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Retrieving earth blocks from masonry couplets for reuse: the role of bond strength

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List of symbols and abbreviations

f_w	Flexural bond strength
f_c	Compressive strength
t	Thickness of mortar joint
DfD	Design for Deconstruction
EBM	Earth Block Masonry
MEB	Moulded Earth Block
FMEB	Frogged Moulded Earth Block
CEB	Compressed Earth Block
SCEB	Stabilised Compressed Earth Block
EM	Earth Mortar
ECM	Earth-Cement Mortar
ESM	Earth-Silicate Mortar
EAM	Earth-Adhesive Mortar
PBL	Prewetting Before Laying
WBR	Wetting Before Reclaiming
IRA	Initial Rate of Absorption
SD	Standard Deviation
CoV	Coefficient of Variation
MC	Moisture Condition
RH	Relative Humidity
SL	Saturation Level

1 Introduction

The built environment bears a significant responsibility for the depletion of resources, carbon emissions, and staggering volumes of waste [1]. As current building regulations aim to reduce operational energy, buildings are becoming more energy efficient [2], [3]. However, the emphasis is widening towards other life cycle phases, such as production and end of life [4]. The circularity paradigm has emerged as a beacon of sustainability within the construction industry to address these challenges [5], [6]. Circular construction aims to prolong the value of building components through cascading material loops [7] and promotes implementing bio- and geo-based building materials to avoid the depletion of virgin resources [8]. This study addresses these strategies by investigating (1) the deconstruction of masonry to increase the reuse potential of masonry units and (2) earth blocks as an environmentally sound alternative to carbon-intensive bricks and blocks.

Masonry is the oldest and still one of the most common building methods [9]. However, conventional masonry is typically executed with fired clay bricks or concrete blocks, requiring energy-demanding production processes that generate substantial greenhouse gas emissions [10]. Moreover, most brickwork is demolished before the end of its service life, and as its recycling possibilities are limited, the majority ends up in landfills [11]. As the reuse of building materials emerges as a primary strategy to implement circular economy principles in the built environment [12], masonry walls should be conceived to enable the reclamation of the masonry units.

Design for Deconstruction (DfD) can be understood as reversed construction and befits an established approach to minimise demolition waste streams and the production of new building materials [13]. Bricks and blocks are generally manufactured in standard sizes, facilitating reuse [14]. Whereas the bond strength between masonry units and mortar is a governing characteristic in imparting strength to the masonry [15], it also impacts the difficulty of recovering the masonry units at the end-of-life phase. Historically, bricks were joined using lime mortar with relatively weak bonds, enabling separation, cleaning, and subsequent reuse [16]. Conversely, contemporary constructions often employ cement mortar possessing strong brick-mortar bonds, rendering the separation process more challenging and frequently damaging the bricks [17]. Hence, the return to lime-mortared brickwork for low-strength applications appears logical. Meanwhile, dry-stacking and mortarless masonry using metallic or plastic connectors are also gaining attention in research and practice [18]. However, both approaches still presume the application of carbon-intensive masonry units such as fired bricks and concrete blocks. On the contrary, earth blocks boast a considerably reduced environmental footprint during production [19].

Although earth block masonry (EBM) typically exhibits lower strength than its conventional counterpart and is vulnerable to water when untreated [20], by applying the correct design principles, EBM can fulfil a variety of building applications where these limitations do not present significant challenges [21], [22], [23]. However, stabilisation of earth-building materials with lime or cement is a common approach to enhance strength and water resistance despite coming at an environmental cost [20]. Considering the increased embodied energy due to stabilisation, prolonging the value of stabilised earth blocks through reuse seems a desired circular strategy. Since lower bond strengths may benefit reclamation, EBM is potentially more amenable to deconstruction. On the other hand, the bond strength should be sufficient for intended building applications and further adoption of EBM in mainstream construction. Therefore, investigating the bond strength of EBM from both a structural and a reuse perspective is a promising avenue.

This study begins with a targeted literature review to summarise the factors influencing bond strength and to highlight a discrepancy between bond strength values prescribed in normative documents and those observed across various studies. Generally, bond strengths in practice are higher than necessary, which may affect reclamation. Next, the flexural bond strength of sixteen earth block-mortar combinations and material properties that influence the bond strength are characterised. The reclamation potential of these combinations is then assessed by the effort required to separate the masonry couplets and clean the recovered blocks using standard tools. Additionally, the effects of two interventions are evaluated for stabilised earth blocks: prewetting the blocks before laying, intended to enhance bond strength for structural performance, and wetting the masonry before reclaiming, aimed at reducing bond strength to facilitate reclamation. **Table 1** gives an overview of the experimental programme.

1 Experimental programme

1.1 Materials

This study considers four earth blocks (**Figure 1**) and four earth mortars (**Figure 2**). The properties of the materials are summarised in **Table 2** for earth blocks and **Table 3** for earth mortars.

1.1.1 Earth blocks

Industrially manufactured, non-stabilised moulded earth blocks (MEBs) are studied with frog (FMEB) or without, and vibro-compacted compressed earth blocks (CEBs) are studied with 5.67% of cement stabilisation (SCEB) or without. The MEBs were developed by an earth product company and industrially manufactured using the infrastructure of a fired brick company. Dimensions are 215 x 100 x 60 mm for MEBs and 230 x 105 x 65 mm for FMEBs, with a rounded rectangular frog of 180 x 60 mm. Similarly, the CEBs were developed by the same earth-building company using the infrastructure of a concrete block manufacturer. Dimensions of the (S)CEBs are 290 x 130 x 90 mm. (F)MEBs were dried over three days in ventilated chambers with temperatures ranging from 30°C to 80°C using residual factory heat. (S)CEBs are cured for ten days in unventilated chambers at 23°C with relative humidity between 50% and 78%. The earth blocks obtained from the manufacturers were transported shortly after drying/curing and stored indoors. The (F)MEBs contain revalorised loam from urban excavations in Brussels, additional clay, sand, and crushed brick waste; the (S)CEBs contain the same revalorised loam, additional clay, sand, and crushed concrete waste.

1.1.2 Earth mortars

The earth mortar (EM) was acquired from the same earth product company providing the earth blocks. It contains the same revalorised loam as the blocks, additional clay, and sand. The EM was stabilised with an additional 8% cement or 10% sodium silicate (from a 36% solution) by mass to make earth-cement mortar (ECM) and earth-silicate mortar (ESM). The earth-adhesive mortar (EAM) was acquired from a different earth product manufacturer and is primarily intended to attach light building and interior insulation boards to various substrates. It contains sand, clay, loam, perlite, talc, plant fibres, and 1% methylcellulose in its dry state.

1.2 Test methods

1.2.1 Characterisation of earth blocks

The bulk density of the earth blocks was determined according to DIN 18945. The moisture content was determined according to NBN EN 772-10. The initial rate of absorption (IRA) was determined following NBN EN 772-11 for SCEBs by immersing the bed faces for one minute. For non-stabilised earth blocks, the IRA could not be determined due to the early dissolving of the blocks. For the same reason, the 24-hour water absorption was only tested for SCEBs according to NBN EN 772-21. By illustration, one non-stabilised CEB was fully immersed until crumbling started and a mass loss was measured. The compressive strength of the blocks in the air-dry state, at the moisture contents specified in **Table 2**, was tested according to NBN EN 772-1 in a ToniCON compression test plant, with a maximum loading capacity of 2000 kN. The non-stabilised (F)MEBs and CEBs were tested at a loading rate of 0.05 N/mm²s, and SCEBs were tested at 0.10 N/mm²s. The frog of FMEBs was filled with earth mortar, and both MEBs and FMEBs were temporarily capped with a 3-mm wood fibre panel to ensure uniform load distribution.

1.2.2 Preparation and characterisation of earth mortars

Following NBN EN 1015-2 procedures, the earth mortars were prepared in a planetary mixer. When qualitatively evaluated as having good workability, the consistency of the fresh mortar was assessed by determining the initial flow by NBN EN 1015-3 using a manual flow table by NBN EN 459-2. Mortar prisms were cast and dried for 28 days, except for the ECM, which was cured in sealed polyethene bags. The drying shrinkage of the mortar prisms was determined according to DIN 18946. To determine the compressive and flexural strength of the hardened earth mortars, NBN EN 1015-11 was followed. The specimens were tested in a DARTEC universal testing machine with a loading capacity of 250 kN. Flexural strength and compressive strength were tested at a loading rate of 10 N/s and 50 N/s, respectively.

1.2.3 Preparation of earth block masonry couplets

EBM couplets were cast according to NBN EN 1052-5 by applying a mortar layer of 10 ± 2 mm for the EM, ECM and ESM. The EAM was applied as a thin-layer mortar using an adhesive spreader, resulting in a 1 to 2-mm layer. After casting, the masonry couplets were stored at ambient temperature and equally prestressed according to the standard. Before laying, the bed faces of both stabilised and non-stabilised blocks were prewetted in a tray of water for one second for enhanced bonding, as recommended by the manufacturer. Based on common prewetting times found in the literature [24], [25], [26] and preliminary tests showing improved bonding at increased prewetting times, the effect of prewetting before laying (PBL) on the flexural bond strength was determined by fully immersing SCEBs in water for 1 minute and 15 minutes before laying. To determine the effect of wetting before reclaiming (WBR) on the bond strength, the EBM couplets were fully immersed in water for 1 minute and 15 minutes before testing. In total, 128 couplet specimens were prepared for testing.

1.2.4 Characterisation of the flexural bond strength

The bond wrench test determined the flexural bond strength of EBM couplets according to NBN EN 1052-5. According to several studies [26], [27], [28], [29], the flexural bond strength determined by the bond wrench test on masonry couplets or prisms corresponds to the flexural strength with the plane of failure parallel to bed joints determined tested on wallet specimens according to NBN EN 1052-2. Three specimens per combination were tested after 28 days of hardening. The force separating the block from the mortar is applied by a cantilevered arm (**Figure 3**), inducing flexural stresses across the mortar bed joint. The masonry couplets were installed on a bench vice, and the bench was loaded to resist the overturning momentum of the increasing container load attached to the lever arm. The flexural tension developed perpendicular to the bed joint was calculated assuming the linear elastic behaviour of the mortar joint. The flexural bond strength f_w at failure is given by

where F_1 is the applied load (N), e_1 is the distance from the applied load to the tension face of the specimen (mm), F_2 is the weight of the bond wrench apparatus (N), e_2 is the distance from the gravitational centre of the clamping system from the tension face of the specimen (mm); *d* is the mean depth of the specimen (mm), *W* is the weight of the masonry unit pulled off the specimen (N), and *Z* is the section modulus of the block (mm^3). The failure mode was recorded for all specimens as per NBN EN 1052-5. During preliminary tests with the (F)MEBs and CEBs, couplets failed by the clamp or the clamp and container weight. To address this issue, a shorter and lighter clamp was used, deviating from the minimum cantilever length e2 of 1 m in NBN EN 1052-5.

1.2.5 Reclamation test

In the absence of standards on the reclamation of masonry units, this study proposes an initial qualitative method to assess the effort needed to retrieve earth blocks from masonry couplets by separation and cleaning. For every block-mortar combination, an additional masonry couplet was made to test deconstruction techniques by iteration using standard tools (**Figure 4**). The upper block was separated first by wrenching, then by punching, and then by chipping. Wrenching was attempted by hand; if unsuccessful, a small clamp with a 62 cm lever arm was used. If wrenching by clamp was not feasible, the upper block was punched onto using a rubber hammer. Finally, if punching was ineffective, the mortar was chipped using a cold chisel. After bond wrench testing and manual separation, the residual mortar was cleaned from all blocks. Half was cleaned using a putty knife, and the other half was cleaned using a steel brush. A qualitative assessment probing the effort needed for deconstruction and cleaning was done to evaluate the reclamation potential in relation to the bond strength. After some preliminary tests, the required effort was assessed on a five-level rating scale ranging from 'none' to 'very little', 'little', 'much', and 'very much'. Failure modes were recorded as per NBN EN 1052-5.

2 Literature review on bond strength

2.1 Review method

To provide a comprehensive foundation for the experimental investigation, a targeted literature review focused on masonry bond strength and factors affecting it. Normative documents were selected as those known by the authors and by screening Belgian, French, German, and European standards. A systematic search was conducted in Scopus to identify pertinent studies containing "masonry" and "bond strength" within the article abstract and limited to "bond strength (materials)" in the keywords. The search encompassed articles in English published from 1990 to 2023 and was limited to journal publications in engineering. The focused literature was refined based on the following selection criteria:

- Laboratory experiments: studies with an experimental campaign incorporating flexural, shear or tensile bond strength tests of masonry.
- Influencing factors: studies directly investigating the influence of one or more parameters on masonry bond strength or vice versa.
- Data collection: studies providing quantitative data on the flexural bond strength from laboratory tests.

The initial search yielded 88 studies, and 24 were withheld by relevance after filtering according to the criteria and by adding studies known by the authors. These studies encompassed a range of experimental conditions, including varying moisture content, masonry unit types and mortar compositions, aligning with the scope of this research. From the selected studies, critical information was extracted, such as parameters influencing the bond strength, material characteristics, and experimental methods. 17 studies were selected for a more detailed review and data collection of flexural bond strengths. These studies revealed variations in methodologies, including specimen preparation, testing procedures, and sample sizes. By incorporating the valuable insights from the selected studies, the experimental results from this study can be critically evaluated to contribute to a deeper understanding of bond strength in EBM.

2.2 Factors influencing bond strength

The targeted literature review reveals that the bond strength between masonry units and mortar is influenced by various factors associated with the properties of the masonry units and the mortar, the conditions to prepare the specimens, the type of bond development, and the methods used to test bond strength.

2.2.1 Testing methods

Three different types of bond strength between masonry units and mortar exist, and they can be measured by three different methods: the bond wrench test (flexural bond strength), the initial shear strength test (shear bond strength), and the direct tensile test (tensile bond strength). The bond wrench test is the most commonly used test to assess the bond strength, according to Venkatarama Reddy [15]. As stipulated by van der Pluijm [26], the brick-to-mortar bond is frequently the weakest link in masonry, notably in tension induced by out-of-plane bending. The bond wrench test indirectly characterises the tensile behaviour and requires a less complex experimental setup than direct tensile tests, as stated by Gaggero & Esposito [27]. For reclamation purposes, the flexural bond strength is a good indicator of the deconstruction effort needed with techniques involving wrenching and, to a lesser extent, punching and chipping. Apart from the type of bond strength tested, the testing procedure and specimen type influence the measurements. The flexural bond strength can be measured using a typical bond wrench test setup on masonry couplets or prisms, although some studies prove the compatibility with masonry wallets or beams. Gaggero & Esposito [27] extensively studied the flexural bond strength using three test setups and two different masonry unit-mortar combinations. Comparing manually operated and computer-controlled setups for laboratory and in-situ testing based on the procedure for the bond wrench test in EN 1052-5, they found similar values in the coefficient of variation. They concluded that the various setups' control and precision could be compared. Additionally, they conclude that the high degree of variability in bond wrench test results must be considered as an intrinsic property of masonry. Furthermore, they recommend testing masonry couplets for design purposes instead of prisms, as it underestimates the flexural strength in wallets. Costigan & Pavía [28] conclude that the bond wrench test on prisms, according to EN 1052-5, compares well with results obtained from flexural tests parallel to bed joints on wallets, according to EN 1052-2. However, the flexural strength perpendicular to bed joints cannot be compared with the bond wrench test or the flexural strength parallel to bed joints because an additional force is required to overcome the friction in the masonry’s contra-rotation sections and cause them to move in a scissor-like manner.

2.2.2 Bond morphology

Bond development between masonry units and mortars has been studied extensively for cement and lime mortars [15]. Mechanical interlock occurs when the dry or partially saturated masonry unit absorbs water from the fresh mortar. The absorbed water is rich in cementitious hydration products that harden in the microscopic pores of the masonry unit when the mortar sets. A chemical bond occurs when pozzolanic materials from the bed surface of the masonry unit react with the free calcium hydroxide released during cement hydration. Gourav & Venkatarama Reddy [30] found that fly ash-lime-gypsum bricks combined with cement-lime mortar showed significantly higher bond strengths, leveraging the pozzolanic reaction to enhance bond strength. Morton [21] states that non-stabilised earth mortars are set by drying instead of chemical hydration, such as cement-based mortars. The literature review revealed no studies about the bond morphology of non-stabilised earth blocks and mortars. The bond development with non-stabilised earth mortars is likely due to mechanical interlock. It could be attributed to clay acting as a natural binder by forming hydrogen bonds [31], [32]. The hardening of earth mortars may introduce an interlocking effect in the block's pores, comparable to chemical binders such as lime and cement. However, such binding mechanisms have yet to be investigated microscopically.

2.2.3 Characteristics of masonry units

The composition and manufacturing methods impact their final properties and bond strength. Surface properties of masonry units, such as the frog, pore size distribution, and porosity, play a crucial role in bond strength development. Morton [21] and Venkatarama Reddy [15] postulate that while most mechanically manufactured materials have smoother surfaces, vernacular bricks usually have a rougher texture that improves bonding. Alternatively, thin slurry mortars can be effectively used on unprofiled bricks with uniform dimensions and smooth surfaces. Sarangapani et al. [33] studied the flexural bond strength of fired bricks using cement, cement-soil and cement-lime mortars. They found that increasing the frog area in masonry units enhances bond strength, suggesting that a larger contact surface provides better mechanical interlock. Venkatarama Reddy et al. [34] observed that roughening the block surface and using cement slurry or epoxy resin coatings enhance the shear bond strength more than by introducing frogs. Contrary to earlier findings, Thamboo et al. (14) discovered that smooth surface textures provide higher bond strengths for thin-layer mortars, suggesting that optimal surface texture for bonding depends on the mortar type and application method.

2.2.4 Characteristics of laying mortars

The composition, application and hardening conditions of the mortar impact the final properties of the masonry and its bond strength. Venu Madhava Rao et al. [35] found that composite mortars (cement-lime/earth-cement) with stabilised earth blocks yield higher bond strength than pure cement mortars, suggesting a synergistic effect between different components in the mortar. However, Walker [36] found that the bond strength decreases with the clay content of earth-cement mortar when bonded to stabilised earth blocks. These findings suggest that clay and cement act synergistically to a limited extent. Sarangapani et al. [33] confirmed higher flexural bond strength for fired bricks with composite cement mortars using lime and earth as plasticising additives. Venkatarama Reddy & Gupta [37], [38] reported that earth-cement mortars provide better tensile bond strength than cement or cement-lime mortars, supporting using earth materials in mortar for improved bonding with cement-stabilised earth blocks.

A few studies explored the influence of mortar consistency and water-retaining properties. Pavía & Hanley [39] found that water retention is the most influential factor for bond strength in natural hydraulic mortars (NHL), followed by their moisture content (flow) and hydraulic strength. Higher water retention and content generally lead to higher NHL mortar bond strength. Venkatarama Reddy & Latha [40] observed that higher drying shrinkage in cement-lime mortars leads to a linearly increased flexural bond strength in stabilised EBM. The drying shrinkage linearly increases with the mortar flow. Venkatarama Reddy & Gupta [41] reported that fine-graded sand decreases the tensile bond strength and increases drying shrinkage for stabilised earth blocks with cement and cement-lime mortar. However, fine-graded sand increases the drying shrinkage and water retentivity. These findings contradict the results from the previously mentioned study, where increased drying shrinkage leads to higher flexural bond strengths.

Regarding mortar strength, Venu Madhava Rao et al. [35] found that flexural bond strength increases with the compressive strength of the mortar for all masonry unit types studied, with stronger mortars providing better mechanical interlock. Nalon et al. [42] reported that higher mortar compressive strength and lower water-cement ratios increase the flexural bond strength of concrete block masonry with cement-lime mortar. Jiao et al. [43] observed that the flexural, shear, and tensile bond strength of concrete hollow block masonry increases non-linearly with the compressive strength of alkali-activated slag mortar, suggesting that different types of mortars may have unique bonding characteristics. However, Walker [36] finds that increasing mortar strength does not necessarily lead to higher bond strength, as other factors such as mortar type, block strength, and moisture condition may govern performance.

Varying results were obtained in studies tackling curing conditions and hardening times of mortars. Walker [36] found no increase in flexural bond strength of stabilised EBM after the initial 24-hour set of cement. This suggests that most bond strength development occurs in the early curing stages. However, Lawrence et al. [44] demonstrated much higher flexural bond strength with age in low-impact earth mortars stabilised with sodium silicate combined with non-stabilised earth blocks, showing the long-term benefits of specific stabilisers. Costigan & Pavía [28] found that the age of NHL mortar highly increased flexural bond strength and attributed it to the lime carbonation over time. This was confirmed by Gaggero & Esposito [27] over more extended periods. Thamboo & Dhanasekar [45] observed shear and flexural bond strength improvements with the age of thin-layer polymer cement mortar and with drying after curing.

2.2.5 Prewetting of masonry units before testing

Many studies have concluded that masonry units' moisture content or saturation level before laying significantly affects brick-mortar interactions and bond strength. Groot [46] and Sahu et al. [47] discussed the critical role of brick absorption and moisture content in bond strength development with cement-based mortars. Relatively dry bricks absorb more water from the mortar, disrupting its hydration process and reducing mortar strength, ultimately resulting in diminished bond strength. Conversely, saturated bricks hinder water absorption from the mortar, impeding the establishment of a robust mechanical connection between brick and mortar, consequently diminishing bond strength. Then again, these observations may differ from the bond development in non-stabilised earth mortars where non-chemical hardening phenomena occur.

Venu Madhava Rao et al. [35] studied the flexural bond strength of stabilised EBM and fired clay masonry with cement and cement-lime/earth-cement composite mortars. They identified an optimum moisture content for maximum bond strength in various masonry units between 10-15% of their weight. However, the bond strength falls rapidly beyond the optimum moisture content. They noted that this optimal level ensures sufficient water retention for hydration without excessive absorption. Walker [36] confirmed the presence of optimal moisture content for stabilised earth blocks and mortars, reinforcing the importance of controlling moisture levels during construction. Venkatarama Reddy & Gupta [38] found that partially saturated stabilised earth blocks perform better than dry or fully saturated ones. Sahu et al. [47] identified that the optimum moisture content for maximum bond strength is about 75% of the saturation level for various bricks, providing a specific guideline for preparing bricks before construction. However, Barr et al. [25] found adverse effects of prewetting sandstones with natural hydraulic lime mortar. They recommend keeping blocks with moderate water absorption rates as dry as possible before laying.

2.2.6 Wetting of masonry before testing

Two studies dedicated (a part of) their experimental campaign to the bond strength of wetted masonry. Sathiparan & Rumeshkumar [48] observed a 10-20% bond strength reduction for low-strength fired brick masonry with cement mortar when specimens were immersed in water 24 hours before testing. Walker [36] also observed decreased flexural bond strength of cement-stabilised earth blocks and mortars soaked in water before testing. The bond strength reduction of saturated masonry is probably due to pore-water pressure effects, swelling, and clays' liquefaction in both the blocks and mortars. However, the reason for conducting these experiments was to assess the peril of incident rainfall combined with lateral wind loads for the structural safety of exposed masonry walls. The present study differs in its intent by considering bond strength reduction as a potential advantage for earth block reclamation.

2.3 Flexural bond strength values

2.3.1 Normative documents

Scanning normative documents for benchmarks and masonry bond strength characteristic values yielded few results. No distinct minimum requirements for bond strength were found in European standards. In EN 1996-1-1 (Eurocode 6), the European standard for general rules for designing masonry structures, masonry bond is defined as the 'disposition of units in masonry in a regular pattern to achieve common action'. The standard states that the adhesion between the mortar and the masonry units 'shall be adequate for the intended use'. Although this section mentions that flexural bond strength is determined according to EN 1052-5, no required characteristic values are given. However, the findings of Costigan & Pavía [28] and Gaggero & Esposito [27] imply that the flexural bond strength according to EN 1052-5 does not considerably differ from the flexural strength with the plane of failure parallel to bed joints. The characteristic flexural strength parallel to bed joints 'shall be determined from the results of tests on masonry' or 'it may be established from an evaluation of test data based on the flexural strengths of masonry obtained from appropriate combinations of units and mortar'. Where test data are unavailable, the standard prescribes values summarised in **Table 4**.

In EN 998-2, the European standard for specifications on masonry mortar, bond strength is defined as the 'adhesion perpendicular to the bed between the masonry mortar and the masonry unit'. However, the standard prescribes that the manufacturer must declare a value for the characteristic initial shear strength, while nothing is mentioned for the flexural bond strength. This declaration can be made based on tests according to EN 1052-3 or tabulated values in Annex C, where only two values are specified: 0.15 MPa for general-purpose and lightweight mortar and 0.3 MPa for thin-layer mortar. If based on tests, 'the characteristic initial shear strength shall not be less than the declared value'.

In the absence of EN standards on EBM, the German and French standards are Europe's most established standards on EBM. DIN 18940, the German standard for designing load-bearing EBM, mentions that the bond must be 'sufficient for the intended use'. The standard refers to DIN 18946, the German standard for earth masonry mortars, where the characteristic adhesive shear strength without additional load must be at least 0.04 MPa when tested according to EN 1052-3 with reference sand-lime blocks. The mortar must have 'sufficient adhesion to the block' for non-loadbearing EBM. The French standard AFNOR XP P13-901 for earth blocks does not mention the bond strength.

2.3.2 Scientific studies

More specific values were found in academic research papers and manuscripts providing design guidelines. An overview of mean values for the flexural bond strength of various masonry unit and mortar combinations is outlined in **Table 5**. Although presented as mean values, the flexural bond strengths of unit-mortar combinations collected from various studies generally exceed the range of characteristic values for flexural strength parallel to bed joints as specified in Eurocode 6 (**Figure 5**). Even in studies incorporating stabilised EBM [35], [36], [40], the flexural bond strength can be higher than those used for masonry design calculations. However, comparing bond strength values should be done carefully due to varying moisture conditions and other testing parameters across the different studies.

Morton [21] reports that non-stabilised earth mortars using similar earth to that of earth blocks show relatively weak bond strength compared to conventional masonry, with values of around 0.0025 MPa. In traditional or vernacular construction, this seldom imposes issues due to the predominantly compressive nature of the loads, coupled with the relatively substantial dimensions and low slenderness ratios of masonry components. In contrast, modern architectural designs often favour slender elements with minimal constraints and high slenderness ratios, necessitating enhanced bond strength. Under these conditions, it may be necessary to improve bond strength, typically accomplished by incorporating additives. Earth mortars enhanced with additives such as starches, sugars, or lignosulfates can attain bond strengths of up to 0.25 MPa [21].

According to Walker [36], the characteristic bond strength is usually lower for stabilised earth blocks and mortars than the values commonly assumed in conventional masonry. However, some combinations in this study reached flexural bond strengths above 0.35 MPa. Lawrence et al. [44] developed a novel low-impact earth mortar stabilised with sodium silicate to be combined with unfired clay bricks. Within seven days, the characteristic bond strength was higher than the target strength of 0.2 MPa, corresponding to the highest design strength with failure parallel to bed joints specified in Eurocode 6. After 182 days, they reached values well above 0.4 MPa. All other studies on the flexural bond strength of EBM, except [24], used stabilised earth blocks combined with cement, cement-lime or earth-cement mortars. Venu Madhava Rao et al. [35] attained values approaching 0.3 MPa with cement mortar, while Venkatarama Reddy & Latha [40] reached values nearing 0.5 MPa with cement-lime mortar.

Fired brick masonry values were between 0.04 MPa and 0.42 MPa, while concrete block masonry ranged between 0.01 MPa and 0.58 MPa. Curiously, higher values are obtained by Costigan & Pavía [28] and Pavía & Hanley [39] for fired bricks with NHL mortar than studies combining fired bricks with cement, cement-lime mortar or earth-cement mortars. Singh and Munjal [49] conducted flexural and shear bond and masonry compressive strength tests on fired bricks and concrete blocks with cement and cement-lime mortar. They conclude that concrete block masonry has inferior bond strength to fired brick masonry due to less contact area at the brick-mortar interface. However, the fired bricks in this study were prewetted for 24 hours, while nothing is mentioned about soaking the concrete bricks. Extremely high values for concrete blocks combined with thin-layer polymer cement mortar were found by Tamboo et al. [50], reaching flexural bond strengths well beyond 1.3 MPa. However, calcium silicate blocks with thin-layer mortar were found below 0.2 MPa in the study conducted by Jonaitis et al. [51], while Gaggero & Esposito reached 0.54 MPa for calcium silicate blocks with cement mortar. As both studies measured the flexural strength parallel to bed joints on wallet specimens, these findings contradict the assumption of a doubling in strength when using thin-layer mortar in Eurocode 6.

3 Experimental results on bond strength

3.1 Characteristics of earth blocks

Most properties influencing the bond strength found in the literature were determined for the studied earth blocks and mortars. In determining absorptive properties, soaking the non-stabilised (F)MEBs and CEBs in water resulted in swift absorption and crumbling, which started shortly after one minute at 27% moisture content. Immersing the SCEBs did not cause any damage, and water absorption stabilised after a few hours. Assuming saturation after 24 hours of immersion, the SCEBs reach a moisture content of 9.6%. According to Sahu et al. [47], the optimum moisture content for maximum bond strength is around 75% of the masonry unit's saturation level. However, the moisture content at ~75% of the saturation level of the SCEBs is 7.2%, corresponding to a 25-minute soaking time of oven-dry specimens. This value is below the moisture content of 7.6% measured for SCEBs at ambient temperature and relative humidity. Hence, the optimum moisture content of the SCEBs studied was already obtained without prewetting them. However, the standard deviation of the moisture content of SCEBs is relatively high, fluctuating around 20% at different soaking times. Water absorption curves are shown for CEBs and SCEBs in **Figure 6**. The cross in (a) indicates where the first mass loss was measured due to dissolution. The horizontal line in (b) indicates the optimum moisture content for maximum bond strength according to [47], expressed as 75% of the block's 24-hour saturation level, and the intersection red dot in (b) indicates the corresponding moisture content for SCEBs. The IRA could also only be measured for SCEBs, and these results are much lower than the ones observed by Walker [36], which could be due to the industrial vibro-compaction process.

When testing the compressive strength of (F)MEBs, the blocks did not show brittle failure in extension, as observed in the (S)CEBs and generally all masonry units. Instead, vertical cracks appeared around the specimen, but the press did not detect a force drop and continued loading the specimen. Similar issues were observed by Fabbri et al. [52] for non-stabilised extruded earth blocks with low slenderness. They recommend considering these types of blocks as soil samples and employing the theories of soil mechanics instead of the usual brittle failure models. The proposed solutions to this problem are not yet well-established, and the comparison with (S)CEBs showing typical brittle failure should be maintained by following similar testing procedures. Therefore, the compressive strength for these blocks was calculated at the yield point, i.e. where the stress-strain diagram's slope changes. SCEBs show by far the highest compressive strength of 18.26 MPa, followed by MEBs and CEBs around 3.5 MPa, and FMEBs with the lowest strength of 2.4 MPa.

3.2 Characteristics of earth mortars

The studied earth mortars have various binder types leading to various consistencies: clay is the natural binder in the EM, the ECM and ESM are stabilised with an additional 8% cement and 10% sodium silicate by mass, respectively, and the EAM contains 1% methylcellulose. Water was added to the fresh mixture until good workability was obtained qualitatively before conducting the flow table test. Higher moisture contents generally lead to higher flow values, except for ESM, showing a meagre flow value of 111 mm for a moisture content similar to that of the other mortars. Although the flow of the EAM was more challenging to assess as part of it adhered to the inside of the mould, its flow is comparable to that of EM. Casting the mortar prisms was feasible by following the standard, except for the EAM, which adhered to the inside of the mould. After multiple tryouts, the EAM could be unmoulded when left inside the mould for at least seven days, covered by a cloth to absorb the top layer of water.

Linear shrinkage was highest for the EAM at 3.21%, followed closely by the EM, and lowest for ESM, approaching zero shrinkage. Curiously, the ECM showed a linear expansion of 1.53%, which could be attributed to shrinkage-compensating additives in the cement. Flexural and compressive strengths of the hardened mortars were highest for the EAM with 3.37 MPa and 1.57 MPa, respectively, followed closely by the EM. Unexpectedly, the ECM and ESM showed the lowest strengths, with values below 1 MPa for both the compressive and the flexural strength. Visually, the ECM turned white and flaky during the last two weeks of the hardening process, whereas the ESM showed white salt crystals at the prism’s edges. However, these aspects did not occur when casting the masonry couplets.

3.3 Flexural bond strength of untreated couplets

All combinations exhibited higher bond strength during preliminary tests when the couplets were prestressed, and the bed faces were prewetted for one second as recommended by the manufacturer. Consequently, these conditions are chosen as the reference bond strength and are henceforth indicated with a soaking duration of zero. The flexural bond strengths are summarised in **Table 6** and visualised in **Figure 7**.

The highest bond strengths are obtained by the EAM combined with MEBs and SCEBs, reaching above 0.4 MPa. Although the EAM also returns the highest bond strengths with FMEBs and CEBs compared to the other mortars, it is remarkably lower, with values just above 0.1 MPa. For FMEBs, this difference could be associated with the frog that increases the mortar volume. Since the EAM is destined to be applied as a thin-layer mortar, the difference could be attributed to the different drying conditions of mortar within the frog. Combining CEBs with EAM leads to similar results as with FMEBs. However, the actual bond strength may be much higher since the block failed by crushing or tension before bond failure occurred. Superior bond strength for MEBs with EAM without these types of failure may be attributed to the block's higher compressive strength and cohesion. Combined with SCEBs, a similar superior value may be due to the smoother surface of the blocks, which allows better contact and adhesion with a thin-layer mortar designed for uniform layer thickness.

Stabilisation of the earth mortar (EM) with sodium silicate (ESM) increases the bond strength for all block types. The ESM also shows the highest bond strengths for all block types after the EAM. It is highest at 0.14 MPa when combined with SCEBs. Combining the ESM with the non-stabilised earth blocks leads to values between 0.05 and 0.08 MPa. It must be noted that the compressive and flexural strength of the ESM were much lower than those of the EM, opposing most observations in the literature [35], [42], [43] where bond strength increases with mortar strength. Cement stabilisation (ECM) does not improve the bond strength for all block types and even lowers it with (S)CEBs. The highest bond strength with ECM is attributed to SCEBs with 0.08 MPa, while combined with the other blocks, the bond strength approaches zero. Such low bond strengths are consistent with observations by Morton [21] and may be due to a lack of mechanical interlock of hardened mortar in the pores of the block.

The non-stabilised EM shows remarkably higher bond strength with SCEBs than the non-stabilised earth blocks, yielding above 0.12 MPa. In contrast, the lowest observed bond strengths are attributed to (F)MEBs around 0.01 MPa. Slightly higher values are obtained with CEBs, possibly due to the different composition or production process. The compaction in MEBs is less thorough and uniform than in CEBs, which could lead to variations in material density and porosity and, thus, uneven mortar adhesion. Block stabilisation may further enhance this effect in the case of SCEBs.

With SCEBs, the bond strength is higher for all earth mortars than with non-stabilised earth blocks. Improved bond strength due to block stabilisation may be due to the lower porosity and, therefore, lower water absorption rates. This helps prevent premature drying of the mortar, ensuring that it remains sufficiently wet to enhance bond development over time. However, as multiple studies pointed out, it may also be related to the much higher compressive strength of SCEBs compared to the other blocks. The effect of block stabilisation could only be studied for CEBs since MEBs are typically made without adding stabilisers.

The bond wrench test prescribes various failure modes according to NBN EN 1052-5, and they can arise at the block-mortar interface (bond), in the block, or in the mortar (**Figure 8**). The distribution of failure modes for all specimens is given in **Table 7**. All failure modes occurred except for tension failure within the block for FMEBs and, additionally, block crushing for SCEBs. This indicates that even for high bond strengths, such as with the EAM, the SCEBs are more robust than the bond. Given that failure modes A2 and A6 are equal except for the presence of the frog and that failure modes A1, A2, and A3 are similar, representing failure at the block-mortar interface (bond), it can be said that bond failure is most present. By grouping A1-3, failure mode A4, i.e. tension failure within the mortar, is the second most present. A4 indicates that the tensile strength of the mortar is weaker than the bond strength. Failure mode A5, i.e. tension failure in the block, occurred once for a MEB-EAM couplet and a CEB-EAM couplet. This type of failure indicates that the bond strength is higher than the cohesion of the block itself. Failure mode A7, i.e. failure due to crushing at the earth block where clamped, occurred once for an FMEB-EAM couplet and twice for CEB-EAM couplets. Such failure is due to the local compressive resistance of the earth block where it is clamped, being weaker than the bond strength. This failure mode may also indicate that the stress where the block is clamped is not sufficiently distributed.

The failure modes of EM and ECM combined were mainly A1, A2 or A6, where the entire mortar layer remains on one of the bed faces. Couplets with ESM failed more by A3 and A4, where the mortar layer adheres to both bed faces or crumbles within the layer itself.

Couplets with EAM failed as per A4 in most cases, although the sparsity of the thin mortar layer made it more challenging to distinguish A3 from A4.

3.4 Flexural bond strength with prewetting earth blocks before laying

Since soaking the non-stabilised earth blocks for longer than one second can cause irreversible damage, studying the effect of PBL was only done with stabilised earth blocks. The flexural bond strength by prewetting the SCEBs for 1 and 15 minutes before laying is compared with the reference flexural bond strength with untreated blocks. The results are summarised in **Table 8** and visualised in **Figure 9**.

Despite the optimum moisture content of 75% saturation, according to Sahu et al. [47], which SCEBs already exceed without prewetting them, increased soaking durations usually show improved bond strength. The highest bond strength improvement by PBL is observed for the EM with 26% at 1 min soaking duration, followed by EAM with 17% and ECM with 14% at 15 min. However, these changes should be taken cautiously due to the high standard deviation, especially for the EM and EAM. Decreased bond strength is observed for the ESM with 26% at 1 min soaking and 34% at 15 min, suggesting that the optimum moisture content of the SCEBs combined with this mortar lies between 0 and 1 min soaking. An unusual scenario is observable with the EAM: the bond strength is decreased by 16% at 1 min soaking and increased by 18% at 15 min. This may suggest that PBL with this type of mortar does not follow the typical curve characterised by an increase in bond strength up to the optimum moisture content, followed by a decrease beyond it [35], [36], [47]. Then again, the high spreading of results, especially at 1 min soaking, does not guarantee a significant change in bond strength for the EAM. The EM shows higher bond strength improvement at 1 min than at 15 min soaking duration. This may be attributed to the SCEBs being excessively saturated for bonding compatibility with the EM. An overly saturated block may cause the EM to absorb excess moisture from the blocks and dilute the mortar layer on the surface, delaying the bond development. This may imply that the optimum moisture content of the SCEBs combined with EM lies between 1 and 15 min soaking.

The failure patterns of couplets with prewetted SCEBs are relatively similar to those with untreated SCEBs (**Table 9**). Failure occurs due to tension at the block-mortar interface (A1-A3) for 71% of tested specimens and within the mortar (A4) for 25% of tested specimens. Only one specimen with EAM failed due to local block crushing (A7), where the upper block is clamped. Failure mode A3 occurs more when the blocks are prewetted: 63% compared to 25% with untreated SCEBs. A possible explanation lies in the differential moisture distribution within the prewetted blocks. The density variations in the blocks can cause uneven water absorption, leading to variations in drying or curing of the mortar and, therefore, to variations in bond development across the bed faces. A complete shift from A1 to A3 is observable for ECM at 1 min soaking, while EM shifts to A3 at 15 min. The failure mode due to tension within the block (A5) did not occur for specimens with PBL, as for untreated couplets.

3.5 Flexural bond strength with wetting masonry before testing

As for the effect of PBL on the bond strength, studying the impact of WBR of EBM couplets on the bond strength was only possible for SCEB couplets since non-stabilised earth blocks would become irrevocably damaged when immersed in water. The flexural bond strength by wetting the SCEB couplets for 1 and 15 minutes before testing is compared with the reference flexural bond strength with untreated blocks. The results of WBR are summarised in **Table 10** and visualised in **Figure 10.**

The highest bond strength reduction by WBR is observed for the EM with 74% at 1 min soaking duration and 100% at 15 min. It should be noted that the EM was largely dissolved at 15 min soaking, making it impossible to perform the bond wrench test. Hence, the bond strength could have approached zero sometime before lifting the couplet from the water tray. The ESM shows the second highest decrease with 77% at 1 min soaking and 87% at 15 min. Lower decreases are observed with the ECM, with a 16% decrease at 1 min and 62% at 15 min. As with the effect of PBL, a different scenario is observed with the EAM compared to the other mortars: the bond strength increases by WBR with 21% at 1 min and 9% at 15 min. However, the very high standard deviation at 15 min soaking indicates that an increase or a decrease is possible compared to untreated couplets.

The failure modes of wet SCEB couplets are relatively similar to those of untreated couplets (**Table 11**). Block-mortar interface failures (A1-A3) are the most representative, with 58% of tested specimens, followed by 25% failing due to tension in the mortar (A4). One specimen with EAM failed due to block crushing (A7) at the clamping area. It must be noted that the three specimens with EM at 15 min soaking could not be attributed to any failure mode, given that the mortar was mostly dissolved. As for untreated couplets and couplets with prewetted SCEBs, failure mode A5 due to tension within the block did not occur for wet SCEB couplets.

4 Retrieving earth blocks from masonry couplets

4.1 Effort needed for deconstruction and cleaning

On every fourth couplet per designation (n = 1), the upper block was manually removed, consecutively trying the following techniques: 1. wrenching by hand; 2. wrenching using a small clamp; 3. punching the block using a rubber hammer; 4. chipping the mortar using a cold chisel. It was found that all specimens could be separated before trying the fourth technique, i.e. chipping. The technique and effort by which the block could be removed and the corresponding failure mode can be found in **Table 12** for untreated couplets and **Table 13** for SCEB couplets with PBL and WBR. The effort of cleaning the blocks (n = 8) was evaluated for the couplets separated by the bond wrench test (n = 3) and by manual separation (n = 1). The mortar from both blocks of the couplet was removed, and half was cleaned by scraping (n = 4), while the other half was cleaned by brushing (n = 4).

The non-stabilised earth blocks can easily be separated by hand when combined with the EM and ECM. Moreover, the mortar often comes off in large chunks, resulting in a fast cleaning process by scraping. Cleaning MEBs is easier and quicker than FMEBs due to the absence of a frog. Much effort was required to separate FMEBs from the ESM by hand, while this was not possible for MEBs and CEBs, needing to switch to wrenching by clamp. The same can be said for the EAM, except with CEBs. The clamp did not suffice, and maximal effort was needed to separate the CEBs by hammering the upper block. Moreover, intensive hammering caused failure by crushing the block before bond failure. Cleaning the CEBs required minimal effort by scraping or brushing, thanks to the smooth block surface. Scraping off the EAM is hard for MEBs and almost impossible for FMEBs due to less accessible mortar in the frog.

The untreated SCEB couplets were impossible to separate by hand, and the EM and ECM required little effort when wrenching using a small clamp. The punching technique was needed with the ESM and EAM, requiring very little and very much effort, respectively. Cleaning the SCEBs was fairly easy for all mortars except with the EAM. When applying PBL with SCEB-EM couplets, nothing changes regarding the techniques and effort needed. However, when applying WBR, wrenching by hand required virtually no effort due to the EM mainly being dissolved. The same accounts for SCEB-ECM couplets, but WBR still requires a small effort from clamping. PBL causes the SCEB-ESM couplets to switch from clamping to wrenching by hand at a 15-minute soaking duration. WBR makes it possible to wrench these couplets by hand at 1 minute of soaking. For SCEB-EAM couplets, both PBL and WBR required maximal separation effort by hammering, which caused the SCEBs with PBL to fail by crushing before bond failure. Scraping off the mortar was sometimes more difficult on wet SCEBs than dry ones, while brushing was always easier.

4.2 Deconstruction effort related to bond strength

Figure 11 visualises the relation between the flexural bond strength and the effort needed to separate the blocks from the mortar for untreated couplets of all block-mortar combinations and SCEB couplets with PBL and WBR, respectively. It shows that when the bond strength increases, the effort needed using the same technique increases or makes it necessary to switch to another tool for which the separation requires less effort. It also shows that specimens with (F)MEBs can still be separated using a more effort-intensive technique for the same bond strength, whereas specimens with SCEBs need a less effort-intensive technique. For instance, MEB-EAM couplets with a bond strength above 0.4 MPa can be separated using little effort by wrenching with a clamp, while SCEB-EAM couplets require very much effort by punching with a hammer. This can be attributed to the larger bonding surface of (S)CEBs, exerting more net bond-breaking resistance than the (F)MEBs. However, it should be noted that no exact relation between the bond strength and the effort/technique can be established since the effort was evaluated qualitatively. For instance, the SCEB-ESM couplet with 15 min PBL attained a bond strength approaching 0.1 MPa and was separable by hand, while the SCEB-ECM couplet with 15 min WBR and a bond strength of 0.03 MPa was not. This may indicate that the effort exerted by hand on the first couplet was much higher than in the latter's case, suggesting a large spread in the effort assessment.

5 Discussion on bond strength and reclamation

5.1 The need for establishing bond strength benchmarks

Conventional masonry is typically designed to achieve high strength and durability. In engineering, bond strength maximisation is pursued to enhance the masonry's ability to withstand in-plane and out-of-plane bending and in-plane forces generating tensile and shear stresses. However, high bond strengths can complicate the separation of masonry units from the mortar for reclamation purposes. Therefore, to Design for Deconstruction (DfD), a balance must be maintained to achieve the minimum bond strength required for specific building applications while not exceeding a level that impedes reclamation.

The results show that high bond strengths do not benefit earth block reclamation. Indeed, combining stabilised earth blocks with a thin-layer earth-adhesive mortar leads to mean flexural bond strengths up to 0.5 MPa and block failure at separation. Meanwhile, the highest characteristic flexural strength parallel to bed joints in Eurocode 6 is specified as 0.2 MPa. Separation requires more effort using the same technique as the bond strength increases, or it causes the blocks to fail before bond failure occurs. Although generalisations to full-scale masonry walls are premature from this investigation, such damage and effort-intensiveness will likely discourage practitioners from considering reclamation.

On the other hand, intermediate bond strengths under 0.2 MPa allowed for deconstruction by wrenching using a small clamp. Low bond strengths under 0.1 MPa were sometimes even separable by hand or demanded little effort using a clamp. Furthermore, block-mortar combinations with low bond strengths generally lead to failure modes that are beneficial for reclamation and reduce the cleaning effort. Non-stabilised earth blocks combined with non-stabilised and stabilised earth mortars can lead to flexural bond strength values below the lower boundary of 0.05 MPa for masonry design, according to Eurocode 6. However, while such low bond strength values may not allow for the slender wall design typically sought after in contemporary architecture, they have been empirically validated throughout history. In modern architecture, they may be sufficient when applied as double-layered bonding patterns for structural applications or as wooden-frame infill for non-loadbearing walls.

The European standards lack information about these application types and their requirements, stating frequently that the bond strength 'shall be sufficient for the intended application'. Then again, this 'sufficiency' generally does not correspond to the values collected from the literature, as these are usually much higher than necessary. For these reasons, the authors encourage considering bond strength sufficiency for specific masonry applications and perceiving low bond strengths as a potential benefit for reclamation rather than a structural shortcoming.

5.2 Weakening the bond strength for reclamation

While previous studies have shown that bond strength can be increased by prewetting the masonry unit before laying (PBL), this study is the first to indicate that under certain circumstances, the bond strength could also be decreased for reuse purposes by wetting the masonry before reclaiming (WBR). This was done by immersing the masonry couplets with stabilised earth blocks before testing. However, it must be said that the purpose and process of PBL and WBR are quite different. PBL aims to improve bond development by varying the moisture content of the blocks, while WBR seeks to weaken the established bond by changing the moisture content of both the blocks and the mortar. The purpose of PBL was not obtained in the case of earth-silicate mortar, as the bond strength decreased with increased soaking duration. Similarly, the purpose of WBR was not obtained in the case of earth-adhesive mortar, as the bond strength increased with increased soaking duration. Therefore, although studying more soaking durations should confirm this trend, applying PBL for earth-silicate mortars and WBR for earth-adhesive mortars is not recommended.

Applying WBR to masonry with earth mortar and earth-silicate mortar is highly recommended when opting for DfD. Then again, fully immersing the masonry before deconstruction is practically challenging. Therefore, exploring the practical feasibility of WBR, such as by spraying, soaking, or permeating, is encouraged as a promising research track. Moreover, it was not investigated how soaking for a shorter duration, followed by waiting for a longer duration, would affect the bond strength. As further water penetration during waiting periods after soaking may further weaken the bonds, the authors suggest investigating the effect of WBR combined with waiting periods. Furthermore, since the bond morphology is only known for earth-cement mortars, the authors propose investigating bond development at the block surface at a microscopical level for non-stabilised earth mortar, earth-silicate mortar and earth-adhesive mortar to provide a better understanding of the underlying mechanisms and their interactions with water.

5.3 Methodological reflections on the reclamation test

As this is the first study to experimentally assess the reclamation potential of earth blocks and possibly masonry units in general, some limitations and recommendations of the methodological approach are given. First, the assessment of the deconstruction effort was based on the iteration between several techniques to determine when a given technique would not suffice to separate the blocks from the mortar. It is important to mention that for low bond strengths, punching the upper block using a hammer may require less effort and be more efficient than wrenching by hand or using a clamp. The same reasoning can be applied to the specimens with high bond strengths: chipping using a cold chisel or powered tools would likely have made it easier to separate the blocks than punching with a hammer. To better compare the effort across various masonry configurations, the authors recommend conducting a similar study using a single tool or technique, such as a hammer drill for deconstruction and a powered brushing tool for cleaning.

Second, the deconstruction and cleaning techniques were studied on masonry couplets with one mortar layer, while in real masonry, the blocks are confined within four mortar layers. Hence, in addition to an increased net bonding surface, the movement limitation of the blocks could significantly increase the effort required for deconstruction, make it more prone to damage and even hinder the use of some techniques. Therefore, the authors suggest investigating the reclamation rates and labour intensity at the full masonry scale.

Third, it must be noted that the bond wrench test is a quasi-static testing method, while manual separation induces various mechanical interactions. Wrenching by hand or by clamp most resembles the bond wrench test. However, the action in manual wrenching is exerted more instantaneously, which may cause different resistance and failure modes. Punching or chipping will likely induce more shear stresses along the block-mortar interface than wrenching techniques and cause additional impact stresses, generating inertial effects. It would, therefore, be interesting to compare the shear and flexural bond strength with deconstruction techniques to determine the weakest link in the masonry and study the mechanical interactions of a given technique with the masonry.

6 Conclusions

This study conducted a literature review on masonry bond strength before characterising the flexural bond strength of sixteen earth block-mortar combinations using the bond wrench test. The reclamation potential of these combinations was then assessed using manual deconstruction and cleaning techniques on masonry couplets. Additionally, the influence of prewetting stabilised earth blocks before laying and wetting masonry with stabilised earth blocks before reclamation was evaluated. These are the main findings and implications:

- The studied earth block-mortar combinations can be manually reclaimed with relatively little effort using standard tools, except for (stabilised) compressed earth blocks with the earth-adhesive mortar, which cause block failure at separation.
- All combinations generally exhibit low to intermediate flexural bond strengths, except for those paired with the thin-layer earth-adhesive mortar, demonstrating exceptionally high values.

- The bond strength can be reduced to facilitate reclamation by wetting the masonry with stabilised earth blocks, except when combined with the earth-adhesive mortar. The effect is most pronounced with earth mortar and earth-silicate mortar.
- The bond strength can, to a lesser extent, be increased by prewetting stabilised earth blocks before laying, except when combined with the earth-silicate mortar.
- Flexural bond strengths of conventional masonry reported in studies are often significantly higher than those prescribed in masonry design standards, potentially hindering the possibility of reclamation.
- Normative documents lack benchmarks on bond strengths required for specific building applications, which could stimulate a balance between adequate performance with bond strengths low enough to facilitate reclamation.

These outcomes offer a new perspective on bond strength as an indicator of reclamation potential and highlight the technical feasibility of retrieving earth blocks from the masonry. However, further research is needed before considering earth block reclamation as an alternative end-of-life scenario to conventional demolition. The bond strength and other technical properties of reclaimed earth blocks should be investigated to validate their fitness for reuse, especially after sustained loading and weathering. Furthermore, evaluating reclamation rates and the labour intensity of earth block reclamation at a larger masonry scale is crucial for weighing the economic, organisational and environmental aspects of reuse compared to recycling.

Data availability

Experimental data used to support the findings of this research are made available by the corresponding author upon request.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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