CHALMERS
UNIVERSITY OF TECHNOLOGY



Assessing Cement Sustainability in Sandcrete Block Production

Process Variability and Substitution Potential in Kyaka, Tanzania

Degree project report in Industrial Ecology, Department of Environmental and Energy Sciences

Sara Nanetti

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

Degree project report 2026

Assessing Cement Sustainability in Sandcrete Block Production

Process Variability and Substitution Potential in Kyaka, Tanzania

Sara Nanetti



CHALMERS
UNIVERSITY OF TECHNOLOGY

Department of Architecture and Civil Engineering
Chalmers University of Technology
Gothenburg, Sweden 2026

Assessing Cement Sustainability in Sandcrete Block Production
Process Variability and Substitution Potential in Kyaka, Tanzania
Sara Nanetti

© Sara Nanetti, 2026.

Supervisor: Raine Isaksson, Uppsala University, Luleå University of Technology
Examiner: Arezou Baba Ahmadi, Chalmers University of Technology

Degree project report 2026
Department of Architecture and Civil Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 31 772 1000

Cover: Sandcrete blocks produced at the case-study site in Kyaka, Kagera Region, Tanzania.

Gothenburg, Sweden 2026

Assessing Cement Sustainability in Sandcrete Block Production
Process Variability and Substitution Potential in Kyaka, Tanzania
Sara Nanetti
Department of Architecture and Civil Engineering
Chalmers University of Technology

Abstract

Construction demand is growing rapidly in Sub-Saharan Africa, where locally produced sandcrete blocks are widely used for affordable housing. Portland cement is both their most expensive ingredient and their main source of embodied emissions, so producers tend to use very lean mixes. However, the water needed for workability and variable field practices can reduce cement efficiency and make block strength unreliable. This creates a difficult balance between affordability, environmental impact, and adequate performance, while also limiting the direct transfer of laboratory findings to local production.

This thesis examines these challenges through a field-based case study of a sandcrete-block producer near Kyaka, Tanzania. Using the Diagnosing–Analysing–Solving structure of the Sustainability Opportunity Study, observations, interviews, and sampling were used to assess current performance, identify likely causes of variability, and explore realistic improvements. A literature-based scenario also considers partial replacement of Portland cement with calcined clay from the region.

Although block weight and dimensions were relatively consistent, compressive strength varied substantially and appeared low in relation to commonly reported residential-block benchmarks. Inconsistent water addition, operator-dependent compaction, and limited measurement were identified as the most plausible and actionable contributors. Better process control could improve the reliability and efficiency of cement use, but high water demand limits what these measures can achieve. Reduced variability cannot safely be converted into cement savings until an appropriate target strength is established and the response of the lean mix to lower cement content is tested.

The immediate priority is therefore to stabilise production through measured, moisture-adjusted water dosing, calibrated compaction, and routine quality checks. Calcined clay represents a complementary longer-term opportunity, but requires trials and a net economic and environmental assessment under the producer's actual conditions. Overall, a stable baseline must precede responsible cement reduction or material substitution.

Keywords: *sandcrete blocks, cement productivity, Sustainability Opportunity Study, process variability, calcined clay, Tanzania, Sub-Saharan Africa.*

Acknowledgements

I am so happy to finally have the chance to officially acknowledge all of the adventures, life lessons, and people that were part of the amazing journey that studying in Sweden, and this thesis, enabled. It was my first time living abroad and experiencing life by myself, leaving behind what I knew as daily life and comfort, and it gave me so much happiness and fulfilment. This chapter is now closing, and I am so glad I have it all in my heart. It is thanks to the people who shared this journey with me that my life fully changed into something incredible, in which boundaries have become something I can keep challenging, pushing myself even further to discover the world and myself. I never knew I could be doing all of this, and I love it.

I grew up a lot throughout this journey, and it was definitely not just thanks to me and my willpower. There were many times when this experience got on my nerves and I needed to reset myself, my expectations, and my attitude towards everything outside of my room. There were moments when I thought I could not make it, that I was not good enough, or simply felt lost.

All of the people mentioned below had a part, small or big, in giving me a sense of safety and reminding me that I was actually on my way towards incredible discoveries of the world and of myself.

I think I will have to go chronologically not to forget anybody. My heart and my head are so full of thank-yous that it is difficult to put them in order.

Before Tanzania, this experience had already taken me through so many places and people. For my time in Sweden, a big thank you to the best boys ever, Pit, Carlito and Luca for our questionable inside jokes, to Cesar for teaching me how to dance, and to Joaquin, Avijah, the Italians and to everyone who made Gothenburg feel like a home. Thank you to the kitchen just above the permafrost in Svalbard, where I made friends for life.

And then, I flew to Tanzania, which was a whole adventure by itself. First and foremost, thank you to my supervisor, Raine, for giving me the chance to join the project which shaped the incredible journey across Tanzania that I loved so dearly. Thank you for the support, the contacts, and the reassurance you provided throughout the entire process. A special thank you also goes to my examiner, Arezou, who believed in this project even when I started doubting it, and helped me reset my perspective and turn my vision into something achievable.

I truly want to thank all the people who became part of my life in Tanzania: the ones I met only briefly along the way and whose paths have already parted from mine, the ones who stayed and whom I hope to carry with me and meet again, and everyone who, in one way or another, found a little place in my heart.

Thank you, Joseph, for welcoming me upon my arrival in Dar es Salaam and for being a safe presence throughout the first weeks of my stay. I am so glad I could count on you. A special mention also goes to your family, who hosted me so warmly when was left stranded in Dar in the middle of the night. And thank you to all the people who were part of those heart-warming random encounters in Dar es Salaam.

Thank you to the Tumaini Open School in Tabora and all the people that I met there, my Swedish friends, all the students, and the staff who welcomed me so warmly and made me feel as though I was living in a little oasis.

And then came my time in Bukoba. What can I say about that? I found a new family who gave me warmth, a feeling of home, and taught me so much about living a life made of simple and beautiful things. The warmest hugs to Erasto, Ruth, Felista, and Faustina. Thank you Swalhinah for being a precious friend out there in the middle of that nowhere where the production plant was, and for taking me to see the Kagera/Nile river. I wish you the chance to explore the world, see the Alps, and find your true passion. And thank you to all the other amazing guys at the plant for being so joyful and genuine. Thank you also to the vendors at the market for always giving me big smiles and some extra mangoes whenever I managed to phrase even the most basic needs in Swahili. That is where I slowly started to feel a little more like a *dada* than a *mzungu*. Thank you green forests, endless banana fields, and to the longest, most overcrowded and uncomfortable bus rides with no internet connection, for giving me the time to breathe, be with myself, and sort out my thoughts.
And then, all of a sudden, I was in Moshi, under the majestic Kilimanjaro, living with Victoria, Kibo, Fox, Piccolino, and all the chickens. Thank you for giving me a home, friendship, endless talks, adventures, and nights out. I had missed that. And thank you to all the kids at the kindergarten, so full of joy, amazing artists, and great desk and leg climbers. While in Moshi and Arusha, I saw some of the wildest and most beautiful parts of Tanzania. I climbed a mountain in the jungle with only my guide Ally, and I saw lions, elephants, giraffes, leopards, thousands of zebras, and everything else that fits in there. The smell of the Serengeti plains is printed into my soul. Thank you to the many friends from all the bits of my life that helped make that possible.
Thank you too, Zanzibar, for making me understand even more clearly why I had loved discovering this country through its details, and why I want to keep doing the same wherever I go next.
And of course, thank you to all the people who were home waiting for me and who were part of this journey nonetheless. Thank you to my family for the support, and to my friends for always reminding me of home and making me feel their presence whenever I felt lonely in this huge world.
And a last, very special thank you to my Svea, who tied me with love and, at the same time, gave me wings to reach for everything I want and more. The sun to my rainy Tanzanian days — next time, you really should come. Thank you Svea for our time in Sweden, Germany, Italy, Austria, Switzerland, Mexico, Svalbard, the States, and everything that's coming, which is a lot. You have been there for every single step and saw me changing into a more fearless version of myself. You also saw me fighting for it, being crushed at times, complain a lot, and somehow getting back up again, and you always reminded me why I was where I was. I know this is only the beginning of a very adventurous and bright life.
Asante sana na tuonane hivi karibuni, Tanzania.

Sara Nanetti, Porto Valtravaglia (VA), Italy, August 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BLEX	Block Excellency
BYF	Belite-Ye'elimite-Ferrite
CC	Calcined Clay
CV	Coefficient of Variation
DAS	Diagnosing-Analysing-Solving
PC	Portland Cement
Q4S	Quality for Sustainability
RoCE2	Roman Cement 2.0
SCM	Supplementary Cementitious Material
SF	Safety Factor
SOS	Sustainability Opportunity Study
SSA	Sub-Saharan Africa
TQM	Total Quality Management
TSh	Tanzanian Shillings
UDM	Understanding-Defining-Measuring
w/c	water-to-cement

Contents

List of Acronyms **x**

List of Figures **xv**

List of Tables **xvii**

1 Introduction **1**
1.1 Context . . . 1
1.2 Problem Description . . . 2
1.3 BLEX and the Case Study . . . 3
1.4 Purpose and Research Questions . . . 3
1.5 Scope and Delimitations . . . 4

2 Theoretical background **5**
2.1 The Leading Frameworks . . . 5
2.1.1 Quality for Sustainability . . . 5
2.1.2 Sustainability Opportunity Study . . . 5
2.2 Sandcrete Blocks and Small-Scale Production . . . 7
2.3 Assessing Block Performance . . . 7
2.3.1 Compressive Strength as a Performance Indicator . . . 7
2.3.2 Standards and Performance Benchmarks . . . 8
2.3.3 Variability in the Production Process . . . 9
2.3.4 Density as a Strength Development Indicator . . . 9
2.4 The Low-Cement Problem: Strength Loss and Cement Inefficiency . . . 10
2.4.1 Cement as a Technical, Economic and Environmental Variable 10
2.4.2 The Compaction Dilemma . . . 10
2.4.3 Cement Productivity . . . 11
2.4.4 Variability and Compensatory Cement Use . . . 11
2.5 Reducing Portland-Cement Use . . . 11
2.5.1 Improving the Existing Process . . . 12
2.5.2 Supplementary Cementitious Materials . . . 12
2.6 Calcined Clay as a Supplementary Cementitious Material . . . 13
2.6.1 Calcination and Pozzolanic Behaviour . . . 13
2.6.2 Benefits and Implementation Requirements . . . 13
2.6.3 Evidence from the Bukoba Region . . . 14

3 Methodology **16**

3.1 Research Approach . . . 16
3.2 Case Study Selection . . . 16
3.3 Data Collection . . . 17
3.3.1 Non-participant Observation . . . 17
3.3.2 Unstructured Interviews . . . 18
3.3.3 Material and Block Sampling . . . 18
3.3.4 Secondary Data . . . 18
3.4 Field Measurement Procedures . . . 19
3.4.1 Sand Moisture Content . . . 19
3.4.2 Hardened Block Density . . . 19
3.4.3 Compressive Strength Testing . . . 20
3.5 Data Analysis and Calculations . . . 21
3.5.1 Current Production Characterisation . . . 21
3.5.2 Statistical Analysis . . . 21
3.5.3 Density–Strength Relationship . . . 21
3.5.4 Lower-Bound Compressive Strength . . . 22
3.5.5 Safety Factor . . . 22
3.5.6 Variability-Adjusted Cement Productivity . . . 22
3.5.7 Reduced-Variability Scenario . . . 23
3.5.8 Indicative Cement Reduction . . . 23
3.5.9 Functional Scaling . . . 24
3.5.10 Relative Cost and Emissions Calculation . . . 24
3.6 Cause Analysis: Application of the 10M Model . . . 25
3.7 Solution Screening Approach . . . 25
3.8 Indicative Calcined-Clay Substitution Potential . . . 25
3.9 Methodological Uncertainty . . . 27
3.10 Ethical Considerations and AI use . . . 27

4 Results **29**
4.1 Current Production . . . 29
4.1.1 Physical and Mechanical Properties . . . 32
4.1.2 Correlation Between Bulk density and Compressive Strength . 33
4.1.3 Strength by Production Batch . . . 33
4.1.4 Lower-Bound Compressive Strength . . . 34
4.1.5 Safety Factor . . . 34
4.2 Improvement Potential . . . 35
4.2.1 Variability-Adjusted Cement Productivity . . . 35
4.2.2 Potential from Reduced Variability . . . 35
4.2.3 Indicative Cement Reduction per Block . . . 35
4.2.4 Functional Scaling and Impact Assessment . . . 36
4.3 Analysis of possible causes . . . 37
4.4 Third step of SOS study: Solving . . . 38
4.4.1 Immediate Process Improvements . . . 39
4.4.2 Indicative Calcined-Clay Substitution Scenario . . . 39

5 Analysis **41**
5.1 Diagnosis of current production and improvement potential . . . 41

5.2 Analysis of causes for the improvement potential 42
5.3 Solution to the diagnosed potential 44
5.3.1 Variability-adjusted scenario 44
5.3.2 Calcined Clay substitution scenario 44
5.3.3 Comparing the Improvement Pathways 45

6 Discussion **47**
6.1 Reflection on Quality in this study 47
6.1.1 The role of compressive strength and variability 47
6.2 Limits of the current system 49
6.2.1 Weaker modelling assumptions in lean mixes 49
6.3 Calcined Clay as substitution material 50
6.3.1 Contextual limitations to calcined clay introduction 51

7 Final remarks **53**
7.1 Conclusions 53
7.2 Implications for Future Research 54

Bibliography **57**

A Supplementary Data and Material **I**
A.1 The 10M Checklist I
A.2 Block Weight, Dimensions and Density Data I
A.2.1 Block Dimensions II
A.2.2 Block Weight, Bulk Density and Strength Test Results II

List of Figures

2.1 Calcined Bukoba clay after cooling (Malisa, 2024). 14

3.1 Left: the Kagera Region in its national context within Tanzania. Right: the location of the case-study block-production plant and the investigated clay deposit, approximately 36 km apart by road. 17
3.2 Blocks nomenclature and storing on site before testing. 18
3.3 Sand drying in direct sunlight to estimate moisture content. 19
3.4 Compressive-strength testing of a 5-inch block at the TANROADS laboratory. 20
3.5 Clay layer at the investigated deposit in the Kagera Region, Tanzania. 26

4.1 Sand storage outside of the production facility. 30
4.2 Detail of the mixer used in the production process. 31
4.3 Vibrating machine used in the production process. 31
4.4 Blocks location during drying and curing phase. 32
4.5 Correlation between Bulk density and Strength of blocks aged 21 days from different mixes 33
4.6 Compressive strength at 21 days for batches 4 and 6, the only batches with at least 5 tested blocks 34

5.1 After demoulding, part of the mix often sticks to the mould surfaces (left) or get a bloated shape due to structural collapse (right) 42
5.2 (Left) Blocks with visible cracks are fixed for sale. (Center and Right) Blocks still show frail edges and surfaces 43
5.3 Cement consumption, cement-related cost and cement-related CO_2 emissions per m^2 of wall for current production, the variability-adjusted scenario and the calcined-clay scenario. Hatched bars below zero show the reduction relative to current production. 45

6.1 Local kiln for burned bricks manufacturing 51

List of Tables

2.1 The Sustainability Opportunity Study matrix combining Diagnosing-Analysing-Solving (DAS) and Understanding-Defining-Measuring (UDM). 6

4.1 Mix raw quantities for 5-inch sandcrete blocks 29
4.2 Summary statistics for block weight, bulk density ($n = 30$) and 21-day compressive strength ($n = 17$) 32
4.3 Indicative cement-related cost and emissions for current and improved production scenarios and saving potential, for 1 block, 1 square meter of wall and yearly in Tanzania 37
4.4 10M analysis: observations on possible causes for the identified improvement potential 37
4.5 Proposed immediate process improvements 39
4.6 Indicative cement-related effects of the calcined-clay scenario, for 1 block, 1 square meter of wall and yearly in Tanzania 40

A.1 Description of the 10M checklist categories I
A.2 Individual dimension measurements for the six representative blocks (batch 7) II
A.3 Block weight, bulk density and, where available, strength-test results, by batch (n=30) II

1

Introduction

1.1 Context

The buildings and construction sector is a major contributor to climate change. Its emissions arise across the full value chain, including material production, construction, building operation, and end-of-life processes (UNEP, 2024). Cement deserves particular attention because its production is highly emission-intensive and accounts for an estimated 5–8% of global CO_2 emissions (Chen et al., 2022).

The future development of the cement industry is closely connected to Sub-Saharan Africa (SSA), where rapid population growth, urbanisation, and increasing housing demand are expected to cause a substantial expansion of construction activity across the region (Isaksson et al., 2023a). Specifically, the population is expected to almost double by 2050 and raise its urbanisation level from 45% to 60% (United Nations, 2024, 2025). Although current cement consumption per person remains relatively low, future regional demand could represent a significant share of global cement production (Isaksson and Buregyeya, 2024).

However, the conditions surrounding construction in SSA differ fundamentally from those in the Global North. Housing is a basic social need, and measures intended to reduce emissions cannot be separated from affordability and accessibility (The Lancet Public Health, 2025; Isaksson et al., 2023a). In this context, a sustainable solution must, at minimum, support both economic affordability and climate neutrality (Isaksson et al., 2023a).

Cement is central to both concerns. It is the main source of embodied emissions in common cement-based products and is also their most expensive ingredient (Isaksson et al., 2023a). In many SSA countries, a single 50 kg bag of cement costs more than a low-income worker's daily wage (Isaksson and Babatunde, 2019). Improving how effectively cement is used could therefore reduce both the environmental impact and the cost of residential construction.

A large share of housing construction in SSA relies on locally produced sand-concrete, *sandcrete*, blocks. These blocks are generally made from sand, Portland Cement (PC), and water, which are mixed, compacted into moulds, cured, and dried. The process commonly takes place in small-scale production units using local unskilled or semi-skilled labour and relatively simple equipment (Isaksson et al., 2023a). Common products include 5- and 6-inch blocks, although dimensions and preferences vary between locations (Isaksson and Buregyeya, 2024).

Block-based construction is particularly suited to incremental housing development, where low-income households construct their homes gradually as financial resources

become available and blocks can be produced locally and purchased in limited quantities (Tusting et al., 2019). Their affordability and compatibility with this building process make them especially important for residential construction in the region.

1.2 Problem Description

Several strategies have been studied to reduce cement-related emissions. These include improving material efficiency and partially replacing PC with Supplementary Cementitious Materials (SCMs), such as volcanic ash, calcined clay, limestone, and processed agricultural residues (Isaksson et al., 2023a). Alternative binder systems, such as Belite-Ye'elimite-Ferrite (BYF) cement and Roman Cement 2.0 (RoCE2), have also shown potential to reduce clinker demand and associated emissions (Ilesanmi, 2025; Isaksson et al., 2026).

However, most research on cement substitution has focused on standard concrete, mortar, or laboratory specimens rather than on sandcrete blocks produced under actual field conditions (Isaksson et al., 2023a, 2026; Malisa, 2024; Ilesanmi, 2025). Laboratory studies can demonstrate the technical potential of a material, but they do not necessarily represent production environments characterised by variable raw materials, manual batching, inconsistent compaction, limited curing control, and strong pressure to minimise costs. Furthermore, current testing commonly uses binder contents considerably higher than the approximately 5–7% cement dosages found in actual low-strength block production (Isaksson et al., 2023a).

This difference is particularly important because low-cement sandcrete production already operates under a known technical constraint. The water required to obtain sufficient workability and compaction can result in high water-to-cement (w/c) ratios and low cement productivity, meaning that a substantial part of the potential strength contribution of cement is not realised (Isaksson and Babatunde, 2019; Isaksson and Buregyeya, 2024). At the same time, simply increasing cement content conflicts with the affordability requirements of the market.

This creates two related improvement questions. The first concerns how efficiently and consistently the existing production process uses cement; the second concerns whether part of the PC demand could eventually be avoided through a suitable alternative material. Before the latter can be meaningfully assessed, the current production process and the causes of its variation need to be understood.

Existing studies indicate that local block production can involve substantial variation in strength and cement efficiency (Isaksson and Babatunde, 2019; Bogren, 2024; Isaksson et al., 2023a). Since producers already minimise cement use because of its high cost, changes in batching, water content, compaction, and curing can strongly affect the final product. Evaluating current performance therefore requires considering not only average compressive strength, but also the variability of that strength and the amount of reliable performance obtained from the cement used (Isaksson and Buregyeya, 2024).

Understanding present performance is consequently a prerequisite for identifying realistic improvement opportunities. In this study, the Sustainability Opportunity Study (SOS) logic of Diagnosing–Analysing–Solving is used to structure this progression: first quantifying the improvement potential, then examining its possible

causes, and finally identifying feasible responses. The causal analysis is guided by the 10M model to structure the technical, operational, and contextual factors that may contribute to the observed performance.
What remains limited in the literature is detailed, field-based evidence that links actual production practices in SSA to quantified performance variability, cement efficiency, and realistic improvement options. Such evidence is needed both to identify measures that can improve the current process and to provide a credible baseline against which future material-substitution scenarios can be assessed (Isaksson et al., 2023a; Isaksson and Babatunde, 2019).

1.3 BLEX and the Case Study

This study is conducted within the broader Block Excellency (BLEX) project, which examines how current block-production performance can be improved and how alternative binders may contribute to more sustainable block production in SSA (Isaksson, 2026). The project focuses on Tanzania through case-study-based research in areas with different economic, environmental, and social conditions.
The present study focuses on a local producer located in Kyaka, Kagera Region, in northwestern Tanzania. The facility produces 5- and 6-inch cement-based blocks, as well as other cement-based products, and operates with more advanced equipment and at a larger scale than many small local producers (Isaksson, 2026).
Located in the same region, clay resources with potential for use as SCMs in block production have previously been investigated by Malisa (2024). Calcined Clay (CC) is therefore considered as the material-specific future option in this case study, while other possible SCMs are outside its scope.
The producer is used as a case study and practical testbed for examining block production under actual operating conditions. The purpose of the case is not to represent every producer in Tanzania, but to provide detailed insight into how materials are used, how consistently the process performs, what causes may explain the observed improvement potential, and which responses are realistic under the existing production conditions.

1.4 Purpose and Research Questions

The purpose of this research is to assess opportunities to improve current block production and to explore the potential of partial CC substitution. Current performance and improvement potential are evaluated through compressive-strength variability, cement use, cost, and CO_2 emissions.
This analysis will be carried out through the following research questions:
RQ1. What is the improvement potential in terms of quality, cost and CO_2 emissions in current block production?
RQ2. What are the main causes for the identified improvement potential?
RQ3. Which solutions could address the identified improvement potential? RQ3 is addressed by combining the results from RQ3a and RQ3b.

RQ3a. Which immediate process improvements could reduce the variability of current production?
RQ3b. What indicative potential does partial substitution of Portland cement with calcined clay offer for reducing cement demand, cost, and CO_2 emissions?

1.5 Scope and Delimitations

The study is delimited to a single block producer near Kyaka, Tanzania, examined as an exploratory case study rather than as a statistically representative sample of production in Tanzania or across SSA (the rationale for this choice is set out in section 3.2). The detailed product scope is 5-inch residential blocks, the product manufactured consistently at the case-study facility; the study is delimited to this product, and findings are not assumed to transfer directly to other block sizes, geometries, production systems, structural concrete, or industrial cement production. The technical assessment uses compressive strength as the main indicator of block performance, considered in relation to factors that could be directly observed or measured on site: mix proportions, block weight and density, and consistency in production and test results. Other performance indicators, such as water absorption, durability, dimensional stability, thermal performance, and weather resistance, are outside the analytical scope.
The economic and environmental assessment is delimited to cement-related cost and CO_2 emissions under defined assumptions. It does not constitute a full business case, life-cycle assessment, supply-chain analysis, or assessment of market acceptance, regulation, training, or investment needs.
The material scope is delimited to calcined clay as the material-specific future SCM considered, following clay resources previously identified in the same region (Malisa, 2024); other locally available SCMs and alternative binder systems fall outside this scope. Consistent with this indicative purpose, the calcined-clay pathway is treated as a modelling scenario informed by prior research rather than experimentally validated within this study, and the producer's implementation readiness is discussed only as a secondary point, based mainly on indicative cost and CO_2-reduction potential.
Overall, the study is delimited to an exploratory, field-based assessment of current production performance and its improvement potential, with calcined-clay substitution considered as a possible future development aligned with the broader aim of reducing Portland-cement use.

2
Theoretical background

2.1 The Leading Frameworks

2.1.1 Quality for Sustainability

Quality for Sustainability (Q4S) extends Total Quality Management (TQM) from a primary focus on customers to the needs of the wider system and its stakeholders. It is based on the idea that an effective process should do the *right thing* in the *right way* over time. While traditional quality management has mainly focused on improving how activities are performed, Q4S first requires an understanding of which outputs and impacts should be improved. Quality and sustainability are therefore treated as levels of system performance, while quality improvement and sustainable development describe the processes through which that performance changes (Isaksson et al., 2025).
Identifying the "right thing" requires defining the system, its purpose, its main stakeholders, and the value and harm generated through its processes. The framework recommends focusing on the vital few impacts rather than attempting to measure every possible sustainability issue. Performance can then be expressed through indicators that relate stakeholder value to harm, where harm may include effects on both People and Planet. Once the relevant output has been understood and defined, established quality-management principles and tools can support "doing the thing right" through process control and improvement (Isaksson et al., 2025). In the specific context of small-scale block production, Isaksson and Babatunde (2019) propose the following vital sustainability impacts: the provision of functional and affordable building blocks as the main People value, material cost as the main People harm, and cement-related CO_2 emissions as the main Planet harm.
Because the customer's functional need is a wall rather than an individual block, value and harm are often more meaningfully compared once block-level performance has been translated into a unit of wall area (Isaksson and Buregyeya, 2024).

2.1.2 Sustainability Opportunity Study

An Opportunity Study is a process-based approach for identifying an improvement opportunity through the three stages of DAS. Diagnosing assesses the improvement potential by comparing current performance with a target, benchmark, or best assessed performance. Analysing investigates the causes of the identified performance gap, while Solving develops feasible responses through which the opportunity could be realised. An opportunity is therefore present when a relevant improvement po-

tential can be identified, its main causes can be reasonably explained, and workable solutions can be proposed (Isaksson, 2015).

A SOS extends the Opportunity Study to situations where the relevant sustainability output or performance indicator is not yet clearly understood or agreed upon. In this situation, the DAS sequence is combined with the first three stages of UDM (Isaksson et al., 2023b). Understanding establishes the scope, purpose, stakeholders, processes, and main sustainability impacts of the system. Defining converts this understanding into a description of sustainability, the desired performance, and the most important causes or solutions. Measuring then identifies suitable indicators for current performance, improvement potential, causes, and proposed change. Combining these stages with the DAS logic gives the theoretical matrix presented in Table 2.1 (Isaksson, 2015; Isaksson et al., 2023b).

Table 2.1: The Sustainability Opportunity Study matrix combining DAS and UDM.

	Understanding	**Defining**	**Measuring**
Diagnosing	Identify the system and its vital sustainability impacts.	Define sustainability and the relevant performance gap.	Identify performance indicators and quantify current performance and improvement potential.
Analysing	Identify the main factors and resources that may explain the performance gap.	Define and prioritise the main causes.	Assess indicators or evidence describing the causes and their relationship with performance.
Solving	Identify possible responses to the main causes.	Define and prioritise feasible solutions.	Estimate the expected improvement and formulate proposed actions.

The Analysing stage can be supported by the Process-Based System Model, which connects system outputs to the activities and resources that produce them. Its 10M checklist includes *Mission, Management, Method, Manpower, Measurement, Machine, Material, Milieu, Market*, and *Means* (summarised in section A.1). These categories provide a structured basis for identifying possible technical, organisational, human, and contextual causes of variation or underperformance. They are intended as a comprehensive checklist rather than a requirement to give equal attention to every category (Isaksson, 2015).

Q4S and SOS can be used as complementary conceptual frameworks. Q4S supports the identification of the system purpose and the performance dimensions that matter, while SOS provides a structured logic for examining current performance, its possible causes, and potential improvement directions. The frameworks serve as guiding principles rather than prescriptive procedures that must be followed in full.

2.2 Sandcrete Blocks and Small-Scale Production

Sandcrete blocks are cement-based masonry units produced primarily from sand, PC, and water. Sand constitutes most of the block mass, while cement acts as the binder and water enables mixing, compaction, and cement hydration. The characteristics and moisture content of the sand influence the amount of water required and the compactability of the mixture (Isaksson and Babatunde, 2019; Isaksson et al., 2023a).
Isaksson et al. (2023a) summarizes how typical production looks like. It begins with batching the materials, commonly by volume or by counting containers rather than by weighing. Cement and sand are first mixed, after which water is added until the mixture is considered sufficiently workable. The mixture is then transferred into a mould and compacted by manual force, vibration, pressure, or a combination of these mechanisms.
The blocks must be low-slump to retain their geometry when removed from the mould. After demoulding, they are placed on a flat surface or production pallet, allowed to develop initial strength, and subsequently cured by regular water application for 14—21 days. Once curing is completed, the blocks are dried and stored until sale or use.
Compaction and curing are particularly important because the mixtures contain little cement and are relatively dry. Insufficient compaction leaves voids in the block, while inadequate curing restricts hydration and strength development.
Sandcrete blocks are often manufactured in decentralised, small-scale facilities located near their markets. Production commonly relies on labour-intensive equipment consisting of a mixer and a vibrating or compressing unit, while batching, material transport, demoulding, curing, and stacking are performed manually.
At the same time, production depends strongly on worker judgement, with visual estimations and lack of formal specifications. Differences in workers, raw materials, weather conditions, and equipment use can consequently generate substantial variation between batches and blocks (Isaksson and Babatunde, 2019; Isaksson et al., 2023a).
Formal process control is often limited. Mix proportions, block mass, curing conditions, and compressive strength may not be recorded systematically, making it difficult to determine whether changes in performance result from materials, methods, equipment, or human practices (Isaksson et al., 2012).

2.3 Assessing Block Performance

2.3.1 Compressive Strength as a Performance Indicator

Compressive strength expresses the maximum compressive stress sustained by a block before failure and is commonly used as the main indicator of technical performance. It is relevant because the blocks must resist loads during handling, transport, construction, and service, and because cement performance is generally classified and compared through strength development (Isaksson and Babatunde, 2019; Isaksson et al., 2023a).

In the value-per-harm framing, compressive strength can be treated as an indicator of the functional value produced by the block. A higher strength does not automatically mean that a product is more sustainable, because strength beyond the level required for its intended function may provide little additional user value while increasing cement consumption. The relevant objective is therefore to provide sufficient and reliable strength with the lowest reasonable cost and carbon footprint.

2.3.2 Standards and Performance Benchmarks

Standards provide reference values for material quality and support comparison between products. Values of approximately 2.2–3.5 MPa are reported as common minimum benchmarks for low-strength residential blocks in different countries (Isaksson et al., 2023a). For Tanzania specifically, the recently revised standard TZS 283:2025, which was updated from the 2002 version, requires an average strength of 4 MPa with no individual result below 3.2 MPa for load-bearing sandcrete blocks (Tanzania Bureau of Standards, 2025).

However, field studies in Tanzania and other parts of SSA have found that many locally produced blocks do not achieve the specified strength levels (Isaksson and Babatunde, 2019). In Dar es Salaam, Sabai et al. (2016) found that 41% of the tested blocks — primarily six inches wide — had compressive strengths below 3 MPa, with a mean of 3.3 MPa and with results ranging from 1.0 to 6.2 MPa. Comparable non-compliance to standards and variability has been reported elsewhere in SSA: Lumor et al. (2021) reported supplier averages that ranged between 1.94 MPa and 4.31 MPa for solid blocks in Ghana. Nigerian studies similarly report commercial block strengths commonly around 0.28-0.95 MPa and non-compliance with national requirements (Afolayan et al., 2008; Awolusi et al., 2015).

This mismatch creates a tension between formal requirements, current production performance, and what is functionally necessary for low-rise residential construction specifically. Previous work has consequently questioned whether standards developed for different construction conditions always define an appropriate minimum strength for simple residential buildings in SSA (Isaksson and Buregyeya, 2024).

Whether this requirement is a real constraint on production is itself debated. Isaksson and Buregyeya (2024) argue that an appropriate lowest acceptable strength for low-rise residential blocks in Tanzania has, in effect, never been properly established: low-cement blocks may already provide sufficient functional quality for simple residential use even where they do not meet the current strength benchmarks. Sabai et al. (2016) reports that even the worst performing 6-inch blocks were still able to support a single-storey wall with a lightweight roof, by calculating a Safety Factor (SF) as the ratio between the measured compressive strength and the estimated vertical stress on the ground-level blocks. The resulting SF values ranged from 4 to 70, indicating that even the weakest blocks were still substantially stronger than the expected working load. This methodology will be further explored and adapted to the current case study in Section 3.5.5.

2.3.3 Variability in the Production Process

Mean strength alone does not fully describe production quality. High variation, often shown through the Coefficient of Variation (CV) value, indicates limited process control and increases the probability that individual products fall below the required performance. Studies of sandcrete production in Dar es Salaam have reported coefficients of variation approaching 40% (Isaksson and Babatunde, 2019), while assessments of a wider sample of Tanzanian producers indicate that typical production varies around 20%, with the best-performing producers achieving values below 10% (Isaksson and Buregyeya, 2024). In other parts of SSA, reported coefficients of variation can even reach values 50% (Awolusi et al., 2015).
High variability in block strength performance is especially relevant for masonry because the weakest blocks can restrict the reliability of the finished wall: additional strength in the strongest blocks does not compensate directly for individual units that fail under lower loads. Reducing variation can improve the lower end of the strength distribution without necessarily increasing the average cement dosage. Strength variation should therefore be considered together with average performance when evaluating the value produced by the process (Isaksson and Buregyeya, 2024). Still, such variation may reflect different inconsistencies along the production and testing process, making it difficult to target and improve specific steps when addressing it.

2.3.4 Density as a Strength Development Indicator

Compressive strength is produced through the interaction of several material and process factors. These include cement content, water content and the w/c ratio, sand grading and moisture, mix homogeneity, compaction, curing conditions, block age at testing, handling and storage, equipment performance, and worker practices (Isaksson and Babatunde, 2019; Isaksson et al., 2023a). No single observable variable can therefore explain all variation in strength.
When blocks have a consistent geometry, block mass provides a simplified indicator of the amount of material placed in the mould and, through bulk density, of the degree of compaction achieved. Better-compacted mixtures generally contain fewer air voids and can develop higher strength. In an early field study of sandcrete production in Dar es Salaam, density accounted for around 60% of the variation in a combined strength-and-yield indicator, explaining a relevant portion of the variability (Isaksson et al., 2012). Field-based experimental work on comparable low-cement block production has likewise found that higher bulk density is associated with increased compressive strength, but that a reliable strength-prediction model needs to combine density with cement and water content rather than relying on density alone (Bogren, 2024). Density should therefore be treated as a proxy for strength and process consistency rather than as a replacement for compressive-strength testing.
Despite the fact that blocks with similar density can have different strengths due to other factors such as cement dosage and curing conditions, density remains attractive for routine control because mass and dimensions are far cheaper and faster to measure than compressive strength, provided that the relationship has first been cal-

ibrated for the relevant block geometry, materials, machine, and production method (Bogren, 2024).

2.4 The Low-Cement Problem: Strength Loss and Cement Inefficiency

2.4.1 Cement as a Technical, Economic and Environmental Variable

PC is the binding component in sandcrete. When cement is mixed with water, hydration reactions form products that bind the sand particles into a hardened matrix and allow the block to develop strength over time. The performance obtained from cement nevertheless depends on the proportions of the mixture and on how effectively it is mixed, compacted, and cured (Neville, 2011).
Cement is also the most expensive constituent of typical sandcrete blocks. A 50 kg bag may cost more than one day of income for many customers in low-income contexts, while the other principal materials are generally available locally at considerably lower cost (Isaksson and Babatunde, 2019). In simple block production, cement can account for a substantial share of the material cost and therefore strongly influence both the producer's decisions and the final price of the product (Isaksson and Buregyeya, 2024; Isaksson et al., 2023a).
Locally conduced studies show that the amount of cement used has been rapidly decreasing over time, from around 5-7% of the mix mass (Isaksson and Buregyeya, 2024), to about 4% or less in the most recent studies conducted undert the BLEX project.
From an environmental perspective, cement causes most of the embodied CO_2 emissions of the block. These emissions arise primarily from the production of clinker, including fuel use and the release of CO_2 during limestone calcination (Isaksson et al., 2023a). Cement use is therefore central to three interdependent dimensions: it provides binding capacity and strength, but it also drives material cost and carbon emissions.

2.4.2 The Compaction Dilemma

Conventional cement theory associates lower w/c ratios (about 0.5) with higher strength, provided that the mixture can be fully compacted. Sandcrete production creates a specific problem because the sand matrix may require approximately 7–10% water by total mass to become sufficiently workable and compactable. When cement content is only about 5%, this can produce w/c ratios of approximately 1.5–2.0 (Isaksson and Babatunde, 2019).
Reducing water would lower the w/c ratio but may also make the mixture too dry to compact with available equipment. Insufficient compaction leaves air voids and can reduce strength more than the lower w/c ratio improves it. Increasing water initially improves workability and density, but once adequate compaction has been reached, additional water increases porosity and reduces the potential hardened strength.

This interaction constitutes the compaction dilemma. A low cement dosage is chosen to reduce immediate cost, but the quantity of water required by the sand and the available compaction method prevents the cement from developing its full binding capacity. Estimates for common sandcrete mixtures indicate that approximately 70–85% of the theoretical strength potential of the cement may be lost, leaving only around 15–30% effectively utilised (Isaksson and Babatunde, 2019).

2.4.3 Cement Productivity

Cement productivity describes the useful performance produced per unit of cement, expressed as compressive strength relative to the cement content of the mix: the higher the value, the more effectively a given amount of cement is being converted into functional strength (Isaksson and Babatunde, 2019). The measure allows blocks with different strength and cement dosages to be compared on this basis, independently of the absolute cement quantity used.
Sandcrete blocks produced with approximately 5% cement and high w/c ratios have been estimated to achieve less than 30% of a reference cement-productivity level derived from conventional mortar or concrete (Isaksson and Babatunde, 2019; Isaksson and Buregyeya, 2024; Isaksson et al., 2026).
The principal value of the cement productivity measure is to indicate the magnitude of the potential loss rather than to demonstrate that full benchmark productivity can be achieved directly in small-scale sandcrete production (Ilesanmi, 2025).

2.4.4 Variability and Compensatory Cement Use

Variation reduces cement efficiency because the producer must consider not only average performance but also the weakest output. When production is inconsistent, adding more cement can be used as a safety margin so that a larger proportion of blocks reaches the desired strength. This approach can conceal weaknesses in batching, compaction, or curing rather than correcting them.
Alternatively, producers may retain the lower cement dosage and accept weak blocks, breakages, rejects, or variable customer performance. Both outcomes waste value: additional cement raises cost and emissions, while failed or unreliable products waste the materials and labour already used. Sustainable block production consequently depends not only on reducing cement content, but on obtaining sufficient and consistent functional performance from the cement used (Isaksson and Babatunde, 2019; Isaksson and Buregyeya, 2024).

2.5 Reducing Portland-Cement Use

Reducing the demand for PC in block production can be pursued along two broad and largely independent routes: improving how effectively the existing process converts the cement already used into strength, or replacing part of the cement itself with an alternative binder material (Isaksson and Babatunde, 2019; Isaksson et al., 2023a).

2.5.1 Improving the Existing Process

The first route is to improve the performance of the existing process, without requiring a new binder or a major change in the product and resource investment, while increasing the proportion of cement that contributes to useful strength (Isaksson and Babatunde, 2019).

Measurement is necessary to determine whether the process is stable and whether an intervention produces an improvement. Relevant field indicators include mix proportions, block mass, dimensions, density, curing time, compressive strength, and variation between blocks and batches. Simple measurements can be more useful than a complex quality-control system that cannot be maintained with the available skills and resources.

Bulk-density monitoring has been proposed as one such accessible, low-cost measure: weighing blocks at creation can help identify changes in compaction and mould filling ahead of periodic strength testing (Bogren, 2024). Because the density-strength relationship depends on the specific materials and process, such monitoring is best combined with, rather than substituted for, less frequent destructive strength tests.

2.5.2 Supplementary Cementitious Materials

SCMs are materials used to replace part of PC while contributing to binder performance. Examples relevant to SSA include calcined clays, volcanic materials, rice-husk ash, cassava-peel ash, and corn-cob ash (Isaksson et al., 2023a). Their use may reduce demand for imported or long-distance cement while creating value from local mineral or agricultural resources.

The performance of an SCM depends on its composition, processing, fineness, dosage, and interaction with PC. A material that performs well under controlled laboratory conditions may be difficult to use consistently where batching is manual, raw materials vary, and quality-control systems are limited. SCM implementation therefore requires attention to both material reactivity and production capability.

Regional assessments indicate that SCMs could reduce cost and CO_2 emissions from block production, although their availability and properties remain poorly mapped (Isaksson et al., 2023a). The achievable replacement level varies considerably between materials and binder systems and should not be assumed to be transferable between different clays, ashes, products, or production methods (Isaksson et al., 2023a, 2026). Beyond partial substitution within a portland-cement blend, alternative binder chemistries such as BYF cement and RoCE2 have also been explored as lower-clinker routes for block production (Ilesanmi, 2025; Isaksson et al., 2026), although these fall outside the material scope of the present study.

2.6 Calcined Clay as a Supplementary Cementitious Material

2.6.1 Calcination and Pozzolanic Behaviour

Clay minerals do not all possess the same suitability as cement substitutes. Kaolinite-rich clays are of particular interest because thermal treatment disrupts their ordered mineral structure through dehydroxylation, producing a largely disordered and substantially more reactive aluminosilicate phase commonly referred to as metakaolin; the activated clay can subsequently act as a pozzolanic supplementary cementitious material when combined with PC and water (Fernandez et al., 2011).
Calcination is generally carried out below clinker-production temperatures, with kaolinite activation typically occurring within approximately 600–900 °C (Sabir et al., 2001; Fernandez et al., 2011). Insufficient thermal treatment results in incomplete dehydroxylation and therefore limited reactivity, while excessive calcination can promote structural reorganisation and recrystallisation into more stable and less reactive phases, reducing the pozzolanic activity of the material (Fernandez et al., 2011).
The resulting metakaolin reacts pozzolanically with calcium hydroxide produced during Portland-cement hydration, contributing to the formation of additional cementitious hydrate phases and thereby influencing the development of strength and microstructure in blended cement systems (Sabir et al., 2001).
Clay suitability must be established rather than assumed from appearance or location alone. Mineralogical composition, kaolinite content, contaminants, particle size, calcination, and grinding all influence performance, so clay extraction and preparation must be treated as part of the binder-production system rather than as a simple raw-material input.

2.6.2 Benefits and Implementation Requirements

Replacing PC with calcined clay can reduce clinker demand and the associated process emissions. Where suitable clay is available locally, it may also reduce dependence on cement transported over long distances and retain a greater share of material value within the region (Isaksson et al., 2023a). The economic benefit nevertheless depends on the costs of extraction, drying, calcination, grinding, quality control, and transport.
Implementation requires a reliable material supply and a process capable of producing clay with sufficiently consistent mineralogy, thermal activation, and fineness. The calcined material must then be stored, proportioned, and mixed consistently at the block plant, which can be demanding in small-scale production where the existing cement–sand process is not yet stable.
Reported substitution rates for calcined-clay binder systems vary considerably with binder chemistry and total binder content. For blended systems combining PC, limestone, and calcined clay at total binder contents of 7–14%, indicative substitution levels of 60–100% relative to the cement reference have been reported, although testing at the approximately 5% binder content typical of common block production

is still needed (Isaksson et al., 2026).
The technical potential of calcined clay therefore does not by itself establish readiness for implementation. A producer must be able to control its current materials, mixing, water addition, compaction, curing, and testing before an additional variable can be introduced reliably. Field application also requires economic comparison and an assessment of whether the expected cement and CO_2 savings justify the added processing requirements.

2.6.3 Evidence from the Bukoba Region

Previous work has investigated kaolinitic clay from the Bukoba area, in the same Kagera Region as the present case study, as a partial cement replacement in sandcrete blocks (Malisa, 2024). Samples were taken from three soil layers spaced one metre apart, and the shallowest layer was selected for testing because it showed the highest kaolinite content. Suitability as a pozzolanic material is generally associated with a kaolinite content above approximately 40%; the selected Bukoba material was found to contain approximately 48%, exceeding this threshold (Malisa, 2024), as illustrated in Figure 2.1.



Figure 2.1: Calcined Bukoba clay after cooling (Malisa, 2024).

The clay was calcined, ground, and tested in mixes where PC was fixed at 50% of a 7%-cement reference mix, while calcined clay was added separately at 40%, 50%, or 60% of that same reference cement content – an asymmetric design in which the clay addition was not simply matched to the cement removed. The highest 28-day compressive strength, approximately 3.9 MPa and closely matching the pure-cement reference, was obtained at the highest clay addition (60%), where the resulting mix also contained more total binder than the reference; the lowest clay addition performed less consistently across curing ages (Malisa, 2024). The results indicate that clay from the broader study region can, at a sufficiently high dosage, contribute to strength levels relevant to low-strength residential blocks, although this was demonstrated at a cement content of 7%, well above the approximately 5% typical of local block production (Malisa, 2024).

These findings provide a basis for discussing calcined clay as a future opportunity in the Kyaka case. They do not demonstrate that all clays in the Kagera Region are suitable or that the same performance would be achieved under the producer's equipment and process conditions. Material sourcing, mineralogical verification, calcination, grinding, mix development, and full-scale block trials would still be required before implementation.

3
Methodology

3.1 Research Approach

This study applies the SOS through the Diagnosing–Analysing–Solving (DAS) logic. The framework is used as a guiding structure rather than as a prescriptive procedure followed in full, with each research question corresponding to one part of the DAS sequence (Isaksson et al., 2023a, 2024).
RQ1 is addressed through *Diagnosis*, which establishes current production performance and quantifies the improvement potential in terms of quality, cement use, cost and CO_2.
RQ2 corresponds to *Analysis*, where possible causes of the identified potential are interpreted through the 10M model.
RQ3 represents the *Solving* stage and combines two complementary questions. RQ3a considers immediate process improvements aimed at reducing current production variability, while RQ3b estimates the indicative potential of partial calcined-clay substitution in terms of cement demand, cost and CO_2.
RQ3b is treated as an independent scenario based on the observed production baseline and is not conditional on the successful implementation of RQ3a. The two parts therefore represent different improvement pathways: process control within the current system and a possible future change to the binder system.
The research is designed as an exploratory mixed-method case study. A case-study approach was selected because the production process is examined under actual technical, economic and organisational conditions over which the researcher has no direct control, and because detailed production records for small-scale blockmaking are limited (Yin, 2018; Isaksson et al., 2023a). Quantitative measurements support RQ1 and the scenario calculations in RQ3, while observations and interviews support the cause analysis in RQ2 and the contextual assessment of RQ3.

3.2 Case Study Selection

The case study focuses on a local producer near Kyaka in the Kagera Region of northwestern Tanzania, whose location within the country is shown in Figure 3.1. The facility produces 5- and 6-inch cement-based blocks and other cement-based products. As an established and comparatively well-equipped producer within the BLEX context, the facility provides a useful practical testbed for examining process variability and improvement opportunities under real operating conditions. Even though production conditions elsewhere may differ in economic context, worker

knowledge, equipment, raw materials, and resource availability, the findings are intended to support analytical transfer and hypothesis generation for comparable production settings rather than claims that the producer statistically represents Tanzania or SSA as a whole.
Moreover, the producer had already participated in the wider BLEX project, providing established access to the facility and prior knowledge of its operating status (Isaksson, 2026). These conditions allowed production to be observed repeatedly under normal operating conditions.
The site is also geographically distant from major cement-production hubs, making cement stand out as a particularly high-cost production input at the facility. Together, these conditions provide an economic reason to investigate more efficient Portland-cement use and possible future substitution with locally sourced material. Suitable clay sources within the Kagera Region had previously been identified and investigated for calcined-clay use by Malisa (2024). As shown in Figure 3.1, the identified clay deposit lies only a short distance from the case-study plant, which made CC the relevant SCM for the indicative substitution scenario considered in RQ3b.

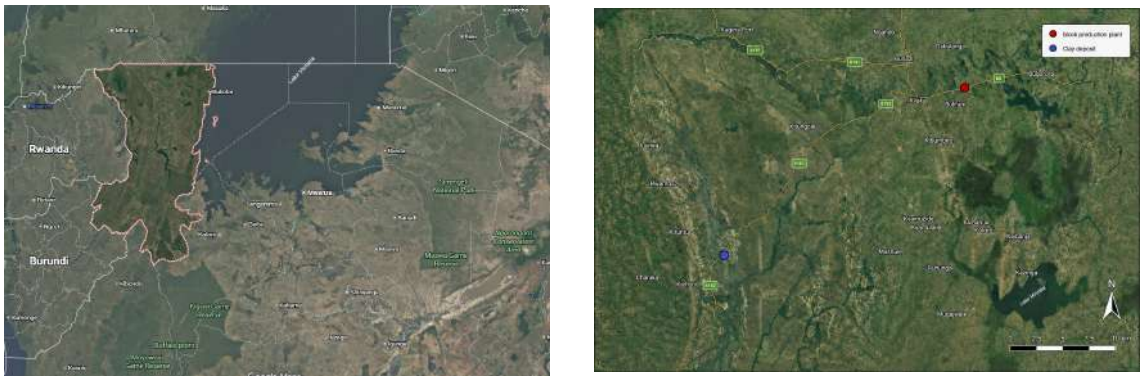


Figure 3.1: Left: the Kagera Region in its national context within Tanzania. Right: the location of the case-study block-production plant and the investigated clay deposit, approximately 36 km apart by road.

3.3 Data Collection

Fieldwork was conducted over approximately six weeks in April and May. The production site was visited almost daily during the first three weeks, allowing complete production cycles to be observed, after which periodic visits were used for curing checks, block testing and observations of whether production practices remained consistent.

3.3.1 Non-participant Observation

Production was observed without participating in the manufacturing process. Recorded variables included cement, sand and water quantities, batch output, visible defects, block dimensions and mass, and mixing and vibration times.

Material quantities were recorded using the units employed by the producer, including cement bags and sand or water buckets, and were subsequently converted to mass where required. Direct observations were also used to document mixing, moulding, compaction, demoulding, curing and storage practices.

3.3.2 Unstructured Interviews

Unstructured interviews were conducted with the owner, site manager and production workers, with additional external contacts consulted on local clay availability. Discussions addressed the reasoning behind mix proportioning, production routines, output, cement and material prices, perceived product quality and practical constraints affecting production.
Most of the time translation was required, and support was provided by a local *fundi*. Interview information was recorded as field notes, and directly observed production data were prioritised over reported values whenever the two conflicted.

3.3.3 Material and Block Sampling

Samples included the fine and coarse sand used in production and full-scale 5-inch blocks from different production batches. Samples and selected blocks were assigned identification codes linking them to their production batch, date and testing condition to maintain traceability throughout the study.
The 5-inch block was used for the detailed production assessment because it was the product manufactured consistently during the initial field-observation period. Blocks from different nominally identical batches were retained separately so that between-batch differences could later be examined (Figure 3.2).



Figure 3.2: Blocks nomenclature and storing on site before testing.

3.3.4 Secondary Data

Secondary sources were used to establish literature benchmarks, previous BLEX procedures (Isaksson, 2026), cement-related emission factors, and evidence on calcined-

clay substitution and implementation constraints (Isaksson and Buregyeya, 2024; Isaksson et al., 2023a; Malisa, 2024).
One additional field visit was made to local clay sources to provide contextual evidence on accessibility and site conditions relevant to RQ3b. These observations were not incorporated into the quantitative production baseline used for RQ1.

3.4 Field Measurement Procedures

3.4.1 Sand Moisture Content

Sand moisture was measured to estimate the water already present in the fine and coarse aggregates before additional mixing water was introduced. Samples were collected from below the exposed stockpile surface, weighed wet, spread on plastic sheets and dried in direct sunlight until the measured mass appeared stable.
The wet-mass moisture content was calculated as:

$$w_{\%} = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{wet}}} \times 100 \tag{3.1}$$

where m_{wet} and m_{dry} are the wet and dried sand masses, respectively. Measurements were repeated on two different days; because the material was sun-dried rather than oven-dried to constant mass, the results were treated as field estimates (Figure 3.3).



Figure 3.3: Sand drying in direct sunlight to estimate moisture content.

3.4.2 Hardened Block Density

For selected production batches, the mass of 30 blocks was recorded and 6 blocks were additionally measured for length, width and height. Each dimension was measured twice and averaged, after which the mean dimensions of the six blocks were used to estimate one representative volume for the batch.
Block volume and bulk density were calculated as:

$$V = lwh \tag{3.2}$$

$$\rho = \frac{m}{V} \tag{3.3}$$

where l, w and h are the mean block dimensions and m is the individual block mass. Since a shared average volume was applied within each batch, calculated density variation primarily reflects variation in block mass rather than the complete dimensional variation of individual blocks.

3.4.3 Compressive Strength Testing

17 blocks from the original batch of 30 blocks were tested at 21 days, since it corresponds to the producer's normal selling age.
Compressive-strength testing was conducted at a Tanzania National Roads Agency (TANROADS) materials laboratory using a motor-driven hydraulic compression machine. Blocks were centred beneath the loading system and rigid plates were placed above and below the specimens where required to distribute the load across the tested surface (Figure 3.4).



Figure 3.4: Compressive-strength testing of a 5-inch block at the TANROADS laboratory.

Load was increased until failure and the recorded failure load was converted to compressive strength using:

$$f_c = \frac{P}{A} \tag{3.4}$$

where P is the maximum failure load and A is the loaded block area. The same orientation and plate arrangement were maintained across the analysed samples.

3.5 Data Analysis and Calculations

The quantitative analysis follows the same sequence used in the Diagnosis: characterisation of current production, assessment of block performance and variability, calculation of the improvement potential, and translation of that potential into cement, cost and CO_2 indicators. Calculations were performed from the field dataset using full-precision values, with rounded values reported in the Results chapter.

3.5.1 Current Production Characterisation

The wet-mix cement fraction was calculated from the cement mass and total wet batch mass:

$$C_{\text{mix}} = \frac{m_{\text{cement}}}{m_{\text{mix}}} \tag{3.5}$$

The cement-to-sand ratio was calculated from their respective masses, while the total w/c ratio included both directly added water and estimated water contained in the wet sand:

$$w/c = \frac{m_{\text{water,added}} + m_{\text{water,sand}}}{m_{\text{cement}}} \tag{3.6}$$

These indicators were used to describe the baseline material system.

3.5.2 Statistical Analysis

For block mass, density and compressive strength, arithmetic mean, standard deviation and coefficient of variation were respectively calculated as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3.7}$$

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{3.8}$$

$$CV = \frac{s}{\bar{x}} \tag{3.9}$$

3.5.3 Density–Strength Relationship

A simple linear regression was used to examine the relationship between hardened bulk density and compressive strength. The coefficient of determination, R^2, was used to describe how much of the observed strength variation was associated with variation in density. Since uncertainties and practices of this specific case-study can differentiate from the ones found in the literature, this step was used to confirm the local applicability of the method.

3.5.4 Lower-Bound Compressive Strength

Production reliability was represented through the lower-bound L-value, which combines average compressive strength and variation:

$$L = \bar{f}\,(1 - k_A CV) \tag{3.10}$$

where $\bar{f}$ is mean compressive strength, s is its standard deviation and k_A is a statistical factor related to sample size. A value of $k_A = 2.5$ was adopted following the indicative approach used by Isaksson and Buregyeya (2024) for samples below 20 observations; the resulting L-value is therefore interpreted as a conservative reliability indicator rather than a certified characteristic strength.

3.5.5 Safety Factor

Before investigating potential reductions in cement consumption, the adequacy of the current production for its intended application must be evaluated. This assessment is necessary even if the material does not satisfy the relevant regulatory strength requirements. The SF, introduced in subsection 2.3.2, is adapted to the current case-study needs by using the L value as the reference strength, instead of the mean strength, to account for the observed high variability in the strength performance.

$$SF = \frac{L}{\sigma_v} \tag{3.11}$$

where σ_v is the vertical stress expected on the ground-level blocks. Following Sabai et al. (2016), it's assumed that a one-storey building will be 12 blocks high, and two more rows will be accounted to cover for the lightweight roof, resulting in 13 blocks weighting on the ground-level block. Therefore, the vertical stress is calculated as:

$$\sigma_v = \frac{13\overline{m}_{\text{block}} g}{lw} \tag{3.12}$$

where $\overline{m}_{\text{block}}$ is the average block mass. The resulting SF is used to assess whether the current production is adequate for its intended application, and to provide a reference point for the subsequent scenario analysis.

3.5.6 Variability-Adjusted Cement Productivity

Mean-based cement productivity was calculated by relating compressive strength to the cement fraction of the mix:

$$CP = \frac{\bar{f}}{C_{\text{mix}}} \tag{3.13}$$

The same indicator was then adjusted for production variability by replacing mean strength with the L-value:

$$CP_L = \frac{L}{C_{\text{mix}}} \tag{3.14}$$

The difference between CP and CP_L was used to show the loss in reliable cement productivity associated with strength variability. Literature benchmarks were used for contextual comparison, but a 28-day cement-productivity benchmark was not used directly as the improvement target because the present baseline represents 21-day production.

3.5.7 Reduced-Variability Scenario

An improved CV of $CV_{\text{improved}} = 8\%$ was used as an indicative good-performance target following Isaksson and Buregyeya (2024). The existing L-value was held constant so that the scenario represents reduced variability without reducing the current lower-bound performance. Holding L constant treats the current lower-bound strength as the reference point for the scenario; it is a modelling choice made to isolate the effect of variability and does not assert that this value represents an adequate or formally established functional strength requirement for the block (subsection 2.3.2).
The mean strength required under the improved variability was calculated as:

$$\bar{f}_{\text{improved}} = \frac{L}{1 - k_A CV_{\text{improved}}} \tag{3.15}$$

This value defines how far the average production strength could theoretically decrease while preserving the same lower-bound strength.

3.5.8 Indicative Cement Reduction

To translate the reduction in required average strength into material savings, the analysis assumes that mean compressive strength changes proportionally with cement input within the simulated range. This proportionality has not been experimentally validated for the present mix. At a cement content of only 3.68% and a w/c ratio of approximately 2.0, the mix operates within the compaction dilemma described in subsection 2.4.2, where water demand, compaction and porosity interact; a simple proportional relationship may not capture these interactions at such low binder content. Under this explicit simplifying assumption, the resulting quantity is referred to throughout this thesis as a *theoretical cement-reduction equivalent* rather than a demonstrated or directly removable amount of cement, and is expressed as:

$$R_{\text{cement}} = 1 - \frac{1 - k_A CV_{\text{baseline}}}{1 - k_A CV_{\text{improved}}} \tag{3.16}$$

The corresponding cement reduction and simulated remaining cement content per block were calculated as:

$$\Delta m_{\text{cement,block}} = m_{\text{cement,baseline}} R_{\text{cement}} \tag{3.17}$$

$$m_{\text{cement,improved}} = m_{\text{cement,baseline}} - \Delta m_{\text{cement,block}} \tag{3.18}$$

The resulting values represent a scenario-based, theoretical cement-reduction equivalent and not an experimentally demonstrated reduction in cement demand. Converting this equivalent into an actual mix change would require establishing an appropriate target strength, stabilising the production process, and validating the assumption experimentally at reduced cement content (section 3.9).

3.5.9 Functional Scaling

Block-level cement, cost and CO_2 results were also expressed per square metre of wall to relate manufacturing performance to the function delivered by the product (Isaksson and Buregyeya, 2024). The number of blocks per square metre was calculated as:

$$N_{m^2} = \frac{1}{lh} \tag{3.19}$$

where l and h are the average block length and height. Mortar-joint thickness was assumed to be zero, meaning that the functional unit represents an idealised block-only wall area used consistently for scenario comparison rather than a complete constructed wall.
A block-level quantity X_{block} was therefore converted to wall level as:

$$X_{\text{wall}} = N_{m^2} X_{\text{block}} \tag{3.20}$$

This scaling procedure was applied both to the reduced-variability scenario and to the independent calcined-clay scenario.
To express the magnitude of the improvement potential, the results are also scaled to Tanzania Mainland's estimated annual cement demand for sandcrete-block production. According to the National Bureau of Statistics (National Bureau of Statistics, 2026), total cement consumption in Tanzania Mainland reached 9,324,518 tonnes in 2025. Of this, it's assumed that approximately 70% of this cement is used for sandcrete-block production, as estimated for Dar es Salaam by Isaksson et al. (2023a).

3.5.10 Relative Cost and Emissions Calculation

The cement price used in the calculations was obtained at the study site as 25,000 Tanzanian Shillings (TSh) for a 50 kg bag, corresponding to 500 TSh/kg. A The exchange rate of 2645 TSh per USD has been used. Cement-related cost savings were calculated as:

$$\Delta Cost = \Delta m_{\text{cement}} P_{\text{cement}} \tag{3.21}$$

where P_{cement} is the local cement price.
A cement emission factor of 700 kgCO_2/tonne cement, or 0.7 kgCO_2/kg, was adopted for the indicative environmental calculation following the value used for the SSA block-production context by Isaksson and Babatunde (2019). Cement-related emission reductions were calculated as:

$$\Delta CO_2 = \Delta m_{\text{cement}} EF_{\text{cement}} \tag{3.22}$$

where EF_{cement} is the selected emission factor. These calculations include only the cement-related material effect and do not constitute a complete life-cycle assessment.

3.6 Cause Analysis: Application of the 10M Model

The Analysis stage of the Sustainability Opportunity Study was guided by the 10M model, which groups possible causes according to Management, Mission, Manpower, Method, Measurement, Machine, Material, Milieu, Market and Means (Isaksson et al., 2024). In this study, the model was used as a structured checklist for interpreting the causes of the improvement potential identified during Diagnosis rather than as a complete organisational assessment.

The categories were organised in a matrix linking each observed condition to its influence on the improvement potential.

Greater emphasis was consequently placed on categories directly supported by production observations and measurements, while categories for which evidence was limited were retained but interpreted more cautiously.

3.7 Solution Screening Approach

RQ3a translates the causes identified during the 10M analysis into possible process improvements. Proposed measures were screened according to their expected ability to reduce production variability and, through improved cement efficiency, contribute to lower material cost and cement-related CO_2 emissions.

Practical feasibility was considered against the equipment, worker skills, routines and financial or technical *Means* already available at the producer. Solutions were consequently separated into measures that could be introduced immediately with little or no additional investment and measures whose effectiveness or feasibility would require further validation before implementation.

3.8 Indicative Calcined-Clay Substitution Potential

RQ3b evaluates calcined clay separately from the reduced-variability scenario. Previous work by Malisa (2024) was used as the basis for local clay availability, calcination suitability and technical plausibility of partial substitution, while one field visit to clay-source locations provided supplementary evidence on accessibility and local conditions (Figure 3.5).



Figure 3.5: Clay layer at the investigated deposit in the Kagera Region, Tanzania.

The scenario assumption follows the best-performing mix reported by Malisa (2024) for calcined clay from the Kagera Region: PC reduced to 50% of its reference content, combined with calcined clay added separately at 60% of that same reference cement content. Because clay is added at a higher fraction than the cement it displaces, this mix contains more total binder than the reference mix, consistent with calcined clay contributing less strength per unit mass than PC. Malisa (2024) established this relationship at a reference cement content of 7% by mass, considerably higher than the baseline cement content observed at the case-study producer. The 50% reduction and 60% addition fractions are therefore applied to the present baseline as an indicative modelling assumption rather than a verified transfer of performance; whether the same relative proportions would reproduce comparable strength at this lower binder content would need to be confirmed through mix trials specific to the case-study process. No calcined-clay blocks were manufactured or tested in the present study, so the analysis does not independently validate this assumption.
The calculation starts from the *baseline* cement consumption rather than from the cement content simulated after RQ3a. For a cement-reduction fraction r_{CC} and a clay-addition fraction r_{clay}, both expressed relative to the baseline cement mass, remaining and displaced PC, and added calcined clay, are calculated as:

$$m_{\mathrm{cement,CC}} = m_{\mathrm{cement,baseline}}(1 - r_{\mathrm{CC}}) \tag{3.23}$$

$$\Delta m_{\mathrm{cement,CC}} = m_{\mathrm{cement,baseline}} r_{\mathrm{CC}} \tag{3.24}$$

$$m_{\mathrm{clay,CC}} = m_{\mathrm{cement,baseline}} r_{\mathrm{clay}} \tag{3.25}$$

The displaced cement was converted to cost and CO_2 values using the same cement price, emission factor and wall-scaling factor applied in RQ1; the added clay mass is reported separately and was not assigned a cost or emission value. The resulting values represent *gross avoided Portland-cement cost and emissions*; clay extraction, calcination, grinding, transport and other implementation-related costs and emissions were excluded.

Equipment requirements, processing needs, worker skills, supply continuity and producer or customer acceptance were considered qualitatively as contextual factors influencing possible future adoption (Isaksson et al., 2023a). These observations support interpretation of the scenario but are not combined into a formal readiness score.

3.9 Methodological Uncertainty

Different sources of uncertainty affect the precision and interpretation of the results and should be considered alongside the findings.
Fieldwork took place over mainly during the Tanzanian rainy season, which caused long periods of production inactivity and some changes in production practices, affecting the continuity and timing of field observations.
Measurement precision is affected by several field conditions. Sand moisture was estimated through field-based sun drying rather than controlled oven drying, introducing uncertainty into the calculated total water content. Strength testing was carried out using a single laboratory and machine setup whose calibration and full standard compliance could not be independently verified. Due to budget constraints and laboratory schedule, the number of blocks that were tested for compressive strength had to be limited to 17, even though a higher amount could have highlighted stronger relationships between the variables assessed.
The study also did not include a formal multi-operator measurement-system analysis; repeatability was instead addressed practically through consistent instruments, repeated dimensional measurements, common testing procedures and sample traceability, meaning that measurement uncertainty should be considered when interpreting small differences between observations.
A further uncertainty affects the scenario calculations in subsection 3.5.8: the proportional relationship assumed there between mean strength and cement content has not been tested experimentally at this producer's binder content, and low-cement mixes are known to be susceptible to non-linear interactions between cement content, water demand, compaction and porosity (subsection 2.4.2). The theoretical cement-reduction equivalent reported in this study should therefore be read as an purely indicative upper estimate of the potential margin.

3.10 Ethical Considerations and AI use

Interviewees participated with their consent, and information collected through conversations was used only for the purposes of the research. Wider socio-economic questions concerning workers, households and communities were outside the study scope and were not interpreted beyond what was required to understand the production process and possible implementation constraints.
Artificial intelligence tools were used as supporting aids at several stages of the research. During fieldwork, to reflect on emerging observations, generate questions, and plan how to organise the remaining activities strategically, and after the fieldwork, with revising and refining of this report.

The underlying logic, critical judgements, and substantive content were developed by the author. The author takes full responsibility for the accuracy, integrity, and final wording of the thesis.

4
Results

This chapter presents the findings that are meant to support the Diagnosis step of the SOS framework, and the preliminary findings that will support the evaluation of future CC implementation.

4.1 Current Production

Table 4.1: Mix raw quantities for 5-inch sandcrete blocks

Item	Value[kg]	Description	Method
Cement	25	Half bag added in bucket to the rim	Remaining cement in bucket weighed with hand scale
Sand (total)	630	21 buckets × 30 kg/bucket	Calculated
Coarse sand	270	9 buckets × 30 kg/bucket	Calculated from bucket count
Fine sand	360	12 buckets × 30 kg/bucket	Calculated from bucket count
Water (added directly)	25	Measured with bucket or with hose directly into mixer	Bucket of water weighed with hand scale
Water (from sand moisture)	25.11	Moisture content contributed by sand	Sand moisture calculations
Total mix weight	680	Cement + sand + water	

The cement used in the facility is Dangote CEM II/B-L 42.5N, and the sand is a mixture of coarse and fine sand with some unquantified clay impurities. Each batch produced 24 blocks, and the material for approximately 2 blocks was often leftover to merge with the following batch.
Given the data in Table 4.1, the cement content of the wet mix was:

$$C_{\text{mix}} = \frac{25}{680} = 0.0368 = 3.68\% \tag{4.1}$$

Sand was stored just outside the production facility in multiple piles that were readily covered by tarpaulins during rainfall (Figure 4.1). The cement-to-sand ratio was approximately 1:25.



Figure 4.1: Sand storage outside of the production facility.

Water was added either via buckets or directly via a hose into the mixer. Direct hose dosing times varied significantly from 1.0 to 2.0 minutes under constant batch parameters (sand moisture and mix proportions), introducing unquantifiable batch-to-batch variation in water content. Sand moisture content was measured to be approximately 4% of the sand weight.

The total w/c ratio was:

$$w/c = \frac{25 + 25.11}{25} = 2.00 \tag{4.2}$$

The observed mixing time varied between approximately 3.48 and 4.46 minutes for the recorded batches (detail of the mixer in Figure 4.2).



Figure 4.2: Detail of the mixer used in the production process.

The compaction and moulding was achieved through an hydraulic vibrating machine that could produce 4 blocks per cycle (Figure 4.3). The vibration time varied greatly between different batches and cycles depending on how the machine operator was perceiving the wetness of the mix, with a range of was approximately 2-6.3 s per block cycle.



Figure 4.3: Vibrating machine used in the production process.

Blocks were subsequently cured in the open court directly in front of the production facility under the sun (Figure 4.4), the blocks being wetted twice a day for the following 14 days, and were normally sold after 21 days.



Figure 4.4: Blocks location during drying and curing phase.

4.1.1 Physical and Mechanical Properties

Block weight, dimensions and bulk density were monitored on a separate sample of $n = 30$ blocks drawn across production batches, following the block-density procedure described in subsection 3.4.2. Six of these blocks were additionally measured for length, width and height, giving nominal average dimensions of approximately $462 \times 125 \times 227$ mm; this batch-representative volume was then used to convert the measured mass of all 30 blocks into bulk density. The observed ranges were used to examine whether differences in block mass and density between batches could help explain differences in compressive strength.

At 21 days, compressive strength was assessed on a sample of $n = 17$ blocks originating from the original batch of $n = 30$ blocks. The summary statistics for block weight, bulk density and compressive strength are reported in Table 4.2.

Table 4.2: Summary statistics for block weight, bulk density ($n = 30$) and 21-day compressive strength ($n = 17$)

	Range	**Average**	**Standard deviation**	**CV (%)**
Weight (kg)	24.78–28.95	27.18	1.16	4.3
Density (kg/L)	1.90–2.22	2.08	0.09	4.3
Strength (MPa)	1.21–2.08	1.483	0.266	17.97

Block weight and bulk density show the same CV (4.3%), as expected from the shared representative volume, whereas the variability of compressive strength (17.97%) was substantially higher than that observed for block weight and density.

4.1.2 Correlation Between Bulk density and Compressive Strength

The relationship between bulk density and compressive strength was also examined and is shown in Figure 4.5.

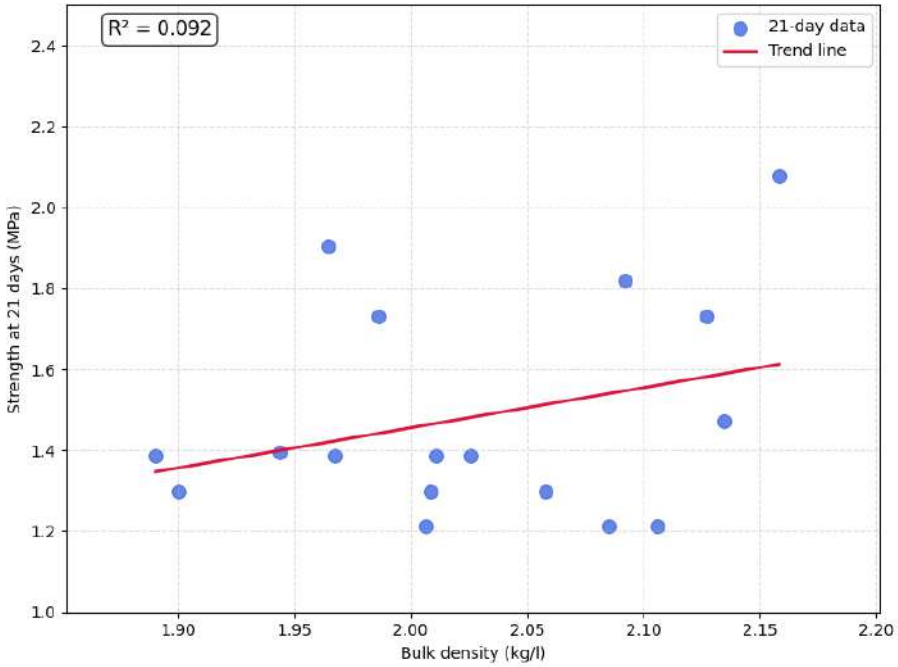


Figure 4.5: Correlation between Bulk density and Strength of blocks aged 21 days from different mixes

With a $R^2 \approx 0.091$, the observed relationship resulted to be weak, indicating that differences in bulk density alone explain only a limited part of the measured strength variability. This motivates the following diagnosis of the combined effect of average strength and production variation.

4.1.3 Strength by Production Batch

The 17 tested blocks originate from five different production batches (subsection A.2.2 in the Appendix), only two of which contributed a representative amount of tested blocks: because a CV calculated from very few observations is not a reliable estimate of the true within-batch spread, only batches with at least five tested blocks are examined individually here; batches 2, 3 and 5 ($n = 1$, $n = 1$ and $n = 3$ tested blocks) are therefore excluded from this comparison, although their results remain part of the pooled statistics reported in the previous paragraphs.

Batches 4 ($n = 7$) and 6 ($n = 5$) are compared in Figure 4.6. Their within-batch coefficients of variation were approximately 20.0% and 17.6%, respectively – both close to, and in the case of batch 4 higher than, the pooled value of 17.97%.

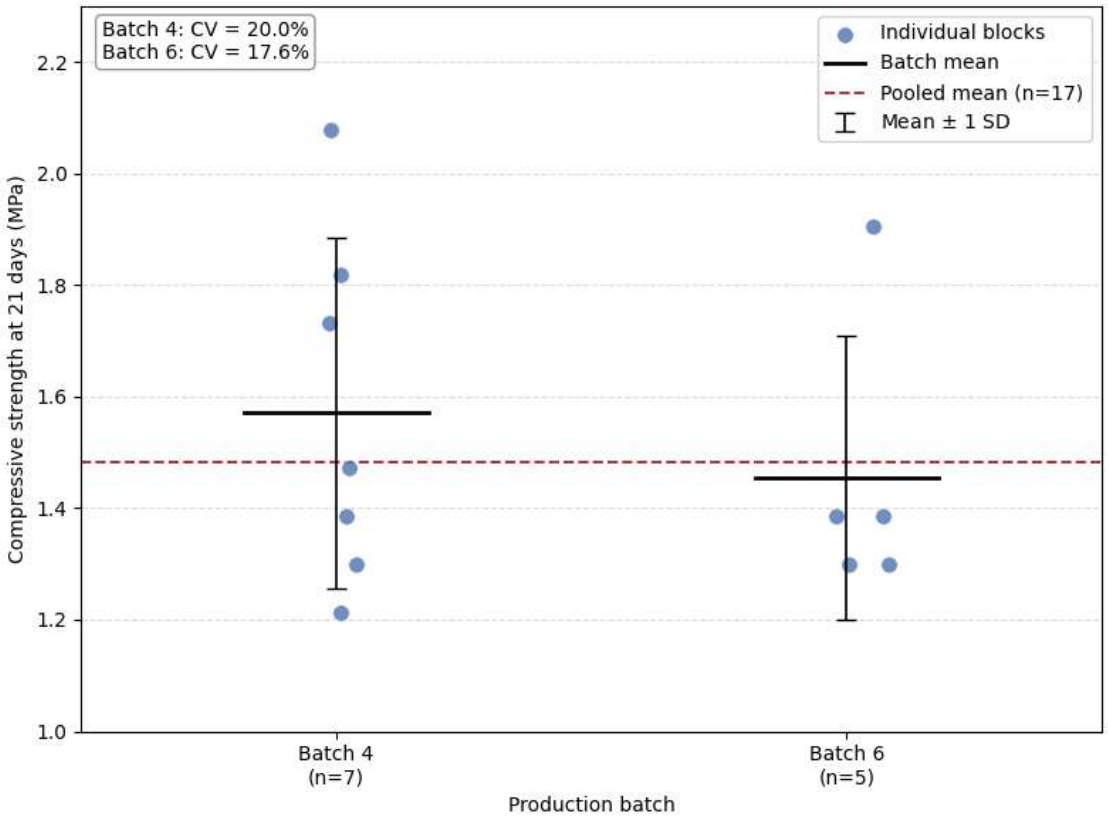


Figure 4.6: Compressive strength at 21 days for batches 4 and 6, the only batches with at least 5 tested blocks

The batch-level comparison above is a descriptive complement, but the CV used throughout the remainder of this chapter (subsection 3.5.4, subsection 3.5.8) is kept from the calculations with all the $n = 17$ tested blocks and therefore already combines between- and within-batch variation.

4.1.4 Lower-Bound Compressive Strength

Using $k_A = 2.5$, the lower-bound strength is:

$$L = 1.483 - (2.5 \times 0.266) = 0.817 \text{ MPa} \tag{4.3}$$

The value represents the variability-adjusted strength of the current production process. It is subsequently combined with cement consumption to assess how efficiently the cement input is converted into reliable block performance. Both the mean and the lower-bound strength are numerically low relative to residential-block benchmarks reported in subsection 2.3.2; this is discussed further in subsection 6.1.1.

4.1.5 Safety Factor

To calculate the SF, the vertical stress on the ground-level blocks needs to be determined:

$$\sigma_v = \frac{13 * 27.18 * 9.81}{462 * 125} = 0.06 \text{ MPa} \tag{4.4}$$

The resulting SF, given the L-value and σ_v, is:

$$SF = \frac{0.817}{0.06} = 13.62 \tag{4.5}$$

which means that the current lower-bound strength is about 14 times higher than the expected vertical stress on the ground-level blocks.

4.2 Improvement Potential

The improvement potential was assessed by first assuming a reduced-variability scenario, and assessing how cement efficiency would be impacted.

4.2.1 Variability-Adjusted Cement Productivity

The current cement fraction of the wet production mix was 0.0368. Therefore, the average cement productivity, without accounting for variability, was:

$$CP = \frac{1.483}{0.0368} = 40.33 \text{ MPa} \cdot \text{ton} \tag{4.6}$$

When production variability is included through the L-value:

$$CP_L = \frac{0.817}{0.0368} = 22.21 \text{ MPa} \cdot \text{ton} \tag{4.7}$$

The reduction from 40.33 to 22.21 MPa·ton shows the effect of production variability on reliable cement productivity.

4.2.2 Potential from Reduced Variability

An improved CV ($CV_improved$) of 8% was used as the target scenario. The current lower-bound strength of 0.817 MPa was kept constant so that the simulated improvement does not reduce the reliable performance of the block.
The mean strength required under the improved variability would therefore be

$$\overline{f}_{\text{improved}} = \frac{0.817}{1 - (2.5 \times 0.08)} = 1.021 \text{ MPa} \tag{4.8}$$

indicating that the same lower-bound performance could theoretically be maintained at a lower average strength if production variability were reduced.

4.2.3 Indicative Cement Reduction per Block

Each production batch uses approximately 25 kg of cement for 24 blocks. The baseline cement consumption per block is therefore:

$$m_{\text{cement,baseline}} = \frac{25}{24} = 1.042 \text{ kg/block} \tag{4.9}$$

Assuming proportionality between mean strength and cement input – an assumption not experimentally validated for this lean, high-w/c mix (subsection 3.5.8) – the theoretical cement-reduction equivalent obtainable through improved consistency is:

$$R_{\text{cement}} = 1 - \frac{1 - (2.5 \times 0.1797)}{1 - (2.5 \times 0.08)} = 0.3115 \tag{4.10}$$

The corresponding theoretical cement saving per block is therefore:

$$\Delta m_{\text{cement,block}} = 1.042 \times 0.3115 = 0.324 \text{ kg/block} \tag{4.11}$$

and the corresponding simulated cement content becomes:

$$m_{\text{cement,improved}} = 1.042 - 0.324 = 0.717 \text{ kg/block} \tag{4.12}$$

The resulting cement reduction represents the improvement potential at the manufacturing level. To express the same potential in relation to the functional output of the blocks, the block-level results were subsequently scaled to 1 m^2 of masonry wall and to the annual masonry-relatede cement need in Dar es Salaam.

4.2.4 Functional Scaling and Impact Assessment

To relate the block-level results to the functional output of the product, the calculated savings were scaled to 1 m^2 of masonry wall using the average block length and height.
Using an average block length of 0.462 m and height of 0.227 m, the scaling factor is:

$$N_{m^2} = \frac{1}{0.462 \times 0.227} = 9.54 \text{ blocks/m}^2 \tag{4.13}$$

This scaling factor is applied to the block-level cement, cost and CO_2 results to express the improvement potential per square metre of wall.
The cost and emission factor per kg of cement presented in subsection 3.5.10, 500 TSh/kg (0.19 USD/kg) and 0.7 $kgCO_2$/kg respectively, are applied to the current production and the calculated cement reduction scenario. The cement-related impacts in terms of cost and emissions are summarized in Table 4.3. The Tanzania rows scale the block-level results to the estimated annual cement demand for sandcrete-block production, calculated as:

$$N_{yr} = 9,324,518 \times 0.70 = 6,527,163 \text{ tonnes/year} \tag{4.14}$$

This is equivalent to approximately 6.27 billion 5-inch blocks annually, assuming the same cement consumption per block as observed at the case-study production site.

Table 4.3: Indicative cement-related cost and emissions for current and improved production scenarios and saving potential, for 1 block, 1 square meter of wall and yearly in Tanzania

Functional unit	**Cement (kg)**	**Cost (TSh)**	**Cost (USD)**	**Emissions ($kgCO_2$)**
Current Production				
1 block	1.042	521	0.20	0.73
1 m^2 of wall	9.94	4970	1.91	6.95
Tanzania	6.53 Mt	3,263.6 bn	1,240.2 M	4.57 Mt
Improved Production				
1 block	0.718	359	0.14	0.50
1 m^2 of wall	6.85	3425	1.34	4.77
Tanzania	4.50 Mt	2,248.6 bn	854.2 M	3.15 Mt
Saving Potential				
1 block	0.324	162	0.061	0.227
1 m^2 of wall	3.09	1545	0.58	2.17
Tanzania	2.03 Mt	1,015.0 bn	385.9 M	1.42 Mt

Under the simulated reduction in production variability from 17.97% to 8%, the current lower-bound strength could therefore theoretically be maintained at a lower average strength, under the assumed proportional strength–cement relationship.

4.3 Analysis of possible causes

The Analysis step of the SOS is carried out through the 10M model shown in Table 4.4. For each category, the table lists the observed condition – distinguishing, where relevant, between conditions directly observed or measured in the field and information obtained through interviews – and an arbitrary classification of the how much they impact the identified improvement potential in this specific case study. Certain observations could fit within multiple categories, but each is reported only under the category deemed most characteristic.

Table 4.4: 10M analysis: observations on possible causes for the identified improvement potential

Category	**Observations**	**Impact**
Management	No documented standard other than site manager opinion *(interview)*.	High
Mission	No explicit quantitative production target *(interview)*. Quality control is limited to visual inspection for cracks *(direct observation. Figure 5.2)*.	High

Table 4.4 10M analysis

Category	Observations	Impact
Manpower	Workers and teams vary between production days, with markedly different levels of experience *(interview)*. Most production steps depend on worker judgement *(direct observation)*. The whole teams is paid per cement bag used *(interview)*.	Medium
Method	The same nominal procedure was followed across batches, but the timing and length of individual steps varied *(direct observation)*.	High
Measurement	Sand and cement batching are measured with buckets, but water addition and vibration time are based on worker's judgement; no post-production measurement of weight is carried out *(direct observation)*.	High
Machine	Production uses a mechanical mixer and a hydraulic vibrating block-making machine that moulds 4 blocks per cycle, both manually operated; similar conditions to other small-scale producers *(direct observation)*.	Medium
Material	The cement-sand-water mix used at the facility reflects the observed industrial standard *(interview; direct observation)*. Sand is locally sourced and internal moisture is not directly controllable *(direct measurement)*.	Low
Milieu	Heavy rainfall interrupts production and alters the condition of stored sand and daily production practices; strong sunilight dries the blocks quickly after demoulding *(direct observation)*.	Medium
Market	The producer is an established supplier of low-cost residential blocks; affordability is described as the main purchasing priority, and most customers lack reliable means of assessing block quality *(interview)*.	Low
Means	The producer reports the financial and technical capability to invest in new equipment, materials or process adjustments *(interview; self-reported)*. Cement is considered highly expensive *(interview)*.	Low

4.4 Third step of SOS study: Solving

The following section reports the Solving step of the SOS study, which assesses how the identified improvement potential could be realised. It is divided into two parts:

(1) immediate process improvements within the current production system, and (2) a longer-term material opportunity that could be explored once the limits of process optimisation are reached.

4.4.1 Immediate Process Improvements

The proposed improvements require little to no capital investment and target the four "High" impact categories of Table 4.4. They are listed in Table 4.5 in the order in which they should be introduced.

Table 4.5: Proposed immediate process improvements

Category	**Proposed improvement**
Management and Mission	Define a measurable production target. Weigh blocks at least twice a day as a low-cost proxy for production quality, and record the result to keep track of any major variations.
Measurement	Replace time-based hose dosing with a measured volume of water (e.g. the bucket already used on site), recorded per batch. Assess sand moisture through the workability judgement of an experienced worker, communicated ahead of the shift.
Method	Once the wetness is established with the above, fix the vibration time per batch at 6 s (value established from Paul (2026)'s parallel work in Dar es Salaam within the BLEX project).

4.4.2 Indicative Calcined-Clay Substitution Scenario

The baseline cement consumption has been calculated at approximately 1.042 kg/block. Following the best-performing clay mix identified by Malisa (2024), the displaced cement demand is:

$$m_{\text{cement,CC}} = 1.042 \times 0.50 = 0.521 \text{ kg/block} \tag{4.15}$$

and the calcined clay added instead is

$$m_{\text{clay,CC}} = 1.042 \times 0.60 = 0.625 \text{ kg/block} \tag{4.16}$$

Using the same scaling and impact factors from subsection 4.2.4, the scaled economic and environmental effect of the cement displacement is shown in Table 4.6.

Table 4.6: Indicative cement-related effects of the calcined-clay scenario, for 1 block, 1 square meter of wall and yearly in Tanzania

Functional unit	**Cement displaced (kg)**	**Clay added (kg)**	**Avoided cost (TSh)**	**Avoided cost (USD)**	**Avoided CO_2 ($kgCO_2$)**
1 block	0.521	0.625	260	0.098	0.365
1 m^2 of wall	4.97	5.96	2,484	0.94	3.48
Tanzania	3.26 Mt	3.92 Mt	1,631.8 bn	620.1 M	2.28 Mt

5
Analysis

This chapter analyses the results through the SOS lenses of Diagnosing, Analysing and Solving. These steps mirror the structure of the RQs, which are answered in section 7.1 after further discussion in chapter 6.

5.1 Diagnosis of current production and improvement potential

Current production conditions are consistent with those reported in previous studies, characterised by a very low cement content (approximately 3.68% of the wet mix), a high w/c ratio (2.0 compared with the commonly recommended range of 0.4–0.6), considerable variability in performance, and a strong reliance on workers' individual judgement.

Due to the blocks being earth-dry masses that need to achieve a zero-slump consistency, an already high w/c, combined with the observed inconsistency in water dosing, can lead to over-watering, causing parts of the mixture to stick to the mould and potentially resulting in block collapse upon demoulding (Figure 5.1).

The results reveal a clear difference between the consistency of the blocks' physical properties and their mechanical performance. While weight and density show relatively low variability (CV of 4.3%), compressive strength varies approximately four times as much (CV of 17.97%). The weak correlation between density and strength ($R^2 \approx 0.091$) further indicates that differences in density alone cannot explain the observed strength variation. Moreover, within-batch variability (20.0% and 17.6%) is comparable to that of the overall sample, suggesting that inconsistencies arise not only between production batches but also during the production of individual blocks.

This variability reduces the reliability of the final product. Although the mean compressive strength is 1.483 MPa, the calculated lower-bound strength is only 0.817 MPa, indicating that the current mix has the potential to deliver more consistent performance. Nevertheless, the calculated SF suggests that this lower-bound strength is sufficient to withstand the estimated vertical loading of a typical wall under the assumptions considered.

The same effect is reflected in cement efficiency. When variability is taken into account, cement productivity decreases from 40.33 to 22.21 MPa·ton, meaning that almost half of the cement's potential performance is not reliably delivered.

The main improvement opportunity therefore lies in reducing production variability. Under the hypothetical scenario of lowering the CV to 8% while maintaining the



Figure 5.1: After demoulding, part of the mix often sticks to the mould surfaces (left) or get a bloated shape due to structural collapse (right)

current lower-bound strength, the calculations indicate an equivalent cement reduction of approximately 31%. This corresponds to 3.09 kg of cement per m^2 of wall, or approximately 2.03 million tonnes when extrapolated to the estimated annual demand in Tanzania Mainland.

In terms of the associated economic and environmental impacts, these indicative savings would correspond to approximately 1,015 billion TSh (385.9 million USD) in avoided cement expenditure and 1.42 million tonnes of avoided CO_2 emissions.

5.2 Analysis of causes for the improvement potential

This step was carried through the 10M model and helped highlight the major contributors and environmental factors that participate in the improvement potential, specifically in the calculated process varaibility.

The conditions relative to Management, Mission, Method and Measurement greatly contribute to the observed variability. These categories are closely connected and reveal the absence of clearly defined and measurable quality targets for block weight, density and compressive strength. Instead, production is primarily guided by the aim of delivering a product that appears acceptable to customers, with the absence of visible cracks serving as the main quality criterion (Figure 5.2).



Figure 5.2: (Left) Blocks with visible cracks are fixed for sale. (Center and Right) Blocks still show frail edges and surfaces

The lack of quantitative targets is reflected in the absence of standardised production procedures. As long as the finished blocks appear acceptable, the production process is generally considered successful, regardless of whether the individual steps are performed consistently. In particular, water addition and vibration time were found to depend almost entirely on workers' judgement, despite being two key factors influencing the final compressive strength of the blocks.

Machine and Material conditions are broadly similar to those reported for other small-scale producers and are largely determined by equipment availability and the regional supply market. Although both can influence block quality, they offer fewer opportunities for immediate improvement within the producer's current operating conditions and were therefore not prioritised.

The remaining categories mainly describe the broader context in which production takes place. Differences in workers' experience may contribute to variations in block quality, although supervision by management can help identify and correct mistakes during production. Similarly, environmental conditions under Milieu cannot be directly controlled, but their effects can be reduced through appropriate adjustments to production practices.

Market and Means are particularly relevant because they determine the producer's financial capacity to implement improvements and its position within the local market. In this case, both appear relatively favourable. The producer is well established and has gained the trust of the local community, which may help explain why its blocks continue to sell despite their relatively low strength and less refined appearance compared with those of some competitors. This established market position could provide an opportunity to invest in improved production practices without compromising the affordability of the final product.

5.3 Solution to the diagnosed potential

5.3.1 Variability-adjusted scenario

The measures proposed in Table 4.5 address the main causes of variability identified in the analysis. They focus on aspects of production that are directly within the producer's control and can be improved without substantial financial investment.

Management and Mission. Establishing clear quality targets provides a reference against which production performance can be assessed. These targets should be accompanied by simple, repeatable checks to identify deviations from normal production conditions. Although compressive strength testing is the most direct way to verify block performance, its cost of 20,000 TSh (approximately 7.60 USD) per block at the TANROADS Bukoba office makes routine testing impractical.

Weighing blocks offers a more affordable alternative for regular monitoring. Although density was found to be a weak predictor of compressive strength in the current dataset, weight measurements can still help identify blocks that differ from typical production. Furthermore, the relationship between density and strength may become clearer once other process variables affecting strength, particularly water addition and compaction, are better controlled.

Measurement. Water addition was identified as an important source of inconsistency, with hose dosing times ranging from 1.0 to 2.0 minutes under otherwise similar conditions. Replacing time-based dosing with a measured water volume would make the amount added more consistent and easier to compare between batches, reducing the risk of block collapse due to to excessive water addition and the resulting loss of zero-slump consistency.

However, the moisture already present in the sand contributed approximately as much water as was added directly during mixing (section 4.1). Water dosing should therefore also account for changes in sand moisture. In the absence of dedicated measuring equipment, a consistent workability assessment carried out by an experienced worker could provide a practical initial approach, although it would remain dependent on subjective judgement.

Method. Vibration time currently depends on the operator's perception of the mix's moisture content, ranging from 2 to 6.3 s per cycle. Standardising this step would therefore be more effective once water content and workability are brought under better control. A vibration time of approximately 6 seconds is suggested as an initial reference. However, longer vibration does not necessarily lead to higher density or strength. The amount of material placed in the mould must also be adjusted to account for the additional compaction and ensure that the intended block dimensions and degree of compaction are achieved (Paul, 2026).

5.3.2 Calcined Clay substitution scenario

The investigated scenario considers the replacement of 0.521 kg of PC per block with the addition of 0.625 kg of calcined clay. Based on the avoided cement consumption alone, this would correspond to a cost reduction of approximately 2,500 TSh (1 USD) and an emissions reduction of 3.5 kg of CO_2 per m^2.

When scaled to the estimated annual national block demand, the potential becomes more significant. Under the same assumptions, approximately 3.26 million tonnes of PC could be displaced, corresponding to an avoided cement expenditure of 1,631.8 billion TSh (620.1 million USD) and approximately 2.28 million tonnes of avoided CO_2 emissions.
However, this analysis can't estimate any difference in improvement potential in terms of strength performance and process variability, as it assumes that the performance achieved with the new binder mix is the same achievable with 100% PC binder.
These figures should anyway be interpreted as indicative gross savings strictly associated with reduced cement consumption, since the costs and emissions associated with clay extraction, calcination, grinding and transportation have not been included. Nevertheless, the scenario highlights the potential of locally sourced calcined clay to reduce reliance on PC.

5.3.3 Comparing the Improvement Pathways

The two improvement pathways are compared to the current production in Figure 5.3, to support the understanding and magnitude of their effects on cement consumption and cement-related costs and emissions. The comparison shows that both scenarios could produce substantial reductions in PC consumption, cost and associated emissions. The calcined-clay scenario provides a larger calculated reduction, but this does not necessarily make it the preferable solution. The two estimates are based on different assumptions and involve different implementation requirements.

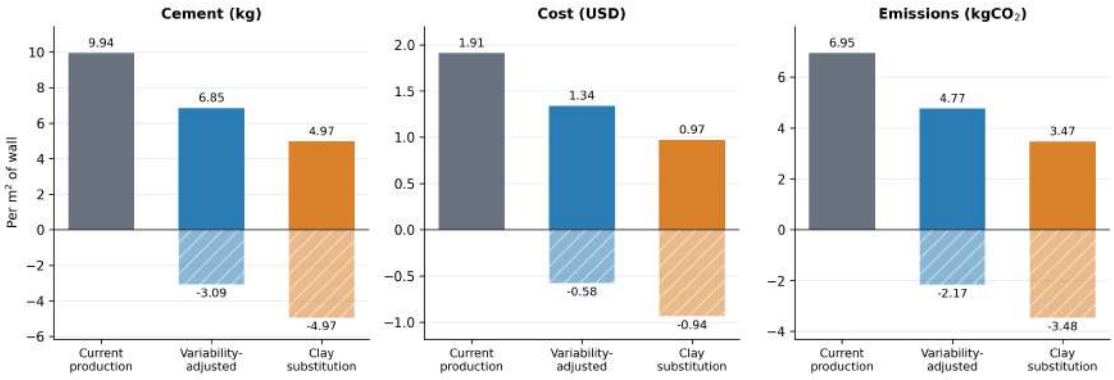


Figure 5.3: Cement consumption, cement-related cost and cement-related CO_2 emissions per m^2 of wall for current production, the variability-adjusted scenario and the calcined-clay scenario. Hatched bars below zero show the reduction relative to current production.

The comparison should therefore be understood as an indication of the magnitude of the two opportunities rather than as a direct assessment of which solution is more sustainable. In particular, the apparent cement-related savings from calcined clay cannot be treated as net savings until the added material and processing requirements are included.

The two pathways can also be interpreted as complementary, as improving the consistency of the existing process would be a practical first step to improve product reliability and provide a more dependable baseline for future experiments. Partial cement substitution could then be investigated as a longer-term option for addressing the limitations that remain after process control has improved.
Both pathways ultimately depend on the definition of a suitable performance benchmark. Without an appropriate strength target, neither reducing the existing cement dosage nor replacing part of it with calcined clay can be assessed fully in terms of quality, affordability and environmental impact. This topic is discussed in subsection 6.1.1

6
Discussion

6.1 Reflection on Quality in this study

Quality was defined in terms of the blocks' functionality: providing housing, expressed as square metres of wall, with sufficient compressive strength and reliable performance. To assess how efficiently cement contributes to this function, the cement productivity index was used to relate the strength achieved to the amount of cement consumed.
The improvement potential was identified as the difference between the current production performance, in terms of quality, cement-related costs and CO_2 emissions, and what could be achieved if process variability were reduced to a level considered realistic in this context.
However, quality also concerns the long-term performance of the blocks, as well as the economic and environmental impacts associated with their production. These aspects are particularly relevant because cement is the main contributor to both material costs and embodied CO_2 in the studied blocks. Expressing the results per square metre of wall therefore strengthens the connection between production efficiency and the function ultimately provided to the customer, in line with previous work suggesting that cement productivity should be related to the functionality of the final product.

6.1.1 The role of compressive strength and variability

When interpreting the compressive strength results, two questions need to be considered: first, whether the strength achieved is reliable, and second, whether this reliable strength is sufficient for the blocks to fulfil their intended function.
Regarding the first question, the results show a considerable difference between average and reliable performance. While the mean compressive strength was 1.483 MPa, the calculated lower-bound strength was only 0.817 MPa. This difference is also reflected in cement productivity, which decreased from 40.33 to 22.21 MPa · ton when production variability was accounted for. Considering how cement productivity relates cement consumption to the strength reliably delivered, this difference provides a basis for identifying the improvement potential. Under the simulated reduction in variability, it corresponds to a theoretical saving of 3.09 kg of cement per m^2 of wall, equivalent to approximately 1,545 TSh and 2.17 kgCO_2 per m^2, while maintaining the current lower-bound strength.
To put these findings into context, they can be compared with the study by Isaksson and Buregyeya (2024), where the reported compressive strength was consid-

erably higher, at approximately 3.3 MPa, with a cement productivity of around 66.8 MPa · ton. At first sight, these figures might suggest better-quality production. However, the associated carbon footprint was also substantially higher, raising the question of whether the additional strength justified the greater environmental impact. Variability helps explain this apparent contradiction: despite the higher mean cement productivity, the variability-adjusted value was lower than in the present study, at 17.1 MPa · ton compared with 22.2 MPa · ton. This illustrates why average strength alone is insufficient to assess cement efficiency, since the value delivered by the material also depends on how reliably that strength is achieved. Similarly, although the potential CO_2 savings identified in the previous study were considerably higher, the present production system shows greater reliability and therefore a smaller improvement margin attributable specifically to variability.

An additional consideration in this comparison, and in comparisons with other studies, is the age at which compressive strength was tested. Most studies report 28-day strength, while the present investigation used 21 days, corresponding to the producer's usual selling age. This limits direct comparability, although previous research indicates that sandcrete blocks can develop approximately 70% of their final strength within the first seven days (Isaksson et al., 2026; Bogren, 2024). The difference was therefore considered acceptable for the purposes of this field-based investigation, while acknowledging that some further strength development may occur.

Turning to the second question, the measured strength levels remain relatively low in absolute terms. The mean 21-day strength of 1.483 MPa falls below both the approximately 2.2–3.5 MPa range reported as a common minimum benchmark for low-strength residential blocks and the TZS 283:2025 requirement of a 4 MPa average, with no individual result below 3.2 MPa (Tanzania Bureau of Standards, 2025).

As discussed in subsection 2.3.2, however, the suitability of these requirements for small-scale producers remains debated, particularly given the high cost of cement relative to the purchasing power of low-income customers. Whether standards should require strengths substantially higher than those commonly achieved in practice is therefore still an open question. One way to approach it is to examine whether the blocks can withstand the loads expected in their intended application. The calculated SF of approximately 13.6 for ground-level blocks, based on a lower-bound strength of 0.817 MPa and an expected vertical stress of 0.051 MPa, suggests that their current strength is not critical under the estimated static vertical load. Considering this result alongside previous studies, many of the reported strength values could be sufficient for this particular loading condition, even when they fall below standard requirements. However, this does not establish the overall suitability of the blocks for housing. Their function must be maintained over time, under exposure to rainfall, erosion, moisture, wind and other conditions that were not assessed in this study.

The existing requirements may therefore be considerably higher than what is necessary for certain applications, especially when technical and affordability constraints are considered. Nevertheless, the available evidence is insufficient to establish a lower strength requirement that would ensure both immediate safety and long-term

durability without making the blocks unnecessarily expensive.

6.2 Limits of the current system

The low cement dosage, below 4% by mass, reflects the pressure to keep blocks affordable rather than a purely technical choice. Despite relatively consistent block mass and dimensions, mechanical performance was considerably more variable. This suggests that the mould and production equipment control block geometry and overall material quantity relatively well, while the factors affecting the internal structure remain less controlled. Compressive strength depends on more than the quantity of material placed in the mould: water distribution, compaction, curing and local differences within the mix can influence porosity and cement hydration without producing equally visible changes in weight or external dimensions.
As discussed previously, the cement content used in sandcrete production has generally decreased over time, contributing to higher w/c ratios. However, achieving an appropriate ratio is not simply a matter of introducing more accurate measurements. Interviews suggested that workers may occasionally add no water at all, assuming that the sand already contains sufficient moisture, although this practice was never directly observed. Rainfall is unpredictable and can substantially alter the moisture content of stored sand. While workers sometimes cover the sand with tarpaulins before rainfall Figure 4.1, this does not protect the entire stockpile or prevent exposure during transport and before the sand reaches the production site. Water content therefore remains an important variable that is difficult to control consistently under actual production conditions.
These difficulties also need to be understood within the broader context of cement use. Cement-based blocks are increasingly valued as an alternative to burnt bricks and are associated with aspirations for improved housing and social status. At the same time, rising cement prices have encouraged producers to reduce the amount used per block. Since these prices depend on manufacturing, transport, fuel and other external factors, cement cannot necessarily be expected to become more affordable. This creates a fundamental limitation that reducing variability alone cannot overcome: the compaction dilemma. The combination of very low cement content and the water needed to achieve sufficient compaction results in a high w/c ratio and consequently low cement productivity. The calculated improvement potential should therefore be understood primarily as an opportunity to make the existing process more consistent and reliable, rather than a complete solution to its underlying cement inefficiency.
Once avoidable variability has been reduced, partial binder substitution becomes a possible longer-term pathway for addressing the remaining limitations of the current mix.

6.2.1 Weaker modelling assumptions in lean mixes

The compaction dilemma also raises questions about the proportional relationship between mean strength and cement content assumed in subsection 3.5.8. At such low binder content, water demand, compaction and porosity interact in ways that

may prevent strength from changing proportionally with cement dosage. The actual relationship could be either more or less favourable than assumed, particularly as the mix approaches the limits of workability before losing zero-slump consistency. Since this relationship was not experimentally investigated for the present production mix, it would need to be verified before translating the calculated variability-reduction potential into an actual reduction in cement consumption.
A further limitation concerns the use of bulk density as an indicator of compressive strength. The measured relationship was weak, with $R^2 \approx 0.091$, compared with the 40–60% reported in previous low-strength block research (Ilesanmi, 2025; Isaksson et al., 2012). Additional variation associated with sand moisture, water addition, vibration and curing may help explain this difference and makes strength difficult to predict from block weight alone. Nevertheless, routine weighing remains a useful and inexpensive option for production monitoring. Greater control over water addition could make the relationship more consistent, although this would need to be verified. In the meantime, weight measurements could help identify deviations from normal production at a much lower cost than compressive testing, even if they cannot reliably predict strength on their own.

6.3 Calcined Clay as substitution material

Calcined clay represents a possible longer-term opportunity to reduce reliance on PC once the limits of process optimisation have been reached.
The substitution scenario was based on an experimental study from Malisa (2024) using locally sourced clay from the Kagera Region. The best 28-day strength was achieved with a 50% reduction in PC, combined with calcined clay added at 60% of the original cement content.
The main limitation in transferring these results to the present case is the difference in binder content. Malisa (2024) established the 50%/60% relationship using a reference cement content of 7% by mass, nearly twice the producer's baseline of approximately 3.68%. It is therefore uncertain whether the same proportions would provide comparable strength in the considerably leaner mix studied here, as it would likely be missing finer particles to participate in bulk density and strength development. The substitution ratio should consequently be understood as a purely indicative modelling assumption, requiring experimental validation under the producer's actual conditions.
Applying this relationship to the current mix would displace approximately 0.521 kg of PC per block while adding approximately 0.625 kg of calcined clay. Expressed per square metre of wall, the avoided cement alone would correspond to approximately 2,484 TSh in material costs and 3.48 kgCO_2 in emissions. However, because the amount of clay added exceeds the cement displaced, the total binder content increases by approximately 10%. These figures therefore represent only the gross benefits associated with avoided PC, without accounting for the costs and emissions of producing and introducing calcined clay.
This scenario is also closely connected to the previous discussion on reducing production variability. Establishing a more consistent baseline would make it easier to distinguish the effects of binder substitution from the variability already present in

production. This is particularly important because the reference study was conducted under laboratory conditions, whereas the actual performance, costs and environmental implications of calcined clay would need to be assessed within the producer's existing practices.

6.3.1 Contextual limitations to calcined clay introduction

Beyond technical performance, the social context also needs to be considered when evaluating the feasibility of substitution. As previously discussed, cement-based blocks carry a certain social value and are often associated with improved housing and economic status. Introducing calcined clay could alter the colour and appearance of the blocks, potentially affecting their market acceptance. Since customers often assess block quality visually, a product that looks noticeably different may be perceived as less desirable, regardless of its actual performance. These considerations emerged from informal interviews and were not included in the quantitative analysis, but they remain relevant because any material transition would ultimately depend on local acceptance.
From a production perspective, introducing calcined clay would also require knowledge and skills that are not currently widespread in rural settings. Even where suitable equipment could be made available, workers would need to learn how to process and calcine clay under controlled conditions. Since technical knowledge among *fundis* is largely transferred informally through practical experience, this could represent a substantial learning challenge and would require appropriate training. Moreover, recent work within the BLEX project on volcanic ash as a supplementary cementitious material in Tanzania has highlighted difficulties in achieving particle fineness comparable to cement (Janze, 2026). Similar grinding challenges could arise with calcined clay. Calcination itself also requires adequate control of temperature and duration to obtain a material with suitable binding properties.



Figure 6.1: Local kiln for burned bricks manufacturing

In Figure 6.1 a local kiln created for larger-scale burned bricks manufacturing is

shown, but the producer stated that the size of the kiln made it difficult to achieve and maintain the desired temperature, indicating that smaller pilots would be necessary for clay calcination.
Although experimental work has explored local calcination methods, their reliability and practical feasibility in rural production settings have not yet been sufficiently established. These questions would therefore need to be addressed through further research before calcined clay could be considered a realistic alternative at this scale.

7

Final remarks

7.1 Conclusions

This study assessed the improvement potential of a very lean sandcrete-block production process affected by substantial variability in mechanical performance, and explored the indicative potential of partial Portland-cement substitution with calcined clay. The study was conducted at a small-scale producer in Kyaka, Kagera Region, Tanzania, following the Diagnosing–Analysing–Solving logic of the Sustainability Opportunity Study.

RQ1. What is the improvement potential in terms of quality, cost and CO2 emissions in current block production?

While mean-based cement productivity was approximately 40 MPa·ton, accounting for strength variability reduced its reliable value to approximately 22 MPa·ton. This difference represents cement that contributes to cost and CO_2 emissions without providing an equivalent level of reliable strength performance.

Assuming a reduction in variability to from 17% to 8% while maintaining the current lower-bound strength of 0.817 MPa, the improvement potential was estimated at a 31% theoretical cement-reduction equivalent, corresponding to potential savings of 0.58 USD/m^2 and 2.17 kg CO_2/m^2.

RQ2. What are the main causes for the identified improvement potential?

Several context-related categories provided insight into the environmental and socio-economic constraints surrounding production, including market pressure, workers' and supervisors' experience, and the physical limitations of the process.

Among the factors that can be controlled without substantial investment, uncontrolled water addition, operator-dependent vibration and compaction, and the absence of routine process and product measurements were identified as the most plausible primary contributors to strength variability. These factors showed directly observed variation and have clear links to the w/c ratio, compaction and porosity.

RQ3a. Which immediate process improvements could reduce the variability of current production?

It's recommended to define a shared knowledge on how to visually identify the sand moisture and the desired mix consistency, and avoid uncontrolled water addition. Upon achieving a more consistent mix wetness, a vibration time of about 6 seconds is also recommended to ensure adequate compaction. On top of this, block-weighing twice a day was suggested as an early-warning for process inconsistency.

The main objective of these measures is to improve process consistency and the reliability of block performance, independently of any immediate cement saving,

while remaining in the producer's current capabilities.

RQ3b. What indicative potential does partial substitution of Portland cement with calcined clay offer for reducing cement demand, cost, and CO2 emissions?

Assuming that partial substitution could maintain strength performance comparable to the PC reference, the indicative scenario would displace approximately 4.97 kg/m^2 of PC while adding 5.96 kg/m^2 of calcined clay. Considering only the reduction in cement consumption, this corresponds to a gross avoided cost of approximately 2,484 TSh/m^2 and avoided emissions of 3.48 kg CO_2/m^2.

The optimal substitution ratio on which the calculations are based on was derived from a study conducted on a mixture containing almost double the amount of cement encountered in this study. This makes the results indicative and further studies are needed to estimate the actual cement removal and clay addition.

RQ3. Which solutions could address the identified improvement potential?

The solutions identified in RQ3a and RQ3b are neither mutually exclusive nor necessarily the only feasible approaches.

RQ3a provides a more immediate response to the identified improvement potential by addressing inconsistencies within the existing production process. RQ3b instead introduces an alternative binder system, using CC to potentially maintain the required functionality while reducing PC-related costs and emissions. However, this solution also depends on a reliable and stable production process to ensure correct clay pre-processing and portioning.

While the partial substitution scenario presents higher saving in terms of cost and emissions, it's also noted that the calculations focus solely on the displaced cement; therefore, this study doesn't conclude any absolute best solution.

7.2 Implications for Future Research

A first priority for future research is to establish a realistic and appropriate compressive strength target for the blocks based on their intended function. This would require a more comprehensive engineering assessment that considers not only the expected structural loads, but also long-term durability, exposure to environmental conditions and the stability of the material over time. Establishing such a target would help determine whether the current production mix can provide sufficient strength and durability, and whether its low cement content allows adequate hydration and long-term performance.

At the production site, further research should focus on quantifying and validating the process improvements proposed in this study. Once an appropriate strength target has been established, a corresponding block weight and density range should be identified to support routine monitoring and the detection of production outliers. From this baseline, controlled trials should investigate the effects of water addition and vibration separately, identifying the conditions that provide the best and most consistent mechanical performance. Repeated measurements would also help determine whether the variability reduction assumed in this study is achievable under normal production conditions.

Beyond improving the existing process, other locally available binder alternatives should be investigated to better understand the potential for reducing reliance on PC. Agricultural ashes are particularly interesting given the amount of agricultural waste generated in the region that currently remains underutilised. RoCE2 could also represent an opportunity, considering the presence of a small local architectural molds factory producing potentially suitable gypsum waste material. However, the availability, composition and continuity of this waste supply would first need to be assessed, as the quantities may be insufficient to sustain block production or justify investment in a new manufacturing process.
For calcined clay specifically, future work should begin with a more detailed assessment of the identified local deposit to establish the quantity and suitability of the available material. A small-scale kiln for calcination and a mill for grinding could then be developed to allow the first trials under actual field conditions, rather than relying exclusively on laboratory results. Using local materials and equipment, these trials should investigate whether the findings of Malisa (2024) can be reproduced at the production site. Once the existing mix has been optimised in relation to the established strength and density targets, different cement-to-clay proportions should be tested at the producer's actual cement content to identify the best-performing combination. This would provide a more realistic understanding of the technical feasibility of substitution, while creating a basis for evaluating its economic and environmental implications under local production conditions.

Bibliography

Afolayan, J., Arum, C., and Ikumapayi, C. (2008). Characterisation of the compressive strength of sandcrete blocks in ondo state, nigeria. *Journal of Civil Engineering Research and Practice*, 5:15–28.

Awolusi, I., Aliu, S., and Oyeyipo, O. (2015). An appraisal of the quality of sandcrete blocks used for construction in lagos metropolis. *Journal of Building Performance*, 6:40–49.

Bogren, L. (2024). Cement reduction in sustainable building blocks: A kth field study in nepal. Master's thesis, KTH Royal Institute of Technology, Stockholm, Sweden.

Chen, C., Xu, R., Tong, D., Qin, X., Cheng, J., Liu, J., Zheng, B., Yan, L., and Zhang, Q. (2022). A striking growth of CO2 emissions from the global cement industry driven by new facilities in emerging countries. *Environmental Research Letters*, 17.

Fernandez, R., Martirena, F., and Scrivener, K. L. (2011). The origin of the pozzolanic activity of calcined clay minerals: A comparison between kaolinite, illite and montmorillonite. *Cement and Concrete Research*, 41(1):113–122.

Ilesanmi, M. F. (2025). Optimizing cement use in sustainable sandcrete blocks: Standardizing low-strength mortar testing and evaluating byf cement feasibility. Master's thesis, Chalmers University of Technology, Gothenburg, Sweden.

Isaksson, R. (2015). Making sense of opportunities in building material production. *The TQM Journal*, 27(6):781–797.

Isaksson, R. (2026). BLEX – block excellency – the BLEX blocks projects arusha, bukoba and dar es salaam. Project presentation, Engineers Without Borders – Tanzania (EWB-TZ). Unpublished project documentation, shared 21 July 2026.

Isaksson, R. and Babatunde, O. (2019). Opportunities for Improved Sustainability in House Building: The Case of Dar es Salaam. *African Journal of Science, Technology, Innovation and Development*, 11(4):457–463.

Isaksson, R. and Buregyeya, A. (2024). Understanding Sustainability – The Case of Building Blocks in Tanzania and Uganda. *The TQM Journal*, 36(7).

Isaksson, R. et al. (2026). Building Blocks Sustainability Improvement Potential in Sub-Saharan Africa – LC2 and Roman Concrete 2.

Isaksson, R., Garvare, R., Karapetrovic, S., Mauléon, C., Searcy, C., and Tontini, G. (2025). Quality for sustainability (q4s) – the case of sweden. In Ciasullo, M. V., Martin, J., and Brunetti, F., editors, *A Human-Centered Approach to Quality and Excellence in Management*, pages 43–67, Cham. Springer Nature Switzerland.

Isaksson, R., Idman, O., Lenhav, O., and Sätterman, J. (2012). Visualising improvement and innovation potential – the case of sustainable building in Dar es Salaam. In *Proceedings of the 15th QMOD Conference on Quality and Service Sciences*, pages 741–754.

Isaksson, R., Rosvall, M., and Babaahmadi, A. (2024). The Sustainability Opportunity Study (SOS) – The Case of Swedish Cement and Concrete.

Isaksson, R., Rosvall, M., Babaahmadi, A., Buregyeya, A., Hazarika, A., Marangu, J. M., Olonade, K., Ramanathan, S., Rucukye, A., and Valentini, L. (2023a). Supplementary Cementitious Materials in Building Blocks – Diagnosing Opportunities in Sub-Saharan Africa. *Sustainability*, 15(7).

Isaksson, R., Rosvall, M., and Ramanathan, S. (2023b). The Sustainability Opportunity Study (SOS) – Diagnosing by Operationalising and Sensemaking of Sustainability Using Total Quality Management. *The TQM Journal*, 35(5):1329–1347.

Janze, E. (2026). From volcano to block - a technical, economic and environmental evaluation of volcanic ash as a supplementary cementitious material for low-strength block production in northern Tanzania. Master's thesis, Uppsala Universitet.

Lumor, R., Abladeyb, L., Tikoli, D., Gand, A., Owusu, E., Offei-Nyako, K., and Edim, I. (2021). A comparative study of the quality of sandcrete cement blocks and quarry dust cement blocks. *Engineering Solid Mechanics*.

Malisa, M. A. (2024). Investigation on the performance of sandcrete blocks with cement partially replaced with calcined bukoba kaolinite clay. Master's thesis, University of Dar es Salaam.

National Bureau of Statistics (2026). Statistical Abstract 2025. Technical report, National Bureau of Statistics, Dodoma, Tanzania. Chapter 8, Table 8.1: Production and Consumption of Cement, Tanzania Mainland, 2009–2025.

Neville, A. M. (2011). *Properties of Concrete*. Pearson Education, Harlow, UK, 5th edition.

Paul, L. (2026). The Role of Building Materials and Architecture in Achieving Sustainable Housing in the Global South - A Case Study from Tanzania. Master's thesis, Luleå University of Technology.

Sabai, S., Isaksson, R., Kinabo, L., Maganga, J., and Minja, S. (2016). Relevance, consequences and change needs of the current tanzania concrete bricks and blocks standard tzs 283:2002. In *2nd International Conference on Advances in Cement and Concrete Technology in Africa 2016 :*, pages 623–634.

Sabir, B. B., Wild, S., and Bai, J. (2001). Metakaolin and calcined clays as pozzolans for concrete: A review. *Cement and Concrete Composites*, 23(6):441–454.

Tanzania Bureau of Standards (2025). Concrete masonry units — specification (tzs 283:2025, 3rd ed.). Technical report, Tanzania Bureau of Standards (TBS).

The Lancet Public Health (2025). Housing: a determinant of health and equity. *The Lancet. Public health*, 10(10):e804.

Tusting, L. S., Bisanzio, D., Alabaster, G., Cameron, E., Cibulskis, R., Davies, M., Flaxman, S., Gibson, H. S., Knudsen, J., Mbogo, C., Okumu, F. O., Jawororkar, N., Lindsay, S. W., and Bhatt, S. (2019). Mapping changes in housing in sub-saharan africa from 2000 to 2015. *Nature*, 568(7752):391–394.

UNEP (2024). Global status report for buildings and construction: Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector. Technical report, United Nations Environment Programme (UNEP), Nairobi, Kenya.

United Nations (2024). World population prospects 2024.

United Nations (2025). World urbanization prospects: The 2025 revision, online edition.

Yin, R. K. (2018). *Case study research and applications: design and methods*. SAGE Publications, Incorporated, sixth edition.

A

Supplementary Data and Material

A.1 The 10M Checklist

Table A.1 summarises the ten categories of the 10M checklist (Isaksson, 2015), used to structure the cause analysis in section 4.3.

Table A.1: Description of the 10M checklist categories

Category	Description
Mission	The purpose and intended output of the process.
Management	Decisions, planning and follow-up governing the process.
Method	The defined or informal procedure used to carry out the process.
Manpower	The people carrying out the process, including their skills and judgement.
Measurement	How process and product performance are monitored and recorded.
Machine	The equipment used to carry out the process.
Material	The raw materials and inputs consumed by the process.
Milieu	The physical and organisational environment surrounding the process.
Market	The customers and market conditions the process serves.
Means	The financial and technical resources available to change the process.

A.2 Block Weight, Dimensions and Density Data

This section reports the raw per-block dataset underlying the block weight, dimensions and bulk-density results in chapter 4 (Table A.2 and Table A.3).

A.2.1 Block Dimensions

Six blocks, all from batch 7, were individually measured for width, length and height (each dimension measured twice), and their averages were used as the representative batch dimensions applied to the full weighed sample (Table A.3). Block IDs follow the batch.block numbering introduced in Table A.3 and are specific to this dimension measurement; they do not identify particular rows of Table A.3.

Table A.2: Individual dimension measurements for the six representative blocks (batch 7)

Block ID	**Width (mm)**		**Length (mm)**		**Height (mm)**	
	1st	2nd	1st	2nd	1st	2nd
7.1	125	124	462	462	225	225
7.2	122	125	463	462	227	228
7.3	125	126	461	460	231	230
7.4	126	125	461	461	226	225
7.5	126	128	462	462	226	225
7.6	123	122	462	462	227	228
Batch average	**124.75**		**461.67**		**226.92**	

A.2.2 Block Weight, Bulk Density and Strength Test Results

Table A.3 reports the weight and bulk density of all $n = 30$ sampled blocks, whether each block was sent for compressive-strength testing, and, where a corresponding record could be identified in the strength-test dataset, the registered failing load and compressive strength. Blocks were matched between the weight and strength-test datasets by weight. Block IDs are given as *batch.block*, where *batch* is the production batch number (subsection 4.1.3) and *block* is a sequential counter within that batch; rows are ordered by ascending batch number. Batch 7 was not sent for strength testing.

Table A.3: Block weight, bulk density and, where available, strength-test results, by batch (n=30)

Mix ID	**Block ID**	**Weight (kg)**	**Bulk density (kg/L)**	**Tested for strength**	**Fail load (N)**	**Strength (MPa)**
2	2.1	26.30	2.013	Yes	70,000	1.212
3	3.1	27.61	2.112	Yes	70,000	1.212
4	4.1	27.34	2.092	Yes	70,000	1.212

Table A.3: (continued)

Mix ID	Block ID	Weight (kg)	Bulk density (kg/L)	Tested for strength	Fail load (N)	Strength (MPa)
4	4.2	26.98	2.064	Yes	75,000	1.299
4	4.3	26.36	2.017	Yes	80,000	1.385
4	4.4	27.43	2.099	Yes	105,000	1.818
4	4.5	27.89	2.134	Yes	100,000	1.732
4	4.6	27.98	2.141	Yes	85,000	1.472
4	4.7	28.30	2.165	Yes	120,000	2.078
5	5.1	25.28	1.934	Yes	80,000	1.396
5	5.2	26.04	1.993	Yes	100,000	1.732
5	5.3	26.55	2.032	Yes	80,000	1.385
6	6.1	24.78	1.896	Yes	80,000	1.385
6	6.2	24.91	1.906	Yes	75,000	1.299
6	6.3	25.80	1.974	Yes	80,000	1.385
6	6.4	25.75	1.970	Yes	110,000	1.905
6	6.5	26.33	2.015	Yes	75,000	1.299
7	7.1	28.50	2.181	No	–	–
7	7.2	27.30	2.089	No	–	–
7	7.3	28.95	2.215	No	–	–
7	7.4	28.25	2.162	No	–	–
7	7.5	27.55	2.108	No	–	–
7	7.6	26.70	2.043	No	–	–
7	7.7	27.70	2.120	No	–	–
7	7.8	27.30	2.089	No	–	–
7	7.9	28.85	2.208	No	–	–
7	7.10	27.70	2.120	No	–	–
7	7.11	28.85	2.208	No	–	–
7	7.12	28.25	2.162	No	–	–
7	7.13	27.90	2.135	No	–	–

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se



CHALMERS
UNIVERSITY OF TECHNOLOGY