OPTIMIZING CEMENT USE IN SUSTAINABLE SANDCRETE BLOCKS:

Standardizing Low-Strength Mortar Testing and Evaluating BYF Cement Feasibility.

Master's thesis in the master's program structural engineering and building technology.

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Abstract

The urgent demand for sustainable and cost-effective construction materials has prompted the exploration of alternative binders to conventional Portland cement. However, a significant methodological gap persists, where alternative binders intended for low-strength mortars are often evaluated using the EN 196-1 standard, which is designed for high-strength cementitious systems and thus not representative of low-strength performance contexts such as sandcrete block production.

This study investigates the technical feasibility of Belite-Ye'elimite-Ferrite (BYF) cement as an alternative binder for low-strength applications, with a particular focus on sandcrete block production for sustainable construction in Sub-Saharan Africa. It introduces a modified testing methodology that adapts standard procedures to the low-strength context. Key modifications include the use of mix design representative of low-strength mortar anchored on bulk density control, and a reduction in specimen replicates from six to three to reflect the operational characteristics of tailored adjustments to casting and compaction protocols.

Experimental results demonstrate that BYF cement specimen at 7% cement content and 14% water content achieves a comparable 1-, 7- and 28-day compressive strength to Portland cement specimen at 7% cement and 11% water (4.5MPa, 5.2 MPa, and 6.7 MPa vs 1.9 MPa, 4.1 MPa, and 6.1MPa respectively), with improved repeatability and reduced variability in test outcomes. Further analysis shows that BYF at 5% cement content and 11% water content achieves a comparable result (3.73 MPa, 6.3 MPa, and 6.7 MPa respectively). XRD analysis confirms early and sustained strength development, supporting its viability as a low-carbon alternative binder. Regression analysis further established a moderate correlation ($R^2 = 0.4046$) between bulk density and compressive strength, with compaction shown to be a critical variable.

The findings support the technical feasibility of BYF cement as a low-carbon alternative for low-cost housing applications and proposes a reproducible testing methodology for evaluating low-strength binders. However, further research is needed on durability performance, field application, and economic feasibility to support broader adoption.

Key words: BYF cement, Portland Cement, Low-strength Application, Sustainable Sandcrete Blocks, EN 196-1 Modified Testing Method, Compressive Strength, Bulk Density, Sub-Saharan Africa, Cement Hydration.

Contents

Preface

This thesis explores the compressive strength of Belite Ye'elimite Ferrite cement in Sandcrete blocks, contributing to sustainable building practice and standardized mortar testing. It is part of an ongoing collaborative study in the application of supplementary cementitious materials in Sandcrete Blocks for Sub-Saharan Africa. It fulfils partial requirements for a Master of Science degree in Structural Engineering and Building Technology at Chalmers University of Technology. The journey of experimentation and discovery was made possible through the invaluable guidance of my supervisors and examiner.

My profound gratitude goes to God almighty for His grace that has brought me thus far against all odds. I am grateful to Professor Raine Isaksson, for his unwavering mentorship throughout this research. His profound knowledge, constructive feedback, and encouragement have been instrumental in shaping the methodology and ensuring the quality of this work. Also, to Dr. Birhan Abdulahi, my supervisor, for his meticulous review and constructive critiques, which significantly enhanced the depth and clarity of the findings presented here.

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This work would not have been possible without the facilities, resources, and conducive academic environment provided by Chalmers University of Technology through the Department of Architecture and Civil Engineering. I am thankful to my Program Coordinator, Despoina Teli, for her support, that has been pivotal to the success of this work. I also want to thank Bruno Gonçalves for his support and assistance during the experimental stage of this work.

Finally, I am totally grateful to my family, who have been a source of support and motivation to me through their love, encouragement, and belief in my abilities in various capacities during this research endeavor.

It is my hope that this research contributes meaningfully to sustainable building practice, providing a foundation for future exploration and innovation in cementitious materials.

Göteborg February 2025

Moronfolu Festus Ilesanmi

Notations

Roman Uppercase Letters

A- Empirical parameter

B- Empirical parameter

M= Mass of specimen

V= Volume of specimen

R^2- Coefficient of determination

Roman Lowercase Letters

n = number of observations

x- Bulk density

y- Compressive strength

w/c- Water-Cement ratio

M_{AW}- Mass of aggregate matrix water content

m_w- Mass of water content

m_T- Total mass of mortar matrix

Greek Letters

σ_c- Compressive strength

σ^2- Variance

x_i= each data point

$\bar{x}$ = mean of the group

ρ- Bulk density

Abbreviations

Avg. Comp. Str.- Average Compressive Strength

BYF- Belite-Ye'elimite-Ferrite

CI- Confidence Interval

CV- Coefficient of Variation

LC3- Limestone Calcined Clay

PC- Portland Cement

SB- Sandcrete Block

SCMs- Supplementary Cementitious Materials

SD- Standard Deviatiation

SSA- Sub-Saharan Africa

SSB- Sustainable Sandcrete Block

STD DEV- Standard Deviation

XRD- X-ray Diffraction

1. Introduction

This chapter offers an insight into the importance of Sustainable Sandcrete Blocks (SSB) and their role in promoting sustainable construction practices in Sub-Saharan Africa. It delves into issues surrounding sustainability of Sandcrete Blocks (SB), outlines the problem statement, enunciates the research aims and objectives, and establishes the context and relevance of the study. Furthermore, it introduces the research questions formulated to align with the defined aims and objectives, highlighting the significance of this investigation and its potential contribution to advancing sustainable building practices.

1.1 Background

1.1.1 Sustainable Building Practices

Sustainable building practices are defined by Isaksson et al. (2023) as those that strike a balance between affordability and climate neutrality, aligning with global commitment to uphold human rights to adequate shelter. This definition highlights the critical intersection of social equity and environmental responsibility. It recognizes that access to housing must be economically viable while minimizing adverse climate impacts. The building value chain plays a pivotal role in this equation, as its practices and materials directly influence both construction affordability and the carbon footprint. Addressing these interconnected priorities will enhance the contribution of sustainable building to broader efforts of alleviating poverty and combating climate change.

1.1.2 Reliance of Global South on Sandcrete Blocks

Sandcrete Blocks (SB) are a mix of sand, binder, and water. They are of two major types; solid and hollow blocks, and which are made in different sizes suitable for specific applications. They are primarily used for constructing non-load bearing walls in high-rise buildings or as main support in bungalows. In the Global South, SB are widely adopted as versatile material, suitable for building design adaptation in building architecture, particularly in Sub-Saharan Africa (SSA) region. Brick and block-based buildings enable building over an extended period, which gives room for managing financing issues (Isaksson et al. 2023). They are mostly handled by medium skilled labour, making building affordable.

1.1.3 Housing Affordability and Environmental Impact in Global South

The cost of cement relative to income level is substantially higher in SSA than in the Global North (Isaksson et al. 2023). The price of materials significantly contributes to high construction cost, and in the case of SSA, cement price drives cost of SB. This makes producers minimize cement addition in SB production, being the most expensive material in the mix. Cement production on the other hand accounts for about 8 % of carbon footprint in the world (Winnefeld et al. 2022). By reimagining the materials used in basic construction components, carbon footprint of building practices could drastically be reduced without compromising affordability or utility. The development of Sustainable Sandcrete Blocks (SSB) that incorporates low carbon binders offers a promising solution.

1.1.4 Supplementary Cementitious Materials

Supplementary cementitious materials are suitable cementitious materials used in partial replacement of Portland cement. They improve mechanical properties of the cement product and reduce environmental impacts. Application of SCMs is widely explored in quest for decarbonization, however they are still faced with limitations. Below are some of the limitations faced with supplementary cementitious materials (SCMs):

- All SCM would still need Portland cement for reaction (Scrivener et al., 2018) which makes it still somewhat challenging.
- There is limited availability of suitable SCMs (Skibsted and Snellings, 2019) due to their dependency on local industrial byproducts, which limit their widespread use where such materials are not readily available
- SCMs exhibit high variation in quality and performance due to inconsistency in mineralogical composition and reactivity depending on their geographical origin and processing method (Pacewska & Wilińska, 2020; Snellings et al., 2023)

1.1.5 Alternative Cements

With the aim of reducing carbon footprint and cost, several alternatives to traditional Portland cement have been proposed in recent years. These materials are eco-efficient based cement materials that could reduce CO_2 emissions, increase durability and performance (Scrivener et al., 2018). Some recognised alternative binders and their limitations are presented below:

- Geopolymers: These are alkali activated SCMs. It has lower CO_2 emissions and highly durable, but they are faced with resource limitations due to dependency on same limited materials used as substitute in blends (Scrivener et al., 2018).
- Limestone Calcined Clay Cement (LC3): LC3 can replace upto 50% clinker and still produce comparative result to PC (Scrivener et al., 2018). However, there is uncertainty around its setting time in transportation and construction processes, which is limiting its general adoption (Zhao & Zhang, 2023).
- Belite Ye'elimite Ferrite (BYF) cement: BYF is an alternative clinker. Modestly, BYF can reduce the CO_2 emission by over 20% due to its benefits concerning the chemical composition and industrial processing (Li et. al., 2019). Its clinkers have the potential of replacing Portland cement clinkers and Portland-Slag cements in many applications; however, the price of its raw materials is still somewhat high (Scrivener et al., 2018).

As an alternative clinker, BYF cement doesn't require change in technology for production as current cement clinker production technology is easily adopted to suit this need (Scrivener et al. 2018). Hence, this makes this cement an interesting alternative for consideration. Currently BYF is used in highway repairs and in jobs where fast execution is required. There is scarce documentation of research on applications of BYF in low strength mortars, nor research of its possible application in Sustainable Sandcrete Blocks (SSB).

1.1.6 Strength of Mix design

SB is a low-strength material usually between 1-7MPa. Strength of mix design is mostly characterized by Academia and practitioners, as a parameter determined by the amount of water-cement ratio. A low water cement ratio is considered as high strength material and vice versa. Popovics (2008), express that the first fundamental assumptions for the strength versus water-cement ratio relationship (Abram's law) as the strength of the cement paste, are the rate of porosity in the paste, and the water-cement ratio. Many does not clearly understand that Abram's law has a consideration for the mix being workable (Bogren, 2024). Workability enhances low porosity which is directly associated with higher compressive strength and durability. Porosity is directly related to bulk density, the less the entrapped air, the higher the density of the material. Optimum water content aids effective compaction and reduces porosity (Ahmed et al., 2024). Aggregate needs a certain amount of water to compact. When cement is reduced the water addition is expected to be reduced to retain a low water-cement ratio. However, reducing water content in Sandcrete blocks means that compaction becomes difficult, and the resulting lower bulk density will lead to loss of strength. Fig 1. Shows the general relationship between compressive strength and water cement ratio.

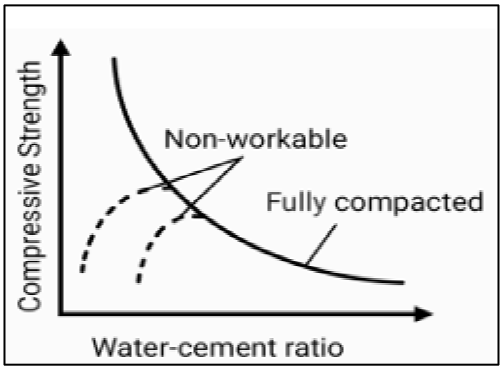

Fig 1.1 Compressive strength Vs water-cement ratio according to Abram's law (Bogren 2024)

The relationship between compressive strength and water-cement ratio is expressed with the formula in equation 1.1 known as Abram's law.

$$\sigma_c = \frac{A}{B^{W/C}} \tag{1.1}$$

Where σ_c is the compressive strength in MPa

A and B are empirical parameters that are obtained by curve fitting to experimental data

w/c is the water-cement ratio

To attain optimal strength in the low strength mortar mix design, the mix design and the bulk density must be optimal.

1.1.7 Testing of Cement Strength in Low-Strength Mortar

To establish the suitability of binders in mortar it is important to determine what strength should be expected with its usage. The performance of cement varies with mix design. Current standard used for testing cement strength is EN 196-1. This standard makes use of a specified mix design for the procedure which makes it somewhat relevant for application in similar mix design.

EN 196-1 is the principal standard for determining cement strength using a prescribed mortar mix composed of cement, standard sand, and water under controlled conditions. While it provides a consistent framework for classification and quality assurance, its relevance diminishes in contexts where mix designs differ significantly from the standard—such as in Sandcrete block production in Sub-Saharan Africa, where low cement content and high water–cement ratios are common. In such cases, EN 196-1 may overestimate in-field performance, highlighting the need for adapted testing protocols or alternative procedures that better reflect the practical usage of binders in local construction scenarios.

1.2 Problem description

The application of a binder designed for high strength purposes in low strength mix design such as SB is a major challenge. SB production requires low cement and high-water content. Mostly, only 5-7% of cement is used by weight for SB production. Sand matrix often needs up to 10% of water for good compaction, meaning w/c ratio is always high in the mixes. However, high water-cement ratio reduces cement productivity e.g. at an addition rate of 5-7% of cement, about 70% of the strength potential is lost (Isaksson & Babatunde, 2019). One solution could be finding a binder with a higher water requirement: in this case BYF cement (Gartner & Sui, 2018). Application of BYF could enable proper compaction of the matrix while optimizing cement strength at low content.

Another critical challenge is the absence of well-documented methodologies for systematically investigating changes in mortar mix design. The adaptation of existing standard testing methods to align with a mix design typical of low strength mortar remains insufficiently explored. Current standards, such as EN 196-1, are formulated for mortar compositions characterized by significantly higher cement contents (approximately 22%) and lower water-to-cement (w/c) ratios (around 0.5), which do not accurately represent the typical 5–7% cement contents and 1.4–2 w/c ratios observed in block production (Isaksson et al., 2023). Consequently, testing strength of binders used in low-strength mortars under EN 196-1 conditions fails to capture the practical performance and characteristics of these binders in production environments. Developing a repeatable and robust methodology that accommodates variations in mix design and laboratory apparatus relative to EN

196-1 specifications will mitigate the risk of underestimating the performance of alternative binders and facilitate the optimized use of such materials in production environment: in this case, sustainable building block (SSB) production.

The lack of documented research on (a) repeatable approach for testing binders used in low-strength mortar mix design and (b) application of alternative cement such as BYF in low-cement, high-water ratio contexts, presents a clear knowledge gap— one that this study aims to address.

1.3 Aims and Objectives

The primary aim of this thesis is to explore the feasibility of producing affordable, and environmentally friendly Sustainable Sandcrete Blocks (SSB) using an alternative binder. The study seeks to address the gap between standard cement testing methods and low-strength application testing by developing and validating a modified testing framework tailored to the material proportions and compaction requirements typical of SSB production. To achieve this aim, the specific objectives of the thesis are as follows:

- Develop and validate a modified EN 196-1 testing procedure by preparing and testing mortar mixes with 5–7% cement content and w/c ratios between 1.5 and 2.0, anchor test design on bulk density control and compare the resulting coefficient of variation with those specified in EN 196-1.
- Evaluate the performance of BYF cement in low-strength mortar applications, particularly in terms of compressive strength.
- Quantify the relationship between bulk density and compressive strength by producing sandcrete block specimens at varying compaction levels, measuring their bulk density, and analyzing the resulting strength data to establish a statistically significant correlation.

By addressing these objectives, the research aims to answer the following key questions:

- How can cement strength testing methods be modified to accurately simulate the material and environmental conditions typical of low-strength applications, such as sandcrete block production in Sub-Saharan Africa?
- Could BYF cement serve as a suitable replacement for Portland Cement in SSB production in terms of compressive strength development and environmental sustainability?
- Does bulk density impact compressive strength?

This study will contribute to establishing relevant testing for low-strength applications and advancing sustainable building practices by identifying cost-effective and low-carbon alternatives for SB production. It will ultimately support; affordable housing in SSA and reduction of carbon footprint in the environment.

1.4 Scope and Limitations

The scope of this research is focused on the experimental evaluation of BYF cement as an alternative binder in the production of SSB in the context of SSA. The study specifically aims to adapt standard testing methods (EN 196-1) to align with typical local block production practices characterized by low cement content (5–7%) and high water/cement ratios (1.4–2.0). The experimental analysis is confined to short-term laboratory-based tests evaluating compressive strength and bulk density of the resulting mortar and block specimens.

The limitations of the research are as follows:

- Geographical Limitations: The research is not extended to on-site or field-based production environments. Consequently, the results may not account for the variability of field conditions, including labor skills, material inconsistencies, and environmental factors.
- Material Scope: Only one alternative binder (BYF cement) is evaluated in detail. Other potential alternatives like LC3 or geopolymers are discussed in the literature review but not included in experimental comparisons.
- Testing Standards: The focus is on adapting the EN 196-1 methods of testing cement — Determination of strength. Other testing protocols (e.g., ASTM C-150) are not considered or validated.
- Performance Metrics: The study focuses primarily on compressive strength, Coefficient of variation of the compressive strength and the bulk density of the specimen. Other critical performance indicators such as durability, thermal insulation, shrinkage, or long-term strength development are beyond scope.
- Time Constraints: Due to the limited timeframe available for a master’s thesis, long-term strength testing and reproducibility studies are not conducted. Only short-term repeatability is considered.

Despite these limitations, the research contributes valuable insights into optimizing binder selection and testing practices for SSB applications in SSA. It also lays the groundwork for further studies on the application of alternative cementitious materials in low strength mortar.

2. Literature Review

This chapter presents a review of existing literature relevant to SB performance, sustainability considerations, cement hydration chemistry, and testing frameworks. It establishes a scientific and technical context for evaluating cement in low-strength applications such as sandcrete block.

2.1 Sustainable Sandcrete Block

Considering the carbon footprint of cement in the environment and cost of cement relative to income level in SSA as stated in chapter 1, it is safe to say that commonly used sandcrete building block made from sand, PC and water is not sustainable. To enhance sustainability, researchers have explored different means including the use of SCMs in sandcrete building block production. Key sustainability metrics include reduced carbon footprint, use of low-energy materials, use of recycled materials, affordability, and long-term durability.

The use of cement with lower clinker content, such as novel binders like BYF, aligns with global decarbonization goals in the construction sector. BYF cement offers reduced calcination temperature and lower CO_2 emissions, making it a promising option for sustainable block production. Moreover, the intrinsic water demand of BYF systems may suit the typical high w/c ratios used in sandcrete fabrication, potentially improving binder utilization and mechanical properties even at low cement dosages.

2.2 Compressive Strength of Sandcrete Blocks

Compressive strength is the primary indicator of a SB load-bearing capacity and is typically defined by regional standards. In SSA, most block standards require 2.2–3.5 MPa (Olonade et al., 2013). Table 2.1 outlines minimum compressive strength requirement across several Global South countries. However, several studies report that blocks produced by local artisans often fall below these standards due to poor quality control (Kahsay, 2014; Olonade et al., 2013)

Table 2.1 Minimum compressive strength of SB in Global South. Based on Sabai et al., (2016)

Standard	Origin	Block Type	Min. Strength	Notes
NIS 87:2007	Nigeria	Hollow Sandcrete	≥ 2.5 N/mm²	Non-Load Bearing
NIS 87:2007	Nigeria	Solid Sandcrete	≥ 3.5 N/mm²	Load Bearing
GhBC:1989	Ghana		≥ 2.75 N/mm²	Load Bearing
GhBC:1989	Ghana		≥ 1.40 N/mm²	Non-Load Bearing
SLS 855:1989	Sri Lanka	Solid Block	≥ 1.2 N/mm²	Single floor building
TZS 283:2002	Tanzania		≥ 3.0 N/mm²	Individual blocks
CD-ARS 950:2014	Africa		≥ 3 N/mm²	Internal partition wall
CD-ARS 950:2014	Africa		≥ 7 N/mm²	Load Bearing walls
SANS 10400-K:2015	South Africa	Hollow Concrete Masonry Units	≥ 3 N/mm²	For single floor building

2.3 Chemistry of Cement in Focus

This section details the chemistry, hydration behavior, and engineering relevance of the two main binders studied; PC (Cem II/A-LL 42.5R) and BYF Cement.

2.3.1 Portland Cement (Cem II/A-LL 42.5R)

Cem II/A-LL 42.5R is a blended PC containing 80–94% clinker and 6–20% limestone by mass (EN 197-1). It exhibits rapid strength development (R-class) and is widely used in different construction applications due to its predictable performance. The addition of Limestone influences the hydration process and the development of microstructure in the hardened cement paste. The following notation are used for easy naming of the main chemical constituents of Portland cement (Aïtcin, 2016) are;

- Calcium oxide (CaO), denoted as C
- Silicon dioxide (SiO_2), denoted as S
- Aluminum oxide (Al_2O_3), denoted as A, and
- Iron oxide (Fe_2O_3), denoted as F.

The chemical components from the raw materials (limestones and clay or shales) undergo a series of complex reactions during calcination (at ~900°C) which causes the breakdown of slake lime ($CaCO_3$), and clinkerization (at ~1450°C) which leads to the formation of cement clinkers. The clinkers of Portland cement are:

- Tricalcium silicate (C_3S), known as Alite, is responsible for the early-strength development of cement.
- Dicalcium silicate (C_2S), known as Belite, is responsible for long-term strength development.
- Tricalcium aluminate (C_3A), controls setting and early strength.
- Tetracalcium aluminoferrite (C_4AF), known as Ferrite, is responsible for the color and some of the strength properties of the cement.

Hydration Reaction: The clinkers react with water to form the hydrated phases that enhance strength and durability of cement. The primary clinker hydrations in PC (Choudhary et al., 2015; Marchon & Flatt, 2016) are:

- Alite (C_3S) Hydration: Alite hydrates rapidly to produce calcium silicate hydrate (C-S-H) and calcium hydroxide (CH).

  $$2C_3S + 6H_2O \longrightarrow C_3S_2H_3 + 3Ca(OH)_2$$

- Belite (C_2S) Hydration: Belite Hydrates more slowly than Alite to produce Calcium silicate hydrate (C-S-H) and calcium hydroxide (CH).

  $$2C_2S + 4H_2O \longrightarrow C_3S_2H_3 + Ca(OH)_2$$

- Tricalcium aluminate (C_3A) Hydration: Tricalcium aluminate reacts with gypsum and water to form ettringite.

  $C_3A + 3CaSO_4{\cdot}2H_2O + 26H_2O \longrightarrow C_3A{\cdot}3CaSO_4{\cdot}32H_2O$

- Ferrite (C_4AF) Hydration: Ferrite participates in secondary reactions, forming ettringite and iron hydroxides, with minor strength contributions.

  $C_4AF + 3CaSO_4{\cdot}2H_2O + 26H_2O \longrightarrow C_3A{\cdot}3CaSO_4{\cdot}32H_2O + Fe(OH)_3$

Microstructural Development.

- Calcium Silicate Hydrate (C-S-H) is the primary binding agent in the hydrated cement paste, responsible for the strength and cohesion of the cement (Richardson, 2008).
- Portlandite (CH) contributes to the alkalinity of the pore solution which influences durability. It also plays a role in the overall performance of hydrated cement (Bahraq et al., 2022).
- Ettringite ($C_3A{\cdot}3CaSO_4{\cdot}32H_2O$) contributes to the initial setting and early strength development. It also helps in controlling the sulfate resistance of the cement (Gu et al., 1997).

2.3.2 Belite-Ye'elimite-Ferrite (BYF) Cement

BYF cement belongs to the class of calcium sulfoaluminate (CSA) cement. It has lesser limestone composition, requires lower clinkering temperatures (~1250°C), resulting in reduced energy usage and CO_2 emissions compared to PC (~1450°C) (Scrivener et al., 2018). The main chemical constituents of BYF cement are;

- Calcium oxide (CaO), denoted as C
- Silicon dioxide (SiO_2), denoted as S
- Aluminum oxide (Al_2O_3), denoted as A,
- Iron oxide (Fe_2O_3), denoted as F.
- Sulfur trioxide (SO_3), denoted as $\hat{S}$,
- Water (H_2O), denoted as H.

The clinker of BYF cement (Gartner & Sui, 2018) comprises of the following:

- Belite (C_2S), A calcium silicate phase that hydrates slowly than Ye'elimite. It contributes to the long-term strength of cement.
- Ye'elimite ($C_4A_3\hat{S}$), A calcium sulfoaluminate phase that hydrates rapidly
- Ferrite (C_4AF). A calcium aluminoferrite phase that contributes to the formation of hydrated products.

Hydration Reactions (Álvarez-Pinazo et al., 2016):

- Belite (C_2S) hydration: Contributes to long-term strength by forming C-S-H.

  $$2C_2S + 4H \longrightarrow C\text{-}S\text{-}H + CH$$

- Ye'elimite ($C_4A_3\hat{S}$) hydration: Ye'elimite reacts with calcium sulfate and water to form ettringite and aluminum hydroxide (AH_3).

  $$C_4A_3\hat{S} + 2C\hat{S}H_2 + 34H \longrightarrow C_6A\hat{S}_3H_{32} + 2AH_3$$

- Ferrite (C_4AF) hydration: Ferrite hydrates to form hydrated aluminoferrites ($C_3(A,F)H_6$).

  $$C_4AF + 2CH + 10H \longrightarrow C_3(A,F)H_6 + C(A,F)H_6$$

Other products of BYF cement hydration include:

- AFm phases (Al_2O_3-Fe_2O_3-mono): Hydrated calcium aluminates and ferrites.
- Stratlingite (C_2ASH_8): A calcium aluminosilicate hydrate.
- Silicious Hydrogarnet ($C_3AS_3H_2$): A hydrated calcium aluminosilicate

Microstructural Development.

- C-S-H is the primary binding agent in the hydrated cement paste, responsible for the strength and cohesion of the cement.
- Ettringite ($C_6A\hat{S}_3H_{32}$) contributes to the initial setting and early strength development. It increases the alkalinity of the cement paste which influences durability.
- Calcium aluminoferrites hydrate $C(A,F)H_6$ contribute to the overall durability and strength of the cement.

BYF's hydration kinetics and phase assemblage make it particularly well-suited to sandcrete contexts, where water availability is high, and long-term performance is desirable. Its compatibility with conventional PC manufacturing technology makes it an ideal candidate for sustainable construction technologies in SSA.

2.4 Application of X-Ray Diffraction in Cement Hydration

X-ray diffraction (XRD), based on Bragg's Law, is an essential technique for identifying and quantifying crystalline phases in cementitious materials. It allows detection of characteristic diffraction peaks corresponding to specific mineral phases as demonstrated by Choudhary et al. (2015), who used Rietveld refinement to tract the transformation of clinker phases—such as alite (C_3S), belite (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF) into portlandite, calcium silicate hydrate and ettringite.

XRD is particularly valuable in assessing the hydration kinetics of alternative binders like Belite-Ye'elimite-Ferrite (BYF) cement, where unique phases such as ye'elimite ($C_4A_3\hat{S}$) form distinct products like ettringite (Zajac et al., 2019). Through quantitative methods such as Rietveld refinement, XRD allows for precise monitoring of phase transformations, helping to understand strength development, setting time, and long-term performance.

The use of XRD in this research provides critical insights into hydration kinetics of the choice cement at benchmarked mix design and supports comparative studies between the cement type.

2.5 EN 196-1: Compressive and Flexural Strength Determination of Cement Mortar

EN 196-1 is a key standard that specifies the procedure for determining the compressive and, optionally, flexural strength of cement mortar. This method is primarily applicable to common cements and to other types of cement or materials where the relevant product standards refer explicitly to EN 196-1. It may, however, be unsuitable for cement types with typical characteristics, such as extremely short setting times.

The test uses a standardized mortar mix composed of cement, EN 196-1 reference sand, and water. Prismatic specimens (40 × 40 × 160 mm) are cast using either reference or validated alternative compaction methods, then cured and tested at defined intervals—most commonly at 2,7 and 28 days. The standard defines both the reference procedure and equipment, while also permitting alternative compaction methods if they have been validated accordingly.

Additionally, this method is used in validating alternative test equipment and confirming the performance of CEN standard sand, ensuring uniformity and comparability across laboratories. Its role in cement classification, quality control, and standardized performance evaluation makes it a cornerstone in cement testing protocols.

In this research, this standard is specifically adopted for its suitability in assessing repeatability of test methods.

2.6 Application of t-Test in Statistical Analysis

A *t*-test is a widely used statistical method employed to compare the means of two independent groups to determine whether any observed differences are statistically significant or likely to have occurred by chance (Kim, 2015). Introduced by Gosset (1908) under the pseudonym "Student," it is especially suitable for small sample sizes and assumes normally distributed data.

This test assumes that the underlying data are normally distributed and that the variances of the two groups are approximately equal. The test calculates t-statistic, which is compared to a critical value from the t-distribution to determine statistical significance. There are three main types:

I. Independent or two-sample t-Test: for comparing means of two unrelated groups. It has two variations which are;
   - Equal Variances Assumed (Pooled t-Test) – Used when the two groups have similar variances.
   - Unequal Variances Assumed (Welch's t-Test) – Used when the two groups have different variances.

II. Paired t-Test: for comparing means within the same group at different times or under different conditions.

III. One-sample t-Test: for comparing a sample mean to a known value.

The test uses the key parameters such as:

- Mean ($\bar{x}$): The average value of the dataset.
- Standard Deviation (SD): Measures data variability within each group.
- Sample Size (n): Number of observations in each group, affecting statistical power.
- Degrees of Freedom (df): Determines the variability in the dataset, calculated based on sample sizes.
- t-Statistic (t-value): Represents the standardized difference between means. A higher absolute value indicates a greater difference.
- p-Value: Determines statistical significance. A p-value < 0.05 (typically) indicates a significant difference.
- Confidence Interval (CI): Provides a range within which the true mean difference is likely to fall, offering additional insight into result reliability.
- Variance (σ^2) :

$$\sigma^2 = \frac{\sum(x_i - \bar{x})^2}{n-1} \tag{2.1}$$

Where:

x_i= each data point
$\bar{x}$ = mean of the group
n = number of observations
$\sum(x_i - \bar{x})^2$= sum of squared deviations from the mean

The selection of the appropriate type of t-test is critical and depends on the study design and the nature of the datasets involved. An important consideration in two-sample tests is the assumption of equal or unequal variances, which influences test selection and interpretation.

In this study, the t-test is used to assess whether differences in the coefficient of variation (CV) of concrete compressive strength measurements arise from sampling techniques or random variation, thus validating the experimental methodology.

3. Methodology

This chapter presents the methodological framework deployed to evaluate and compare the performance of conventional Portland cement (PC) and Belite-Ye’elimite-Ferrite (BYF) cement in low-strength applications, particularly for sandcrete block productions. The methodology integrates adapted standard procedures, experimental design, material testing, and analytical techniques to ensure reliability, repeatability and validity of the results.

3.1 Methodological Framework

The methodology aims to establish a consistent and repeatable approach for assessing the compressive strength of binders in low-strength applications, particularly sandcrete block production. It aligns with existing standards while introducing a target bulk density as one of the factors guiding mix design. By anchoring the mix to a defined bulk density, the methodology aims to enhance both the reproducibility of results and their practical relevance in construction. To achieve this objective, a sequential comparative experimental methodology was designed and implemented as follows:

- Establishing a bulk density threshold: The geometrical parameters of the prism, as stipulated in EN 196-1:2016, were employed to calculate an anticipated bulk density threshold. This value served as a guiding reference for the formulation of an appropriate and consistent mix design.
- Adaptation of standard testing protocols: Modification of the SS EN 196-1:2016 standard to suit strength test of binder in low-strength application and laboratory condition.
- Method Evaluation: An assessment of the testing methodology was conducted by analysing the relationship between compressive strength test outcomes and their respective coefficients of variation. Additionally, t-test statistical analyses were employed to evaluate the influence of two variables: the method of specimen selection (random selection versus specimens from the same mold), and the number of specimens tested per condition (three versus six). This evaluation was aimed at identifying potential sources of variation and enhancing the reliability and reproducibility of the experimental results. The outcomes of this methodological assessment are presented and discussed in Chapter 4.
- Strength testing, material characterization, and comparative analysis: Compressive strength tests were conducted at 1, 7, and 28 days to evaluate early-age strength development. Complementary material characterization using X-ray Diffraction (XRD) was performed on benchmark mix designs to investigate hydration performance. The performance of BYF cement was systematically compared to that of conventional PC to assess its viability as a sustainable alternative. The findings from these analyses are likewise detailed in Chapter 4.

3.2 Materials and Preliminary Mix Proportions

3.2.1 Materials

The primary materials used in this study include:

- Cementitious Binders:
  - Reference cement: Traditional PC (CEM II/A-LL 42.5R), compliant with EN 197-1, containing 80–94% clinker and 6–20% limestone.
  - Alternative Cement: BYF Cement, a low-carbon binder containing Belite, Ye’elimite, and Ferrite phases.
- Aggregates: CEN standard sand was used throughout the experiments.
- Water: Potable tap water was used for mixing and curing throughout the experiment.

3.2.2 Mix Proportions

The mix proportions were designed to suit the hydration and rheological behaviour of each binder. While the mass of sand remained constant throughout all experiments, the w/c ratio was optimized to ensure workability, compaction, and target density.

For the reference (Portland) cement, the w/c ratio varied between 1.4 and 2.2. Initial trials using 7% cement content explored w/c ratios in the range of 1.4 to 1.7 in line with conventional SB practice. Subsequently, the cement content was reduced to 5%, corresponding to a w/c ratio of 2.2, to investigate the mechanical performance of PC at lower binder content and higher water level. The detailed mix proportions for the reference cement are presented in Table 3.1. The benchmarked mix design was 7% cement and w/c ratio of 1.6.

Table 3.1 Preliminary mix proportions examined for reference (Portland) cement.

Samples	Water-Cement ratio	Cement (g)	Sand (g)	Water (g)
1	1.4	113.9	1350.0	162.7
2	1.6	115.2	1350.0	181.1
3	1.7	117.0	1350.0	200.0
4	2.2*	80.4	1350.0	176.8

For the alternative (BYF) cement, the benchmark mix design for PC was aimed to be used for BYF, but due to high water demand of BYF cement, the mix was too dry for compaction and as such was rolling like a pellet. To ensure true study of the influence of the binder, no admixtures were used. The initial trials explored 7% cement content and w/c ratios in the range of 1.6 to 2.0. Subsequently, the cement content was reduced to 5%, exploring w/c ratios 2.2 and 2.8, to investigate the mechanical performance of BYF cement at much lower binder content and higher water demand. The detailed mix proportions for the reference cement are presented in Table 3.2.

Table 3.2 Preliminary mix proportions examined for alternative (BYF) cement.

Samples	Water-Cement ratio	Cement (g)	Sand (g)	Water (g)
1	1.6	115.2	1350.0	181.1
2	1.9	118.1	1350.0	219.4
3	2.0	119.6	1350.0	239.3
4	2.2*	80.4	1350.0	176.8
5	2.8*	83.4	1350.0	233.4

The optimal mix design for each binder was determined by selecting specified mortar properties such as a combination of workability of the mix, target specimen bulk density capable of producing repeatable results and compressive strength. The benchmark mix design used for the experimental study for the reference binder is 7% cement with w/c ratio of 1.6 and for the alternative binder is 7% cement and w/c ratio of 2.0. Figure 3.1 describes typical process of designing mortar mix. The results of the preliminary mix design were discussed in Chapter 4 of this report.

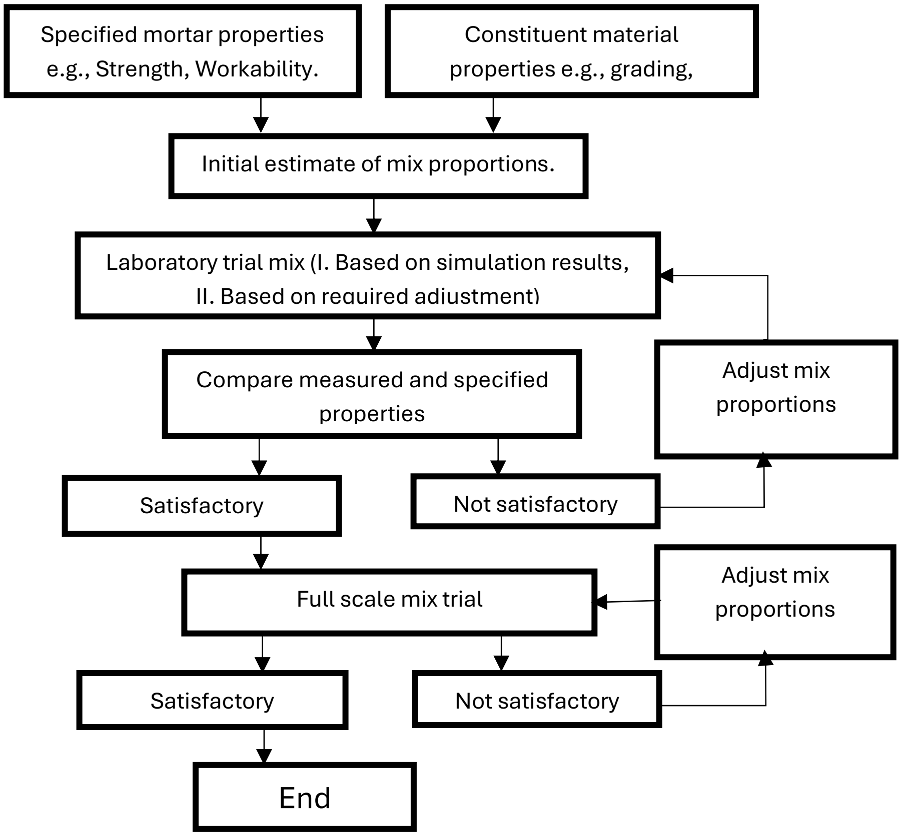

Figure 3.1 Typical mix design workflow process.

3.3 Adaptation of SS EN 196-1:2016 Standard

To establish a repeatable and comparative method for testing strength of binder in low-strength mortars, the SS-EN 196-1:2016 standard was adopted and adapted. The modifications include laboratory constraints and simulation of necessary real-world field conditions. Table 3.3 below outlines the primary key similarities and differences between the standard and adapted procedures.

Table 3.3 Key similarities and differences between SS-EN 196-1:2016 standard and the adapted procedure.

Aspect	SS-EN 196-1: 2016 Standard Procedure	Adapted Procedure
Mixer	Standard laboratory mixer	Same
Mix Ratio (Cement: Sand: Water)	1:3:0.5 (high cement, low water)	1:11.7:1.6 (low cement, lower water)
Sand Type	CEN Standard Sand	CEN Standard Sand
Mold Specification	3 compartments steel mold (40x40x160 mm^3)	3 compartment plastic mold (40x40x40 mm^3).
Test Duration	Approx. 10 mins	Approx. 35 mins
Compaction Apparatus	Jolting Apparatus	Vibrating table modified with clamps.
Specimen Dimension	Prisms: 40x40x160 mm^3	Cubes: 40x40x40 mm^3
Compaction	120 Jolts (60 jolts per layer)	120 seconds (60secs per layer).
Demolding	Manual with hand tools.	Pressurized air method.
Curing Environment	Water curing at 20 ± 2 °C and ≥90% RH	Moist curing in Moist cabin at 20 ± 2 °C and 85–90% RH
Flexural Testing	Maybe	Not applicable
Strength Testing Time	1,2,3,7 and 28 days	1,7 and 28
Testing Load Rate	2400 ± 200 N/s	2400 ± 200 N/s

3.3.1 Variations Justification and Implementation

Mix design:

The cement content of the benchmarked mix for both the reference cement and the BYF cement is approximately 74% lower than the standard specification, while the water content is approximately 19.5% lower for reference cement, and 1% lower for BYF cement. The mortar composition in SS-EN 196-1:2016 is (450 ± 2) g of cement, (1350 ± 5) g of sand and (225 ± 1) g of water. This reduction is necessary to simulate field application of low strength mortar.

Mold and Specimen:

Plastic molds (40 x 40 x 40 mm^3) were adopted due to equipment compatibility and reduced mix volume. Figure 3.2 below shows for the pictorial view of the specified and the adopted molds.

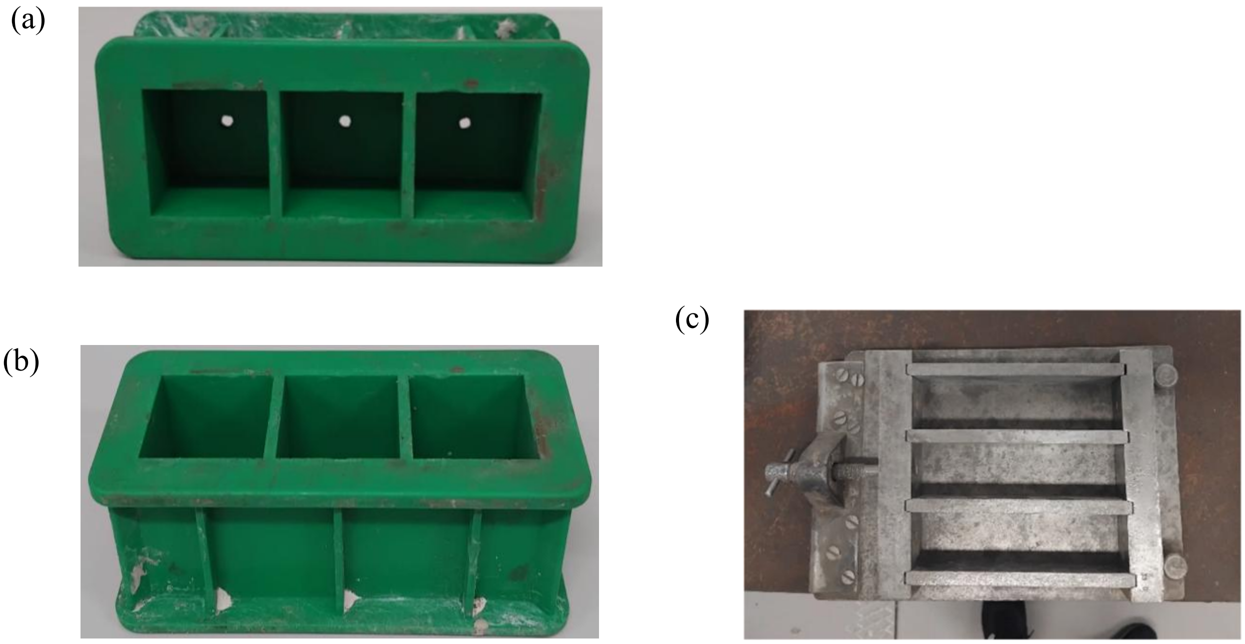

Figure 3.2 Pictorial view of the specified and the adopted molds (a) Inner view of adopted mold, (b) outside view of adopted mold (c) plan/aerial view of specified steel mold.

The impact of this changes is that flexural strength test cannot be carried out with the produced specimen, and this is not mandatory in any case. Also, one batch of mix used in this research will produce 11 to 12 specimens of 40 x 40 x 40 mm^3 depending on the binder in use, whereas one batch of mix specified in EN 196-1:2016 will produce 3 specimens of 40 x 40 x 160 mm^3.

Compaction:
For compaction, SS-EN 196-1:2016 prescribe the use of a jolting apparatus that consist of rectangular table rigidly connected by two light arms (constructed of round tubing) connected to a pivot at nominally 800 mm from the centre of the table. In operation, the mold is to be fasted to the table which is raised by a component called cam and allowed to fall freely from a height of (15,0 ± 0,3) mm before the lug strikes the stop (i.e. one jolt). This operation is allowed to continue for 60 times (i.e. 60 jolts) for every layer of compaction. Alternatively, SS-EN 196-1:2016 allows the use of alternative compaction equipment provided they have been validated in accordance with the provisions of the standard.

In this study, a vibratory table (380×260 mm) was employed as a substitute for the standard jolting apparatus, delivering equivalent compaction energy through timed vibration. There was initial issue of uneven compaction due to mold displacement, causing mortar to compact like pellet. This was resolved by securing the mold with a custom fabricated steel bracket. Figure 3.3 illustrates the adapted setup alongside typical conventional jolting apparatus.

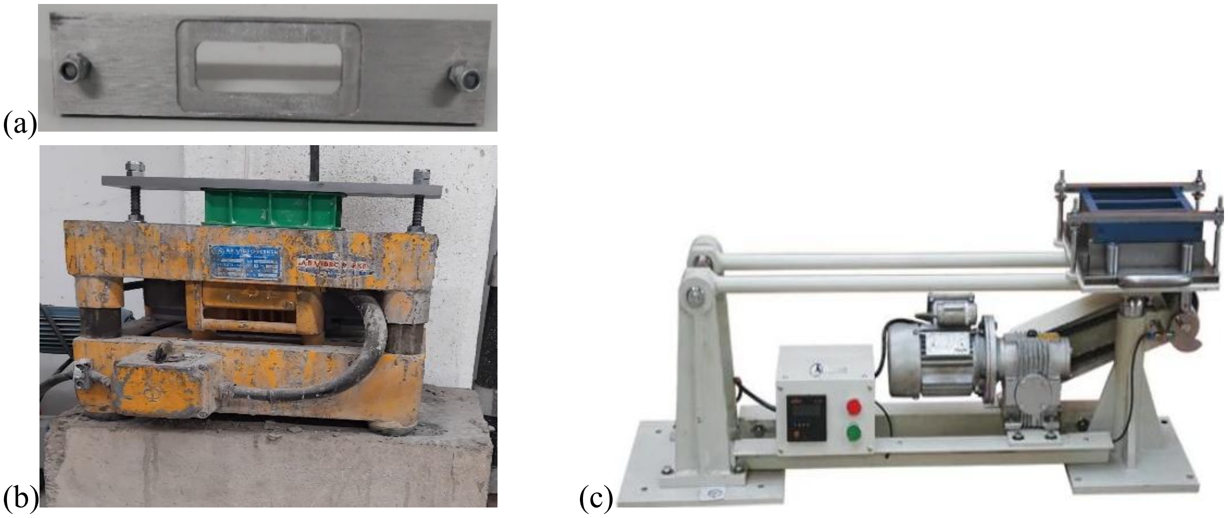

Figure 3.3 *(a) Clamp and (b) mounting arrangement (c) typical jolting apparatus https://theconstructor.org/wp-content/uploads/2020/08/Standard-Specification-of-Hollow-and-Solid-Concrete-Blocks.jpg*

Demolding:

After 24hours from the time that the mix was prepared, demolding of the specimen was done through application of pressurised air from the bottom side of the mold. Pressurized air enabled damage-free removal after 24±1 hours.

Curing:

A moist cabin simulating realistic curing was used (Figure 3.4). Capillary-fed fiber cloth ensured uniform hydration. This method mimics practical curing of sandcrete blocks, as they are normally not submerged in water.

The moist cabin provides a simple and effective solution for maintaining controlled moisture conditions for curing. As shown in Figure 3.4 below, it consists of a sealed plastic container containing a mesh rack covered by a fibre sheet. The sheet extends into the water below, enabling continuous capillary action to ensure unform sample moisture.

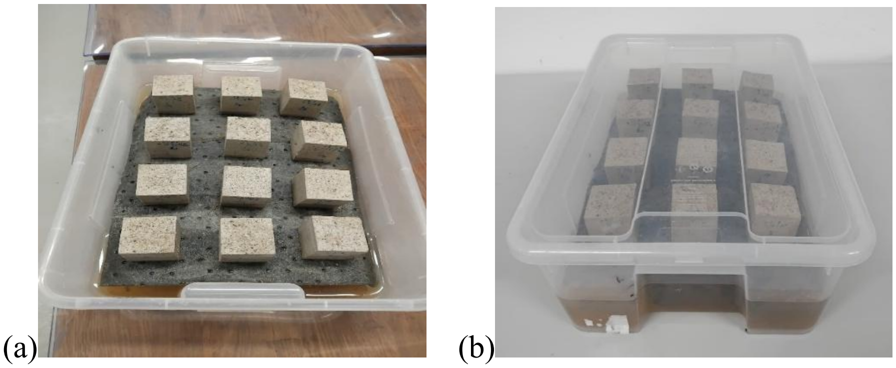

Figure 3.4 *Curing of low strength specimen (a)Moist cabin set-up (b)Moist cabin inner detail.*

3.4 Methodological Repeatability and Validation

According to SS EN 196-1, short-term repeatability measures the consistency of compressive strength tests on nominally identical cement samples when conducted in the same laboratory, by the same operator, with the same equipment, and over short time intervals. The standard specifies the following coefficient of variation (CV) for compressive strength tests to be:

- ≤ 3% at 2 days
- ≤ 2.5% at 7 days
- ≤ 2% at 28 days

Given the lower strength of mortars in this study (5–7 MPa), proportionally smaller absolute variations may yield higher CVs. Statistical tools were applied (see Chapter 4) to validate the repeatability of results, accounting for inherent variability in low-strength tests.

3.5 Experimental Procedures

3.5.1 Preparation of Specimens

Mold Preparation
Prior to casting, each Mold was cleaned and uniformly lubricated using paraffin oil to prevent bonding between the Mold and mortar, thereby facilitating smooth demolding. A sealing tape was applied to the bottom aperture of each Mold to prevent leakage during casting.

Mixing Procedure
The mixing was performed in an automatic mechanical laboratory mixer with a preset time and speed for both high and low speed, compliant with SS EN 196-1:2016. The procedure involves first combining the water and the cement in the bowl, gently diluting it for 10 seconds and mounting the bowl, after which the mixer is switched on. Then the fresh cement paste is mixed at low speed over the next 30 seconds after which sand is added through the automatic controlled opening at the top part of the mixer. The speed then automatically switches to high speed and the mixing continues for an additional 30s after which the mixer stops for 90s to allow scraping of the walls and bottom of the bowl into the middle of the bowl. Thereafter, the mixing continues at high speed for a further 60s before the mixing comes to an end.

Compaction Process
Mortar was introduced into the molds in two equal layers. Each layer was evenly distributed using a spatula prior to compaction. Compaction was performed on a vibrating table measuring 380 mm × 260 mm, modified with a clamp to securely hold one mold at a time. Each layer was compacted for approximately 60s, replicating the effective energy input of the jolting apparatus prescribed by EN 196-1.

3.5.2 Demolding and Curing

Demolding Procedure

Specimens were demolded 24 ± 1 hours after casting. To avoid damage during removal, compressed air was applied through a dedicated port at the base of each plastic mold. The demolded cubes were visually inspected to ensure they were free from surface defects or fractures.

Curing Conditions

1-day Specimens were wrapped in polyethylene to preserve internal moisture. Specimens were cured in a moist environment designed to simulate moderate field conditions. Each sample was placed on a fiber sheet moistened via capillary action within a sealed plastic curing chamber. The internal environment of the chamber was maintained at 25 20 ± 2 °C and 85–90% relative humidity. For 1-day tests, specimens were wrapped in polyethylene film to minimize moisture loss before demolding. Curing durations were set at 1, 7, and 28 days to assess strength development over time.

3.3.4 Testing Procedure

Bulk Density Determination

The bulk density of hardened specimens was determined prior to compressive strength testing. Each cube was dried to surface saturation and weighed using a digital balance with 0.01 g precision. Volume was calculated based on the known mold dimensions (64,000 mm³ or 0.064 L). Bulk density (kg/L) was determined using the equation:

$$\rho = \frac{M}{V} \tag{3.1}$$

Where:

M= Mass of specimen (kg)

V= Volume of specimen (L)

Three readings per test-set were taken and averaged for accuracy. Based on EN 196-1:2016, a standard mortar prism has dimensions of 40x40x160mm^3, and an average specimen mass of ~580 g (0.58 kg) was giving. The bulk density is then calculated as follows:

volume (V) = 0.04 m × 0.04 m × 0.16 m) × 1000 = 0.256 L

Bulk density (ρ) = mass / volume = 0.58 kg / 0.256 L ≈ 2.3 kg/L

This bulk density threshold was used as a design reference to guide mix proportions and compaction efforts during the experimental process. It provides insight into the compactness and potential mechanical properties of the blocks.

Compressive Strength Testing

Compressive strength tests were performed using a computerized compression machine with a capacity of 300 KN: having an accuracy of ± 1,0 % of the recorded load in the upper four-fifths of the range and programmed to provide a load increase of 2400 ± 200 N/s, in line with EN 196-1 requirements. Each 40 mm cube was positioned centrally between the platens, ensuring even distribution of load. Maximum load at failure and compressive strength (MPa) were recorded automatically. The compressive strength (MPa) can also be calculated by using the formula:

$$\text{Compressive Strength} = \frac{\text{Maximum load (N)}}{\text{Loaded Area (mm}^2\text{)}} \tag{3.2}$$

Each test set included 3–6 specimens at each curing interval (1, 7, and 28 days), with average values computed to the nearest 0.1 MPa.

PC and BYF Hydration

X-ray Diffraction (XRD) was used to study hydration reactions of PC and BYF cement pastes at benchmarked mix design. Cement pastes were prepared with w/c ratios of 1.6 (PC) and 2.0 (BYF). Each paste was sealed with Kapton film and tested using a Siemens D5000 diffractometer with a Bruker SolX detector under the following settings:

Voltage: 40 kV

Current: 30 mA

Radiation: CuKα

2θ Range: 7° to 50.02°

Step Width: 0.020°

Time per Step: 1.79 seconds

Over a 22-hour period, 33 diffraction patterns were obtained to track hydration phase evolution.

3.3.5 Data Analysis

The results were subjected to statistical analysis to assess repeatability and compliance as close as possible to EN 196-1:2016 standard variability limits (≤2.0% CV at 28 days). Outlier readings, if present, were excluded based on GruSBs' test for statistical validity. Statistical repeatability was assessed using coefficient of variability and described in Chapter 4.

Chapter 4: Results and Analysis

4.1 Evaluation of Impact of Key Elements of Modification

The impact of key elements of modification are analyzed in this section as stated earlier in section 3.1 above. It involves comparative analyses of preliminary test results using appropriate analytical tools such as charts and t-test statistical analyses. The evaluation aimed to identify potential sources of variation and aid necessary improvement to enhance the reliability and reproducibility of the experimental results.

4.1.1 Influence of Water-Cement Ratio

The water-cement (w/c) ratio is a key determinant of mortar strength and significantly impacts the bulk density of specimens. A higher ratio increases bleeding, segregation, and porosity, while a lower ratio leads to a stiffer mix, both of which can compromise test consistency and specimen integrity. Achieving an optimal w/c ratio is essential for ensuring adequate hydration, compaction, and workability which directly influence the repeatability and reliability of compressive strength testing result.

The average compressive strength at 28-day for a 5-7% cement content is 1-7 MPa (Isaksson et al., 2023). The target compressive strength at 28-day for this research is 7 MPa. The target bulk density is 2.3 kg/L, based on parameters specified in SS EN 196-1:2016. The water-cement (w/c) ratio varied across multiple mixes to simulate real-world application conditions and to meet these performance targets for binders in low-strength applications. Table 4.1 details the trend observed between different w/c ratios, corresponding average bulk density and their corresponding 1-, 7- and 28-day compressive strengths for PC. Bulk density was recorded at 1 day, as changes thereafter were negligible and attributed mainly to water absorption during curing.

*Figure 4.1 Varying w/c ratio of Portland cement mortar, corresponding average bulk density and average compressive strength at 1-,7- and 28-day. (*executed at 5% cement, while others were done at 7% cement)*

w/c Ratio	Avg. Bulk Density (kg/L)	1-Day Avg. Comp. Str. (MPa)	7-Days Avg. Comp. Str. (MPa)	28-Days Avg. Comp. Str. (MPa)
1.4	2.0	1.5	2.5(est.)	2.9 (est.)
1.6	2.2	1.9	4.1	6.1
1.7	2.2	1.7	4.5	5.9
2.2*	2.1	0.6 (est.)	1.9	2.7

As stated in section 3.2.4 above, the values of the compressive strength were computerized by the compression machine to the nearest 0.1 MPa. The compressive strength (MPa) can also be calculated by inserting the values of maximum load and area of the specimen in eqn. (3.2), repeated below:

$$\text{Compressive Strength} = \frac{\text{Maximum load (N)}}{\text{Loaded Area (mm}^2\text{)}} \qquad (3.2)$$

The following observation was drawn from the experimentation and the values presented in table 4.1 above. It was observed that at.

- w/c = 1.6: Provides the optimal results, which achieve an average bulk density of 2.2 kg/l and compressive strength of 6.1 MPa at 28 days.
- w/c = 1.7: This mix exhibited increased fluidity, which aided compaction but caused noticeable bleeding. It achieved the same bulk density (2.2 kg/l) but a slightly lower compressive strength of 5.9 MPa.
- w/c = 1.4: This mix was significantly stiffer, complicating compaction. Entrapped air and incomplete mold filling resulted in poor-quality specimens, which rolled during compaction. Hence, the 7- and 28-Day strength wasn't tested.
- w/c = 2.2 (5% cement): Many specimens crumbled during demolding at 1 day due to insufficient binder strength. They were tested instead on 7 and 28 days. The average compressive strength was significantly lower, at 2.7 MPa at 28 days.

The value for 1-day compressive strength for the mix design at w/c ratio 2.2 was estimated and likewise the values for 7- and 28-day average compressive strength for 1.4 w/c ratio were estimated. The clustered column bar chart in Figure 4.1 details the varying w/c ratio and the corresponding Average compressive strength for PC mortar.

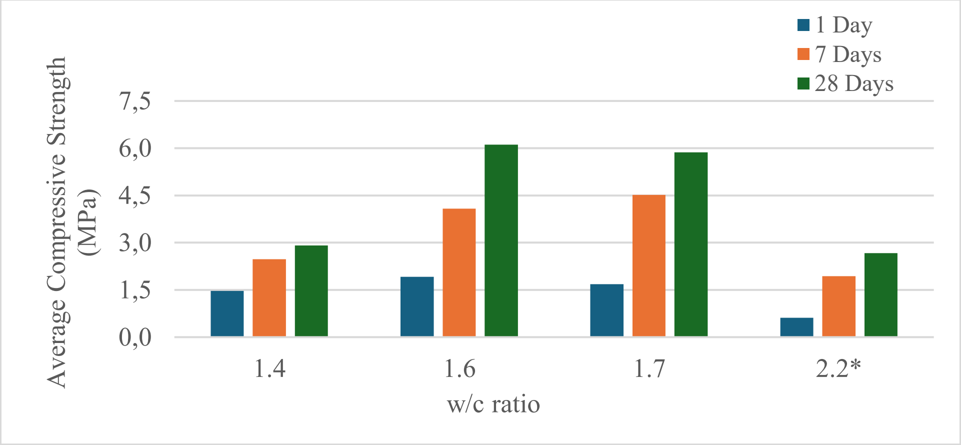

*Figure 4.1 Varying w/c ratio of Portland cement and corresponding average compressive strength at 1-, 7- and 28-day (*executed at 5% cement, while others were done at 7% cement).*

The mix design of 1.6 w/c ratio was benchmarked as reference mix because of its strength development. Also, there was no bleeding from the mix during compaction. The benchmark mix of reference cement was adopted for the BYF cement. However, during experimentation, it was observed that the 1.6 w/c ratio was too stiff for BYF cement. Figure 4.2 shows the specimen obtained from 1.6 w/c ratio.

Figure 4.2 BYF specimen at 1.6 w/c ratio

Due to the above reason, BYF cement was subjected to further testing to find a suitable mix design for this experiment. Table 4.2 presents the average bulk density and compressive strengths at various curing ages.

*Table 4.2 Varying w/c ratio of BYF cement mortar, corresponding average bulk density and average compressive strength at 1-,7- and 28-day. (*executed at 5% cement, while others were done at 7% cement)*

w/c Ratio	Avg. Bulk Density (kg/L)	1-Day Avg. Comp. Str. (MPa)	7-Day Avg. Comp. Str. (MPa)	28-Day Avg. Comp. Str. (MPa)
1.6	2.1	4.1	10.9	8.0 (est.)
1.9	2.1	5.8	7.0	6.9
2.0	2.1	4.5	5.2	6.7
2.2*	2.2	3.7 (est.)	6.3	6.7
2.8*	2.1	1.3 (est.)	3.0	4.8

The following observations were drawn from the experimentation and the above result. It was observed that.

- w/c = 1.6: The mix was stiff and became increasingly unworkable after initial casting. Produced irregularly shaped specimens due to poor compaction. Despite workability challenges, this ratio showed the highest 7-day strength, suggesting strong early hydration once properly compacted. It achieved a slightly lower compressive strength of 8.0 MPa (estimated) at 28-Day.
- w/c = 1.9: Offered better workability than the 1.6 mix with a slight slightly higher early strength at 1-Day. Exhibited a more balanced strength gain across all ages. Produced more uniformly shaped specimens due to improved casting consistency but with still some level of porosity. It achieved the same bulk density (2.1 kg/l) but a slightly lower compressive strength of 6.9 MPa at 28-Day.

- w/c = 2.0: This ratio provided optimal workability among the 7% BYF mixes. Showed consistent strength development across 1 to 28 days. Considered the most practical mix for achieving a balance between ease of casting and compressive performance. It achieved the same bulk density (2.1 kg/l) but a slightly lower compressive strength of 6.7 MPa at 28-Day.
- w/c = 2.2 (5% cement): Despite having lower cement content, this mix matched the 28-day strength of the 7% cement/2.0 w/c mix. It achieved the maximum recorded bulk density in the study. It indicates that 5% BYF cement with 11% water (2.2 w/c) is a potentially optimal combination in terms of density and efficiency.
- w/c = 2.8 (5% cement): Excessive water content significantly reduced strength across all ages. They were tested instead on 7- and 28-Day similar to reference cement. The average compressive strength was significantly lower, at 4.8 MPa at 28-Day.

The value for 1-day average compressive strength for the mix design at w/c ratios 2.2 and 2.8 were estimated. Likewise, the 28-Day average compressive strength for the mix design at w/c ratio 1.6. The clustered column bar chart in Figure 4.3 details the varying w/c ratio and the corresponding Average compressive strength for BYF mortar.

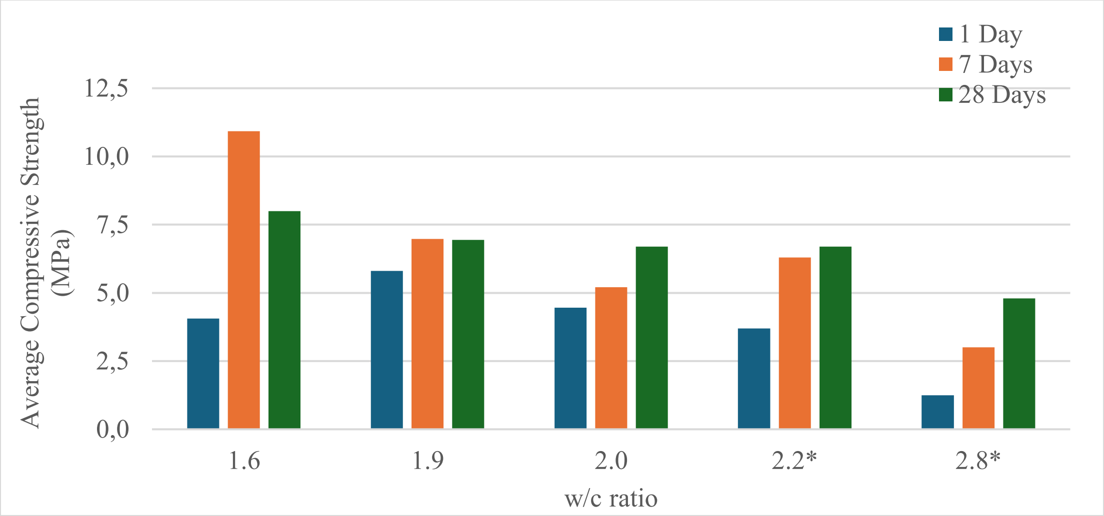

Figure 4.3 Varying w/c ratio of BYF cement and corresponding average compressive strength at 1-, 7- and 28-day. 2.2 and 2.8* have 5% cement content while 1.6, 1.9 and 2.0 have 7% cement.*

The optimal mix design for BYF is between a w/c ratio of 1.9 and 2.2 which appears to provide the best compromise between ease of handling and mechanical performance. However, w/c ratio of 2.0 was adopted as a suitable mix design for this study. For comparative purposes, Table 4.3 below summarizes the comparative overview of the strength performance of both cement at key w/c ratio.

Table 4.3 Comparative overview of the strength performance of PC (CEM II) and BYF cement at key w/c ratio.

Features	1-Day			7-Day			28-Day		
Cement Content in mix	5 wt%	7wt%		5 wt%	7wt%		5 wt%	7wt%	
w/c ratio (%)	2.2	1.6	2.0	2.2	1.6	2.0	2.2	1.6	2.0
Avg. Bulk Density (kg/L)	2.2	2.2		2.2	2.2		2.2	2.2	
PC Avg. Comp. Str. (MPa)	0.6 (est)	1.9		1.9	4.1		2.7	6.1	
BYF Avg. Comp. Str. (MPa)	3.7 (est)		4.5	6.3		5.2	6.7		6.7

At 7% cement content, BYF produce more than twice the strength of PC in 1-Day, despite high water level difference. At 7- and 28-Day, PC samples gain massive strength against BYF samples, but still short. The 5% cement content at 2.2 w/c ratio provides an interesting comparison because it contains an equal proportion of cement, sand and water. At every age, BYF produce atleast more than double the strength of PC.

The performance of BYF at low (5%) cement and high (11%) water is an eye opener, which calls for deep consideration. Low cement means low cost and reduced carbon footprint. The strength value at this level of cement is advantageous to SSB production in addition to early high strength development characteristic of BYF.

4.1.2 Hydration Kinetics and Strength Development

The benchmark mix design for PC at 1.6 w/c ratio and for BYF cement at 2.0 w/c were used for the study of the hydration kinetic of the respective cement. 5g of cement and corresponding water content was used for respective cement in this experiment. Figure 4.4a and 4.4b presents the X-ray diffraction (XRD) patterns for PC and BYF cements at w/c ratios of 1.6 and 2.0, respectively.

The hydration behavior of BYF cement differs notably from that of Portland cement due to their distinct mineralogical composition. In 24 hours, ettringite that is responsible for early strength and volume stability is rapidly produced in BYF than in PC which produced a very low amount which is due to the rate of hydration of clinkers of both cements.

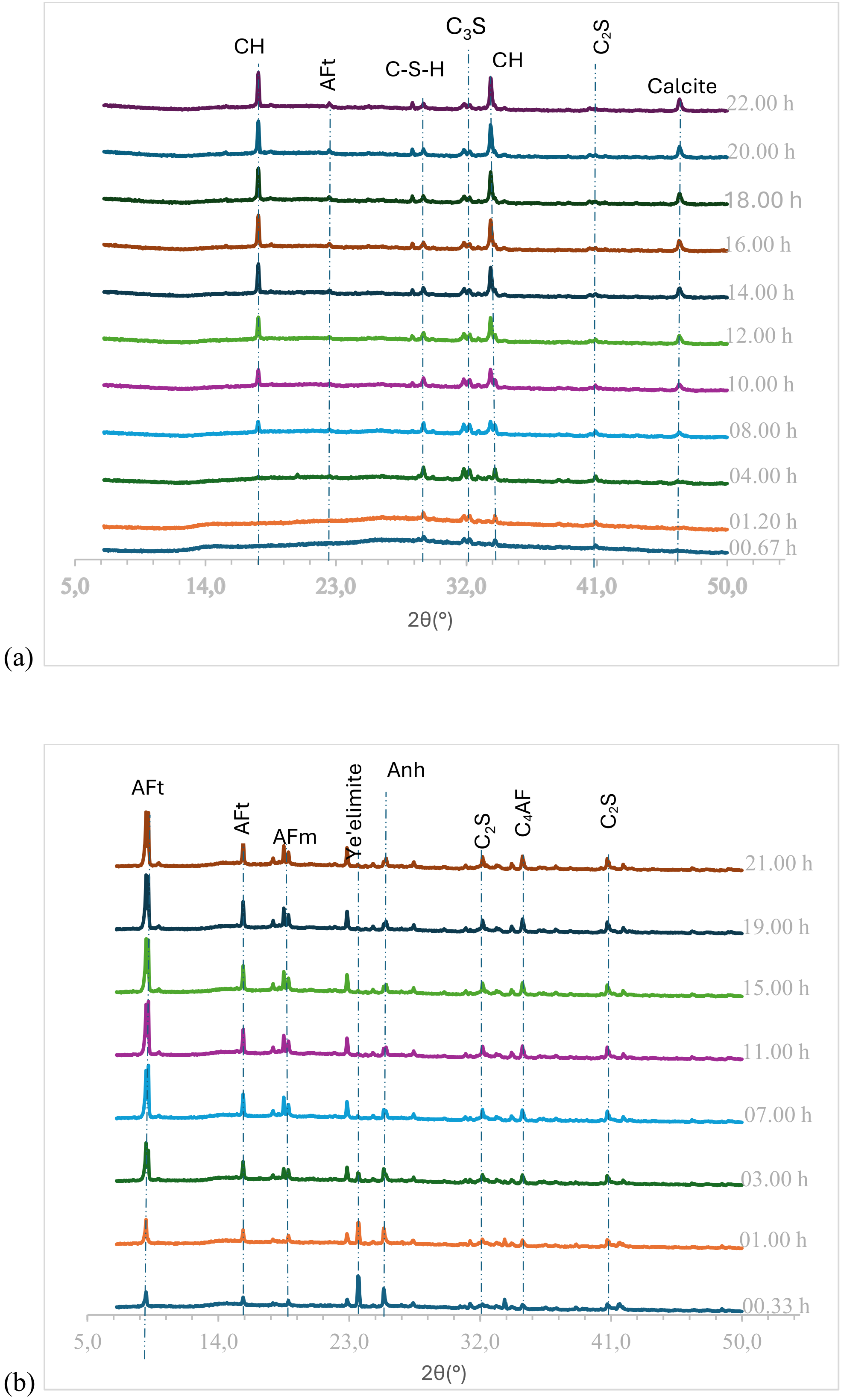

Figure 4.4 *24 hours XRD analyses for (a) CEM II at 1.6 w/c ratio (b) BYF cement at 2.0 w/c* ratio

In XRD analyses of PC (CEM II), peaks of alite (C_3S) at ~32° 2θ and belite (C_2S) at ~41° 2θ were seen early in the hydration process at 0.67 h. These clinker phases reduce gradually over 24 hours. Also noticed at 0.67 h were the peaks of C-S-H at ~29° 2θ and CH at ~33.5° 2θ. Low peak of Ettringite (AFt) was noticed at ~22.5° 2θ from 4 h with a mild growth over the 24 h period. The CH and C-S-H are the major hydrated products of CEM II PC. These peaks were observed growing continuously over the remaining duration.

Conversely in BYF cement, peaks of belite (C_2S) at ~32° 2θ and ~41° 2θ, together with ferrite (C4AF) at ~ 35° 2θ were observed within 0.33 h of the hydration process, and throughout the period of 24 hours, they remain inert in agreement with (Winnefeld & Lothenbach, 2010). The peaks of ye'elimite at ~23.5° 2θ, anhydrite at ~25.5° 2θ, monosulphate (AFm) at ~18.5° 2θ, ettringite (AFt) at ~9° 2θ and ~16° 2θ, were also seen within 0.33 h. While the peaks of ye'elimite and anhydrite were rapidly reducing with increase in time, the peaks of ettringite and monosulphate were increasing with time, indicating the ye'elimite rapid hydration. Table 4.4 below shows the summarized interpretation of the 24-hour hydration of PC (CEM II) and BYF cement for comparative purposes.

Table 4.4 Summarized comparative interpretation of 24-hour hydration of PC (CEM II) and BYF cement.

Feature	PC (CEM II) (a)	BYF (b)	Impact/comment
Alite hydration	Started within first hour	Absent	Responsible for the gradual and low early strength
Belite hydration	Present	Expected beyond 24 h	Responsible for the long-time strength
Ye'elimite hydration	Absent	Present	Responsible for high water demand
Ettringite formation	Started around 8 h mark	Started within the first hour	Responsible for rapid and high early strength, early setting and volume stability
CH formation	Present	Expected beyond 24 h	Influences durability
C-S-H formation	Present	Expected beyond 24 h	Responsible for primary binding in cement

BYF cement requires a higher w/c ratio for adequate hydration, especially due to the rapid reaction of Ye'elimite, which forms ettringite that is responsible for early-age strength. High w/c is beneficial for compaction of sand matrix, while early strength development is advantageous for SBB production

4.1.3 Influence of 40 × 40 × 40 mm^3 Plastic Mold

The primary influence of the chosen plastic mold is that it requires longer time for placing the mix, as it must be cast 3 to 4 times. Whereas the SS EN 196-1:2016 method requires shorter placing time, because it's casted once. Each mix in this study was cast three to four times, producing approximately 11 and 12 pieces of 40 × 40 × 40 mm^3 specimens per batch of mix for PC and BYF respectively. Due to multiple casting, each mold has the possibility of experiencing little variations that can impact the result. This analysis was done with PC being the reference cement.

During the compressive strength testing, six cube specimens (6-S) from two or more molds and three specimens from single (3-SS) or multiple (3-SM) molds were used alternatingly to study impact of this variation. Figure 4.5 below presents the column bar chart comparing the CV of the compressive strength of three specimen collected from single mould (3-SS) with the CV of the compressive strength of three specimen collected from multiple moulds (3-SM). Each 6-S compressive strength data was split into two 3-S subsets (3-S1 and 3-S2), and the compressive strength was measured. The combined 6-S group consistently showed higher CV in 75% of the Test set, suggesting greater variability when using specimen from multiple molds per test.

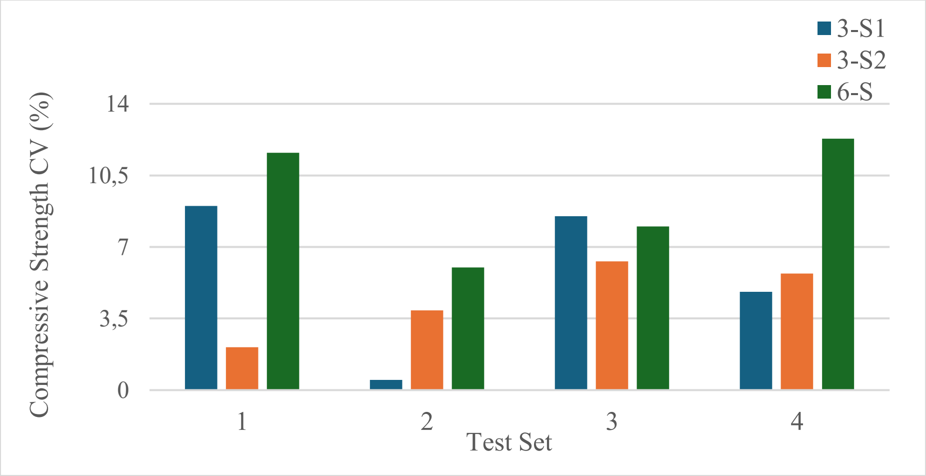

Figure 4.5 Comparison of average Compressive strength, CV of three specimens (3-S) data and six specimens (6-S) data

Furthermore, a two-sample t-test assuming equal variances was performed to evaluate statistical significance between the 3-S and 6-S groups. Table 4.5 presents the key parameters used in selection of the appropriate t-Test model.

Table 4.5 Key Parameters for selecting appropriate t-Test for statistical comparison of CV for 3-S Combined and 6-S12 Groups

Group	Sample Size (n)	Mean CV (%)	Variance
3-S1,3-S2	8	5.1	8.61
6-S12	4	9.48	8.92

The key parameters of interest are the sample size, Mean CV and the Variance of each group. From Table 4.5 above the ratio of the variance is close to 1, hence a two-sample t-Test assuming equal variances was conducted to compare the CV of Compressive strength of 3-S and 6-S group. Table 4.6 below details the result of the test.

Table 4.6 t-Test result summary for comparison of CV for 3-S Combined and 6-S Groups.

Parameters	t-Test: Two-Sample Assuming Equal Variances	Significance (α=0.05)
Pooled Variance	8.701	
Hypothesized Mean Difference	0	
Degrees 0f freedom	10	
t Stat	-2.422	
P(T<=t) one-tail	0.018	Significant
t Critical one-tail	1.812	
P(T<=t) two-tail	0.036	Significant
t Critical two-tail	2.228	

As shown in Table 4.6, the t-test produced a t-value of -2.42 with 10 degrees of freedom (df) and a p-value of 0.036. Since the p-value is less than the significance level (α), the null hypothesis is rejected, indicating a statistically significant difference in CV between the 3-S and 6-S groups. This suggests that using six specimens from multiple moulds increases variability.

Furthermore, a comparative analysis was conducted to access whether selecting three specimens from single (3-SS) or multiple (3-SM) moulds within a single batch affects test variability. Figure 4.6 presents the corresponding bar chart comparing the CVs of the 3-SS and 3-SM groups.

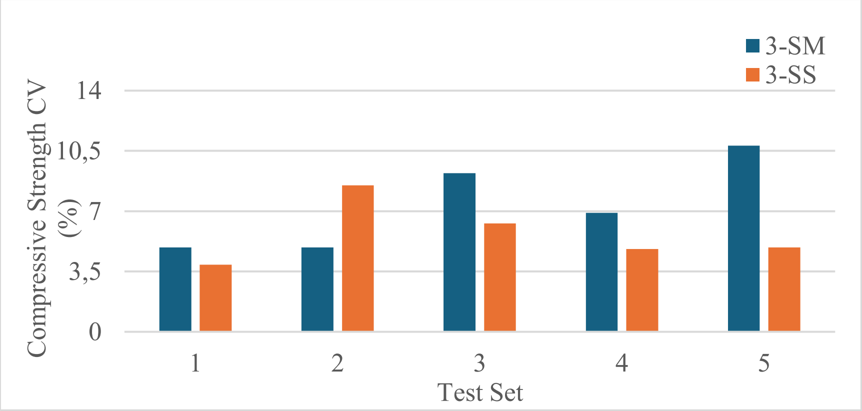

Figure 4.6 Comparison of Compressive strength CV of 3-SS and 3-SM

It can be observed that in 80% of the cases, combining specimens from multiple moulds results in a higher CV compared to using specimens from a single mould. The bar chart shows that the 3-SM group exhibits a higher mean CV than the 3-SS group, reflecting increased variability with random sampling. However, a two-sample t-test assuming unequal variances yielded different results. Tables 4.7 presents key parameters for selection of appropriate t-Test for this analysis.

Table 4.7 Key Parameters for selection of appropriate t-Test for statistical comparison of CV for 3-SM and 3-SS

Group	**Sample Size (n)**	**Mean CV (%)**	**Variance**
3-SS	5	7.34	6.88
3-SM	5	5.68	3.22

The value of the variance ratio from Table 4.7 is far greater than 1. Hence, a two-sample t-test assuming unequal variances was conducted. Table 4.8 presents the result of the test below.

Table 4.8 t-Test result summary for comparison of CV for 3SM and 3-SS sampling choice.

Parameter	t-Test: Two-Sample Assuming Unequal Variances	Significance (α=0.05)
Hypothesized Mean Difference	0	
Degrees of freedom	7	
t Stat	1.168	
P(T<=t) one-tail	0.141	insignificant
t Critical one-tail	1.895	
P(T<=t) two-tail	0.281	insignificant
t Critical two-tail	2.365	

Although the 3-SS group exhibited a slightly lower mean CV, the difference was not statistically significant, as the p-Value exceeded the significance threshold (α). Consequently, the null hypothesis could not be rejected. As a result, the study adopted three-specimen sets from a single mould for subsequent testing to enhance consistency and reduce outliers. Figure 4.7 presents the (a) modified and (b) standard statistical verification.

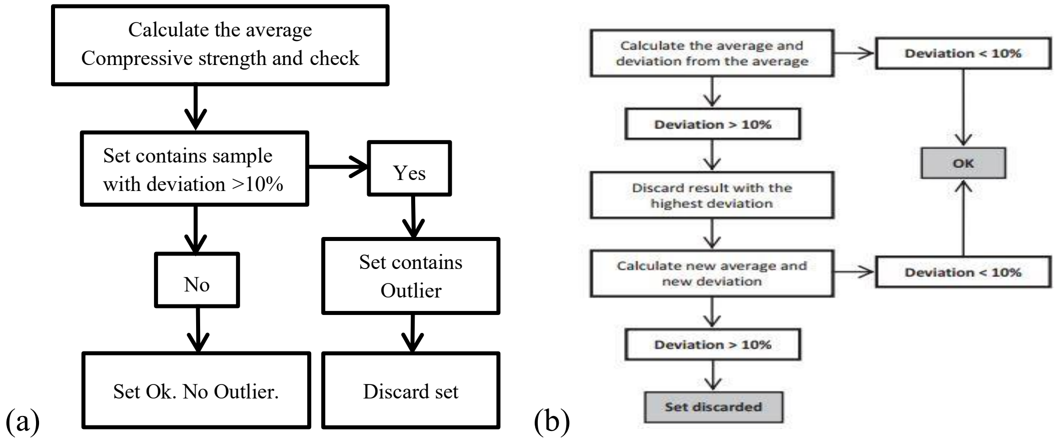

Figure 4.7 Flow chart of data verification (a) in this research (b) SS EN 196-1:2016 specification (Galobardes et. al, 2016).

4.2 Verification of Method Repeatability

SS EN 196-1:2016 outlines the repeatability assessment of compressive strength tests through short-term or long-term variability evaluations which is defined as follows:

- Short-term repeatability: Same operator, equipment, and conditions within a short time frame.
- Long-term repeatability: Conducted over an extended period (up to one year) using different operators and possibly different equipment but with a single homogenized cement sample.

This research employed short-term repeatability, examining 7-day and 28-day compressive strength results. According to EN 196-1, the acceptable coefficients of variation (CV) for short-term repeatability are:

- 2 days: 3.0%
- 7 days: 2.5%
- 28 days: 2.0%

For 7% Portland cement with 11% water content, test results for 7-day are summarized in Table 4.9 below. The CV is calculated as:

$$\mathrm{CV} = \frac{STD\ DEV.}{Average\ Compressive\ Strength}\% \tag{4.1}$$

Table 4.9 7-day compressive strength expressed as coefficient of variation for PC benchmark mix design; 7% PC and 11% water content

Samples	Weight (g)	Max. Load (KN)	Bulk Density (kg/L)	Compressive Strength (MPa)
B1	137.3	6.0	2.1	3.8
B2	138.1	6.6	2.2	4.1
B3	137.5	7.0	2.1	4.4
AVERAGE	137.6	6.6	2.2	4.1
STD DEV.	0.3	0.4	0.0	0.3
CV	0.2%	6.3%	0.2%	6.3%

For age 7-day specimens an average strength: 4.1 MPa and CV = 6.3% was recorded with no outlier. The data for 28-day compressive strength test expressed as coefficient of variation for PC specimen were detailed in Table 4.10 below.

Table 4.10 28-day compressive strength expressed as coefficient of variation for PC benchmark mix design; 7% PC and 11% water content

	Weight (g)	Max. Load (KN)	Bulk Density (kg/L)	Compressive Strength (MPa)
C1	138.7	9.4	2.2	5.9
C2	139.2	9.6	2.2	6.0
C3	139.0	10.5	2.2	6.5
AVERAGE	139.0	9.8	2.2	6.1
STD DEV.	0.205	0.472	0.003	0.295
CV	0.1%	4.8%	0.1%	4.8%

For age 28-day specimens an average strength: 6.1 MPa and CV = 4.8% was recorded with no outlier.

Similarly, For BYF benchmark mix, 7% cement and 14% water content, test results for 7-day are summarized in Table 4.11 below:

Table 4.11 7-day compressive strength expressed as coefficient of variation for BYF cement benchmark mix design; 7% cement and 14% water content

Samples	Weight (g)	Max. Load (KN)	Bulk Density (kg/L)	Max. Strength (MPa)
D1	133.4	7.9	2.1	4.9
D2	132.8	7.9	2.1	4.9
D3	134.5	8.9	2.1	5.6
AVERAGE	133.6	8.2	2.1	5.1
STD DEV.	0.704	0.482	0.011	0.302
CV	0.5%	5.9%	0.5%	5.9%

For age 7-day BYF specimens an average strength: 5.1 MPa and CV = 5.9% was recorded with no outlier. The data for 28-day compressive strength test expressed as coefficient of variation for BYF specimen were detailed in Table 4.12 below.

Table 4.12 28-day compressive strength expressed as coefficient of variation for BYF cement benchmark mix design; 7% cement and 14% water content

Samples	Weight (g)	Max. Load (KN)	Bulk Density (Kg/L)	Max. Strength (MPa)
A1	278.3	12.8	2.2	8.0
A2	278.3	12.1	2.2	7.5
B1	276.5	12.2	2.2	7.6
B2	276.5	12.0	2.2	7.5
C1	276.1	12.9	2.2	8.1
C2	276.1	12.7	2.2	7.9
AVERAGE	277.0	12.4	2.2	7.8
STD DEV.	1.0	0.4	0.0	0.2
CV	0.3%	3.0%	0.3%	3.0%

As a trial during the experiment, considering that the volume of BYF mix could fill the steel mold, a one-time experiment was done with the steel mold fastened with bracket and tested at age 28-day. For age 28-day BYF specimens an average strength: 7.8 MPa and CV = 3.0% was recorded with no outlier.

While the CVs exceed SS EN 196-1:2016 thresholds slightly, they remain within acceptable margins when scaled for lower-strength mortars. For comparison, a CEM II 42.5 R cement would be allowed a 0.9 MPa variation at 28 days (2% CV), while this study showed only 0.2 MPa variation at 28 days, for significantly lower strengths. The result of the BYF with the steel mold further confirms how close these results are compared to EN 196-1.

These results confirm that the methodology is repeatable, though the variation is slightly higher due to the lower strength range of the tested mix and prolonged placing time due to the mold size.

4.3 Impact of Bulk Density on Compressive Strength

Bulk density is a critical property influencing the mechanical performance of mortars. This section evaluates the relationship between bulk density and compressive strength through statistical and graphical methods.

4.3.1 Relationship between Water-Cement Ratio, Bulk density and Compressive Strength: Graphical and Theoretical Insights

To establish this comparative analysis, Table 4.1 above was summarized to Table 4.13 below focusing on w/c ratio, bulk density and the 28-day compressive strength.

Table 4.13 *Varying w/c ratio of Portland cement mortar, corresponding average bulk density and 28-day average compressive strength (*executed at 5% cement)*

w/c Ratio	Avg. Bulk Density (kg/L)	28-Days Avg. Comp. Str. (MPa)
1.4	2.0	2.9 (est.)
1.6	2.2	6.1
1.7	2.2	5.9
2.2*	2.1	2.7

As seen in the above table, the bulk density increases with an increased w/c ratio from 2.0 kg/L at 1.4 w/c ratio up to 2.2 kg/L at 1.6 –1.7 w/c ratio. Beyond this optimal point, further increase in w/c ratio results in decrease in bulk density. Similarly, compressive strength experiences the same trend as the bulk density with the drop in compressive strength starting immediately after the optimal (~1.65 w/c ratio) point. Figure 4.8a below presents the relationship between compressive strength and w/c ratio as examined in this study. This can be compared with a conceptual workability vs compaction curve Abram’s law in Figure 4.8b below, to visualize the impact of bulk density on compressive strength.

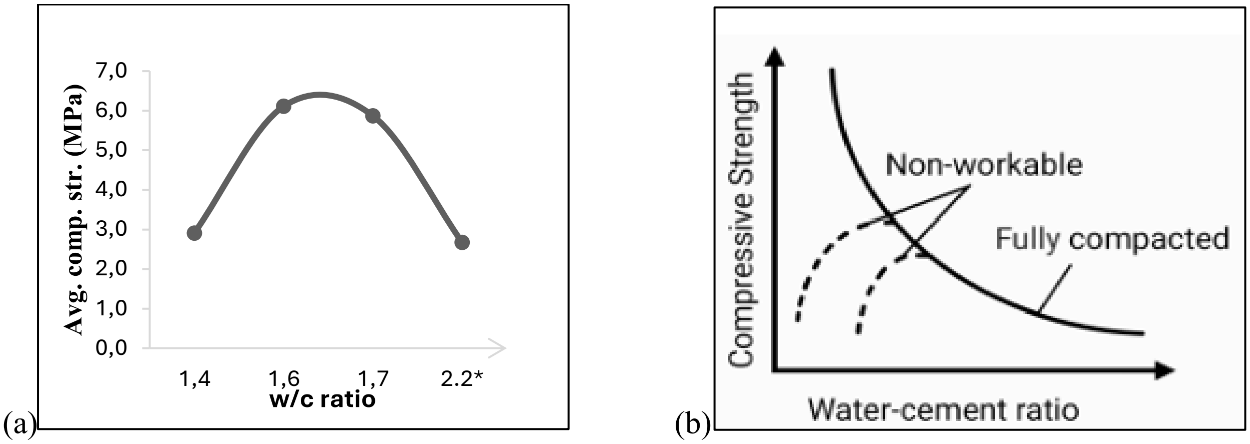

*Figure 4.8 Impact of w/c ratio on compressive strength according to Abram’s law (a) using 7% PC content and 11% water content. (*done at 5% PC content) (b) conceptual workability vs compaction curve* [(Bogren, 2024)](#).

The left side of Figure 4.8a above mirrors the non-workable region of the Abram’s curve where low w/c ratio mixes lack enough water to achieve good compaction. This trend is consistent with Bogren (2024) interpretation of Abram’s law. As w/c ratio increases (from 1.4 to 1.6) moderately, this improves workability which allows better compaction leading to an increased bulk density and simultaneously resulting in an initial increase in compressive strength.

In between 1.6 –1.7 w/c ratio, the mix likely achieves the peak compressive strength (~6.3 MPa). This point corresponds to full compaction at which the bulk density is maximum (~2.2 kg/L) which corresponds to a point along the fully compacted curve in Figure 4.8b. It is the point at which bulk density is highest, and the compressive strength is at the peak. It is consistent with fundamental interpretation of workability impact on strength development.

Beyond the optimal point (~1.65 w/c ratio), increase in water content leads to reduced bulk density and consequently, reduced compressive strength. This trend is consistent with fundamental interpretation of Abrams’ law where an inverse relationship between w/c ratio and strength. Arguably, the cement content at 2.2 w/c ratio is 5%, but a 7% cement at 2.2 w/c ratio might not make so much difference to the curve.

It is also interesting to note that the maximum density and the peak compressive strength were observed to have occurred at ~11% water content. This value correlates with sand matrix water content of EN 196-1 mix design. Table 4.14 below presents the mass of each material in key mix designs used in this research alongside EN 196-1 standard mix.

Table 4.14 Mass of materials in research key mix design alongside with EN 196-1 standard mix.

Mix Samples	w/c ratio	Mass of Cement (g)	Mass of Sand (g)	Mass of Water (g)	Total Mass (g)
EN 196-1	0.5	450.0	1350.0	225.0	2025.0
PC @ 7%	1.6	115.2	1350.0	181.1	1646.3
BYF @ 5%	2.2*	80.4	1350.0	176.8	1607.2

The aggregate water matrix (M_{AW}) is expressed as the percentage of water content in the mix matrix relative to the total mass of the mortar matrix. This can be calculated as;

$$M_{AW} = \frac{m_w}{m_T} \times 100 \qquad \text{eqn (4.2)}$$

Where:

M_{AW} is the percentage of water content in the mortar matrix in (%).

m_w is the mass of water content in the mix in (g)

m_T is the total mass of the mortar matrix in (g)

4.3.2 Regression Analysis and Correlation

To explore this relationship, nine specimens from a single batch of PC mortar at 7% cement and 11% water content was used. The specimens were exposed to uniform curing conditions and were subjected to compressive strength testing at 7 days. The bulk density and compressive strength of the specimens were calculated and presented in Table 4.15 below.

Table 4.15 Bulk density and 7- day compressive strength of mortar at 7% PC and 11% water.

Sample	Bulk Density (kg/L)	7- day Compressive Strength (MPa)
A1	2.145	3.772
A2	2.158	4.109
A3	2.148	4.401
B1	2.186	4.300
B2	2.189	4.328
B3	2.175	4.284
C1	2.183	5.001
C2	2.189	4.786
C3	2.177	4.542

Additionally, a scatter plot chart with a fitted regression line to analyze the results is presented in Figure 4.9 below. The chart reveals a moderate positive correlation between bulk density and compressive strength.

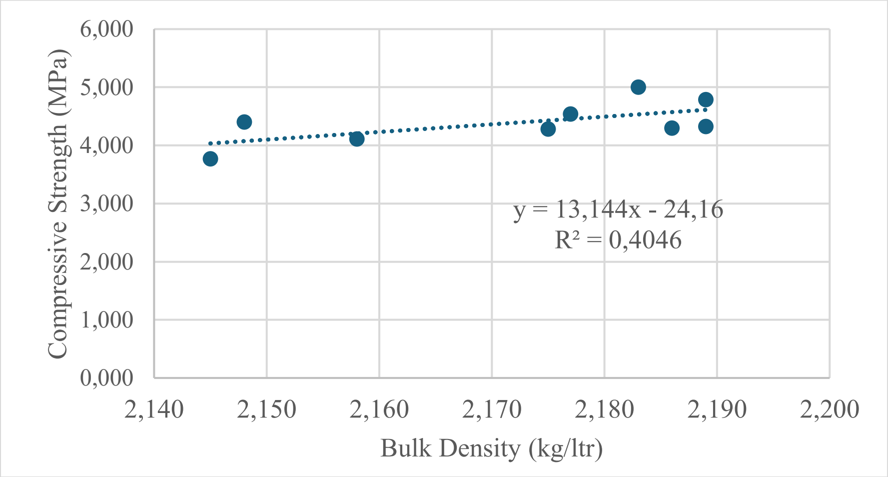

Figure 4.9 Bulk density vs 7-day strength of 7% PC specimens

The linear regression equation derived is,

$$y = 13.144x - 24.16 \qquad \text{eqn (4.3)}$$

Where: y = Compressive strength (MPa) & x = Bulk density (kg/L)

This equation implies that an increase in bulk density results in an increase in compressive strength, which highlights the role of particle packing and reduces void content in improving strength.

The coefficient of determination ($R^2 = 0.4046$) indicates that approximately 40.46% of the variability in compressive strength can be attributed to changes in bulk density. This suggests that other factors, such as curing conditions, w/c ratio, and cement quality also play a significant role.

4.3.3 Statistical Significance

To assess the statistical validity of the regression model, an F-test was conducted. This test evaluates whether the regression model significantly explains variability in compressive strength.

- F-value = 4.7569
- p-value = 0.0655

Although the F-value indicates a potential relationship, the p-value is slightly above the conventional significance level of 0.05. This suggests the model is not statistically significant at the 95% confidence level, and further data or variables may be needed to establish a stronger relationship.

5. Final Remarks

This section summarizes the study's key findings regarding testing adaptations, performance evaluation of BYF and Portland cements, and the role of bulk density in compressive strength development. It also outlines recommendations for future research.

5.1 Conclusion

To draw conclusions on this study, recalling the research questions is of high necessity. The questions are as follows:

- How can cement strength testing methods be modified to accurately simulate the material and environmental conditions typical of low-strength applications, such as sandcrete block production in Sub-Saharan Africa?
- Could BYF cement serve as a suitable replacement for Portland Cement in SSB production in terms of compressive strength development and environmental sustainability?
- Does bulk density impact compressive strength?

These questions are reviewed with reflections under the following headings:

Developing a Repeatable and Context-Sensitive Methodology

A significant contribution of this research is the adaptation of the SS EN 196-1:2016 cement strength testing standard to better reflect the material realities of sandcrete block production. These modifications included recalibrating mix designs to suit a low cement content (5–7%) and elevated w/c ratios (1.6–2.2) and reducing the number of specimen replicates from six to three in light of the variability introduced by the compaction method and moulding tools used. The adapted method produced consistent and reliable strength data, resolving the discrepancy in applying a high-strength cement testing framework to low-strength applications. These adjustments address practical limitations in laboratory settings and enhance the translational relevance of experimental data to on-site block production.

Is BYF Cement Feasible for Low-Strength Applications?

This study confirms the technical feasibility of Belite-Ye'elimite-Ferrite (BYF) cement as a sustainable alternative to Portland cement for low-strength applications, particularly in sandcrete block production. When applied at a low cement content of 5% and a high w/c ratio of 2.2, BYF achieved compressive strengths of 3 MPa in 1 day and 6.7 MPa at 28 days. These values are comparable to those obtained with mixes containing higher Portland cement content, demonstrating BYF's material efficiency. The lower clinker content and reduced carbon emissions further reinforce BYF's potential as a low-carbon binder suitable for achieving housing affordability and promoting environmental sustainability in conscious construction environments, such as those prevalent in Sub-Saharan Africa.

Additionally, BYF cement's superior early strength makes it advantageous in SB operational settings where demoulding within 24 hours, stacking and transportation within 7 days are required. In this context, early strength of 1- to 7-day is critical to prevent: Cracking during handling, Deformation under self-weight and Damage during transportation. Its rapid early strength gain could support accelerated production and construction cycles. It could enhance efficient use of space during SSB production in production sites with limited space and in areas with high housing demand.

Understanding BYF's Hydration Behaviour

Hydration analysis revealed marked differences between BYF and Portland cement, underscoring the need for binder-specific mix strategies. XRD analysis indicated that BYF undergoes rapid ettringite formation and early setting due to its ye'elimite phase. As a result, BYF required a higher w/c ratio (2.0) compared to Portland cement (1.6) to achieve suitable workability and consistent strength development. This tailored mix approach ensured that hydration reactions were not hindered, enabling reliable early and long-term performance. The distinct kinetics of BYF hydration also align with its utility in fast-paced construction contexts, making it advantageous for applications that prioritize early demoulding and through-handling.

Does Bulk Density Impact Compressive Strength?

The study found a moderate but meaningful correlation between bulk density and compressive strength. Regression analysis showed that approximately 40.46% of the variability in strength could be explained by bulk density ($R^2 = 0.4046$), with a p-value of 0.0655—suggesting a near-statistically significant relationship. A positive regression slope (13.14 MPa per unit increase in density) further supports the influence of compaction quality on strength outcomes. These findings highlight that, while bulk density is a key parameter, it interacts with other factors such as w/c ratio, cement type, curing duration, and aggregate grading. Improved compaction—particularly in mixes with low cement content and high w/c ratios—can offer a low-cost and scalable strategy for enhancing mortar performance and uniformity in block production.

Overall, this study advances understanding of how specific standards can be adapted to better suit field and laboratory conditions. It confirms BYF cement as a potential binder in sustainable low-strength applications and highlights the critical role of density and mix design in strength development of sandcrete block.

5.2 Future Research Recommendations

This research has made significant progress in validating a modified compressive strength testing protocol tailored for low-strength binders and assessing the performance of Belite-Ye'elimite-

Ferrite (BYF) cement as a viable alternative to traditional Portland cement. The results demonstrated methodological reliability and confirmed BYF cement's potential through comparable 1-, 7- and 28-day strength development and favorable hydration kinetics. However, to support the broader adoption of BYF cement in construction, particularly in low-strength applications such as sustainable sandcrete block productions, several important areas of future research must be addressed.

Firstly, long-term durability and environmental performance remain critical topics for further investigation. While this study has confirmed the short-term strength development and hydration stability of BYF cement, its behavior over extended periods under varying environmental conditions has not yet been thoroughly examined. Future research should focus on evaluating its resistance to sulphate attack, carbonation, and freeze-thaw cycles. Additionally, study should be carried out on how to control rapid hardening of BYF cement in low strength application.

Secondly, a detailed economic feasibility assessment is necessary to complement the technical findings of this study. While the environmental advantages of BYF cement are widely acknowledged, its market viability depends on a comprehensive cost-benefit analysis. Future work should evaluate the relative costs of raw materials and manufacturing processes, in addition to performance benefits compared to Portland cement. Additionally, lifecycle assessments that quantify environmental savings could provide strong evidence to support the material’s broader commercial adoption.

In addition to economic considerations, field trials and real-world implementation are essential to validate the laboratory findings under practical conditions. This study’s results were derived from controlled environments, which may not capture the complexities encountered on construction sites. Applying BYF cement in full-scale sustainable sandcrete block production, for instance, would allow researchers to identify logistical, climatic, and material handling challenges, while also offering opportunities to refine mix designs and construction practices for field use.

Lastly, another important avenue for further study involves refining and standardizing the modified testing protocols introduced in this research. Although the adaptations made to the SS EN 196-1:2016 procedure such as bulk density anchoring and strength development proved effective, broader validation is needed to ensure reliability across different contexts and laboratories. Testing standards should provide procedures for testing the strength of rapid hardening cements. It should be further calibrated to reflect the unique characteristics of sandcrete block production, which typically involves lower cement content and higher water-to-cement ratios than standard mortars.

In conclusion, this research has laid a strong foundation for the use of BYF cement in sustainable construction. However, addressing the outlined areas, ranging from long-term durability and cost analysis to field validation and methodological refinement will be crucial for facilitating the material’s transition from experimental validation to widespread practical application.

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