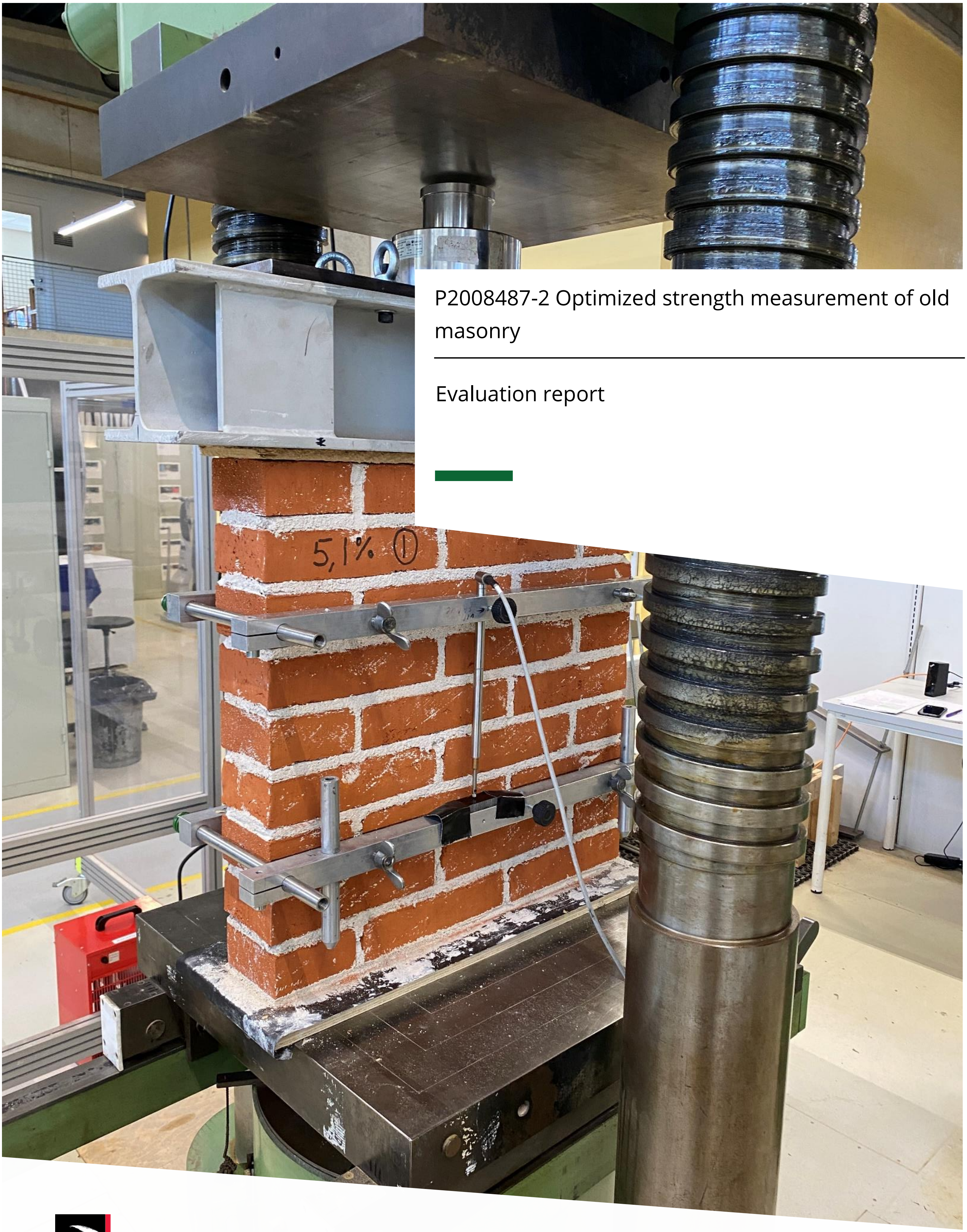

P2008487-2 Optimized strength measurement of old masonry

Evaluation report

DANISH
TECHNOLOGICAL
INSTITUTE

August 2022

Title:
P2008487 – Optimized strength measurement of old masonry
Evaluation report

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1. Introduction

Danish Technological Institute have conducted this project for Grundejernes Investeringsfond to assess the development of the modulus of elasticity of lime-based masonry during a one-year period. The purpose of the project is to enhance the existing method of cross-drill (X-drill), which is used to determine the strength properties of e.g., lime-based masonry. This can improve the possibilities in relation to renovation projects, which demands documentation of greater strength properties, than the previously used experiential values.

2. Background

Masonry is being renovated for millions of DKK, either in project with the installation of a new balcony, new and larger window openings, or a change in the use of the building. According to SBI 223 "Documentation of load-bearing structures", static documentation must be prepared for the structures during and after renovations/remodelling. However, there are several challenges in connection with the design of older masonry. Some of the most important are:

1. The building code requirements are in a constant change
2. It is assumed that older masonry cannot be calculated according to current Eurocode requirements
3. Effective determination of strength parameters.

Points 1 and 2 are closely related, as the applicable standards – Eurocodes – have been developed on the basis of trials with new constructions. It is therefore widely believed that Eurocodes cannot immediately be used for calculations regarding older masonry. If the assumption is correct, there should be another calculation basis. This subject is dealt with in an ongoing project, led by SBi and co-financed by GI, and includes, among other things, the publications SBi 251 and SBi 248. The last, and ongoing part of the project, "Safety assessment of masonry constructions during conversion/renovation of apartment buildings", examines failure possibilities, structural design and execution methods in renovation.

Point 3 is standard-independent. Regardless of which basis of calculation is used for the existing constructions, the strength parameters of the material are decisive. With the X-drill method, the compressive strength of mortar can be determined. However, very low calculated results of the masonry modulus of elasticity are often obtained, which makes renovation/remodelling unnecessarily complicated and costly.

The present project will therefore establish a direct correlation between the measured strengths at cross drills and the modulus of elasticity, to achieve a more precise and probably often higher value. The project's results complement the ongoing project, as the material parameters must be used, regardless of which calculation model is chosen (Eurocode or SBI 248, or a combination).

3. The end-user

The end-user of the project is:

- Builders who can achieve documentation for better and more precise strength properties of their masonry, and thus can renovate more cheaply.
- Consultants who can achieve better and more precise strength properties of the masonry, thereby simplifying the design task.

4. Project activities

The activities include laboratory tests and calculations which determine the correlation between X-drill measurements and the modulus of elasticity for masonry with lime-based mortars, like older masonry, as well as underpinning already existing correlation with strength.

A series of laboratory tests have been carried out with:

- Masonry wall sections built with lime mortar where the modulus of elasticity is measured 5 times over the course of approximately one year, by a non-destructive compression test according to EN 1052-1. After the final test at 365 days, the walls were loaded to failure to determine the compressive strength. A selection of pictures from the tests is shown in Annex 1.
- Mortar samples according to EN 1015-11, cast with the same mortar as the wall sections mentioned above. The amount of mortar samples was such, that the development of the mortar's strength, could be determined for 90, 145, 230, 300 and 370 days of curing.
- On the same days of testing the mortar prisms, X-drill tests were carried out on wall sections to compare the results for the mortar compressive strength obtained by the two methods: EN 1015-11 and X-drill method.

Based on the above laboratory data, and with the inclusion of previous tests with X-drill tests and wall sections, the formula sets from Eurocode 6 (new masonry) and SBI 248 (older masonry) are evaluated. If necessary, a new expression for the modulus of elasticity in older masonry is defined, which provides a better match with test results.

5. Evaluation and assessment of results

The laboratory tests results are shown in detail in "P2008487-1 Optimized strength measurement of old masonry – Test report".

The results are summarized in the following.

5.1. Mortar analysis

5.1.1. Mortar lime content

The three applied mortar types were with 5.1%, 6.6% and 9.0% lime content. These amounts of lime content cover the span of range for lime content in older Danish masonry. The lime content was determined for the mortar mixed to produce the wall and mortar prism samples. The exact determined contents were 5.1%, 6.3% and 9.1% lime, however for the purpose of simplicity and consistency in this report, the mortars will in the following be referred to as 5.1%, 6.6% and 9.0% lime mortars.

5.1.2. Mortar strength f_m

The three mortar types were tested at the beforementioned dates: 90, 145, 230, 300 and 370 days of curing. The details of the result are shown in the test report, Table 2. The average values for the compressive strength are summarized below in Table 1. Note that the values for the compressive strength f_m have been corrected according to DS/INF 167:2021, 3.2.2 (1) as ML = 1/2MC.

	Average f_m	Std. Dev.
5.1%	0,41	0,03
6.6%	0,46	0,02
9.0%	0,52	0,03

Table 1. Average f_m values for lime mortar samples 5.1%, 6.6% and 9.0% tested according to EN 1015-11. The values are the average of all the tests conducted during the 1-year test period.

5.1.3. Mortar carbonization

The mortar samples were analysed further after the determination of the flexural- and compressive strength. The condition of the carbonization was assessed by applying phenolphthalein on the cross section of a newly broken mortar prism. Phenolphthalein is used as an indicator for acid-based titrations. For this application, it turns colourless in acidic solutions and pink in basic solutions, while the latter indicates unfinished carbonization of the lime mortar. Apart from analysing the mortar prisms, samples containing two bricks joined with mortar, were also analysed. These samples were prepared on the same days as all the wall and prism samples. The last-mentioned samples were tested with phenolphthalein along the entire depth of the bed joint. Pictures showing the state of carbonization during the 1-year period can be seen in Annex 2. Based on the observations, it appears that even after a 1-year curing period the lime mortar has yet not fully cured in the entire cross section. As seen on the photos taken after 370 days, it appears that the curing depth is up to 10-15mm. Potentially indicating higher strength properties than those recorded in this research.

5.1.4. Comparison of results from X-drill method and EN 1015-11

The results for the mortar compressive strength f_m have been compared in the table below. The values show the relation between compressive strength values determined according to the two methods: X-drill and EN 1015-11.

	Days of curing				
	90	145	230	300	370
5.1%	1,45	1,09	0,95	0,93	2,28
6.6%	1,24	1,02	0,89	0,90	1,34
9.0%	0,46	1,12	1,45	1,71	1,33

Table 2. Relation between $f_{m,x\text{-}drill}$ / $f_{m,EN1015\text{-}11}$

The closer the values are to 1, the better the correlation between the two methods. For many cases the correlation is good, but in some cases the difference is significantly large. This could perhaps be explained by the general uncertainty of the methods themselves, or by the relatively fragile composition of lime mortar joints in relation to the X-drill method.

5.2. Normalized compressive strength f_b

The normalized compressive strength of the brick type applied for the wall samples was tested and determined according to EN 772-1: f_b = 14.2 MPa.

5.3. Characteristic compressive strength f_k

The characteristic compressive strength for each test date is shown in the table below. The characteristic compressive strength of masonry, f_k, is calculated according to DS/EN1996-1-1:2022, 5.7.1.4(1):

$$f_k = K \cdot f_b^{0.7} \cdot f_m^{0.3} \qquad (1)$$

Where f_b is the normalized compressive strength of the brick, f_m is the mean compressive strength of the mortar and K is a constant according to DS/EN1996-1-1:2022 Table 5.3.

	Days of curing				
	90	145	230	300	370
5.1%	2,7	2,8	2,7	2,7	2,7
6.6%	2,8	2,8	2,8	2,9	2,8
9.0%	2,9	2,9	2,8	2,9	2,9

Table 3. Characteristic compressive strength of masonry, f_k

The tested value for the characteristic compressive strength of masonry f_k at day 370 was 5.0 MPa for all three mortar types. The details of the results are given in the test report, Table 4. As it appears, the load at which the first crack appeared, and the failure load are quite close to each other.

5.4. Calculation of Modulus of elasticity according to DS/EN 1996

The modulus of elasticity for masonry is calculated according to DS/EN 1996-1-1:2022, 5.8.2(3):

$$E = K_E \cdot f_k \quad (2)$$

The value K_E for masonry based on lime mortar is determined as follows according to DS/EN 1996-1-1 DK/NA:2019, 3.7.2(2):

$$K_E = 150 \cdot f_m \quad (3)$$

	Value K_E Days of curing				
	90	145	230	300	370
5.1%	60	71	59	60	60
6.6%	68	68	68	75	71
9.0%	81	78	71	77	81

Table 4. Value K_E

	Modulus of elasticity E Days of curing				
	90	145	230	300	370
5.1%	161	198	155	161	161
6.6%	187	187	187	215	198
9.0%	237	226	198	220	237

Table 5. Calculated Modulus of elasticity E according to DS/EN 1996-1-1:2022

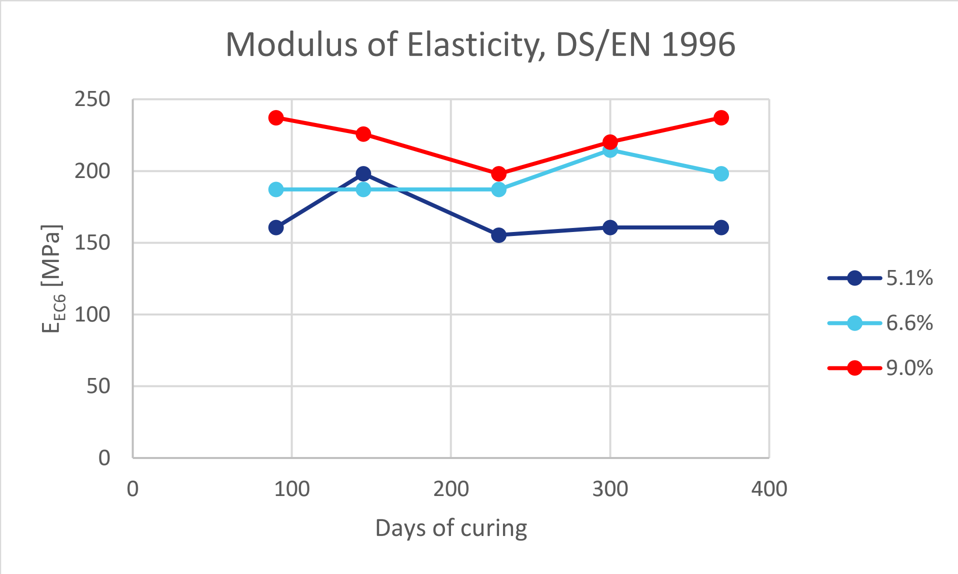

Figure 1. Modulus of elasticity calculated according to Eurocode 6 based on mortar compressive strength determined according to EN 1015-11.

Since the modulus of elasticity is dependent on the K_E factor, and the K_E factor is dependent on the mortar strength, naturally the variation of the modulus of elasticity on the figure above will follow the variation of the measured mortar strength. Generally, the modulus of elasticity appears constant during the 1-year testing period, indicating that there is no further development of the modulus of elasticity.

5.5. Experimental results of Modulus of Elasticity

The experimental results are shown in Table 6 below and on Figure 2.

	Modulus of elasticity E Days of curing				
	90	145	230	300	370
5.1%	1296	1132	1081	1086	1056
6.6%	1246	1217	1112	1054	1028
9.0%	1232	1178	1010	1013	900

Table 6. The results for the experimentally determined modulus of elasticity according to EN 1052-1.

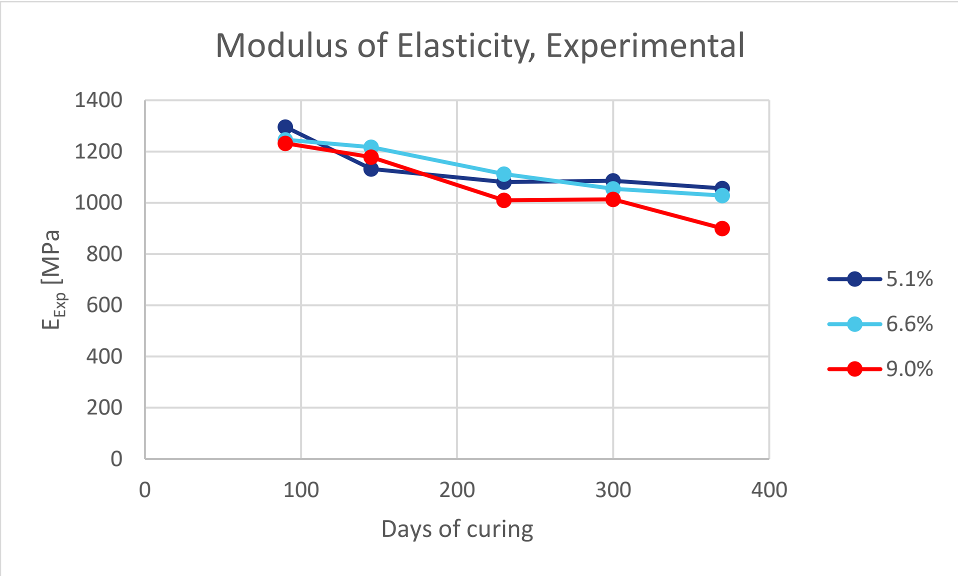

Figure 2. Modulus of elasticity determined according to EN 1052-1 during a 1-year period.

The curve appears downwards going, which perhaps is caused by the repetitive re-loading of the wall samples. However, by observing the development from 230 days to 300 days, the values appear steady and constant, with minor differences, which can be explained by the expected variation in the testing results. All in all, it indicates that the modulus of elasticity is reaching a steady level at around 1-year of curing.

Based on the obtained results and the observations in this research there is no sign of differences between the different lime contents, in relation to the strength properties. At least not in the time span of these tests. The mortar analysis with phenolphthalein suggested that the mortars were not fully carbonized.

5.6. Comparison of Experimental and Theoretical results

Evidently the experimentally determined modulus of elasticity for masonry with lime-mortar is significantly higher than the theoretically determined modulus of elasticity. To visualize the relation between the two, a graph has been plotted, see Figure 3. The linear line indicates a 1:1 relation – which in some way could be regarded as safety lower bound. The experimentally determined values are relatively high above this line.

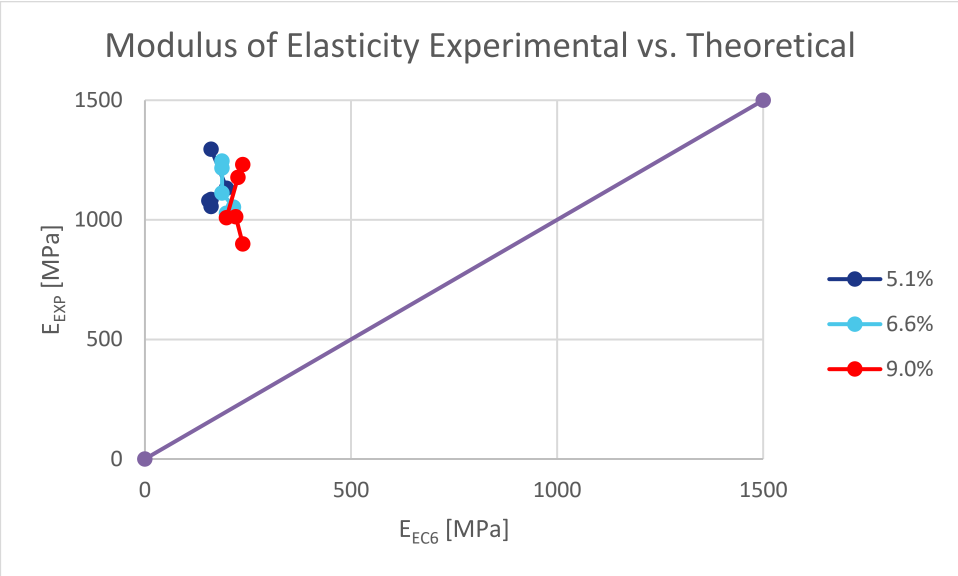

Figure 3. Relation between the experimentally and calculated modulus of elasticity.

6. Implementation of results in DS 11990

Values for K_E have been calculated based on the results for the experimentally determined modulus of elasticity, see the table below. The values are calculated based on:

$K_{E,exp} = E_{exp} / f_k$

where f_k is determined according to formula (1) using the tested values for f_b and f_m.

$K_{E,exp}$	Days of curing				
	90	145	230	300	370
5,1%	484	403	407	406	395
6,6%	449	439	401	368	366
9,0%	421	407	360	352	307

Table 7. Values for K_E calculated based on the experimentally determined modulus of elasticity.

The $K_{E,exp}$ values are much higher than the values for K_E determined according to Eurocode 6, see Table 3 for comparison.

This proves that the material factor in formula (3), which currently is 150 for lime mortar, is in fact higher. For now, this factor is called f_E. Given formula (3), the material factor f_E is calculated by: $f_E = K_E / f_m$. The material factors f_E have been calculated for each modulus of elasticity, see Table 7.

Material factor	Days of curing				
	90	145	230	300	370
5,1%	1210	857	1043	1014	986
6,6%	999	975	891	737	779
9,0%	779	782	765	690	569

Table 8. Calculated material factors f_E for each modulus of elasticity.

Based on these results, it is safe to assume that a higher material factor can be applied when calculating the modulus of elasticity for masonry with lime mortar according to Eurocode 6.

The results from this research have provided the basis for proposing a higher material factor f_E when calculating K_E. The proposal is, on the release date of this research, currently still under consideration, however implemented in an upcoming standard DS11990.

The official code proposal in the above-mentioned standard is as follows:

For masonry based on lime mortar, with strength at least at 150 days.

$$K_E = min\begin{cases} 20 \cdot f_b \\ \mathbf{500} \cdot f_m \\ 1000 \end{cases} \quad (4)$$

7. Recommendations

The proposed range for determining the K_E in (4) will not always necessarily result in higher values, since it is also dependant on f_b. In the actual case, where f_b = 14.2MPa, K_E will be 284. So, the change for the material factor f_E from 150 to 500 will primarily have an impact in those situations where f_b is relatively higher. Nevertheless, the strength measurement of old masonry with primarily lime mortar will be optimized by the increased material factor. For that reason, it is recommended in a renovation project to determine the actual strength properties for the brick and mortar.

8. Annexes

Annex 1: Photos from the tests
Annex 2: Photos of the mortar carbonization by phenolphthalein

Annex 1: Photos from the tests

In this annex a selection of photos from the tests is showed, to illustrate the test setup and arrangement of equipments. Mainly pictures from the tests performed after 370 days of curing are showed, because on these dates the wall test samples were loaded to failure. Notice that initially the wall samples were tested non-destructive to determine the modulus of elasticity. The displacement measuring equiptment was afterwards removed and the wall tested again until failure. Finally, the walls on which the X-drill measurements were performed were also tested to compare the failure load and to see wether or not the drilled holes in the joints would affect the final failure load.

5.1% – 370 days

Picture 1

Picture 2

Picture 3

Picture 4

Picture 5

Picture 6

Picture 7

Picture 8

Picture 9

Picture 10


90
90
90
145
145
145
145
90
145
90
145
230
230
230
300
230
300
230
300
300
300
300
370
370
370
370
370
370

Picture 11

Picture 12

Picture 13

Picture 14

6.6% – 370 days

Picture 15

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Picture 16

Picture 17

9.0% – 370 days

Picture 18

Picture 19

Picture 20

Picture 21


90-1
90-2
90-3
145-1
145-2
230-2
90-4
145-3
90-5
145-4
145-5
370-1
230-3
370-2
370-3
370-4
370-5
370-6
370-7

Picture 22

Picture 23

Annex 2: Photos of the mortar carbonization by phenolphthalein

5.1% Mortar – 90 days

Picture 24

6.6% Mortar – 90 days

Picture 25

9.0% Mortar – 90 days

Not photo documented

5.1% Mortar – 145 days

Picture 26

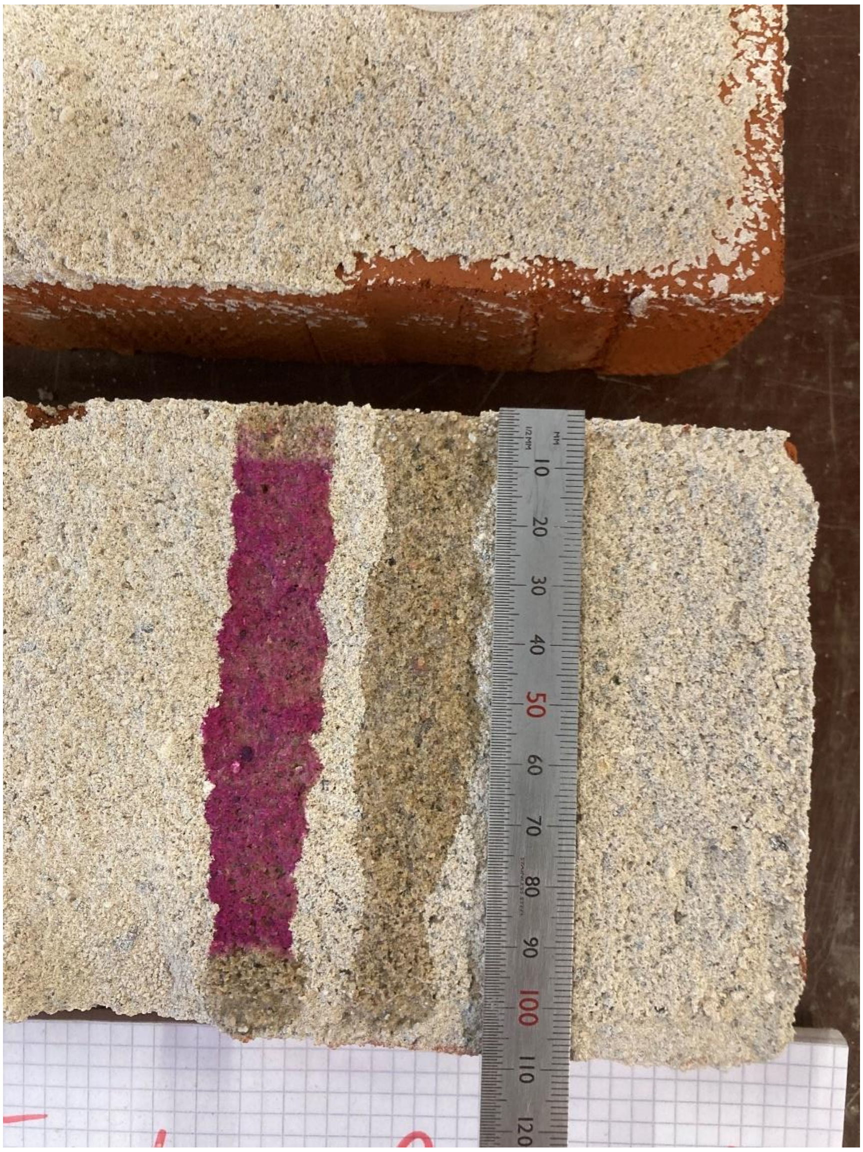
6.6% Mortar – 145 days

Picture 27

9.0% Mortar – 145 days

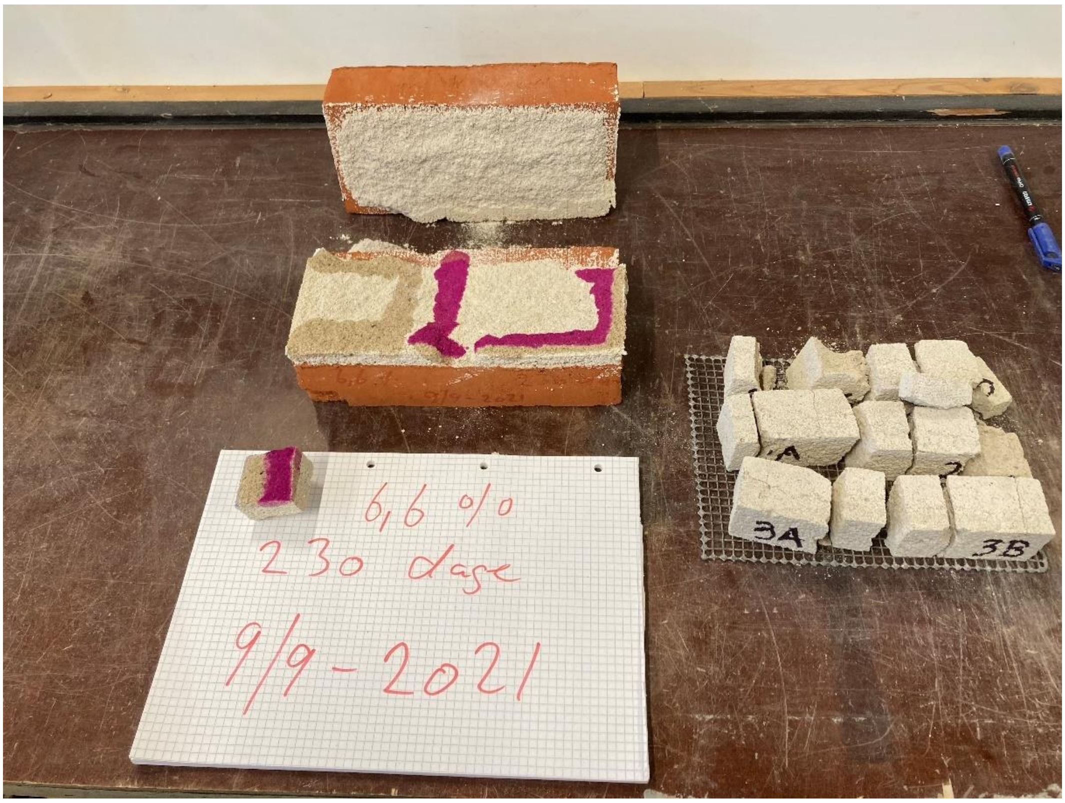
Picture 28

5.1% Mortar – 230 days



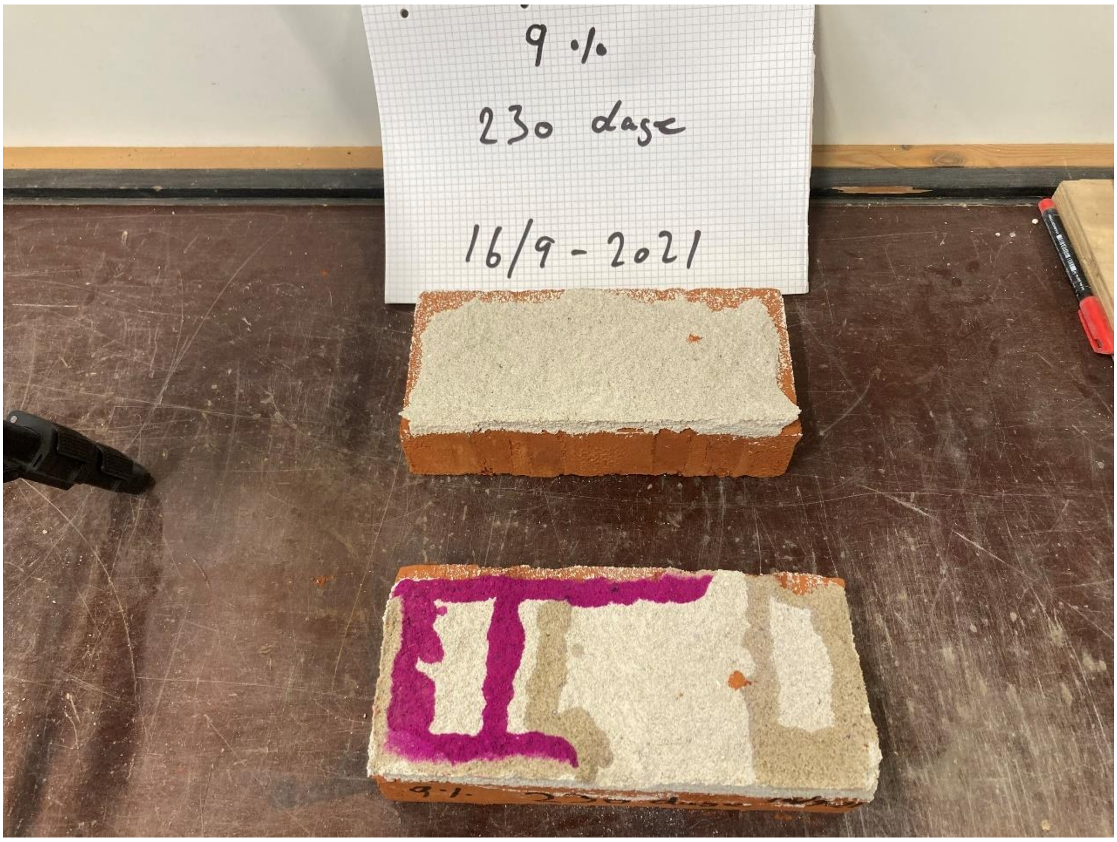
Picture 29

6.6% Mortar – 230 days



Picture 30

9.0% Mortar – 230 days

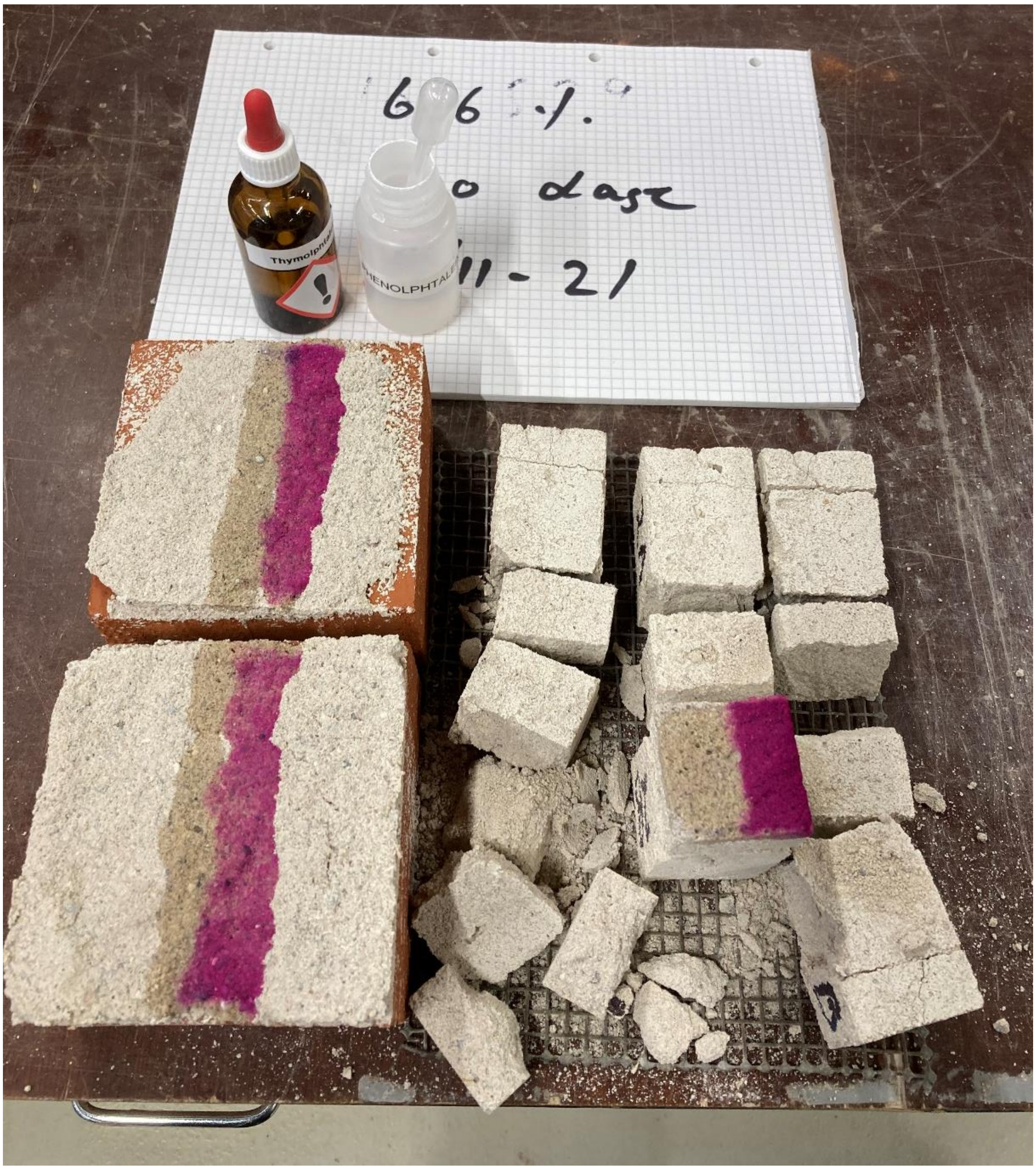


Picture 31

5.1% Mortar – 300 days

Picture 32

6.6% Mortar – 300 days



Picture 33

9.0% Mortar – 300 days

Picture 34

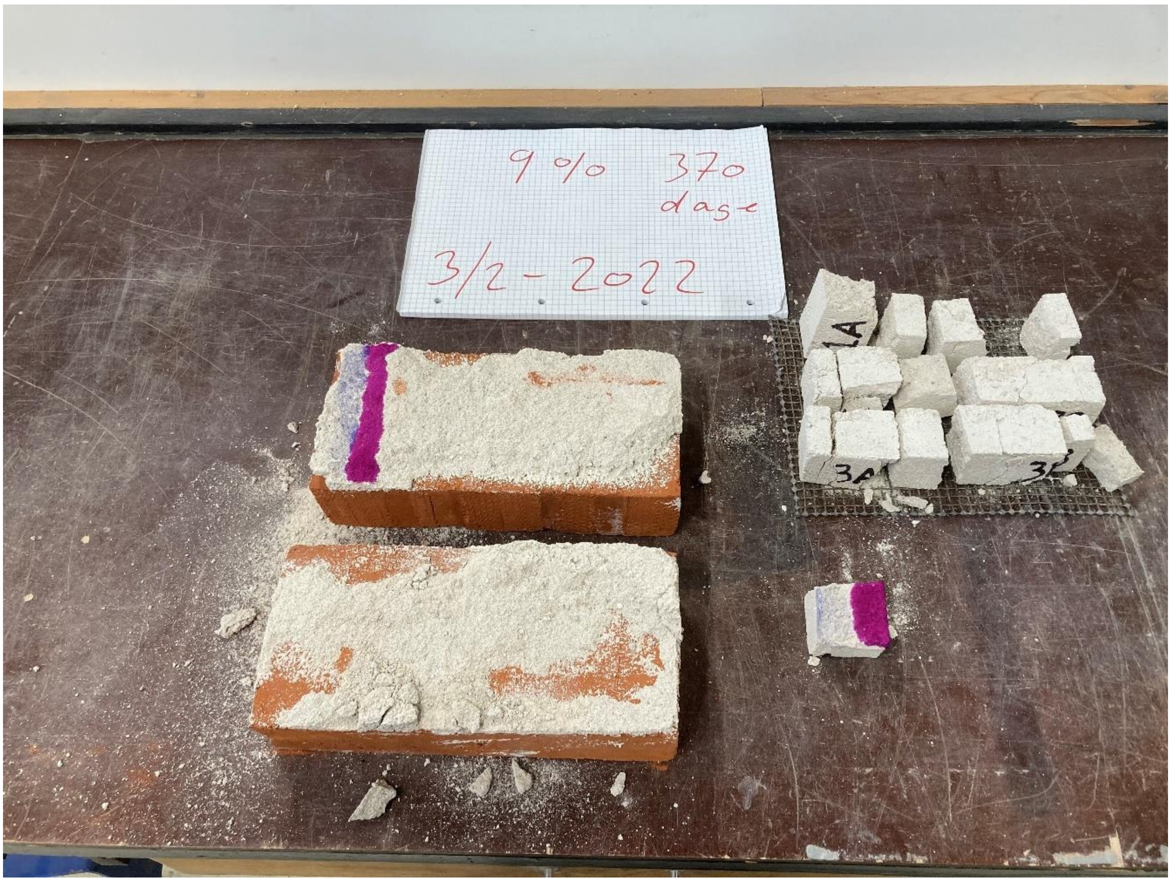
5.1% Mortar – 370 days

Picture 35

6.6% Mortar – 370 days

Picture 36

9.0% Mortar – 370 days



Picture 37