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Load-bearing capacity of earth masonry – an experimental and numerical analysis

The structural design of load-bearing earthen masonry in Germany is based on the *Lehmbau Regeln* [1]. The verification procedure outlined in these regulations is based on a global safety concept that no longer corresponds to the state of the art from a reliability theory perspective. As a result, the structural design concept for earthen masonry will most likely be discontinued by the German Institute for Building Technology (DIBt) in 2023. A structural verification of load-bearing earthen buildings would then only be possible in Germany with an approval for individual cases (ZiE) or a project-related permit type (vBg). Both methods are associated with considerable additional work and higher costs, which is a decisive disadvantage for earthen masonry construction compared to conventional masonry construction. In order to enable a straightforward practical application of earthen masonry, the Federal Institute for Materials Research and Testing (BAM), the Institute for Solid Construction of the Technical University of Darmstadt and ZRS Engineers are laying the groundwork for an updated structural design concept based on the product standards for earth blocks [2] and earthen masonry mortar [3]. The project will also investigate the extent to which the design rules based on the simplified calculation methods for unreinforced masonry according to DIN EN 1996-3/NA [4] can be transferred to earthen masonry construction. If the normative verification procedure can be applied to earthen masonry, it would be conceivable to include earth blocks and earthen masonry mortar in the national appendix of Eurocode 6 in the future, which would result in a significant expansion of the field of application of earthen masonry.

Various scientific studies have shown that the strength and deformation properties of earthen masonry building materials relevant to structural design are strongly dependent on the prevailing material moisture level [5] [7], which is essentially determined by the relative humidity (RH) in the hygroscopic water content range [8]. The interim results of the current research project for the development of a structural design concept for earthen masonry also showed a clearly recognisable dependency between the material moisture level and the relevant strength and deformation properties. Detailed knowledge of the moisture-dependent material behaviour of earth blocks, earthen mortar and masonry is absolutely essential to developing a consistent and reliable structural design concept for earthen masonry. Within the framework of the current research project, extensive tests on the pressure load bearing capacity of earth blocks and earthen mortar as well as earthen masonry after conditioning at different RH levels are therefore being carried out and analysed. Furthermore, numerical models are being calibrated on the basis of the experiment results, which facilitate a detailed analysis of the bending pressure bearing capacity of earthen masonry.

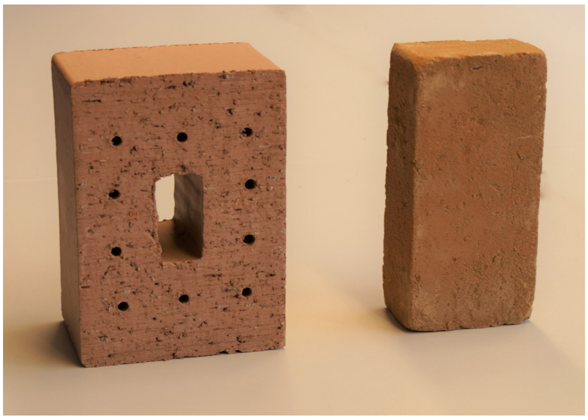
This paper presents, firstly, the interim results obtained so far concerning the experimentally determined moisture-dependent material characteristics of earth blocks, earthen mortar and masonry. Based on this material, numerical investigations for determining the system bearing capacity of earthen masonry under the influence of moisture are carried out and explained.

Experiment investigations

Materials and test methods

Blocks and mortar

The earth blocks and earthen masonry mortars investigated in the research project originate from factory production. Experimental investigations were carried out on both compression-moulded normal-format solid blocks (NF) and on extruded solid blocks in 3DF



01 Extruded earth block 3DF (left), compression-molded earth block NF (right)

format (see Figure 1). In addition, mortars of compressive strength classes M2 and M3 according to DIN 18946 [3] were tested.

After storage of the test specimens in climates with different humidity levels, tests were carried out to determine the compressive strength and deformation behaviour of the blocks and mortars in order to quantify the influence of the RH on strength and deformation properties. In addition to the standard climate for earthen building materials (23°C/50% RH), the test specimens were conditioned at 20°C/65% RH and 23°C/80% RH until constant mass was reached and were then tested immediately after removal from the climatic chamber.

The compressive strength of the mortars was determined in accordance with DIN 18946 [3] on prisms measuring $40 \times 40 \times 160$ mm^3. Deformations were tested on large prisms with dimensions of $100 \times 100 \times 200$ mm^3 in accordance with DIN 18555-4 [9], whereby the load application was carried out in accordance with DIN 18945 [2] in three load branches up to one third of the maximum load. Thus, the deformation properties could be determined without creep effects, which is not the case with the load scheme provided in DIN 18555-4 [9] using a test duration of 15-20 minutes until breakage. The strain was measured continuously using clip-on extensometers.

The compressive strength of the 3DF blocks was determined in accordance with the earth block standard using a full block levelled with gypsum mortar. The compressive strength of the NF blocks was tested according to DIN 18945 [2] using half blocks stack-bonded on top of each other and in accordance with DIN EN 772-1 [10] using a full block. In tests according to DIN EN 772-1 [10] the determined compressive strengths were normalised with the shape factors specified in the standard. After comparing the results of both test methods, it can be assessed whether the shape factors for conventional masonry are also suitable for testing earth blocks. In both test methods, the load application surfaces were also levelled with

02 Test specimen for determining the modulus of elasticity taken from three whole 3DF blocks (left) and three half NF blocks mortared on top of each other (right)

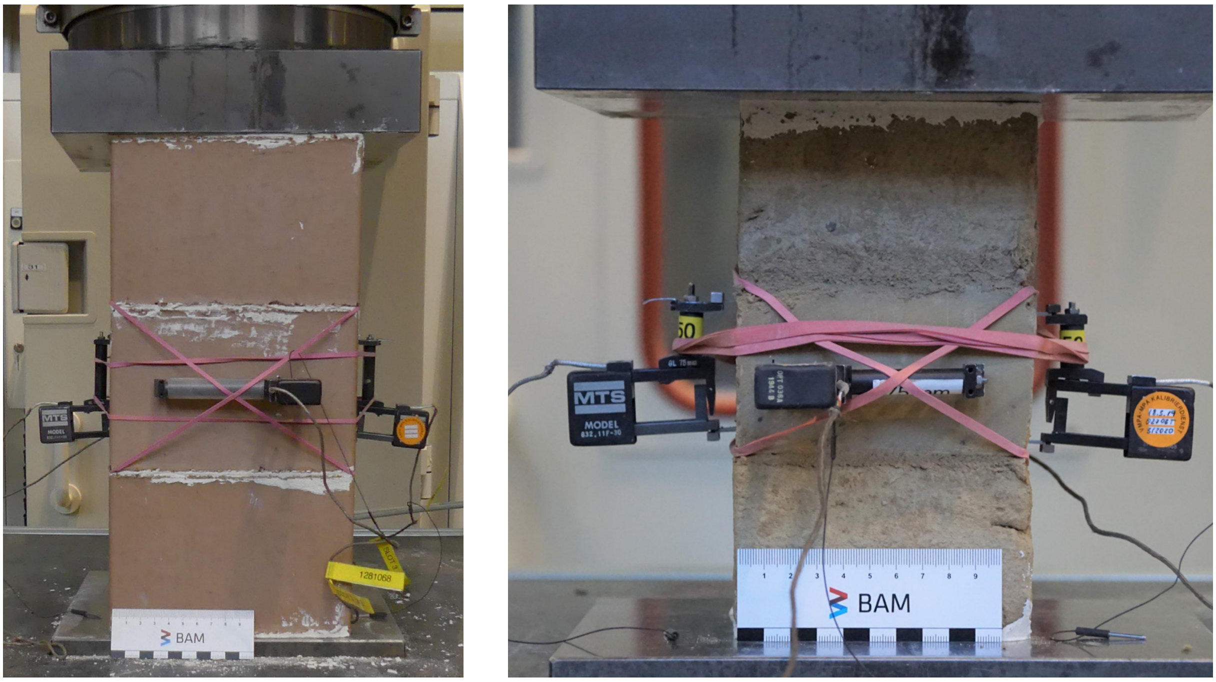


Table 1: Overview of the test programme on blocks and mortars

Block /	Compressive strength			Modulus of elasticity		
Mortar	Samples	Test procedure	Quantity	Samples	Test procedure	Quantity
NF	halved, stack-bonded	DIN 18945	10	3 half blocks stack-bonded	Method according to Schubert in conjunction with DIN 18946	3
	full block	DIN EN 772-1	10			
3DF	full block	DIN 18945 and DIN EN 772-1	10	3 full blocks stack-bonded		3
M2 / M3	Prism 160 × 40 × 40 mm³	DIN 18946	6	Large prism 100 × 100 × 200 mm³	DIN 18555-4 in conjunction with DIN 18945	3

gypsum mortar. The strains were determined on test specimens consisting of three blocks stack-bonded on top of each other with as thin a layer of gypsum mortar as possible (≤ 2 mm) (see Figure 2). The chosen test specimen geometry was based on SCHUBERT [11], as this facilitates strain measurement in the middle third of the test specimen height, which is almost free of lateral strain obstruction. Furthermore, the strain measurement is not influenced by a horizontal joint in the measurement range as would be the case for normal sized blocks according to DIN 18945 [2]. The load is applied in three cycles up to one third of the maximum load with corresponding holding times according to [2]. As with the mortar tests, the strain was measured continuously using clip-on extensometers. An overview of the test specimens and methods can be found in the following table.

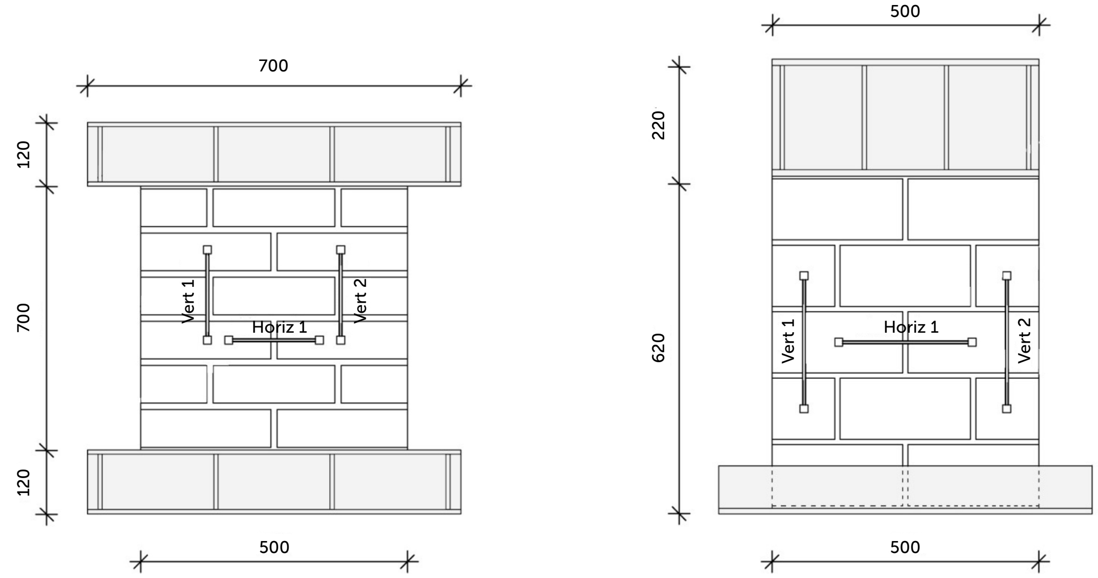
Masonry

The determination of centric masonry compressive strength was carried out on RILEM specimens. During the production of the test specimens, the earth blocks were pre-wetted by immersing them in a container with approx. 10 mm of water for about 5 seconds. A total of four block-mortar combinations were tested: NF/M2, NF/M3, 3DF/M2 and 3DF/M3. Three test specimens were prepared for each block and mortar combination and stored at 23°C/50% RH or at 23°C/80% RH until constant mass was reached. A further test series at 20°C/65% RH still needs to be carried out. The test was carried out in accordance with DIN EN 1052-1 [12], whereby the time of testing was determined by duration to reach a constant mass and not after a defined period of 28 days. The load was constant and regulated at a loading speed that causes a break after approx. 15 minutes. The strains were continuously recorded on the front and rear sides using three inductive displacement transducers each. For each side of the specimen, the transverse strains were measured once and the longitudinal strains were measured twice. The layout and length of the measuring sections can be seen in Figure 3 and Figure 4.

Results

Blocks and mortar

The compressive block strengths determined in accordance with DIN 18945 [2] after conditioning in a standard climate (23°C/50% RH) averaged 4.38 N/mm² for the NF blocks and 4.98 N/mm² for the 3DF blocks, with the lowest individual values exceeding 3.0 N/mm² in each case. Both blocks can therefore be assigned to compressive strength class 3. The mortar compressive strengths were 4.13 N/mm² for the mortar classified as M3 and 3.99 N/mm² for the mortar classified as M2. The mortars can therefore be assigned to strength classes M3 or M4 according to DIN 18946 [3] and are therefore both one compressive strength class higher than specified by the manufacturer. As expected, the compressive strength of mortar and blocks decreases with increasing RH. Likewise, the modulus of elasticity of the blocks decreases with increasing RH. An overview of the test results can be found in Table 2 and Table 3. For the normal format blocks, both the results of the stack-bonded halved blocks (NF_{half}) and the results tested on the full block and normalised by means of the shape factor (NF_{full}) are given. The normalised compressive strengths are on average approx. 10% higher than the values of the test on the stack-bonded halved block according to DIN 18945 [2]. However, in order to be able to make a reliable statement about the applicability of the shape factors according to DIN EN 772-1 [10] for the testing of earth blocks, further investigations need to be carried out.



03 Layout and length of the measuring sections of the RILEM test specimens taken from NF blocks (a) and 3DF blocks (b)

Figure 5 shows the compressive strength ($f/f_{50\%}$) and modulus of elasticity ($E_{0.33}/E_{0.33,50\%}$) of the earth blocks based on standard climate (23°C/50% RH). If the RH is increased from 50 to 80%, the compressive strength of the 3DF blocks is reduced by approx. 35% and that of the NF blocks by approx. 25%. With the same increase in RH, the reduction in the modulus of elasticity is somewhat higher at approx. 42% for the NF blocks and approx. 45% for the 3DF blocks. On the basis of the inserted linear interpolation, it is easy to see that there is an almost linear relationship between RH and compressive strength and modulus of elasticity. Only in the case of the 3DF blocks is this trend less pronounced.

Figure 6 also shows the related compressive strengths ($f/f_{50\%}$) of the earthen mortars. Here the reduction in compressive strength due to an increase in RH from 50 to 80% is approx. 29%.

Masonry

As with earth blocks and earthen mortars, an increase in the RH of earthen masonry is accompanied by a decrease in compressive strength and modulus of

04 Masonry specimens taken from NF blocks (left) and 3DF blocks (right) including measurement equipment used during the test

Table 2 Average values of the test results for earth blocks

Block	Test climate	Compressive strength NF_{half}/NF_{full}	Coefficient of variation NF_{half}/NF_{full}	Modulus of elasticity	Coefficient of variation	Transverse strain module	Coefficient of variation
	T/RH [°C/%]	f [N/mm²]	Vk [%]	$E_{0.33}$ [N/mm²]	Vk [%]	$Q_{0.33}$ [N/mm²]	Vk [%]
NF	23/50	4.38/4.57	5.9/1.6	2806	2.8	15743	12.7
NF	20/65	4.03/4.23	3.6/3.7	2167	4.4	16315	8.3
NF	23/80	3.30/3.63	3.5/2.4	1629	4.2	15615	10.5
3DF	23/50	4.98	3.3	3350	20.5	7372	24.5
3DF	20/65	3.98	1.5	3011	12.4	5845	13.6
3DF	23/80	3.28	3.0	1874	5.5	10304	39.8

Table 3 Average values of the test results for earthen masonry mortar

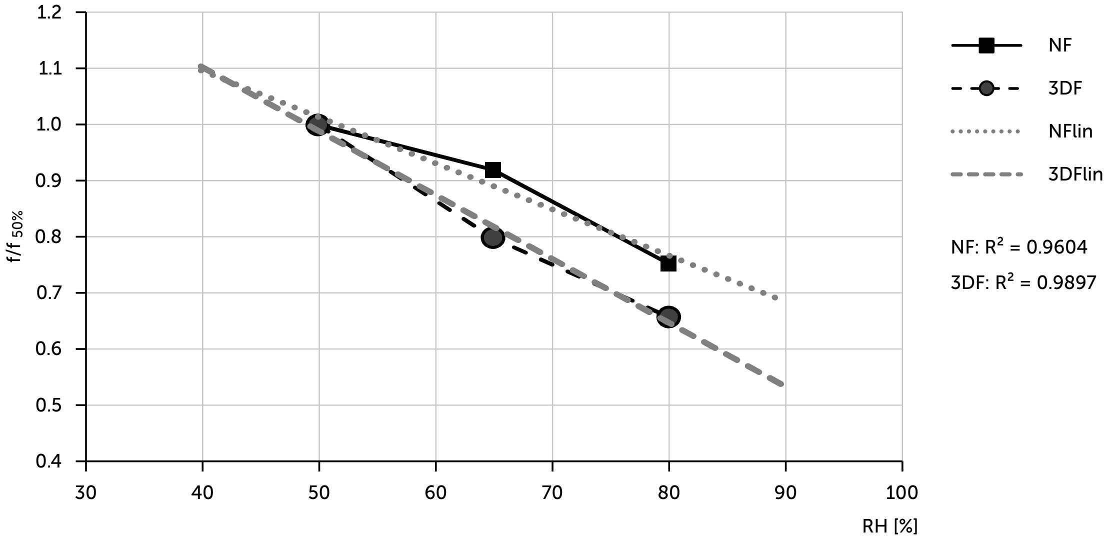
Mortar	Test climate	Compressive strength	Coefficient of variation	Modulus of elasticity	Coefficient of variation
	T/RH [°C/%]	f [N/mm²]	Vk [%]	$E_{0.33}$ [N/mm²]	Vk [%]
M2	23/50	4.13	8.7	3258	4.6
M2	23/60	3.71	7.2	pending	pending
M2	23/70	3.42	7.4	pending	pending
M2	23/80	2.94	7.8	2691	41.4
M3	23/50	3.99	5.2	5450	4.2
M3	23/60	3.35	9.4	5139*	3.3*
M3	23/70	3.04	7.9	5139*	3.3*
M3	23/80	2.86	6.8	3118	12.9

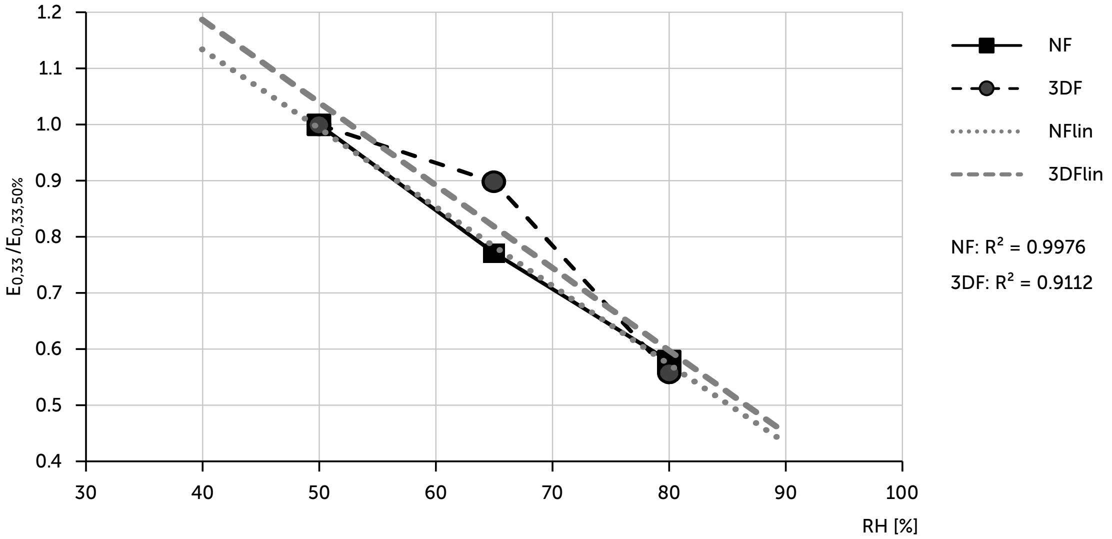
** Values determined at 20°C/65% RH*

elasticity. For masonry made of normal-sized blocks, an increase in the RH from 50 to 80% results in a reduction in compressive strength of approx. 33%, regardless of the mortar used. The modulus of elasticity of the test series produced with mortar M2 decreases by about the same amount, i.e. approx. 34%, whereas the modulus of elasticity of masonry produced with mortar M3 decreases by only 13%. Compressive strengths and moduli of elasticity of masonry test specimens made of 3DF blocks decrease between 34% and 37%. The results are given as average values of the respective test series in Table 4.

A comparison of the compressive strengths of masonry with the same type of block and RH shows that the mortar has hardly any influence on the compressive strength of the masonry, which is mainly due to the very similar compressive strengths of the masonry mortars used (see Table 3: Average values of the test results for earthen masonry mortar).

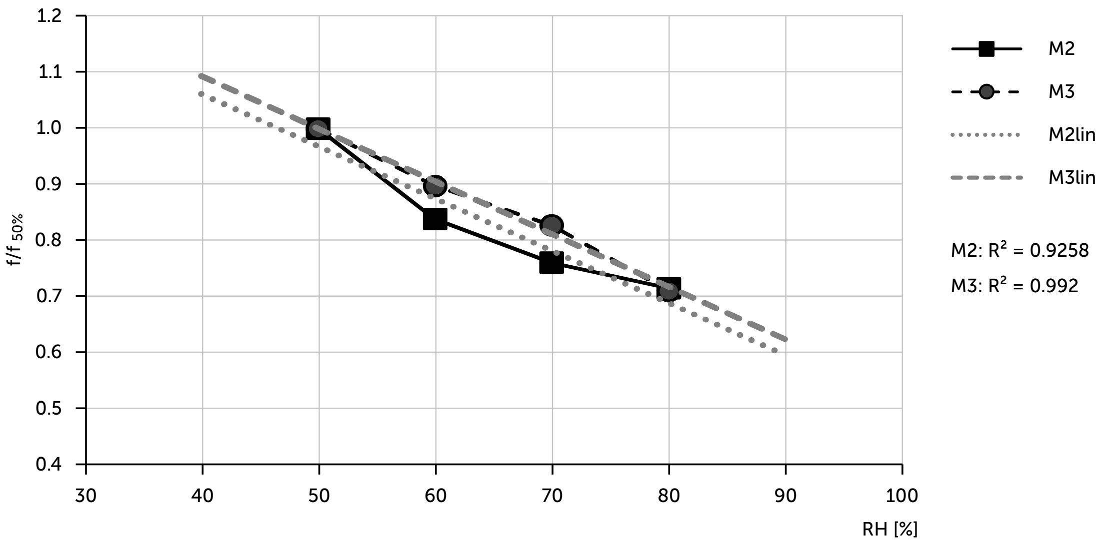
As Müller et al. [13], [14] have already established, the load-bearing behaviour and failure mechanisms of earthen masonry are in principle the same as those of conventional masonry which can be clearly observed in the crack formations in the failure pattern. In contrast to conventional masonry, however, the elongation at break of earthen masonry is comparatively high and increases with increasing RH. This correlation becomes clear when comparing the stress-strain curves. Figure 7 shows the normalised stress-strain curves of the earthen masonry specimens as average values of the tests. The higher elongations at break of the test series carried out at 80% RH can be seen. Additionally, the stress-strain curves of masonry made of fired bricks and aerated concrete were entered with the key figures for determining the modulus of elasticity according to DIN EN 1996-1-1/NA [15] in order to illustrate the different elongations at break.





05 Related compressive strengths (left) and modulus of elasticity (right) of NF and 3DF blocks

06 Related compressive strengths of the mortars



Furthermore, it can be stated that the relationship of modulus of elasticity to compressive strength in earthen masonry is significantly lower than in sand-lime or fired brick masonry. In order to facilitate a comparison of the relationships, the average values of the masonry compressive strengths were converted into characteristic strengths using the factor of 1.2 specified in DIN 1052-1 [12]. The corresponding values of masonry made of normal-sized blocks are $E0._{33/fk}$ = 460 – 600, which is approximately in the value range of $E0._{33/fk}$ = 500 – 650 [15] specified for aerated concrete masonry. In masonry made of 3DF blocks, however, the relationship of modulus of elasticity to characteristic compressive strength is considerably lower at $E0._{33/fk}$ = 280 – 310, although the elasticity moduli of the 3DF blocks are significantly higher than those of the NF bricks, at least under standard climatic conditions (see Table 2: Average values of the test results for earth blocks). The exact cause of this is to be determined in the further course of this research work.

Numerical investigations

Modelling of earthen masonry

Based on the material parameters obtained in the experiment, a numerical model is being developed to estimate the influence of moisture on the global bearing capacity of earthen masonry under centric and eccentric compressive loads. The calibration of the model is based on the test results of masonry specimens made of normal sized earth blocks. For modelling, the approach of a simplified micro modelling approach has been chosen in which the individual masonry blocks are modelled as masonry prisms together with half of the adjacent mortar joints. A masonry prism is separated using 10 × 10 × 10 mesh elements. Rigid load application plates are provided at the base and top of the model to avoid singularities in support and load application areas. The support conditions at the upper and lower wall end merely facilitate free rotation around the longitudinal axis of the model. The bond conditions between the individual block rows are defined by contact elements in the bedding joints. These are assigned a discrete crack model without tensile strength. The geometry of the numerical model is shown in Figure 8.

The masonry prisms are modelled with the aid of a total strain crack model (see Figure 9), which allows both non-linear material behaviour under uniaxial bending pressure stress to be depicted as well as different pressure and tensile behaviour to be taken into account. The material law according to DIN EN 1992-1-1 [16] is used to model the stress-strain relationship under compressive stress:

$$\frac{\sigma}{f} = \begin{cases} \dfrac{k\cdot\eta-\eta^2}{1+(k-2)\cdot\eta} & \text{with } \eta \le \dfrac{\varepsilon_{\mathrm{ult}}}{\varepsilon_{\mathrm{f}}} \\ 0 & \text{with } \eta \ge \dfrac{\varepsilon_{\mathrm{ult}}}{\varepsilon_{\mathrm{f}}} \end{cases} \qquad (1)$$

07 Comparison of the stress-strain curves of earthen masonry at different RHs including the idealized stress-strain curves of brick and aerated concrete masonry according to EC 6

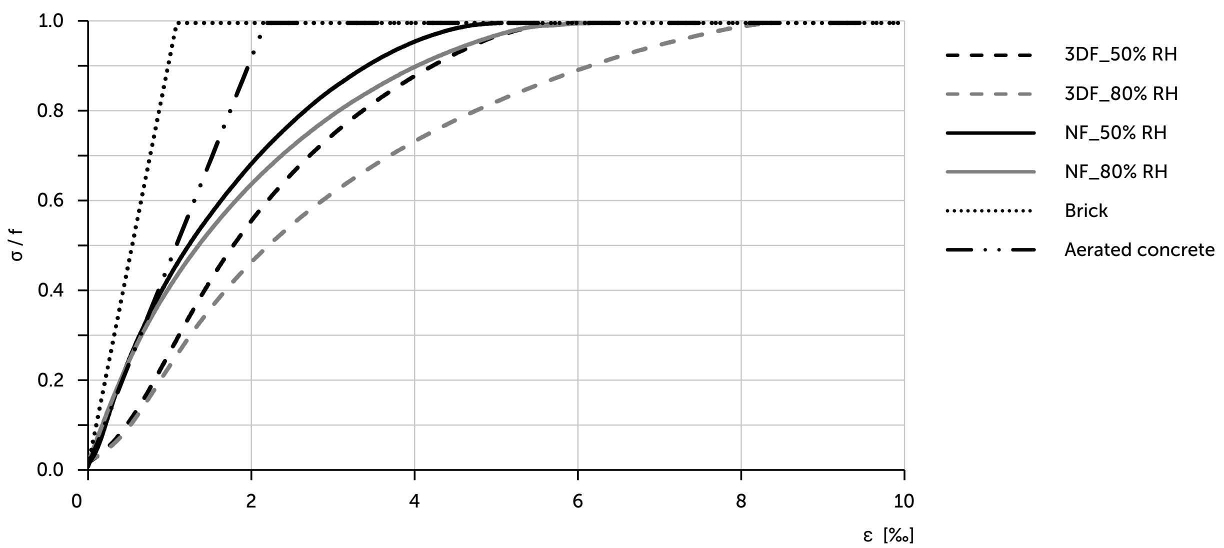


Table 4 Average values of test results for earthen masonry

Test series	Test climate	Quantity	Compressive strength	Coefficient of variation	Modulus of elasticity	Coefficient of variation
Block/Mortar	T/RH [°C/%]	[-]	f [N/mm²]	Vk [%]	$E_{0.33}$ [N/mm²]	Vk [%]
NF/M2	23/50	3	3.72	3.8	1656	6.9
	23/80	3	2.51	3.1	1093	10.9
NF/M3	23/50	3	3.66	6.2	1399	3.9
	23/80	3	2.43	4.4	1225	12.1
3DF/M2	23/50	3	3.56	0.2	911	8.5
	23/80	2	2.36	1.25	592	13
3DF/M3	23/50	3	3.59	3.4	848	17.9
	23/80	2	2.27	3.6	570	1.4

with:

$$k \approx 1.05 \cdot E_{0.33} \cdot \frac{\varepsilon_f}{f}$$

$$\eta = \varepsilon / \varepsilon_f$$

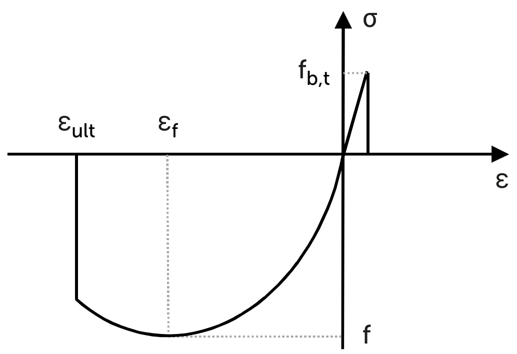
The tensile behaviour of the masonry prisms is approximated with a linear course and brittle post-cracking behaviour. The applied tensile strength corresponds to the bending tensile strength of the earth blocks under the respective ambient climate conditions determined in the experiment. Since the contact elements in the bedding joints have no tensile strength, however, they determine the bending tensile strength of the entire model.

Table 5 summarises the input parameters for the modelling of the masonry prisms. In the numerical analysis, it is assumed, for simplification purposes, that the moisture content of the building component and thus also the strength and deformation properties are constant throughout the wall thickness.

To validate the model, Figure 10 shows the numerically generated stress-strain relationships under centric compressive loading for a relative humidity of 50% and 80% compared with the tensile test diagram determined in the experiment. It is apparent that the non-linear course of the stress-strain relationship can be approximated well by means of the numerical model. Further information on numerical modelling of earthen masonry can be found in Brinkmann et al. [17].

Load bearing capacity of earthen masonry under the influence of moisture

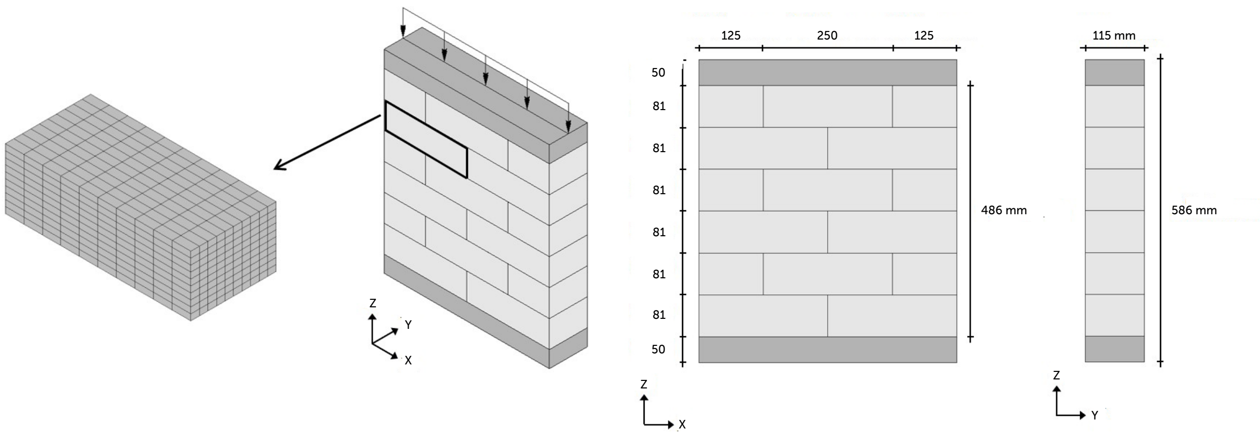
The numerical model is used to analyse and compare the system load-bearing capacity of earthen masonry under compressive stress at 50% RH and 80% RH. Both the slenderness of the model as well as the ec-



09 Total strain crack model of the masonry blocks

Table 5 Input values for modelling

Test climate	f	$f_{b,t}$	$E_{0.33}$	ε_f	ε_{ult}
T/RH [°C/%]	N/mm²	N/mm²	N/mm²	[‰]	[‰]
23/50	3.69	1.59	1527	5.08	6.06
23/80	2.47	1.17	1159	6.44	7.90



08 Geometry of the numerical model

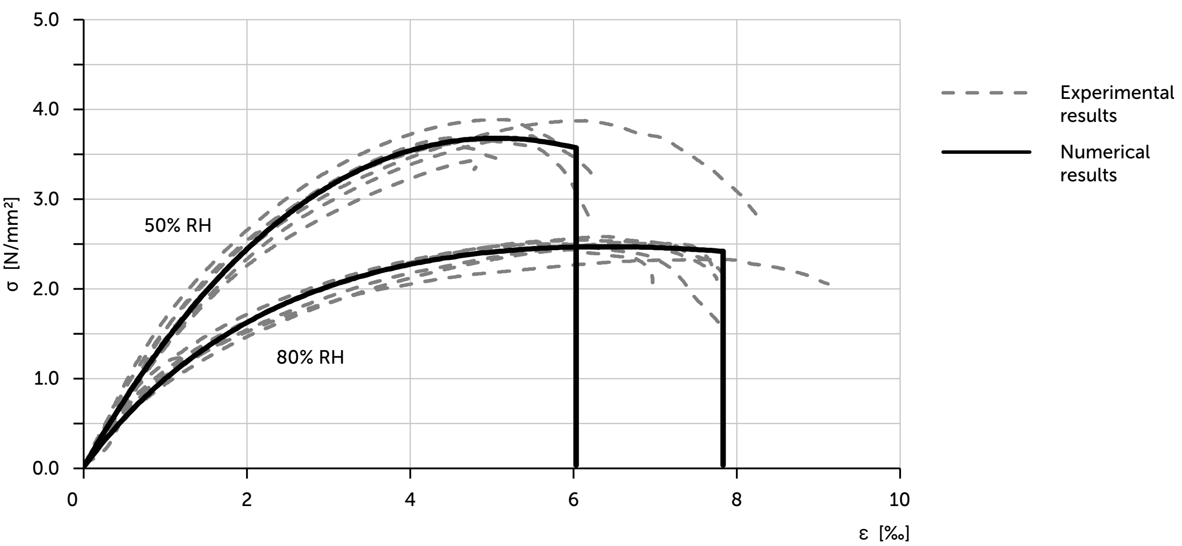
centricity of the pressure normal force acting on it are varied. The results of the load analyses are shown in Figure 11.

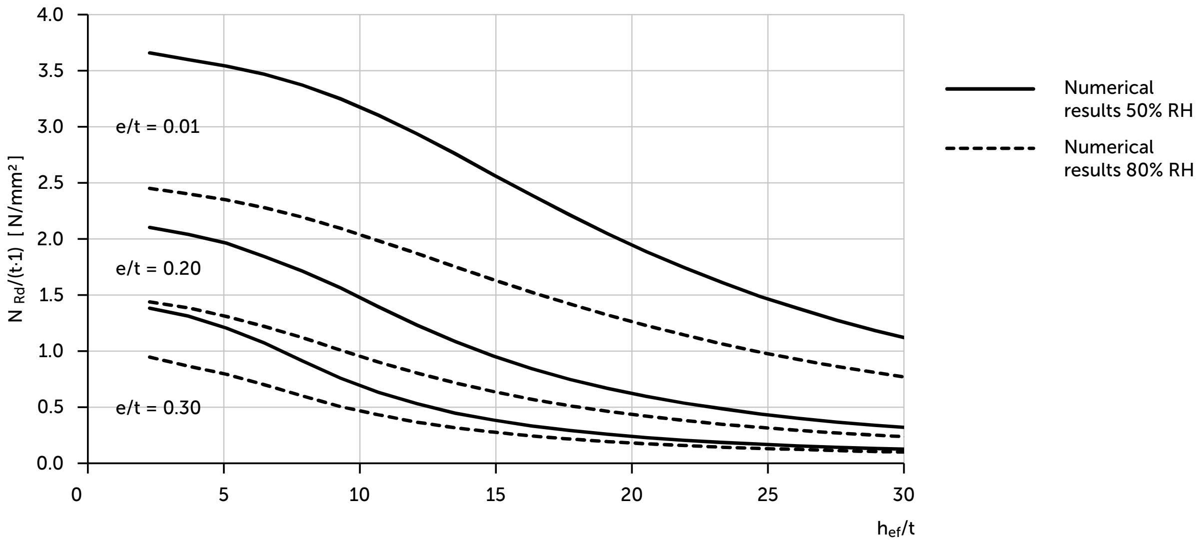
It can be observed that the load-bearing capacity of earthen masonry is significantly reduced when the RH is increased. As cross-sectional failure is generally decisive in the case of low slenderness, the compressive strength of the masonry determines the maximum normal force that can be absorbed. Due to this, the load-bearing capacity of compact earthen masonry walls is reduced, as expected, by the ratio of the compressive strengths under the respective climatic conditions of $f_{80\%}/f_{50\%}$ = 0.67 when the RH increases from 50% to 80%. As shown in Figure 12, however, the ratio $N_{Rd,80\%}/N_{Rd,50\%}$ remains almost constant even at greater slenderness. Since the load-bearing capacity of masonry in the area of stability failure no longer depends on the compressive strength but primarily on the stiffness of the masonry, this effect suggests that the stiffness of earthen masonry is reduced to a similar extent as the compressive strength when humidity increases. This fact can lead to a significant simplification in the creation of moisture-dependent design formulas since the reduction of the bearing load at increased humidity can be taken into account using a uniform factor for both cross-sectional and stability failure.

Conclusions and outlook

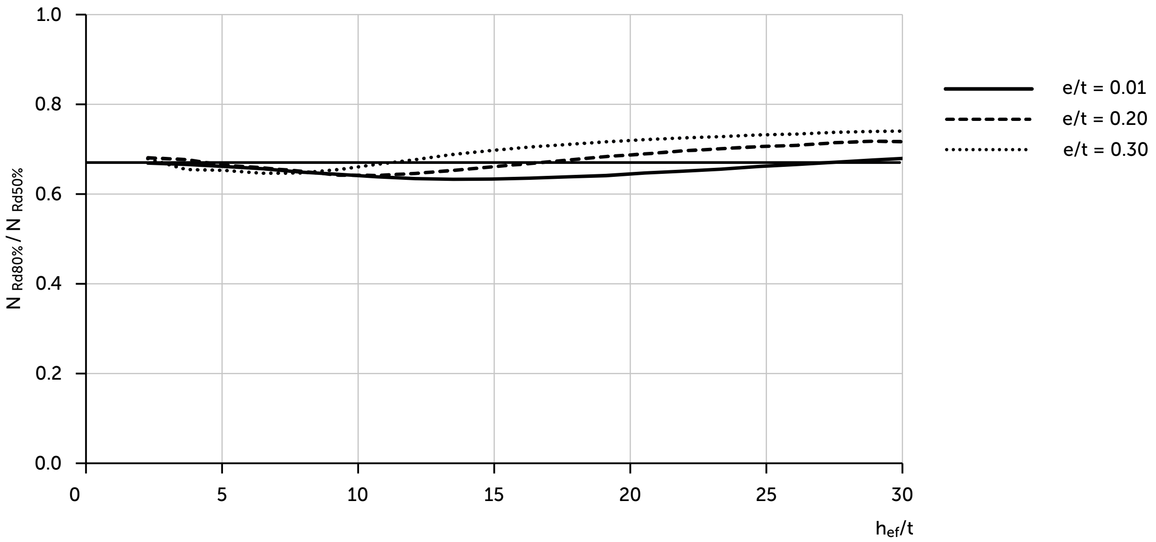
This paper has presented experiment investigations to determine the strength and deformation properties of earthen building materials under different climatic conditions. It was shown that the compressive strength and modulus of elasticity of earthen masonry and its individual components decrease with increasing relative humidity. An increase in relative humidity from 50 to 80% led to a reduction in the compressive strength of the tested earthen building materials of 25-35% and a reduction in the modulus of elasticity

10 Experimental and numerical stress-strain relationship under centric compressive load





11 Numerically determined bearing capacity of earthen masonry under eccentric compressive load at 50% RH and 80% RH



12 Ratio of load capacity at 80% RH to load at 50% RH

of 25-45%. Furthermore, it could be determined that the current valid standard test procedure for earth blocks provides similar results to the test procedure for conventional masonry blocks according to DIN EN 772-1 [10] with subsequent conversion via the shape factors defined there. The extent to which the shape factors for earth blocks actually provide valid results must be clarified in the course of further research. However, against the background of a possible structural design of earthen masonry according to DIN EN 1996-3/NA [4] it appears to make sense in principle to align the determination of the compressive strength for earth blocks with the test specifications common in masonry construction. Due to the low influence of the mortar compressive strength on the compressive strength of masonry, it can be taken into consideration whether the relatively narrow classification grades of the mortar compressive strength classes according to DIN 18946 [3] are appropriate or whether here too, an alignment with the mortar classes according to DIN EN 998-2 [18] should take place. Load-bearing earthen masonry mortars usually have strengths of 2.5 N/mm^2 to 5 N/mm^2 and could therefore be assigned to mortar classes M 2.5 or M 5. In the course of designing earthen masonry according to the simplified calculation methods of DIN EN 1996-3/NA [4] a minimum mortar compressive strength of f ≥ 2.5 N/mm^2 may be sufficient without accepting significant losses in terms of masonry compressive strength.

In order to analyse the bearing capacity of earthen masonry under different climatic conditions, a numerical model was calibrated on the basis of the material characteristics determined in the experiment. The load-bearing capacity under eccentric compressive stress was reduced at 80% RH to approximately two thirds of the load-bearing capacity at 50% RH. Interestingly, the ratio $N_{Rd,80\%}/N_{Rd,50\%}$ corresponds approximately to the ratio of compressive strengths $f_{80\%}/f_{50\%}$ not only in the area of cross-sectional failure, but also in the area of stability failure as well as with varying eccentricity. This fact leads to the conclusion that the stiffness of earthen masonry decreases with increasing RH to a similar extent as its compressive strength. However, the tests carried out so far have always been carried out after conditioning to constant mass, i.e. the test specimens have reached their equilibrium moisture content through the entire cross-section. Depending on the climate and test specimen volume, this took up to seven weeks for the masonry test specimens. In the case of application, there are usually unsteady climatic conditions which result in a corresponding gradient of humidity through the cross section. Which building component moisture level actually occurs over the course of the year, depending on the wall construction and the application situation, will be determined in the further course of the research project via long-term moisture measurements on earthen masonry.

In order to gain further insights into the load-bearing behaviour of earthen masonry, experiment investigations will be carried out under different climatic conditions on eccentrically loaded earthen masonry walls of different slenderness ratios in the further course of the project. In addition, the long-term behaviour of earthen masonry will be investigated in the form of creep and endurance tests at different relative humidities.

Ultimately, it is necessary to combine the results of the laboratory tests carried out under steady-state conditions with the humidity measurements oriented to the application case under actual climatic conditions in order to allow conclusions to be drawn about the load-bearing behaviour under transient and cyclical climatic conditions. Thus, the influence of moisture on the load-bearing capacity of earthen masonry can finally be quantified and adequately taken into account within a structural design concept.

Acknowledgements

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Reference literature

[1] Volhard, F., Röhlen, U.: *Lehmbau Regeln: Begriffe – Baustoffe – Bauteile*. Wiesbaden: Vieweg + Teubner, 2009.

[2] DIN 18945: 2018-12. *Lehmsteine – Anforderungen, Prüfung und Kennzeichnung*.

[3] DIN 18946: 2018-12. *Lehmmauermörtel – Anforderungen, Prüfung und Kennzeichnung*.

[4] DIN 1996-3/NA: 2012-01. *Nationaler Anhang – National festgelegte Parameter – Eurocode 6: Bemessung und Konstruktion von Mauerwerksbauten – Teil 3: Vereinfachte Berechnungsmethoden für unbewehrte Mauerwerksbauten*.

[5] Bui, Q.-B. et al.: *Effect of moisture content on the mechanical characteristics of rammed earth*. In: Construction and Building Materials 54, S. 163–169, 2014.

[6] Champiré, F. et al.: *Impact of relative humidity on the mechanical behavior of compacted earth as a building material*. In: Construction and Building Materials 110, S. 70-78, 2016.

[7] Müller, U. et al.: *Eigenschaften industrieller Lehmbauprodukte für den Mauerwerksbau und Verhalten von Lehmsteinmauerwerk*. In: Mauerwerk 16, S. 17-28, 2012.

[8] Willems, W. M. (Hrsg.): *Lehrbuch der Bauphysik – Schall – Wärme – Feuchte – Licht – Brand – Klima*. Wiesbaden: Springer Vieweg, 2017.

[9] DIN 18555-4: 2019-04. *Prüfung von Mörteln mit mineralischen Bindemitteln – Teil 4: Bestimmung der Längs- und Querdehnung sowie Verformungskenngrößen von Mauermörteln (Festmörtel) im statischen Druckversuch*

[10] DIN EN 772-1: 2011-07. *Prüfverfahren für Mauersteine – Teil 1: Bestimmung der Druckfestigkeit*.

[11] Schubert, P.: *Prüfverfahren für Mauerwerk, Mauersteine und Mauermörtel*. In: Mauerwerk-Kalender 16, Berlin [u.a]: Ernst & Sohn, S. 685 – 697, 1991.

[12] DIN EN 1052-1: 1998-12. Prüfverfahren für Mauerwerk – Teil 1: Bestimmung der Druckfestigkeit.

[13] Müller, P. et al.: *Versuchsgestützte Kalibrierung von Teilsicherheitsbeiwerten im Lehmmauerwerksbau – Empfehlungen für die Erarbeitung eines Bemessungskonzepts*. In: Mauerwerk-Kalender 42, Berlin: Ernst & Sohn, S. 181–194, 2017.

[14] Müller, P. et al.: Development of partial safety factors for earth block masonry. In: Materials and Structures 50, S. 1 – 14, 2017.

[15] DIN 1996-1-1/NA: 2019-12. *Nationaler Anhang – National festgelegte Parameter – Eurocode 6: Bemessung und Konstruktion von Mauerwerksbauten – Teil 1-1: Allgemeine Regeln für bewehrtes und unbewehrtes Mauerwerk*.

[16] DIN EN 1992-1-1: 2011-01. *Eurocode 2: Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken – Teil 1-1: Allgemeine Bemessungsregeln und Regeln für den Hochbau*.

[17] Brinkmann, M., Graubner, C.-A.: *Load-bearing capacity of slender earth masonry walls under compression*. 17th International Brick and Block Masonry Conference, 2020.

[18] DIN EN 998-2: 2017-02. *Festlegungen für Mörtel im Mauerwerksbau – Teil 2: Mauermörtel*.

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