hydration of other compounds. Results obtained from previous studies using different methods were not in agreement/correlated with compressive strength development. This makes the methodology employed to investigate the problem unreliable. Therefore, this study attempts to fill the gap by investigating the pozzolanic reactivity of bagasse ash using rapid, relevant, and reliable (R^3) testing approach.

CHAPTER 3 MATERIALS AND EXPERIMENTAL PROGRAM

3.1 Materials Used for the Research

3.1.1 Introduction

Different materials were used to achieve the objective of this study. The major ones are Ordinary Portland Cement (OPC) from Messobo cement factory, bagasse ash from Wonji sugar factory, standard sand imported from France, quartz powder imported from the United Kingdom, and water from Addis Ababa Water and Urban Sewerage Authority.

3.1.2 Bagasse Ash

The bagasse ash used in this study was brought from Wonji sugar factory which is situated about 110Km from Addis Ababa to the south. The fresh bagasse ash released from the furnace which was cooled in the air was collected. It was not treated with any chemicals. The bagasse ash was sieved and those grain sizes that pass through 125 μ m were used. The sieved bagasse ash is shown in Figure 3.1 below.



Figure 3.1 Bagasse Ash

The gradation of the bagasse ash was made to be similar to that of the cement. The grain size distribution for bagasse ash and Messobo OPC are shown in Table 3.1 below.

Table 3.1 Grain Size Distribution for Bagasse Ash and Messobo OPC

Sieve Size	Percentage Passing (Bagasse ash)	Percentage Passing (Cement)
125 μ m	100	100
75 μ m	89	93
63 μ m	80	81
32 μ m	35	32

The particle size distribution of bagasse ash and Messobo OPC is shown graphically for a simple comparison in Figure 3.2 below.

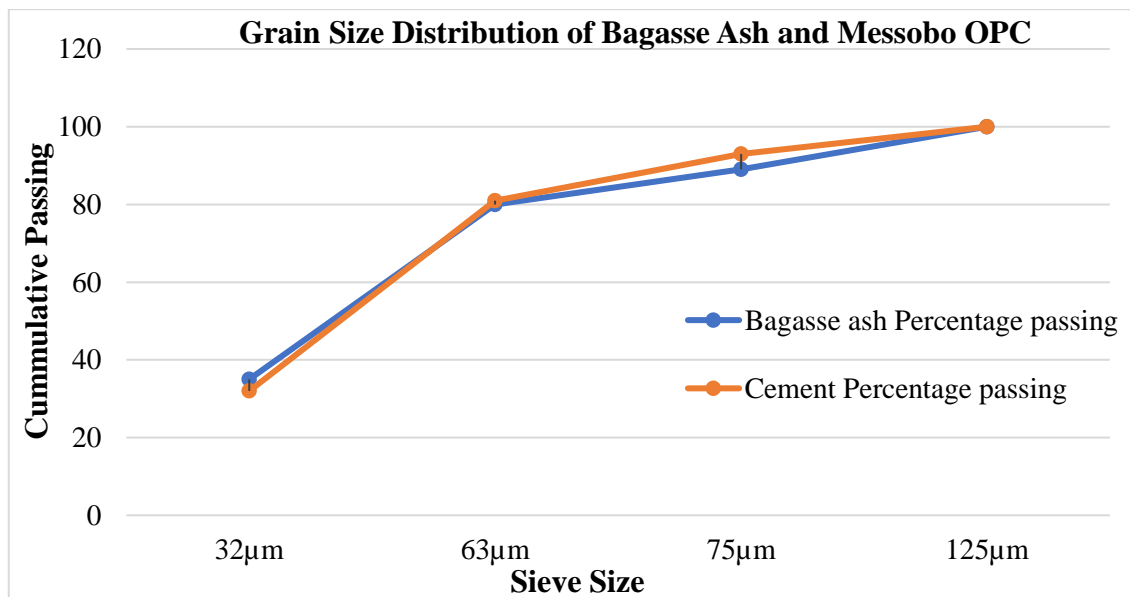


Figure 3.2 Grain Size Distribution of Bagasse Ash and Messobo OPC

3.1.3 Cement

Messobo OPC which complies with the requirements of Ethiopian standards ES-EN-197-1 (2013) is used in this study. It is not freely available in the Addis Ababa market. So, it was bought from cement distributors in Mekele city. Messobo OPC is preferred because of its fineness as compared to others and OPC is used to obtain a clearly seen result when cement is replaced partially based on previous results (Hailu 2011), (Shruthi, Eramma et al. 2014). Particle size plays an important role in the determination of reactivity. The finer the cement particles the faster the reactivity which is the main objective to be investigated in this study.

3.1.4 Quartz

Non-reactive quartz (SiO_2) powder with a specific gravity of 2.5g/cm^3 was used. The quartz powder was sieved and the gradation was made to resemble that of cement.

3.1.5 Sand

The sand used in this study is a Sable Normalise standard sand which was produced by Société Nouvelle du Littoral (S.N.L.) according to CEN EN 196-1 and ISO 679: 2009 in France. It is natural sand in which particles are more or less isometric and rounded in shape (Société-Nouvelle-du-Littoral-S.N.L. 2019). The sand is packed in Polyethylene bags each $1,350 \pm 5$ g.

Physical and chemical properties

The standard sand used in this study has the following physical and chemical properties:

- has a solid physical state and more than 95% SiO_2 Content
- has crystalline form, a sub-angular form of grains, white color, odorless smell, and a PH of 7.
- has an absolute mass volume of 2.63 g/m^3 and an apparent mass volume of 1.6 g/cm^3 (Société-Nouvelle-du-Littoral-S.N.L. 2019).

The standard sand used in this study is shown in Figure 3.3 below.



Figure 3.3 Standard Sand in Polyethylene Bag and During Pouring into Mixer (Right)

The grading measured by sieving and the analysis is complemented by bag mass controls, water content controls, and strength controls were in accordance with EN 196-1 and ISO 679: 2009. Standard conformity is carried out by Laboratoire d'Essais des Matériaux de Laville de Paris (L.E.M.V.P.)-Material Test Laboratory in Paris and Production certified by Association Française de Normalisation (AFNOR) (Société-Nouvelle-du-Littoral-S.N.L. 2019). The gradation of the standard sand is given in Table 3.2 below.

Table 3.2 Standard Sand Grading (Société-Nouvelle-du-Littoral-S.N.L. 2019), (ES-1176-1 2005)

Mesh Size	Cumulative (%) Retained (CEN-196)	Cumulative (%) Passing (CEN-196)
2.00mm	0	100
1.60mm	7 ± 5	93 ± 5
1.00mm	33 ± 5	67 ± 5
0.50mm	67 ± 5	33 ± 5
0.16mm	87 ± 5	13 ± 5
0.08mm	99 ± 1	1 ± 1

The graphical representation of gradation of the standard sand in cumulative passing percentage is shown in Figure 3.4 below.

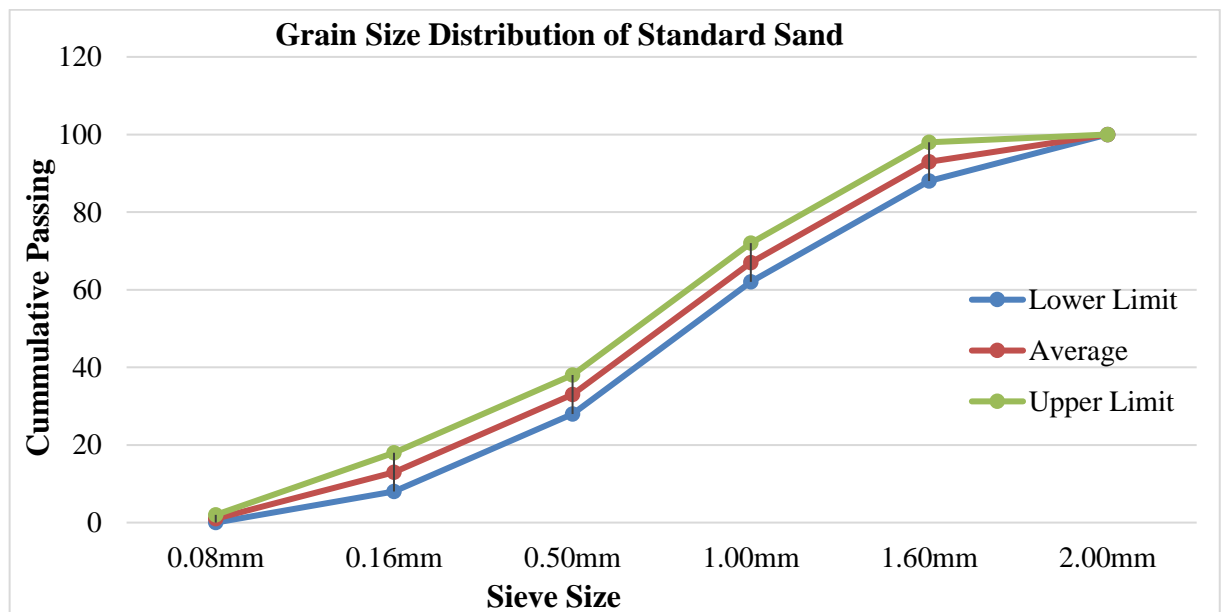


Figure 3.4 Grain Size Distribution of Standard Sand

3.1.6 Water

Portable water supplied by Addis Ababa Water and Urban Sewerage Authority (AAWUSA) was used at Addis Ababa Institute of Technology (AAiT).

3.2 Experimental Program

3.2.1 Introduction

The objective of this study is to investigate the pozzolanic reactivity of bagasse ash using compressive strength development while partially replacing cement. The replacement was made at a 10% level of cement by volume. To achieve this, six experiments were conducted.

The first experiment was on the determination of fineness of cement and bagasse ash and also on normal consistency and setting time of the blended paste. The second experiment was on the characterization of the microstructure of pastes. The third experiment was on the measurement of heat of hydration of pastes using isothermal calorimetry. The fourth experiment was on the determination of bound water in hardened cement paste using oven thermal treatment. The fifth experiment was on the determination of the pozzolanic activity of bagasse ash using the Modified Chapelle test. Finally, the sixth experiment was on the measurement of Compressive Strength development in mortar cubes. The program of each experiment is given in the upcoming sections.

3.2.2 Experiment I: Physical Property Determination

The first experiment was conducted to determine the fineness of cement and bagasse ash, the normal consistency, and the setting time of the reference and blended pastes.

3.2.2.1 Fineness Test

The fineness of the bagasse ash and cement was determined by the blain air permeability method. The blain air method of determining the specific surface area is based on the relationship between the surface area of the particles in a porous bed and the rate of fluid flow through the bed.

In order to keep the volume of cementitious material per unit volume of the mix constant, replacement of the bagasse ash was made by volume. According to ACI-211.1-91 (2002) to compute the volume equivalency of the bagasse ash, Equation 3.1 was used assuming that a 1% replacement.

$$Fw = \frac{1}{\left(1 + \left(\frac{Gc}{Gp}\right)\left(\left(\frac{1}{Fv}\right) - 1\right)\right)} \dots\dots\dots \text{Eq 3.1}$$

Where: -

Fw = Pozzolanic materials percentage by weight expressed as a decimal factor

Gp = Specific gravity of pozzolanic materials (Gp = 2.0343)

Fv = Pozzolanic materials percentage by absolute volume of the total absolute volume of cement plus pozzolanic materials expressed as a decimal factor (Fv = 0.01).

Gc = Specific gravity of Portland cement (Gc = 3.15). (ACI-211.1-91 2002)

$$Fw = \frac{1}{\left(1 + \left(\frac{3.15}{2.0343}\right)\left(\left(\frac{1}{0.01}\right) - 1\right)\right)} = 0.006481 = 0.6481\%$$

Implying that replacing 1% volume of cement by equal volume of bagasse ash is equivalent to replacing 0.65% weight of cement with bagasse ash. That is 1kg of cement will be replaced by 0.65kg of bagasse ash in order to account for the lower density of bagasse ash which is 2.0343g/Cm³. Based on this ratio, a replacement was made at 10% of cement by bagasse ash by volume.

Similarly, the volume equivalency for quartz was calculated and found that 1% volume of cement would be replaced by equal volume of quartz which is 0.8% of the weight of cement. Meaning that 1kg of cement will be replaced by 0.80kg of quartz in order to account for the lower density of quartz.

3.2.2.2 Normal Consistency Test

The normal consistency test of pastes was measured according to ASTM C187 method by a Vicat apparatus. It measures the resistance of the paste to the penetration of a plunger or needle weighing 300gm released at the surface of the paste. The procedure used in this test is explained in ASTM C187 (ASTM-C187 1998).

Reference cement and blended cement pastes were prepared by replacing part of the Portland cement with bagasse ash. The water content was varied for each of the pastes produced until a normal consistent paste is obtained.

3.2.2.3 Setting Time Test

Setting time tests for hydraulic cement was determined according to ASTM C191 method (ASTM-C191 2004). The initial setting time of the paste was determined by the duration of 25mm penetration of Vicat needle into the paste in 30 seconds after it has been released while the final setting time was determined by measuring the time related to zero penetration of the needle into the paste.

3.2.3 Experiment II: Characterization of the Hardened Paste

The second experiment was conducted to characterize the hardened paste using XRD Analysis. Samples from the same batch were cast for XRD and cured at 25°C. XRD was used to characterize the crystalline phases formed and to follow the portlandite consumption. Measurements were carried out on independently cast pastes on day 1. The hardened pastes were ground with agate and prepared in powder form.

3.2.4 Experiment III: Heat of Hydration Measurement

The cumulative heat of reaction was measured using 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. The schematic representation of the test is given in Figure 3.5 below.

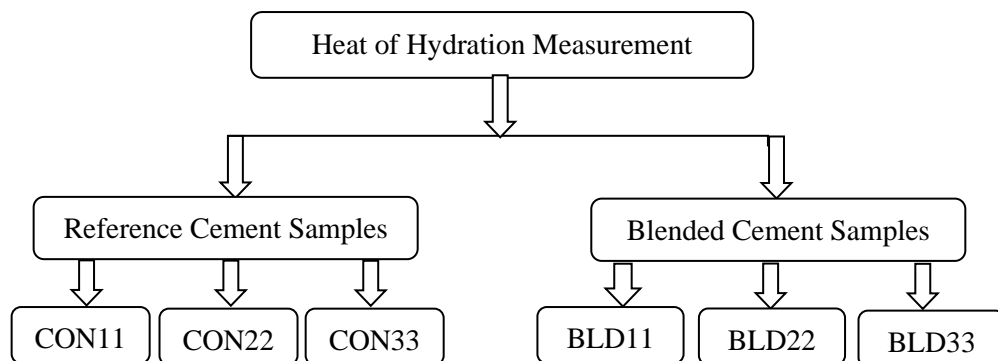


Figure 3.5 Schematic Representation of Heat of Hydration Measurement

3.2.5 Experiment IV: Bound Water Determination

Reference and blended samples were prepared and cast on plastic sheets in triplicate with 4mm thickness and sealed at 25°C for 24 hours. This was done to create similar conditions as the tests carried out at 25°C using an isothermal calorimeter.

The slices were dried at 110°C in an oven. According to ASTM C642 (ASTM-C642 1997) 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 400°C for 2 hours and cooled down to 100°C. The thermal treatment was limited to 400°C since higher temperatures resulted in portlandite dehydroxylation, which is not desired in this study. The schematic representation of the test is given in Figure 3.6 below.

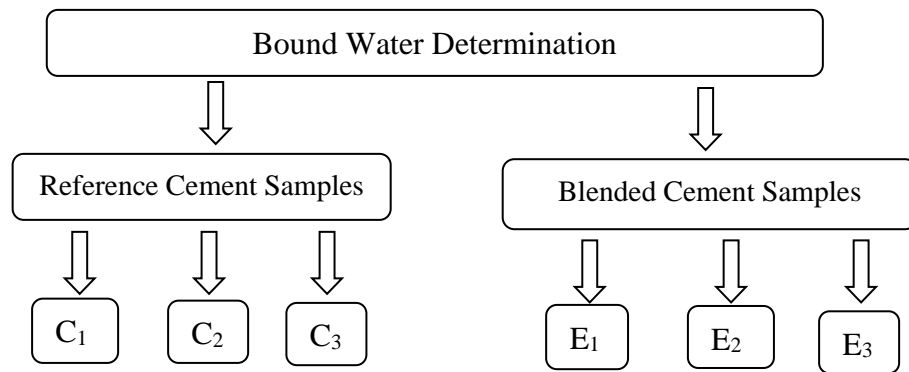


Figure 3.6 Schematic Representation of Bound Water Determination Test

Finally, the bound water was determined according to Equation 3.2 indicated below by calculating the mass change after heating the samples.

$$\text{Bound Water}(\%) = \frac{m_{110^{\circ}\text{C, Stabilized}} - m_{\text{Cooled, } 100^{\circ}\text{C}}}{m_{110^{\circ}\text{C, Stabilized}}} \dots\dots\dots \text{Eq. 3.2}$$

3.2.6 Experiment V: Determination of the Pozzolanic Activity of Bagasse Ash

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 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

(Avet, Snellings et al. 2016). For this test, 1g of bagasse ash was mixed with 2g of calcium oxide and 250ml of deionized water.

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 (room temperature), 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 et al. (2016) and Scrivener, Lothenbach et al. (2015), the amount of bound portlandite meaning that the PABA is determined using Equation 3.3 given below.

$$PABA = \text{mg CH/g Bagasse Ash} = 2 \left(\frac{V_1 - V_2}{V_1} \right) * \frac{74}{56} * 1000 \dots\dots\dots \text{Eq. 3.3}$$

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.

3.2.7 Experiment VI: Compressive Strength Determination

Standard mortar cubes were cast to determine the strength development of the blended and reference samples over time. A 10% replacement of OPC by bagasse ash and quartz (by volume) and a reference (OPC only) mix was used for the cubes.

3.2.7.1 Mortar Mix Proportions

Mix proportions were made with 1 part of cement to 3 parts of sand with water to cement ratio of 0.5 as per EN 196-1 and ES 1176-1:2005 (ES-1176-1 2005).

Note that Ethiopian Standard ES 1176-1:2005 on “Methods of testing cement Part 1, Determination of strength” is adopted from European Standard EN 196-1: 1994 (ES-1176-1 2005).

Mix proportions and materials used for mortar specimens were prepared according to Table 3.3 shown below.

Table 3.3 Mix Proportions and Materials for Mortar Specimens

Mix	Cement Type	Cement (gm)	BA (gm)	Quartz (gm)	W/B	Water (gm)	Sand (gm)
BAM 0	OPC	1,350	0	0		675	4,050
BAM 10	OPC	1,260	90.74	0		675	4,050
QM 10	OPC	1,240	0	109.74		675	4,050

3.2.7.2 Mortar Specimen Preparation

Materials were prepared, weighed, and mixed while they were dry. Then the mortar was prepared using an automatic mixer in the AAiT Material testing laboratory. It was cast in a steel mold of cubes 50x50x50 mm. It was unmolded after 24 hours and cured in a water tank until tested.

The compressive strength measurement was carried out on mortar cubes at 1, 3, 7, 28, 56, and 90 days after casting. Three mortar specimens were prepared on reference, bagasse ash blended and quartz blended samples for each age of mortars.

3.2.7.3 Mortar Trial Mix

A trial mix was prepared using OPC and cast according to the above mix proportions. The test was done after 7 days and found a reasonable result (an average compressive strength of 31MPa).

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

In this section, test results and discussion are presented. Results on physical and chemical property of OPC and bagasse ash, characterization of the microstructure of pastes using XRD analysis, the heat of hydration measurement using Isothermal calorimeter, bound water determination using oven treatment, determination of the pozzolanic activity of bagasse ash using Modified Chapelle test and determination of the compressive strength of mortar cubes were presented.

Quartz was used as partial cement replacing material to investigate whether the improvement in compressive strength development is due to filler effect and to compare its effect with bagasse replacement.

Besides, the correlation between the tests and compressive strength development of mortar cubes were carried out. Related previous works were also discussed in relation to the findings of the study.

Experiments were carried out at Messebo cement factory Mekele, Addis Ababa Institute of Technology-Material Testing Laboratory, Water Treatment Laboratory, Chemical Engineering Laboratories, Addis Ababa University-Chemistry Department, and Ethiopian Public Health Institute-Food and Nutrition Laboratory. Test results and discussion on each experiment are given in the following sections.

4.2 Test Results and Discussion on Experiment I: Physical and Chemical Property Determination

Physical properties such as fineness, surface area, and density of cement and bagasse ash were measured. The chemical composition of cement and bagasse ash was investigated and discussed. Consistency and setting time of the reference and blended paste were also tested and discussed in this part.

4.2.1 Physical Property Test Results and Discussion

Among the physical properties of cement and bagasse ash density, blain air, and average sieve size in which 50% of the particles pass was considered. Density and Blain air of cement were done in Messobo cement factory, quality control laboratory at Mekele. The density of bagasse ash was measured in the material testing laboratory at AAiT and the Blain air of bagasse ash was done in the Chemical engineering laboratory at AAiT. The average size of the sieve was calculated using linear interpolation of sieve size at which 50% of the particles pass. The physical properties of cement and bagasse ash are shown in Table 4.1 below.

Table 4.1 Physical Properties of Cement and Bagasse Ash

Material	Density in g/cm³	Blain air in cm²/g	Average size (μm)
OPC	3.15	3601	43.39
BA	2.0343	4546	42.33

From table 4.1 above, the bagasse ash was found to have a density of 2.0343g/cm³ and a Blaine surface area of 4,546 cm²/g. Whereas the Messobo OPC has a density of 3.15g/cm³ and a Blaine surface area of 3,601cm²/g. These show that the bagasse ash has a lower density and higher surface area as compared to Messobo OPC.

Although the higher surface area of the bagasse ash creates an additional nucleation site for reaction, in this study the bagasse ash was made to have a similar particle size to that of cement.

Half of the cement particles pass in an average sieve size of 43.39μm on the other hand half of the bagasse ash particles pass in an average sieve size of 42.33μm. This implies that the cement and bagasse ash had more or less similar particle size.

4.2.2 Chemical Property Test Results and Discussion

The chemical properties of bagasse ash and cement were investigated using different techniques. Chemical composition of bagasse ash was done using X-Ray Fluorescence (XRF) from the Ethiopian Geological survey using LiBO₂, Fusion, HF attack, Gravimetric,

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Colorimetric, and AAS analytical method. It was done again in Messobo cement factory at Mekele using the Gravimetric and Complex metric method to confirm the findings of the XRF result. More or less similar results were obtained and the XRF result was considered since it is the most reliable one. The chemical composition of cement was also done in Messobo cement factory, using the Gravimetric and Complex metric method. The complete Silicate analysis report is attached on Annex A.B and the chemical composition of Messobo cement and Bagasse ash is given in Table 4.2 below.

Table 4.2 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 ₂ O ₃	5.08	11.54	5.66
Fe ₂ O ₃	3.60	2.28	3.42
CaO	61.82	1.12	1.26
MgO	1.93	0.60	1.63
Na ₂ O	0.29	0.64	
K ₂ O	0.21	1.92	
MnO	-	<0.01	
P ₂ O ₅	-	0.42	
TiO ₂	-	0.09	
H ₂ O	-	1.10	
SO ₃	2.58	-	
LOI	0.94	5.81	
Cl	-	-	
SiO₂ + Al₂O₃ + Fe₂O₃	-	89.80	79.18

* Chemical composition was done using the XRF method.

**Chemical composition was done using chemicals.

Based on the chemical composition of bagasse ash result: SiO₂ + Al₂O₃ + Fe₂O₃ = 89.80%. This value is greater than 70% and the LOI value of the bagasse ash was found to be less

than 10% (5.81%). Thus, based on these ASTM C-618 classifies the pozzolanic material to be in Class N (ASTM-C618 1999).

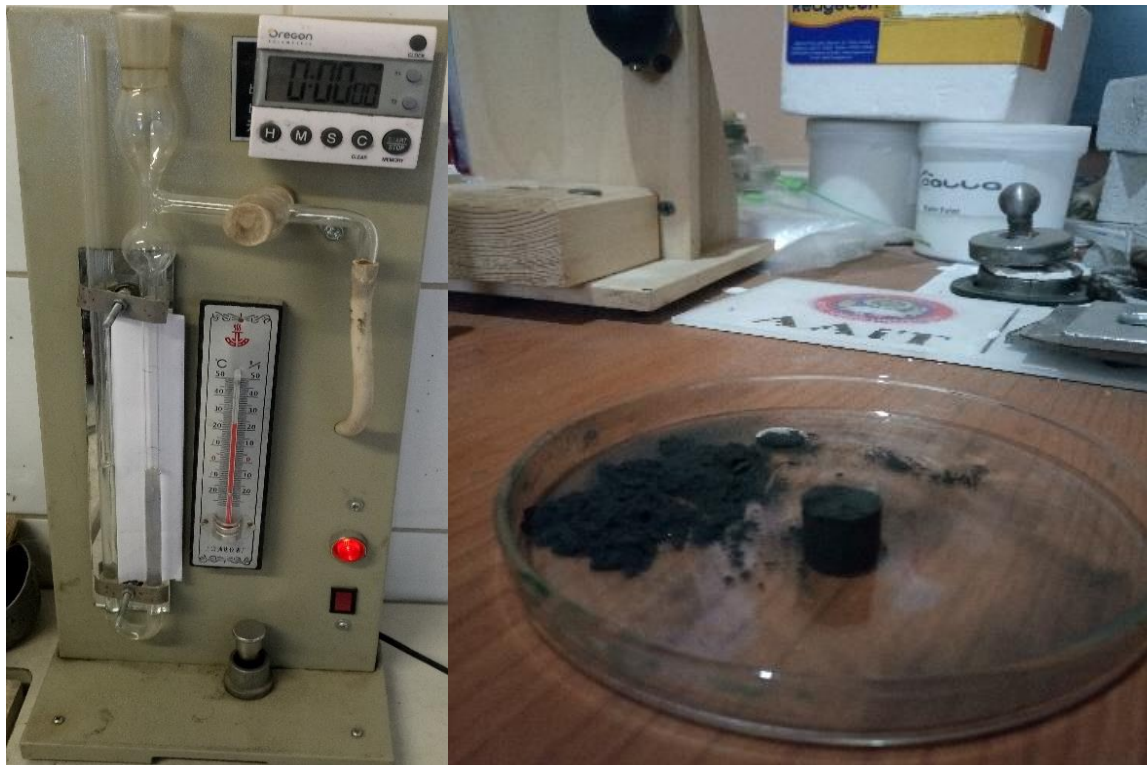


Figure 4.1 Blaine Value Apparatus(left) and Measured Samples(right)

4.2.3 Consistency Test Results and Discussion

Three 500g each from the reference and blended sample were prepared. Blending was made using an automatic dry mixer. Prepared material and automatic mixer are shown in Figure 4.2 below.

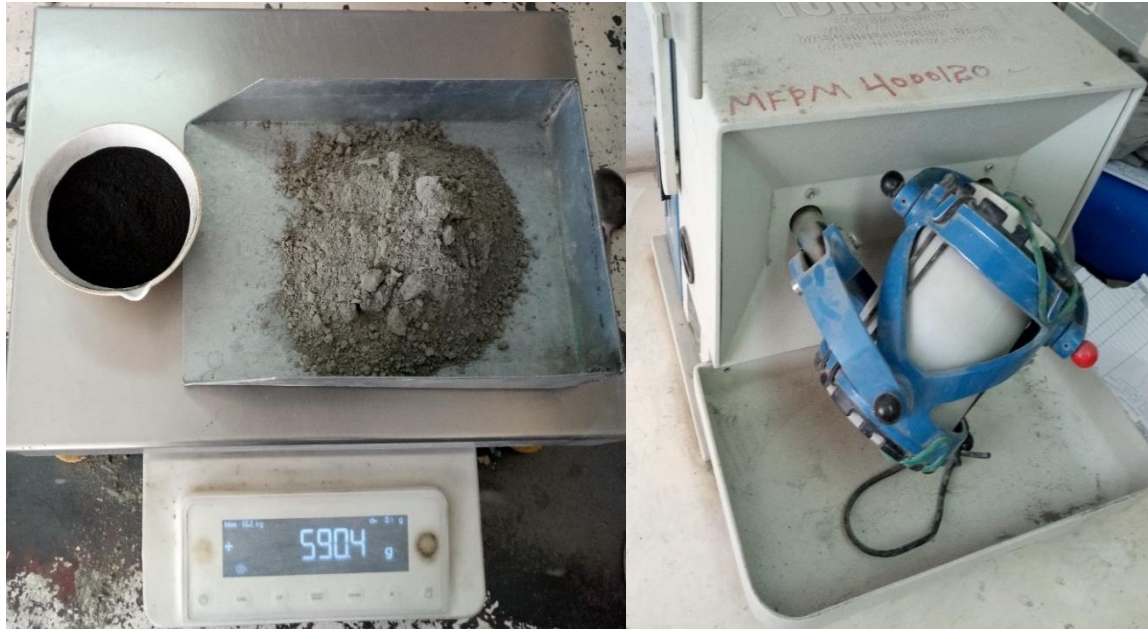


Figure 4.2 Materials Prepared for Consistency and Setting Time Test (left) and Automatic Mixer (right)

The standard consistency test of pastes was made in Messobo cement factory at Mekele and the results are given in Table 4.3 below.

Table 4.3 Standard Consistency Test Results

Mix Code	Standard Consistency (gm)	W/C (%)
Reference	139	27.8
BA1	169	33.8
BA2	167	33.4
BA3	168	33.6

The normal consistency of reference paste was found to be 27.8%. Implying that, it needs 139g of water to prepare a standard consistency of paste. Normal consistency of blended pastes with bagasse ash of samples 1, 2, and 3 were found to be 33.8%, 33.4%, and 33.6% respectively. Implying that, they need 169g, 167g, and 168g of water to prepare a standard consistency of paste respectively.

The water demanded by the blended mixes were higher than the reference mixes. Usually, the range of water to cement ratio for normal consistency is taken between 26% and 33%

(Dinku 2002). The blended pastes showed slightly higher values of water to cement ratio and this is probably due to the higher specific surface area ($4546 \text{ cm}^2/\text{g}$) of the bagasse ash as compared to cement. This is in line with the findings of Amin (2011), Ganesan, Rajagopal et al. (2007), and Hailu (2011) in their study of bagasse ash as cement replacement material. According to (Zareei, Ameri et al. 2018) the increase in water demand is due to the unburned carbon content, irregular shape, and porous nature of sugar cane bagasse ash.

4.2.4 Setting Time Test Results and Discussion

The initial and final setting time for reference and blended pastes were measured and results are given in Table 4.4 below.

Table 4.4 Setting Time Test Results

Mix Code	Setting time (min)	
	Initial Setting Time(min)	Final Setting Time(min)
Reference	120	385
BA1	155	410
BA2	150	465
BA3	150	420

Reference paste samples were measured to have an initial setting time of 120 minutes and a final setting time of 385 minutes. Whereas blended paste samples 1, 2, and 3 were measured to have an initial setting time of 155, 150, and 150 minutes and a final setting time of 410, 465, and 420 minutes respectively.

Ethiopian standard limits the initial and final setting time of cement to be greater than 45 minutes and less than 600 minutes (10hours) respectively (Dinku 2002). All the findings were within this standard range.

The increase in water demand enhances the initial and final setting time. Blending makes the initial setting time to increase by 32 minutes and the final setting time by 47 minutes

as compared to the reference sample. This is due to the adsorption of water by the bagasse ash surface. Similar results were found by Amin (2011), Ganesan, Rajagopal et al. (2007), and Hailu (2011).

4.3 Test Results and Discussion on Experiment II: Characterization of the Hardened Paste

The second experiment was done to study the microstructure of pastes at an early age. This was done by characterizing the hardened paste in both samples using XRD analysis on day 1. The test was carried out in Addis Ababa University-Chemistry department using a $\text{CuK}\alpha$ radiation diffractometer. Samples were analyzed, compounds were identified, and XRD patterns were drawn. From these, peaks and patterns of compounds were studied. The analysis result is given in Figures 4.3 and 4.4 below. XRD analysis pattern of raw bagasse ash done by Fekadu (2019) is attached on Annex A.C.3 for comparison purpose

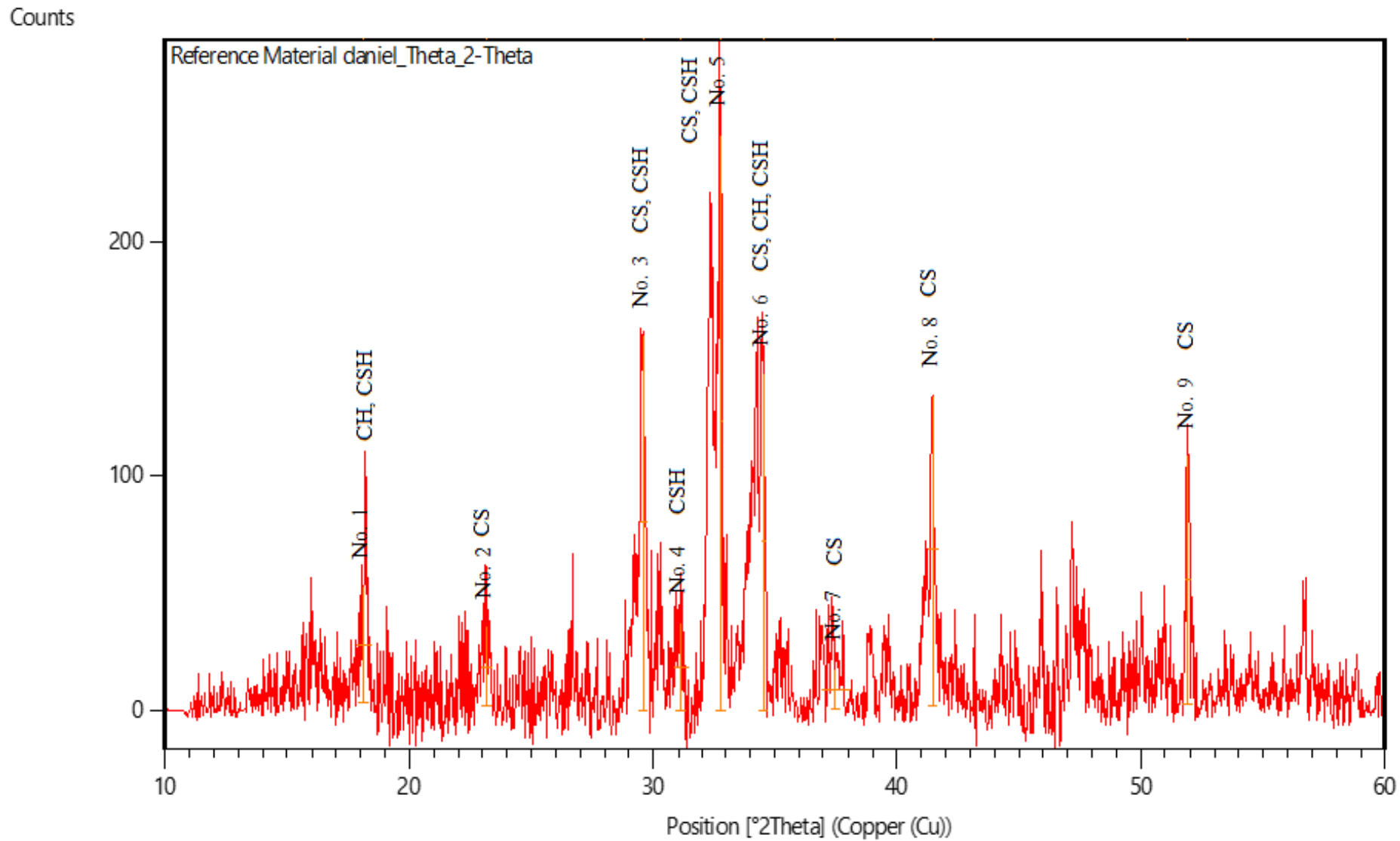


Figure 4.3 Chemical Compounds Detected in Reference Sample at Day 1

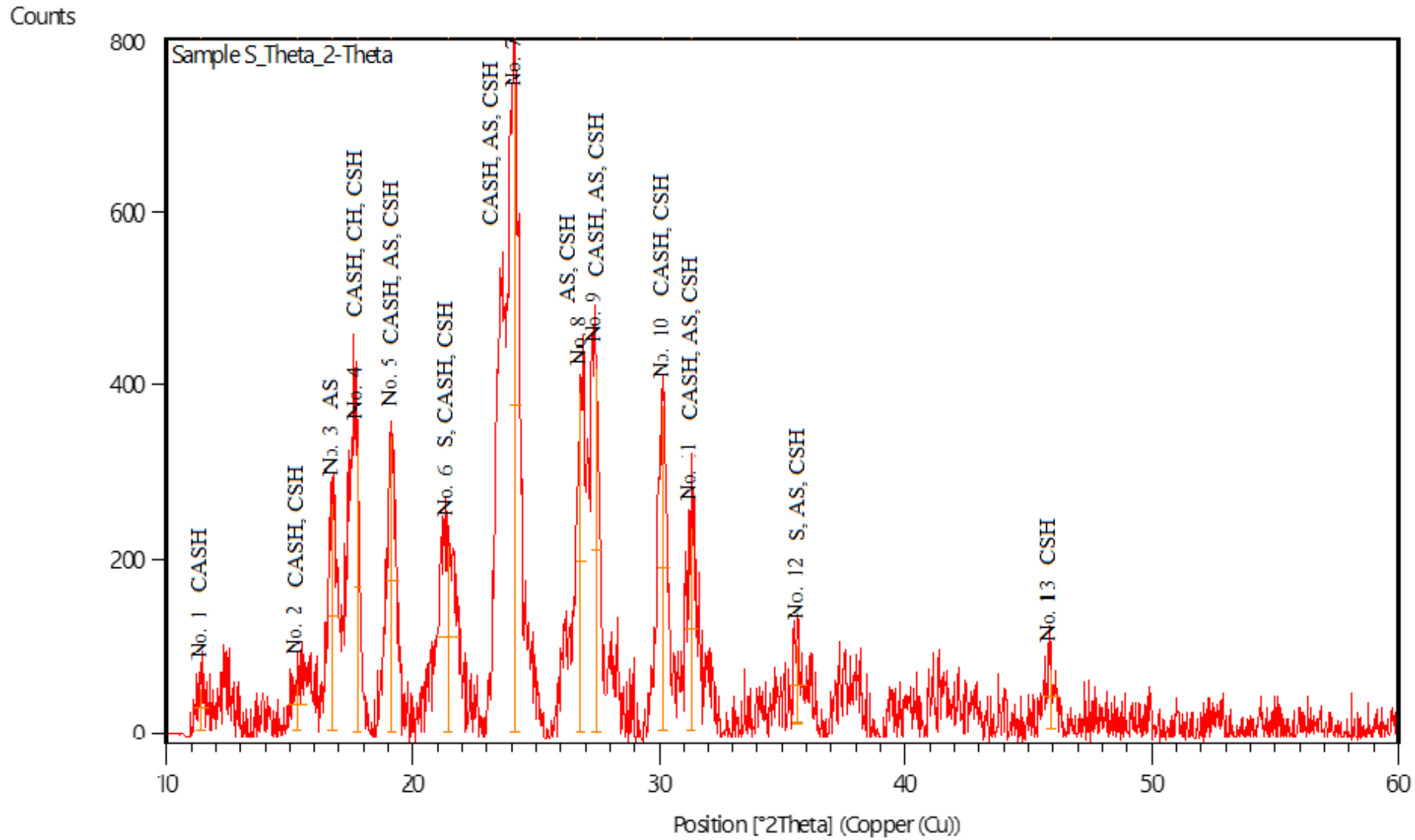


Figure 4.4 Chemical Compounds Detected in Blended Sample at Day 1

Table 4.5 Abbreviations Used for Compounds in the Above XRD Analysis Diagrams

S.N.	Abbreviation	Compound Name	Chemical Formula
1	S	Silicon Oxide	SiO ₂
2	CS	Calcium Silicate	Ca ₃ SiO ₅
3	AS	Aluminum Silicate	Al ₂ SiO ₅
4	CH	Calcium Hydroxide	Ca(OH) ₂
5	CSH	Calcium Silicate Hydrate	Ca ₃ Si ₃ O ₉ ·H ₂ O
6	CASH	Calcium Aluminate Silicate Hydrate	CaAl ₂ Si ₃ O ₁₀ ·H ₂ O

From the above XRD results C₃S, CH, and CSH were the peaks in the reference sample whereas S, CASH, AS, CH, and CSH were the peaks in the blended sample. More peaks with unreacted C₃S in the reference sample and more peaks with unreacted SiO₂ in the blended sample were observed. Compounds with Aluminum elements were found in the blended sample. Unreacted compounds were observed since the samples were 24 hours of age.

The peaks in the reference sample were found in a position of 2θ between 18.1299° and 51.9328° and only 2 out of 9 peaks were found in less than 28°. Whereas the peaks in the blended sample were found in a position of 2θ between 11.3964° and 45.9212° and 9 out of 13 peaks were found in less than 28°. The detailed peak and pattern list of both samples are given in Table 4.6, 4.7, and on Annex A.C in Table A.C.1, A.C.2.

Fewer peaks were observed in the reference sample than in blended. Having fewer peaks shows the presence of more reaction than the one with more peaks (Fekadu 2019). This indicates that the reaction retarding effect of blending and is in line with the results of the heat of hydration in section 4.4 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 et al. (2014), the extent of reaction measured by XRD is related to the amount of cumulative heat of hydration that evolved.

Besides, in the reference sample, most of the cementitious compounds detected are CH and CSH phases which are major contributors to strength. This makes the reference sample to get more strength than the blended samples on day 1. The presence of unreacted SiO₂

and CH shows the unfinished pozzolanic reaction in the blended sample. The reaction between SiO₂ 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 in accordance with the findings of Qing, Tao et al. (2019) and Maldonado-García, Hernández-Toledo et al. (2018). This is also in line with the findings of the compressive strength of mortar cubes in section 4.7.2 in this study. Formation of CH, AS, CASH, and CSH indicate the occurrence of pozzolanic reaction in the blended sample. This will be investigated thoroughly and proved further in the upcoming sections.

In addition to this, the crystal size is calculated based on the XRD data. In the absence of detailed shape information K is approximated as 0.9. The size of particles of crystals in the form of powder is determined using Scherrer's equation as:

$$D = \frac{K * \lambda}{\beta * \cos \theta}$$

Where: -

D = Crystallites Size(nm)

K = 0.9

λ = 0.15406nm

β = FWHM (radians)

θ = XRD peak position(radians), one half of 2θ

Based on this the crystallite size of each peak and the average crystallite size in each sample are calculated in Tables 4.6 and 4.7 below.

Table 4.6 Peak List and Crystallite Size in Reference Sample

Pos. [°2Th.]	Height [cts]	FWHM Left [°2Th.]	d-spacing [Å]	Rel. Int. [%]	Crystallite Size(D(nm))
18.13	61.9	0.58	4.88912	26.86	13.96661
23.16	40.63	0.38	3.83808	17.63	21.11794
29.56	151.46	0.34	3.01915	65.73	24.453
31.09	41.28	0.58	2.87427	17.92	14.31585
32.78	230.41	0.19	2.72998	100	43.12898
34.54	133.23	0.19	2.59434	57.82	43.33055
37.5	22.38	1.15	2.39637	9.71	7.28258
41.45	120.57	0.38	2.1766	52.33	22.11977
51.93	99.54	0.29	1.75931	43.2	30.68159
Average(D(nm))					24.48854

Table 4.7 Peak List and Crystallite Size in Blended Sample

Pos. [°2Th.]	Height [cts]	FWHM Left [°2Th.]	d-spacing [Å]	Rel. Int. [%]	Crystallite Size(D(nm))
11.396	47.7	0.576	7.75817	6.38	13.86066
15.299	52.75	0.768	5.78693	7.05	10.437
16.722	260.13	0.384	5.29747	34.78	20.9105
17.748	327.55	0.336	4.99339	43.79	23.93017
19.143	340.24	0.48	4.63271	45.49	16.78425
21.4	213.71	0.96	4.14881	28.57	8.421733
24.132	747.94	0.48	3.68499	100	16.9245
26.801	389.69	0.384	3.32379	52.1	21.26727
27.44	416.73	0.384	3.24783	55.72	21.29588
30.113	372.29	0.48	2.96527	49.77	17.13899
31.274	231.27	0.48	2.85783	30.92	17.1867
35.64	86.9	0.768	2.51711	11.62	10.86541
45.921	66.13	0.576	1.97463	8.84	14.9789
Average(D(nm))					16.46169

The average crystallites size in the reference sample is 24.49nm whereas the average crystallites size in the blended sample is 16.46nm. These are thicknesses of particles that are perpendicular to the crystal plane. This shows that the reference sample has a larger crystallite size. Implying that the reference sample diffracts at a larger angle than the blended. This is in agreement with the XRD analysis pattern shown in Figures 4.3 and 4.4.

4.4 Test Results and Discussion on Experiment III: Heat of Hydration Measurement

The heat of hydration measurement was done using Toni isothermal calorimeter at a constant temperature of 25°C. Three 10g samples each from reference and blended samples were mixed with 0.5 water to binder ratio in a test tube and placed in an isothermal calorimeter for 7 days (170 hours). The calorimeter used for measuring is given in Figure 4.5 below.



Figure 4.5 Heat of Hydration Measuring Calorimeter

Results on the instantaneous and cumulative heat evolved in reference and blended sample pastes are shown together in Figure 4.6 and 4.8 below. The graph of the heat flow rate of reference and the blended sample is truncated to show clearly the trends between samples and shown in Figure 4.7. To compare the difference between the two samples, average values were taken and indicated in Figure 4.9 below. The detailed graph of each sample is shown in Annex A.D.

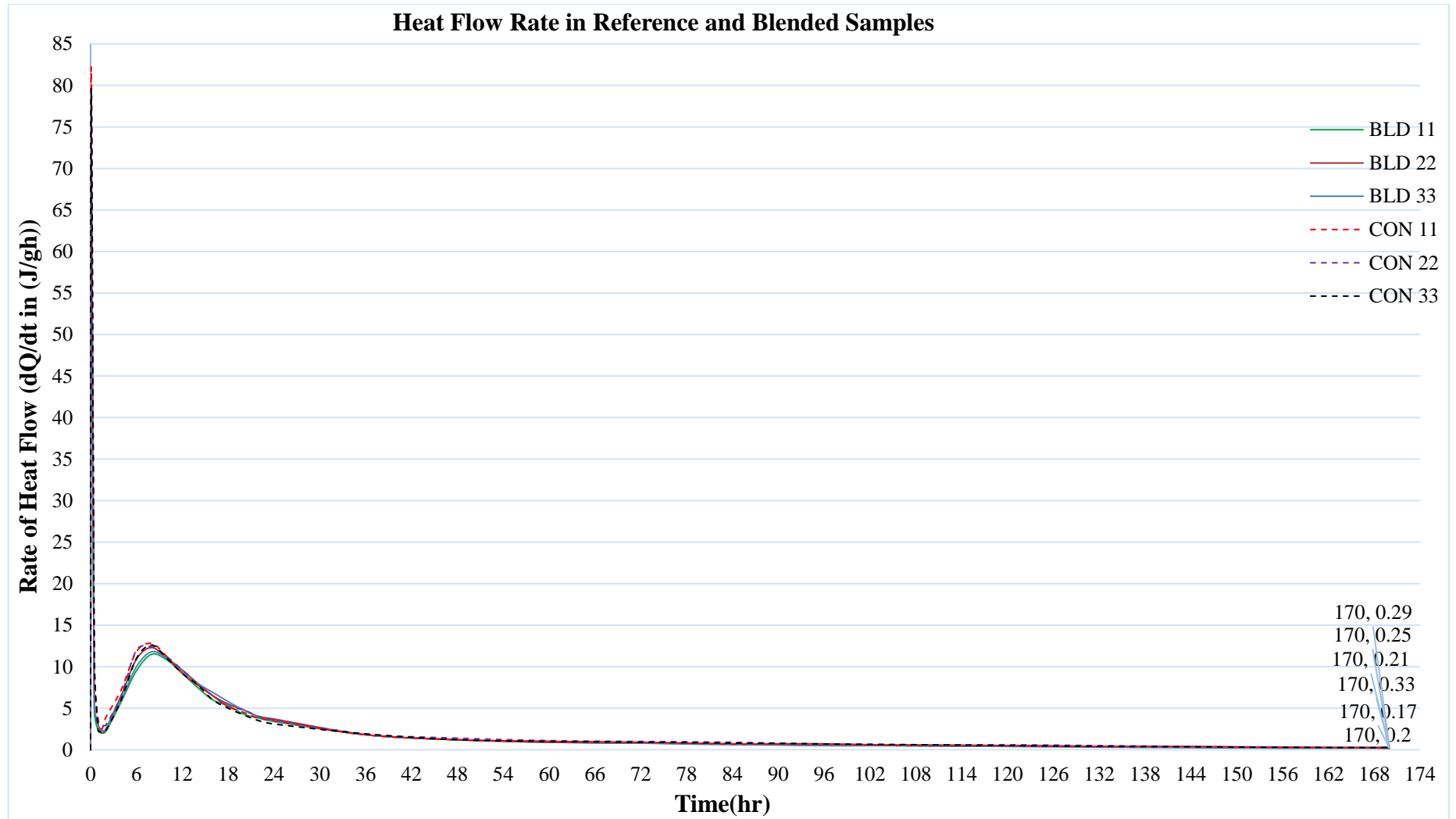


Figure 4.6 Instantaneous Heat Evolved in Reference and Blended Sample Pastes

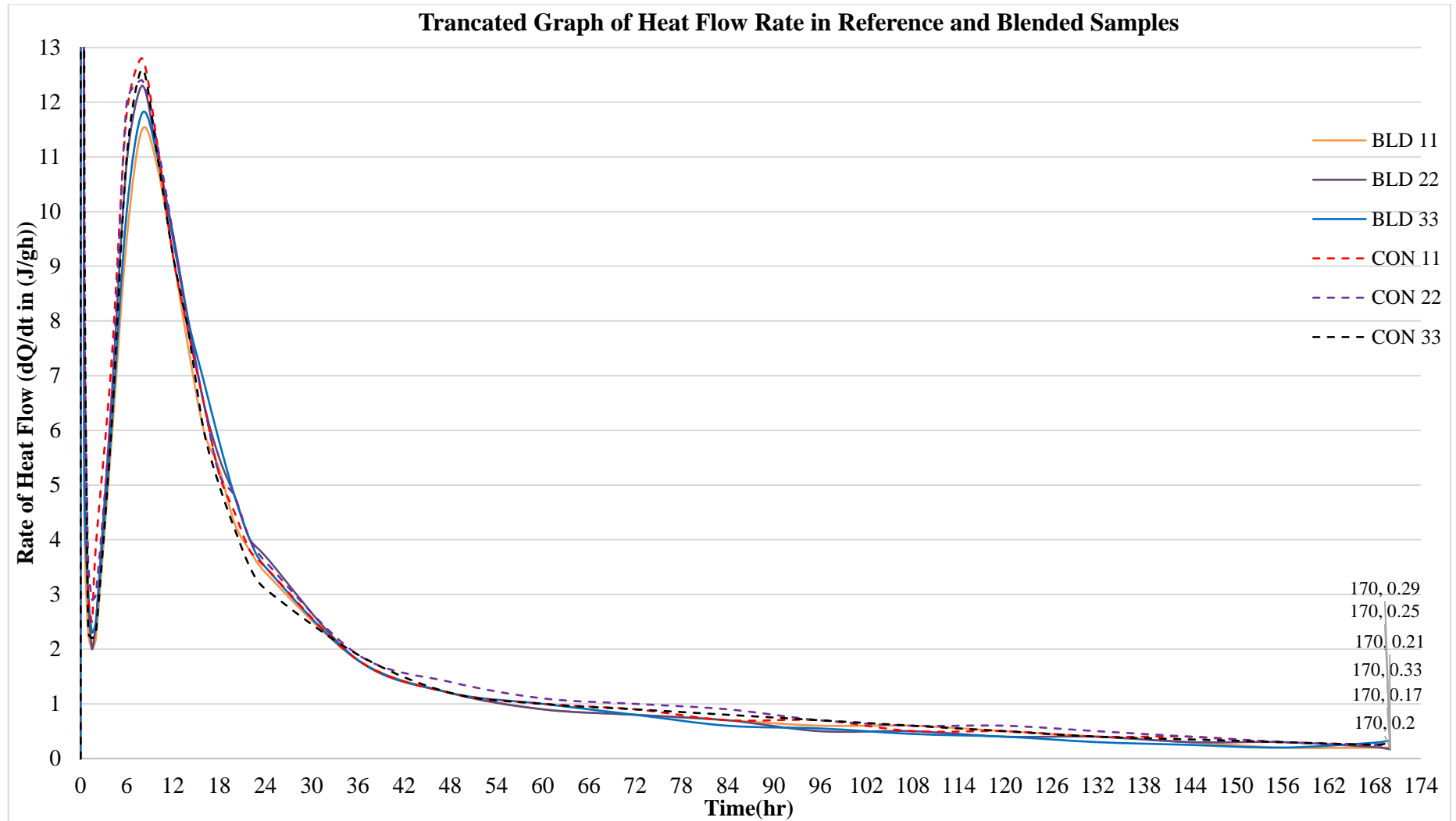


Figure 4.7 Truncated Graph of Instantaneous Heat Evolved in Reference and Blended Sample Pastes

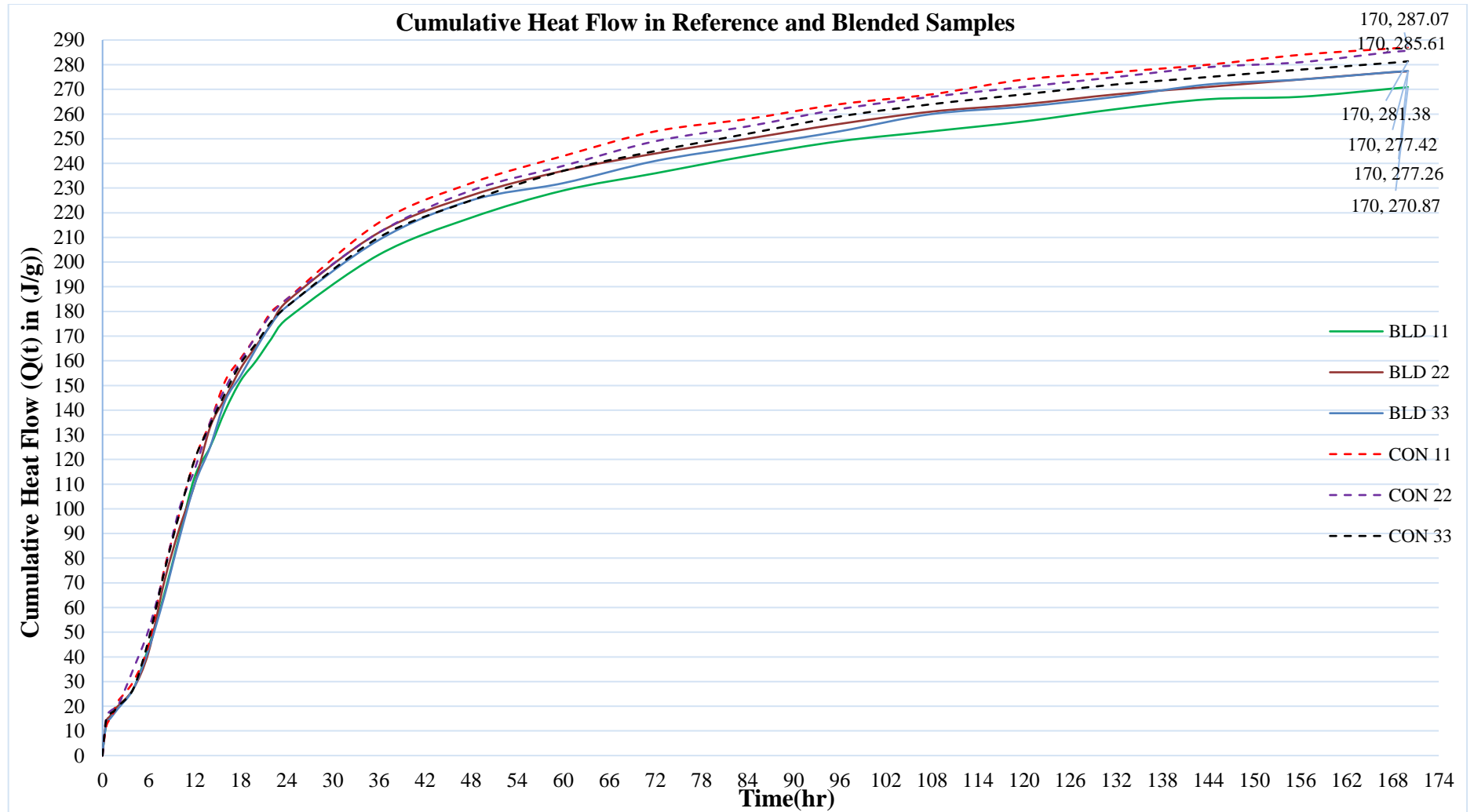


Figure 4.8 Cumulative Heat Evolved in Reference and Blended Samples

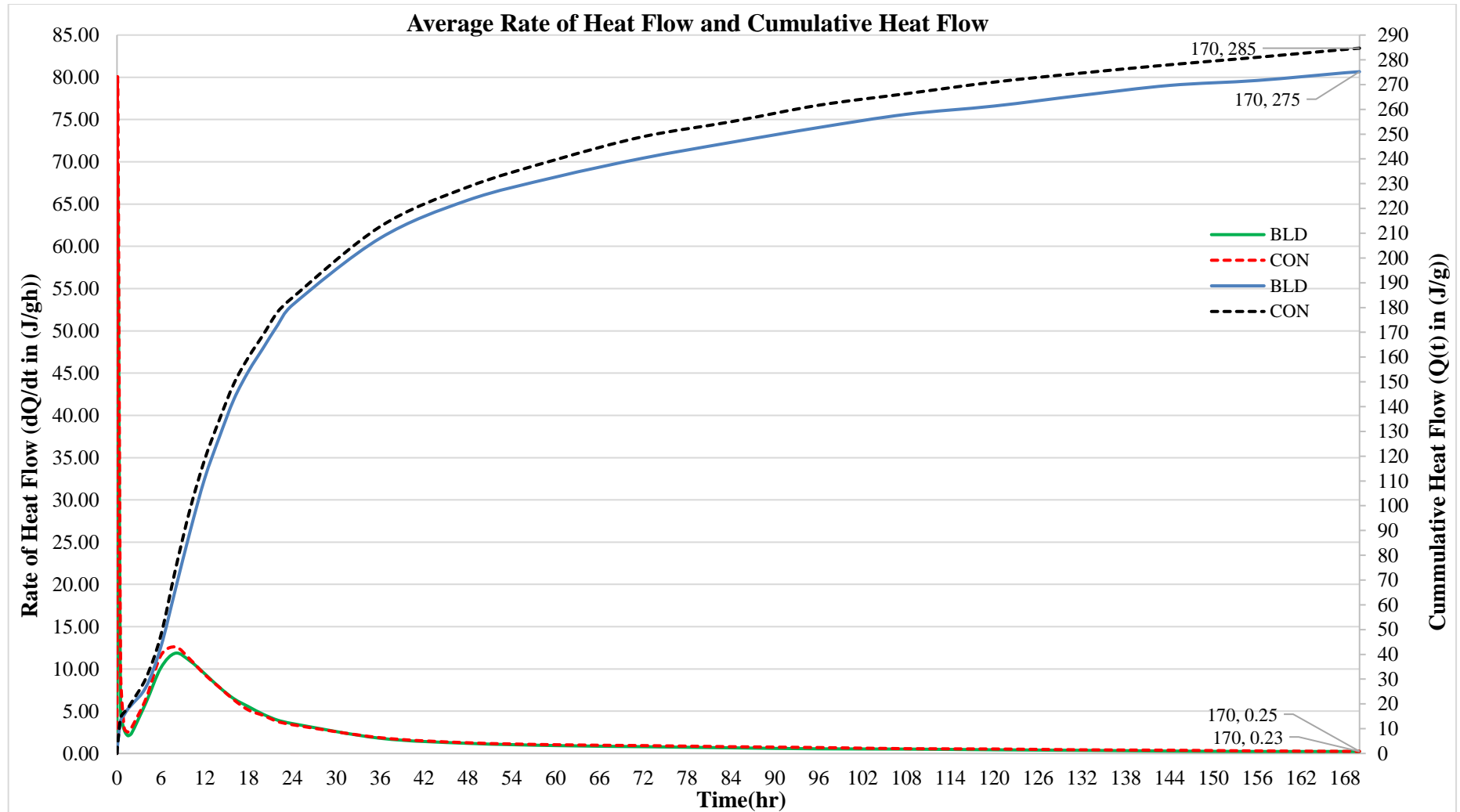


Figure 4.9 Average Rate of Heat Flow and Cumulative Heat Evolved in Reference and Blended Samples

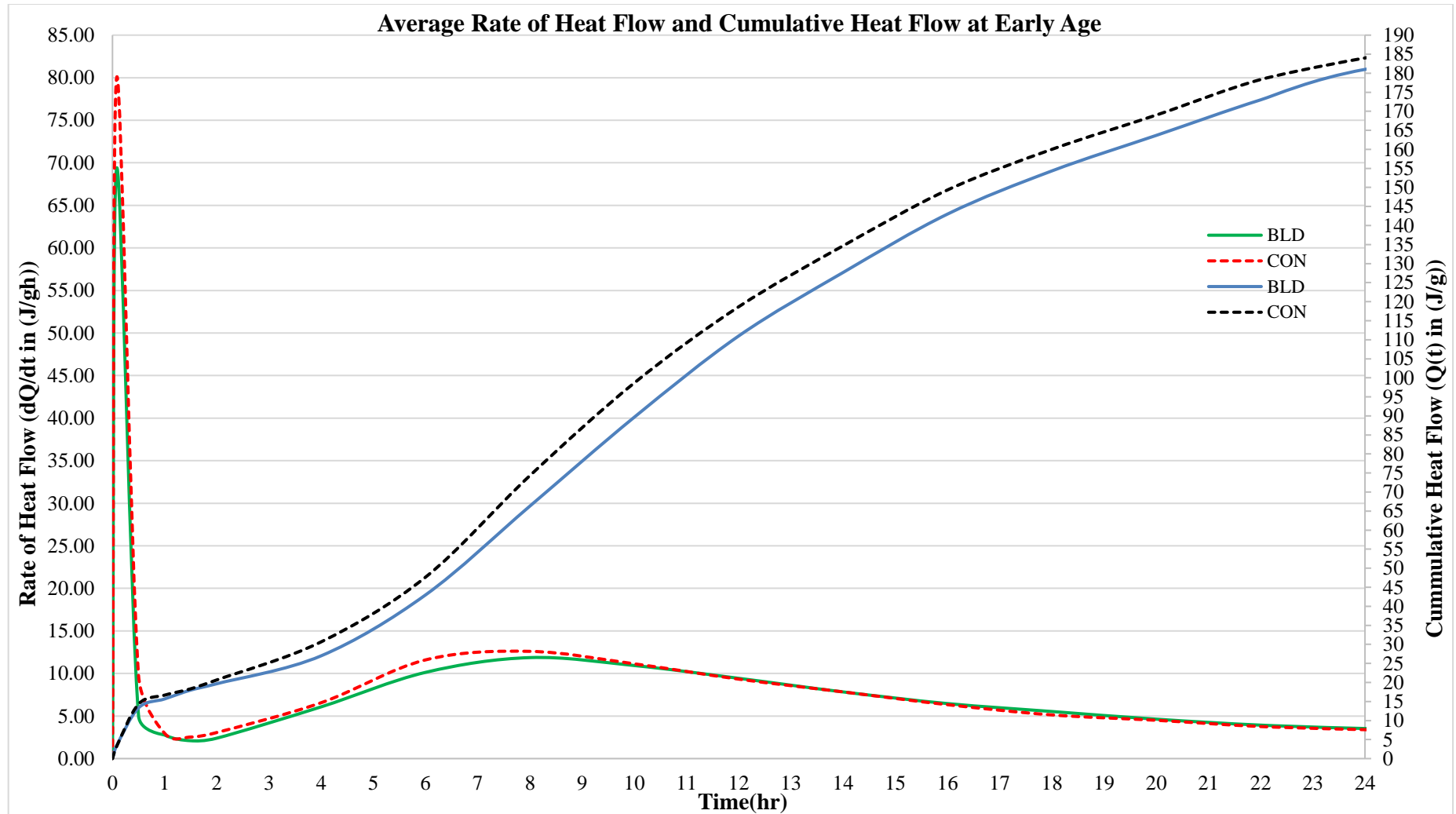


Figure 4.10 Average Rate of Heat Flow and Cumulative Heat Evolved in Reference and Blended Samples at Early Age

From the calorimetry test results, the rate of hydration and cumulative heat evolved is lower in blended samples than the reference cement pastes during the first 7 days (170 hours) of hydration. This shows that the addition of bagasse ash has a decreasing effect on the instantaneous and total heat evolved. This is in agreement with findings by Chusilp, Jaturapitakkul et al. (2009) in their study of utilization of bagasse ash as a pozzolanic material in concrete. They found that the addition of ground bagasse ash decreases the heat of evolution.

Incorporation of bagasse ash 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 (2016) in his study on the investigation of physical properties of graphene-cement composite for structural applications. According to Feng, Zhang et al. (2019) blending makes the cumulative heat of hydration to reduce and this helps in the reduction of autogenous shrinkage of cement and concrete products. The optimum values in each sample are given in Table 4.8 below.

Table 4.8 The Maximum Rate of Heat Flow and Cumulative Heat Flow of Test Samples

Sample Code	Time for Maximum	Maximum	Cumulative Heat Flow(J/g)
	Rate of Heat Flow (Minute: Second)	Rate of Heat Flow(J/gh)	
CON 11	0:04:14	82.22	285.07
CON 22	0:04:04	78.37	285.6
CON 33	0:04:25	79.65	281.38
Average	0:04:14	80.08	284.02
BLD 11	0:05:16	67.35	270.87
BLD 22	0:05:07	69.88	277.26
BLD 33	0:05:16	70.99	277.42
Average	0:05:13	69.41	275.18

In the reference samples, the cumulative heat flow was found to be 284.02J/g and the maximum rate of heat flow was 80.08J/gh which was found at 4 minutes and 14 seconds.

In the blended samples, the cumulative heat flow was found to be 275.18J/g and the maximum rate of heat flow was 69.41J/gh which was found at 5 minutes and 13 seconds.

Blending makes the maximum rate of heat flow to reduce by 10.67J/gh on average and to delay the time at which this pick is achieved by an average of 59 seconds (\approx 1 minute). The cumulative heat flow was also found to decline by an average of 8.833J/g.

The average rate of heat flow and cumulative heat evolved in reference and blended samples at an early age (\leq 1 day) are shown in Figure 4.10 above. Reference samples show higher values than the blended samples. But the difference between the two samples is smaller as compared to the heat evolved in later ages.

According to Snellings, Salze et al. (2014), the heat released on different days is assumed to be directly proportional to the degree of reaction. But this will work for materials with similar chemical composition. It shouldn't be used to compare one pozzolan with another.

Each sample will be compared to its group at different ages. Meaning that 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 to the pozzolanic reactivity of the blended samples as well. These results correspond with the trend in compressive strength of the reference and blended cement mortars. Alujas, Fernández et al. (2015) also find similar results in their study of clays calcined at different temperatures. The cumulative heat flow of both reference and blended samples from isothermal calorimetry is shown in Figure 4.11 below.

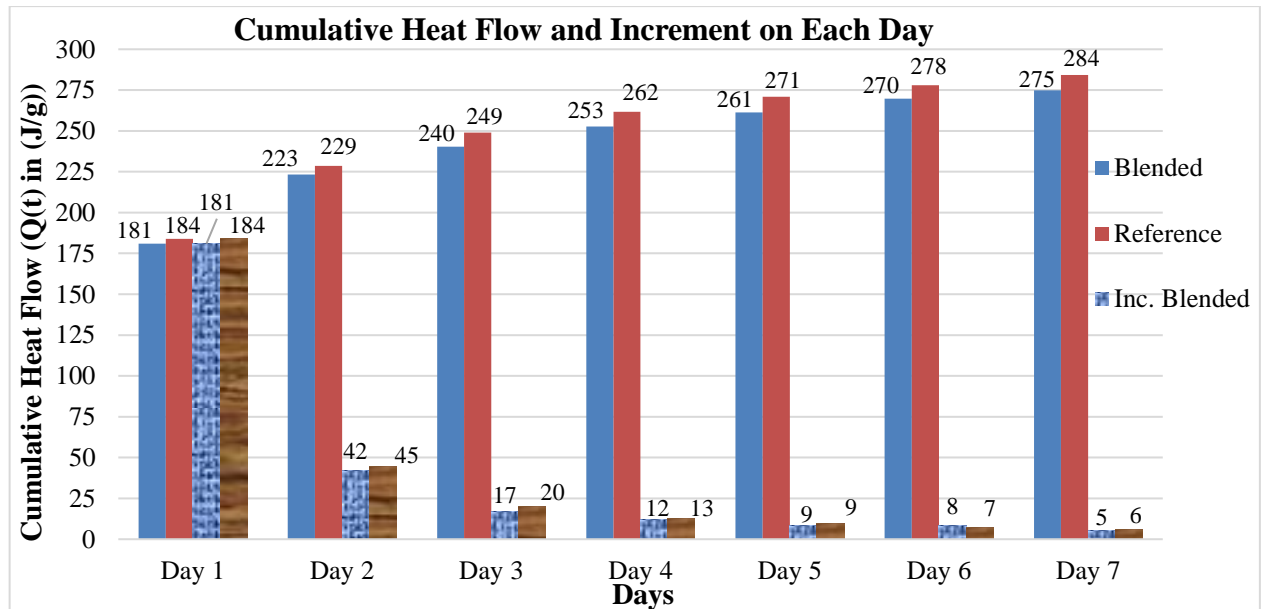


Figure 4.11 Average Cumulative Heat Evolved in Reference and Blended Samples on Each Day

Almost 65.9%, 81.3%, and 87.5% of the heat of hydration from the total (at 170 hours) are released during days 1, 2, and 3 in blended samples respectively. Almost 64.7%, 80.5%, and 87.61% of the heat of hydration from the total (at 170 hours) are released during days 1, 2, and 3 in reference samples respectively. All these show that majority (88%) of the heat is released within the first 3 days. Increments after the third day are minimal and become very small after the sixth day. This is in line with the findings of Avet, Snellings et al. (2016).

The difference in heat of hydration between the reference and blended sample rises as time increases. The difference starts from 3J/g and ends up in 9J/g on the 7th day. Implying that, developments in the evolved heat between the two consecutive samples are in correspondence with the trend in compressive strength of mortars in the two samples.

4.5 Test Results and Discussion on Experiment IV: Bound Water Determination Test

Three samples each with a mass of 150g from control and experimental samples were prepared, cast, and put in a 25°C enclosed environment for 24 hours. This is made to create a similar environment with that of samples prepared for the heat of hydration. After 24

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development

hours the samples were put in an oven at 110°C for 48 hours and masses were measured. Samples were put in the furnace at 400°C for 2 hours and decrease the temperature to 100°C. Samples were taken in a desiccator to avoid moisture absorption from the atmosphere and weighed by a beam balance. Cast samples are indicated in Figure 4.12 below.



Figure 4.12 Samples Prepared for Bound Water Determination Test

Results of the experiments showed that the reference samples were found to have 2.89% bound water (gm) on average whereas the blended samples were found to have 2.58% bound water (gm) on average. The blended samples had a lower amount of bound water. Measurements on cast samples and the calculated bound water amount are given in Table 4.9 below.

Table 4.9 Bound Water Determination Test Results

Sample	Mass after 2 days in Oven(gm) @ 110°C	Mass after furnace for 2hrs(gm) @400°C and Cool to 100°C	Bound Water (gm)%	Bound Water (gm)%	Average
C ₁	27.5659	26.7774	0.028604181	2.860418125	2.887622185
C ₂	30.6527	29.7771	0.028565183	2.856518349	
C ₃	37.3091	36.21	0.029459301	2.945930081	
E ₁	45.5632	44.4011	0.025505232	2.550523229	2.579049192
E ₂	35.7722	34.8751	0.025078133	2.50781333	
E ₃	45.8375	44.6096	0.026788110	2.678811017	

According to Prochoña and Piotrowskia (2016) specimens with a higher content of Al_2O_3 and SiO_2 show lower values of bound water parameter. 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.

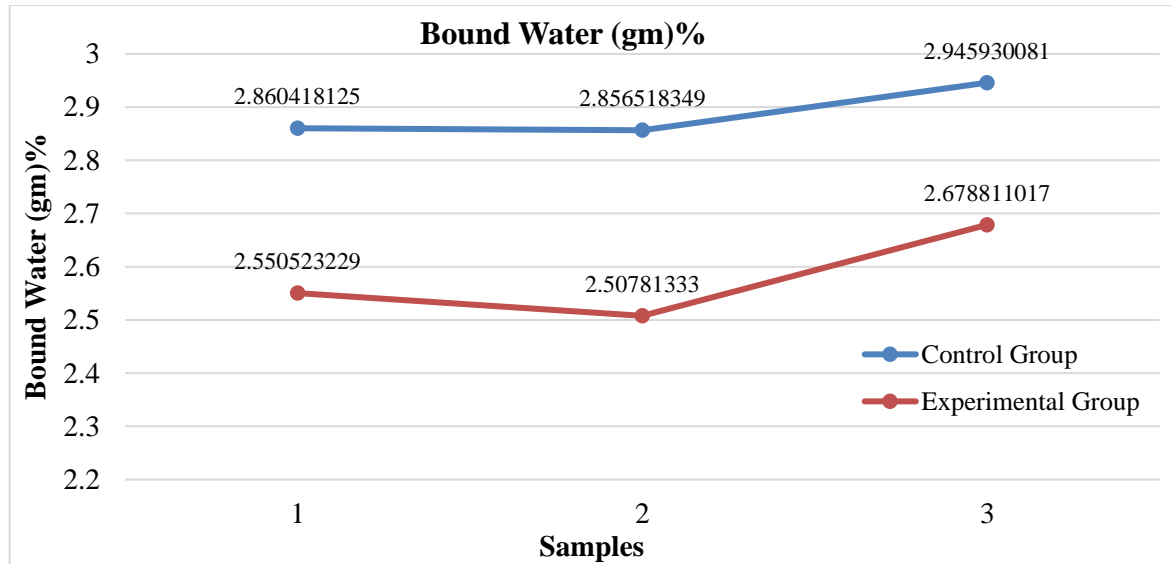


Figure 4.13 Graphical Representation of Bound Water Determination Experiment Results

The amount of chemically bound water found by ignition is used for the determination of the degree of hydration in the cement mix. The above result showed a more percentage of bound water in reference samples. Implying that there is more hydration reaction (CSH formation) in reference samples during the last 24 hours showing higher strength. Hydration reaction is retarded because of the addition of bagasse ash. According to Fagerlund (2009), there is a direct proportionality between the amount of chemically bound water and the amount of cement that has reacted. But when reactive mineral admixtures are added to cement or concrete the direct proportionality will not be valid. Corrections need to be done when other reactive minerals are added to figure out the amount of cement that has reacted (Fagerlund 2009).

Similarly, Bougara, Lynsdale et al. (2010) found 9.3% and 11.4% bound water for Algerian and United Kingdom(UK) slag blended pastes respectively at 90 days. Almost 22% higher amount of bound water reflecting that higher strength for the UK blast furnace slag blended pastes at 90 days.

4.6 Test Results and Discussion on Experiment V: Determination of the PABA

The PABA was determined using the Modified Chapelle test in Ethiopian Public Health Institute-Food and Nutrition Laboratory. The test uses a direct laboratory method to evaluate the PABA by quantifying the fixed portlandite. The test setup and titration of the filtered solution are shown in Figure 4.14 below.



Figure 4.14 Modified Chapelle Test Experiment Under Investigation

The calcium hydroxide that was not consumed is quantified by HCl titration. The test was done in replicas and similar results were found. The result is expressed in mg of fixed $\text{Ca}(\text{OH})_2$ per gram of bagasse ash. Results on PABA is given in Table 4.10 below.

Table 4.10 The Determined Amount of PABA

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)
1	B1	25.9	22.6	336.73
	B2	25.9	22.5	346.94
	Average	25.9	22.55	341.84
2	B1	25.6	22.3	340.68
	B2	25.7	22.2	359.92
	Average	25.65	22.25	350.32
Grand Average		25.775	22.40	346.078

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. Based on this an average pozzolanic activity value of 346.08mg Ca(OH)₂/ g bagasse ash was obtained. This shows the presence of a pozzolanic reaction.

In a similar study on Brazilian bagasse ash Cordeiro, Toledo Filho et al. (2008) found a minimum of 36mg CaO/g bagasse ash and a maximum of 298mg CaO/g bagasse ash. In another study, Quarcioni, Chotoli et al. (2015) 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. Ferraz, Andrejkovicová et al. (2015) in their study of pozzolanic activity of metakaolin using Modified Chapelle test were found a pozzolanic value of 1,240mg Ca(OH)₂/ g metakaolin. This value is high since Metakaolin is a highly reactive hydraulic material.

4.7 Test Results and Discussion on Experiment VI: Compressive Strength Test

In this part, the workability of mortar and compressive strength of mortar cubes were given and discussed.

4.7.1 Workability of Mortar

The workability of mortar was checked using a flow table test. Based on this, the flow table test results for both reference and blended samples are given in Table 4.11 below.

Table 4.11 Mortar Flow Table Test Result

Mix Type	Flow(mm)
Reference Mix	146
Blended Mix	144

Results showed that a slight reduction in the blended mix than in the reference mix. This is due to the high surface area of the blended bagasse ash.

4.7.2 Compressive Strength of Mortar Cubes

Both blended and reference mortar cubes were tested for compressive strength at different ages. Average strength results are given in Table 4.12 below and the detailed result is given in Annex A.A. In this part, blending of cement was made one with bagasse ash and the other with quartz samples to compare compressive strength development with each other and with the reference sample.

Table 4.12 Average Compressive Strength of Mortar Cubes

Age of Mortar	Average Compressive Strength					
	Reference Sample		BA Blended Sample		Quartz Blended Sample	
	Load (kN)	Strength (N/mm ²)	Load (kN)	Strength (N/mm ²)	Load (kN)	Strength (N/mm ²)
1 day	24.2	9.69	23.1	9.22	23.65	9.46
3 days	51.6	20.65	53.6	21.43	46.55	18.62
7 days	61.3	30.95	64.2	31.85	71.275	28.51
28 days	82.08	50.85	85.05	52.65	111.4	44.56
56 days	146.34	58.54	150.45	60.18	128.3	51.32
90 days	160.23	64.09	165.7	66.28	141.95	56.78

The above compressive strength values are averages of three specimens prepared from both mixes. According to Ahmad, Adekunle et al. (2014), variation in compressive

strength of the individual specimens should be within the acceptable range (with standard deviation within 3 MPa). All test results fall within this range.

On day 1 the compressive strength of bagasse ash blended mortar cubes was lower than the reference sample. This is due to the amount of hydration products formed by the pozzolanic reaction not yet to compensate for the dilution effect. According to Cyr, Lawrence et al. (2006) the main contribution of SCMs to the hydration process at an early age is strongly related to the filler effect, so the degree of reaction of the clinker phases is enhanced due to the extra space available for the hydrates to grow. It is also due to the higher water to clinker ratio and the additional surface provided by the very fine SCM, which could act as nucleation sites for the hydration products.

Berodier (2015) also found that the slower reaction of SCMs makes the SCM only to contribute significantly after the main clinker reactions. During this inert period, the SCM particles act as a filler and accelerate the kinetics.

According to Lothenbach, Scrivener et al. (2011), 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. The hydration of the aluminate phases, which occurs after the main silicate hydration peak is often more sensitive to nucleation effects.

Alujas, Fernández et al. (2015) also found a similar result in their study on calcined clays blended with the OPC system. They found that calcined clays on blended system hydration are a combination of a filler effect, enhancing the hydration of Portland cement at early ages, and the pozzolanic reaction of the calcined clays later on. Calcined clays, with highly reactive aluminate-rich phases, favor the formation of AFm-type phases and influence the microstructure of hydration products microstructure, increasing C–A–S–H chain length where Al is substituting for Si.

Snellings and Scrivener (2016) in their study of SCMs blended system found that all blended cement shows lower strengths at day 1 of hydration than the reference Portland cement and over the long-term, however, all blended cement except the quartz filler

surpassed the OPC reference. The timing at which the reference is surpassed depends on the reactivity of the SCM.

Results obtained from local studies by Hailu (2011) and Geremew (2017) in Figure 4.15 below on mortar and concrete cubes respectively at 10% level of replacement of cement by bagasse ash are given for comparison. These are in line with the findings of this study given in Figure 4.16.

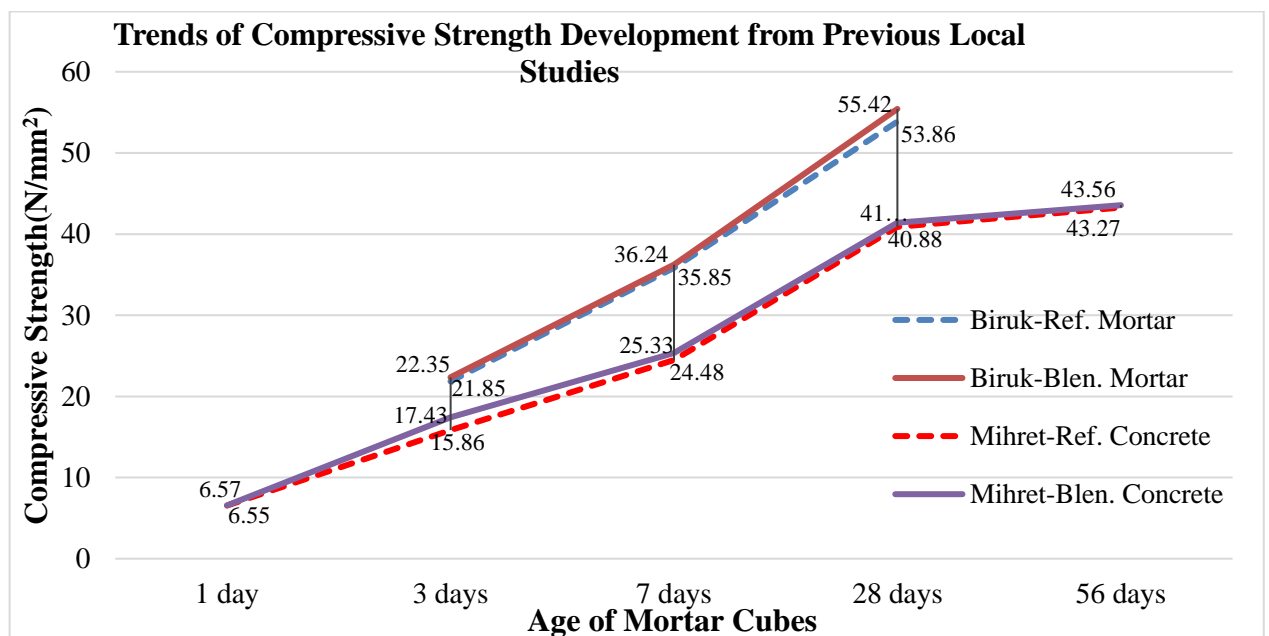


Figure 4.15 Trends of Compressive Strength Development from Previous Local Studies

Results on the compressive strength development of mortar cubes at different ages is shown in Figure 4.16 below.

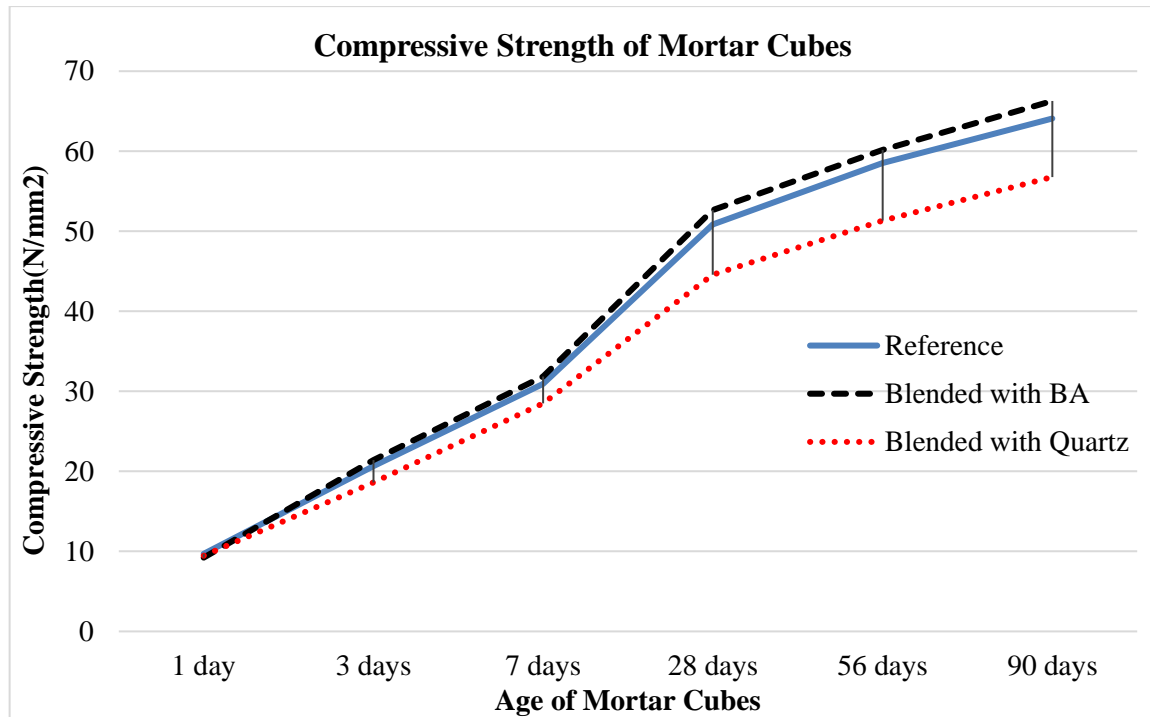


Figure 4.16 Compressive Strength Development of Mortar Cubes at Different Ages

The compressive strength results in Figure 4.16 above 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. 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 et al. (2018) found similar result and according to their study addition of quartz powder do not change the type of hydration product but had dilution effect and crystal nucleation effect. This shows that 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.

The maximum compressive strength achieved was 64.09MPa in reference, 66.28MPa in bagasse ash blended mortar cubes, and 56.78MPa in quartz blended mortar cubes.

4.8 Correlation Between Tests and Compressive Strength Development

The compressive strength development tests were compared to four different SCM screening tests. According to Snellings and Scrivener (2016), the main objective of the SCM screening test is to accurately predict the strength development of blended cement with SCMs and this over a wide range of compositions and conditions. In this study, 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. A correlation was found between tests and compressive strength development.

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 to have better compressive strength on day 1. Similar results were found in compressive strength measurement on day 1 in this study.

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 increase during later days. Similarly, compressive strength development of the blended and reference mortar cubes (9.22 and 9.69MPa) show a similar increment at an early age and a significant increment after 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 that more strength. Likewise, at an early age (≤ 1 day), a little bit higher compressive strength was found in reference samples showing that higher reactivity.

Results from the determination of PABA also strengthen the above findings. Measurements using the Modified Chapelle test confirmed the presence of pozzolanic reactivity of the bagasse ash.

The above results correspond to findings obtained by different researchers on other SCMs at different times. The proposed method met all the criteria of the SCM screening test. It

also correlated well to compressive strength development. Results were achieved rapidly and findings were reliable. The testing method was also relevant.

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The general objective of this study is to evaluate the pozzolanic reactivity of bagasse ash while partially replacing cement via compressive strength development. To achieve this objective standard consistency test, characterization of the hardened paste, measurement of the heat of hydration, determination of the amount of bound water, determination of the PABA, and determination of the compressive strength of mortar cubes were made. Correlation between each test with compressive strength development was also established. Based on this the following major finding were obtained.

- The chemical analysis result showed that the bagasse ash used in this study is composed of mainly SiO_2 (75.98%) and the total amount of SiO_2 , Al_2O_3 and Fe_2O_3 is 89.80% w/w. It has a LOI value of less than 10% (5.81%). According to ASTM C-618, the material is classified as pozzolanic material of Class N.
- XRD analysis results indicated that in reference sample C_3S , CH, and CSH were the peaks whereas in blended sample S, CASH, AS, CH, and CSH were the peaks. Fewer peaks were observed in the reference sample than in blended. In the reference sample, more peaks with unreacted C_3S and in blended samples more peaks with unreacted SiO_2 were observed.
- The water demand (standard consistency) of the blended samples was relatively higher than the reference sample. This is due to the fineness of the bagasse ash added as a cement replacement. The initial and final setting time of the blended cement samples were also higher than the reference samples.
- Reference samples were found to have a cumulative heat flow of 284.02J/g and a maximum rate heat flow of 80.08J/gh at 4 minutes and 14 seconds. Whereas blended samples were found to have a cumulative heat flow of 275.18J/g and a maximum rate heat flow of 69.41J/gh at 5 minutes and 13 seconds.
- Blending makes the maximum rate of heat flow to reduce by 10.67J/gh on average and to delay the time at which this pick is achieved by an average of 59

seconds(\approx 1minute). The cumulative heat flow was also found to decline by an average of 8.833J/g.

- Almost 65% of the heat of hydration at 7days (170 hours) was released during day 1 and 88% were released within 3 days. The difference in heat of hydration between the reference and blended samples increased as time increases starting from 3J/g on the 1st day to 9J/g on the 3rd day.
- Reference samples were found to have 2.89% bound water (gram) content whereas blended samples were found to have 2.58% bound water (gram) content on day 1. The lower bound water amount is obtained in blended samples showing that slower hydration than the reference.
- Compressive strength at an early age (\leq 1 day) is lower in the blended sample due to the addition of the bagasse ash in the experimental mortar cubes. But in the later days (3, 7, 28, 56, 90 days) compressive strength of bagasse blended cement mortar cubes were higher than the reference sample. The maximum compressive strength at 90days was found to have 64.54MPa in the reference mortar, 66.28MPa in the bagasse ash blended mortar, and 56.78MPa in quartz blended mortar cubes.
- The determined amount of pozzolanic activity of bagasse ash was found to be 346.08mg of $\text{Ca}(\text{OH})_2$ /g of bagasse ash.
- 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 to compressive strength development. Results were achieved rapidly and findings were reliable. The testing methods were also relevant.

In short, the 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 heat of hydration properties. So, the bagasse ash can be utilized as an effective partial cement replacing material for concrete structures. The methods utilized to investigate the pozzolanic reactivity of bagasse ash were found to have coherent results.

5.2 Recommendation

Based on the findings of this study the following recommendations are forwarded.

- The findings of this study are in accordance with the findings of other similar studies conducted on bagasse ash produced by sugar industries. The abundance of this material as industrial waste, pozzolanic reactivity, and technical advantages that the material showed during the studies are promising findings that support an effort made in the future to utilize this material in a standardized form.
- The findings of this study can be used as focus areas to improve the concrete property in construction while using in blended system. Findings and methodologies can be used as a checklist to test other similar SCMs and to get a better-quality concrete.

Further study area

- The results of this research were based on a sample of bagasse ash from the Wonji sugar factory. Future research should investigate bagasse ash produced by other sugar factories in the country.
- A number of possible future studies using the proposed approach are also strongly recommended. More information on this area would help us to establish standards for further utilization of the material in the construction industry.

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ANNEX

Annex A.A Results of Compressive Strength of Mortar Cubes

Table A.A.1 Detail Results of Compressive Strength of Mortar Cubes


No.	Test Age (days)	Dimensions(mm)			Weight (gm)	Failure Load(KN)	Compressive Strength(MPa)
		L	W	H			
At 0% BA-Cement Replacement							
1	1	50	50	50	304.6	26.1	10.42
2		50	50	50	303.2	24.4	9.75
3		50	50	50	305.8	22.3	8.9
Average					304.5	24.2	9.69
At 10% BA-Cement Replacement							
1	1	50	50	50	300.1	21.1	8.44
2		50	50	50	299.8	22.8	9.11
3		50	50	50	302.2	25.3	10.12
Average					300.7	23.1	9.22
At 0% BA-Cement Replacement							
1	3	50	50	50	305.1	49.9	19.95
2		50	50	50	303.2	52.0	20.81
3		50	50	50	304.2	53.0	21.19
Average					304.2	51.63	20.65
At 10% BA-Cement Replacement							
1	3	50	50	50	302.5	54.0	21.6
2		50	50	50	299.4	52.0	20.8
3		50	50	50	301.3	54.8	21.9
Average					301.1	53.6	21.43
At 0% BA-Cement Replacement							
1	7	50	50	50	306.5	76.0	30.41
2		50	50	50	305.0	78.7	31.49
3		50	50	50	304.4	77.4	30.96
Average					305.3	77.4	30.95
At 10% BA-Cement Replacement							
1	7	50	50	50	302.6	80.3	32.10
2		50	50	50	299.2	81.3	32.50
3		50	50	50	302.8	77.4	30.95
Average					301.5	79.6	31.85

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development

No.	Test Age (days)	Dimensions(mm)			Weight (gm)	Failure Load(KN)	Compressive Strength(MPa)
		L	W	H			
At 0% BA-Cement Replacement							
1	28	50	50	50	304.7	129.4	51.76
2		50	50	50	306.3	127.4	50.94
3		50	50	50	307.1	124.6	49.85
Average					306.0	127.1	50.85
At 10% BA-Cement Replacement							
1	28	50	50	50	300.1	128.9	51.55
2		50	50	50	300.9	133.8	53.5
3		50	50	50	302.5	132.3	52.9
Average					301.2	131.6	52.65
At 0% BA-Cement Replacement							
1	56	50	50	50	306.9	144.7	57.89
2		50	50	50	305.3	146.7	58.68
3		50	50	50	304.2	147.6	59.04
Average					305.5	146.34	58.54
At 10% BA-Cement Replacement							
1	56	50	50	50	298.8	152.6	61.05
2		50	50	50	301.5	149.9	59.94
3		50	50	50	302.4	148.9	59.55
Average					300.9	150.45	60.18
At 0% BA-Cement Replacement							
1	90	50	50	50	307.0	158.6	63.42
2		50	50	50	304.8	160.0	64.0
3		50	50	50	305.5	162.1	64.85
Average					305.8	160.23	64.09
At 10% BA-Cement Replacement							
1	90	50	50	50	302.4	167.6	67.05
2		50	50	50	303.1	164.3	65.70
3		50	50	50	300.5	165.2	66.09
Average					302.0	165.7	66.28

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development

Annex A.B Chemical Composition Test Result

	GEOLOGICAL SURVEY OF ETHIOPIA	Doc.Number: GLD/F5.10.2	Version No: 1
	GEOCHEMICAL LABORATORY DIRECTORATE		Page 1 of 1
Document Title:	Complete Silicate Analysis Report	Effective date:	May, 2017

Issue Date: -19/07/2019
Request No:- GLD/RN/475/19
Report No:- GLD/TR/416/19
Sample Preparation: - 200 Mesh
Number of Sample:- One (1)

Customer Name:- Daniel Alemaychu

Sample type:- wonji bagasse Ash

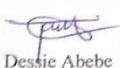

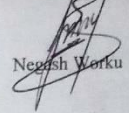
Date Submitted: - 10/07/2019


Analytical Result: In percent (%) Element to be determined Major Oxides & Minor Oxides

Analytical Method: LiBO₂ FUSION, HF attack, GRAVIMETERIC, COLORIMETRIC and AAS

Collector's code	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	P ₂ O ₅	TiO ₂	H ₂ O	LOI
Wonji-SCBA	75.98	11.54	2.28	1.12	0.60	0.64	1.92	<0.01	0.42	0.09	1.10	5.81

Note: - This result represent only for the sample submitted to the laboratory.

Analysts Yirgalem Abriham Tihitna Beletkachew Tizita Zemene Yohanis Getachew Bethelhem Tefera	Checked By  Dessie Abebe	Approved By  Gosa Haile	Quality Control  Negash Worku
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Annex A.C XRD Analysis Test Result

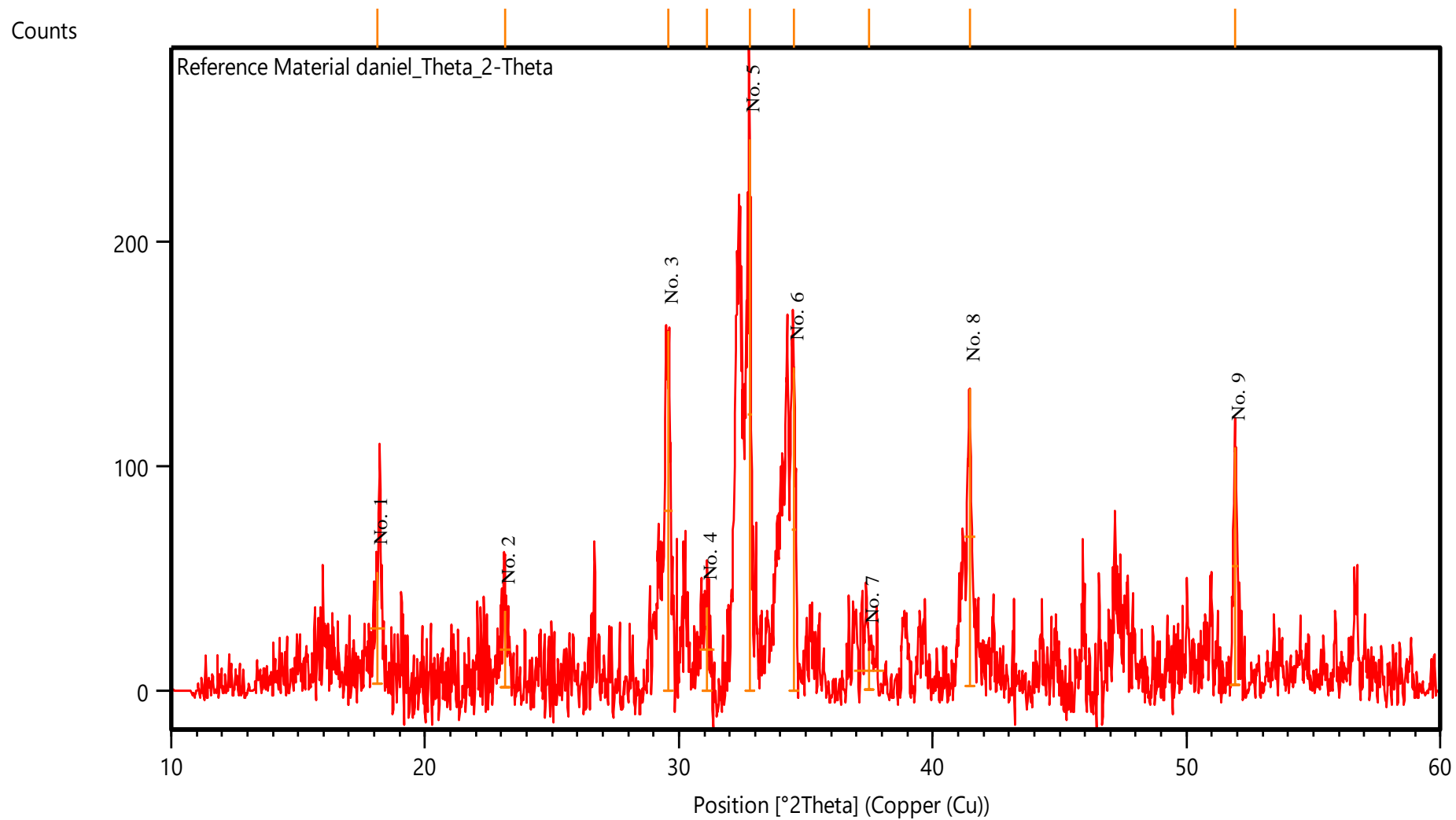


Figure A.C.1 Crystalline Peaks Detected Using XRD Analysis in Reference Sample at day 1

Table A.C.1 Pattern List of the Reference Sample

Number	Ref. Code	Score	Compound Name	Displacement [°2Th.]	Scale Factor	Chemical Formula
1	00-042-0551	43	Calcium Silicate	0.000	0.759	Ca ₃ Si O ₅
2	00-004-0733	17	Calcium Hydroxide	0.000	0.336	Ca (O H) ₂
3	00-040-0513	16	Calcium Silicate Hydrate	0.000	0.401	Ca ₄ Si ₃ O ₁₀ !2 H ₂ O

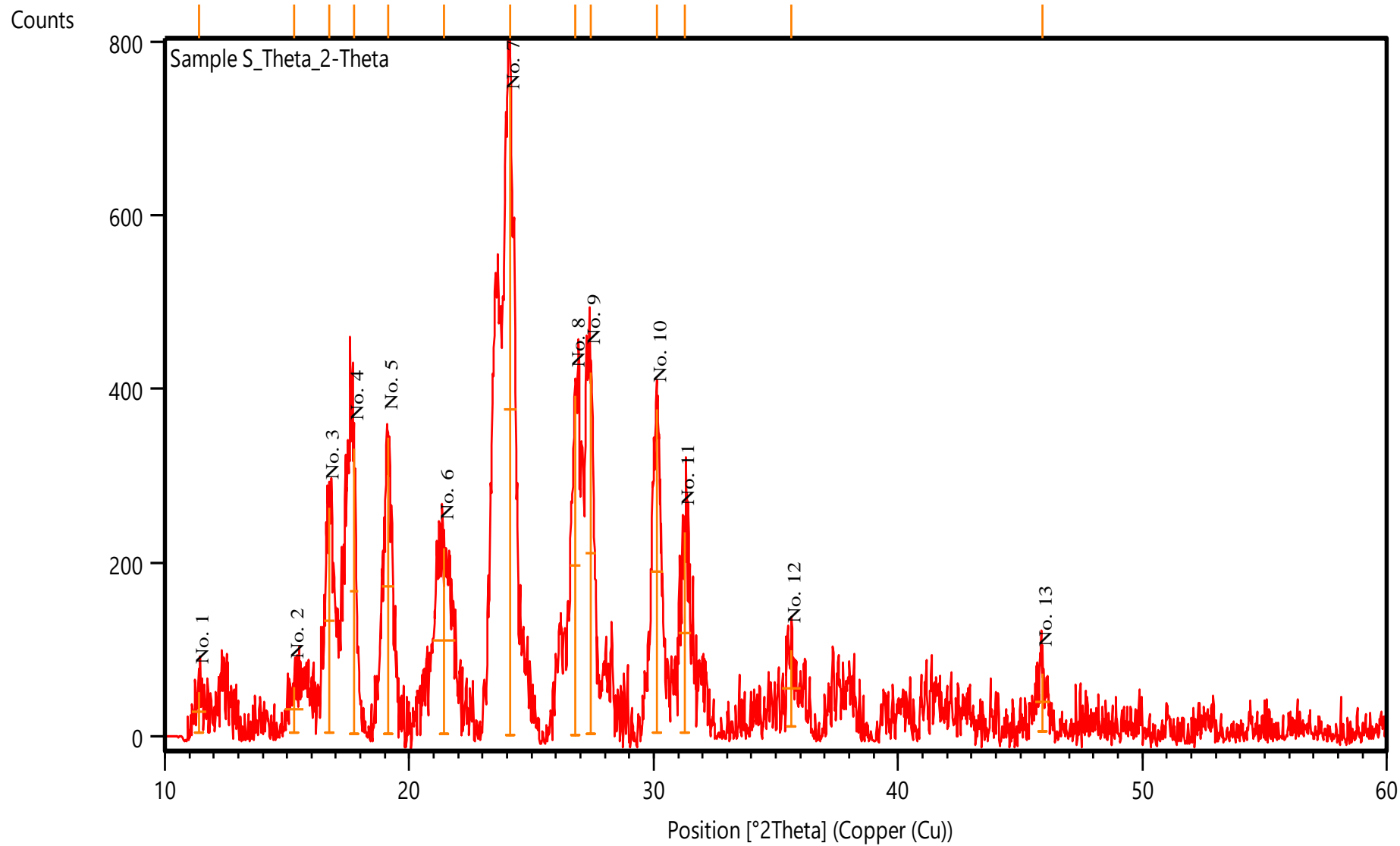


Figure A.C.2 Crystalline Peaks Detected Using XRD Analysis in Blended Sample at Day 1

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength
Development

Table A.C.2 Pattern List of the Blended Sample

Number	Ref. Code	Score	Compound Name	Displacement [°2Th.]	Scale Factor	Chemical Formula
1	00-027-0605	31	Silicon Oxide	0	0.253	Si O ₂
2	00-029-0286	28	Calcium Aluminum Silicate Hydrate	0	0.894	Ca Al ₂ Si ₃ O ₁₀ !6 H ₂ O
3	00-022-0018	7	Aluminum Silicate	0	0.2	Al ₂ Si O ₅
4	00-044-1481	2	Calcium Hydroxide	0	0.057	Ca (O H) ₂
5	00-019-0250	10	Calcium Silicate Hydrate	0	0.165	Ca ₃ Si ₃ O ₉ ! H ₂ O

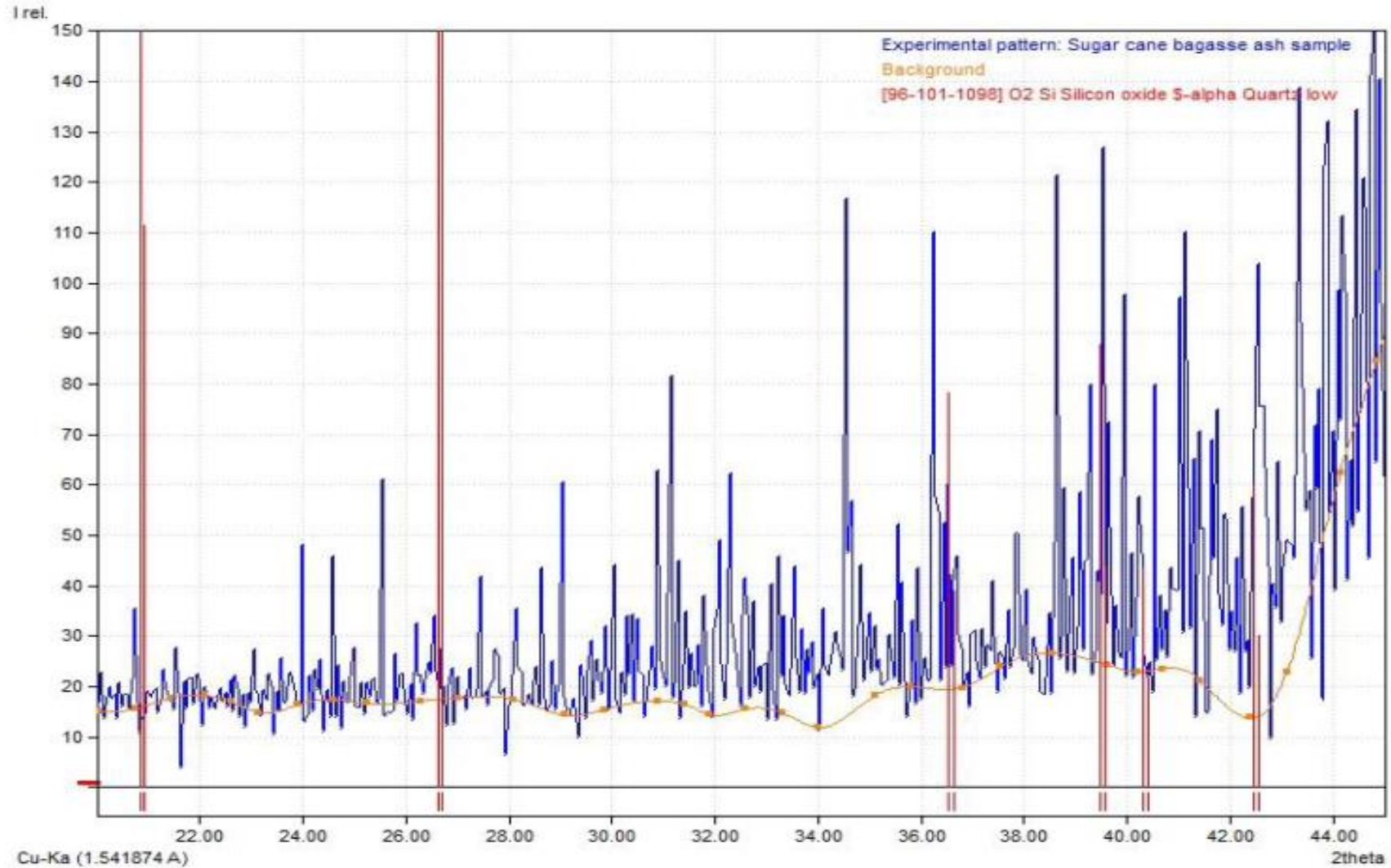


Figure A.C.3 XRD Analysis Pattern of Raw Bagasse Ash (Fekadu 2019)

Annex A.D Graphical Representation of Heat of Hydration Results of Each Sample

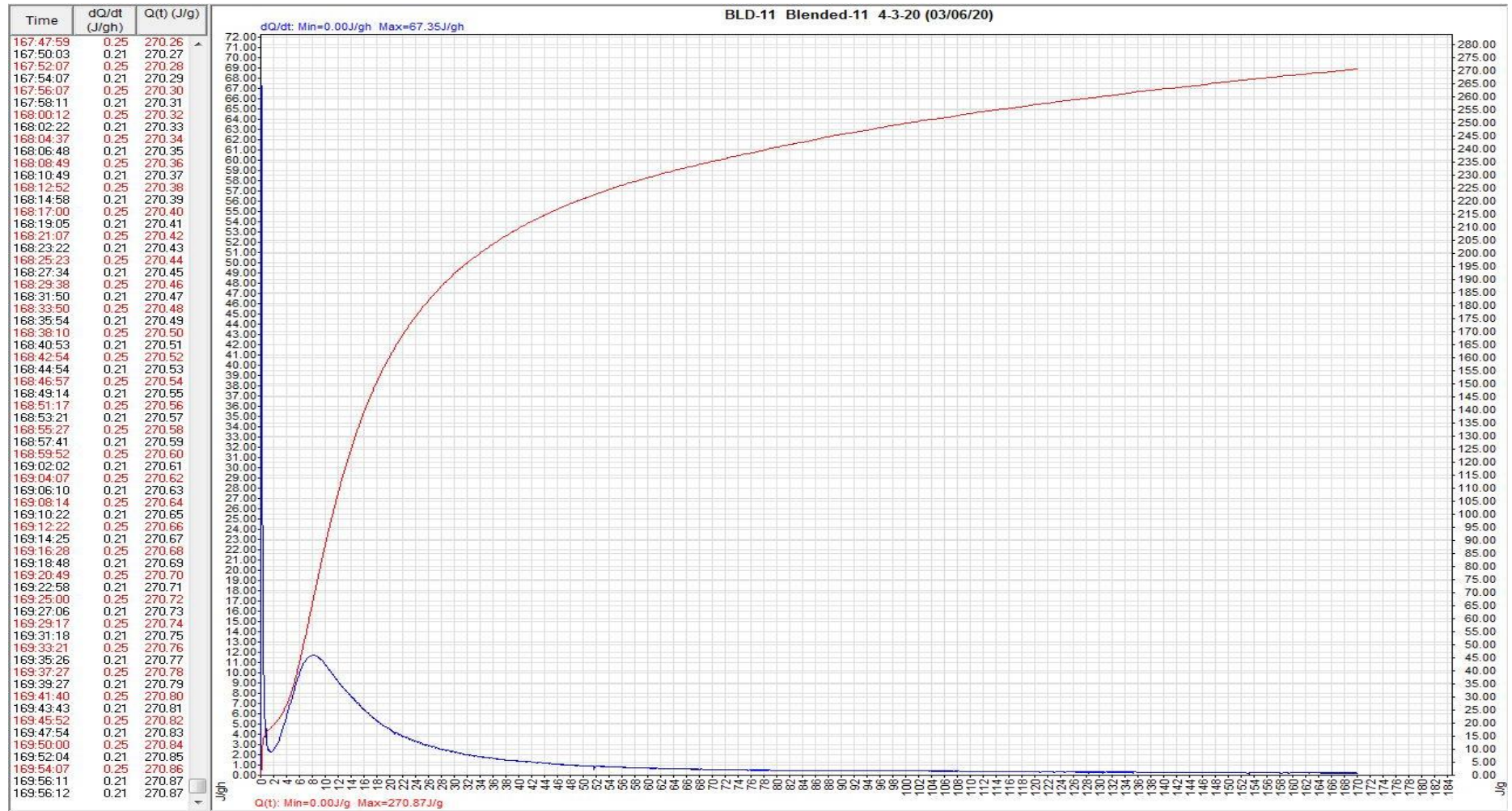


Figure A.D.1 Graphical Representation of Heat of Hydration for Blended Sample BLD-11

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development

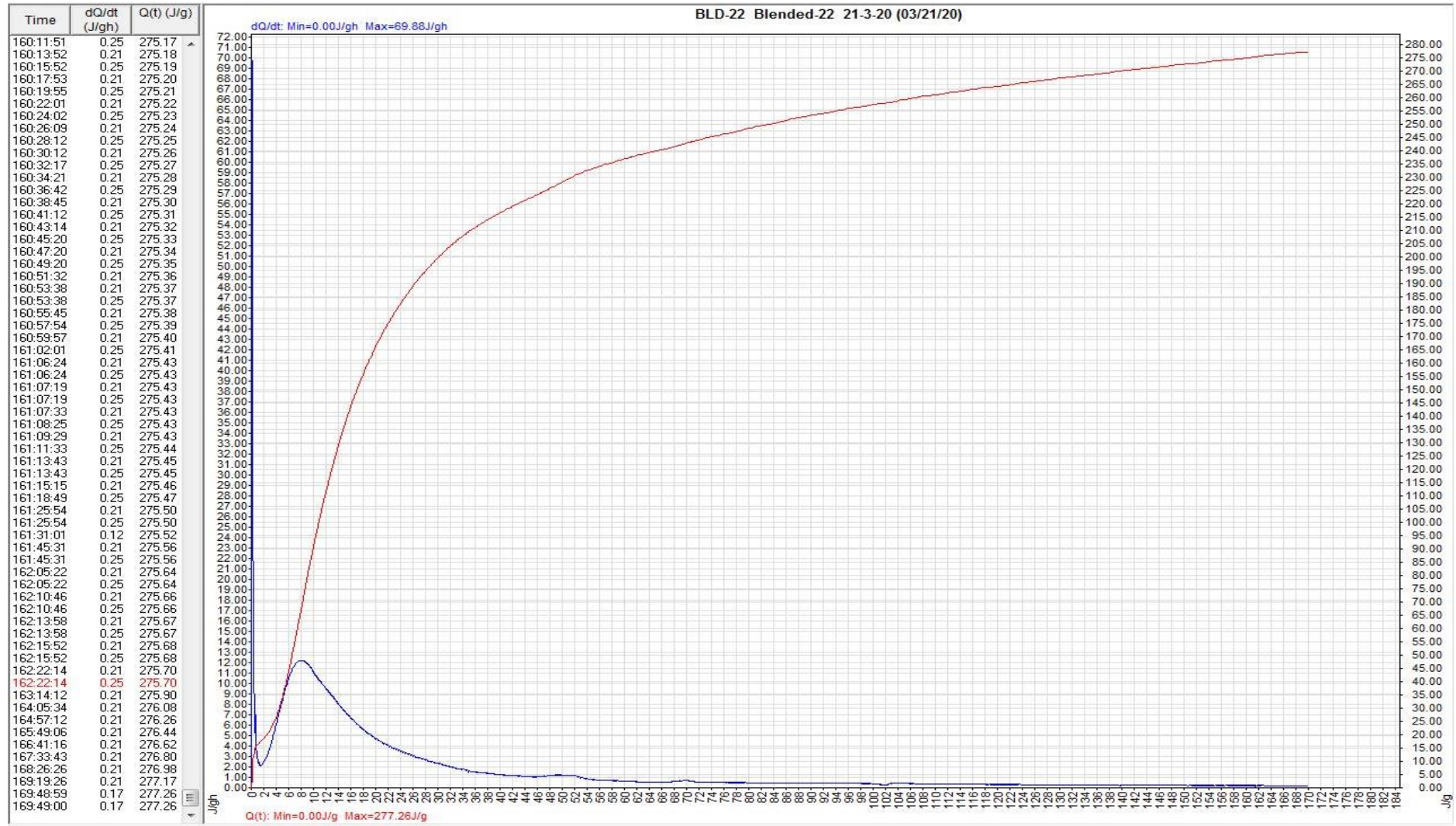


Figure A.D.2 Graphical Representation of Heat of Hydration for Blended Sample BLD-22

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development

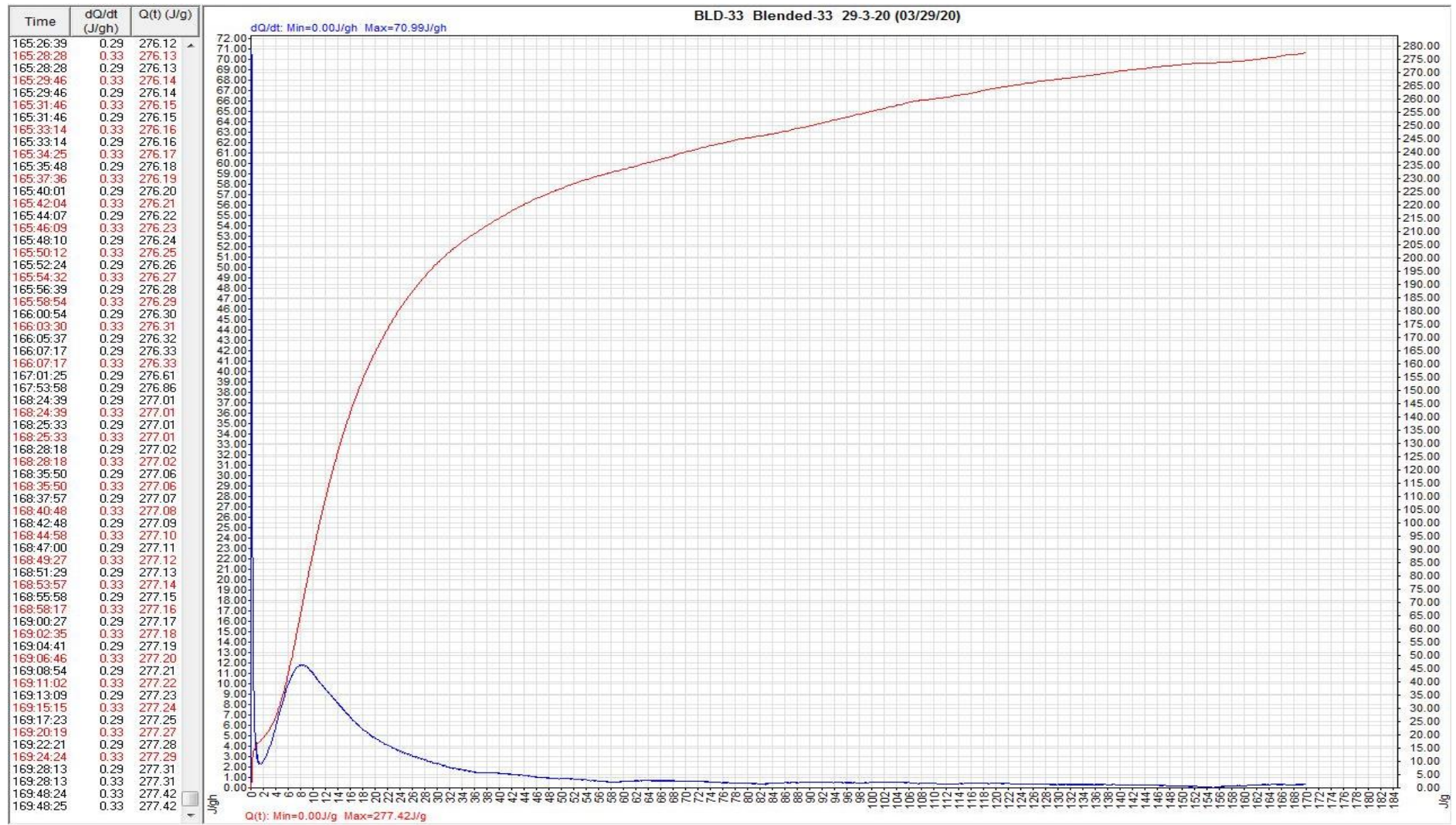


Figure A.D.3 Graphical Representation of Heat of Hydration for Blended Sample BLD-33

Investigation of the Pozzolan Reactivity of Bagasse Ash Via Compressive Strength Development

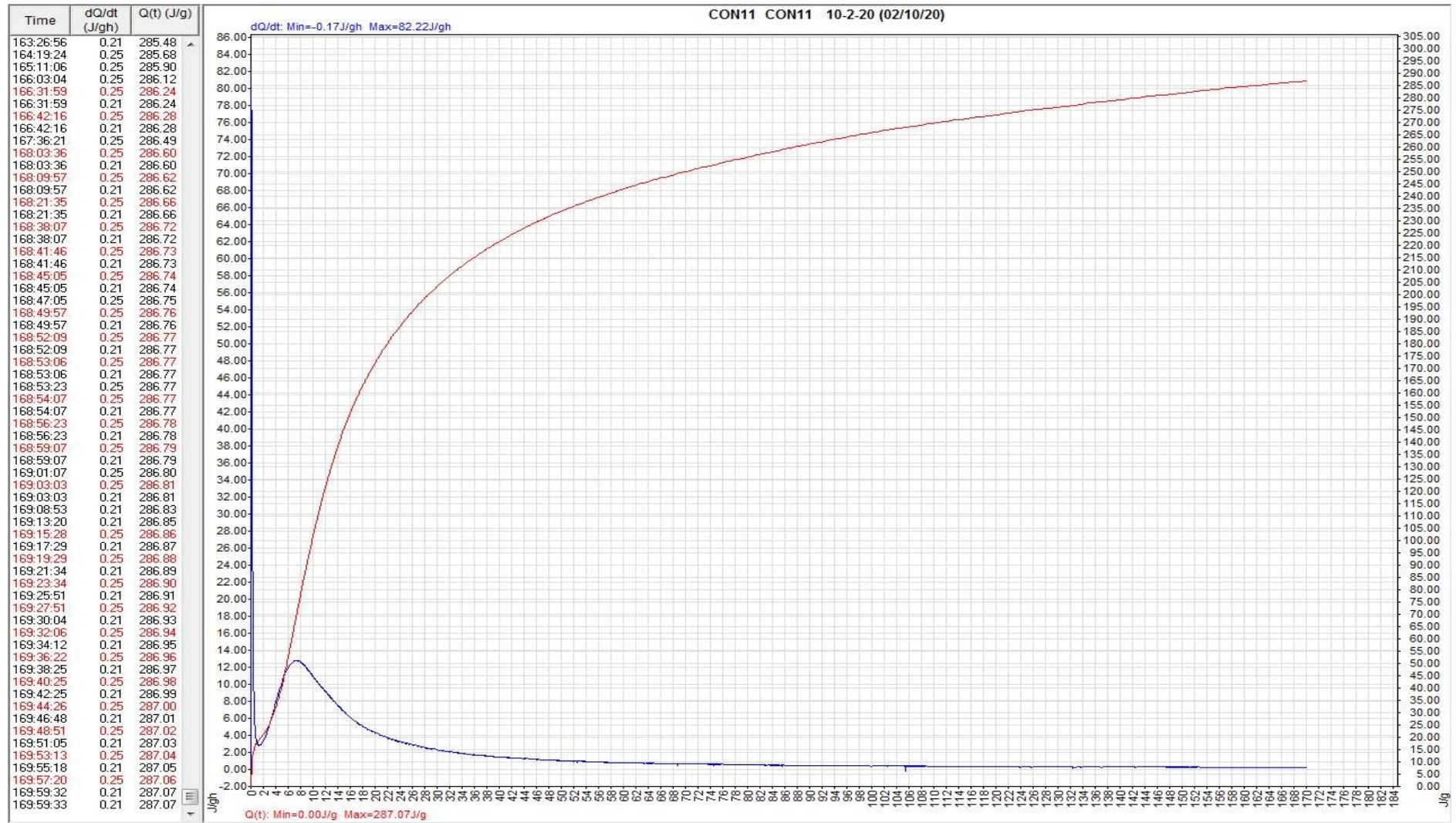


Figure A.D.4 Graphical Representation of Heat of Hydration for Reference Sample CON-11

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development

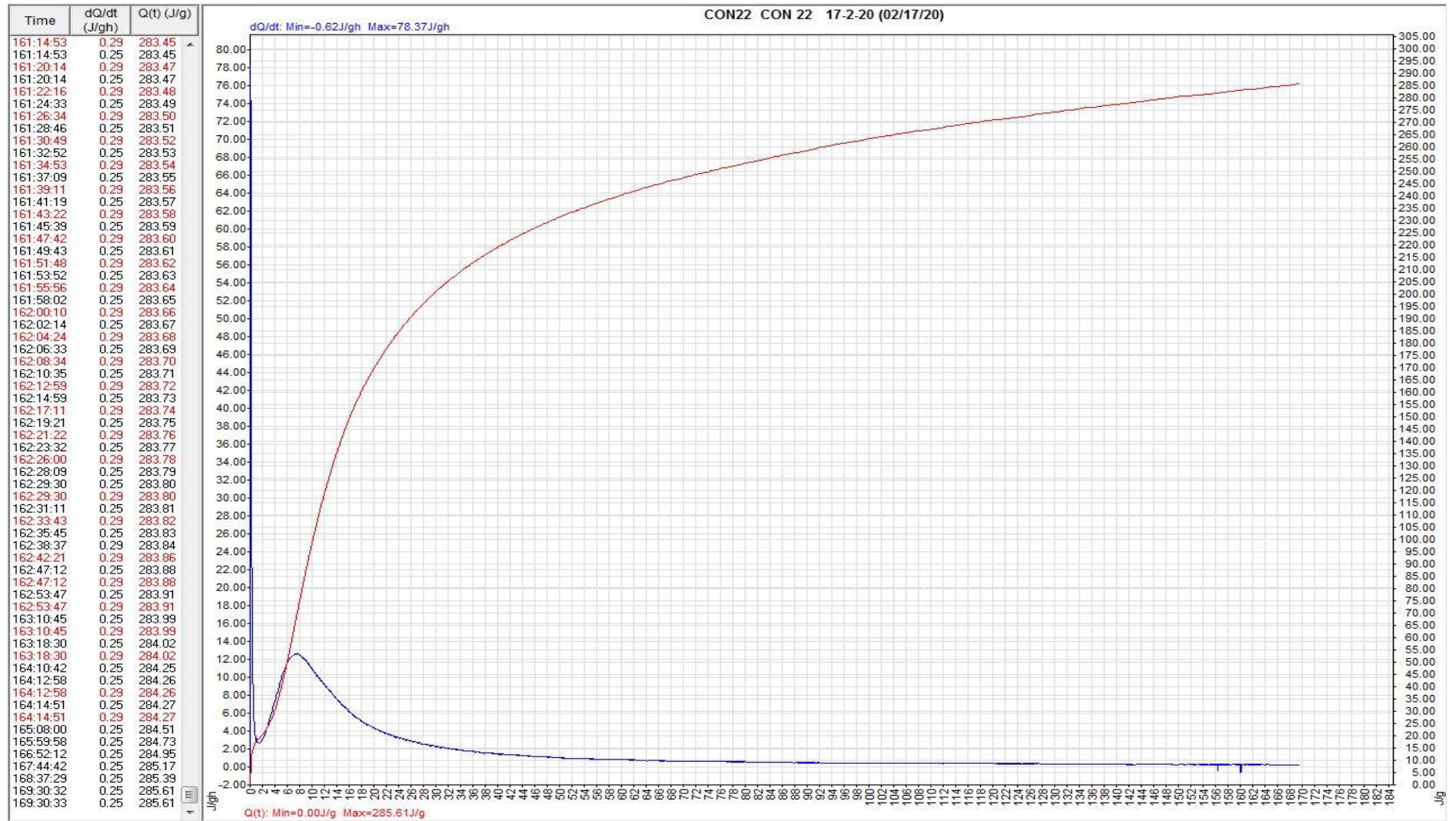


Figure A.D.5 Graphical Representation of Heat of Hydration for Reference Sample CON-22

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development

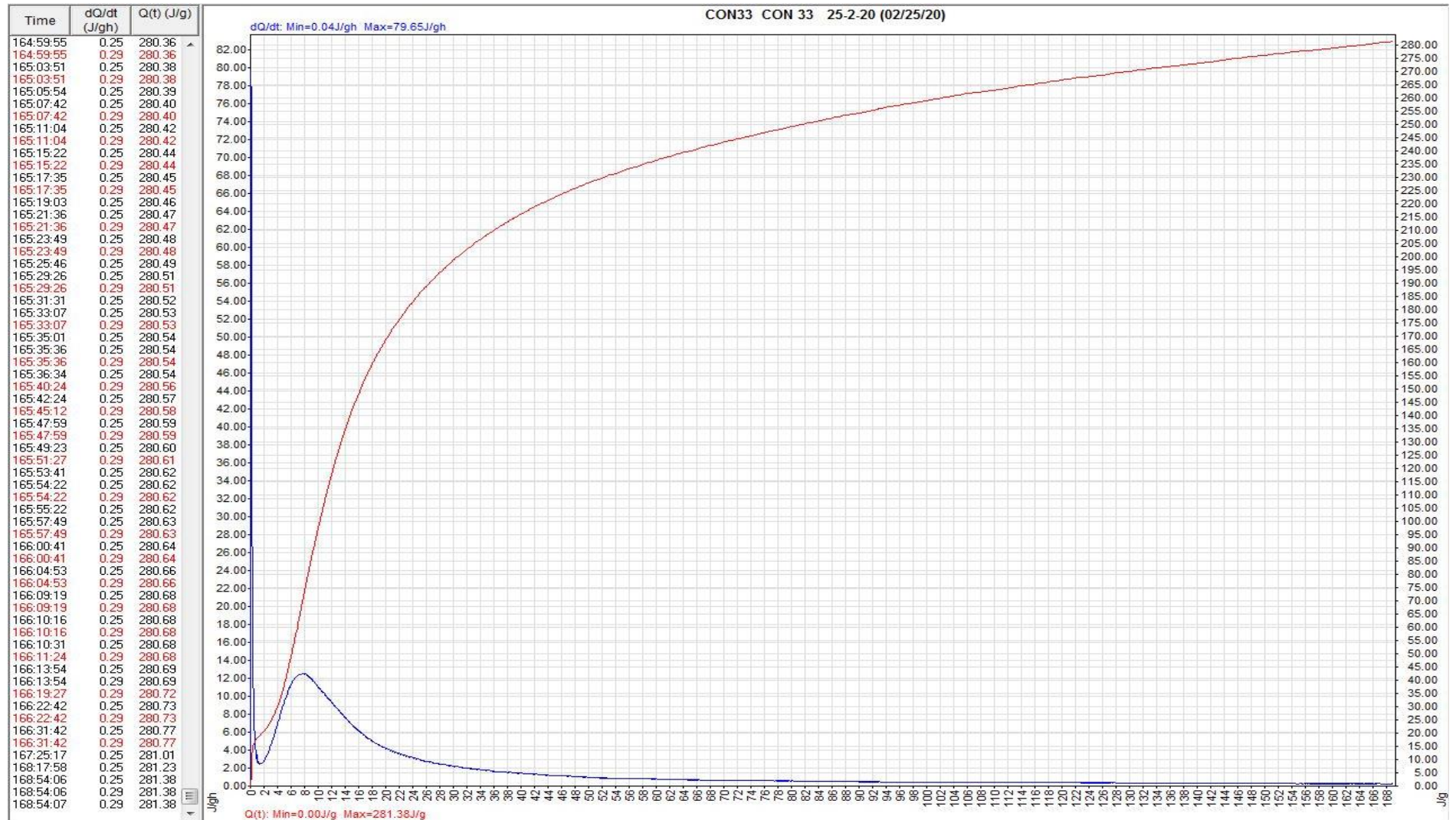


Figure A.D.6 Graphical Representation of Heat of Hydration for Reference Sample CON-33

Annex A.E Pictures During Research



Figure A.E.1 Sieving and Material Preparation

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development

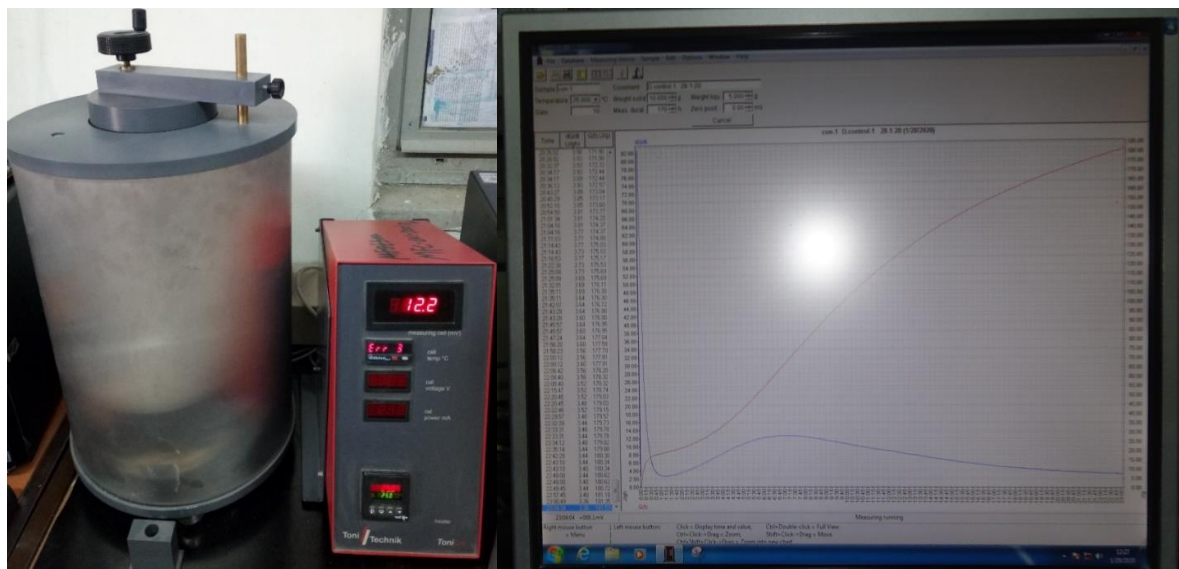


Figure A.E.2 Isothermal Calorimeter with Displaying Unit



Figure A.E.3 Samples for XRD and Crushing Agate



Figure A.E.4 Samples in the Process of Bound Water Determination

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development



Figure A.E.5 Modified Chapelle Test Setup and Measuring Instruments

Investigation of the Pozzolanic Reactivity of Bagasse Ash Via Compressive Strength Development



Figure A.E.6 Materials, Automatic Mixer and Mixed Paste



Figure A.E.7 Compressive Strength Test and Tested Cubes



Figure A.E.8 Mortar Cube Curing Pond Used for the Study