Towards Circular Construction: Optimizing Brick-Mortar Bond Strength for Reusable Masonry in Cold Climate

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Abstract

Masonry reuse has gained increasing attention within sustainable construction due to the substantial use and the large environmental impact associated with construction and demolition waste. The bond between brick and mortar plays a critical role in both the structural performance of masonry and the potential for future brick reclamation. Strong brick–mortar bonds improve structural capacity but may reduce separability and increase the risk of brick damage during demolition and cleaning. This study therefore investigated how mortar composition, brick properties, and curing conditions influence flexural bond strength and failure behaviour in masonry couplets, with particular focus on implication for brick reuse.

Experimental testing was conducted using the bond wrench test according to SS-EN 1052-5. Three brick types and four mortar types were combined under both laboratory and cold–climate curing conditions, resulting in 24 different brick–mortar–curing combinations. The mortars varied in composition, compressive strength, air content, and water transport properties. Flexural bond strength and failure modes were evaluated for all combinations. Statistical analysis using ANOVA was performed to assess whether the investigated parameters had statistically significant effects on the measured flexural bond strength.

The measured flexural bond strength values ranged on an average from 0.06 MPa to 0.61 MPa. Mortar type was identified as the most influential parameter affecting flexural bond strength. The results indicated that mortar compressive strength alone could not explain the measured bond behaviour, since one mortar type achieved the highest compressive strength but did not produce the highest bond strength values. Instead, the findings suggest that bond development depends on the interaction between parameters such as mortar composition, air content, moisture transport properties, and brick absorption characteristics. Brick type also significantly influenced bond performance, while cold–climate curing generally reduced bond strength and increased variability, although its influence was smaller and less consistent than that of mortar and brick type.

Failure modes showed clear differences between mortar combinations and provided important insight into brick separability. Stronger mortar combinations frequently produced failure within the mortar bed or brick unit, increasing the risk of brick damage during separation. Weaker mortars more commonly resulted in interface-related failure, which is considered more favourable for brick reclamation. The results therefore suggest that moderate bond strengths may provide a more suitable balance between structural performance and reuse potential.

Overall, the study demonstrates that optimisation of masonry systems for both durability and circularity require a holistic approach considering not only mechanical strength, but also failure behaviour, moisture transport, and material compatibility at the brick–mortar interface.

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1 Introduction

1.1 Background

The construction and demolition (C&D) sector is among the largest contributors to material waste globally. Within the European Union (EU), more than two tonnes of construction and demolition waste (CDW) are generated per capita each year, amounting to between 500 million and 1 billion tonnes of waste annually [1]. This accounts for approximately one-third of all waste produced in the EU. CDW encompasses all materials derived from the construction, renovation, and demolition of buildings and infrastructure, including concrete, bricks, wood, glass, and metals [2]. Mineral waste fractions, including concrete, bricks, and ceramics, account for a large share of CDW [3], [4], highlighting the relevance of masonry materials in circular construction strategies. In Sweden, the building sector accounts for approximately 21% of national greenhouse gas emissions [5]. The building sector is also responsible for approximately 40% of all waste generated in Sweden annually [6].

The environmental impact of C&D activities extends far beyond the volume of waste produced. These activities are responsible for substantial greenhouse gas emissions, resource depletion, and energy consumption throughout the building life cycle [7]. The extraction and production of conventional building materials are particularly important in this context. Among these materials, cement is particularly important due to its widespread use in mortar production; cement production alone accounts for approximately 8% of global CO_2 emissions [3]. These figures highlight the need to shift from a linear "take-make-dispose" model towards a circular construction economy.

Within this circular framework, the reuse of building materials offers a high-value strategy for reducing raw material extraction, waste generation, and the environmental footprint of the C&D sector. Fired clay brick has a considerable potential for reuse, provided it can be separated from the mortar without significant damage. In many older buildings currently being demolished, this is still achievable because they were constructed with air lime-based mortars, which generally develop weaker bonds with bricks than modern cement-based mortars and therefore facilitate separation during demolition [8].

From approximately the 1950s and onwards, particularly during the "Million Programme" initiative in Sweden, masonry construction increasingly shifted towards cement-based and lime-cement mortars. These mortars generally develop stronger bonds with bricks and provide improved structural performance, but they can also reduce the recovery rate of reusable bricks [9]. As a result, the bond between brick and mortar has become a key factor influencing the reuse potential of masonry.

A bond that is too strong can prevent clean separation during demolition and cause damage to the brick, while a bond that is too weak may compromise structural performance during the service life [10]. Achieving a balance between structural requirements and future separability represents an important challenge in the design of modern masonry systems. Since bond strength is largely influenced by mortar composition and binder proportions, the selection of mortar becomes a central parameter in this balance.

1.2 From load-bearing masonry to veneer wall systems

Historically, masonry buildings were commonly constructed with massive load-bearing walls. In these structures, the masonry itself carried vertical loads and contributed to the stability of the building. The mortar used in the massive walls was therefore not primarily required to act as a high-strength adhesive between brick and mortar. Instead, it transferred compressive stresses between bricks, accommodated surface differences, and provided cohesion of the wall system. Lime-based mortars were commonly used in such constructions as they were compatible with the behaviour of massive masonry walls [11].

During the twentieth century, increasing urbanization and higher demands for material efficiency contributed to a transition from massive load-bearing masonry walls towards framed structures with thinner masonry façade layers. This development was driven by demands for taller buildings, more efficient use of floor area, improved thermal performance, faster construction, and year-around construction [11]. In these systems, masonry is often used as a veneer or façade layer, while the main structural loads are carried by the frame or inner wall structure [11].

Although veneer masonry is usually non-load bearing in relation to the main structural system, it must still meet mechanical and durability requirements. It must resist out of plane actions, such as wind pressure and suction, and provide sufficient shear capacity above openings. Local stress concentrations may also occur around openings, supports, and restraint points. Exposure to moisture, temperature variations, and frost also places demand on mortar durability [11]. These requirements contributed to the increased use of cement-based and lime-cement mortars, which generally provide faster strength development, higher early strength, and improved durability compared with traditional lime-based mortars. However, stronger brick–mortar bonds can make later separation of bricks more difficult and reduce their potential for reuse.

Therefore, the development of modern masonry systems has made it important to consider brick–mortar bond strength not only from a structural perspective, but also from a reuse perspective. Bond strength can be evaluated using different test methods, depending on the type of loading considered (e.g., flexural, shear, or tensile). It is also affected by several interacting parameters, including mortar composition, brick properties, curing conditions, and workmanship. In the following sections mortar composition and properties as well as brick properties and curing conditions are reviewed.

1.3 Objectives

The objective of this master's thesis is to investigate the flexural bond strength (hereafter also referred to as bond strength) between four mortar types and three brick types, and to evaluate how the material properties of both bricks and mortars influence this behaviour. Since bond strength is used as an indicator of brick separability, the study aims to assess whether lower-strength mortars compared to those commonly used in veneer systems today, can provide sufficient bond performance for masonry applications while enhancing the potential for brick reclamation. Additionally, the thesis examines how cold curing conditions affect bond strength. This is relevant in Nordic construction practice, where masonry is often constructed in low temperature conditions that may influence hydration and bond development between brick and mortar. Through this combined structural and circular perspective, the work aims to contribute knowledge that supports the design of masonry systems optimized for reuse and that reduce climate impact within the construction sector by building material banks rather than disposable buildings.

1.4 Previous research and research gap

Extensive research has been conducted on the bond strength between brick and mortar [11] - [16]. Much of this research has focused on improving the structural integrity and mechanical performance of masonry systems, in which bond strength plays a central role. In addition, several studies have focused on developing sustainable alternatives to conventional cement-based mortars while maintaining adequate bond strength, which remains an important requirement [17], [18]. These studies commonly investigate the incorporation of supplementary materials, such as fly ash, to reduce environmental impact while maintaining or improving mechanical performance [17]. Other approaches include reinforcing mortars with materials such as carbon fibres, to aim for an increased bond strength and overall structural capacity [19]. From this structural perspective, stronger bond development has often been regarded as beneficial.

From a reuse perspective, however, the role of bond strength becomes more complex. High bond strength may improve structural performance, but it can also make brick separation more difficult during deconstruction and increase the risk of damage to the units. Previous studies have shown that mortar type strongly affects this balance. Lime-based mortars, for example, are generally more flexible and develop weaker bonds than cement-based mortars, which can facilitate separation and improve the reuse potential of bricks [20].

However, focusing only on lime-based mortars does not fully address the challenges of more recent masonry construction, where cement and lime-cement mortars are commonly used. Comparatively limited attention has been given to whether lower-strength, cement-based or lime-cement mortars can provide adequate bond for masonry veneer applications while still allowing improved brick separability at the end of life. This is particularly relevant for masonry veneer applications, where the required bond strength can be potentially balanced with the potential for future reclamation.

Another limitation in previous research is that bond strength is often investigated under controlled laboratory curing conditions at approximately room temperature. Few studies address how low-temperature curing conditions affect bond development, despite their relevance to Nordic construction practice. This creates uncertainty regarding how mortar type, brick properties, and curing climate interact to determine both bond strength and separability.

This thesis addresses these research gaps by investigating the flexural bond strength of masonry specimens made with four mortar types and three brick types under both laboratory and cold–climate curing conditions. The study investigates whether mortars with reduced cement content, including an M1 masonry mortar and CS II classified mortar/render products, can provide sufficient performance for masonry veneer applications compared with the commonly recommended M2.5 mortar, while enhancing the potential for brick reclamation [20], [21].

1.5 Research approach

To address the research objectives, the work is structured into two main components: a literature review and an experimental investigation. The literature review presents parameters influencing bond strength between brick and mortar and their relation to brick separability. The experimental investigation evaluates how flexural bond strength varies with different combinations of brick type, mortar type, and curing condition. Masonry couplet specimens are prepared, cured under both standard laboratory and cold–climate conditions, and tested using the bond wrench method. Failure modes are then classified to assess whether failure occurs at the brick–mortar interface, within the mortar, or within the brick. Brick separability is evaluated indirectly based on measured bond strength, observed failure behaviour, and the physical condition of the specimens after testing.

2 Literature review and theoretical background

The literature review focuses mainly on flexural bond strength in masonry, with particular attention to mortar composition, brick properties, and curing conditions in relation to masonry separability and reuse potential. The literature review was identified through targeted database searches, reference chaining, and recommendations from previous studies. Key search terms included "bond strength", "flexural bond strength", "masonry", and "brick and mortar". The literature was identified using academic search platforms and databases, including Google Scholar, Finn/LUBsearch, and ScienceDirect. The chapter first presents relevant bond strength test methods, followed by the main parameters influencing bond behaviour and brick separability.

2.1 Bond strength test methods

Bond strength in masonry can be evaluated under different loading conditions, including flexural, shear, and tensile loading [14]. Several test methods for evaluating the bond strength have been proposed in previous research [16], [22] - [24]. However, many of these methods are associated with practical limitations, such as complex specimen preparation, large specimen sizes, difficulties in achieving purely axial loading conditions, or the influence of additional stress components during testing [25]. As a result, the bond wrench test has become one of the most used methods for evaluating flexural bond strength in masonry, due to its relatively simple setup and its ability to directly assess brick–mortar interface behaviour [25].

2.2 Mortar properties

Several mortar-related parameters can influence the flexural bond strength of masonry, including mortar composition, binder content, air content, water retention, and curing behaviour [11], [15] - [16], [26] - [29]. These parameters are strongly interrelated, as bond development depends on the combined interaction between mortar properties, brick properties, and curing conditions. The following sections therefore review the mortar properties considered most relevant for interpreting the bond behaviour and the experimental results obtained in the study.

2.2.1 Mortar composition

Mortar composition strongly influences bond development at the brick–mortar interface. In general, mortars with higher cement content and higher compressive strength may develop stronger bonds. However, this relationship cannot alone explain bond development [16], [26]. According to Sugo et al. [15], an insufficient cementitious material can result in weak bonding between mortar and brick. Excessive cement content may also be unfavourable, as it may lead to particle buildup on the brick surface and limit the penetration of cementitious material into the brick pores, and therefore limiting the bond development and reduce adhesive bond formation at the brick–mortar interface [15].

When cement mortars are applied to bricks with high capillary suction, several studies have shown that bond strength increases with increasing water-cement ratio [16]. Although a higher water-cement ratio generally reduces the compressive strength of the hardened mortar, the additional water can improve the workability, flow, and moisture transport in the fresh mortar. This may allow better penetration of cementitious material into the brick pores and enhance adhesion and mechanical interlocking at the brick–mortar interface. These findings indicate that bond development is influenced not only by mortar strength, but also by moisture exchange and hydration conditions during curing.

Increased cement content may also reduce mortar elasticity. The most common mortar today consists of a cement-lime mixture, where lime improves workability and deformability, while cement contributes to strength development [16], [26]. Lime content in mortars creates a weaker bond, which can be favourable for the salvageability of the bricks. Lime may also help limit crack propagation compared with pure cement mortar, due to its deformability. This is one reason why cement and lime are often combined in masonry mortars [20].

2.2.2 Air content

Air in mortar consists of both entrapped air introduced during the mixing and entrained air introduced through air-entraining additives. The air content is affected by binder type, sand fractions, mixing procedure, water content, temperature, and additives introduced in the mixture. During mixing, air bubbles are inevitably introduced into the mixture, and their amount and stability depend on the mix composition and mixing procedure. Air content can influence both the workability and the durability of both fresh and hardened mortar [27].

In general, the reviewed literature indicates that increased air content may reduce mortar strength and negatively affect masonry bond strength by decreasing the effective contact area at the mortar-brick interface [11], [27]. However, the influence of air content on bond strength also depends on the absorption characteristics of the bricks. According to the Portland Cement Association (PCA) [27], improved bond performance has in some cases been observed when air-entrained mortars are combined with high-suction (high initial rate of absorption, IRA) bricks, while reduced bond strength has been reported for low-suction bricks used with increasing air content mortars. This suggests that air content not only affects the mechanical properties of the mortar itself but also moisture exchange and interfacial interactions between the mortar and the brick during curing.

2.2.3 Water retention

Water retention is an important property affecting bond strength development in masonry, as it influences the availability and movement of water from the mortar to the brick. A mortar with adequate water retention can resist excessive suction from bricks, thereby maintaining sufficient moisture for cement hydration and ensuring the formation of a continuous binder that promotes adhesion and mechanical interlocking in the masonry [16]. If water is lost too rapidly, the mortar may stiffen prematurely, limiting contact with the masonry surface and weakening bond development. Conversely, sufficient retained water allows continued hydration and may improve the development of interfacial strength [16].

The reviewed literature generally indicates that the influence of water retention on bond strength is closely related to the moisture exchange occurring between the mortar and the masonry unit during curing. However, water retention should be considered alongside the brick's actual water uptake, since both retained water within the mortar and water absorbed by the masonry unit influence bond performance. This demonstrates that bond strength development depends on the combined interaction between mortar properties, brick absorption characteristics, and curing conditions, rather than on water retention alone [16]. Supporting this, studies on masonry strength indicate that bond formation is governed by moisture exchange at the interface, where controlled water availability enhances adhesion, while excessive or insufficient moisture can negatively affect bond development [28].

Although water retention is widely considered an important parameter for bond development, the literature does not consistently identify it as an influential factor. Groot [29] reported considerable variability in bond strength, even under controlled testing conditions, indicating that the influence of water retentivity is strongly dependent on its interaction with other parameters, such as mortar composition, brick suction properties, and curing environment.

2.3 Brick absorption properties

Brick properties play an important role in masonry bond strength, as they influence moisture transport and interaction between fresh mortar and the brick surface at the brick–mortar interface. Previous studies have shown that parameters such as the initial rate of absorption (IRA) and total water absorption capacity can influence cement hydration, adhesion, and mechanical interlocking between brick and mortar [16], [27], [30]. However, these properties do not act independently. Their influence depends on their interaction with mortar-related parameters, including water retention, mortar composition, air content, as well as curing conditions. This means that bond development should therefore be understood as the result of moisture exchange between the masonry unit and the mortar, rather than as the effect of a single brick property.

The water absorption properties of bricks are widely recognized as important parameters influencing masonry bond development, as they govern moisture exchange at the brick–mortar interface during curing [16], [30] - [31]. Previous research has primarily focused on three related but distinct absorption properties: IRA, which describes the short-term absorption rate of the brick surface; 24-hour water absorption, which describes the total absorption capacity of the brick; and the water absorption coefficient, which quantifies the rate of capillary water uptake. While these parameters are all associated with capillary transport within the brick, they quantify different aspects of moisture absorption and should therefore be interpreted separately.

IRA is typically determined by laboratory testing, in which the brick is placed in 3-5 mm of water and the amount of water absorbed over 1 minute is measured [32]. The reviewed literature indicates that IRA can strongly influence bond development. Excessively high IRAs may cause rapid suction of water from the mortar, reducing workability and limiting proper hydration, which may result in weak or incomplete bond formation [16]. However, excessively low IRAs may also negatively affect bond development, as insufficient suction can reduce the penetration of cementitious material into pores, thereby limiting adhesion and mechanical interlocking [16]. Briceño et al. [31] therefore suggest that the relationship between IRA and bond strength is not linear but rather governed by an optimal range of absorption rates that promotes balanced moisture transfer at the interface.

To regulate this moisture exchange, pre-wetting of high-suction bricks is often recommended. By reducing absorption rates, pre-wetting can improve hydration conditions and enhance bond development [31]. This practice is also reflected by standards such as EN 1996-2:2006 [33], which emphasize the importance of appropriate moisture conditions at the interface. However, pre-wetting must be applied selectively, as excessive moisture in low-suction bricks may reduce bond development by limiting water transfer from the mortar.

The literature suggests that brick absorption properties influence bond strength through moisture transport mechanisms at the brick–mortar interface. Högberg [16] reported that both excessively low and excessively high brick suction may negatively affect mortar bond, suggesting that an intermediate absorption range is generally more favourable for bond development. However, neither IRA nor 24-hour water absorption alone is sufficient to explain bond behaviour fully. The resulting bond strength depends on the interaction between brick absorption properties, mortar composition, water retention, mortar air content, and curing conditions [16], [27].

2.4 Curing conditions

Curing conditions are widely recognized as an important factor influencing the development of masonry bond strength, as it affects hydration of cement and hydraulic lime, moisture exchange, and the interaction between mortar and brick. Temperature and relative humidity are particularly important, since they influence both the rate of mortar hardening and the availability of moisture at the brick–mortar interface [16]. Appropriate curing conditions should maintain sufficient moisture within the masonry system to support continued hydration and prevent excessive mortar drying. If moisture is lost too rapidly, the mortar may stiffen prematurely, reducing contact at the interface and weakening bond development [16].

Many previous studies investigating masonry bond strength have been conducted under controlled laboratory curing conditions at room temperature or elevated temperatures up to approximately 30ºC [11] - [12], [27] - [28]. Under such conditions, cement hydration and moisture transport generally occur without major disturbance from cold–climate or moisture loss. However, relatively few studies have investigated masonry bond development under cold–climate curing conditions representing Nordic construction environments.

If the mortar or bricks experience low temperatures before sufficient early strength has developed, hydration may be disrupted and moisture movement at the interface reduced, resulting in poor adhesion between brick and mortar [34]. In addition, cold, wet, or frozen bricks may show reduced absorption capacity because water within the pores can limit capillary suction, further affecting bond development [34].

To control these effects, several protective measures have been proposed in previous studies and construction guidelines, including preheating of bricks, heating materials, shielding, and maintaining suitable curing temperatures during construction. Preheating bricks may reduce heat transfer from the mortar, thereby lowering the risk of cold–climate impact during early curing stages. However, increased temperatures may also increase the absorption rate, potentially leading to excessively rapid water extraction from the mortar and negatively affecting bond development [34]. This demonstrates that the influence of curing conditions on bond strength is strongly dependent on the interaction between temperature, brick absorption properties, mortar composition, and moisture availability at the interface.

2.5 Brick separability and reuse potential

Studies on brick reclamation show that reuse rates are influenced by both bond characteristics and the demolition and cleaning procedures used. When bricks are strongly bonded to the mortar, separation and cleaning often require more intensive mechanical separation, such as repeated impacts, mechanical handling, or vibration-based cleaning. These processes impose additional stresses on the bricks, potentially increasing the risk of cracking, edge damage, and material loss [35]. This indicates that high bond strength can reduce practical salvageability, even when separation is technically possible.

Masonry constructed with weaker mortars generally shows a higher degree of natural separability into individual units during demolition, which can simplify both separation and cleaning. Moesgaard [35] reported reuse rates of 76-89% of bricks constructed with mortars with lower binder content. This supports the assumption that reducing bond strength can significantly improve practical salvageability without entirely compromising structural performance throughout the service life [35].

According to Brukspecialisten (a company specialized on reclamation of bricks) [36], the connection between components is a key factor for enabling brick reuse. Brukspecialisten [36] also acknowledge that salvageability is highly dependent on the mortar being weaker than the brick itself to allow separation without damaging the unit. However, brick separability is not determined solely by mortar strength, it also depends on the interaction between brick properties, mortar properties, and the resulting brick–mortar bond.

Brukspecialisten [36] further highlights that higher material strength does not necessarily lead to better circular performance. For instance, bricks with compressive strength from 10-45 MPa in combination with a low-strength mortar of 1 MPa give approximately the same reclamation rate as bricks with strengths from 35-80 MPa in combination with mid-strength mortar of 2.5 MPa, while the reclamation rate overall for a high-strength mortar of 5 MPa gives a much lower reclamation rate of bricks.

2.6 Summary

Previous research shows that flexural bond strength in masonry is governed by the interaction between mortar properties, brick absorption characteristics, and curing conditions rather than by any single parameter alone. Mortar composition, binder content, air content, and water retention influence bond development by affecting moisture exchange, adhesion, and mechanical interlocking at the brick-mortar interface. Similarly, brick absorption properties such as IRA and water uptake affect moisture transport and hydration conditions, with both excessively high and low absorption potentially reducing the bond strength. Curing conditions, particularly temperature and moisture availability, further influence hydration and bond formation, with cold climates posing additional challenges. Studies on brick reclamation indicate that lower bond strengths can improve brick separability and reuse potential, highlighting a trade-off between structural performance and circularity.

3 Materials and methods

3.1 Brick

Three different brick types and four different mortar types were considered in this study. The bricks were Danish standard-format with approximate dimensions 108×228×54 mm. To distinguish between brick types, they are referred to as brick types X, Y, and Z throughout the thesis. The material properties of the three brick types were determined under controlled laboratory conditions. For each brick type, ten units were tested. The investigated properties included 24-hour water absorption, net density, water absorption coefficient, A_w, initial rate of absorption (IRA), and compressive strength, f_b. The test methods were based on relevant European standards with Swedish national implementation, as summarized in Table 1.

Table 1: Brick material properties, determined in laboratory environment according to current standards. Values that are presented are average of testing results for each property. Within parenthesis the coefficient of variation [%] is presented.

Brick type	*X*	*Y*	*Z*
Colour	Yellow	Red	Yellow
Dry weight [g]	2278	2318	2247
24h Water Absorption, W_s [%]	13 (2)	12 (3)	16 (1)
Initial Rate of Absorption, IRA [kg/ (m^2 × min)]	1.17 (15)	2.73 (14)	2.61 (9)
Water Absorption Coefficient, A_w [kg/ ($m^2 \times s^{0.5}$)]	0.18 (11)	0.37 (6)	0.35 (3)
Compressive Strength, f_b [MPa]	42.2 (15)	14.8 (10)	25.4 (7)

The 24-hour water absorption test was conducted in accordance with SS-EN 772-21 [37]. The bricks were first dried in an oven at 105 °C, cooled to room temperature, and weighed to determine the dry mass, M_d [g]. The dry mass was recorded for ten units of each brick type. The bricks were then fully immersed in water for 24 hours, as shown in Figure 1.

Figure 1: 24h absorption test of bricks where ten bricks were put into water buckets for 24 hours after drying at 105 °C.

After 24 hours of immersion, the saturated mass, M_s, was recorded. The 24-hour water absorption W_s, was calculated according to Equation (3.1), in accordance with SS-EN 772-21 [37].

$$W_s = \frac{M_s - M_d}{M_d} \times 100\ \% \tag{3.1}$$

where W_s is the 24-hour water absorption [%], M_s is the saturated mass [g], and M_d is the dry mass [g].

The net density of the bricks was determined in accordance with SS-EN 772-13 [38]. The net density ρ [kg/m^3] of the ten sampled bricks was computed based on Archimedes' Principle. First the net volume, V_n [mm^3], was calculated for each one of the bricks, according to Equation (3.2).

$$V_n = \frac{M_s - M_{s,water}}{\rho_{water}} \tag{3.2}$$

where M_s is saturated mass of the brick [g] and, $M_{s,water}$ [g] is the apparent mass of the saturated brick when fully immersed in water and, ρ_{water} [g/mm^3], is the density of water.

The net density, ρ [kg/m^3], was then calculated by dividing the dry mass, M_d [g], by net volume, V_n [mm^3], according to Equation (3.3).

$$\rho = \frac{M_d}{V_n} \times 10^6 \tag{3.3}$$

The water absorption coefficient, A_w [g/m^2×s$^{0.5}$], was determined in accordance with SS-EN 1925 [39]. The brick was dried at 105°C, then cooled to room temperature, and weighted to determine dry mass, M_d. The exposed surface area, A, was measured on the bed face of each brick, since this study investigates bond development at the brick–mortar interface. The bricks were then placed with the bed face in contact with water at a depth of 3–5 mm, as shown in Figure 2. At intervals of 1, 3, 5, 10, 15, 30, and 60 minutes, the bricks were removed from the water, excess surface water was wiped off, and the mass of each brick, M_i, was recorded. The water absorption coefficient was then determined based on the absorbed water per exposed area as a function of the square root of time using Equation (3.4).

Figure 2: Brick in water of a depth of 3-5mm for water absorption coefficient determination.

$$A_w = \frac{M_i - M_d}{A\sqrt{t_i}} \tag{3.4}$$

where M_i [g] is the mass at time t_i [s], M_d [g] is the dry mass, A [m^2] is the exposed surface area, and t_i is the exposure time.

The initial rate of absorption (IRA) was determined in accordance with SS-EN 772-11 [32]. IRA [kg/(m^2 × min)] was calculated using the mass increase after one minute of water exposure, according to Equation (3.5).

$$IRA = \frac{M_{s,min} - M_d}{A \cdot t} \times 10^3 \tag{3.5}$$

where $M_{s,min}$ is the mass of the brick [kg] after one minute of water exposure, M_d is the dry mass [kg], A is the exposed bed-face area [m^2], and t is the exposure time [min], set to one minute. The same dry mass and exposed surface area was used for the water absorption coefficient.

Finally, the compressive strength of the brick was determined in accordance SS-EN 772-1 [40]. The bricks were cut to approximately half-brick size, and the loaded surfaces were prepared to reduce surface irregularities. The specimens were then tested in a compression testing machine. Due to the difference between the tested specimen size and the standard brick size used in practice, the measured compressive strength was normalised using the procedure given in Appendix A in SS-EN 772-1 [40]. The compressive strength was calculated using the maximum applied load (kN) divided by the loaded area. This value was then multiplied with the normalising factor. The results are summarized in Table 1. See Figure 3 for illustration of brick placed in cube press.

Figure 3: Brick unit in cube press to determine compressive strength capacity of brick.

3.2 Mortar

Four mortar types were used in this study. Three mortars, denoted N, O, and P, were supplied by manufacturers and are classified as designed mortars. One mortar, denoted M, was mixed in the laboratory according to a prescribed recipe and is therefore classified as a prescribed mortar. Two of the manufacturer-supplied designed mortars, O and P, are product types intended for both brick laying and rendering/plastering according to the manufacturer information. These mortars are therefore referred to here as mortar/render products. Their declared strength class is CSII described in SS-EN 998-1 [41], which should be distinguished from masonry mortar strength classes such as M1 and M2.5. In this study, the comparison between mortars is therefore based not only on declared strength class, but also on binder composition, declared minimum compressive strength, and measured fresh and hardened mortar properties.

For the designed mortars, the binder type, declared composition, and minimum strength were specified by the manufacturers, see Appendix A-C for manufacturer details. However, the exact additive compositions were not disclosed. This should be considered when interpreting differences in fresh and hardened mortar properties, such as consistency, air content, water retention, and strength development. Mortar M was mixed in the laboratory in accordance with the prescribed mix proportions given in the Swedish National Board of Housing, Building and Planning regulations EKS11 [42], lime type used in mortar M is CL90, in accordance with standard EN 459-1 [43]. The binder type, composition, strength class, and declared minimum strength of each mortar are summarized in Table 2.

Table 2: Mortar types by pre-known composition by weight and properties. In the composition column L stands for lime, C stands for cement, and S stands for sand. For design mortars, see also appendix A, B and C, where appendix A is for mortar N, appendix B for mortar O, and appendix C for mortar P.

Name	*Type*	*Binder*	*Composition*	*Cement type*	*Strength class*	*Minimum strength [MPa]*
M	Prescribed	Lime cement	L:C:S 50:50:650	CEM II	M1	1
N	Design	Cement	C:S 100:600	CEM II	M2.5	2.5
O	Design	Lime Cement	L:C:S 50:50:650	CEM II	CSII	1.5
P	Design	Cement	C:S 100:1000	CEM II	CSII	1.5

All mortar types were tested in both fresh and hardened states. For the fresh mortars, consistency was determined using the flow table method in accordance with SS-EN 1015-3 [44]. Air content was determined in accordance with SS-EN 1015-7 [45], and water retention was determined in accordance with SS-EN 413-2 [46]. Mortar prisms with dimensions of 160×40×40 mm was cast for the hardened mortar tests. For each mortar type, three prisms were prepared for laboratory curing and three prisms for cold–climate curing, giving a total of six prisms per mortar type. The specimens were cured for 28 days under the two curing regimes described in Section 3.4. Under laboratory curing conditions, the prisms were covered with plastic sheet to limit moisture loss.

After curing, the hardened mortar prisms were tested for flexural and compressive strength in accordance with SS-EN 1015-11 [47]. First, the flexural strength was determined by loading each prism until failure, splitting the prism into two halves, as shown in Figure 4. The two halves were then tested in compression, as shown in Figure 5.

Figure 4: Flexural capacity test of mortar prism.

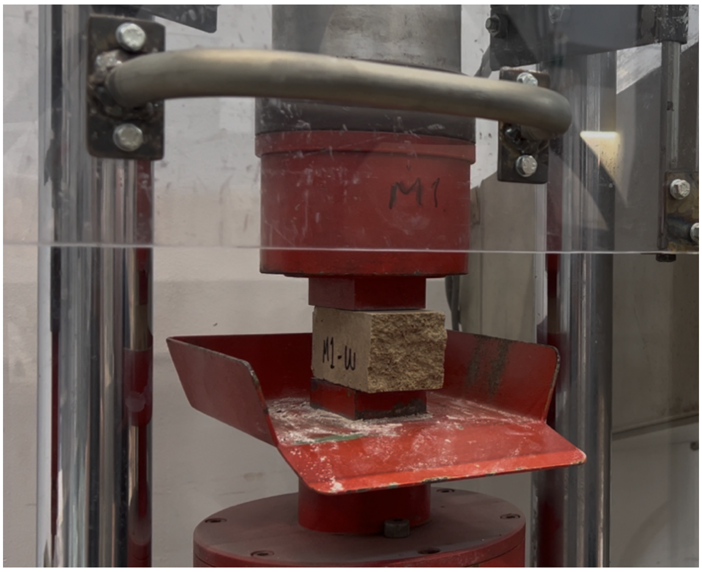

Figure 5: Compression strength testing of mortar prisms.

Table 3: Result of mortar properties tested on fresh mortar.

Mortar Type	*M*	*N*	*O*	*P*
Consistency (flow table) [mm]	180	187	172	189
Air Content [%]	2	13	19	12
Water Retention [%]	97.5	96.5	98.3	98.5

Table 4: Results of mortar properties when testing hardened mortar prisms for flexural and compressive strength in two different climate conditions, lab (L) and cold–climate (C) curing, for curing conditions see section 3.4.

Mortar type	*Climate*	*Flexural strength* Avg [MPa] (Coefficient of Variation %)	*Compressive strength, f_m* Avg [MPa] (Coefficient of Variation %)
M	L	0.82 (15.7)	2.45 (8.6)
	C	0,98 (4.2)	3,10 (1.7)
N	L	2.08 (9.4)	6.29 (5.2)
	C	1.96 (5.7)	6.31 (5.1)
O	L	0.97 (7.9)	2.44 (5.1)
	C	0.78 (6.5)	2.05 (6.0)
P	L	0.57 (9.4)	1.11 (8.3)
	C	0.64 (4.4)	1.66 (2.8)

3.3 Specimen preparation

Masonry couplet specimens were prepared using a timber mould placed around the lower brick to control the bed joint thickness and ensure consistent mortar height between specimens. Mortar was placed on the bed face of the lower brick and levelled within the mould, as shown in Figure 6.

Figure 6: Preparation of masonry couplet specimens using a timber mould to control bed joint thickness.

After placing the mortar, the mould was carefully removed, and the upper brick was positioned to complete the couplet specimen. Immediately after assembly, the specimens were pre-compressed in accordance with SS-EN 1052-5 [48]. The standard specifies that a uniformly distributed mass should be applied to give a vertical stress between 2×10^{-3} and 5×10^{-3} N/mm². In this study, two bricks of the same type were placed on top of each specimen to provide the pre-compression, as shown in Figure 7. The applied vertical stress varied slightly with brick weight and was approximately 2×10^{-3} N/mm², corresponding to the lower limit specified in the standard. The specimens were kept pre-compressed and undisturbed during curing.

Figure 7: After Specimens are assembled, two bricks are added onto the top to create pressure of approximately 2×10^{-3}MPa for the curing process.

3.4 Curing Regimes

After assembly, the specimens were subjected to two curing regimes: laboratory curing and cold–climate curing. The curing took place under approximately 28 days in both climates. For each brick–mortar combination, at least ten specimens were cured in the laboratory environment, covered with polyethylene sheets to limit moisture loss in accordance with SS-EN 1052-5 [48]. At least six specimens from each combination were placed in a climate chamber to simulate cold–climate curing conditions.

Table 5: Temperature and relative humidity for the different curing climate conditions.

Climate	*Laboratory*	*Cold–climate*
Average temperature [ºC]	20.9	5.6
Average relative humidity [%]	99.2	91.8

3.5 Bond strength test setup

The flexural bond strength between brick and mortar was determined using the bond wrench method in accordance with SS-EN 1052-5 [48]. The test setup is shown in Figures 8 and 9. Two loading arrangements were used. In the first arrangement, the load was applied by attaching a bucket to the end of the bond wrench. The bucket was connected to a load cell, which continuously recorded the applied load. Water was added to the bucket at a flow rate of 1.5–5.0 L/min until failure occurred. For specimens with higher bond strength, where the bucket load was insufficient to cause failure, a hydraulic jack was connected to the end of the wrench. The same load cell was used to record the applied load, as shown in Figure 10.

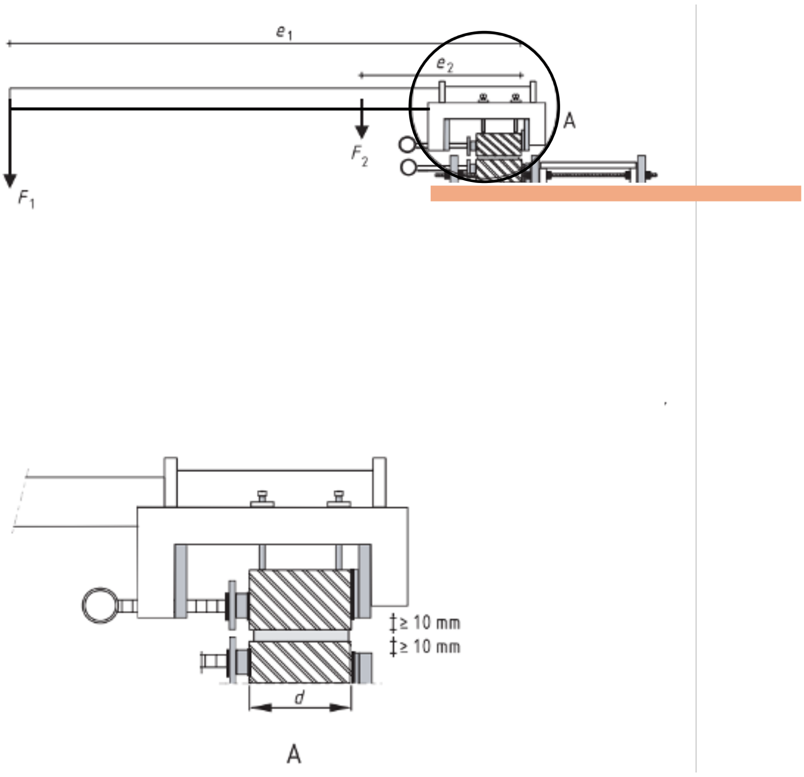

Figure 8: Bond wrench test method set up, where d is the depth of the brick, F1 is the applied load and e1 is the lever arm for the applied load, F2 is the weight of the bond wrench and e2 the lever arm until centre of gravity where F2 acts. Source:[48].

Figure 9: Bond wrench setup used in this study. The purple stand located at the centre of the figure was installed as a safety measure. In the event of specimen failure, the lever arm may become detached and fall; therefore, the stand acts as a barrier to prevent the lever arm from falling.

Figure 10: Hydraulic jack attached to the end of the wrench.

To compute the bond strength f_w [MPa] the following formula has been used:

$$f_w = \frac{F_1 e_1 + F_2 e_2 - \frac{2}{3} d (F_1 + F_2 + \frac{W}{4})}{Z} \qquad [3.6]$$

Where $Z = \frac{bd^2}{6}$

And	b	mean width of bed joint in mm;
	d	mean depth of specimen in mm;
	e_1	distance from the applied load to the tension face on specimen
	e_2	distance from the centre of gravity of the lower and upper clamp from the tension face of specimen in mm;
	F_1	applied load with bucket, loadcell and water in N;
	F_2	weight of bond wrench in N;
	W	weight of the masonry unit pulled off the specimen and any adherent mortar attached to this brick.

See Figure 8, for specified distances and load locations on bond wrench.

3.6 Evaluation of brick separability

Brick separability was evaluated indirectly based on three indicators: measured flexural bond strength, observed failure modes, and qualitative observations made during removal of residual mortar after testing. The measured bond strength was used as an indicator of the force required to separate brick and mortar. Higher bond strength was interpreted as less favourable for separability, since stronger adhesion at the brick–mortar interface may increase the risk of brick damage during reclamation. Conversely, very low bond strength may favour separability, but may not provide adequate bond performance during service life [35]. The removal of residual mortar after testing, qualitative observations were made regarding brick damage during handling and cleaning. These observations were used together with measured bond strength and failure mode classification to assess brick separability.

Failure modes were also analysed according to SS-EN 1052-5 [46]. Interface-related failure modes, such as A.1 and A.2, were interpreted as more favourable for reuse, since separation occurred mainly at the brick–mortar interface. Failure modes involving damage to the brick, such as A.5 and A.7, were interpreted as less favourable for reuse, since they indicate a higher risk of brick damage during separation, see Figure 11 for failure mode description.

The measured flexural bond strength values were compared with those given in SS-EN 1996-1-1, Table 5.5 [47], to provide an indicative assessment of whether the tested combinations reached bond strength levels relevant for masonry veneer applications. This comparison was used to discuss the balance between bond performance and reuse potential. However, it should not be interpreted as a complete structural verification, since the performance of veneer masonry also depends on factors such as wall geometry, support conditions, ties, loading, exposure, and detailing.

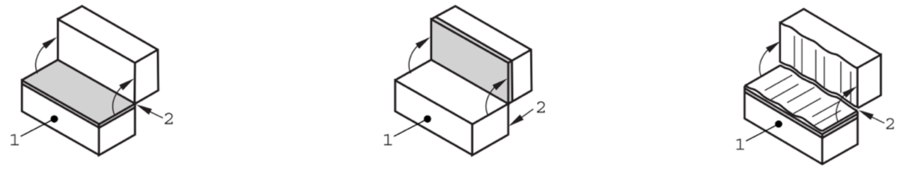

Figure A.1 — Failure at interface between mortar and upper unit

Figure A.2 — Failure at interface between mortar and lower unit

Figure A.5 — Tension failure within unit near interface

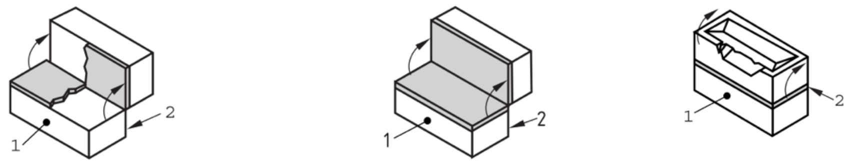

Figure A.3 — Failure at interface between mortar and both units

Figure A.4 — Tension failure within mortar bed

Figure A.7 — Crushing/shearing failure of unit where clamped

Figure 11: Description and illustration of relevant failure modes for this study. Source: [48].

4 Result and discussion

The average measured flexural bond strength, f_w, values and observed failure modes for all brick–mortar combinations are presented in Table 6. The average influence of mortar type, brick type, and curing condition on flexural bond strength is illustrated in Figure 12, while the detailed results for each specimen group are shown in Figure 13.

The measured flexural bond strength values ranged on an average from 0.06 MPa to 0.61 MPa depending on brick type, mortar type, and curing condition. The highest average bond strength was measured for specimen group X-M-L, consisting of brick type X combined with mortar M under laboratory curing conditions, with an average value of 0.61 MPa. The lowest value was measured for Z-P-C, consisting of brick type Z combined with mortar P under cold–climate curing conditions, with an average value of 0.06 MPa.

The ANOVA analysis indicated statistically significant effects of mortar type, brick type, and curing condition on flexural bond strength. Mortar type showed the strongest statistical influence, followed by brick type, while curing condition showed the smallest effect.

Table 6: Results of flexural bond strength and failure mode for all different brick-mortar combinations for both laboratory and cold–climate. For lab-climate curing, 10 specimens of each combination was tested and for cold-climate curing, 6 specimens of each combination was tested.

Brick type	*Mortar type*	*Climate*	*Flexural bond strength, f_w Avg [MPa] (Coefficient of Variation %)*	*Failure mode*
X	M	L	0.61 (36.9)	A4
		C	0.45 (17.5)	A4
	N	L	0.33 (32.0)	A2
		C	0.35 (17.5)	A2
	O	L	0.27 (31.9)	A2
		C	0.27 (17.1)	A4
	P	L	0.15 (40.6)	A1
		C	0.19 (19.5)	A1
Y	M	L	0.41 (24.1)	A5
		C	0.39 (13.2)	A5
	N	L	0.34 (26.8)	A5
		C	0.23 (76.4)	A1
	O	L	0.25 (25.7)	A5
		C	0.22 (37.9)	A4

	P	L	0.12 (41.9)	A1
		C	0.11 (37.2)	A4
Z	M	L	0.40 (24.6)	A4
		C	0.37 (24.2)	A4
	N	L	0.20 (35.0)	A2
		C	0.24 (48.6)	A4
	O	L	0.25 (28.4)	A2
		C	0.16 (30.8)	A4
	P	L	0.09 (71.1)	A1
		C	0.06 (58.7)	A1

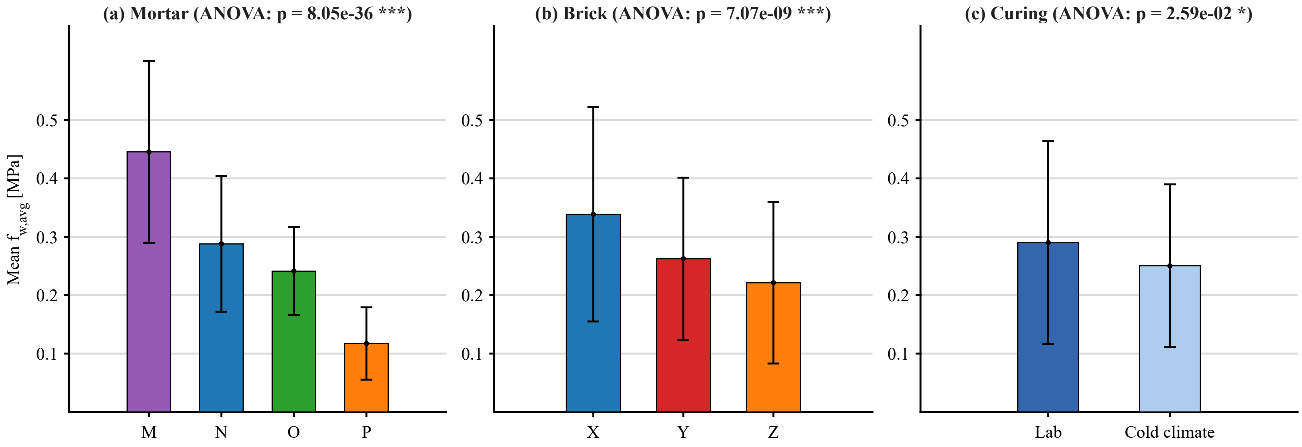

*Figure 12: Strength development impacted by mortar, brick and curing climate respectively. ANOVA shows how much significance the factor has, where *** indicate very strong significance, and * indicate significant but low impact.*

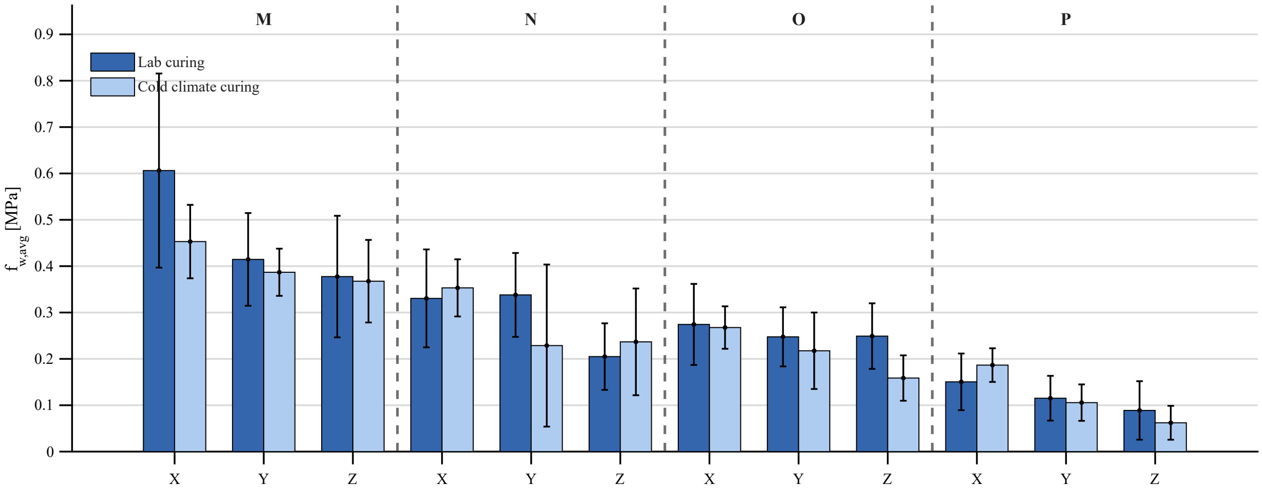

Figure 13: Climate curing impact for different curing climate conditions.

4.1 Influence of mortar type on flexural bond strength

Figure 12(a) shows the average flexural bond strength results for the different mortar types. Mortar type had a clear influence on the measured bond strength values. Mortar M consistently produced the highest flexural bond strength values across all brick types and curing conditions. The highest measured value was obtained for specimen group X-M-L at an average of 0.61 MPa, while mortar M generally produced values between 0.40 MPa and 0.61 MPa under laboratory curing conditions and on an average between 0.37 MPa and 0.45 MPa under cold–climate curing conditions.

In contrast, mortar P consistently produced the lowest flexural bond strength values. The lowest measured value was observed for Z-P-C at 0.06 MPa. Mortar P generally produced bond strengths between 0.06 MPa and 0.19 MPa regardless of curing condition.

Mortars N and O produced intermediate bond strength values between those obtained for mortars M and P. Mortar N generally resulted in bond strengths between 0.20 MPa and 0.35 MPa, while mortar O produced average values between 0.16 MPa and 0.27 MPa depending on brick type and curing condition.

The ANOVA results, seen in Figure 12(a), suggests a statistically significant effect of mortar type on flexural bond strength.

The results indicate that mortar compressive strength alone did not determine the measured flexural bond strength. Mortar N, corresponding to strength class M2.5, achieved the highest measured compressive strength of approximately 6.3 MPa, but did not produce the highest flexural bond strength values. In contrast, mortar M, corresponding approximately to strength class M1, produced the highest bond strengths despite a lower measured compressive strength of approximately 2.5–3.1 MPa.

This suggests that bond development depended more strongly on the interaction between mortar composition, air content, workability, and moisture exchange at the brick–mortar interface than on compressive strength alone. This agrees with previous findings by Högberg [16], who reported that bond development is strongly influenced by moisture transport and interface formation rather than mortar compressive strength alone.

The higher bond strengths obtained for mortar M may partly be related to its lower measured air content. Mortar M contained approximately 2% air, compared with approximately 13%, 19%, and 12% for mortars N, O, and P respectively. Increased air content may reduce the effective contact area at the brick–mortar interface and limit mechanical interlocking, which may partly explain the lower bond strengths obtained for mortars N, O, and P. Similar observations were reported by the Portland Cement Association [27], showing that increased air content may negatively influence bond performance, depending on the brick absorption properties.

The mortar composition may also have influenced the bond behaviour. Mortar M consisted of a cement–lime mortar, while mortar N was primarily cement-based. The presence of lime may have improved mortar workability and deformability, allowing improved contact and moisture exchange at the brick–mortar interface. This interpretation agrees with previous studies indicating that lime may improve workability and interface contact while reducing brittleness within the masonry system [16], [26].

Mortar O, with a lime:cement (proportioned by weight) of 50:50 composition, produced intermediate bond strength values around 0.25 MPa. Although mortar O contained the same lime–cement proportions to mortar M, the measured bond strengths were substantially lower. One possible explanation may be the considerably higher measured air content of mortar O, approximately 19%, compared with 2% for mortar M. This may have reduced the effective interface contact and limited bond development. As the additives of the mixture for mortar O are not disclosed by the manufacturer, these can also have an unknown effect to the bond development.

The measured water retention values ranged from 96.5% to 98.5% for all mortars. Since the variation was small, the individual influence of water retention could not be clearly separated from the effects of mortar composition and air content. The results therefore suggest that flexural bond strength depended on the combined compatibility between fresh mortar properties and brick absorption behaviour rather than on a single mortar parameter.

4.2 Influence of brick type on flexural bond strength

Figure 12(b) presents the average flexural bond strength results for the different brick types. Brick type X generally produced the highest flexural bond strength values, followed by brick type Y, while brick type Z generally produced the lowest values.

The highest measured bond strength was obtained for X-M-L at 0.61 MPa. For mortar M under laboratory curing conditions, brick type X produced a bond strength of 0.61 MPa, compared with 0.41 MPa for brick type Y and 0.40 MPa for brick type Z.

Brick type Z resulted in lower bond strength values for several mortar combinations, particularly in combination with mortar P, where Z-P-C produced the overall lowest measured value of 0.06 MPa.

The ANOVA results indicated a statistically significant effect of brick type on flexural bond strength, although lower effect than mortar type.

Previous studies commonly identify the initial rate of absorption (IRA) as an important parameter governing moisture exchange between brick and mortar during curing, ultimately affecting bond development [16], [31].

However, the present results suggest that the relationship between IRA and flexural bond strength was not directly proportional. Brick type Z exhibited higher IRA values than brick type X but generally produced lower flexural bond strengths. Brick type X instead consistently produced the highest bond strengths, particularly in combination with mortar M.

These findings support previous literature suggesting the existence of an optimal absorption range, where sufficient suction promotes bond development without excessively reducing the water available for hydration [16], [31]. Excessively high suction may extract water too rapidly from the mortar, while excessively low suction may reduce mechanical interlocking and adhesion at the interface.

Brick compressive strength also appeared to influence the observed behaviour. Brick type X showed the highest measured compressive strength, approximately 42.2 MPa, and produced the highest flexural bond strengths. However, brick compressive strength alone could not explain the measured bond behaviour. Brick type Y, with a measured compressive strength of 14.8 MPa, generally produced higher bond strengths than brick type Z, which had a compressive strength of approximately 25.4 MPa.

The results therefore suggest that bond development depended more strongly on the compatibility between brick absorption behaviour and fresh mortar properties than on brick compressive strength alone. However, the interaction between brick absorption behaviour and mortar properties is complex, and the present results do not isolate the contribution of individual parameters independently. Combinations where this compatibility appeared favourable, such as X-M-L and X-M-C, produced both high and relatively consistent bond strength values.

4.3 Influence of curing conditions on flexural bond strength

Figure 12(c) presents the influence of curing conditions on flexural bond strength. In general, laboratory curing conditions resulted in higher bond strength values than cold–climate curing conditions. However, the magnitude of the difference varied depending on the brick–mortar combination, which is illustrated in Figure 13.

The largest reduction was observed for mortar M combined with brick type X, where the measured bond strength decreased from 0.61 MPa for X-M-L to 0.45 MPa for X-M-C. In contrast, smaller differences were observed for several other combinations. For example, Y-M-L produced a bond strength of 0.41 MPa, while Y-M-C produced 0.39 MPa.

Some combinations showed slightly higher bond strength values under cold–climate curing conditions. For example, X-N-C produced a slightly higher value than X-N-L, while similar behaviour was observed for X-P-C and Z-N-C.

The ANOVA analysis indicated a statistically significant effect of curing condition on flexural bond strength, although the statistical influence was smaller than for mortar type and brick type.

The results generally indicate that cold–climate curing conditions reduced bond development compared with laboratory curing conditions. This agrees with previous studies showing that lower curing temperatures may slow cement hydration and delay the development of adhesion and mechanical interlocking at the brick–mortar interface, as the bond will increase over time [16], [34]. The limited curing time of this study can therefore have an impact in why the cold–climate curing generally showed a decrease in bond development.

The reduction observed for specimen groups such as X-M-C compared with X-M-L may therefore be related to slower hydration rates under lower curing temperatures. Reduced hydration may weaken the development of interface contact during the early curing stages.

However, the influence of curing conditions was not consistent for all combinations. Some specimen groups, including X-N-C and Z-N-C, showed slightly higher bond strengths under cold–climate curing conditions than under laboratory curing conditions. This indicates that curing condition did not act independently but instead depended on the specific brick–mortar combination.

One possible explanation may be the higher relative humidity within the cold–climate curing environment, which may have reduced excessive moisture loss from the mortar. Reduced drying may partly have compensated for the lower curing temperature in some combinations. Similar observations were discussed by Högberg [16], who emphasized that moisture exchange at the interface is strongly dependent on the combined interaction between curing environment, mortar properties, and brick absorption behaviour.

The higher scatter observed for several cold–climate specimen groups also suggests that bond development under cold curing conditions was more sensitive to local variations within the brick–mortar interface.

4.4 Failure modes and implications for brick separability

The observed failure modes varied considerably between the tested brick–mortar combinations. Specimens with mortar P mainly showed A1 failure, corresponding to failure at the brick–mortar interface. In contrast, specimens with mortar M mainly showed A4 and A5 failure modes.

Brick type Y, the red brick, showed A5 failure in several combinations, particularly under laboratory curing conditions. A5 corresponds to tensile failure within the brick unit near the interface and A4 corresponds to tension failure within the mortar bed.

Specimen groups with high bond strength values, such as X-M-L and Y-M-L, were generally associated with A4 and A5 failure modes, while lower bond strength combinations, such as Z-P-C and Y-P-L, were mainly associated with A1 failure.

The failure modes are important for interpreting the practical separability and reuse potential of bricks. Failure mode A1 indicates separation at the brick–mortar interface and is therefore generally favourable for brick reclamation, since the bricks can separate with a lower risk of damage. In contrast, A4 and A5 indicate failure within the mortar or brick unit, increasing the risk of brick damage during mechanical separation.

Mortar P consistently produced A1 failure together with the lowest bond strength values, including 0.06 MPa for Z-P-C. This suggests favourable separability conditions. However, the lowest measured values did not fulfil the minimum flexural bond strength requirement of 0.10 MPa according to SS-EN 1996-1-1 for mortars with compressive strengths below 5 MPa.

Mortars N and O produced intermediate behaviour, with combinations showing both interface-related failures and failures within the mortar bed. This suggests a balance between structural bond performance and practical separability.

Brick type Y showed A5 failure in several combinations, indicating increased brick damage during testing. Brick type Y also showed the lowest measured compressive strength, approximately 14.8 MPa, compared with 42.2 MPa for brick type X and 25.4 MPa for brick type Z. This may partly explain why brick damage occurred more frequently for brick type Y. However, brick compressive strength alone should not be considered the only explanation, since the observed failure modes also depended on the corresponding mortar type and bond strength.

The results generally agree with demolition and reclamation studies reported by Moesgaard [35], which showed that stronger brick–mortar bonds often require more aggressive mechanical separation and therefore increase the risk of brick damage during cleaning and reuse. Similarly, the high reuse rates reported for weaker mortars correspond well with the consistent A1 failures observed for mortar P.

Overall, the results suggest that moderate bond strengths combined with interface-related failure modes may provide the most favourable balance between structural performance and practical brick separability for reuse applications.

4.5 Future work

The results of this study indicate that further research is needed regarding the cleaning and reclamation process of reused bricks. During the separation and cleaning of the masonry specimens, damage of the bricks was frequently observed, particularly for the red brick specimens, which appeared more sensitive to mechanical cleaning compared to the higher compressive strength bricks X and Z. Future studies should therefore investigate gentler and more controlled cleaning methods that can reduce brick damage while still allowing effective mortar removal. This is important for improving the practical reuse potential of bricks. It is also highly relevant in today's masonry industry as more bricks get fired at lower temperature to reduce the climate impact of the manufacturing process. Ultimately, this lowers the compressive strength capacity of the bricks.

In addition, only a limited number of mortar types were investigated in this study. While the results showed clear differences in bond strength and failure behaviour between the tested brick–mortar combinations, further studies should evaluate a wider range of mortar compositions. More mortar types would help to better understand how varying binder ratios, cement contents, air contents, and water retention properties, would impact both structural performance and brick separability.

The relatively limited number of specimens in each test series should also be considered, especially for the cold–climate curing conditions. Increasing the number of tested specimens would improve the statistical reliability of the results and reduce the uncertainty associated with the result variations.

Furthermore, the experimental work in this study was performed under controlled laboratory and simulated cold–climate environments. Future studies should investigate masonry bond development under real outdoor conditions, including both winter and summer early construction environments. Sush studies would provide a better understanding of how natural variations in temperature, moisture, wind, and curing conditions influence bond strength development and masonry separability in practical construction applications.

Finally, future research should compare the tested lime-cement and cement-based mortars with traditional air-lime mortars. Air-lime mortars have historically been associated with lower bond strength and improved brick separability, but their slow strength development, durability, and suitability for modern veneer masonry applications need further evaluation. Such comparisons could provide valuable insight into the balance between bond performance, durability, and circular reuse of masonry materials.

5 Conclusions

As a conclusion all the results of this study are derived from a controlled laboratory environment. In real masonry construction, external factors such as wind, rain, workmanship, as well as loading conditions will influence the bond development and overall structural performance. Therefore, while the findings provide important insights into material behaviour, they should be interpreted with consideration of real construction conditions.

The study suggests that mortar type appears to be the most influential parameter affecting flexural bond strength, with mortar M consistently producing the highest bond strength and mortar P the lowest. However, high bond strength did not necessarily correspond to favourable reuse potential. Stronger mortar combinations generally improved structural performance but made the bricks more difficult to separate. Strong mortars tend to shift failure modes into the brick or composite system, leading to damage and reduced reuse potential, whereas weaker mortars favour interface failure and easier separation but may not fulfil structural performance requirements.

Brick properties also played a significant role, as demonstrated by the consistently higher bond strength values obtained for brick type X across most combinations. The findings suggest that bond strength could not be explained by a single parameter such as compressive strength or IRA alone, but instead depended on the compatibility between different properties, such as mortar composition, air content, water transport properties, and brick characteristics. The results further support the concept of an optimal balance between mortar water supply and brick suction, rather than maximising individual material properties independently.

Curing conditions were found to influence bond development, with cold–climate generally reducing bond strength and increasing variability. However, the influence was less consistent than the effects of mortar type and brick type, indicating that material properties had a greater influence on bond development than the studied curing conditions.

From a reuse perspective, the study indicates that moderate bond strength may represent a favourable balance. Mortar types such as N, which provide sufficient structural performance while still allowing failure in the brick mortar interface in several cases, may offer a practical compromise between durability and future reuse potential. This aligns with the broader objective of sustainable construction, where material recovery and circularity are increasingly important.

Overall, the results suggest that optimizing masonry for both structural integrity and reuse requires a holistic approach, considering not only strength but also failure behaviour and material interaction. Future research should focus on validating these findings under real construction conditions, investigating long-term durability effects, and further exploring mortar compositions and water transport properties specifically designed to balance performance and reversibility in masonry systems.

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Appendix A

Murbruk B M 2,5

Användningsområden

Murning av tegel, kalksandsten, betongblock, lättklinkerblock.

Produktkvalitet

Bösarps Murbruk B är tillverkat av typgodkänt bindemedel.

Åtgång

Vid tegelmurning 1/2-stens väggtjocklek åtgår ca 70 kg/kvm.

Vid putsning 10 mm tjocklek åtgår ca 18 kg/kvm.

Förpackning/Lagring

Bösarp Murbruk B förpackas i papperssäckar om 25 kg/förp.

Förpackas även i storsäckar om 1000 kg.

Vi levererar även bruket i storbehållare som rymmer upp till 10 ton.

Kontakta oss gärna när det gäller vår hyrutrustning av ovanstående.

Torrbruksprodukter skall förvaras torrt, varvid lagringstiden kan uppskattas till ca 12 månader.

Tekniska Data

Bindemedel	Portland cement
Ballast	Sand 0–2 mm & fingraderad Dolomit
Tillsatsmedel	Luftrorsbildare, konsistensgivare
Lufthalt	ca 20 %
Viktproportionering	100/600
Murbruksklass	Murbruk B M 2.5
Frostbeständighet	God
Tryckhållfasthet	28 dygn 2,5–4 Mpa
Vattenbehov	ca 16 %

Bruksanvisning

Bösarp Murbruk M 2,5 blandas maskinellt med tvångsblandare eller snabblandare ca 10 minuter med 4 liter vatten per säck om 25 kg, vilket ger ca 16 liter färdigt bruk.

Pratiska tips

Blandat bruk bör användas inom två timmar.

Skydda ytan mot nederbörd de första dygnen, håll bruket fuktigt i minst 3 dygn, väderskydda alltid ytan för att förhindra snabb uttorkning.

Skall putsning och murning ske under +5 grader skall alltid vinteråtgärder utföras.

Vid eventuella oklarheter om användningen kontakta oss gärna. Då arbetsutförandet ligger utanför vår kontroll är vårt ansvar begränsat till kvaliteten hos levererad vara.

Appendix B

KC Putsbruk C Fin

KC Putsbruk C Fin används vid finputsning, filtning, slamning och lagning av KC-putsade underlag.

Arbetsanvisning

Förarbete:
Kontrollera att rätt produkter används.
Kontrollera underlaget och dess beskaffenhet.
Rengör samtliga ytor noggrant. Underlaget ska vara damm- och fettfri.
Underlaget ska förvattnas vid behov – Använd slang med finspridarmunstycke.

Bruket blandas, enligt de blandningsförhållanden som anges i tabellen för tekniska data, maskinellt cirka 10 minuter i en långsamtgående blandare. Blandningstiden ska inte vara längre än vad som fordras för att få ett homogent och smidigt bruk. Rent kranvatten ska användas. Samma vattenmängd och blandningstid ska alltid användas. Putsning får inte utföras med för blött bruk. Det ska säkerställas att rätt vattenmängd doseras, då ett felaktigt blandat bruk påverkar dess egenskaper negativt. Bruk som har börjat att härda får inte blandas ut med mer vatten."
Specialkvalitet krävs vid användning av genomströmningsblandare.

Bruk med genomströmningstillsats ska endast användas med genomströmningsblandare. Om bruk med genomströmningstillsats används tillsammans med annan blandningsutrustning, som t.ex. planblandare, får bruket avsevärt sämre prestanda än deklarerade värden.

Putsning:
För arbetsgång, putsning - se anvisning "Hjälp vid - Putsning" på www.finja.se.

Bruket slås på underlaget.

Om bruket har börjat hårdna ska det kasseras. Brukets bearbetningstid beror till stor del på väder och temperaturen i luften. Finja tar inget ansvar för bruksblandningar som har kontaminerats/förorenats med otillåtna tillsatser på arbetsplatsen så som till exempel diskmedel, T-sprit eller liknande.

Eftervattna det hårdnande putsskiktet för ökad hållfasthet – Använd slang med finspridarmunstycke.

Användningsråd:
Skydda alltid ytan mot regn. Under varma förhållanden ska murverket skyddas mot direkt exponering av sol. Eftersträva en jämn temperatur över 15 °C under härdningstiden. Vid användning under 5 °C ska vinteråtgärder vidtas, det vill säga isolering, snöskydd och uppvärmning av blandningsvatten med mera. Eftersträva en brukstemperatur på ca 20°C, på det färdigblandade bruket.
Frostskyddstillsats får ej tillsättas i putsbruket.

För mer information gällande vinteråtgärder se handboken "Rätt från början – Murat & Putsat", Svenskbyggtjänst.

Underhåll:
Se handboken "Rätt Murat & Putsat", Svenskbyggtjänst, Kapitel 10: Ombyggnad, Renovering och Underhåll.

Viktigt att notera:
Kulörvariationer kan förekomma mellan olika tillverkningsbatcher av bruket. Produkten är inte avsedd att användas som slutligt ytskikt. För att uppnå önskad finish och hållbarhet ska bruket alltid kompletteras med en lämplig ytbehandling, såsom till exempel färg.

Teknisk data

Bindemedel	Kalk och cement
Vattenåtgång	Ca. 4 liter per 25 kg
Ballast	Natursand 0–1 mm
Frostbeständighet	God
Bearbetningsbar	Ca 2 tim
Rek. skikttjocklek	Max 5 mm
Tillval (för 1000 kg Storsäck alt. Bruksbehållare)	Art.nr.
Tillsats för blandning i genomströmningsblandare	5919
Åtgång	Ca 9 kg/m² vid 5 mm putsskikt

Förpackning

Produkten levereras i 25 kg säck. 25 kg förpackningen består delvis av återvunnen plast och sorteras som mjukplast eller enligt lokala anvisningar i kommunen.

Lagring

25 kg plastsäckar ska användas inom 24 månader från tillverkningsdatumet på förpackningen. Förutsätter torr förvaring i obruten förpackning. Storsäckar som förvaras torrt och täckt ska användas inom 6 månader från tillverkningsdatum.

Appendix C

Weber putsbruk C enaé

• FÖR HANDAPPLICERING OCH PUMP • FÖR BÅDE MURNING OCH PUTSNING • CS II (C)

OM PRODUKTEN

Putsbruk i hållfasthetsklass CS II anpassat för mineraliska underlag. Bruket innehåller ballast 0-3 mm och kan slås på för hand eller med lämplig putsspruta.

ANVÄNDNINGSOMRÅDE

Bruket är ett kombinationsbruk för mur- och putsningsarbeten ovan mark, samt invändig putsning. Putsbruk C enaé är lämpligt för murning och putsning av skorstenar. Ska ej användas på konstruktioner av lättbetong, på detta underlag rekommenderar vi Grundningsbruk KC och Base 131 Lättbetongputs C.

UNDERLAG

Tegel, leca, tidigare putsade fasader.

BEGRÄNSNINGAR

- Används ej vid temperaturer under +5 grader

BRA ATT VETA

Blandat bruk måste användas inom två timmar. För att förhindra snabb uttorkning ska alla ytor förfuktas och fasaden täckas in. Regntak ska alltid användas.

TEKNISK SPECIFIKATION

Materialåtgång	20 kg/kvm/10 mm
Rekommenderad skikttjocklek	10 mm
Minsta skikttjocklek	8 mm
Maximal skikttjocklek	12 mm
Vattenbehov	ca 4 liter
Bindemedel	Cement
Ballast	0-3 mm
Tryckhållfasthetsklass	CS II
Maskin och utrustning	Planblandare, maskinvisp. Automatstation, obs GS-tillsats krävs. Brukspump P25/P70
Lagring	12 månader
Förpackning	20 kg säck 1000 kg SSK Löst i ficka
Klimatavtryck (GWP-GHG) enligt EPD A1-A3	0,081 kg CO_2e/m^2

FÖRBEHANDLING

Förvattna innan grovputsningen påbörjas. Använd slang med finspridarmunstycke. Vid putsningsarbeten ska underlaget tunngrundas med weber grundningsbruk KC.

BLANDNING

Blanda med ca 4 liter vatten i snabbgående blandare 3 - 4min eller i långsamtgående blandare 7 - 10min. 20 kg ger ca 12,8 L bruk. Sista delen vatten tillsätts tills önskad konsistens uppnås. Kan även blandas i genomströmningsblandare om GS tillsats har valts.

ANVÄNDNING

Mura med fyllda fogar, var extra noga med stötfogarna. Stryk och/eller borsta fogarna när bruket är relativt torrt. Vid putsning slås bruket på med slev alternativt lämplig putsspruta till ca 10mm per påslag. Komprimera med skånska och drag av med rätkäpp. Putsen brädrivs/skuras till önskad struktur.

EFTERBEHANDLING

Skydda murverket mot nederbörd de första dygnen. Putsskiktet ska hållas fuktigt i minst 3 dygn. Använd slang med finspridarmunstycke.

OBSERVERA

Putsning och murning får inte ske då risk för temp. under +5° C föreligger utan att vidta vinteråtgärder. Kalla stenar kan förlänga härdningstiden. Sträva efter en temperatur på ca +15- 20° C under arbete och härdning.

ÅTERVINNING

På se.weber/retursystem finns information kring hantering av överblivet material, förpackningar och emballage.

FRISKRIVNINGSKLAUSUL

Då det vid varje tillfälle råder olika förhållanden och förutsättningar, kan Saint-Gobain Sweden AB inte ansvara för annat än att den information som lämnas här under rubriken ”Produktspecifikation” är korrekt. Exempel på information och förhållanden, som ligger utanför Saint-Gobain Sweden ABs ansvar (vare sig detta särskilt påpekas eller inte), innefattar lagring, konstruktion, bearbetning, samverkanseffekt med andra produkter, arbetsutförande och lokala förhållanden.