



CHALMERS
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Interlocking CSEB buildings in Nepal

Performance and failure behaviour investigated by masonry prism and triplet shear testing

Master's thesis in the Master's Programme Structural Engineering and Building Technology

Kajsa Lilja
Kalle Edström

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF STRUCTURAL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
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Department of Architecture and Civil Engineering
Division of Structural Engineering
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone +46 31 772 1000

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An image of a one and a half story interlocking CSEB building under construction. Photo by Kalle Edström.

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AI-use statement

Artificial intelligence (AI) tools have been used to support the coding of data representation, support writing by critique and rephrasing of certain sentences.

ABSTRACT

Nepal is situated in-between the Indian and Eurasian tectonic plates resulting in a long standing history of seismic activity. The company Build up Nepal, was founded as a response to the major 2015 earthquake in Nepal and works with interlocking Compressed Stabilised Earth Blocks (CSEBs) which are made up from soil, sand, cement and water which are compressed and cured. Build up Nepal works with engaging communities, creating jobs and helping people build their own house as well as providing engineering services.

Modern interlocking CSEBs present a viable alternative in reconstructing seismic resilient houses in a economical way, yet its complex structural behaviour lacks universally established building codes. Build up Nepal seeks to make this construction method standardised in Nepal and get further government approval for the system. In order to achieve approvals, more reliant data on the performance of their system is needed.

Based on the system implemented by Build up Nepal, this thesis investigates methods of testing and possible improvements for interlocking CSEB masonry. By exploring how testing can be done in a simple way, which parts of the system contribute to overall strength, and what improvements are feasible in rural Nepal, this thesis aims to support Build up Nepal's goal of standardising this construction method.

The standard *Determination of initial shear strength* was adapted for the equipment available in the workshop connected to Build up Nepal's office in Kathmandu and a testing plan was developed. Together with experimental testing a field trip to constructions sites in western Nepal was conducted to understand the circumstances and context.

During testing, several limitations of the setup were acknowledged. The precision of certain testing equipment was low, indicating that a future step for the company is to move testing to a laboratory environment. A key issue with the test setup was the unintended increase of pre-compression loads; these are supposed to remain constant, which proved impossible with the current equipment.

The results from the experimental testing demonstrate that increasing the cement content in grout and adding bed mortar improves overall system strength. However, insights from the site visit show that grout mix might be varying and application of bed mortar potentially is a challenge. The interlocking keys do not only support alignment during mason but also provides a 83% gain in shear strength compared to specimens without the keys. The recommendations are to continue using the interlocking keys and to further investigating bed mortar before widely adopting it in construction. Moreover, the cement to sand ratio of one to three should be used and simple measuring equipment should be provided to ensure consistency in batch size and mix proportions.

Key words: Nepal, Earthquake, Interlocking, CSEB, Shear, Masonry, Keys, Grout, Mortar, Capacity.

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Preface

This master's thesis has been conducted as a collaboration between Engineers without borders (EWB), Build Up Nepal (BUN) and Sweco, at the Department of Architecture and Civil Engineering, Division of structural engineering, Chalmers University of Technology.

First, we would like to thank EWB for making this collaboration possible, and especially Henrik Gustavsson for guidance during the grant application process. By the generous donation from the Kullman family through the global mentorship program, a field study trip to Nepal was possible, which was essential for data collection. We would also like to thank our mentors, Karin Falk and Fredrik Elieson, for their support and valuable discussions before and during our time in Nepal. Thanks to Micelle Godio for his expertise in testing and masonry structures giving us valuable insights and support.

This work would not have been possible without the warm welcome and continuous support we received from everyone at Build up Nepal. Their knowledge, openness, and commitment to innovation created an inspiring working environment and made it possible for us to collect the data required for this study. Living and working closely with the team in Nepal also gave us valuable insights into the practical challenges and opportunities within local construction practices. A special thanks to Aavash Shrestha for his help with everything and making out time in Nepal truly memorable.

We would also like to express our gratitude to our supervisor and examiner, Joosef Leppänen for continuous support throughout the project. Finally, we would like to thank Emy Tiderman and Carl Hoff from Sweco for their support and expertise in structural engineering.

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Kajsa Lilja

Kalle Edström

Notations

Roman upper case letters

BUN	Build Up Nepal
CSEB	Compressed Stabilised Earth Block
CSSB	Cement Stabilised Soil Block
CV	Coefficient of variation
FEM	Finite Element Model
ICEB	Interlocking Compressed Earth Block
NBC	Nepal National Building Codes
OPC	Ordinary Portland Cement
PC	Pre-Compression
PGA	Peak Ground Amplitude
RC	Reinforced Concrete
w/c	Water-Cement Ratio

Notation

A_i	Cross-sectional area of specimen [mm ²]
CO_2	Carbon dioxide [–]
E_i	Modulus of elasticity [MPa]
E_m	Mean modulus of elasticity [MPa]
F_{cr}	Critical crack load [kN]
$F_{i,uc}$	Ultimate compressive load [kN]
$F_{i,us}$	Ultimate shear load [kN]
F_{pi}	Pre-compression load [kN]
f_{cr}	Critical crack stress [MPa]
f_m	Mean compressive stress [MPa]
f_n	Normal compressive stress [MPa]
f_{pi}	Pre-compression stress [MPa]
ϵ_i	Strain [–]
μ	Coefficient of friction [–]
τ	Joint shear strength [MPa]
τ_m	Mean shear strength [MPa]
τ_{v0}	Initial shear strength [MPa]
ϕ	Angle of friction [°]

1 Introduction

Situated on the highly active boundary between the Indian and Eurasian tectonic plates, Nepal has a long history of destructive earthquakes. In 2015, Nepal experienced the largest earthquake since 1934, with a magnitude of 7.8. Two weeks later, another major earthquake with a magnitude of 7.6 struck the country. These seismic events had severe consequences, 8,891 people were confirmed dead and more than 22,000 people injured. In addition approximately 605,000 houses were destroyed and 288,000 houses damaged, highlighting the significant vulnerability of the buildings under seismic load (OCHA, 2015). November 2023, another big earthquake hit Nepal damaging 62,000 homes in the western rural regions of the country (Government of Nepal & United Nations Humanitarian Country Team, 2024).

The non-profit organisation Build Up Nepal (BUN), was founded in response to the 2015 Gorkha earthquake (Build Up Nepal, 2025). BUN aims to promote the development of safe, green and affordable houses for all. The solution is interlocking Compressed Stabilised Earth Blocks (CSEBs), made from a mix of soil or stone dust, cement, and water. The components are mixed either manually or with mechanical mixers. The mixture is then pressed using hand-powered machines provided by BUN.

During an earthquake large lateral movements are introduced, generating horizontal forces and shear stresses in walls, beams and columns. Low shear strength can lead to brittle and sudden failures, hence the shear capacity of a masonry system is important.

BUNs work has a strong connection to entrepreneurship and innovation. Their work has led to a reduction of over 100,000 tons of CO₂ emissions and created more than 2,000 full-time jobs, 25% of which are held by women (Build Up Nepal, 2022). The blocks are produced on site by local workers, ensuring local engagement and skill development. Since its inception, BUN has supported over 300 small businesses and helped construct more than 12,000 homes across Nepal. By, 2030 they aim to have built 100,000 houses, saved 1 million tonnes of CO₂ emissions and continued to expand the system to south Asia (Build Up Nepal, 2022).

1.1 Aim and objectives

The aim of this thesis is to; develop a test methodology applicable in Build up Nepal's workshop, build a reference set of test data and find structural improvements options of interlocking CSEB adoptable in rural Nepal, associated with shear performance. More specifically it will answer the research questions:

- RQ1. How can the shear capacity of interlocking CSEB be determined in a simple way?
- RQ2. Which components of the interlocking CSEB system contribute the most to the shear strength?
- RQ3. Which of these structural improvements are practically feasible to implement in rural Nepal?

1.2 Limitations

Several external and internal limitations are imposed on the study because of local constraints and to keep the scope of the thesis manageable. The thesis focuses on the geometric and material configuration of CSEBs provided by BUN at this time. Alternative block mixtures and geometries are outside the scope of this thesis.

Due to the accuracy of the available laboratory and testing equipment being utilised, no characteristic material parameters are obtained. Consequently, no comparison with required design shear capacity is performed.

1.3 Methodology

The methodology to answer the research questions are: literature review, site visit and laboratory testing. The initial phase focuses on developing the methodology in collaboration with participating stakeholders.

A literature study is conducted to understand CSEB:s and regulations by Nepal National Building Codes (NBCs). Additionally, previous studies performed, both in collaboration with BUN and others, on the subject of CSEB:s are read during the literature review.

Site visits are used to understand the building site and construction process, which is vastly different from conventional western conditions. These visits are essential for development and suggestions of reasonable improvements.

Experimental testing is used to find relative strength and find possible improvements. For each test, a specification is written describing how the test should be prepared, how the load is applied, and how the results are measured to make the test reliable and repeatable. To the extent possible testing standards are available, those standards are used.

1.4 Societal, ethical and ecological aspects

Writing a master thesis in a socio-economically vulnerable country carries a responsibility to contribute and transfer knowledge in a respectful and meaningful way. This project was conducted in close collaboration with Build up Nepal that already works actively with education and engaging local entrepreneurs and communities. The knowledge and findings from this thesis can therefore be effectively implemented in the context.

To perform data collection, travelling to Nepal was necessary. Being there made it possible to collaborate and discuss everyday issues, making all participants part of the process. It also enabled testing on the blocks Build up Nepal produces and development of a method tailored to Build up Nepal's context making it actually valuable.

Knowledge gained orally was noted down during conversation to be captured accurately. To be represented in the correct way, the final texts were sent for review to all participating individuals before finalised.

2 Earthquakes

Earthquakes are the most destructive natural phenomena regarding both social and economic consequences. During the last century, earthquakes are responsible for 1,260,000 fatalities and more than 10 millions of seriously injured people worldwide. Earthquakes are unpredictable and oscillatory in nature, understanding their nature is critical to prevent damage (Jia, 2018).

The tectonic plates are in constant movement towards each other. As plates move relative to each other, friction along the boundaries prevents smooth motions, causing stress accumulation. When two plates collide the plates deform and build up stress. When this stress increases to a level beyond the strength of the plates a sudden slip (elastic rebound) occurs. The elastic rebound releases the stored energy in forms of seismic strain waves producing an earthquake. A major earthquake may also trigger local aftershocks within days, limited to a distance away from the epicentre of the earthquake. Tectonic related earthquakes are responsible for about 90% of all earthquakes (Armouti, 2015).

2.1 Measuring of earthquakes

The size of an earthquake is characterised by its magnitude, representing the total energy released at the source, while the effect experienced at different locations is described by the intensity, which depends on the site condition and distance from the epicentre. The magnitude is measured by the Richter Scale representing a logarithmic function of the amplitude (Armouti, 2015). The intensity is a subjective measurement called Mercalli scale and based on the human feelings and observation, typically divided into 12 grades, from “not felt” to “total damage”.

From an engineering perspective, accelerograms are widely used to represent the earthquake loading for seismic analysis, as they provide a quantitative measure. An accelerogram records the ground acceleration as a function of time. The largest absolute acceleration recorded during an earthquake is defined as the peak ground acceleration (PGA) (Douglas, 2003). PGA is one of the most commonly used intensity measurements in seismic engineering and form the basis for seismic hazard mapping and seismic engineering parameters in several building codes (“Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings”, 2004), (Kramer, 1996). Data on peak ground accelerations can be used to model and understand worst case scenarios for structures during seismic events.

2.2 Earthquake history in Nepal

The documented earthquake history of Nepal dates back to the 13th century. However, early records lack details regarding exact location and magnitude. According to the Nepalese government it is estimated that close to a third of the population in the Kathmandu Valley was killed during the earthquake 1255. The most recent earthquake with more reliable data and descriptions is the earthquake in 1833, which significantly

affected the Kathmandu Valley with a magnitude of 7.8 and caused widespread damage (Government of Nepal and Development Partners, 2015).

1934 the Nepal-Bhiar earthquake with an estimated magnitude of 8.1 struck Nepal. This earthquake resulted in more than 16,000 fatalities and extensive damage to infrastructure in Nepal and India. Another major earthquake occurred in 1988, the Udayapur earthquake, which struck eastern Nepal with a magnitude of 6.9, causing considerable structural damages (Government of Nepal, 2025).

In 2015 the Gorkha earthquake hit Nepal with a magnitude of 7.6, it was the largest natural disaster in over 80 years in Nepal. The earthquake was followed by over 300 aftershocks with magnitudes greater than 4.0. Four major aftershocks with a magnitude over 6.0 were determined. The disaster was large, 8,891 people were confirmed dead and more than 22,000 injured. The destruction was widely spread, over half a million buildings were destroyed including, schools, resident buildings and historical buildings (Government of Nepal and Development Partners, 2015). The most recent major earthquake in Nepal occurred in 2023 and had its epicentre in the Jajarkot district in western Nepal. It reached a magnitude of 6.4 with over 300 aftershocks causing major damage (Government of Nepal & United Nations Humanitarian Country Team, 2024).

Following the Udayapur earthquake 1988, the Nepalese Government initiated a systematic effort to develop and improve the national building codes and the standard *NBC 105 Seismic Design of Building in Nepal* was published in 1994. After the Gorkha earthquake 2015, the code underwent a major revision published 2025, resulting in the current standard NBC 105:2025 (Government of Nepal, 2025). The primary objective of NBC 105:2025 is to ensure that buildings are designed to achieve an acceptable level of safety during seismic loading. The structure shall be capable of withstanding seismic actions corresponding to a return period of 475 years without experiencing structural collapse. Furthermore, damage to essential non-structural components, especially those critical for evacuation, shall be limited to ensure safe evacuation. The buildings shall be designed to withstand seismic actions with a return period of 20 years, ensuring limited and repairable damages (Government of Nepal, 2025).

2.3 Building response during earthquakes

During an earthquake, the ground moves, giving rise to lateral movement of the building. These movements, in turn, result in inertia forces according to Newton's second law: $F = m \cdot a$. This induces vibrations, bending, and shear stresses in the structure (Tomazevic, 1999). Masonry inherently exhibits low resistance to out-of-plane bending but possesses strength in-plane. To effectively manage seismic loads, buildings must transfer horizontal forces to these stronger, in-plane walls. This load transfer is typically achieved through diaphragm action provided by the floor structure or, in the case of interlocking CSEB systems, through reinforced concrete (RC) seismic bands. This is what creates what is called a "box action" of the building, making the whole building accelerate as one box distributing the lateral forces to all walls.

However, directing forces to the in-plane walls is only effective if the masonry system itself is robust. Structural irregularities in the floor plan, excessively large openings, and

poor material quality compromise the structural integrity of masonry buildings. When the transferred seismic forces exceed the in-plane shear capacity of the walls, it commonly leads to severe damage or collapse. This failure often manifests as sliding along the bed joints (sliding shear) or as characteristic diagonal tension cracks in the load-bearing piers between windows (Tomazevic, 1999).

3 Build up Nepal

This chapter outlines Build up Nepal's work and the interlocking CSEB building system. It details how an interlocking CSEB house is constructed in the field and introduces how BUN operates economically and socially. The chapter examines the post-earthquake reconstruction efforts by BUN specifically within the Jajarkot and Rukum districts. Finally, it summarises the current state of technical research and material testing conducted by Build up Nepal to date.

3.1 Interlocking CSEBs

Build up Nepal's construction model is based on Interlocking Compressed Stabilised Earth Block (CSEB) technology, incorporating several block variants and material compositions adapted to locally available resources. The primary raw material consists of locally sourced soil or stone dust, sand, cement, and water. Uniform and strong masonry units are achieved by compacting the mixture under high pressure using a manual press and letting the cement cure.

The blocks are designed with an interlocking geometry consisting of a male and female dowel, which enable automatic alignment between courses and provide a mechanical interlock between adjacent layers, shown in Figure 3.1. This reduces construction errors and minimise the need for skilled labour.

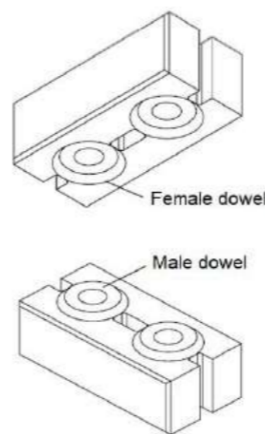


Figure 3.1: Illustration of interlocking CSEB units showcasing male and female keys (dowels). Illustration by Build up Nepal

Unlike conventional kiln-fired bricks, CSEBs are not subjected to high temperature firing. Instead soil, sand, cement and water are mixed and pressed to blocks before being water cured and air dried, this procedure takes around 40 days in total. Removing the need for kiln-firing lowers CO₂ emissions. With a single manual press approximately 400 - 500 blocks can be produced in a working day. Sourcing of soil, mixing of materials and pressing of CSEBs can be seen in Figure 3.2.



(a) Soil procurement and soil sieving machine.



(b) Block pressing machine with block being pressed.



(c) Soil, sand, cement and water mixing.

Figure 3.2: Overview of the block production.

When constructing a house a foundation is first dug out before being filled with large aggregate concrete. Reinforcement is anchored in foundation and extends vertically. A reinforced concrete plinth band is cast before the interlocking CSEB is laid on top. The foundation dug out and plinth band are shown in Figure 3.3.



(a) Foundation dug out of house. Vertical rebar prepared for anchoring.



(b) Foundation and plinth band cast with vertical rebar sticking up.

Figure 3.3: Foundation preparation and casting of plinth band with vertical rebar.

Once cured, the blocks are assembled in a running bond on top of a concrete foundation and beam. The interlocking system guides placement and no bed mortar is used in the horizontal joints between blocks, instead the block cavities, the two circular holes, the central rectangular void and the two side voids are filled with cement-sand grout.

To enhance structural integrity the CSEB walls are reinforced with both vertical and horizontal steel reinforcement. Vertical reinforcements are placed at regular intervals (typically every 1.2 meter) as well as at the critical locations such as corners, wall intersections and around openings. These reinforcements are anchored into the reinforced concrete foundation. The horizontal reinforcement is provided through reinforced concrete bands (RC bands) placed at key levels, including below and above openings, as well as at the top of the wall, as seen in Figure 3.4. These bands act as tie elements, improving the overall stability. Gable walls, forming triangular wall sections, supports the roof structure and are constructed using full and half blocks. Once the gable wall is completed a final tie band beam is cast at the top, after which the roof structure can be installed. Figure 3.5 shows an overview of superstructure construction, grout filling of voids, rebar preparation for RC band, casting of sill band and roof construction.

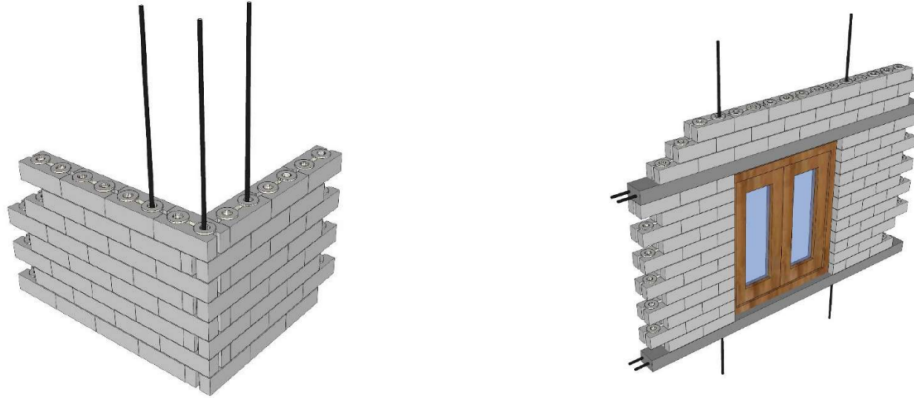


Figure 3.4: Vertical reinforcement in corner and RC-bands at window opening.



(a) Grout pouring in CSEB voids.



(b) Rebar preparation for lintel band.



(c) Casting of sill band.



(d) Laying of roof beams on gable wall.

Figure 3.5: Construction process of interlocking a CSEB house.

3.2 Business model

The information in this chapter is based on communication with employers at Build up Nepal during the site visit in Jajarkot, Nepal (20-26/3, 2026)

Build up Nepal has two models regarding their business, an entrepreneur based model where they sell the machine to an entrepreneur wanting to sell the blocks and a community based model where the machine is lent to a community without cost.

The process of becoming an entrepreneur begins with an individual expressing interest to become a CSEB entrepreneur. The entrepreneur then invests in a CSEB production machine, with a typical cost ranging from 200,000 to 400,000 NPR, (about 12,000 - 24,000 SEK) depending on the machine specification. After purchase, BUN provides a four-day initial training program free of charge. This training focuses on the production of CSEBs, including material selection, mixing procedure, compression techniques and basic quality control. In addition to the initial training, BUN offers continuous technical support to ensure proper implementation, quality and to assist with any operational challenges.

Entrepreneurs operate independently and are responsible for setting the market price of the blocks and finding their customers. However, they are encouraged to inform BUN about ongoing construction projects using their blocks. This enables BUN to provide technical guidance during the construction phase and promote the correct use of the interlocking CSEBs. To maintain quality, BUN conducts follow-up visits approximately every three months.

In addition to the entrepreneur-driven model, BUN also implements a community based approach. A local community comes together and the construction is typically carried out collectively by the members themselves, often without hiring external labour. Through external donations, BUN can provide communities with CSEB compression machines and training free of charge. Once the construction projects within a community are complete, the compression machine is either relocated by BUN to another area in need or, someone in the community chooses to purchase the machine to establish a local enterprise.

3.3 Work in Jajarkot and Rukum

Jajarkot and Rukum are two mountainous and hilly districts situated in the middle Himalaya of western Nepal. The terrain is characterised by significant elevation variations and they suffer from limited infrastructure. Low access to drinking water, sanitation and electricity contributing to the remoteness. The two districts have a population of approximately 400,000, with the majority living in rural settlements and many households depending on agriculture and seasonal migration. Jajarkot and Rukum are considered two of the poorest and most remote districts in Nepal (Central Bureau of Statistics, 2012). Jajarkot is marked on the map of Nepal in Figure 3.6.



Figure 3.6: Jajarkot district marked in red. Drawn by Hégésippe Cormier and licensed under CC3

In the evening of November 3rd 2023, an earthquake of magnitude 6.4 struck the region, followed by more than 300 aftershocks. The event caused widespread destruction across the region. The severity of the impacts can be explained largely due to weak housing construction, mainly made of stone and mud masonry. In total, approximately 250,000 people were affected with 154 fatalities and 366 injured. More than 60,000 households were either partially or completely damaged (Government of Nepal & United Nations Humanitarian Country Team, 2024).

The Nepali governments responded to the humanitarian disaster, initially lifesaving actions with support from other countries and organisations was prioritised. Temporary shelters and basic sanitary were provided through government donations. The lifesaving phase was followed by recovery and reconstruction. Through the government cash grant reconstruction of the region has started (Government of Nepal & United Nations Humanitarian Country Team, 2024).

Prior to the earthquake 2023, Build up Nepal had established two local entrepreneurs in Jajarkot and the neighbouring district Rukum. In the region approximately 20 buildings had been constructed using the interlocking CSEB technique. BUN performed a damage assessment after the earthquake and a total 16 buildings were inspected. According to the internal damage report, none of the CSEB buildings exhibited visible structural damage. Several important observations were made, two thirds of the CSEB buildings lacked the seismic band, which is considered a critical feature for earthquake resistance. Despite this, no structural damage was observed on buildings. One exception was identified in a school building, where severe cracks were observed. This was attributed to insufficient spacing between the adjacent building, which caused a "hammering effect" during the earthquake. This finding highlights the importance of following building codes regulating the minimum distance between structures.

In contrast, approximately 95% of the houses constructed with traditional stone and mud mortar were either totally damaged or had severe structural cracks. These houses did not follow any building code, had no seismic band and round stones were used instead of flat stones. Buildings with solid concrete blocks cast on site performed better than the stone house but the lack of reinforcement caused structural damages. Houses with RC and stone masonry infill walls also did not follow building code, lacked seismic bands and subsequently showed severe cracks.

The number of local entrepreneurs collaborating with BUN has over the last years increased to approximately 50 in Jajarkot and Rukum districts. This expansion reflects the growing demand for rebuilding resilient housing post-disaster. To meet the increasing demand of houses in the region BUN opened an office mainly focusing on technical support. The office consists of several site engineers monitoring key parts of construction, answering queries and help assuring good workmanship is practised, team-leaders handling more long-term questions, establishing of new enterprises and building sites, sales, and marketing personnel.

In these regions there is production of both interlocking CSEBs (compressed earth) and interlocking stone dust blocks. The choice is based on availability on site to minimise costs. Both material bases follow the same production method and are assumed to have comparable strength according to Build up Nepal.

3.4 Research

Much of the material properties of Build up Nepal are based on research done on similar blocks in other countries (Maniini Satprem, 2005). Simple tests have been done in external labs and internal testing in a workshop-setting to ensure compliance with existing guidelines on compression strength. No large scale laboratory test has yet been performed on blocks produced by Build up Nepal.

Decisions on development of block and changes have been based on theoretical analysis done by in-house engineers, external consultants, third-party research on similar blocks, and feedback from the field: both from supervising engineers, masons and homeowners. A recent effort to get more effect of grout channels was made, increasing the diameter on the circular voids.

To yield reliable data, a rigorous and long-term research strategy is essential. Build up Nepal is actively working toward a more diligent approach, making clear efforts to establish a baseline database and structure future testing frameworks systematically.

4 State of the art in CSEB

Compressed Stabilised Earth Blocks (CSEBs) are simple masonry units which can be produced with little experience and with mostly local and inexpensive materials. There exists multiple different names of the same and similar variants of blocks in different literatures: Cement Stabilised Soil Block (CSSB), (Weed et al., 2020) Interlocking Compressed Earth Block (ICEB) (Qu et al., 2012). To ensure terminological consistency this thesis uses the term, interlocking CSEB (or only CSEB) in accordance with Build up Nepal's nomenclature.

While earth construction is an ancient practice, the development of modern interlocking CSEB systems represents a novel and rapidly evolving field of study. No general agreed upon building codes exist for CSEB or interlocking CSEB construction. Current research is broad, with various block geometries, stabilisation methods, and construction techniques being investigated in parallel to optimise structural performance, ease of construction, price, and sustainability. This section presents an overview of recent advancements and the established mechanical behaviours of both individual CSEB units and assembled masonry systems.

4.1 CSEB units

CSEBs are made from up to 90% earth materials such as soil and sand with addition of water and a stabiliser. Unlike traditional fired brick, CSEB does not require a burning procedure during manufacturing. Instead, the soil mix is compacted under high pressure to enhance mechanical stabilisation within the material. The compaction rearranges and increases the contact of the soil particles to enhance a denser structure with fewer voids. This improves the strength and durability while also reducing the materials sensitivity to moisture and water exposure (Seco et al., 2017). Compaction efforts are studied by (Mahdad et al., 2021) and the study concluded an increase of 72% when going from a compaction effort of 2 to 5 MPa and an increase of 13% when going from 5 to 7 MPa.

Portland cement is the most commonly used stabiliser to improve the strength and durability of blocks. Cement content between 5-10% is generally considered sufficient for achieving adequate structural performance while limiting environmental impact (Walker, 1995; Minke, 2006). However, due to the high carbon emission associated with cement production, alternative stabiliser such as fly ash, lime and rice husk ash have been investigated as partial cement replacement (Sinha et al., 2026) but despite the ongoing research on alternative stabiliser, cement remains the dominant choice. A study by Mahdad et al. (2021) on cement content in CSEBs shows an increase in strength with each incremental increase in cement percentage, from 0% up to 8%, with the 8% mixture yielding the highest strength. Similar results are found by (Karemba et al., 2026) showing how increase in cement gives a close to linear increase in compressive strength of blocks in the 2-10% range.

4.2 CSEB masonry and triplets

Traditional CSEBs masonry relies primarily on the mortar joints to ensure load transfer and alignment. In contrast, the interlocking CSEB technology employs a mechanical interlocking locking mechanism between the blocks, which improves construction efficiency and reduces, or in some systems eliminates, the need of mortar (Vivek Prasad et al., 2014). Although the geometry of the interlocking system varies among different CSEBs systems, their fundamental purposes remain the same. The use of dry stacking the masonry significantly reduces the construction time and lower the demand for highly skilled labour. However, several studies have shown that block imperfections, height variations and surface roughness have a considerable influence on the compressive load bearing capacity of dry stacked masonry, as the stress concentrations develop at the contact points between blocks (Yehia et al., 2019).

One effective way to improve the compressive load-bearing capacity and the overall structural performance of interlocking CSEB walls is to introduce vertical reinforcement combined with grout. Experimental studies demonstrate that reinforced grout-filled cavities significantly enhance the axial load capacity and stiffness of CSEB (Tripura and Kasinikota, 2023; Yehia et al., 2019). The use of grout provides a more uniform stress distribution and the reinforcement contributes to increases axial and lateral performance.

Although many interlocking CSEB systems are designed for dry stacking construction, the addition of bed mortar can significantly improve the structural performance of the masonry. According to Prasad et al. (2014), the use of bed-mortar in an ungrouted system increased the flexural strength by 46 % and shear strength by 23%. The improvement is primarily attributed to a more uniform load distribution between the blocks, reduced stress concentration at the contact surface and ability to resist loads in multiple directions.

A study on geometry parameters of CSEBs concluded weight and reinforcement capabilities as the most important factors when asking an expert panel of field engineers, masons, academics and architects (Khan et al., 2025). Showing that structural performance and constructibility in terms of labor-ergonomics were valued most important.

The shear capacity of dry-stacked masonry is highly dependent on the applied compressive load, as increased vertical compression enhances frictional resistance up to a limit. A study by Karemba et al. (2026) on interlocking blocks demonstrated this phenomenon by testing triplets under compressive stresses ranging from 10% to 60% of their ultimate compressive strength. They observed that the shear strength steadily increased with each 10% increment up to 50%. However, at a 60% load ratio, the shear strength decreased. This reduction is attributed to the high stress confinement, which induces early material crushing and accelerates crack propagation, causing the blocks to fail before their maximum frictional sliding capacity was reached.

The compressive strength of CSEBs exhibits a progressive reduction as the structural level increases from a single unit to prism and full scale walls. According to Saari et al. (2025), the compressive strength of a prism is approximately 24 % the unit, while the full scale wall further reduced to about 13%. A study on alkaline stabilised CSEB shows

a reduction to 40 % of the unit's strength in a dry stacked masonry prism (Silva et al., 2015). A third study focusing on material parameters got results with less difference between units and prisms, moving from an average strength of 6.03 MPa in units to 4.46 MPa in the prism (five in height and dry stacked) (Nadeem et al., 2023), showing relative strength of a prism 74 % to that of a unit.

4.3 Material data of CSEB

The composition of the sand used in CSEB is an important factor affecting the performance and durability of the block. Table 4.1 presents the recommended soil composition for CSEB production according to (Government of Nepal, 2012; Maniini Satprem, 2005).

Table 4.1: Recommended soil composition.

	Sand [%]	Silt [%]	Clay [%]	Gravel [%]
Soil	50	15	20	15

The final material properties of CSEB are strongly influenced by the soil characteristics, cement content, and production method. Consequently, the material properties are typically presented as ranges rather than fixed values, as summarised in Table 4.2. This is to be seen as an indication rather than design values.

Table 4.2: Typical material parameters for CSEB.

Property	Range	Unit
Dry density	1900–2000	kg/m ³
Dry compressive strength	3–10	MPa
Wet compressive strength	2–3	MPa
Shear strength (28 days, dry)	1–2	MPa
Modulus of elasticity	700–1000	MPa
Poisson's ratio	0.15–0.25	–

Note: Data estimated from various sources (Maniini Satprem, 2005; Government of Nepal, 2012).

4.4 Material models

Material models are theoretical and mathematical frameworks used to describe the physical and mechanical behaviour of a material under load. For a complex, composite system such as interlocking CSEB masonry, understanding structural response requires an understanding of its constituent properties. These theoretical models provide the necessary foundation to accurately interpret experimental test data.

This chapter presents the theoretical background for key material properties and interaction mechanisms governing the structural performance of interlocking CSEB. The chapter begins by introducing the modulus of elasticity it then transitions into interface mechanics, examining the roles of friction, cohesion, and adhesion, which collectively dictate the shear transfer and bond strength between the masonry units and the mortar. Finally, the structural contribution of mechanical interlocking shear keys is presented.

4.4.1 Modulus of elasticity

The elastic modulus, E , is a measure of a material's stiffness in the linear elastic region. It describes the relation between stress and strain for small deformations and is defined as the slope of the stress-strain curve within the elastic range (Dowling, 2013).

The modulus of elasticity can be determined from a compression test by evaluating the stress-strain response. In practice, a secant modulus is commonly used, since the initial part of the stress-strain curve may be affected by seating effects, local imperfections, and measurement inaccuracies. The secant modulus is determined between two defined stress or strain levels and represents the average stiffness within this interval. By excluding the initial nonlinear portion of the response through the use of a fixed strain or stress offset, the influence of seating effects and local irregularities can be reduced, resulting in a more consistent and representative evaluation of the material stiffness ("ASTM C469/C469M: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression", 2022).

For masonry as a composite material, the determination of the elastic modulus is more complex. As discussed by Moayedian, Hejazi (2010) and J.J. Brooks (2015), the stiffness of masonry depends not only on the properties of the individual unit, but also the mortar, the unit-mortar interface and construction factors such as joint thickness and workmanship.

4.4.2 Friction

Friction develops as a result of surface roughness and mechanical interlocking between contacting materials.

In masonry, the shear resistance along bed joints is governed by the interaction between adhesion and friction at the interface between units and mortar or between units in a dry stacked system. When a normal compressive load is applied it enhances the contact between surfaces, thereby increasing the resistance to sliding, increasing friction which leads to a linear relationship between shear strength and normal stress.

This behaviour can be described using Mohr-Coulombs failure criteria, where the shear strength increases with applied normal stress:

$$\tau = \tau_{v0} + \mu f_n \quad (4.1)$$

where τ is the joint shear strength [MPa], $\tau_{v,0}$ is the shear bond strength at zero normal stress [MPa], μ is the coefficient of friction and f_n is the applied compressive stress normal to the bed joint [kN] (Drysdale et al., 1994). By testing specimens for shear strength under varying pre-compression load the friction coefficient can be calculated through linear regression of shear strength as a function of compression. However, for CSEBs this becomes an “equivalent friction” if interlocking keys are included in the system as they contribute to shear strength.

4.4.3 Cohesion

Fundamentally, cohesive strength represents the internal force required to break the molecular or chemical bonds holding a single material together. The theoretical cohesive strength is approximately a tenth of the elastic modulus (Dowling, 2013), however the practical cohesion is significantly lower as damage propagates from microscopic defects.

In the context of CSEB masonry, cohesion dictates the internal shear and tensile strength of the mortar or the block itself. If a failure occurs entirely within the mortar layer, rather than at the interface with the block, it is classified as a cohesive failure. Factors such as improper mix proportions, inadequate compaction, or under-hydrated cement can compromise the cohesive strength of the mortar or grout, leading to failure of the masonry system.

4.4.4 Adhesion

Adhesion is the mechanism that facilitates the transfer of stress across the interface between two distinct materials, such as the mortar and the CSEB units. In masonry, the bond is primarily achieved through microscopic mechanical adhesion, which occurs when hydration products from the wet mortar penetrate the surface pores of the masonry unit and crystallise, enhanced by the porosity of earth blocks (Reddy et al., 2007).

A complex set of parameters influences adhesive strength, including the moisture content of the block during construction, mortar workability, and surface roughness. The extent to which micro-mechanical interlocking versus chemical bonding dominates the adhesive strength is debated; however, it is generally accepted that a larger and rougher contact surface promotes more thorough wetting and extensive bonding (Ebnesajjad & Landrock, 2015). An adhesion failure (or de-bonding) is characterised by a clean separation at the interface, with no significant damage to either the mortar or the block itself.

4.4.5 Interlocking shear key

Shear keys, also referred as interlocking keys or mechanical locks, are integrated structural components designed to replace traditional mortar joints in dry stacked masonry or to join segments in large scale concrete structures (Abdelrahman & Galal, 2015).

The primary function is to provide a mechanical interlocking, allowing the structure to transfer shear forces and maintain stability. Dry shear keys typically consist of a female and male geometries that mechanically engage with each other, while friction and surface roughness between the contact surface contributes to shear transfer shear load (Shamass et al., 2015).

In a CSEB system the interlocking, the interlocking keys are a central feature enabling dry stacked construction. This significantly simplifies the assembly process and reduces the required amount of mortar, thereby lowering the construction cost and material use. Additionally, the interlocking geometry improves the alignment during construction, which is particularly beneficial for rapid construction and unskilled labour (Build Up Nepal, 2025).

The geometry and number of keys have a significant influence on the structural capacity. Previous studies have shown that increased key depth improves the load distribution across the bed joints and increases the resistance against relative sliding between adjacent blocks (Vivek Prasad et al., 2014).

The contribution of interlocking keys influences the stress strain response due to the progressive engagement of the interlocking mechanism. An initial seating phase is commonly observed, where relatively large deformation occurs under low stress levels. This behaviour is primarily caused by manufacturing tolerance and small gaps between the block and key. As the loading progresses and the gaps close and the additional interlocking key becomes engaged resulting in increased stiffness (Abdelrahman & Galal, 2015). Furthermore, systems with grout-filled channels generally exhibit a more stable and stiffer mechanical response, as the grout fills internal voids and minimises seating effects.

4.5 Masonry test standards

Standardised test methods are used to ensure repeatability, comparability and reliability of experimental results. In masonry research, standardised procedures define specimen geometry, loading conditions, testing apparatus, instrumentation and evaluation procedures.

4.5.1 Unit compression

The compressive strength of masonry units is commonly determined through uniaxial compression testing. The test provides information regarding the load-bearing capacity of individual units and may further be used to evaluate stiffness, deformation and failure behaviour.

Testing procedures for masonry units are standardised in EN 772-1 (“Methods of test for masonry units – Part 1: Determination of compressive strength”, 2015), the primary outputs are the mean compressive strength and the coefficient of variation (CV) between specimens. The CV is determinate as the ratio between the standard deviation and mean shear strength.

In addition to compressive strength, the stress-strain response obtained during testing may be used for determination of modulus of elasticity.

4.5.2 Prism compression

The mechanical response of masonry prisms differs from individual masonry units due to the interaction between masonry units and mortar joints. Masonry prism compression tests are therefore commonly used to evaluate the larger scale compressive behaviour of masonry.

ASTM C1314 (2021) and EN 1052-1:1998 (1998) describes a standardised procedure for determining the compressive strength of masonry prisms subjected to an axial compression loading. The primary output from both standards is the mean compressive strength. In addition, EN 1052-1:1998 1998, allows the stress-strain response to be used for evaluation of modulus of elasticity. The modulus of elasticity is expressed as a secant modulus, corresponding to one third of the maximum compressive stress and the average strain over the specimen height, according to:

$$E_i = \frac{F_{i,uc}}{3 \cdot \epsilon_i \cdot A_i} \quad (4.2)$$

where $F_{i,uc}$ is the maximum compressive load, ϵ_i is the measured mean strain and A_i is the loaded cross sectional area.

4.5.3 Triplet shear

The in-plane initial shear behaviour of masonry can be evaluated using triplet shear tests according to BS EN 1052-3:2002, (2002). The test consists of applying a constant pre-compression load perpendicular to the bed joints while simultaneously increasing the horizontal shear load until failure occurs. The method is primarily used to determine the initial shear strength of masonry and to investigate failure mechanisms.

The shear strength is calculated as:

$$\tau = \frac{F_{i,us}}{2A_i} \quad (4.3)$$

where $F_{i,us}$ is the maximum applied shear load and A_i is the cross sectional area of the specimen.

The corresponding pre-compression stress is determined from:

$$f_{pi} = \frac{F_{pi}}{A_i} \quad (4.4)$$

where F_{pi} is the applied pre-compression load.

The test standard recommends testing under at least three different levels of pre-compression in order to evaluate the frictional behaviour and initial shear strength. By applying different levels of normal stress the relationship between the shear resistance and pre-compression can be established and used to evaluate the angle of friction and initial shear strength.

Four principle failure modes are identified in the standard, shear failure in unit/mortar interface (adhesion failure), shear failure of mortar, shear failure of unit (cohesion failure), and crushing and/or splitting failure in the units (cohesion failure).

5 Preliminary tests

A preliminary testing phase was conducted, the purpose of this phase was to develop an improved understanding of the test setup, implement a test matrix and identify potential challenges associated with the experimental procedure. The key takeaways are summarised below in this chapter.

5.1 Test matrix

Preliminary testing together with literature studies informed the decisions on relevant tests for the testing phase. As the primary focus of the experimental programme triplet shear testing was chosen. In addition to the triplet shear tests, auxiliary tests: unit compression and masonry prisms were included to support the results.

The unit compression series was designated as series A, while the masonry prism test was designated as series B. A summary of the developed test program is presented in Table 5.1.

Table 5.1: Summary of unit and masonry specimens.

Series	Configuration	Test
A1	Without key	Unit compression
A2	1:4 mortar, fired brick	Unit compression
A3	1:3 grout cube	Cube compression
A4	1:6 grout cube	Cube compression
B1	Dry-stacked	Masonry prism
B2	1:3 grout	Masonry prism
B3	1:4 fired brick	Masonry prism

The configurations of the triplet specimens were selected to systematically evaluate the influence of the parameters governing the mechanical behaviour of the masonry system. The parameters investigated were friction, interlocking keys, grout strength, bed mortar, and reinforcement. By varying the parameters in a systematic way the contribution of each component to the overall structural response could be evaluated. The matrix in Table 5.2 summarise how different configurations of triplets were used to investigate the influence of the parameters.

The grouted 1:3 (C1) triplet represents the basic configuration of the system and provides a reference for comparison with the other series. The dry-stacked (C5) triplet series was included to investigate the fundamental contribution of friction and the mechanical interlocking provided by the keys. To evaluate the influence of grout properties, two different grout strengths were selected, (C1, C6). Additional series with bed mortar, (C2, C4, C9), were included to determine the extent to which mortar

enhances the performance of the masonry system. To further evaluate the contribution of the interlocking mechanism, specimens without keys (C7, C6) were tested. Finally, reinforced specimens (C3, C4) were included to investigate the potential strengthening effect of reinforcement.

Table 5.2: Summary of the triplet shear test programme and investigated parameters.

Series	Configuration / variable	Friction	Key	Grout	Mortar	Rebar
C1	1:3 grout	x	x	x		
C2	1:3 grout + mortar		x	x	x	
C3	1:3 grout + reinforcement	x	x	x	x	x
C4	1:3 grout + reinforcement + mortar		x	x	x	x
C5	Dry-stacked	x	x			
C6	1:3 grout, without key	x		x		
C7	Dry-stacked, without key	x				
C8	1:6 grout	x	x	x		
C9	1:6 grout + mortar		x	x	x	

5.2 Scale of testing and production

As a compromise between statistical reliability and practical constraints three tests for each series was planned. This decision was supported by recommendation in BS EN1052-3 (2002). A review of previously produced specimens revealed significant variability in the quality of triplet produced. This variability, combined with the approximately 14-day production period required, including curing and drying, motivated the decision to produce twice the number of specimens required for testing. This approach ensured that at least three specimens of acceptable quality could be selected for each test series and allowed additional complementary testing to be performed on the surplus specimens if needed. This ensured the the fetures of the system would be represented in an accurate way in the tested samples.

5.3 Grinding on CSEBs

Ensuring uniformly distributed load on the top block together with the interlocking keys, was difficult. The solution was to remove the interlocking keys on the top block and to evaluate if the preparation process of grinding the interlocking keys of the CSEB units was non-destructive, a simple comparative study was conducted. Figure 5.1 shows blocks with keys left and ground off.

Three units were tested in their standard (non-ground) state, and three units had their keys removed via grinding. Grinding was performed using a machine powered hand tool. All units were tested using a plate with holes to account for grout voids, resulting in a net compression area of 25 510 mm². The results of the ultimate compression tests are summarised in Table 5.3.



(a) CSEB with keys left intact.



(b) CSEB with keys ground off.

Figure 5.1: CSEBs before and after keys being ground off.

Table 5.3: Comparison of compressive strength between non-ground and ground CSEB specimens.

Specimen	Strength [MPa]
<i>Non-ground</i>	
1	4.53
2	5.88
3	5.44
Mean	5.28
<i>Ground</i>	
1	5.44
2	4.83
3	4.98
Mean	5.08

The non-ground specimens showed a mean compressive strength of 5.28 MPa, while the ground specimen an average of 5.08 MPa. This minor difference suggests that the grinding process does not significantly degrade the structural integrity of the units, confirming it as a viable preparation method for testing.

5.4 Pre-compression load

A pre-compression load was determined based on load calculations for a typical interlocking CSEB building developed by BUN, resulting in a calculated load of 4.5 kN. The complete calculation procedure is presented in Appendix A. Due to limitations related to the sensitivity of the testing machine and dial gauge system, the pre-compression level was adjusted to 5 kN. This load level was maintained constant for all standard test configurations.

To investigate the influence of different pre-compression loads and enable evaluation of initial shear resistance, testing with varying pre-compression was implemented. The configurations with grout, grout - mortar, and grout - reinforcement were chosen to evaluate the influence of different pre-compression loads. The choice of pre-compression load was based on the standard, BS EN 1052-3:2002 and set to 0.1, 0.3 and 0.5 MPa.

5.5 Test protocol

Data had to be recorded manually by reading dials on the test rig, including both load and displacement. Based on experience from the initial tests, and the identification of critical data, a structured test protocol was developed for data logging during testing, see Appendix D. These protocols were subsequently used during the testing phase.

6 Main tests

This chapter outlines the method employed in the study: the production and testing of the specimens and post-processing of the data. The procedures for material preparation, the manufacturing of all tested samples are detailed and finally the specific testing protocols and data analysis methods are described, establishing the framework for the results presented in the subsequent chapter.

6.1 Block production

A total of 1,044 CSEB units were produced over a 4-day period in accordance with the standard production procedure provided by BUN (Interlocking Brick Association of Nepal, Resilient Structures Pvt. Ltd., & Build Up Nepal Engineering Pvt. Ltd., n.d.). The units were used for unit compression tests, prism compression tests and triplet shear tests.

6.1.1 Geometry of CSEB

The geometry of the blocks produced by BUN is 300 mm in length, 150 mm in width and 100 mm in height. The blocks have multiple unique features. They have 7 mm long chamfered edges at a 45 degree angle. The blocks also have a pair of positive and negative circular displacements 10 mm high with a starting diameter of 100 mm and ending of 80 mm for the positive one and reversed for the negative side. The block has multiple holes going through it vertically, three angular and two circular, with the two circular being tapered. Figure 6.1 illustrates the dimensions and features of the CSEB.

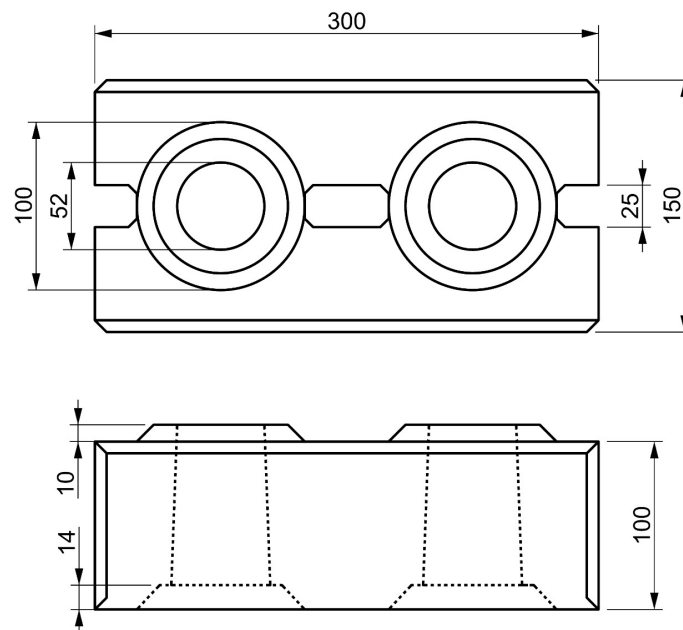


Figure 6.1: Drawing of CSEB unit according to BUN's standard in mm.

6.1.2 Materials

The soil used for the CSEB testing was collected from Kotdada, Lalitpur in Nepal from a depth of 0.12 - 0.15 m. A sedimentation test was performed to determine the clay and silt content in the soil. A volume of 330 ml of the soil was placed in a jar, after which 670 ml of water was added. The soil and water were mixed thoroughly and the jar was then set to rest for 30 minutes before the height of sediment was measured, this sediment was assumed to be sand. After this the jar was left to set for 24 hours and it was determined that remaining content was clay and silt, results are presented in Table 6.1.

Table 6.1: Soil composition from Kotdada based on the jar test.

Soil fraction	[%]
Clay and silt	99
Gravel	1

The particle size distribution of the soil and additional sand was determined using sieve analysis in accordance with ASTM D6913 (2025). The analysis was performed on 1 kg samples using sieve sizes of 4.75, 2.36, 1.18, 0.60, 0.45, 0.15, and 0.075 mm. A scale with an accuracy of ± 5 g was used to determine the retained mass on each sieve. The resulting particle size distributions for the soil and sand are presented in Figure 6.2.

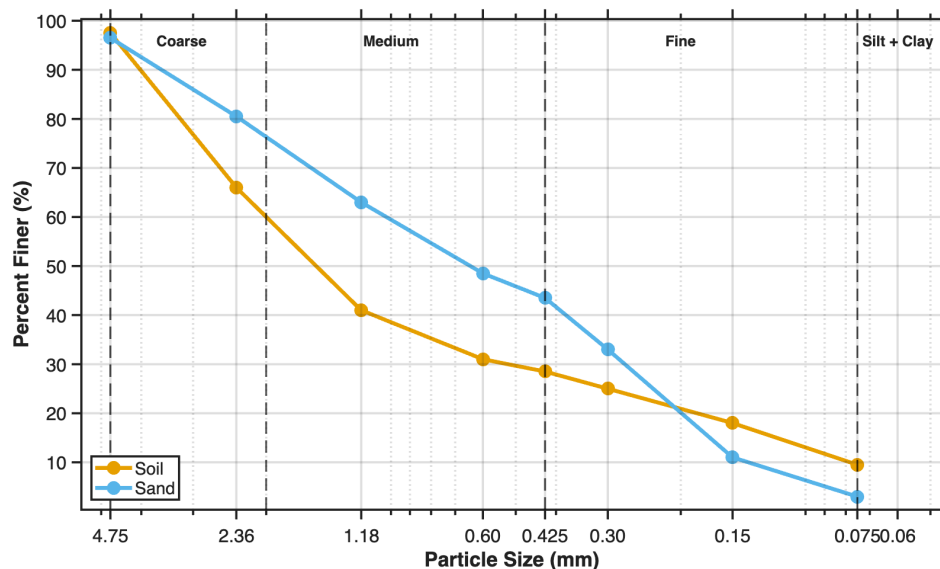


Figure 6.2: Sieve analysis for soil and sand used in CSEB production.

The material specification for the constituents used in the CSEB production are summarised in Table 6.2.

Table 6.2: Material specifications used in CSEB production.

Material	Description	Density [kg/m ³]
Soil	Kotdada, Kathmandu	1850
Additional sand	–	1600
Cement	OPC 43 grade (Hongshi)	1220

6.1.3 Unit production

Prior to the block production, the soil was sieved to retain particles within a certain size range. Additional sand was added with a ratio of 1.2 kg sand per 1 kg soil in order to achieve the recommended particle grading. The mix proportion between the soil-sand mix and cement was 1:8 by dry weight. The required quantities of each material were determined based on dry mass using a scale with an accuracy of ± 5 g. The soil and cement were dry mixed in a pan mixer until a homogeneous mixture was obtained. Water was then gradually added while mixing to ensure uniform distribution throughout the mixture. The final water to cement ratio was 0.29. An interlocking compressed earth block machine, provided by BUN, was used to produce the blocks, as shown in Figure 6.3.



Figure 6.3: Interlocking Compressed Stabilised Earth Block machine built and produced by BUN.

The mould was filled with approximately 165–170 mm of fresh mix and pre-compacted by hand to ensure uniform distribution and complete filling of the mould. The material

was then mechanically compacted to a final block height of 100 mm. After de moulding, the blocks were placed on phenolic coated plywood and stored under dry conditions for the first 24 hours. Three blocks from each batch were weighed to ensure that the minimum required average mass of 8 kg was achieved.

After the initial drying period, the blocks were stacked according to the pattern shown in Figure 6.4, and the curing process was initiated. During the curing, the blocks were watered three times per day to maintain adequate moisture content. The curing conditions varied throughout the curing period, with ambient temperatures ranging approximately between +10 °C and +25 °C and exposure to both sunny and cloudy weather. In cases where rainfall was expected, the specimens were covered with plastic sheeting to prevent uncontrolled wetting. After 22 days, the curing period was completed, and the specimens were allowed to dry under ambient conditions.



Figure 6.4: Stack of CSEB units curing/drying in field in Jajarkot.

6.2 Specimen production

Units, triplets and grout specimens for testing were produced in the workshop over a five day period. A summary of the production method is presented in this chapter and a detailed day to day lab log can be viewed in Appendix C.

6.2.1 Grout and mortar

In total three different grout/mortar recipes were used with varying cement to sand ratios, 1:3, 1:4 and 1:6. The ratios were measured in volume and converted to weight using their density. The sand and cement material properties are presented in Table 6.2 and mix proportions by weight are presented in Table 6.3.

Table 6.3: Mix proportions with constant cement mass (5 kg) and proportional sand content by weight.

Material / property	(1:3)	(1:6)	(1:4)
Cement [kg]	5.00	5.00	5.00
Sand [kg]	19.72	39.43	26.30
W/C ratio	1.00	1.85	0.60-0.75
Water [kg]	5.00	9.25	3.00-3.75
Volume ratio (C:S)	1:3	1:6	1:4

A primary challenge during the grout preparation was the moisture content of the sand, the moisture content was not possible to measure or control. To mitigate this and ensure consistency, the sand was air-dried in the sun prior to passing it through a 3 mm sieve. The water-to-cement (w/c) ratio was determined empirically by systematically increasing the water content until adequate workability was achieved. Ultimately, a w/c ratio of 1.0 was adopted for the 1:3 grout, and 1.85 for the 1:6 grout. These ratios were held constant for all subsequent batches, despite potential variations in the sand's moisture content. The sand, cement and water were weighed using a scale with an accuracy of ± 5 g and thoroughly mixed, with water added gradually. Despite the high w/c ratio of 1.85, the 1:6 grout remained coarse and drier than the 1:3 mix. Consequently, the 1:6 grout exhibited poor workability and proved difficult to fully compact within the grout holes.

Due to timing and weight constraints, each grout batch was proportioned to produce six triplet specimens. In cases where extra grout remained, it was utilised for the next set of triplets. Care was taken to ensure that each individual void was filled using the same grout batch to avoid creating a weak layer.

6.2.2 Unit and mortar specimen

The preparation of the unit and mortar specimens is summarised in Table 6.4. For the CSEB unit specimens, the interlocking keys were removed, detailed methodology regarding this process is provided in Section 5.3. The production date was recorded on each individual block. The curing and drying followed the procedure in section 6.2.4.

The fired brick specimens were soaked in water for 2–3 minutes before a 10 mm thick mortar layer (utilising a 1:4 cement-to-sand ratio, as detailed in Table 6.3) was applied to fill the frogs. To ensure consistency and quality, the mortar was applied by an experienced mason, and a plywood board was utilised to achieve a level top surface.

The mortar cubes were prepared by first lubricating steel moulds with dimensions of 50×50×50 mm before the mortar was poured into the moulds. The moulds were compacted manually through vibration, and additional mortar was added when necessary to ensure complete filling. The mortar cubes were then left to cure for 24 hours, after which the moulds were stored in water for three days. Following this initial curing period, the moulds were removed and the cubes were subsequently stored in water

for an additional four days.

Table 6.4: Summary of unit and mortar specimens.

Series	Configuration	Quantity	Test
A1	Without key	6	Unit compression
A2	1:4 mortar, fired brick	6	Unit compression
A3	1:3 grout cube	3	Cube compression
A4	1:6 grout cube	3	Cube compression
Total		18	

6.2.3 Triplet specimen

Each triplet specimen consists of three blocks on top of each other stacked, a bottom, middle and top block. The general preparation procedure was to select the required blocks with the correct date one day prior to the triplet production. The key was removed on the top blocks to ensure a smooth top surface for pre-compression force and testing of blocks without keys. The grinding was performed by a mechanic in the workshop using electric powered hand tools, see section 5.3 for further details.

A summary of the production of specimens is presented in Table 6.5. Each specimen was labelled according to production date, grout composition and configurations, where G: denotes grouted, M: mortar bed, R: reinforcement, D: dry stacked and w/o key: indicates removal of all keys. Series starting with B are made for masonry prism tests and series starting with C are made for triplet shear testing.

All voids were initially filled two-thirds with grout. A 10 mm diameter rebar was then used to compact the grout by tapping 15–20 times in each void. The remaining volume was subsequently filled with grout. For the reinforced series C3, the same stacking and grouting procedure was used, with the addition of a centrally placed 10 mm Fe500 reinforcement bar inserted into one of the circular voids.

For the series with bed-mortar, C2 and C9 the bottom block was placed on a phenolic coated plywood. A 5 mm thick mortar layer, with the same composition as the grout, was applied by an experienced mason. The middle block was placed on top of the bottom block and gently pressed into position, followed by another layer of mortar and placement of a flat top block. The voids were then filled using the same method as for the grouted series. The series with both grout, bed-mortar, and rebar, C4, utilises a combination of the method from the mortar and grout series and rebar.

The production of grouted series B2, C1 and C8 followed the same procedure. The bottom block was placed on a phenolic coated plywood followed by the middle block and a top block without keys. Between the adjacent set of triplets a phenolic coated plywood was used as formwork for the side voids, Figure 6.5.

Table 6.5: Summary of total triplet production over five days.

Series	Configuration	Quantity	Naming notes
B1	Dry-stacked	6	D
B2	1:3 grout	6	1:3 G
B3	1:4 mortar, fired brick	6	1:4 M
C1	1:3 grout	24	1:3 G
C2	1:3 grout + mortar	24	1:3 G, M
C3	1:3 grout + reinforcement	24	1:3 G, R
C4	1:3 grout + reinforcement + mortar	6	1:3 G, R, M
C5	Dry-stacked	6	D
C6	1:3 grout, without key	6	1:3 G, w/o key
C7	Dry-stacked, without key	6	D, w/o key
C8	1:6 grout	6	1:6 G
C9	1:6 grout + mortar	6	1:6 G, M
Total		126	



Figure 6.5: Triplet specimen production with phenolic coated plywood between triplets.

The dry stacked series B1, C5 and C7 were dry stacked on top of each other and placed for curing and drying. The series with fired bricks, B3, were prepared by an experienced mason. The bricks were soaked in water for 2-3 minutes prior a 10 mm thick mortar layer was applied. A plywood board was used to ensure a smooth and level top surface.

In total, 126 triplet specimens were produced over a five day period, corresponding to twice the number required for the initial testing program. The surplus allows for selection of three quality specimens from each series and ensures availability for complementary tests not yet established at time of production.

6.2.4 Curing and drying

During the curing and drying procedure the specimens were kept in a varied environment between +20 - +30 degrees protected from direct sunlight. The unit and triplet specimen followed the same curing and drying process.

Twenty-four hours after production of the CSEB triplets the side formwork was removed and the specimen was moved to a storage spot for curing. The curing procedure for the CSEB triplets, fired brick triplets and unit specimens were equal. Water was applied three times a day during 7 days. After 7 days the drying period commenced and the specimens were stored in the same spot until testing.

6.3 Testing

The experimental test program consists of three main test types, unit compression, masonry prism compression and triplet shear. For each test series six test specimens were manufactured, from these three representative specimens were selected for testing based on visual inspection and geometric consistency. This approach was adopted to reduce the influence of production irregularities.

6.3.1 A - Unit and mortar cube compression

The unit compression test program included CSEB units, fired brick units, and mortar cubes. The test matrix is summarised in Table 6.6. The test method was based on the EN 772-1 1998 with necessary modifications primarily related to the load application procedure and number of specimens.

Table 6.6: Test programme for unit and mortar compression.

Series	Configuration	Area [mm ²]	Quantity
A1	CSEB	36 845	3
A2	fired brick	22 500	3
A3	1:3 mortar cube	2 500	3
A4	1:6 mortar cube	2 500	3

A hydraulic Compression Testing Machine (CTM), shown in Figure 6.7, was used to apply uniaxial compressive load to the unit specimen. The machine consists of a steel frame equipped with a manually operated hydraulic jack and an analogue pressure gauge

for load monitoring. The Setest-branded Bourdon tube dial gauge ranges from 0 to 1 000 kN, with one division corresponding to 5 kN. The compression testing machine was calibrated by Pulchowk Campus prior testing, with calibration details presented in Appendix B.

The specimen was positioned centrally between two steel plates in the compression machine. For CSEB and fired brick units the load was manually applied incrementally in steps of 25 kN. After each load increment, the stability of the system was evaluated. Once stable conditions were achieved, typically after 20 - 30 seconds, the applied load was recorded. If a load drop smaller than < 20 kN occurred, the test continued with increments of 25 kN. For load drop equal or greater than ≥ 20 kN, the previous load level was repeated once before increasing the load again in order to evaluate any remaining load carrying capacity. This procedure continued until specimen failure. The loading protocol for the CSEB and fired brick units is illustrated in Figure 6.6.

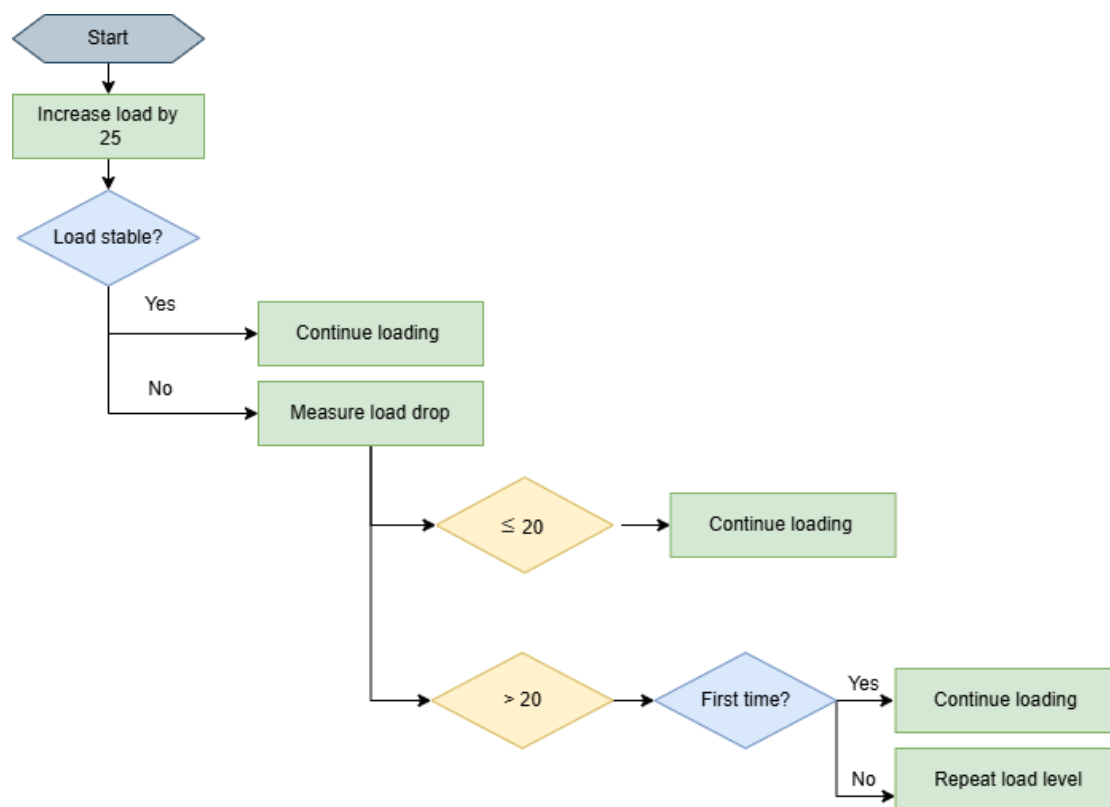


Figure 6.6: Loading protocol CSEB and fired brick unit.



Figure 6.7: Hydraulic Compression Testing Machine (CTM) located at the workshop.

For the mortar cubes, the load was applied incrementally in steps of 5 kN until failure. Vertical displacement measurements were not included due to insufficient measurement accuracy for capturing small deformations.

6.3.2 B - Masonry prism test

The masonry prism test was conducted on two series of CSEB triplets, B1 and B2, and one series of fired brick triplets, B3, as shown in Table 6.7. The test procedure was based on a combination of ASTM C1314 and EN 1052-1, with the primary modifications related to the controlled load application procedure.

Table 6.7: Test programme for masonry prisms.

Series	Configuration	Area [mm ²]	Quantity
B1	Dry-stacked	36 845	3
B2	1:3 grout	45 000	3
B3	1:4 mortar, fired brick	22 500	3

The masonry prism test was conducted using a manually operated hydraulic compression press mounted vertically within a rigid steel frame, as shown in Figure 6.8. The machine

operates using a hydraulic jack mechanism in which pressure is generated through manual pumping. The hydraulic jack is positioned at the top of the frame and transfers the load through a steel piston with a diameter of 70 mm.

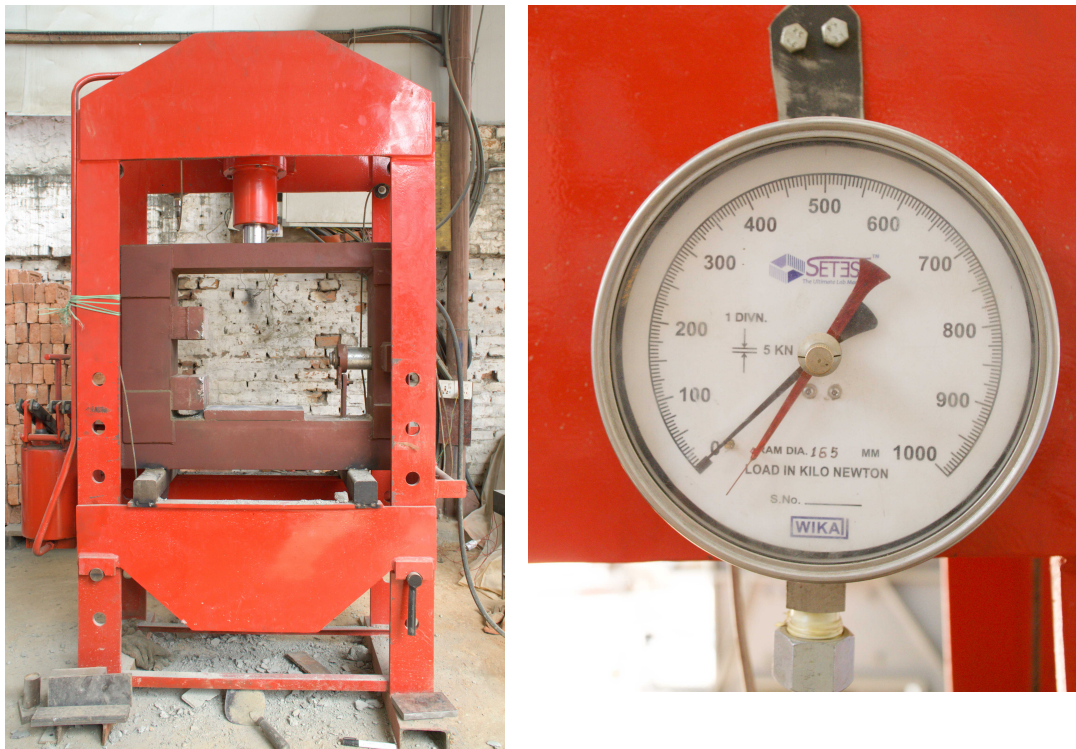


Figure 6.8: Main experimental setup - 40-tonne manual hydraulic compression press and dial gauge.

The hydraulic system had a maximum capacity of 400 kN (40 tonnes). The applied load was measured using a Setest-branded Bourdon-tube dial gauge (manufacturer: WIKAI), with a measurement range of 0-1000 kN, where one division corresponds to 5 kN. The pressure dial gauge was calibrated by a representative from Pulchowk Campus prior testing, as described in Appendix B.

The specimen surface was prepared by sanding the top surface to remove excess grout and to ensure a level and uniform bearing surface. The specimen was then carefully aligned centrally in the testing machine. A steel plate with a thickness of 40 mm was placed on top of the specimen to evenly distribute the applied load.

The load was applied using the same loading protocol as for the unit compressive test, see Figure 6.6. When a visible crack appeared, the load at which the crack appeared was noted on the test protocol and on the specimen.

6.3.3 C - Triplet shear test

In total 54 triplets shear test series were conducted, in Table 6.8 the test program is summarised. The triplet shear test method was based on the standard BS EN1052-3.

Modifications regarding test setups, load application and measuring of results has been done. The used method is presented in this chapter.

Table 6.8: Triplet shear test programme, including configuration, number of specimens, and pre-compressive load.

Series	Configuration	Quantity	Pre-compression [kN]
C1-1	1:3 grout	6	5
C1-2	1:3 grout	3	15
C1-3	1:3 grout	3	25
C2-1	1:3 grout + mortar	6	5
C2-2	1:3 grout + mortar	3	15
C2-3	1:3 grout + mortar	3	25
C3-1	1:3 grout + reinforcement	6	5
C3-2	1:3 grout + reinforcement	3	15
C3-3	1:3 grout + reinforcement	3	25
C4	1:3 grout + reinforcement + mortar	3	5
C5	Dry-stacked*	3	5
C6	1:3 grout, without key	3	5
C7	Dry-stacked, without key*	3	5
C8	1:6 grout	3	5
C9	1:6 grout + mortar	3	5
Total		54	

*Note: * Reduced CSEB cross-sectional area.*

The compressive stress specified in the standard was converted into a pre-compression load using the compressive area of the blocks. Due to the 5 kN resolution of the dial gauge, both the reduced and full CSEB areas resulted in the same applied pre-compression load. The conversion is presented in Table 6.9.

Table 6.9: Rounded conversion of compressive stress to pre-compression load.

Block type	Stress [MPa]	Area [mm ²]	Force [kN]
CSEB	0.1	45 000	5
CSEB	0.3	45 000	15
CSEB	0.5	45 000	25

A separate inner steel frame was specially designed and fabricated at the workshop to enable testing of the triplet shear capacity. The inner test frame consists of four steel

members forming a ridged rectangular structure. Each member is composed of C-channels with dimensions 150x75x5.7/9.0 (web/flanges) mm welded together to increase the bending stiffness. The corners have been stiffened with additional steel plates welded externally to increase rigidity.

Two 50 mm thick steel plates were attached to the inside of the inner test frame with a vertical distance of 100 mm, corresponding to the height of one block. On the opposite side of the frame, two additional steel plates are installed to allow attachment of an external horizontal loading device. This setup allows application of shear force to the specimen while maintaining a constant vertical load. The portable inner frame can be seen in Figure 6.8.

An external manual single hydraulic jack was used as the horizontal force attached to the inner test frame. The jack piston has a diameter of 50 mm, with a cross-sectional area $A_{piston} = 25^2\pi = 1963.5 \text{ mm}^2$ and maximum capacity of 16 tonnes, shown in Figure 6.9.

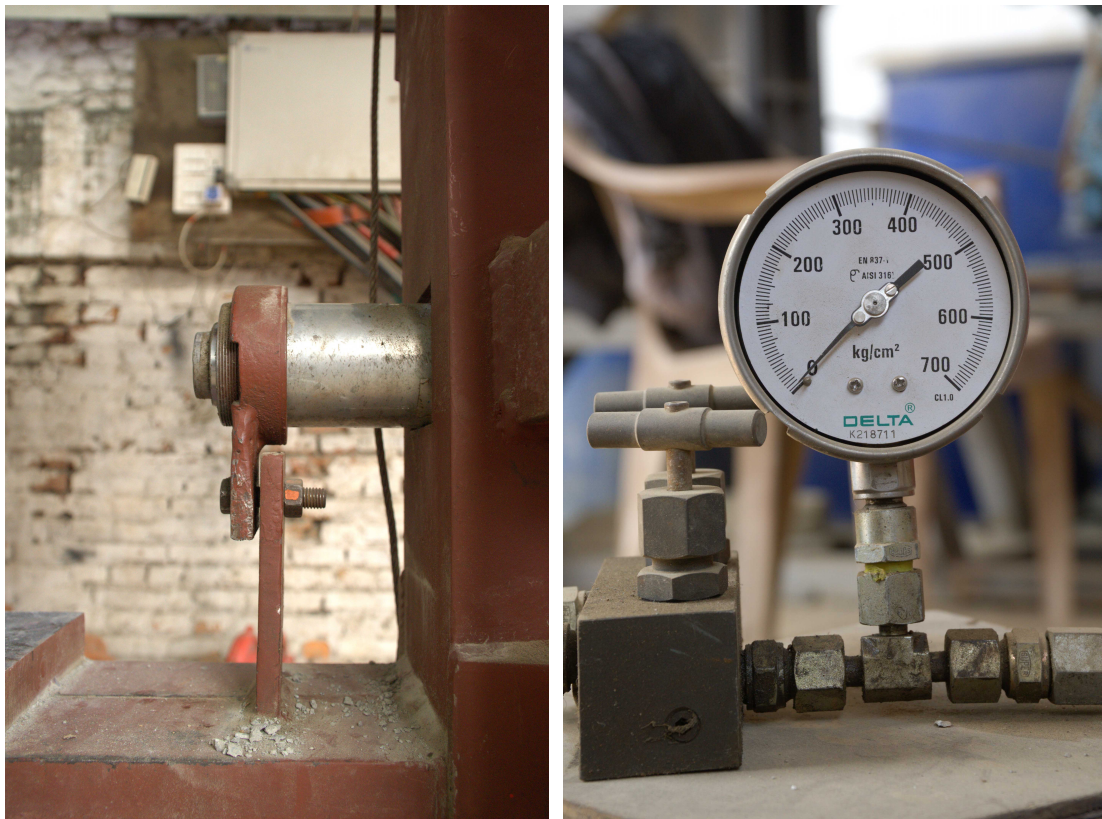


Figure 6.9: Horizontal hydraulic piston and associated dial gauge showing pressure in kg/cm^2 .

The applied pressure was measured using a Delta pressure gauge (K218711, EN 837-1, AISI 316L) with range 0-700 kg/cm^2 and division of 5 kg/cm^2 . The applied pressure was converted to applied force, kN, through the area of the piston and the gravity as followed;

$$F_h [\text{kN}] = P [\text{kg}/\text{cm}^2] \cdot A_{piston} [\text{cm}^2] \cdot \frac{g \cdot 10^{-3} \text{ kN}}{\text{kg}} \quad (6.1)$$

with $A_{piston} = 1963.5 \text{ mm}$ and $g = 9.81 \text{ kN}$.

A load distribution steel-plate with dimension 190 mm x 90 mm x 15 mm was placed between the piston jack and the block to ensure that the load was applied on the entire block.

Calibration by an external expert was performed, adjusting the pressure dial. The calibration was deemed accurate for pressure levels of 400 kg/cm^2 resulting in about 77 kN. This was sufficient for an initial set of the tests but showed to be insufficient during the testing phase. The solution was to use a load cell (with a capacity of 15 tonnes) in series with the piston. This showed to give accurate results correlating well with the pressure dial, when this correlation was established the tests were altered to to use the load cell as load indicator and the horizontal piston was used up to load levels of 14 500 kg (142 kN). The final test set up is shown in Figure 6.10.



Figure 6.10: Final test setup for triplet shear. Load cell and dial gauge to the right in series with hydraulic piston.

Prior testing, the top surface of the specimen was sanded with a sand paper. The triplet specimen was placed inside the inner test frame, special attention was given to ensure that the middle block was free to move horizontally within the frame and full contact with the supporting steel plate. If the middle block was restrained by touching the left support, a thin steel plate was inserted at the base to enable free movement. If a gap was observed between the specimen and the supporting steel plate, additional steel plates were inserted to ensure proper contact.

In cases where the specimen had initial misalignment or tilting, and the test frame dimensions were insufficient to fully support the triplet, the specimen was positioned so that an equal portion of the specimen extended the supporting steel plate.

Horizontal displacement was measured using an Asahi dial gauge with a measurement range of 0 to 25 mm and an accuracy of 0.01 mm, shown in Figure 6.11. The gauge was attached to a magnetic adjustable holder positioned right of the steel plate.

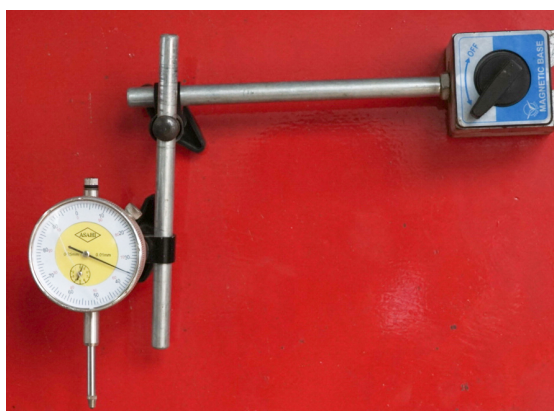


Figure 6.11: Asahi displacement dial gauge attached to magnetic holder, used for all displacement measurements during testing.

The test starts with application of the constant pre-compression load. The horizontal load was applied manually and increased incrementally in steps of 25 kg/cm^2 . After each load increment, the stability of the system was evaluated. When the system was considered stable, the applied load and the corresponding displacement were recorded approximately 20–30 seconds after the load application.

In the event of a load drop smaller than 20 kg/cm^2 , the test was continued by increasing the horizontal load by an additional 25 kg/cm^2 . If a load drop equal to or greater than 20 kg/cm^2 was observed, the previous load level was repeated. This procedure was allowed once. If a second load drop equal or greater than 20 kg/cm^2 the load was increased by 25 kg/cm^2 . If a load drop greater than 45 kN was observed, the loading was resumed from the dropped load level and increased in steps of 25 kg/cm^2 in order to assess the ability of the system to develop additional load-carrying capacity. This procedure was repeated until failure occurred. Figure 6.12 shows the loading protocol for triplet shear test. The crack pattern was documented on the specimen and the load at which the first crack appeared was documented on the protocol.

Due to the use of a manually operated hydraulic piston, continuous load control could not be maintained during the experiments. Throughout the triplet shear testing, a consistent phenomenon was observed where the pre-compression force increased over the duration of the test. This effect was most pronounced when the initial pre-compression was set to lower levels (e.g. 5 kN). The increase in normal force became evident after a certain degree of shear displacement, typically reaching approximately 20 kN by the conclusion of the test. This behaviour is assumed attributed to the chamfered geometry of the interlocking keys; as the blocks slid across the keys, they were forced vertically upward against the fixed piston. This displacement inadvertently increased the internal hydraulic pressure and, consequently, the normal stress acting upon the masonry specimen. This issues was not resolved during the testing phase and these events were recorded for each test.

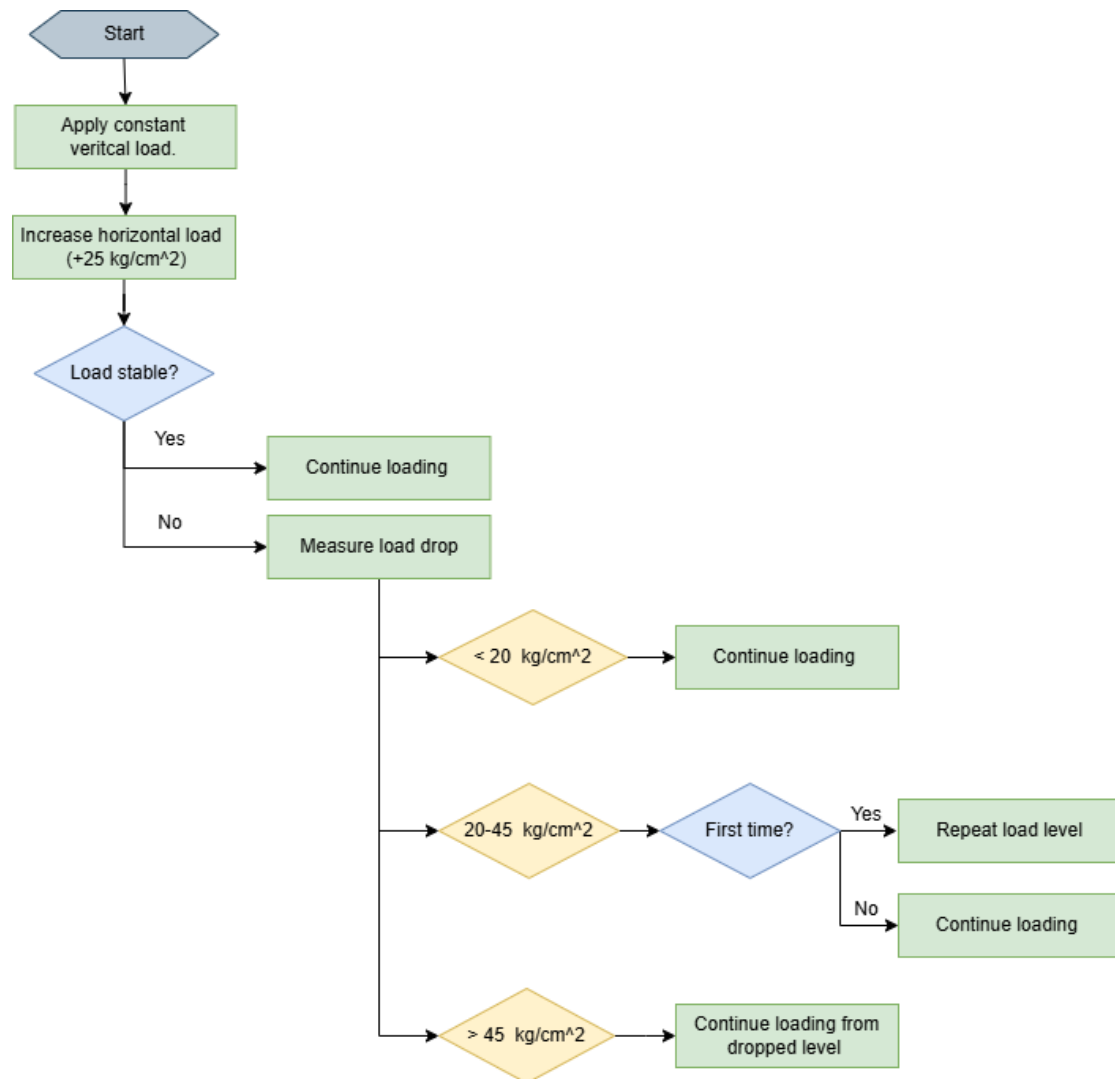


Figure 6.12: Loading protocol for triplet shear test.

6.3.4 D - Additional tests

When the original test series A, B, and C had been completed and the preliminary evaluation of the results was conducted, it was decided that several triplet shear tests needed to be repeated. The primary reason was that the maximum calibrated capacity, without the additional external load cell, of the horizontal loading system had been reached before specimen failure occurred.

To address these issues, an additional test series, designated as Series D, was conducted. The specimens used in the additional series were produced from surplus triplets remaining from the original production phase.

It should be noted that the specimens in Series D were subjected to different drying conditions compared to the original test series. While the original series were tested after 7 days of drying, the specimens in Series D were tested after 14 days of drying. Consequently, the results from Series D cannot be directly compared with the results from the original series. Table 6.10 summarises the repeated test series and the

corresponding reasons for the additional testing.

Table 6.10: Additional triplet shear test programme, including configuration, number of specimens, and pre-compressive load.

Series	Configuration	Quantity	PC [kN]	Reason
D1	1:3 grout, w/o key	3	5	Max. calibration
D2	1:3 grout	3	5	Updated measuring method
Total		6		

The triplet shear testing procedure for series D follows the same procedure as described in section 6.3.3.

As part of the additional testing, the internal structure of the blocks was examined to evaluate the compaction and dispersion of the grout within the channels. To achieve this, the specimens were marked along the perimeter of the grout channel and sectioned using a stone cutter, thereby exposing the internal core of the grouted sections for visual inspection. See Figure 6.13 for the setup of block sectioning.



Figure 6.13: Stone cutter and setup used for block sectioning.

6.4 Post processing

During the testing phase, large datasets were generated for each specimen. The raw data consists of a first load reading (initial peak) followed by a second load reading once the displacement dial reached a stable state together with a displacement reading and notes (if any). The duration required for stabilisation was minimal at low loads and increased to approximately 20–30 seconds for higher loads. Displacement was recorded as discrete dial readings alongside a starting value for each test.

To make this data workable, the recorded values were first translated into standard values. Loads were converted to kN where necessary and relative displacement was calculated by subtracting the initial dial reading. A coefficient of variation was calculated for each series as the ratio of the standard deviation to the mean of each sample's peak load.

To present all data of a test in a figure the system of Figure 6.14 was used. The force–displacement diagram shows the stable load connected with the displacement read simultaneously, data points are connected linearly. For each data point the initial load is represented as an error-bar above the point, typically this discrepancy is low in early phases of a test and large in late stages. Typical notes recorded during the test were that the pre-compression increased progressively, these “events” are represented as symbols marked out on their corresponding data point with a legend describing the event. A legend indicating the samples and one describing the series specimens are included.

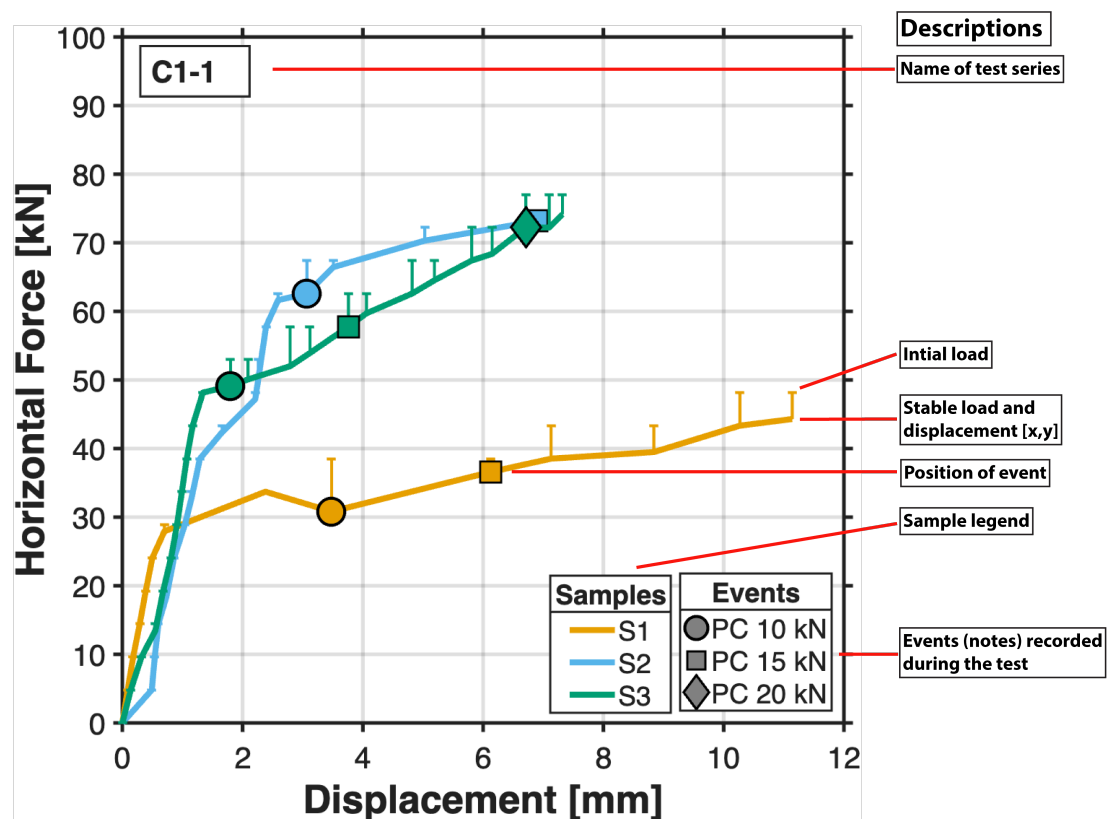


Figure 6.14: Descriptive plot of test results. Highlighting key features of the data representation.

The peak load was defined as the highest load achieved in the piston during testing, even when the load was not sustained. This was chosen because of the loading condition with a pumped hydraulic and as this was seen as the load giving a certain failure. Failure mode was identified from recordings and images of the tests.

7 Test results

This chapter presents the experimental results from the unit compression, masonry prism, and triplet shear tests. First, an overview of the average strength and data spread for all test series is provided. Following this general summary, detailed presentation of all shear results including all samples are presented to examine individual behaviour and failure modes.

All general strength results are summarised visually in Figures 7.1 and 7.2, and numerically in Tables 7.1 and 7.2. In the figures, the thick horizontal lines represent the mean value for each test series, while the shaded bounding boxes indicate the data spread (minimum to maximum values). Tables also include critical crack load and modulus of elasticity where applicable. All originally recorded data can be reviewed upon request to authors.

7.1 Compression tests

The unit compression tests reveal a significant difference in load-bearing capacity between the CSEB and fired bricks. The CSEB units (A1) demonstrated a mean compressive strength of 7.24 MPa, whereas the fired bricks (A2) achieved a strength of 18.00 MPa. While the relative variance (CV) is higher for the CSEB units (10.8%) compared to the fired bricks (4.5%), the absolute variance between samples was roughly similar for both series, as shown by the data spread in Figure 7.1.

The compressive strength for the mortar cubes (Series A3 and A4) demonstrates the impact of the cement to sand ratio. The 1:3 mortar cubes (A3) achieved a mean compressive strength of 12.85 MPa, whereas the 1:6 mortar cubes (A4) averaged significantly lower at 2.71 MPa. As seen in Table 7.1, both series exhibited relatively low variance between samples, with coefficients of variation (CV) of 8.3% and 9.5%, respectively.

For the masonry prisms, the dry-stacked CSEB prisms (B1) yielded an average compressive strength of 3.62 MPa, while the grout-filled CSEB prisms (B2) showed a slightly higher average capacity of 4.07 MPa. The fired brick prisms (B3) achieved the highest average compressive strength at approximately 5.04 MPa. However, the fired brick specimens exhibited a significantly larger variation in compressive strength compared to the CSEB specimens. As indicated by the data spread in Figure 7.1 and the CV values in Table 7.1, the CSEB prisms maintained relatively consistent behaviour with a lower scatter between samples (CV of 7.9–10.8%) compared to the fired brick (CV of 30.0%). Table 7.1 summarise the peak compressive load, peak compressive strength, critical crack strength and coefficient of variable for all compression tests.

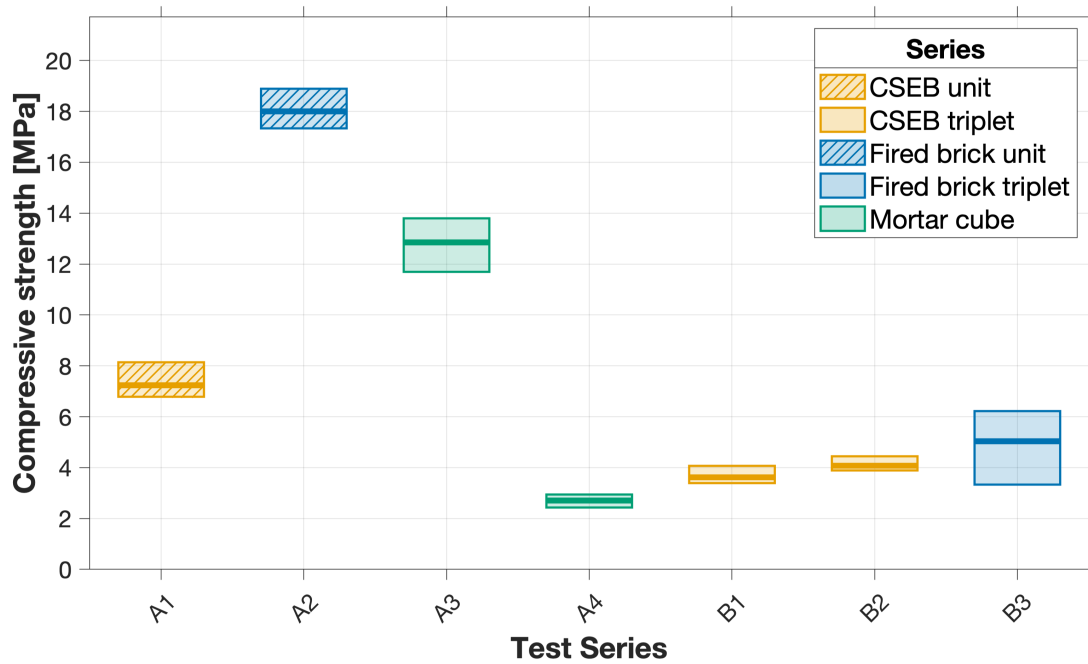


Figure 7.1: Compression test results showing mean values and spread of all tests.

Table 7.1: Summary of results from unit and masonry testing.

Series	A [mm ²]	F_{uc} [kN]	f_m [MPa]	f_{cr} [MPa]	E_m [MPa]	CV [%]
A1	36 845	267	7.24	-	342	10.8
A2	22 500	405	18.00	-	345	4.5
A3	2 500	32	12.85	-	-	8.3
A4	2 500	7	2.71	-	-	9.5
B1	36 845	133	3.62	0.67	-	10.8
B2	45 000	183	4.07	2.22	-	7.9
B3	22 500	113	5.04	10.0	-	30.0

Note: The specimen cross-sectional areas differ between series.

7.2 Triplet shear tests

A general summary of the peak horizontal loads of the triplet shear tests, corresponding shear strengths, and data variance is presented in Table 7.2. As visually indicated by the data spread in Figure 7.2, the shear response varied significantly depending on the specific joint composition and applied pre-compression. A detailed comparative analysis of a selection these specific parameters and their corresponding failure mechanisms is provided in the following section. For each test series a figure describing the relevant test data is presented, for a reference on how the figures are to be read see Figure 6.14. The typical behaviour of progressively increasing pre-compression load can be read from the presented figures of each test.



Figure 7.2: Comparison of shear strengths across all test series showing mean values and spread of each series. ***Note:** For series marked with C*, the maximum capacity of the calibration equipment was reached, and the test was terminated prior to ultimate failure.

Table 7.2: Summary of results from all shear testing.

Series	F_{us} [kN]	τ_m [MPa]	CV [%]
C1-1	66	1.46	23.5
C1-2	72	1.61	20.1
C1-3	95	2.11	4.1
C2-1	107	2.38	8.2
C2-2	105	2.33	20.2
C2-3	77	1.71	20.6
C3-1	80	1.77	7.6
C3-2	84	1.86	6.2
C3-3	92	2.04	19.2
C4**	77	1.71	0.0
C5*	32	0.86	10.5
C6**	76	1.68	4.1
C7*	5	0.15	20.4
C8	51	1.13	13.4
C9	50	1.12	36.2
D1	92	2.05	2.0
D2	100	2.22	8.5

Note: *Reduced area. ** Maximum capacity of the calibration.

7.2.1 C1 - 1:3 grout

Series C1 investigates the shear behaviour of triplets constructed with 1:3 grout under varying levels of pre-compression (0.1, 0.3, and 0.5 MPa). The corresponding test results are summarised in Table 7.3.

An increase in shear strength was observed with increasing pre-compressive stress. The mean shear strength increased from 1.46 MPa to 1.61 MPa (approximately 10%) when the pre-compression level was increased from 0.1 MPa to 0.3 MPa. A further increase in pre-compression from 0.3 MPa to 0.5 MPa resulted in an increase in mean shear strength from 1.61 MPa to 2.11 MPa, corresponding to an increase of approximately 31%. Based on the experimental results, the derived Mohr–Coulomb parameters for Series C1 were determined as $\tau_{v0} = 1.24$ MPa and $\phi = 58.1^\circ$ ($\mu = 1.61$).

No clear correlation between the initial crack load, F_{cr} , and the ultimate shear strength within an individual series can be observed. However, it can be observed that an increase in pre-compressive load generally results in higher initial crack loads.

Figure 7.3 shows the horizontal force as a function of displacement for three different pre-compression levels and the Mohr–Coulomb failure criterion graph. A noticeable variation between individual specimens within the series. In particular, Sample 1 of

Series C1-1 exhibited a substantially lower peak load (48.2 kN) compared to the remaining specimens within the same group. A similar variation can also be observed in series C1-2. Furthermore, sample 3 in series C1-2 reached the maximum calibration of the machine. Consequentially, the actual ultimate shear strength of the specimen is likely higher than the recorded value.

The failure mechanism observed in Series C1 is characterised by the formation of a distinct longitudinal crack within the blocks, occurring independently of the applied pre-compressive stress level as shown in Figure 7.4.

Table 7.3: Shear test results for series C1 - 1:3 grout.

Series	PC [MPa]	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
C1-1	0.10	1	48.2	38.5	1.07
	0.10	2	72.2	24.1	1.61
	0.10	3	77.0	53.0	1.71
		Mean	65.8	38.5	1.46
C1-2	0.30	1	77.0	–	1.71
	0.30	2	55.9	54.4	1.24
	0.30	3	83.8	29.1	1.86
		Mean	72.2	41.8	1.61
C1-3	0.50	1	97.7	72.0	2.17
	0.50	2	90.4	19.4	2.01
	0.50	3	96.2	82.9	2.14
		Mean	94.8	58.1	2.11
Mohr–Coulomb parameters					
$\tau_{v0} = 1.24$ MPa, $\mu = 1.61$					

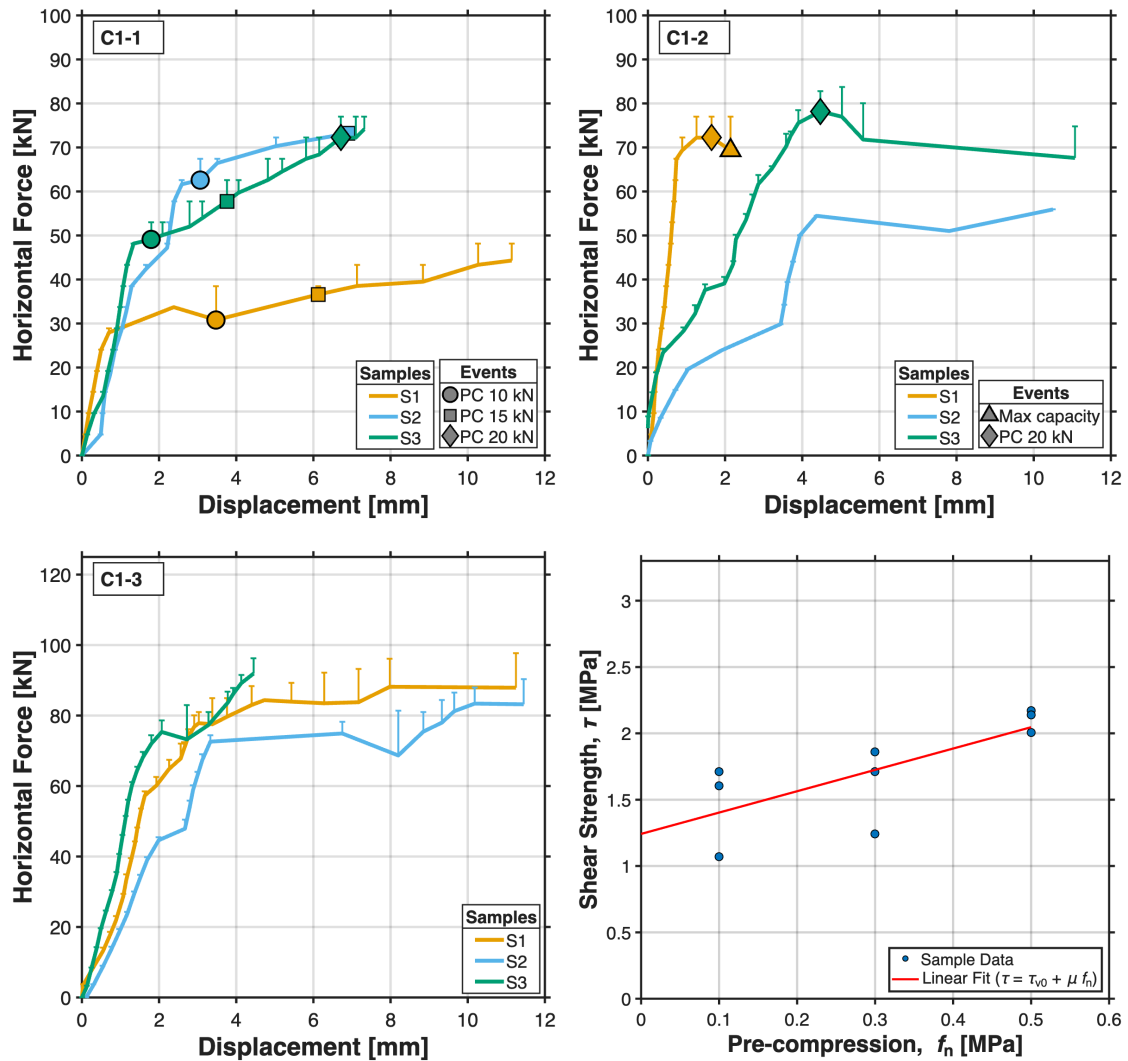


Figure 7.3: Presentation of results from test series C1 - 1:3 grout with different pre-compression loads.

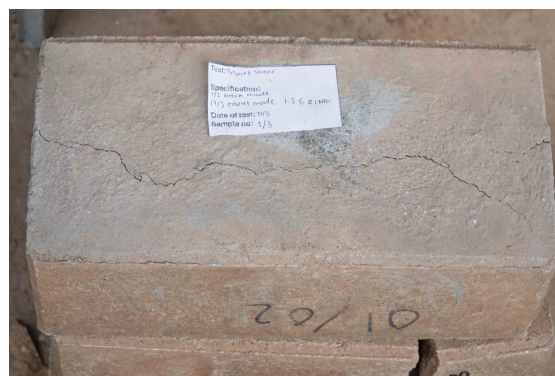


Figure 7.4: Typical failure behaviour of series C1 - 1:3 grout, showing a big crack through the full block.

7.2.2 C2 - 1:3 grout and mortar

The shear behaviour of triplets constructed with 1:3 grout and mortar joints under varying levels of pre-compression (0.1, 0.3, and 0.5 MPa) are represented with series C2. Table 7.4 and Figure 7.5 demonstrate a reversed behaviour, where shear capacity decreases with higher levels of applied pre-compression. The mean peak horizontal force (F_{max}) drops from 107.1 kN at 0.1 MPa to 77.2 kN at 0.5 MPa, which produces a decreasing Mohr-Coulomb curve with parameters determined as $\tau_{v0} = 2.64$ MPa and $\phi = -58.9^\circ$ ($\mu = -1.66$). In Figure 7.5 the Mohr-Coulomb failure criterion graph is presented.

In Figure 7.5 a significant variance within the individual samples is observed. Sample 2 in C2-2 series exhibits a substantially lower peak capacity of 81.5 kN compared to the remaining specimens in that group averaging 116.5 kN. A similar outlier is found in series C2-3, where Sample 2 records a lower capacity of 59.5 kN than the rest of its group with an average of 86.0 kN. In series C2-1 and C2-2 the initial pre-compression load was increased at displacements of 1.5 mm and 2 mm, respectively. For series C2-3 the initial pre-compression load was constant.

Table 7.4: Shear test results for series C2 - 1:3 grout and mortar.

Series	PC [MPa]	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
C2-1	0.10	1	115.8	94.3	2.57
		2	107.1	95.9	2.38
		3	98.3	54.5	2.18
		Mean	107.1	81.6	2.38
C2-2	0.30	1	122.9	112.5	2.73
		2	81.5	63.5	1.81
		3	110.0	72.9	2.45
		Mean	104.8	83.0	2.33
C2-3	0.50	1	81.7	35.0	1.82
		2	59.5	55.2	1.32
		3	90.3	67.7	2.01
		Mean	77.2	52.6	1.71
Mohr-Coulomb parameters					
$\tau_{v0} = 2.64$ MPa, $\mu = -1.66$					

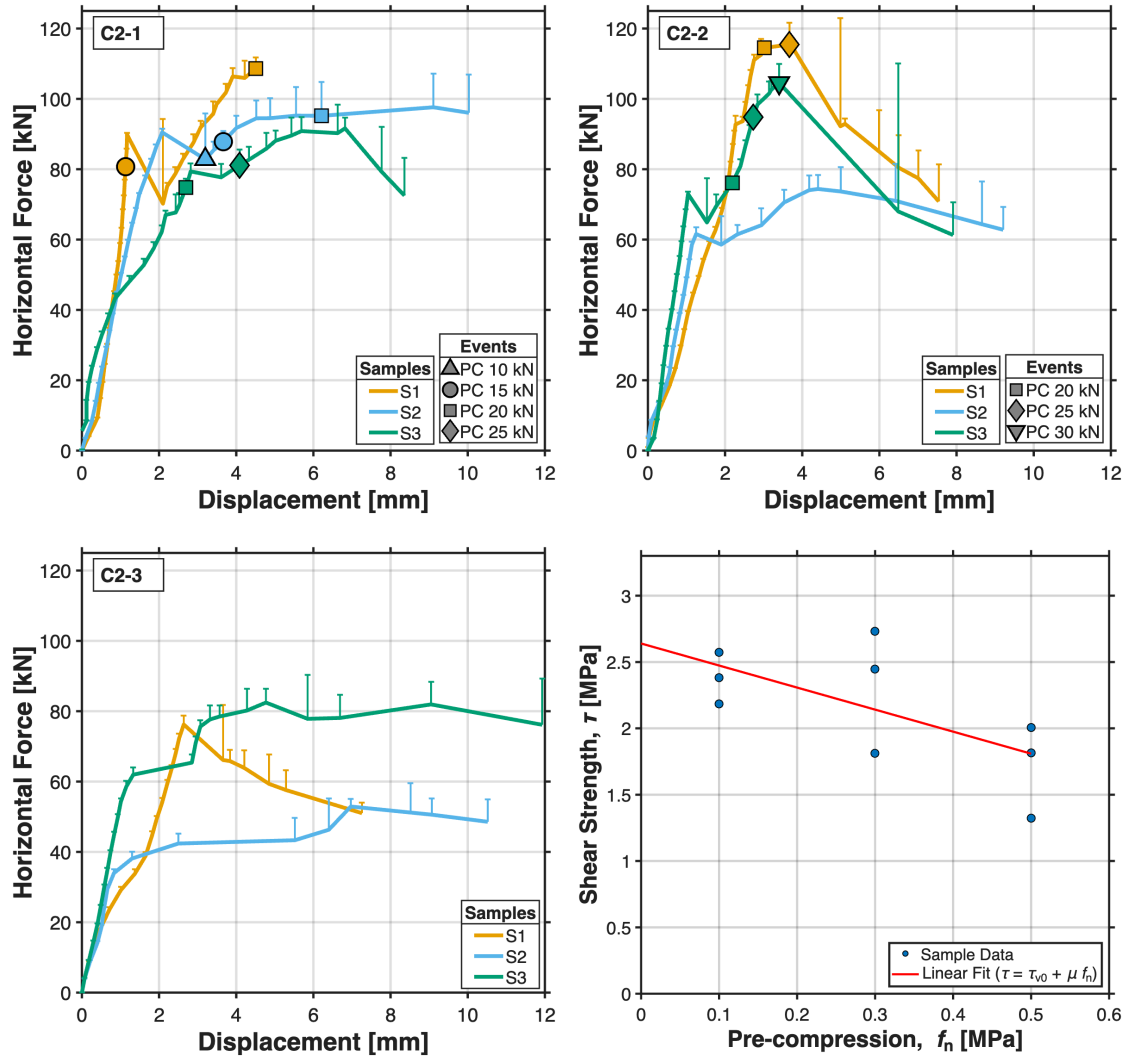


Figure 7.5: Presentation of results from test series C2 - 1:3 grout and mortar with different pre-compression loads.

7.2.3 C3 - 1:3 grout and reinforcement

Series C3 investigates triplets constructed with 1:3 grout and reinforcement under varying levels of pre-compression (0.1, 0.3, and 0.5 MPa). The results, presented in Table 7.5 and Figure 7.6, demonstrate an increase in shear capacity with higher levels of applied pre-compression. The mean peak horizontal force, F_{max} , rises progressively from 79.5 kN at 0.1 MPa pre-compression to 91.7 kN at 0.5 MPa. This increase gives the Mohr-Coulomb parameters $\tau_{v0} = 1.64$ MPa and $\phi = 34.1^\circ$ ($\mu = 0.68$), Figure 7.5 shows the Mohr-Coulomb failure criterion graph.

In Figure 7.6, the variation between individual specimens in Series C3-1 is relatively small, whereas larger differences are observed in Series C3-2 and C3-3. In Series C3-2, the peak load occurs at different displacement levels. For Samples 1 and 2, the peak load is reached at 1–2 mm displacement, whereas for Sample 3 the peak load is reached at a significantly larger displacement of more than 6 mm. Generally the specimens had large damage after testing, as seen in Figure 7.7 showing all units of C3-1 after testing.

Table 7.5: Shear test results for series C3 - 1:3 grout and reinforcement.

Series	PC [MPa]	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
C3-1	0.10	1	74.3	74.3	1.65
	0.10	2	78.3	59.5	1.74
	0.10	3	86.1	63.4	1.91
		Mean	79.5	65.7	1.77
C3-2	0.30	1	83.4	68.8	1.85
	0.30	2	89.1	89.1	1.98
	0.30	3	78.8	69.6	1.75
		Mean	83.7	75.8	1.86
C3-3	0.50	1	105.9	103.6	2.35
	0.50	2	97.2	34.3	2.16
	0.50	3	72.0	29.4	1.60
		Mean	91.7	55.8	2.04
Mohr–Coulomb parameters					
$\tau_{v0} = 1.64$ MPa, $\mu = 0.68$					

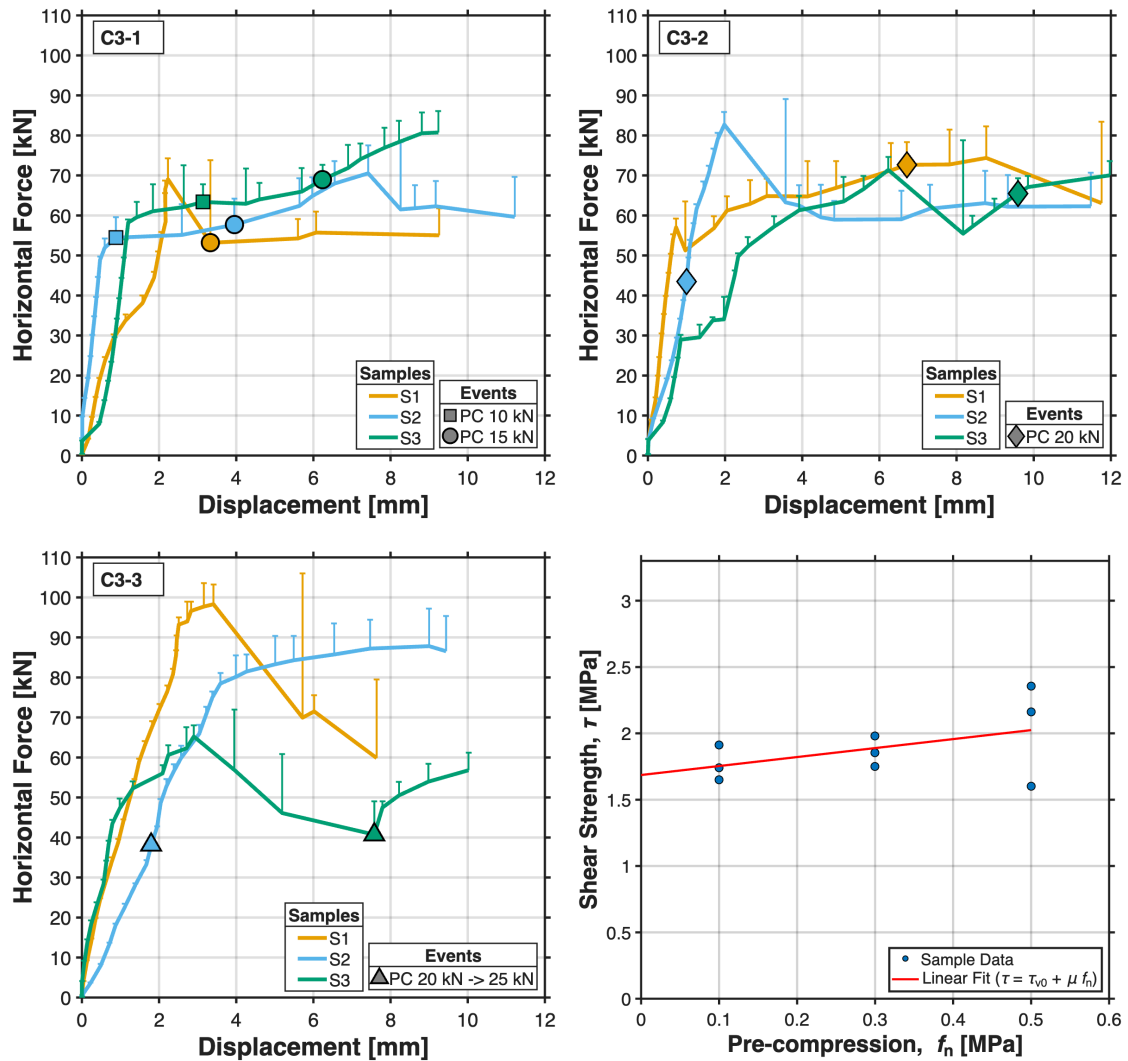


Figure 7.6: Presentation of results from test series C3 - 1:3 grout and reinforcement with different pre-compression loads. Events when pre-compression decreased and was subsequently increased are recorded.

Another deviation is observed in Series C3-3, where the initial pre-compressive load decreased during testing. When this reduction occurred, the pressure was subsequently adjusted back to the initial level. Series C3-3 also exhibits a larger scatter between specimens, sample 3 shows a substantially lower peak load (72.0 kN) compared to the remaining specimens in the group (101.6 kN), indicating increased variability in the response.



Figure 7.7: Series C3-1 after test.

7.2.4 C4 - 1:3 grout, reinforcement and mortar

Test series C4 investigates the shear behaviour of triplets constructed with 1:3 grout, reinforcement, and mortar joints under a pre-compression level of 0.1 MPa. The tests were performed prior to the implementation of the external load cell system. Consequently, all specimens reached the maximum calibrated capacity of the horizontal hydraulic, as shown in Table 7.6. The reported peak loads should therefore be interpreted as lower-bound values of the actual shear capacity.

Table 7.6: Triplet shear results for series C4 - 1:3 grout, reinforcement and mortar.

Series	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
C4	1	77.0	—	1.71
	2	77.0	38.5	1.71
	3	77.0	—	1.71
Mean		77.0	38.5	1.71

The force–displacement response for Series C4 is presented in Figure 7.8. The specimens exhibit a stiff initial response with relatively small displacements throughout the loading. The variation between individual specimens is limited, indicating a consistent structural response within the series. Sample 3 deviates slightly from the remaining specimens. During testing, one of the side plates came into contact with the bed mortar joint, which may have influenced the recorded response.

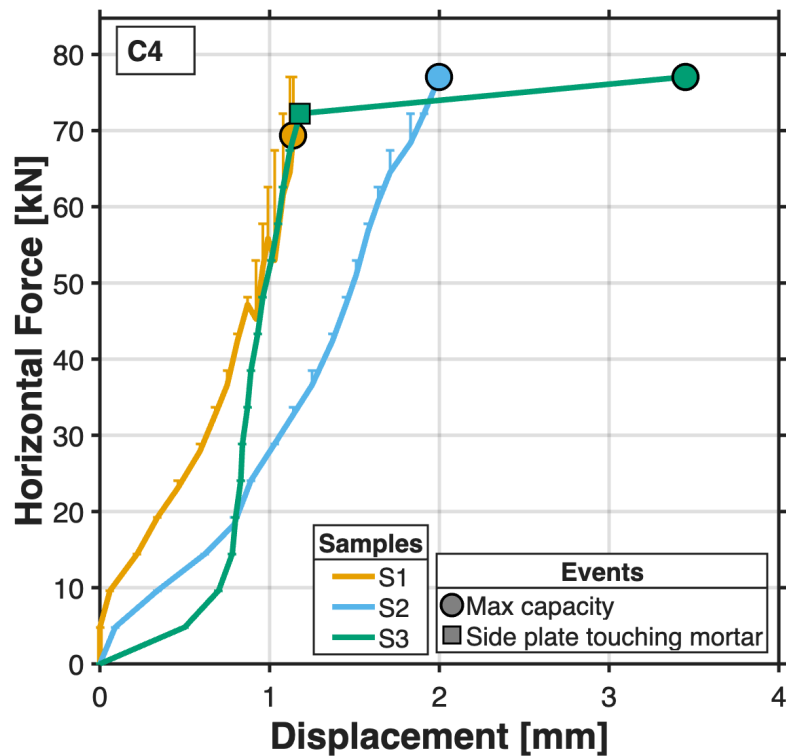


Figure 7.8: Force-displacement diagram for series C4 - 1:3 grout, reinforcement and mortar.

7.2.5 C5 - Dry stacked

Series C5 evaluates the contribution of geometric interlocking to the shear resistance of dry-stacked CSEB triplets. For Series C5, the load increased progressively with increasing displacement until peak load was reached. Following peak response, the specimens were capable of sustaining relatively high load levels before a sliding-dominated behaviour developed as shown in Figure 7.9. The variance within the the series is low both in behaviour (Figure 7.9) and with a coefficient of variance of 10.5%.

Series C5 reached shear strength between 0.76 to 0.91 MPa for the 3 samples with an average of 0.86 MPa, where the shear transfer is governed by a combination of surface friction and geometric interlocking.

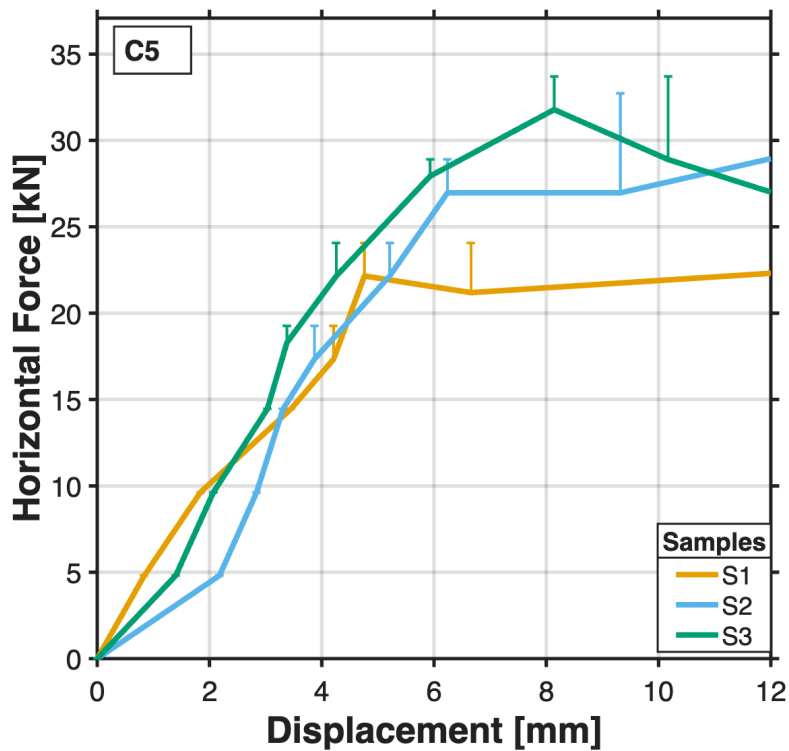


Figure 7.9: Force-displacement diagram for series C5 - Dry stacked.

Table 7.7: Triplet shear results for series C5 - Dry stacked.

Series	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
C5	1	27.9	—	0.76
	2	33.7	28.9	0.91
	3	33.7	—	0.91
	Mean	31.8	28.9	0.86

7.2.6 C6 - 1:3 grout without key

Test series C6 represents triplets where the original interlocking keys of the CSEBs were removed for all units and the voids subsequently filled with 1:3 grout. This procedure resulted in shear keys consisting entirely of grout material filling the key voids, as illustrated in Figure 7.10.

The tests for Series C6 were performed prior to the implementation of the external load cell system. Consequently, the maximum calibrated capacity of the horizontal hydraulic was reached during testing. The shear strengths presented in Table 7.8 should therefore be interpreted as lower-bound estimates of the actual system capacity.



Figure 7.10: View of the grout key formed within the interlocking void post testing.

Table 7.8: Triplet shear results for series C6 - 1:3 grout without key.

Series	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
C6	1	78.0	43.3	1.73
	2	77.0	—	1.71
	3	72.2	72.2	1.61
	Mean	75.8	57.8	1.68

The variation between specimens in Series C6 is relatively limited, indicating a consistent response within the test series, as shown in Figure 7.11. Furthermore, the results show a clear increase in pre-compressive load with increasing displacement throughout the loading process.

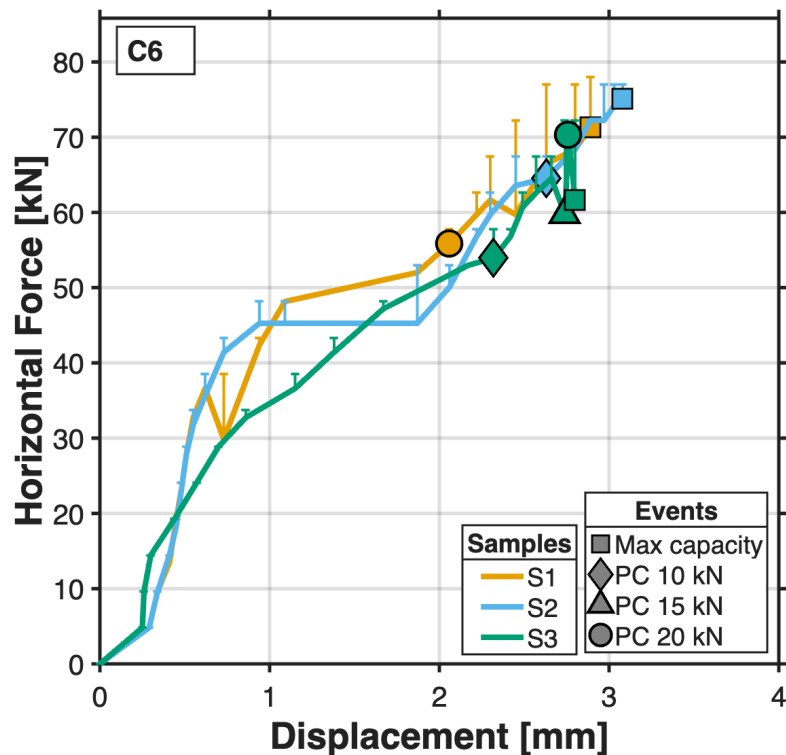


Figure 7.11: Force-displacement diagram for series C6 - 1:3 grout without key.

7.2.7 C7 - Dry stacked without key

Series C7 consists of dry stacked specimens without interlocking keys, representing a friction dominated interface response. As shown in Figure 7.12 the specimen exhibited sliding at low load levels, approximately 4.8 kN. Due to the early onset of sliding, only a limited number of stable data points were obtained within the applied loading scheme. Despite this, the scatter between individual specimens remained relatively small, and all samples initiated sliding at comparable load levels. Units showed close to no damage showing that the failure occurred only in sliding friction, see Figure 7.13.

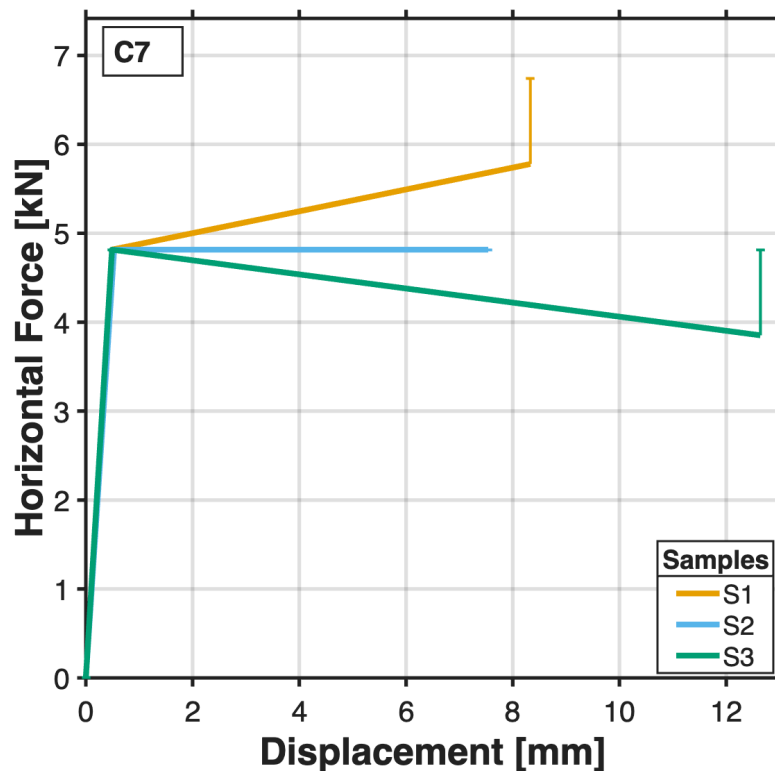


Figure 7.12: Force-displacement diagram for series C7 - Dry stacked without key

Table 7.9: Triplet shear results for series C7 - Dry stacked without key

Series	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
C5	1	6.7	—	0.18
	2	4.8	—	0.13
	3	4.8	—	0.13
	Mean	5.5		0.15



Figure 7.13: Series C7 - dry stacked triplet without keys showing no damage after testing.

7.2.8 C8 - 1:6 grout

The influence of the grout strength was investigated through series C8 which was filled with 1:6 grout mix. The shear strength of the series ranges between 0.99 to 1.11 with an average of 1.13 MPa, the results are summarised in Table 7.10.

In Figure 7.15 series C8 shows a sliding-dominant behaviour at loads below 20 kN. At relatively large displacements, above 6 mm, the initial pre-compression load starts to increase. The failure pattern is presented in Figure 7.14.

Table 7.10: Triplet shear results for series C8 - 1:6 grout.

Series	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
C8	1	44.44	34.00	0.99
	2	57.88	53.00	1.29
	3	49.76	—	1.11
Mean		50.69	43.50	1.13

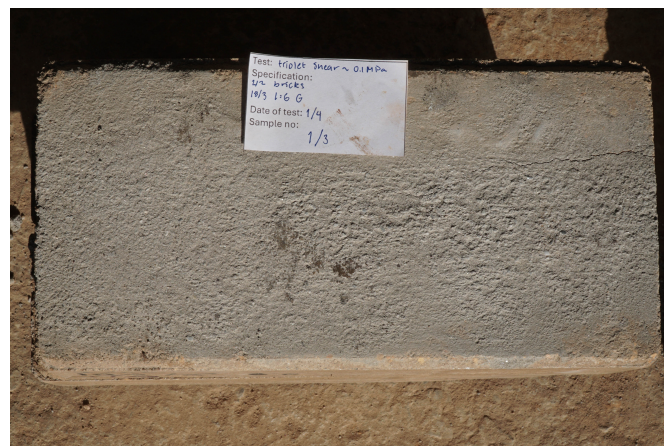


Figure 7.14: Series C8 - 1:6 Grout typical sample post testing.

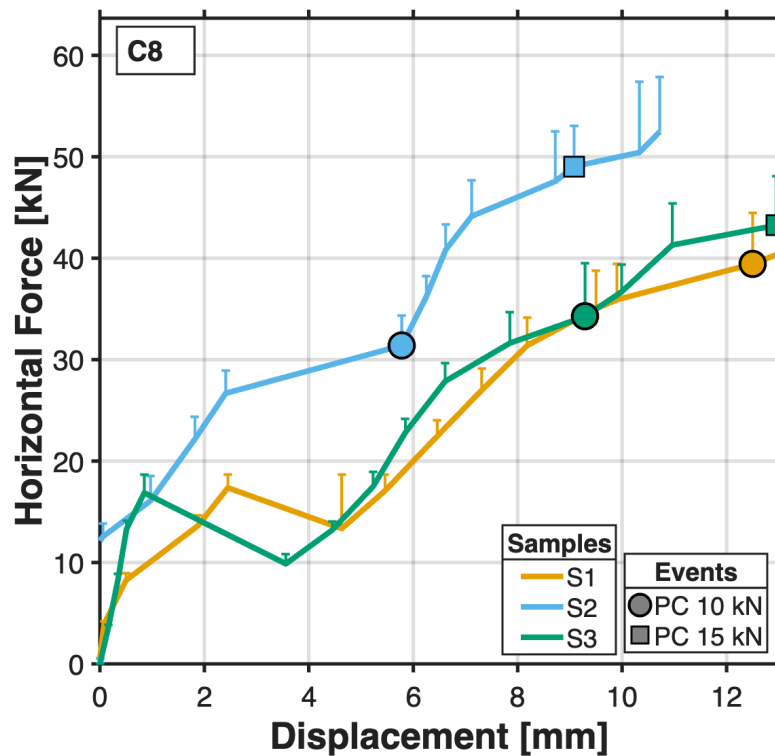


Figure 7.15: Force-displacement diagram for series C8 - 1:6 grout.

7.2.9 C9 - 1:6 grout and mortar

Series C9 evaluates triplets constructed with the leaner 1:6 grout mix alongside bed mortar joints. There is a clear shift in behaviour at a point somewhere under 2 mm for all samples, where a very stiff behaviour transitions to a more sliding behaviour. As shown in Figure 7.16 there is a clear outlier in sample 3 with a shear strength of 1.58 MPa which is well above the remaining average of 0.89 MPa. Figure 7.17 shows the failure patterns with large cracks but no splitting of the blocks in their long direction.

Table 7.11: Triplet shear results for series C9 - 1:6 grout and mortar.

Series	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
C8	1	41.0	23.8	0.91
	2	38.7	29.3	0.86
	3	71.5	65.6	1.58
	Mean	50.3	39.6	1.12

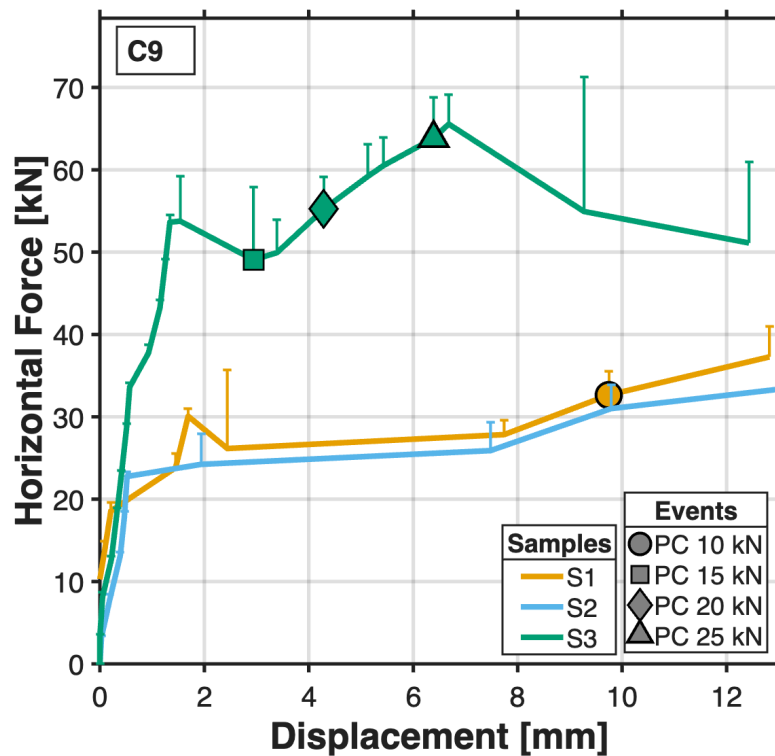


Figure 7.16: Force-displacement diagram for series C9 - 1:6 grout and mortar.

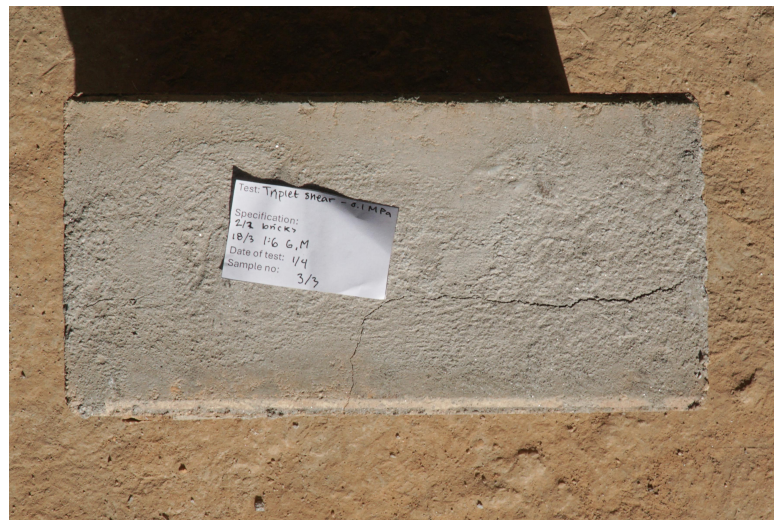


Figure 7.17: Series C9 - 1:6 grout and mortar typical sample post testing.

7.2.10 D1 - 1:3 grout without keys

Series D1 represents a second test of series C6, where the original interlocking keys were removed and the resulting voids filled with 1:3 grout. The average shear strength of the system was determined to 2.05 MPa, with relatively low variation between individual specimens, as shown in Table 7.12.

Table 7.12: Triplet shear results for series D1 - 1:3 grout without key.

Series	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
D1	1	91.4	87.0	2.03
	2	90.6	90.6	2.01
	3	94.2	85.8	2.09
	Mean	92.1	87.7	2.05

Although the peak shear strengths are very similar, Figure 7.18 shows a variation in displacement behaviour between the specimens. Initially, sample 1 exhibits a negative displacement response before returning to positive displacement at approximately 20 kN. Sample 3 displays a slightly softer response, whereas Sample 2 exhibits the stiffest behaviour within the series.

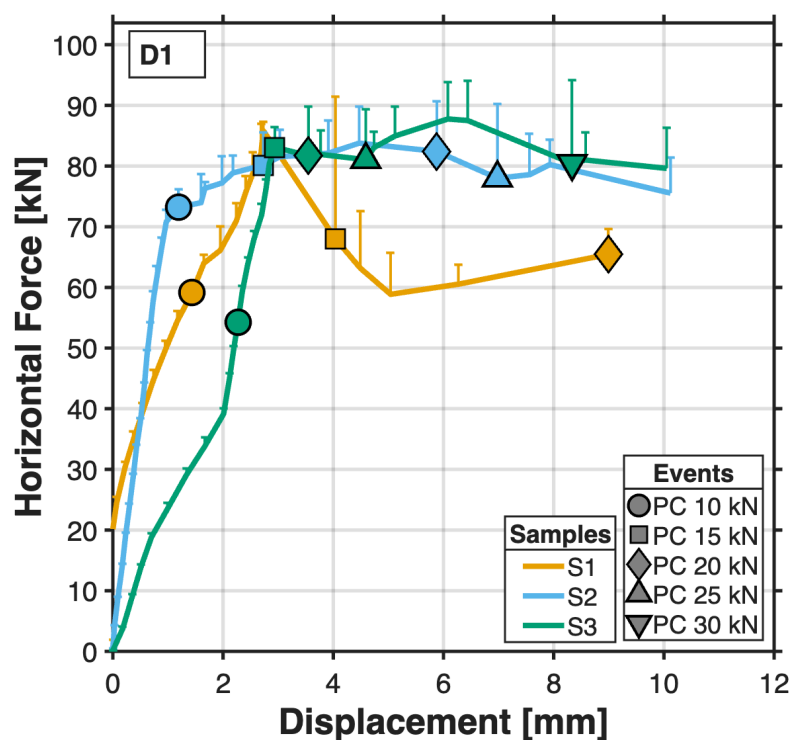


Figure 7.18: Force-displacement diagram for series D1 - 1:3 grout without keys.

Post peak load, Samples 1 and 2 maintain a relatively stable post-peak response and are capable of sustaining load during continued displacement. In contrast, Sample 3 exhibits a notable reduction in load-carrying capacity after peak response.

For all specimens within the series, the pre-compressive load increases progressively with increasing displacement throughout the loading process.

7.2.11 D2 - 1:3 grout

Series D2 represents a second test series corresponding to Series C1-1, consisting of specimens constructed with 1:3 grout under a pre-compression level of 0.1 MPa. The measured shear strength ranged between 2.00 MPa and 2.33 MPa, with a mean shear strength of 2.22 MPa, as shown in Table 7.13.

Table 7.13: Triplet shear results for series D2 - 1:3 grout.

Series	Sample	F_{us} [kN]	F_{cr} [kN]	τ [MPa]
D2	1	104.2	78.7	2.31
	2	90.0	86.7	2.00
	3	105.0	64.1	2.33
	Mean	99.7	76.5	2.22

Figure 7.19 shows relatively small variation in mechanical response between the individual specimens. Notably, Sample 1 initially exhibits a non-physical negative displacement response before returning to positive displacement at approximately 15 kN. Samples 1 and 2 display relatively similar behaviour and strength levels, whereas Sample 3 exhibits a generally lower capacity throughout the test.

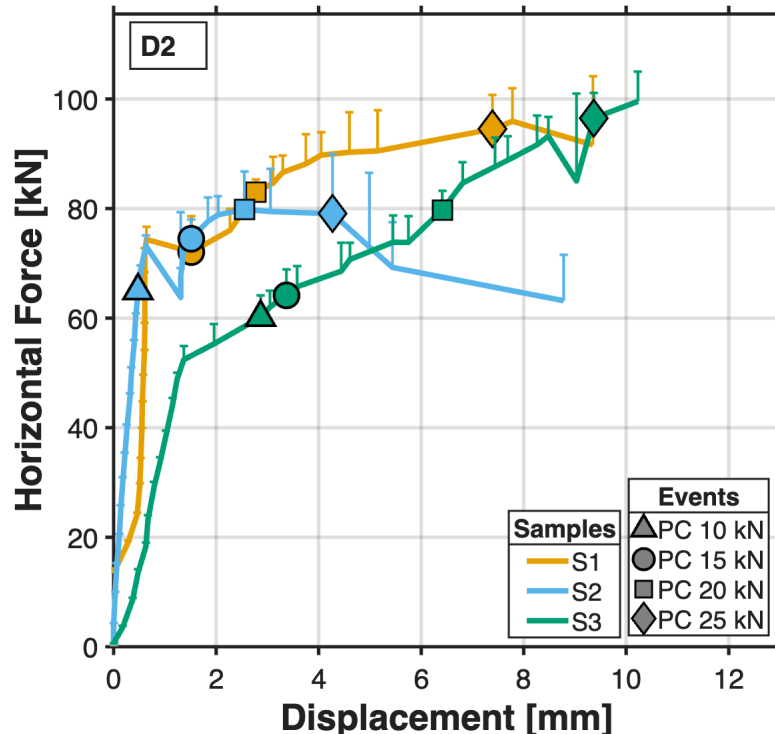


Figure 7.19: Force-displacement diagram for series D2 - 1:3 grout.

8 Parametric results

To understand how the different parameters affect the system the series are compared and discussed in terms of; average strength, typical behaviour during testing and failure mechanisms.

8.1 Size effects

As shown in Figure 7.1, there is a clear size effect when scaling up from individual units to masonry prisms. Masonry prisms exhibit a significantly lower compressive strength compared to individual units, demonstrating a reduction of approximately 53% for CSEBs and 28% for fired bricks. This reduction can be attributed to differences in the failure mechanisms; while the individual unit specimens typically exhibit cracking along their side faces, the failure of masonry prisms is heavily governed by the interface between the blocks. This size effect is consistent with existing literature (Saari et al., 2025; Silva et al., 2015).

8.2 Pre-compressive load

In series C1 and C3 there is a positive trending Mohr-Coulomb failure criterion as expected, however in series C2 a negative trend is observed. C1 shows the largest increase of shear strength in relation to pre-compression. One reason for this could be that C1 provides the best conditions for the keys to utilise their full capacity, and that the increasing pre-compression increases the capacity up through engagement of the keys and friction. Series C3 with grout and rebar shows less sensitive to changes in pre-compression compared to the grout series C1. This suggests that the strength contribution from the rebar reduces the need for the friction and key driven strength which are more governed by pre-compression.

The negative trend of the grout and bed mortar in series C2 is surprising and hard to deduce the reason for. Possible hypotheses are that the mortar contributes to stress concentrations creating damages or that the mortar bed raises the block, giving the key less height to interlock. Examining the triplets post test show cohesion failure of the mortar, making continuous sliding depend on friction mortar to mortar instead of block against block.

Interestingly, the differences in shear strength between the series are less for high pre-compression compared to low. For 0.1 MPa pre-compression the coefficient of variation between the average shear strengths between series C1, C2 and C3 is 25% and for 0.5 MPa pre-compression it is 11%. Possibly suggesting that the differences in system matters less at high pre-compression, however the trends for each are as mentioned above very different so it might be a coincidence that the values cluster at 0.5 pre-compression.

8.3 Influence of keys

Series C5 and C7 were tested to evaluate the contribution of geometric interlocking to the shear resistance of dry-stacked CSEB triplets. Series C5 represents dry-stacked specimens with interlocking keys, whereas Series C7 consists of specimens without interlocking keys. A substantial reduction in shear resistance was observed when the interlocking keys were removed. Series C5 reached an average shear strength of 0.86 MPa, whereas Series C7 exhibited a mean value of only 0.15 MPa, corresponding to a reduction of approximately 83%.

A clear difference in displacement behaviour can also be observed between the two series. For Series C5, the displacement initially increased approximately linearly with increasing load. At displacements of around 2 mm, the load could increase further with limited additional displacement, indicating activation of the interlocking keys. The initial sliding response may be attributed to manufacturing tolerances between the block interfaces and the interlocking keys. Following peak load, the system exhibited a sliding-dominated behaviour characterised by large displacements under relatively small load increases.

In contrast, Series C7 exhibited a clear sliding behaviour already at low load levels. Although some variation in post peak behaviour was observed between specimens, all samples displayed large displacements for relatively small increases in load. This indicates that friction alone between the block surfaces is insufficient to effectively resist horizontal shear forces beyond 5 kN.

A further comparison can be made between Series C1-1 and C6 in order to evaluate the effect of replacing interlocking keys with grout-formed keys constructed from 1:3 grout. A direct comparison of the mean shear strengths indicates an increase from 1.46 MPa for Series C1-1 to 1.68 MPa for Series C6, corresponding to an increase of approximately 15%. However, it should be noted that the reported shear strength for Series C6 does not necessarily represent the ultimate shear capacity of the system, since the specimens reached the maximum calibrated capacity of the testing equipment during the experiments.

Furthermore, Sample 1 in Series C1-1 exhibited a notably lower shear strength compared to the remaining specimens and may therefore be considered an outlier. Excluding this specimen results in an adjusted mean shear strength of approximately 1.66 MPa for Series C1-1, reducing the difference between the two series to approximately 1%. This result is more consistent with the results obtained for series D1 and D2, which was tested one week later. These series indicates instead a slight reduction in shear strength, approximately 7.7%, when grout formed keys are used instead of the original interlocking keys.

The results demonstrate that the geometric interlocking contributes significantly to the overall shear capacity of the dry-stacked system but replacing the original interlocking keys with grouted keys did not improve the overall shear strength.

8.4 Influence of mortar

The influence of the bed mortar can be evaluated by comparing series C1 with C2, as well as series C8 with C9. Series C1 represents specimens constructed with 1:3 grout, whereas series C2 consists of specimens with 1:3 grout combined with bed mortar. Considering first the specimens subjected to a pre-compression level of 0.1 MPa, the presence of bed mortar increased the mean shear strength from 1.46 MPa to 2.38 MPa, corresponding to an increase of approximately 63%.

A similar trend can be observed at a pre-compression level of 0.3 MPa, where the inclusion of bed mortar increased the shear strength by approximately 45%. A clear difference in the mechanical behaviour was also observed, series C2-2 shows a significantly stiffer behaviour than series C1-2, indicating that the bed mortar contributes to an increased stiffness of the system.

In contrast, when the pre-compression level was increased to 0.5 MPa, the presence of bed mortar resulted in a reduction in shear strength of approximately 18.6%, decreasing from 2.11 MPa in series C1-3 to 1.72 MPa in series C2-3. A comparison of the load–displacement curves also indicates that the differences in stiffness between series C1-3 and C2-3 were considerably smaller than those observed at lower pre-compression levels. The general trend of decreasing shear strength with increasing pre-compression stress, as observed in series C2, makes it difficult to draw clear conclusions from the results. However, the result still indicates a tendency towards increased shear capacity in the presence of bed mortar, particularly at lower pre-compressive stress.

Furthermore, the effect of adding a bed mortar with 1:6 grout, as in series C8, decreases the shear strength by barely 1% compared with series C9 with only 1:6 grout. If the sample 3 in series C9 is treated as an outlier and exuded, the mean shear strength is reduced with 21.1% when bed mortar is introduced. The mechanical behaviour nevertheless indicates a stiffer response for series C8, although this did not translate into a higher ultimate shear strength. This indicates that adding a bed mortar with low strength decreases the global strength of the system although it makes the system stiffer. This behaviour may be explained by a reduction in the engagement of the interlocking keys, since the bed mortar increases the joint height and thereby reduces the degree of mechanical interlocking. Meanwhile a bed mortar of 1:3 grout increases the shear strength, indicating that a bed mortar with higher strength contributes more to an effective load transferring within the system.

8.5 Grout strength

To understand how the grout strength affects the system the series C1-1, C2-1, C8 and C9 are tested and compared. Series C1-1 and C2-1 represent 1:3 grout strength with grout and grout and bed mortar respectively. C8 and C9 are tested with 1:6 grout, also with grout and grout and bed mortar respectively.

Comparing the average shear strength between grouted series C1-1 (1:3 grout) and C8 (1:6 grout) shows an increase of shear strength approximately 30% in series C1-1

compared to series C8. This is in line with the compressive strength of the 1:3 grout being higher than the 1:6, that difference was however much larger with an increase of 374%. Comparing the series C2-1 (1:3 grout and mortar) and C9 (1:3 grout and mortar), the averages of shear strength shows a significant difference, C2-1 has an increase in strength of 113% compared to C9. That is including the outlier of C9, removing the outlier the increase from C9 to C2-1 is 169%. Showing that the grout strength makes a significantly bigger differences on the bed mortar compared to the grout channels.

Beyond differences in peak strength, the mechanical response of the series differs: Series C1-1 (Figure 7.3) exhibits a notably stiffer initial response at low load levels (30–50 kN) and small displacements (up to 2 mm). In contrast, series C8 exhibits a sliding-dominant behaviour at low loads (below 20 kN). This suggests that the higher-strength grout in series C1-1 facilitates a more effective cohesion of grout or “engagement” of grout channels within the masonry interface. Conversely, the C8 series appears unable to mobilise the same degree of grout-driven stiffness, potentially due to lower strength of the grout or localised interface defects. With the inclusion of bed mortar in series C2-1 and C9 the behaviour between the two is similar initially, however the weaker C9 starts sliding at lower loads and is typically not able to build much more strength after the first big displacement.

Comparing the failure mechanisms in Figures 7.4 and 7.14, it is clear one has more damage to the block than the other, this was generally the case with the different grout strengths. Samples with stronger grout mix generally showed bigger cracks and even full splitting of the blocks lengthwise. This is inline with the hypotheses of low engagement of the 1:6 grout, not having sufficient strength to damage the blocks before shearing off.

Cutting open the block revealed defects in the grout even before testing as seen in Figure 8.1. The defects are in key areas, in the interface between two blocks where shear resistance is crucial. The two different grout strengths show different defects, the 1:3 mix have partly flowed out in the key voids and subsequently developed cracks while the 1:6 has major voids from compaction rods.



Figure 8.1: Block cut without being tested. 1:3 grout mix left and 1:6 grout mix right.

8.6 Rebar addition

The addition of vertical reinforcement (rebar) to the grout channels was evaluated in Series C3 and C4. Series C3 represent grouted channels with a rebar in one channel tested under increasing pre-compression loads and C4 tested systems with grout, bed mortar and one vertical reinforcement in one channel. By comparing these results against the unreinforced, grout-filled series (C1), the specific influence of the rebar on the triplet shear capacity can be viewed.

Comparing series C1-1 to C3-1 reveals a similar overall load-displacement behaviour as seen in Figures 7.3 and 7.6. However evaluating the shear strength the rebar option has an increase of 21%. Interestingly, this strength difference between C1 and C3 diminishes as the applied pre-compression increases. At 0.3 MPa pre-compression, the strength increase between C1-2 and C3-2 drops to 16%. At the highest pre-compression level of 0.5 MPa, the relationship is close to equal, with the grouted C1-3 series proving approximately 3% stronger than the reinforced C3-3 series.

This indicates that a system with reinforcement is less affected by the pre-compression load than a system without reinforcement. Possibly describing how the rebar improves the initial shear strength (with zero pre compression) but does not improve the coefficient of friction.

In series C4 all tests reached the capacity of the calibration with the first measuring system (77 kN) only providing a lower bound value of strength. It is therefore not possible to properly compare the shear strength between C2-1 and C4.

Typical failure mechanisms (Figure 7.7) of the rebar series showed substantial damage to the blocks indicating possible crushing of the blocks due to the stiff rebar creating stress concentrations.

9 Discussion

Conducting experimental tests in a workshop or field-based environment presents several practical challenges. Furthermore, undertaking a novel experimental study of this nature requires significant methodological decision-making. It necessitates adapting and referencing standardised testing procedures that were originally developed for materials with fundamentally different physical prerequisites, failure mechanics, and a more equipped lab setting.

The experimental methodology employed in this study demonstrated both notable successes and limitations. Documenting these methodological outcomes is crucial for refining future testing protocols at Build up Nepal, thereby contributing to the continuous development of their testing capabilities and general knowledge.

One of the key issues that needs to be resolved in future testing is the progressively increasing pre-compression load. It is known that the pre-compression affects the shear capacity and not being able to keep it steady does affect the results. Possible improvements could be utilising a more accurate hydraulic system and continuously compensating the pressure, or transitioning to a dead-weight loading system. Both options pose their own difficulties; the handling of the pre-compression manually would be a challenge and a dead-weight system adds the need to handle a weight of around 500 kg for a 5 kN pre-compression. In addition, the use of a hydraulic with a capacity sufficiently exceeding the expected load levels is considered important. These guidelines are now feasible due to the establishment of baseline strength values for triplet specimens obtained in this study.

Geometric imperfections and slight misalignments in the specimens occasionally posed challenges within the strict dimensional restriction of the current test rig. Furthermore, achieving uniform load distribution across the top surface proved difficult, even with the adopted method of grinding the tops flush. Any irregularities in load application can prevent the internal grout channels from fully engaging under pressure, which is an essential mechanism for developing the maximum shear capacity of the system.

Continued rebar testing at the triplet level is unlikely to yield further actionable insights for system improvement. Instead, the broader structural effects of vertical reinforcement should be evaluated on larger masonry scale, such as wall panel tests. Furthermore, tests without keys and grout with lower strength is not expected to yield substantially more information than already obtained. A future study could however be deployed varying the geometry of the keys, with the goal of increasing their contribution to strength further.

In this study, three samples in each series were tested, in accordance with relevant standards for determining the initial shear capacity. However, considerable variations was observed between specimens in certain series. An increased number of tested specimens would improve the reliability and statical confidence in the results. With the current number of samples, it is difficult to determine whether certain results should be considered outliers or representative behaviour.

Variations and uncertainties in the workshop environment should be understood together with the uncertainties that emerges in field. Construction is performed in remote settings by a mix of skilled and unskilled labour, and with varying standardisation in construction instructions.

10 Conclusions

Triplet shear testing based on BS EN 1052-3:2002 with described alterations, proved to be an adequate method for testing many samples in a simple workshop. Consequently, the continued refinement and application of this methodology represents a highly viable approach for future research and quality control by Build up Nepal in the workshop. However, due to the simplified setup and limitations in measurement accuracy, the results obtained in this study should primarily be considered for comparison between test series rather than definitive material parameters.

In this study three clear contributions the shear strength of the interlocking CSEB triplets were identified. The interlocking keys enhance the overall shear behaviour of the system, a higher cement content in grout increases the shear strength, and the inclusion of bed mortar increases strength only when used with high-strength grout.

The interlocking keys provide mechanical interlocking that enhances the shear strength when tested alone. These keys are responsible for maintaining residual capacity, allowing the masonry to sustain loads even after large displacements and the ultimate shear failure of the internal grout channels.

Further, the cement content in the grout is crucial for overall structural performance, double the amount of cement from a ratio from 1:6 to 1:3, cement to sand ratio, increases the shear capacity with 30 %. Since the cement content is found critical a recommendation is that Build up Nepal provides simple, standardised measuring equipment, such as calibrated buckets to ensure uniform batch sizes with correct cement to sand ratio. Implementing this measure would significantly improve quality control in field construction and reduce the need for extensive on-site monitoring.

Finally, the use of bed mortar is complex. High-quality mortar increased the systems shear capacity, whereas low-strength bed mortar decrease it. The recommendation of adding bed mortar is also undesirable from a construction point of view, as it introduces complexity to the building process; increasing grout strength is a simpler option to implement. A study on the effects of poor workmanship in bed mortar laying could inform the potential of recommending bed mortar for all construction.

This study provides Build up Nepal with much needed reference data that should be used comparatively with future studies. Moreover this data can serve as a base for methodology development in terms of machine capacities needed and timelines expected.

10.1 Future studies

The testing methodology described in this study serves as a strong baseline and reference for future research by Build up Nepal, as it provides a clear structure regarding the time frames of production and testing. The successes and shortcomings of this methodology are highlighted. Maintaining a constant pre-compression, as described in Chapter 6, is a key issue to be resolved.

An important aspect for future studies is to define a clear target in terms of required shear capacity under earthquake loads. This may be obtained from design norms or validated through a numerical approach such as FEM analysis. Without a clear defined threshold there is a risk of continuing to increase the capacity, with economic and environmental aspect being compromised in the singular pursuit of higher strength.

It is recommended to continue testing at the triplet level, conducting targeted studies to evaluate varying grout strengths, compaction methods of grout, and geometry of interlocking keys. Future research should also scale up the sample size to at least six specimens per series. These studies should be carried out before selecting 2-3 optimal variations and validate with an external lab to achieve reliable material parameters. Future steps are then to scale up to larger masonry test of wall segments.

A recommended modification to the test rig is increasing its inner dimensions by 5–10% facilitating slightly crooked and misaligned specimens. Furthermore, load distribution should be enhanced by utilising either a cement capping or a separate rubber pad for example. This may be implemented together with grinding of the top surface as demonstrated in the methodology of this study. This procedure also contributes to ensuring full pressure of the grout channels, which is considered essential for the development of the shear capacity.

The occurrence of grout damage within the internal channels was an unexpected observation when sectioning the blocks. Because this was a late discovery, targeted experimental studies to understand and mitigate this could not be conducted. Investigating the causes, prevention, and structural implications of this internal grout damage should be a primary focus for future research.

Future research should adopt a standard 28-day curing period for the masonry triplets, aligning with conventional testing protocols for cementitious materials. In this study, a shortened 14-day curing regime (7 days wet, 7 days dry) was utilised due to logistical limitations regarding field access. However, supplementary testing demonstrated that an additional 7 days of dry curing increased the specimen strength by approximately 50%. It is highly probable that allowing the specimens to reach their full 28-day strength potential could alter the relative performance margins observed between the different test series.

Once it is established that the system meets the required shear capacity, the focus can shift from increasing the strength to optimisation of achieved strength. In this phase, minimising environmental impact and cost reduction can be the goal.

11 References

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A Load calculation on a single CSEB

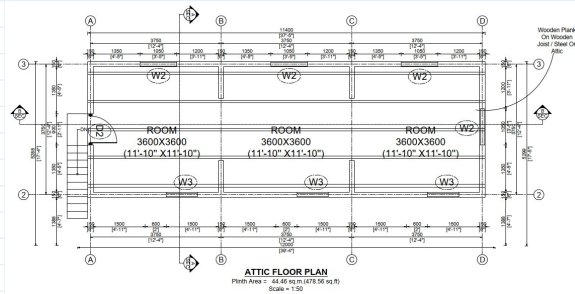
Load calculation CSEB block for triplet shear
Single storey with attic 3 room.
Load on bottom block.

$$h_{building} := 3600 \text{ mm}$$

$$h_{block} := 100 \text{ mm}$$

$$l_{block} := 300 \text{ mm}$$

$$w_{block} := 9 \text{ kg}$$



$$widthTrib_{attic} := l_{block}$$

$$lengthTrib_{attic} := 1900 \text{ mm}$$

live load according to NBC

$$LL_{room} := 2 \frac{\text{kN}}{\text{m}^2}$$

$$LL_{roof} := 0.45 \frac{\text{kN}}{\text{m}^2}$$

$$noBlocksVert := \frac{h_{building}}{h_{block}} = 36$$

$$totw_{blocks} := noBlocksVert \cdot w_{block} = 324 \text{ kg}$$

$$AreaTrib_{attic} := widthTrib_{attic} \cdot lengthTrib_{attic} = 0.57 \text{ m}^2$$

$$DeadLoad := totw_{blocks} \cdot g = 3.177 \text{ kN}$$

$$LiveLoad := (LL_{room} + LL_{roof}) \cdot AreaTrib_{attic} = 1.397 \text{ kN}$$

$$Total := DeadLoad + LiveLoad = 4.574 \text{ kN}$$

B Calibration certificates

This appendix presents the calibration certificates and documentation for the testing equipment used in the experimental programme.

Ref No: 2082-12-11
 Receipt No: 2082-12-11
 Date: 2082-12-11
 Time: 6:00 PM
 Temperature: 15.0°C
 Valid Upto: 2083-12-10

TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS
DEPARTMENT OF CIVIL ENGINEERING
CENTRAL MATERIAL TESTING LABORATORY
CALIBRATION DATA SHEET

Clients Details:
 Calibrated For: Build up Nepal Engineering
 Project:
 Location: Kusumti Height, Ring Road Uthar, Lalitpur

Machine Details:
 Instrument: Hydraulic Jack Hand Pump
 Manufacturer: N.A.
 Operating Type: Manual
 Unit: kg/cm²
 Display Type: Analog
 Capacity: 700 kg/cm²
 Least Count: 5 kg/cm²
 Ram Dia: 48 mm
 Serial No.: N.B.

Master Instruments Details
 Calibration Machine: Standardizing Box
 Manufacturer: J. Ragau Industries
 Dial Gauge Sr. No: 28059
 Serial No: 2476/28059
 Capacity: 3000 kN
 Least Count: 0.05 kN
 Dial Gauge: 0.05 kN/Div.
 Date of Calibration: 02/12/2025
 Valid Until: 04/12/2027
 Traceability: NPL, New Delhi

Calibration Details
 Method: Comparison

Preloading	1	2	3
	450	450	450

Applied Load	Observed Reading In Standardizing Box				Standard Value		Remarks
	Set-1 0°	Set-2 90°	Set-3 180°	Set-4 360°	Load	Dial Gauge	
50	9.35	9.50		9.50	200		
100	19.32	19.40		19.60	400		
150	29.60	20.50		20.05			
200	39.61	39.40		39.40	600		
250	49.50	49.60		49.60			
300	59.05	59.05		59.05	800		
350	68.54	68.50		68.40			
					1000		
					1200		
					1400		
					1600		

Witnessed by: [Signature]
 Calibrated by: [Signature]

Amalanda Niketan, Pulchowk, Lalitpur, Nepal. Tel: 3348833, Email: cmil@ioe.edu.np

Figure B.1: Calibration certificate for the horizontal hydraulic testing machine.

**DEPARTMENT OF CIVIL ENGINEERING
CENTRAL MATERIAL TESTING LABORATORY
CALIBRATION DATA SHEET**

Time: 4:40 PM
Temperature: 16°C
Valid Upto: 2083-12-10

Clients Details:

Calibrated For: Build UP Nepal Engineering.

Project: _____

Location: Kusunti Height, Ring Road Uttar, Lalitpur

Machine Details:

Instrument: Hydraulic Jack Hand pump Display Type: Analog

Manufacturer: N.A Capacity: 400-500 kN

Operating Type: Manual Ram Dia: 75 mm

Unit: kN Serial No.: N.A

Master Instruments Details

Calibration Machine: Standardizing Box	Least Count: 0.05 kN
Manufacturer: J. Ragau Industries	Dial Gauge : 0.05 kN/Div.
Dial Guage Sr. No: 28059	Date of Calibration: 02/12/2025
Serial No : 2476/28059	Valid Until: 04/12/2027
Capacity : 3000 kN	Traceability: NPL, New Delhi

Calibration Details

Method: Comparison

Preloading	1	2	3
	400	400	400

Applied Load	Observed Reading In Standardizing Box				Standard Value		Remarks
	Set-1	Set-2	Set-3	Set-4	Load	Dial Guage	
	0°	90°	180°	360°			
50	50.20	50.65		50.60	200		
100	100.65	100.75		100.60	400		
150	149.70	149.55		149.50			
200	198.64	199.25		199.00	600		
250	248.22	249.00		249.10			
300	298.00	299.55		299.30	800		
350	348.61	349.71		349.70			
					1000		
					1200		
					1400		
					1600		

Calibrated by: _____

Witnessed by: B. W. D. B.

Ananda Niketan, Panchowk, Lalitpur, Nepal, Tel: 3348833, Email: cmtd@ioc.edu.np, www.cmtl.com.np

Figure B.3: Calibration certificate for the blue vertical hydraulic testing machine.

C Lab Log: Production of test specimens

These notes were recorded in notebooks during the testing and transcribed using AI-tools and checked to be accurate.

Detailed daily lab log of production of test specimens including the specimen production, preparation and material processing, grouting method, grout recipes, curing and post production notes.

Lab Log: Production of Test Specimens (15/03/2026)

This log details the preparation and production of Compressed Stabilised Earth Block (CSEB) triplets performed on March 15, 2026. These specimens are scheduled for testing after a 14-day curing and drying period. A surplus of 3 specimens compared to testing schedule was made.

Specimen Production Overview

A total of 36 specimens were prepared using CSEB units produced on January 29. The production breakdown is summarised in Table C.1.

Table C.1: Overview of specimens produced on 15/03/2026.

Specimen Type	Test Purpose	Quantity
Grouted Triplets	Compression	6
Grouted Triplets	Shear	6
Dry Stacked Triplets	Compression	6
Dry Stacked Triplets	Shear	6
CSEB Unit	Compression	6
Fired Brick Unit	Compression	6
Total		36

The specimens will be cured until March 22, followed by a drying period, with final testing scheduled for March 29.

Preparation and Material Processing

Prior to assembly, the interlocking keys of the CSEB units intended for unit compression tests and the top blocks of each triplet were sanded off to ensure a flat loading surface. A wood plank was used as the base and side of the triplet.

Coarse sand was purchased and sieved through a 3 mm mesh before being incorporated

into the grout mixture, removing rocks and gravel.

Grouting Method

The dry materials (cement and sand) were first mixed in a container. Water was added incrementally and hand-mixed to achieve the desired consistency. The process for filling the voids in the triplets was as follows:

1. The grout mixture was poured 2/3 of the height of the triplet cavities (3 stacked CSEB units).
2. A 10 mm reinforcement rod was used to "rod" the grout up and down 20 times per hole to ensure compaction and vibration.
3. All holes were filled to the top and leveled to be flush with the upper surface.
4. Specimens were left in their molds for 24 hours before being moved to the curing area.

Grout Recipes

Two main batches of 1:3 grout were prepared. Initially, a water-to-cement (w/c) ratio of 0.75 was intended; however, this resulted in a consistency that was too coarse and hard to work with. Consequently, the w/c ratio was increased to 1.0 for all production batches. Each batch is intended to be sufficient for a set of 6 triplets.

Table C.2: Grout mixing proportions (1:3 ratio, w/c 1.0).

Material	Batch 1 [g]	Batch 2 [g]
Cement	4 465	6 250
Sand	17 610	24 650
Water	4 465	6 250
Total Weight	26 540	37 150

Note: Batch 1 was insufficient to fill all specimens. Batch 2 was scaled up to ensure adequate coverage. An additional small "extra" batch was mixed using 1 kg cement, 3 kg sand, and 1 kg water to finish the remaining voids.

Lab Log: Production of Test Specimens (16/03/2026)

This log details the production of CSEB triplets and unit blocks performed on March 16, 2026. A total of 24 triplets were prepared

Specimen Production Overview

The specimens produced this day are categorised into four distinct sets of triplets. The breakdown is presented in Table C.3.

Table C.3: Overview of specimens produced on 16/03/2026.

Specimen Type	Configuration	Quantity
Triplets	Without key + Grout	6
Triplets	Grout + Reinforcement	6
Triplets	Grout + Mortar	6
Triplets	Without key (Dry-stacked)	6
Total		24

Preparation and Application

For the application of the mortar, assistance was provided by an experienced mason to ensure consistency.

Grout and Mortar Recipes

Three batches were mixed using a 1:3 cement-to-sand ratio and a water-to-cement (w/c) ratio of 1.0. Notably, the third batch served for both the grout and mortar sets, as the same mix design was utilised for both applications.

Table C.4: Mixing proportions for Grout and Mortar (1:3 ratio, w/c 1.0).

Material	Batch 1 [g]	Batch 2 [g]	Batch 3 [g]
Cement	5 358	6 251	8 930
Sand	21 130	24 651	35 217
Water	5 358	6 251	8 930
Total Weight	31 846	37 153	53 077

Note: Batch 1 was used for the "without key + grout" triplets but was found to be slightly insufficient, lacking enough material for approximately half a block. Batch 2 was used for the "grout + reinforcement" triplets and provided sufficient coverage. Batch 3 was scaled up significantly to cover the requirements for both the grout and mortar sets, this showed to be too much and remaining grout was discarded.

Curing and Post-Production Notes

Following the completion of today's production, the side forms from the previous day's batch (15/03) were removed. These specimens were then moved in the workshop to

begin their curing.

To ensure traceability and accurate data collection during testing, each specimen was marked with identifying notes immediately after creation. These markings include the production date (16/03), the material ratio (1:3), and the specific configuration code: "G" for Grout, "M" for Mortar, and "R" for Reinforcement.

Lab Log: Production of Test Specimens (17/03/2026)

This log details the production activities performed on March 17, 2026. The focus was on producing more triplets.

Specimen Production Overview

A total of 36 specimens were produced during this session, including various triplet configurations and unit compression blocks. The breakdown is presented in Table C.5.

Table C.5: Overview of specimens produced on 17/03/2026.

Specimen Type	Configuration / Target	Quantity
Triplets	Reinforcement + Grout + Mortar	6
Triplets	1:3 Grout	6
Triplets	1:3 Grout	6
Triplets	1:3 Grout	6
Triplets	1:4 Grout Fired brick	6
Unit Blocks	Fired brick (Unit Compression)	6
Total		36

Preparation and Specialised Application

Several specialised preparation steps were taken during this session:

- **Fired Brick Preparation:** The fired bricks were submerged in a container of water for approximately 10-20 minutes prior to mixing the mortar to prevent the bricks from absorbing moisture from the mix.
- **Bed Mortar:** A 10 mm thick mortar layer was applied to the 6 sets of fired brick triplets. All bed mortar application was performed by a skilled mason to ensure uniformity.
- **Reinforcement:** For triplets with reinforcement, all voids were filled with grout except for the specific void containing the rebar. As a final step, the rebar was placed in the center of the remaining void and it was filled with grout. The rebar was held in place while filling and compacting by hand and then let go when grout was filled to the top.

- **Surface Leveling:** A 1:4 grout was utilised to create a smooth, level surface on the 6 unit fired bricks to ensure even load distribution during testing. This mix was done by the skilled mason.

Grout and Mortar Recipes

Five batches were mixed today. Four Batches followed the standard 1:3 ratio, while Batch 3 noted a change in moisture content, and batch 5 followed a 1:4 ratio and was produced by a skilled mason in conventional way.

Table C.6: Mixing proportions for 17/03/2026.

Material	Batch 1 [g]	Batch 2 [g]	Batch 3 [g]	Batch 4 [g]
Cement	6 251	6 251	6 251	4 465
Sand	24 652	24 652	24 652	17 610
Water	6 251	6 251	6 251	4 465
Total Weight	37 154	37 154	37 154	26 540

Note: Batch 1 was sufficient for 7 triplets. Batch 2 was sufficient for 7.5 triplets. Batch 3 appeared significantly more fluid than previous mixtures; this was attributed to the sand potentially being wetter (1 : 1 w/c ratio was still used). Batch 3 was used for the bed mortar of 6 triplets and the grout for 5 + 1/2 triplets. Batch 4 was used as the grout for the remaining triplets.

Curing and Post-Production Notes

The specimens produced on 16/03 was accidentally watered at 10:00 before the forms were removed. At 13:00 the specimens were moved to the storage area and the forms were removed. The curing continued with watering 14:00 and 17:00. Curing for the 15/03 triplets continued with watering at 10:00, 14:00, and 17:00.

Consistent with previous days, specimens were marked for traceability. For example, reinforced triplets with bed mortar were marked: **[17/3 1:3 G, R, M]** indicating date, ratio, Grout, Reinforcement, and Mortar.

General Observation: Special care was taken regarding the compaction of the grout holes for the triplets made on the 15th and 16th. Some specimens showed signs of "bleeding" or minor grout leakage from the sides, particularly where the forms were not perfectly flush. For future batches, dryer sand should be used to improve consistency.

Lab Log: Production of Test Specimens (18/03/2026)

This log details the production activities performed on March 18, 2026. The session focused on producing several sets of triplets with varying grout ratios (1:3 and 1:6) and

bonding configurations.

Specimen Production Overview

A total of 30 triplets were produced. The three sets using 1:3 ratios were laid out and prepared during the previous session. The breakdown of today's production is presented in Table C.7.

Table C.7: Overview of specimens produced on 18/03/2026.

Specimen Type	Configuration / Ratio	Quantity
Triplets	1:3 Grout + Mortar (Set 1)	6
Triplets	1:3 Grout + Mortar (Set 2)	6
Triplets	1:3 Grout + Mortar (Set 3)	6
Triplets	1:6 Grout only	6
Triplets	1:6 Grout + Mortar	6
Total		30

Preparation and Application

Key observations and preparatory steps for this session included:

- **1:6 Grout Workability:** A new 1:6 grout recipe was adopted for the final two sets. Initial attempts with a w/c ratio of 0.75 proved too dry and coarse. Water was added in stages until acceptable workability was achieved at a final w/c ratio of 1.85. Even with the increased water, the mix remained notably coarser than the 1:3 batches and was difficult to pour evenly into the grout holes.
- **Masonry Work:** As in previous days, a mason assisted with the application of bed mortar for the 1:3 sets and the 1:6 set requiring mortar.
- **Preparation for 19/03:** Preparations for the next session were initiated by sanding down the top blocks (removing keys) and laying out the blocks for tomorrow's production.

Grout and Mortar Recipes

Five main batches were mixed. Batches 1–3 utilised a 1:3 ratio, while Batches 4 and 5 used the 1:6 ratio.

Table C.8: Mixing proportions for 18/03/2026.

Material	Batch 1 [g]	Batch 2 [g]	Batch 3 [g]	Batch 4 [g]	Batch 5 [g]
Cement	6 250	6 250	6 250	3 570	2 540
Sand	24 650	24 650	24 650	28 170	20 000
Water	6 250	6 250	6 250	6 605	4 700
Ratio	1:3	1:3	1:3	1:6	1:6
<i>w/c</i>	1.0	1.0	1.0	1.85	1.85

Note: Batch 1 provided bed mortar for two sets and grout for one. Batch 2 provided mortar for the final 1:3 set and grout for the second. Batch 3 was used for the grout of the final 1:3 set; a small extra mini-batch (90g cement, 340g sand, 90g water) was required to finish the last holes. Batch 4 was used for the 1:6 bed mortar and grout. Batch 5 was slightly reduced in volume to avoid waste and filled the final 5 specimens.

Curing and Post-Production Notes

The specimens produced on 17/03 were moved for the standard curing and drying cycle.

All today's specimens were marked for identification according to the established naming scheme. For example, the 1:3 sets with grout and mortar were marked: **[18/3 1:3 G, M]**.

Lab Log: Production of Test Specimens (19/03/2026)

This log details the final production session performed on March 19, 2026, before a scheduled one-week break for curing. The session focused on completing the reinforced triplet sets and preparing fired brick specimens with a masonry expert.

Specimen Production Overview

A total of 24 triplets and several mortar test cubes were produced. The triplet blocks were prepared during the previous day's session. The breakdown is presented in Table C.9.

Table C.9: Overview of specimens produced on 19/03/2026.

Specimen Type	Configuration / Ratio	Quantity
Triplets	1:3 Grout + Rebar (Set 1)	6
Triplets	1:3 Grout + Rebar (Set 2)	6
Triplets	1:3 Grout + Rebar (Set 3)	6
Triplets	1:4 Fired Bricks	6
Mortar Cubes	1:3 Mortar (from Batch 3)	3
Mortar Cubes	1:6 Mortar (Mini-batch)	3
Total Triplets		24

Preparation and Specialised Application

- **Rebar preparation:** A total of 18 pieces of 10 mm diameter rebar were prepared for the reinforced triplets. These were intentionally cut approximately 3–5 mm shorter than the specimen height to prevent any interference with the pre-compression plate during the testing phase.
- **Reinforced Triplets:** Production began with the 1:3 grout and rebar sets. Voids not containing reinforcement were filled first.
- **Fired Bricks:** Six fired brick triplets were produced using a 1:4 ratio. These were assembled by a masonry expert to ensure consistency in the mortar joints.
- **Material Constraints:** Batch 2 was mixed as a half-recipe due to an initial shortage of sand in the workshop. More sand was subsequently located to complete the final batches.
- **Mortar Cubes:** To verify mortar strength, three cubes were cast using the remainder of Batch 3. Additionally, a mini-batch of 1:6 mortar was mixed specifically for three additional test cubes.

Grout and Mortar Recipes

Multiple batches were utilised, including a placeholder for Batch 3 which requires a secondary verification of measurements.

Table C.10: Mixing proportions for 19/03/2026.

Material	Batch 1 [g]	Batch 2 [g]	Batch 3 [g]	Mini-Batch [g]
Cement	6 250	3 125	7367	130
Sand	24 650	12 325	29054	1000
Water	6 250	3 125	7367	235
Ratio	1:3	1:3	1:3	1:6
w/c	1.0	1.0	1.0	1.85

Curing, Storage, and Workshop Maintenance

Following production, several logistical tasks were completed to prepare for the curing week:

- The batch produced on 18/03 was moved to its designated curing area.
- All triplet batches were audited to ensure they were placed in the correct order for the curing and drying sequence.
- Every batch was clearly marked with specific dates for watering, drying, and final testing.
- The workshop was tidied and organised before leaving the site for the one-week curing period.

D Test protocol

This appendix presents the testing protocols used in the experimental programme.

[illegible]

Figure D.1: Protocol for logging of data during testing.

