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Experimentally determined material properties of stabilised compressed earth block masonry

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Abstract

This study presents an experimental investigation of the mechanical behaviour of an earthen masonry system composed of cement-free stabilised compressed earth blocks (CEBs) and earthen mortar. The test program included compressive strength tests on individual masonry components, shear bond tests under varying pre-compression levels, and compressive strength tests on wall elements with horizontal and inclined bed joints.
The results show that the strength of a CEB does not allow for a prediction of the masonry strength. The strength test of a single CEB leads to an overestimation and interactions between units and mortar influence structural response. The initial shear strength value deducted from shear bond tests shows considerable variation depending on the precompression levels considered for evaluation, limiting the suitability for deriving design parameters. In contrast, wall tests with inclined bed joints provide a more consistent representation of the combined normal–shear stress state and allow reliable assessment of strength and failure mechanisms.
A pronounced reduction in compressive strength was observed with increasing bed joint inclination, followed by a plateau up to the internal friction angle and a subsequent drop to very low strength levels corresponding to sliding failure. This behaviour is comparable to that observed in conventional masonry with fired bricks. The findings indicate that established design approaches, such as SIA 266, may be applicable to earthen masonry, provided material-specific aspects are considered. Further investigations on additional diverse earthen raw materials are required to generalise the results.

Keywords: Stabilised compressed earth block masonry, Material properties, Test methods, Shear bond tests, Wall tests with inclined bed joints.

1 Introduction

Earthen masonry is increasingly considered in sustainable construction due to its low environmental impact and use of local materials. For broader application, however, its structural safety in load-bearing functions must be better understood. A key limitation remains the lack of studies and regulations on the load bearing behaviour. Specifically, it is necessary to assess to what extent the mechanical models established for conventional masonry design (e.g., ideal-plastic stress fields) are valid for earthen masonry.

Earthen masonry is one of the most widely used structural systems in contemporary earthen construction and is particularly common in Germany. The recent introduction of the German standard DIN 18940 in 2023 [1] represents an important milestone, as it provides the first regulatory framework for the design of vertically load-bearing earthen masonry and thereby facilitates its broader application in practice.

A major contribution to the development of this standard resulted from Wiehle et al. [2]. The research included tests on masonry units, wall elements, and full-scale wall systems, with a particular focus on the influence of ambient humidity on compressive strength. The findings led to the introduction of an environmental humidity factor used to account for the moisture dependence of mechanical properties in the design provisions of DIN 18940.

Previous studies have shown that the structural behaviour of earthen masonry is broadly comparable to that of conventional masonry constructed with fired clay bricks. Comparable behaviour has been observed regarding compressive strength, deformation characteristics, and typical failure mechanisms under vertical loading [3]. However, the pronounced sensitivity to moisture represents

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a key difference between earthen materials and conventional masonry materials and must be considered in structural design.

The influence of moisture on the mechanical behaviour of earthen materials has therefore been the subject of several research studies, as by Q.-B. Bui et al. [4] on rammed earth or by F. Champiré et al. [5] demonstrated the effect of relative humidity during the service life of compacted earth. These studies highlight the importance of considering moisture conditions when evaluating the structural behaviour of earthen building materials.

Besides compressive behaviour and moisture effects, the shear behaviour of earthen masonry represents another important aspect for structural design, several studies have addressed (for example [6] and [7]). Experimental investigations carried out by Becker et al. [8] focused on determining key parameters required for shear design, including the tensile strength of masonry units (f_t), the initial shear strength (f_{v0}), and the friction coefficient (μ) according to (acc. to) EN 1052-3 [9]. Additional shear tests conducted at BAM [10] also contributed to the understanding of the shear behaviour of earthen masonry systems. However, these studies emphasize the need for further investigations to establish a more comprehensive experimental database and to examine the shear behaviour of larger masonry elements.

Within the larger framework of the Innosuisse Flagship Project Think Earth, the present study aims to expand the experimental database of earthen masonry by determining the key material parameters required for structural design. It particularly investigates whether the design concepts established for conventional masonry in the Swiss standard SIA 266 [11] can be applied to earthen masonry. The environmental humidity factor proposed by previous research is adopted, while further investigations on moisture dependence are outside the scope of this work. The experimental program also evaluates the suitability of different testing methods for earthen masonry systems.

2 Materials and methods

The experimental program consisted of three test series: characterization of individual masonry components, shear bond testing to determine initial shear strength, and friction coefficient, and testing of walls with horizontal and inclined bed joints under vertical loading. Examples of specimens from the three test series are illustrated in Figure 1.

2.1 CEB and mortar testing

Both the compressed earth blocks (CEBs) and the earthen mortar were manufactured from excavated soil and stabilised with a mineral-based admixture (Oxabrick® Loko, Oxara). The stabilization is 2 % in the CEBs and approximately 5 % in the mortar. Both components are completely cement-free, with the clay fraction in the soil acting as the primary binder in combination with the minor stabilization.

The CEBs (Oxabloc S) were industrially produced by vibro compaction by Terrabloc with a maximum particle size of 16 mm. The blocks were produced about half a year in advance and conditioned for 10 days at 20 °C and 50 % relative humidity prior to testing to achieve equilibrium moisture content.

The earthen mortar was freshly prepared acc. to EN 1015-11 [12] from the same soil as the units. The recipe per 10 L consisted of 12 kg clay, 8.5 kg sand, 1 kg Oxabrick® Loko, and 1.7 L water. Dry components were mixed for 1 minute, followed by 3 minutes of wet mixing with continuous water addition. Spread tests were carried out aiming for 11–12 cm, and prisms were cast for compressive strength testing. The mortar prism samples were conditioned at 20 °C and 50 % relative humidity.

Three different test configurations were used to characterise the CEB compressive strength. At HSLU, the confined compressive strength was determined by testing individual horizontal blocks, in the direction of compaction during production. The procedure was carried out in general accordance with SN EN 12390-3 [13]. In the laboratories of Oxara AG the block compressive strength was determined acc. to DIN 18945 [14], by testing two half blocks joined with a cement mortar. To assess the unconfined compressive strength, the block was tested in vertical direction. It is expected that the middle third of the block is not confined by the supports of the testing machine. This loading configuration is not defined in the standard. All compressive strength tests on the masonry units were performed at a loading rate of 3 kN/s.

The details of the test program for the masonry components, including specimen type, number of tests per condition, measured properties, and applicable standards, are summarised in Table 1.

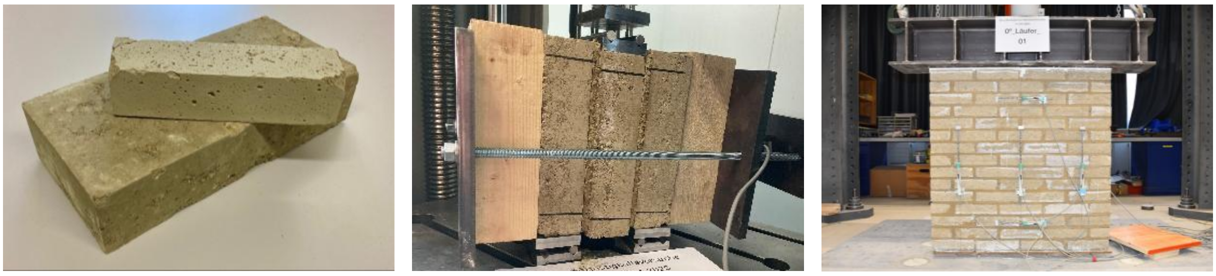
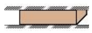
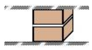
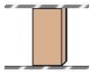


Figure 1. Test specimen samples (left to right): masonry components, three-block-specimen, and masonry.

Table 1. Test programme of the masonry components.

Sample	Specimen LxWxH [mm]	No. of tests per condition	Property	Norm
CEB (single)	250x120x60	 **3**	Confined compressive strength f_b	adapt. from SN EN 12390-3
CEB (two half)	125x120x130	 **2**	Block compressive strength f_b	acc. to DIN 18945
CEB (vertical)	120x60x250	 **4**	Unconfined compressive strength f_b	adapt. from SN EN 12390-3
Mortar	160x40x40	**40**	Mortar compressive strength f_m	acc. to EN 1015-11

2.2 Shear bond tests

The initial shear strength of the masonry was determined on two experimental series: one with pre-wetting of the bearing surfaces and one without. In the "wet" series, the contact surfaces of the units were pre-wetted by briefly immersing them in clean water before laying. Specimens were prepared as three-unit prisms of type A acc. to SN EN 1052-3 [9] with total dimensions of 20 × 12 × 25 cm (L × W × H). Mortar was mixed no longer than 2 h before casting to ensure workability.

Immediately after preparation, the specimens were preloaded acc. to SN EN 1052-3 to simulate initial stress conditions. The prisms were then stored undisturbed at 20.1 °C and 55.1 % relative humidity and covered with foil during the first seven days to prevent rapid drying. All specimens were tested at an age of 28 ± 1 days. Mortar compressive strength was determined in parallel acc. to EN 1015-11.

For the shear bond tests, a three-block specimen is subjected to a normal precompression (N), applied as a stress in N/mm². The shear force (F) required to displace the central unit is measured, and the corresponding shear strength (f_{vi}) is calculated. The relationship between shear strength and normal stress is described by the Mohr–Coulomb criterion:

$$f_{vi} = f_{v0} + \mu \cdot \sigma_n$$

where (f_{v0}) is the initial shear strength, (μ) the friction coefficient, and (σ_n) the normal stress in the bed joint.

In total six precompression levels, referred to as load stages (LS), were applied, as summarised in Table 2. Two LS were chosen acc. to DIN 18946 [15], excluding the LS of 0.05 N/mm^2, as it was technically not possible. Higher LS commonly used for conventional masonry were included following SIA (SN EN 1052-3). Some intermediate LS were chosen, without recommendation by a norm.

Table 2. Overview of the investigated LS.

LS [N/mm^2]	According to the standard		Data combination for evaluation		
	DIN 18946	**SIA**	**all LS 6**	**lowest 3**	**highest 3**
0.10	X		X	X	
0.20	X	X	X	X	
0.35			X	X	
0.60		X	X		X
0.80			X		X
1.00		X	X		X

All tests were conducted on a Zwick/Roell AllroundLine testing machine under displacement control at a loading rate of 2.5 mm/min. The evolution of the applied precompression (N) during the test was measured using a separate load cell. Since the two load cells were measured independently, the corresponding data were manually aligned based on their respective measurement signals for subsequent evaluation.

The details of the test program for the shear bond tests, including specimen type, number of tests per condition, measured properties, and applicable standards, are summarised in Table 3.

Table 3. Test program of the shear bond tests.

Sample	Specimen LxWxH [mm]	Number of samples per LS		Property	Norm
Three-bloc-specimen 200x120x250		Pre-wetted:	3	Initial shear strength f_{v0}	SN EN 1052-3
		Dry:	3	Friction coefficient μ	Method A

2.3 Wall tests

Prior to the main experimental program, a preliminary test series commissioned by Oxara and Terrabloc was conducted at p+f expert ag. This series is referred to as the p+f series and is also reported here. In this series, compressive strengths perpendicular to the bed joints (f_x) and perpendicular to the head joints (f_y, with minor lateral confinement) of masonry walls were determined acc. to SIA 266/1 [16] and SN EN 1052-1 [17]. Three specimens were tested for each configuration. The CEB used differed slightly from those tested in the HSLU study with respect to specimen dimensions (Oxabloc M) of 29.5 x 14 x 9 cm. Stone strength and mortar strength are comparable (block = 11.8 MPa, mortar 5.4 MPa) see Table 5.

In the HSLU study, two masonry systems were examined: a Stretcher wall with a thickness of one block and an English bond wall with a thickness of two blocks. The influence of the bed joint inclination angle (α) on the load-bearing behaviour was investigated using walls with inclined bed joints. For the stretcher bond, α = 0°, 15°, 30°, and 45° were tested, while for the English bond α = 0°, 30°, and 45° were investigated. Two specimens were tested for each inclination angle. For the English bond with α = 45°, three specimens were available, including one preliminary test that showed consistent behaviour and was therefore included in the evaluation.

The walls were constructed using mortar not older than 2 hours after mixing. The masonry units were pre-wetted prior to laying, and the bed joints were constructed with an average thickness of approximately 10 mm. To ensure accurate reproduction of the inclined joints, the walls were built in a formwork using a paper template.

The wall elements were removed from the formwork approximately two days after construction and stored for at least 28 days before testing. During this period. The average temperature was 18.4 °C and the average relative humidity 52.0 %.

The deformation behaviour of the wall–loading system was measured using displacement transducers installed on the load distribution beam and on the wall surface. In total, eleven sensors were placed on the wall to record vertical, horizontal, and diagonal deformations as shown in Figure 2.

Prior to testing, a 10 mm gypsum levelling layer was applied to the top surface of each wall to ensure uniform load transfer. Flat steel plates with Teflon sliding layers were used at the wall head and base to allow lateral deformation and to approximate a uniaxial stress state. The walls were tested under vertical compression using a load distribution beam. Loading was applied at an approximately constant rate of 0.2 kN/s until failure. Crack development and the final failure mode were documented using digital photography. The modulus of elasticity was determined as the secant modulus at 30 % of the ultimate load.

The details of the test program for the two series of wall tests, including specimen type, number of tests per condition, measured properties, and applicable standards, are summarised in Table 4.

3 Results

3.1 Masonry components

The compressive strength of the used stabilised masonry units and mortar are listed in Table 5. The CEBs exhibit a compressive strength at the upper end of the typical strength range for similar earthen building materials, as used in the shear bond tests conducted by Becker et al. [18] or in the research from Wiehle et. al. [2]. However, a considerable variation in compressive strength is observed depending on the testing method, with values ranging from 11.3 N/mm² (single) to 7.9 N/mm² (two half, acc. to DIN) and 3.1 N/mm² (vertical).

3.2 Shear strength tests

The results of the initial shear strength tests are summarised in Table 6. Specimens were evaluated at six precompression levels (LS: 0.1, 0.2, 0.35, 0.6, 0.8, and 1.0 N/mm²). Figure 3a) shows all individual test results for both series (dry- and wet-laid), together with their corresponding mean values. The wet-laid samples exhibit slightly higher shear strengths and friction coefficients across most LS compared to the dry-laid samples, although these differences are small and may not be statistically meaningful. A statistical comparison (F-test, confidence level 0.932) indicates that the two datasets could be attributed to the same population.

Nevertheless, dry-laid specimens tended to disintegrate more easily during handling, suggesting that pre-wetting the blocks is advisable, in line with findings by Miccoli et al. [19].

For the wet-laid series, different evaluations based on selected LS show a wide range of results (see Figure 3b). Considering the lowest three LS (adapted from DIN 18946) yields an initial shear strength (f_{v0}) of 0.09 N/mm². Using the SIA-based evaluation, the initial shear strength is 0.19 N/mm² with a friction coefficient (μ) of 0.8. Evaluating the highest three LS gives f_{v0} = 0.06 N/mm² and μ = 0.96, corresponding to a friction angle (φ) of 43.8°. Overall, the derived friction angles vary considerably, from 38.7° to 49.2°, highlighting the strong dependence of the shear parameters on the precompression levels considered.

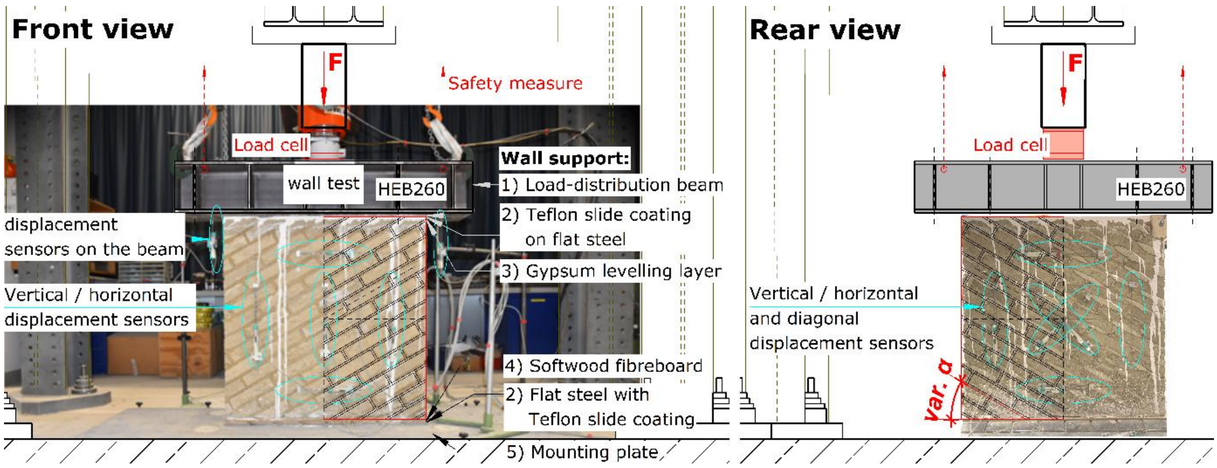


Figure 2. Test setup: a) Front view; b) Rear view.

Table 4. Test program of the masonry wall tests.

Sample	Specimen LxWxH [mm]	Number of tests per bed joint inclination	Property	Norm
Series 1: p+f				
Masonry element f_x	600x140x707	3	Masonry strength f_x Modulus of elasticity E_x	according to SN EN 1052-1
Masonry element f_y	400x140x1060	3	Masonry strength f_y	according to SIA 266/1
Series 2: HSLU				
Masonry **Stretcher**	1040x120x1040 00°	2	Masonry strength f_x Modulus of elasticity E_x	adapted from SN EN 1052-1
Inclined bed joints	15° 30° 45°	2 2 2	Masonry strength f_α Modulus of elasticity E_α	
Masonry **English bond**	1040x120x1040 00°	2	Masonry strength f_x Modulus of elasticity E_x	
Inclined bed joints	30° 45°	2 3	Masonry strength f_α Modulus of elasticity E_α	

Table 5. Strength test results of masonry components.

Sample	Compressive strength [N/mm²]	Standard deviation *s* [N/mm²]	Coefficient of variation *var.* [%]
CEB (single)	11.3	1.03	9.2
CEB (two half)	7.9	-[a]	-[a]
CEB (vertical)	3.1	0.62	20.5
Mortar	5.4	0.56	10.5

[a] insufficient data for statistical analysis

Table 6. Results of the shear bond tests.

Parameter	Term (LS [MPa])	Dry-laid (all: 0.1; 0.2; 0.35; 0.6; 0.8; 1.0)	Wet-laid (all: 0.1; 0.2; 0.35; 0.6; 0.8; 1.0)	Wet-laid (lowest 3: 0.1; 0.2; 0.35)	Wet-laid (acc. to SIA: 0.2; 0.6; 1.0)	Wet-laid (highest 3: 0.6; 0.8; 1.0)
Initial shear strength	f_{v0} [N/mm²]	0.14	0.16	0.09	0.19	0.06
Friction coefficient	μ [-]	0.83	0.86	1.16	0.80	0.96
Friction angle	φ [°]	39.7	40.7	49.2	38.7	43.8
Standard deviation	*s* [-]	0.09	0.13	0.18	0.10	0.08
Coefficient of variation	*var.* [%]	8.4	13.0	17.2	10.5	7.7

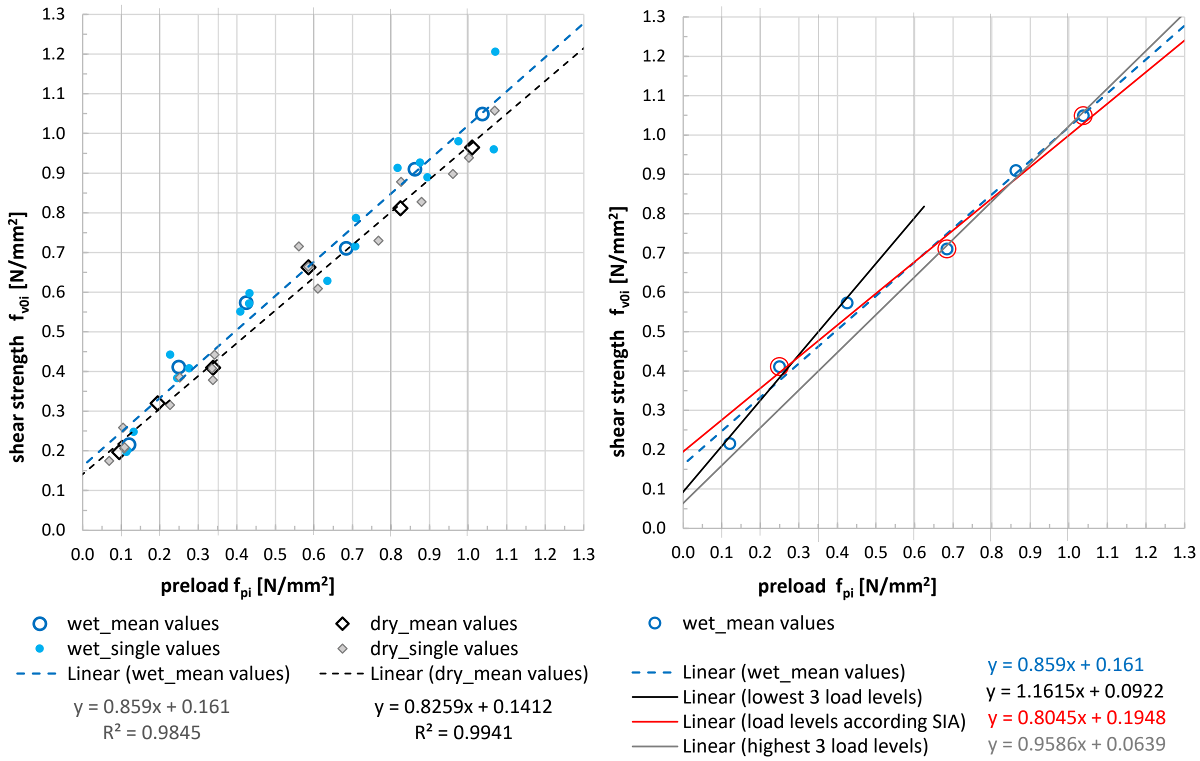


Figure 3. a) Results of the shear strength tests; b) evaluation on different precompression levels.

3.3 Compression test on wall elements

The results of the p+f series are summarised in Table 7. The compressive strength perpendicular to the head joints (f_y) was found to be higher than the compressive strength perpendicular to the bed joints (f_x).

The results of the wall tests conducted at HSLU are summarised in Table 8. For walls with horizontal bed joints (α = 0°), the stretcher bond system exhibited a mean compressive strength of 3.21 N/mm², whereas the English bond system reached 2.62 N/mm². This corresponds to a reduction factor of $v = 0.82$ for the English bond relative to the stretcher bond configuration.

With increasing bed joint inclination angle (α), a progressive reduction in compressive strength was observed for both masonry systems. In general, the English bond specimens exhibited a softer deformation behaviour compared to the stretcher bond walls. One stretcher bond specimen showed a very sudden failure, characterized by a compressive strain at fracture of 3.28 ‰.

For the Stretcher system, an approximately linear elastic behaviour can be observed up to about 60 % of the ultimate load, in agreement with the assumption of a linear elastic material law for masonry at moderate stress levels. For the English bond the linear elastic behaviour shows up to about 50%. The stress–strain response shows a pronounced dependence on the bed joint inclination angle (α). With increasing α, the curves become progressively flatter, indicating a reduction in stiffness and a softer structural response, accompanied by lower ultimate stresses.

Table 7. Series 1: p+f; Compressive strength f_x and f_y [N/mm²] of wall elements (mean values).

Wall elements	Compressive strength f_x or f_y [N/mm²]	Standard deviation s [N/mm²]	Coefficient of variation *var.* [%]
00° (f_x)	2.6	0.06	2.2
90° (f_y)	2.9	0.20	6.9

Table 8. Series 2 (at HSLU); Compressive strength f_α [N/mm²] of wall elements depending on their bed joint inclination (mean values).

Wall elements	Compressive strength f_α [N/mm²]	Modulus of elasticity E_α [N/mm²]	Compressive strain at fracture ε_y [‰]
Stretcher			
00° ($f_{x.\alpha}$)	3.21	2’200	3.28
15°	2.00	2’300	3.92
30°	2.00	2’000	6.62
45°	1.11	3’100	6.04
English Bond			
00°	2.62	1’500	5.21
30°	1.62	1’900	3.47
45°	1.20	1’400	4.35

Compared to the Stretcher, the English Bond, exhibits a generally softer behaviour and a larger scatter in stiffness, consistent with the results obtained from the vertical compression tests with horizontal bed joints. The wall specimens with α = 45° show a particularly large scatter in the stress–strain response, reflecting the strong reduction in compressive strength for inclination angles exceeding the internal friction angle (φ). In addition, specimens reaching higher ultimate stresses tend to exhibit more brittle failure behaviour, while the English Bond specimens reach ultimate strains in the order of 3–4 ‰.

For reference, Figure 4 shows the stress–strain curves obtained from the wall tests with inclined bed joints for the Stretcher (top, a) and the English Bond (bottom, b). The diagrams relate the applied principal compressive stress (σ_n) to the corresponding vertical strain (ε_y).

The changes in stress–strain behaviour are also reflected in the crack patterns of the wall elements. Crack patterns were determined from high-resolution photographs taken immediately before failure. Visible cracks were manually traced using a drawing software based on the photographic documentation to obtain a schematic representation of the crack development.

For horizontal bed joints (α = 0°), the main cracks develop predominantly in the vertical direction. As the inclination angle increases, the cracks progressively rotate towards the direction of the bed joints. At small inclinations, a local shear failure of the individual blocks is visible, with characteristic stepped cracks propagating along the bed and head joints and through the blocks. For α = 45°, most cracks develop along the inclined joints, indicating sliding failure. These observations are illustrated in Figure 5 using superimposed crack patterns.

4 Discussion

The relation between the masonry unit strengths obtained from standard tests on single components and the strength obtained from masonry wall testing requires further consideration. Although both the compressive strength of the masonry units and the mortar are relatively high, this is not fully reflected in the masonry compressive strength determined on the wall elements. Similar investigations on pure clay blocks by Wiehle et al. [2] even reported lower component strengths but slightly higher masonry compressive strength. This indicates that the load-bearing behaviour of masonry is not governed solely by the strength of its individual components, but rather by the interaction between units and mortar as well as by the prevailing stress state.

In addition, the determination of the compressive strength of the masonry units remains subject to uncertainty, as different testing approaches lead to significantly different results. Tests on single units may introduce confinement effects, while tests on halves according to DIN standards require cement-based bedding layers that can influence the measured strength, also by confinement effects. Vertical testing of units without lateral confinement avoids these effects but does not correspond to the original compaction direction during manufacturing. For sure, the vertical block test represents the lower minimum of the "true" block strength. Consequently, the representative compressive strength of the masonry units is not uniquely defined.

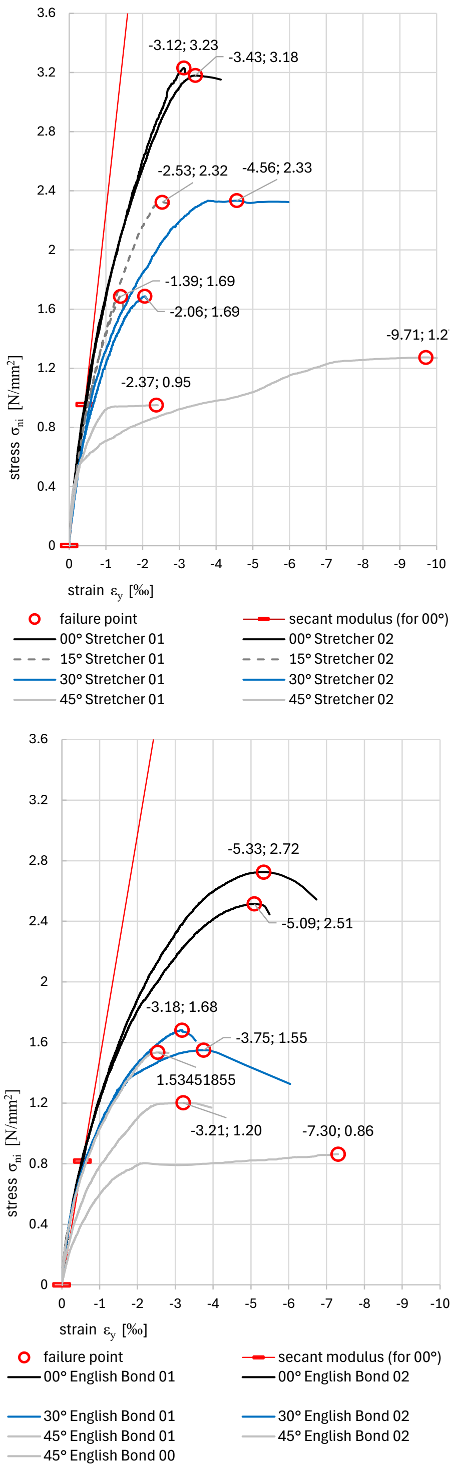


Figure 4. Stress–strain curves from compression tests on wall specimens with inclined bed joints; top: Stretcher (one-block wall thickness) and bottom: English Bond (two-block wall thickness).

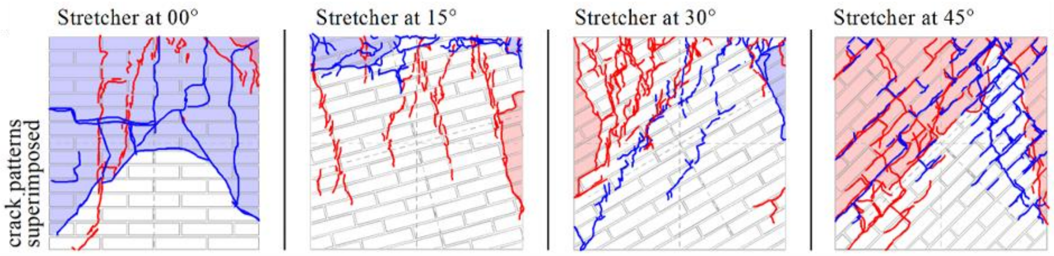


Figure 5. Crack patterns of the Stretcher wall elements shortly before failure.

In the p+f series (see Section 2.3, Table 7), the masonry strength f_y exceeded f_x (2.9 MPa compared to 2.2 MPa), which may be partly attributed to the minor lateral confinement applied during the determination of f_y. This behaviour is consistent for solid masonry units, where forces are transferred through the full cross-section in both directions, resulting in a column-like load-bearing mechanism. This differs fundamentally from conventional masonry with perforated units, for which design concepts such as SIA 266 have been developed. In such systems, inclined loads are mainly transferred through the webs, typically leading to lower strengths perpendicular to the bed joints ($f_y < f_x$).

The present results show that the strengths f_α for $\alpha < \varphi$ are significantly lower than f_y. Thus, using $f_y = f_{90}$, as determined according to SIA 266/1, may considerably overestimate the load-bearing capacity under combined normal and shear loading. Wall tests with inclined bed joints provide a more realistic representation of the stress state (Figure 6) and are therefore essential for determining reliable material parameters for structural design.

The following Figure 6 illustrates the stress field in a shear wall subjected to in-plane loading and its idealisation by means of a wall element with inclined bed joints. This idealisation provides the mechanical basis for interpreting the behaviour of masonry under combined normal and shear loading.

The results of the wall tests with inclined bed joints can be interpreted as shown in Figure 7, which presents the masonry compressive strength (f_α) as a function of the bed joint inclination angle (α). The data points correspond to the experimental results, while the failure regimes according to Ganz [20], transferred to a uniaxial stress state, are schematically indicated by fitted lines. The internal friction angle φ (acc. to SIA), derived from the shear strength tests (Section 3.2), is also indicated. A pronounced reduction in compressive strength is observed once the bed joints are inclined. With further increase in α, the strength reaches a plateau over a certain range of inclination angles, where the design value ($f_{y\alpha}$) may be defined for shear verification. For larger inclination angles, a significant drop in compressive strength is observed, corresponding to a transition towards shear failure (sliding) along the bed joints.

This characteristic behaviour reflects a transition from predominantly compressive load transfer at $\alpha = 0°$ to a combined normal–shear stress state, and ultimately to a friction-controlled mechanism at higher inclination angles. The observed plateau corresponds to shear-dominated failure within the masonry units for $0° < \alpha \leq \phi$, while the sharp reduction in strength at larger angles indicates that the frictional resistance is exceeded and a shift to sliding-dominated failure along the bed joints occurs. The plateau is also consistent with the results from the shear strength tests (Section 3.2), which indicate an internal friction angle (φ) of approximately 38.7°.

The shear bond tests provide additional insight into the frictional properties of the masonry. However, the scatter observed in Figure 3a indicates a sensitivity of the results to specimen preparation and installation accuracy. In addition, bending effects within the three-unit specimens may influence the measured shear strengths, depending on the block format. The evaluation further reveals a strong dependence of both the initial shear strength (f_{v0}) and the friction coefficient (μ) on the selected precompression levels (Figure 3b), which limits the reliability of these tests for determining a unique friction angle.

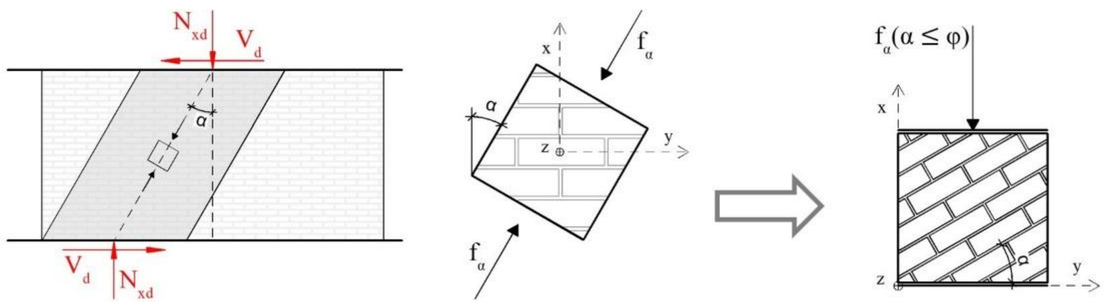


Figure 6. Stress field in an in-plane loaded shear wall and idealisation using inclined bed joints.

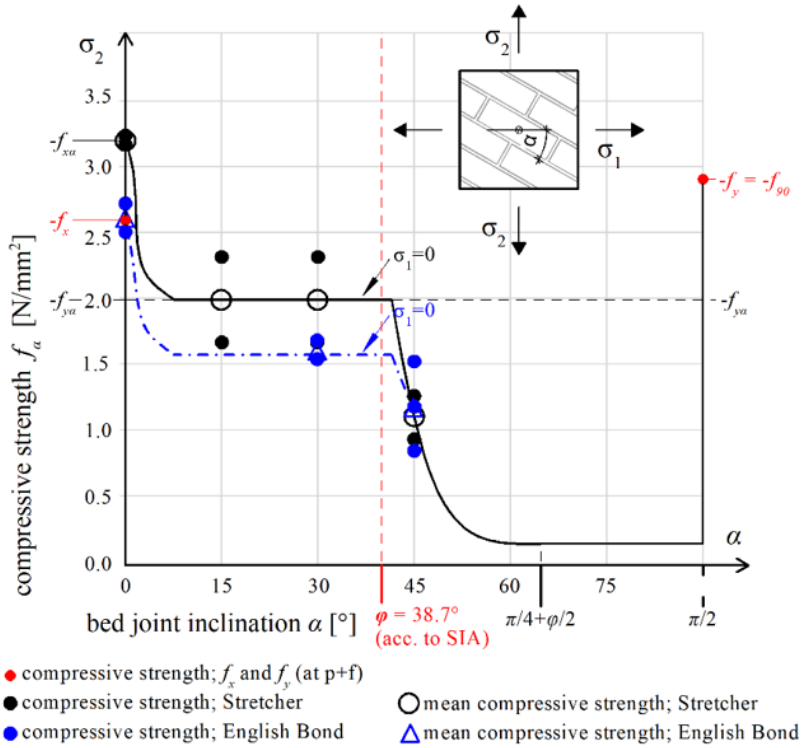


Figure 7. Masonry compressive strength f_α depending on the bed joint inclination angle α.

In contrast, the wall tests with inclined bed joints provide a more consistent representation of the friction-controlled behaviour. Although not primarily designed for this purpose, the results shown in Figure 7, together with the observed crack patterns, allow the friction angle (φ) to be estimated within a comparatively narrow and physically meaningful range. This indicates that wall elements capture the interaction between normal and shear stresses more reliably than small-scale shear bond specimens

The sudden failure of one of the stretcher walls was somewhat unexpected, as CEBs are generally deformable and earth-based materials typically exhibit a "softer" behaviour. This highlights the importance of testing complete wall elements to capture potential brittle failure mechanisms and to ensure early identification of critical conditions. The finding emphasises that small-scale tests alone may not fully reveal the risk of abrupt structural failure, and that large-scale wall testing is essential for a reliable assessment of the load-bearing performance of earthen masonry. Overall, the observed behaviour of the earthen masonry system is generally comparable to that of conventional masonry.

From a design perspective, the results indicate that established masonry design concepts can, in principle, be applied to stabilised compressed earth block masonry. However, the pronounced influence of bed-joint orientation and the observed differences between small-scale and wall-scale testing highlight the need for material parameters derived from representative masonry elements. The presented results provide a basis for the further development and validation of design approaches for load-bearing earthen masonry.

5 Conclusion

The experimental programme provided a comprehensive characterisation of the selected earthen masonry system, including vertical compressive strength, initial shear strength, and the behaviour of walls with varying bed-joint inclinations. The results demonstrate that the tested masonry exhibits mechanical behaviour comparable to conventional masonry in terms of compressive strength, deformation characteristics, and failure mechanisms under vertical and inclined loading. The results also show that the compressive strength of the masonry system cannot be directly derived from the strengths of individual units and mortar specimens. In addition, the measured unit strength was found to depend significantly on the selected testing method, with confinement effects leading to substantial differences in the obtained values. This highlights the importance of masonry-scale testing for the determination of representative design parameters.

The shear bond tests revealed a strong dependence of the derived parameters, including the initial shear strength (f_{v0}) and friction coefficient (μ), on the selected precompression levels. Consequently, these tests appear more suitable for comparative investigations within a given material system than for the determination of unique material parameters for structural design. In contrast, wall tests with inclined bed joints provided a more consistent representation of the interaction between normal and shear stresses and allowed a physically meaningful estimation of the friction-controlled behaviour.

The wall tests further showed that increasing bed-joint inclination leads to a significant reduction in masonry strength and a transition from compression-dominated failure towards shear-controlled failure mechanisms. The observed behaviour is consistent with established masonry mechanics concepts and indicates that the design provisions of SIA 266 may also be applicable to earthen masonry, provided that appropriate material parameters and the environmental humidity factor are considered. For in-plane shear verification, the results suggest that the relevant masonry strength should be determined from wall tests with inclined bed joints ($f_{y\alpha}$), as presented in this study.

The findings are limited to the investigated masonry unit–mortar combination. Further studies on additional material systems and larger datasets are required to confirm the observed trends and to support the development of reliable design recommendations for load-bearing earthen masonry.

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Authorship statement (CRediT)

Iris Durrer: Investigation; Writing – Original Draft; Writing – Review & Editing. **Caderas Letizia:** Writing – Review & Editing. **Teutsch Uwe:** Writing – Review & Editing; Conceptualization; Supervision.

References

[1] DIN, Tragendes Lehmsteinmauerwerk, Norm 18940, Berlin: DIN Deutsches Institut für Normierung, 2023, p. 25.

[2] P. Wiehle, M. Brinkmann, M. Thiele, C. Ziegert, C.A. Graubner, Schaffung von Bemessungsgrundlagen für Lehmmauerwerk auf Basis von DIN EN 1996/NA mittels experimenteller und numerischer Untersuchungen, Bundesanstalt für Materialforschung und -prüfung Fachbereich 7.2 Ingenieurbau; Technische Universität Darmstadt Institut für Massivbau; ZRS Ingenieure GmbH, 2023, p. 69.

[3] P. Muller, U. Muller, P. Fontana, Versuchsgestützte Kalibrierung von Teilsicherheitsbeiwerten im Lehmmauerwerksbau – Empfehlungen für die Erarbeitung eines Bemessungskonzepts, in: W. Jager (Ed.), Mauerwerk Kalender 2017, 1st ed., Wiley, 2017, pp. 181–194. https://doi.org/10.1002/9783433607565.ch5

[4] Q.-B. Bui et al., Effect of moisture content on the mechanical characteristics of rammed earth, Constr. Build. Mater. 54 (2014) 163–169. https://doi.org/10.1016/j.conbuildmat.2013.12.067

[5] F. Champiré et al., Impact of relative humidity on the mechanical behaviour of compacted earth as a building material, Constr. Build. Mater. 110 (2016) 70–78. https://doi.org/10.1016/j.conbuildmat.2016.01.027

[6] K. Abdulla, L. Cunningham, M. Gillie, Effectiveness of Strengthening Approaches for Existing Earthen Construction, Conference Paper, University of Manchester, Edinburgh, UK, 2018, p. 17.

[7] I. Kafodya, F. Okonta, P. Kloukinas, Role of fiber inclusion in adobe masonry construction, J. Build. Eng. 26 (2019) 100904. https://doi.org/10.1016/j.jobe.2019.100904

[8] A. Becker, C. Fischer, D. Waldmann, Experimentelle Untersuchung der Scherfestigkeit von unstabilisiertem Lehmmauerwerk, Fachartikel, Institut für Massivbau, TU Darmstadt, Germany, 2024, p. 10.

[9] SIA, Prüfverfahren für Mauerwerk – Teil 3: Bestimmung der Anfangsscherfestigkeit (Haftscherfestigkeit), Norm SN EN 1052-3, Zürich: Schweizerischer Ingenieur- und Architektenverein, 2002, p. 17.

[10] P. Fontana, L. Miccoli, Experimental investigations on the initial shear strength of masonry with earth mortars, Technical Report, Bundesanstalt für Materialforschung und -prüfung (BAM), 2018, p. 20. https://doi.org/10.1504/IJMRI.2018.089051

[11] SIA, Mauerwerk, Norm 266, Zürich: Schweizerischer Ingenieur- und Architektenverein, 2015, p. 56.

[12] SIA, Prüfverfahren für Mörtel für Mauerwerk – Teil 11: Bestimmung der Biegezug- und Druckfestigkeit von Festmörtel, Norm SN EN 1015-11, Zürich: Schweizerischer Ingenieur- und Architektenverein, 2019, p. 18.

[13] SIA, Prüfung von Festbeton – Teil 3: Druckfestigkeit von Probekörpern, Norm SN EN 12390-1, Zürich: Schweizerischer Ingenieur- und Architektenverein, 2021, p. 24.

[14] DIN, Lehmsteine – Anforderungen, Prüfung und Kennzeichnung, Norm 18945, Berlin: DIN Deutsches Institut für Normierung, 2018, p. 24.

[15] DIN, Lehmmauermörtel – Anforderungen, Prüfung und Kennzeichnung, Norm 18946, Berlin: DIN Deutsches Institut für Normierung, 2018, p. 19.

[16] SIA, Mauerwerk – Ergänzende Festlegungen, Norm 266/1, Zürich: Schweizerischer Ingenieur- und Architektenverein, 2003, p. 16.

[17] SIA, Prüfverfahren für Mauerwerk – Teil 1: Bestimmung der Druckfestigkeit, Norm SN EN 1052-1, Zürich: Schweizerischer Ingenieur- und Architektenverein, 1999, p. 11.

[18] A. Becker, C. Fischer, D. Waldmann, Experimentelle Untersuchung der Scherfestigkeit von unstabilisiertem Lehmmauerwerk, Institut für Massivbau, TU Darmstadt, Germany, 2024, p. 10.

[19] L. Miccoli, U. Muller, P. Fontana, Mechanical behaviour of earthen materials: A comparison between earth block masonry, rammed earth and cob, Constr. Build. Mater. 61 (2014) 327–339. https://doi.org/10.1016/j.conbuildmat.2014.03.009

[20] H.R. Ganz, Mauerwerksscheiben unter Normalkraft und Schub, Institut für Baustatik und Konstruktion, ETH Zürich, Zürich, 1985, 133 pp.