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VARIATION IN MECHANICAL PROPERTIES OF MORTAR AND MASONRY

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ABSTRACT

For over a year mortar prisms were tested to validate the mechanical properties of industrially made masonry mortar. The goal was to establish the variation of the tested mortar from the declared property values and the influence on strength of parameters like age, moisture content, and mass per volume. The compressive strength and modulus of rupture were almost twice the values declared by the manufacturer. Tendencies with respect to the relationship between compressive strength and the mentioned test parameters were as expected. Shear and bending tests on masonry made with the tested mortar were also performed and the results compared. Due to the relatively large variation in mechanical properties, no significant relationship between the strength of small scale specimens and larger test walls was found. Variation of properties in one wall was similar to the variation over a number of walls that were made in a one-year period.

KEYWORDS: shear, bond wrench, mortar properties, moisture effect, fracture surface.

INTRODUCTION

On various occasions for over a year, the same types of industrially made mortar and bricks were used to build masonry specimens. Because factories often produce a higher strength than required to prevent disapproval, the produced mortar usually will be stronger than specified. To validate the mechanical properties of the mortar used, prisms were tested according to EN 1015-11 [1] (which is similar to [2]) and bond wrench and shear tests were performed. The main goal was to establish the variation of the mortar from the declared values, the standard deviation and the influence on strength of parameters like age, moisture content during building, and mass per volume. A further goal was to find numerical values for shear and bending strength, to allow for numerical simulation of the experiments on walls.

Mortar properties (e.g. compressive strength) may vary due to:
- differences in composition,
- differences in time of production, early, i.e. direct after mixing a batch, late, i.e. a relative long time (several hours) after preparation,
- differences in the amount of added water at the time of taking a sample from a batch,

- differences in building procedures,
- curing conditions
- differences in the units.

The mortar prisms were made simultaneously with building of brick test walls in several projects for over a year. Three mortar specimens (40 x 40 x 160 mm^3) were prepared for each batch of mortar (75 kg). Each time, the mortar used was of the same brand and type and prepared and applied in the same manner. In order to obtain masonry for testing that would have as little as possible variation in properties all the soft mud bricks used were also of the same brand with a mean absorption rate of 1.5 $kg/m^2/min$ and a mean compressive strength of 27 MPa. More details on brick properties are given in [3]. All variation in material properties was unintended.

The mortar in real brickwork may have properties different from the properties found with mortar prism tests. Therefore, shear and bending tests were also performed and the results linked with the results from mortar prism-tests. A relatively large variation in mechanical properties, based on earlier studies [3] and [4], was expected.

EXPERIMENTS ON MORTAR PRISMS

The tested mortar, which is frequently used for masonry test walls, was a standard M7.5 mortar according NEN 3835:1991 [2]. According EN 1015-11:1999 [1] it would be qualified as a M5 mortar with a compressive strength of 5 MPa. Per mortar batch of 75 kg, three 40x40x160 mm^3 prisms were made using a steel mould. One day after making them, the prisms were taken out of the mould and stored for seven days at 100% RH and approximately 20°C. Then they were stored in a climate chamber at 60% RH and 20°C until testing. The mortar prisms were weighed directly after taking them out of the mould, after seven days storage and prior to testing.

The mortar specimens were made from mortar samples taken half way through a mortar batch of 75 kg. During building, the mason scrapes the surplus of mortar from the fresh brickwork and throws it back into the container. It is expected that this way of working could reduce mortar quality. Incidentally, the mason added water after some time to keep the mortar workable, which also could reduce strength.

In total, 68 series of three mortar prisms were prepared according to [2], where rules are similar to those in [1]. Per prism, the following parameters were recorded: date of production, test date and weight after demoulding, after seven days and prior to testing. From these data, the age of the specimen and the loss of weight were derived. Then the mortar prisms were tested in flexure and subsequently, the two remaining pieces were tested in compression via a steel platen of 40 x 40 mm^2.

MORTAR TEST RESULTS

From the mortar tests, a mean compressive strength of 9.51 MPa with a standard deviation of 1.76 MPa (C.o.V. = 18%) was determined. The smallest value was 6.10 MPa and the largest was 14.76 MPa. The mean tensile strength in bending test was 2.93 MPa with a standard deviation of 0.40 MPa (C.o.V. = 14 %). On average, the compressive strength is 3.25 times the modulus of rupture (C.o.V. 10.6 %). Values are shown in Table 1.

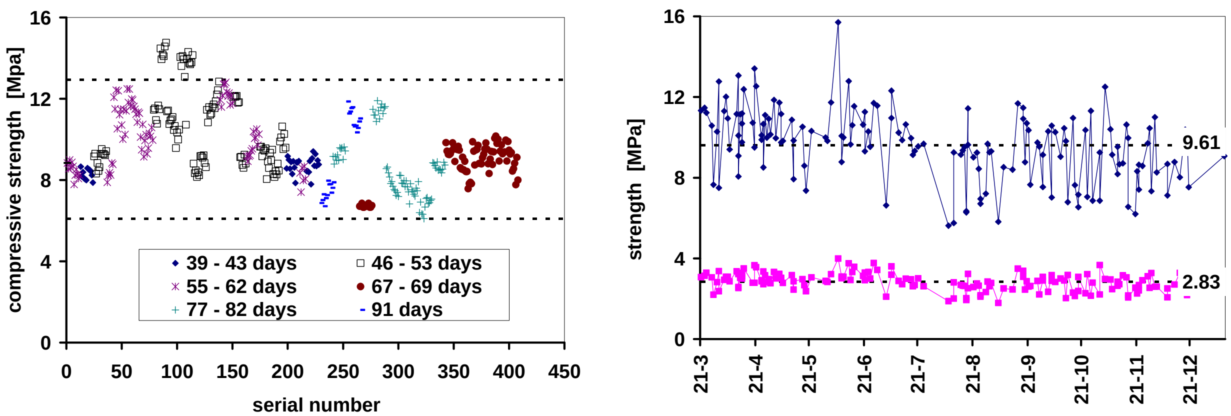
Time effects. Figure 1a shows the compressive strength plotted versus serial number. Clusters of six results can be recognized. Three clusters of six lay above the 95% upper-limit of 12.94 MPa (stronger) and no cluster lays below the 95% lower-limit of 6.09 MPa (weaker).

Usually, it is assumed that compressive strength of mortars increases over time. The specimen's age varied between 39 days and 91 days, and was 63 days on average. During this time, compressive strength showed no significant relationship (R^2 = 0.082), as shown in Figure 2.

According to the certification procedure, the manufacturer tested his mortar on a daily base using randomly taken samples. In Figure 1b, the manufacturer's mean values per day for modulus of rupture and compressive strength are plotted versus the test date. Table 1 shows values found with tests in the laboratory (specimens made during building of walls) and values given by the manufacturer. The resemblance is clear. The ratio between mean value and standard deviation (the C.o.V.) is smaller for the modulus of rupture than for the compressive strength.

Table 1: Mortar properties according to manufacturer and laboratory tests.

	modulus of rupture			compression		
	mean MPa	st.dev. MPa	C.o.V. %	mean MPa	st.dev. MPa	C.o.V. %
factory	2,83	0,43	15,11	9,61	1,74	18,45
laboratory	2,93	0,40	13,73	9,51	1,76	18,08
ratio	1,03	0,93	0,91	0,99	1,01	0,98



a b

Figure 1: a) Compressive strength versus serial number, and indication of age
b) Compressive strength and modulus of rupture (factory test results) versus test date

Moisture effects. When preparing prefabricated mortar and during building of walls, water is added to the mortar to obtain and maintain good mortar workability and to allow mortar hardening. In principle, a prescribed flow (170 mm in diameter) was aimed for, in combination with the mason's wishes for good workability. This means that sometimes water was added during the process. The specimens were all made from mortar samples taken during the building process of the wall. The mean mass of the prisms just before compressive testing was 460 gram, i.e. dry density equals 1797 kg/m^3 (C.o.V. 1.9%).

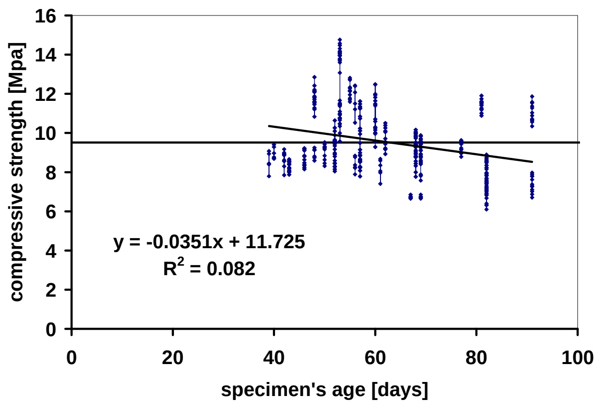


Figure 2: Compressive strength versus specimen's age.

A larger mass of prism indicates that more material per unit volume is present, consequently yielding a larger load bearing capacity. In Figure 3a, the compressive strength is plotted versus prism's mass just before testing. From a linear best fit procedure, a R^2 of 0.29 was established which shows that there is no significant relationship between compressive strength and dry mass. However, the increasing tendency is as expected: larger mass (less pores) results in a higher strength.

Compressive strength may be related to loss of weight. The amount of evaporated water while the prism dries is a measure of the amount of pores and more pores will lead to a smaller compressive strength. In Figure 3b, compressive strength is plotted versus loss of weight. The R^2 of 0.24 on the linear best fit line indicates that there is no significant relationship between compressive strength and loss of weight. However, the decreasing tendency is as expected.

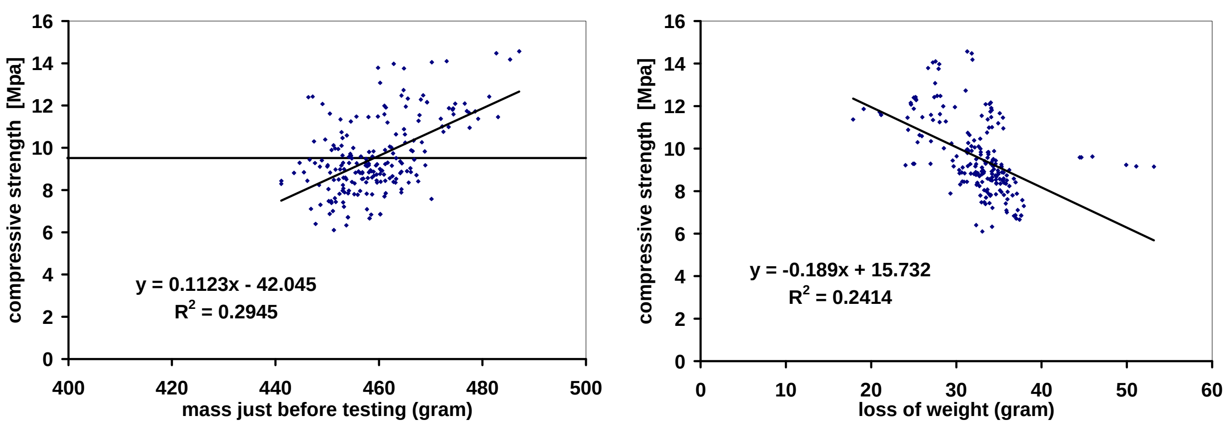


Figure 3: Compressive strength versus a) mass just before testing and b) loss of weight.

SHEAR TESTS

Per wall or part of a wall, shear specimens were made simultaneously with and in the same manner as the walls. The shear specimens were built of three units with two (bed) joints. The masonry was laid in stretcher bond using the prefabricated mortar mentioned above. The joints were pointed on one side. At the other side, the extruding mortar was only scraped off. Loose material (sand) was wiped off with a soft broom.

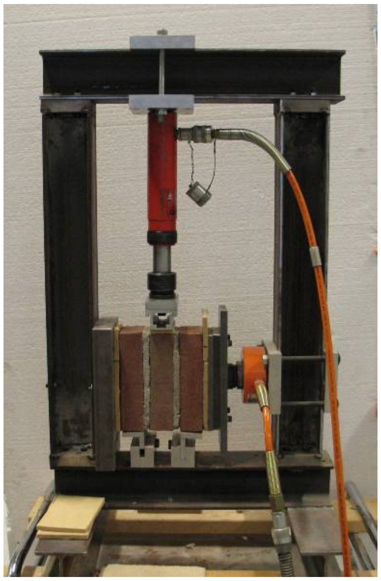
Walls and shear specimens were made with soft mud clay bricks, brand Rijswaard [5]. The main brick properties were: dimensions 206x96x50 mm^3, free water absorption 15.5 mass%, dry density 1630 kg/m^3, compressive strength 27 MPa and splitting strength ± 2MPa.

Shear strength was established according NEN EN 1052-3 [6] using the set-up shown in Figure 4a. The brick in the middle is sheared. Therefore, the two outer bricks are supported at the bottom while the middle one is vertically loaded on top with a controlled jack displacement speed of 0.1 mm/min. A varying precompression load is applied perpendicular to the shear surface, i.e. horizontally. Three precompression levels, 0.2 MPa, 0.6 MPa and 1.0 MPa were applied. The introduction points of the loads allowed for some adjustment for warp and dimensional variation in the specimens, as seen in Figure 4a.

Measured characteristics for each test are:

- the maximum shear load ($F_{i,max}$) and the matching precompression load (F_{pi}),
- the residual shear load ($F_{i,res}$) and the matching precompression load (F_{pi}).

The precompression load may fluctuate when the specimen cracks and shearing starts. Therefore, while testing, both vertical shear load and horizontal precompression were measured every second and plotted versus time. Figure 4b shows an example. Maximum shear load, residual load and corresponding precompression loads can be derived from these graphs and the measured data.



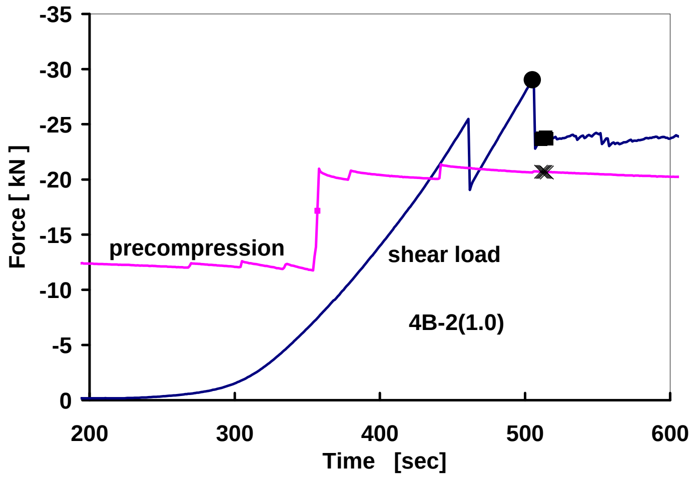


Figure 4: a) Shear test set up. b) Precompression and shear loads versus time

In some cases, when one joint cracked, the load dropped but resumed to increase as the jack moved further, as seen in Figure 4b. Then another peak level was reached. The shear strength was established using the maximum value of the measured load. To find the residual shear load, the average of five measurements was taken, starting five seconds after the maximum shear load occurred. In the example, the residual shear load was 23.72 kN with a precompression of 20.63 kN. The two-peak-phenomenon occurred more often; usually the first peak was lower than the second one. In the cracking phase of the test, the precompression load fluctuates most. Therefore, the average of five measurements was taken.

SHEAR TEST RESULTS

In Figure 5, the shear strength (τ) was plotted versus precopression (σ). A linear best fit (least squares method) through all results at the three applied precompression stress levels showed a Mohr Coulomb relationship with a moderate correlation of $R^2 = 0.35$.

Relatively low test results in Figure 5 are indicated. Some of these results were found using specimens with 'loose' bricks. After storage, the top brick was loose from the specimen, probably caused by shrinkage. In those cases, when testing started, the broken pieces were held together until precompression was applied. Other possible causes for the lower shear test results are: 1) the positioning of the specimen in the set-up and 2) the irregular shape of the mortar-brick contact area, which causes both uneven shear and precompression stresses and torsion in the joint.

When extreme values are excluded, the following equations are obtained:

$$\tau_{initial} = 0.6593 \cdot \sigma + 0.3261 \quad (R^2 = 0.65) \qquad (1)$$

$$\tau_{residual} = 0.7645 \cdot \sigma \quad (R^2 = 0.92) \qquad (2)$$

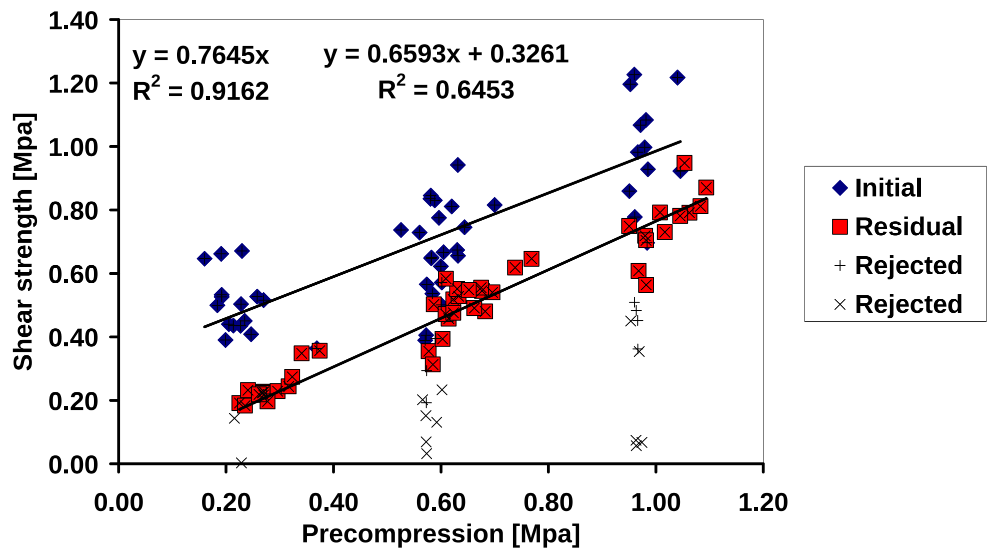


Figure 5: Shear strength versus prestress

When the coefficient of friction is assumed to be equal before and after cracking of the specimen, both initial and residual results can be used to find a best fit surface instead of a line, with precompression and ‘crack condition’ as parameters. This results in:

$$\tau = 0.70\sigma + \alpha \cdot 0.30 \qquad (3)$$

with:
σ = precompression
α = factor for the cracked (α = 0) or the uncracked (α = 1) condition.
The un-cracked condition (α = 1) concerns the initial (τ_{init}) value with similar values as found with equation (1).
All factors in the equations (1), (2) and (3) are based on a loaded gross area equal to the averaged dimensions of the bricks used, i.e. 96 x 206 mm^2. The net area is smaller and varies in shape and dimensions, as seen in Figure 6.

Figure 6: Contact areas after shear testing

<u>Specimen’s age.</u> Besides the precompression, the age of the specimen probably plays a role. It is expected that mortar and, consequently, masonry strength increase over time. A first impression was obtained from the mortar tests results discussed earlier. The age varied between 39 days and 91 days (63 days in average) and in this time period the age of the mortar specimens had no significant effect on compressive strength.

Subsequently, a multiple regression analysis model was developed, in which the age and precompression stress were used as parameters. This resulted in the following equation:

$$\tau = 0.6093 \cdot \sigma + 0.29228 \cdot \alpha + 0.000092 \cdot age \qquad (4)$$

From equation (4), it follows that the age had no effect on shear strength. The product of the age-factor and age (say 90 days) is 0.0082, which contributes little to the final outcome for τ. For this analysis, the complete set of data was used. The other factors in equation (4) are comparable with those from equation (3), which also confirms the negligible contribution of the age on strength.

BOND WRENCH TEST RESULTS

The principle of a bond wrench test is that one brick is loaded in bending [7]. Therefore, it is clamped in a steel holder which, in turn, is loaded via a lever arm of approximately one meter in length. The head joints close to the brick to be tested are cleared, using a large, Widia toothed hand saw. The load was applied via a bucket on a rope. The bucket was slowly filled with weights untill fracture occurred. In this way, the brick-mortar bond surface is mainly loaded in bending. The result of the test is the applied weight at which the mortar joint fractures. This value is used in the calculation of the bond strength for which linear elastic behaviour is assumed.

The tests were performed on five walls, with 91 tests in total. In Figure 7, the results are represented by plotting the strength versus test position (number of layer) in height. The layers were numbered top to bottom. On average, the bond-wrench strength is 0.45 MPa, with a standard deviation of 17 MPa (C.o.V. 37%) which results in a 95% confidence level of 0.18 MPa. Mean values per wall are given in Table 2. The considerable C.o.V. value was comparable with values known from literature, [7] and [8]. One of the reasons for large variation in test results is perhaps the shape and size of the irregular shaped bond surfaces as shown from bond wrench tests in Figure 8 and those from shear tests in Figure 6.

Table 2: Mean values for bond-wrench strength per wall

	number of tests	average MPa	Standard deviation MPa	C.o.V. %
Wall 18A	23	0.44	0.14	31
Wall 17A	18	0.46	0.19	42
Wall 18 B	15	0.47	0.15	31
Wall 17 B	12	0.51	0.21	41
Wall 7B	21	0.41	0.17	41
Mean	91	0.45	0.17	37

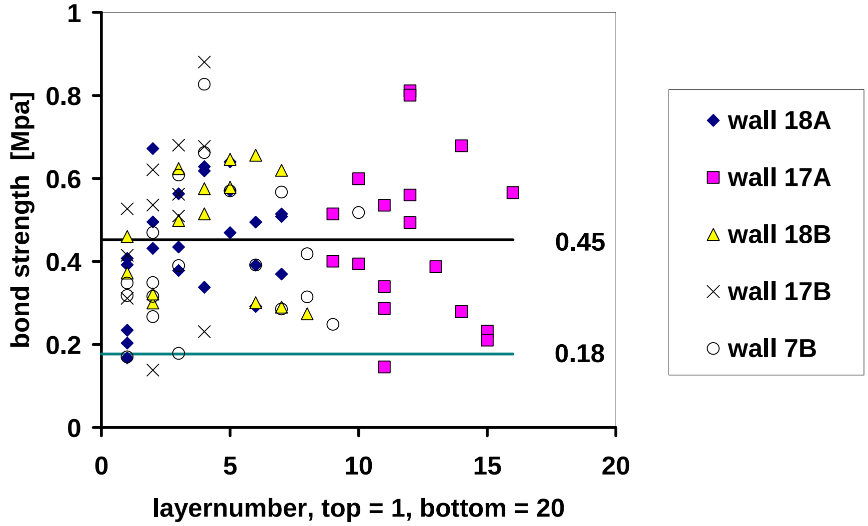


Figure 7: Bond wrench strength plotted versus position in height with mean and 95% level.

Figure 8: Irregular shaped mortar brick bond surfaces after bond wrench testing

CONCLUSION

The mortar compressive strength was almost twice the value desired according EN 1015-11:1999 [1].

The results from quality control tests by the manufacturer of the mortar are the same as those from the laboratory tests on mortar prisms made simultaneously with building of the masonry.

Tendencies with respect to the relationship between compressive strength and test parameters like age, mass and loss of weight are as expected. For a specimen's age between 30 days and 90 days, the age has no significant effect on strength.

It is no longer necessary to weigh the specimens because no statistical significant relationships between weight or loss of weight and compressive strength were found.

Bond wrench test results, and to some extent shear test results, show that properties vary over one masonry wall in a similar manner as they vary over a number of walls built on several occasions in a one year period.

Due to the relatively large variation in mechanical properties, no significant relationship between the strength of small scale specimens and larger test walls was found.

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