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EXPERIMENTAL INVESTIGATIONS ON THE INFLUENCE OF THE WATER ABSORPTION OF CALCIUM SILICATE MASONRY UNITS ON THE MORTAR PROPERTIES IN THE JOINT

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ABSTRACT

Masonry is a construction method primarily suited for building structures under compressive load. The decisive characteristic to assess the load bearing capacity of such building members is their compressive strength. In Eurocode 6, presently the masonry compressive strength can only be determined by approximation on the basis of test results, applying an empirical equation which only considers the uniaxial compressive strength values of unit and mortar. However, numerous investigations on the load bearing and fracture mechanisms of masonry under compressive load already showed that the masonry compressive strength does not only depend on the strength of the single components but also on their different deformation behaviours. Usually, the mortar has a significantly higher lateral strain than the masonry unit which is, however, restrained by the bond between both materials. The obstruction of the lateral expansion of the mortar results in additional compressive stresses in the mortar joint and tensile stresses in the unit, normal to the loading direction. This leads to a triaxial state of stress in the unit which can decrease the masonry strength depending on the height of the lateral tensile stresses in the unit and the lateral deformability of the mortar. Thus, the Poisson's ratios and the elastic moduli of unit and mortar can be specified as essential influencing parameters. Furthermore, the interaction between the suction behaviour of the masonry unit and the water retention of the mortar considerably influences the properties of the joint mortar. Therefore, extensive tests were conducted to examine the influence of the water absorption of masonry units on the mortar properties in the joint using the example of calcium silicate masonry.

KEYWORDS: *masonry, modulus of elasticity, mortar properties, Poisson's ratio, water absorption*

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INTRODUCTION

The masonry compressive strength depends on a number of parameters. The unit compressive and tensile strength, the joint compressive strength, the ratio of the radical strain coefficients and also the moduli of elasticity of unit and mortar as well as the bond behaviour can be specified as possible primary influencing parameters. Some of these, however, depend on secondary influencing parameters, such as the suction behaviour of the units and the water retention of the mortars. Despite many investigations regarding this subject, still the masonry compressive strength can only be derived experimentally from compression tests on wall specimens or by approximation, applying the following empirical equation by Mann [1] which depends on the uniaxial compressive strength values of the single components unit and mortar:

$$f_k = K \cdot f_{st}^{\alpha} \cdot f_m^{\beta} \tag{1}$$

where f_k = characteristic compressive strength of the masonry; K, α, β = parameters, calculated by regression; f_{st} = converted average minimum compressive strength of the masonry unit; and f_m = strength class of the masonry mortar.

The constant K to be placed into equation 1 as well as the exponents α and β are parameters which are specified depending on the respective unit-mortar combination. Generally, the standard compressive strength of the mortar hardened in steel moulds exponentiated with β is inserted, even though the accuracy of the approximation is expected to be higher when the joint mortar compressive strength is applied, cf. Metje [2]. The aspect to be considered in this context is the water content in the mortar joint depending on the interaction between the suction behaviour of the masonry unit and the water retention of the mortar which considerably influences the hardening mechanism as well as the strength of the mortar in the bed joint. It is obvious that the determination of the masonry compressive strength based on the uniaxial compressive strength values of the units and mortar without considering further essential influencing parameters must inevitably lead to deviations from the actual strength. Therefore, it was the aim of the investigations presented in this paper to examine the influence of different suction behaviours of masonry units depending on their moisture content during placing in a first step on the properties of the mortar in the bed joint, but also on the load bearing and deformation behaviour of masonry under compressive load.

MATERIALS

The examinations were conducted on calcium silicate masonry units (CS), which - according to the manufacturer label - can be assigned to strength class 20, meaning that the target compressive strength f_{st} has to be higher than 20 Mpa (single values) and 25 Mpa (mean value), respectively. The dimensions of the units are approximately 248 mm · 240 mm · 249 mm (unit length · unit width · unit height). As masonry mortars, two customary general purpose mortars, a lime-cement mortar of strength class M2.5 (target mean compressive strength: $f_m \geq 2.5$ Mpa) and a cement mortar of strength class M5 (target mean compressive strength: $f_m \geq 5.0\ Mpa$) according to DIN EN 998-2, were used.

EXPERIMENTAL INVESTIGATIONS

Water absorption of the masonry units

The water suction characteristics can be described directly by experimentally determining the capillary water absorption and the water absorption coefficient, respectively. For this purpose, cubes with an edge length of 100 mm were firstly sawn from the CS units, so that one surface of each sawn cube originated from the bed joint area. Secondly, three cubes for each moisture content (oven dry, 4 % by weight, 10 % by weight) were conditioned. Then they were wrapped airtight so that the moisture could spread evenly across the cross-section of the cube. After one week the cubes were taken out of the bags and the lateral surfaces were carefully sealed. The water absorption coefficient was determined by partial immersion. During this test, the water level was kept about 5 mm above the highest point of the bottom side of the cubes. The area-related increase in mass Δm_t was determined at specified times within a period of 24 h and plotted against the square root of weighing time $\sqrt{t}$, see Figure 1 left. The suction behaviour of the CS units can be quantified by means of the water absorption coefficient $W_{w,24h}$. This coefficient results as ratio between the water quantity absorbed by the specimens per unit area and the square root of time, see Figure 1 right.

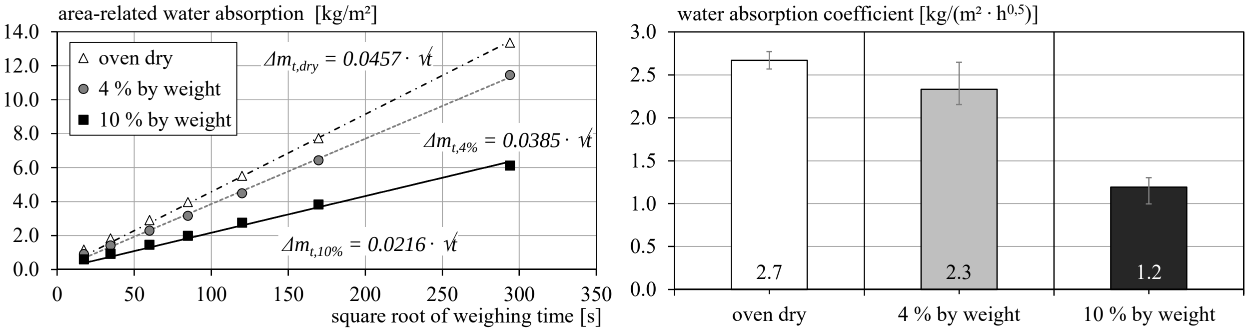

Figure 1: Water absorption (left) and water absorption coefficient (right) of calcium silicate masonry units with different initial water contents

On the oven dry specimens, a water absorption coefficient of $W_{w,24h} = 2.7\ kg/(m^2 \cdot h^{0.5})$ was determined. This corresponds to the values specified in the literature regarding dry CS units, cf. Schubert & Laurini [3], where CS units were classified as highly absorbent. As expected, a higher initial moisture content of the units reduced their suction and hence their water absorption coefficient. The specimens conditioned to 4 % by weight featured a 13 % lower value than the dry samples. The water absorption coefficient determined on the almost saturated specimens (10 % by weight) amounts to only about 45 % of the value determined on the dry cubes.

Compressive and tensile strength of the masonry units

Furthermore, the influence of the moisture on the strength properties of the masonry units was examined. For this purpose, the calcium silicate units were firstly adjusted to the aforementioned moisture contents and wrapped airtight for at least one week before testing. During the test, the axial and lateral deformations were recorded on the units. Figure 2 exemplarily shows a prepared specimen to examine the compressive strength in the direction of the unit height (a) and the tensile strength in the direction of the unit length (b) as well as the respective arrangement of the measuring points on the test specimens. The test results are shown in Figure 3. The mean values of the compressive strength (Figure 3 left) and the tensile strength (Figure 3 right) are illustrated as well as the scatter (min/max) of the single tests (5 single values, each).

Figure 2: Determination of the compressive (a) and tensile strength (b) of the CS units

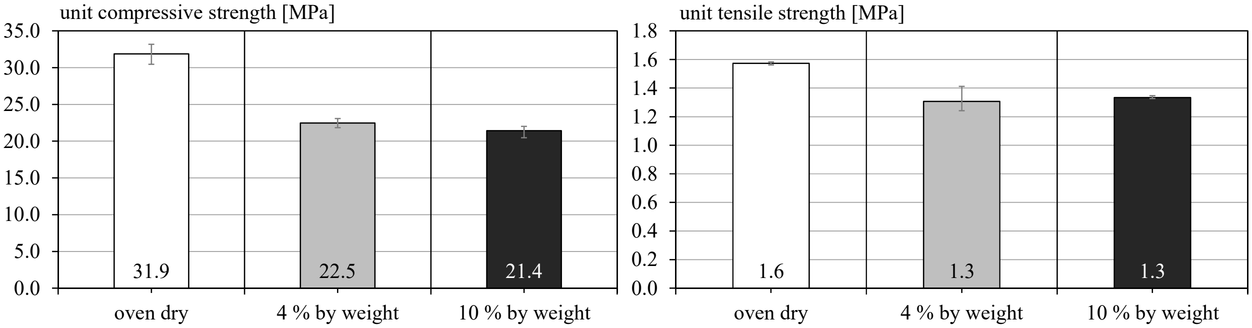

Figure 3: Compressive strength (left) and and tensile strength (right) of the CS units

As can be seen in Figure 3, the moisture content of the masonry units also exerts a significant influence on their compressive and tensile strength. The highest strength values were reached by the oven dry units. The compressive strength in the direction of the unit height as well as the tensile strength in the direction of the unit length decreases with increasing moisture. Related to the strength in the oven dry state, the compressive strength in the wet state amounts to between 0.67 (10 % by weight) and 0.71 (4 % by weight). The ratios of the tensile strength range between 0.83 (4 % by weight) and 0.85 (10 % by weight).

With regard to the masonry itself, however, it cannot be assumed that the moisture content of the masonry units during placing has a similar effect on the strength of the units and also on the masonry during testing because the moisture content does not remain constant in the period between manufacturing and testing.

Joint compressive strength

According to experience, the standard compressive strength to be usually determined on mortar prisms manufactured in steel moulds generally differs significantly from the actual strength of the joint mortar since the suction behaviour of the masonry units and, furthermore, possible compacting effects due to the weight of the units are not taken into account. On the contrary, the influence of different sample dimensions can be considered insignificant.

In order to closely examine the influence of the water suction on the mortar properties in the bed joint, 18 test series with two 2-unit specimens were manufactured, see Table 1. For this purpose, the CS units were placed on top of each other using both general purpose mortars. After different periods of time, the units were separated again in order to take samples from the joint mortar which had hardened in contact with the masonry unit. The joint compressive strength was determined on the same day of sample taking.

Table 1: Test matrix

Mortar type	**Initial moisture content of the masonry units**	**Extraction and test age**		
		7d	**14d**	**28d**
M2.5	oven dry	*	*	*
	4 % by weight	*	*	*
	10 % by weight	*	*	*
M5	oven dry	*	*	*
	4 % by weight	*	*	*
	10 % by weight	*	*	*

* two 2-unit specimens, each

At first, the units were conditioned to three different moisture contents, analogous to the method described in connection with the determination of the water absorption coefficient. Before manufacturing the specimens, the bed joint areas were treated with a kaolin suspension; see Figure 4 (a). After the applied kaolin layer had dried, the 2-unit specimens were manufactured, see Figure 4 (b). This preparation method has proven to be useful in the past because, on the one hand, the suction behaviour of the units is not influenced and, on the other hand, the bond between mortar and unit is weakened by the kaolin layer, which allows an easier extraction of the hardened joint mortar independent of the different moisture contents of the masonry units, see figure 4 (c). On the same extraction day, square flat prisms with an edge length of about 50 millimetres and a thickness corresponding to that of the bed joints were dry sawn from the mortar joints, see Figure 4 (d).

Afterwards, the central area of the flat prisms was subjected to compression by means of a round stamp according to method III of DIN 18555-9, see Figure 5 left. Since the load application area of the prisms normally is not entirely flat, a rigid felt layer was placed on top and at the bottom of the test specimens.

Figure 4: Manufacturing of 2-unit specimens and extraction of prisms

The test results of both examined mortars are compiled in Figure 5 right, according to initial moisture content of the units and extraction age. In addition to the determined joint compressive strength (mean values from 16 to 20 single values) and the scatter of each test series, the diagram also displays the compressive strength values determined on the standard prisms without contact to the masonry unit.

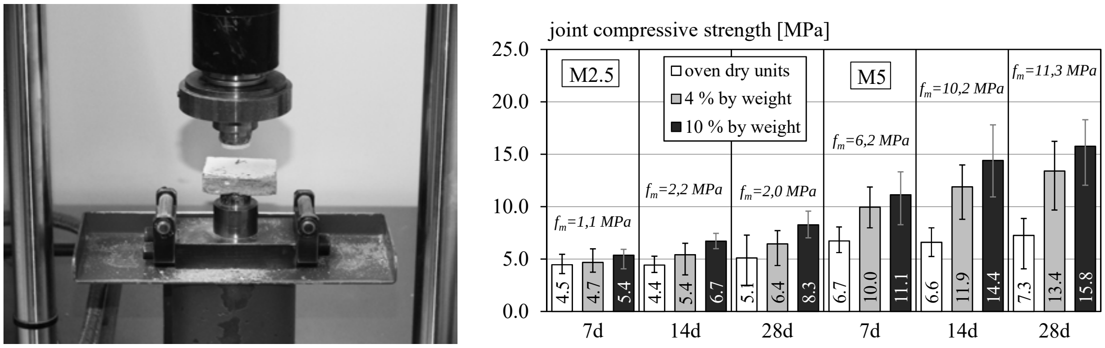

Figure 5: Joint compressive strength; test setup (left) and test results (right)

It can be noted that in most cases the compressive strength of the joint mortar deviates significantly from the standard compressive strength of the respective mortars due to the contact with the calcium silicate unit. Moreover, it can be discerned from the results illustrated in Figure 5 that the strength development of the mortars is influenced by the suction behaviour of the masonry units in varying degrees. It can be observed that the strength development of the joint mortar is pretty much completed after 7 d when it comes in contact with oven dry calcium silicate units. The difference between the 7 d and the 28 d strength values is very small. This is due to the fact that large quantities of the water required for the strength development were previously absorbed by the highly absorbing, dry CS units at an early age of the mortar. Depending on mortar type and moisture content of the units during placing, significantly higher or lower values of the joint compressive strength can result, compared to the standard compressive strength f_m. In general it can be stated that the compressive strength of the joint mortar increases with increasing initial moisture of the units. Furthermore, the compressive strength values determined on prisms from the joint are always considerably higher when these come in contact with the moist or wet calcium silicate units (4 % by weight and 10 % by weight) than the values f_m determined on mortar prisms manufactured in steel moulds.

Dynamic modulus of elasticity of the joint mortar

Next, the influence of the contact between the masonry units and the mortar on the dynamic modulus of elasticity of the joint mortar was examined. Therefore, an additional mortar prism with a length of about 100 mm, a width of about 50 mm and a thickness corresponding to that of the bed joint thickness was extracted from the joint of each 2-unit specimen. In this study, the pulse transit-time method was chosen to determine the dynamic modulus of elasticity of the joint mortar influenced by the water absorption of the units. Here, the time taken by ultrasonic pulse to get through a mortar prism (in axial direction) is measured between pulse generator and receiving sensor, see Figure 6 left. The dynamic modulus of elasticity is calculated as follows:

$$E_{dyn} = \frac{(1+\nu)\cdot(1-2\cdot\nu)}{(1-\nu)}\cdot\rho\cdot\left(\frac{l}{t}\right)^2 \tag{2}$$

where E_{dyn} = dynamic modulus of elasticity; ν = radical strain coefficient ($\nu = 0.2$); δ = density of the mortar prism; l = length of the mortar prism and t = pulse transit-time.

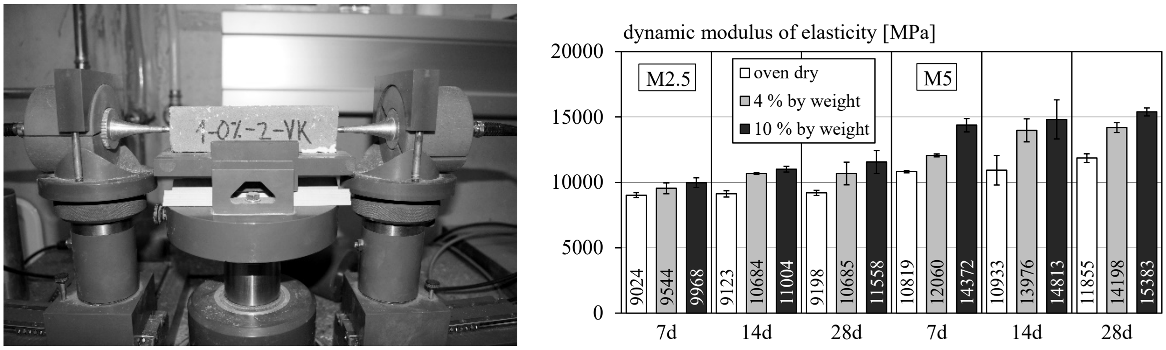

Figure 6: Dynamic modulus of elasticity of mortar; test setup (left) and test results (right)

The test results are compiled in Figure 6 right, separated according to the initial moisture of the units and the extraction age. A significant influence of the initial moisture content of the units on the dynamic modulus of elasticity can be detected at both examined mortars. In all test series, the calculated values of the dynamic modulus of elasticity increase with rising initial moisture of the CS units during placing. However, the difference between the results of the three extraction dates is comparatively small. Analogous to the joint compressive strength, the dynamic modulus of elasticity of the joint mortar only changes slightly when beeing in contact with the oven dry calcium silicate units at the age of between 7 d and 28 d.

Static modulus of elasticity of the joint mortar

Up to now, there is no standardised test method to determine the static modulus of elasticity of the joint mortar affected by the masonry unit. However, to still be able to examine the influence of the suction behaviour of the units on the deformation behaviour of the joint mortar, tensile tests were performed on additional prisms (140 mm · 40 mm · 12 mm) which were extracted from the joint of 2-unit specimens at the age of 28 d. In addition to units with the aforementioned moisture contents, units with an increased moisture content of 13 % by weight were additionally used for manufacturing of the 2-unit specimens. The lateral strain was measured with two strain gauges each with a measuring length of 20 mm, which were applied to the prisms perpendicular to the load direction. The axial deformations were determined with two displacement transducers DD1 (measuring length 50 mm). The load introduction was made by steel mounting plates, glued on the test specimens (see Figure 7 left) and flexibly attached to the testing machine with jointed eye screws. Figure 7 right exemplarily shows a prepared specimen as well as the arrangement of the strain gauges and the displacement transducers on the test specimens. The test results are compiled in Figure 8.

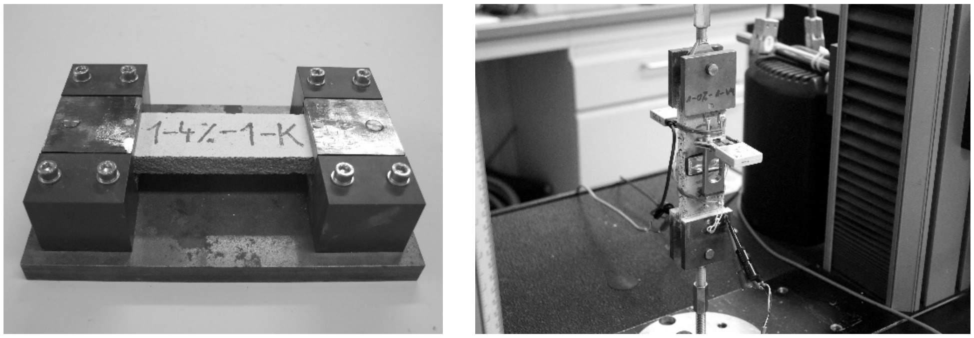

Figure 7: Tensile specimen; application of steel mounting plates (left) and test setup (right)

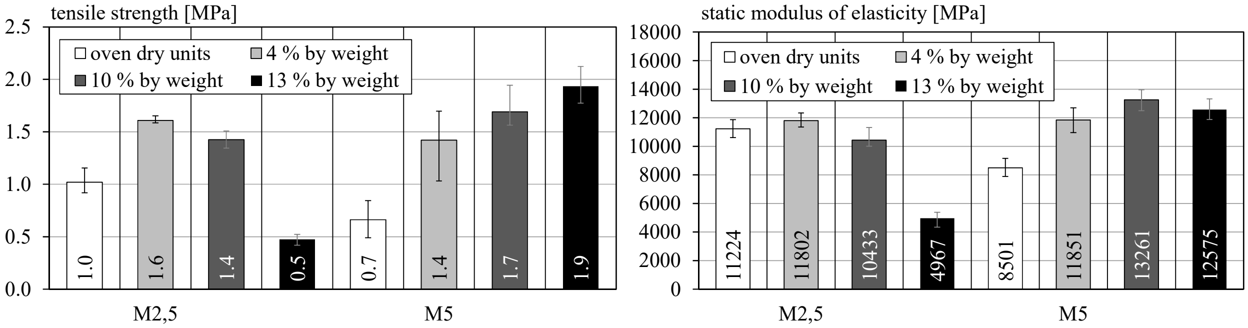

Figure 8: Test results; tensile strength (left) and static modulus of elasticity (right), extracted from the joint of 2-unit specimens at the age of 28 d

As can be seen in Figure 8, the unit moisture also has a significant influence on the tensile strength and the elastic modulus of the joint mortars. In the test series with mortar M5, the tensile strength clearly increases with rising initial moisture of the units during placing. This is largely the case also for the values of the elastic modulus, but, when comparing the series with a moisture content of 13 % by weight and 10 % by weight, no further increase but a slight decrease can be observed. This is different with mortar M2.5. Though the values of the tensile strength and the elastic modulus also increase in the test series with a moisture content of 4 % by weight compared to the series with dry units. The higher moisture contents of 10 % by weight and 13 % by weight, on the other hand, lead to a partial even considerable decrease in tensile strength and modulus of elasticity, possibly caused by incomplete hardening of the lime-cement mortar in contact with the saturated masonry units.

A clear influence of the unit moisture on the Poisson's ratio of the joint mortar can not be derived due to the small measured lateral strains as well as the quite high scatter of the single tests.

Load bearing and deformation behaviour of masonry

In order to examine the influence of the suction of the masonry units on the load bearing and deformation behaviour of masonry, altogether six test series with three masonry pillars, each, were manufactured and tested at the age of at least 28 days. Again, the CS units were placed with different moisture contents in combination with both mortars. Numerous deformation measurements were performed on the masonry pillars using inductive displacement transducers in axial and lateral direction.

The specimen geometry and the arrangement of the measuring points are illustrated in Figure 9.

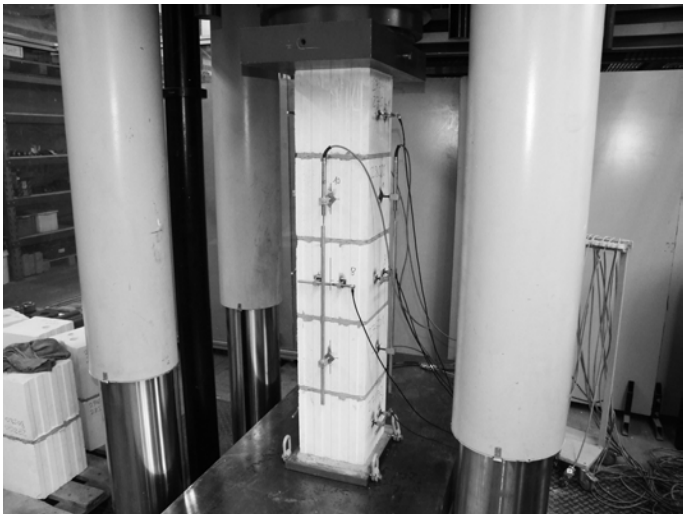

Figure 9: Determination of the masonry compressive strength and modulus of elasticity

The determined stress-strain curves are displayed as mean value curves in Figure 10. A summary of the test results is shown in Figure 11. The mean values of the masonry compressive strength

(Figure 11 left) and of the elastic moduli (Figure 11 right) as well as the scatter of the single tests are illustrated.

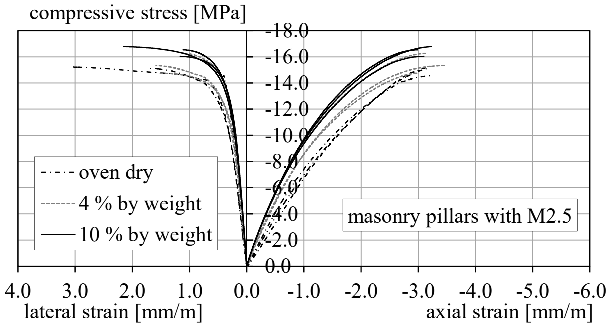

Figure 10: Stress-strain curves of masonry pillars with mortar M2.5 (left) and M5 (right) under compressive load (3 pillars/series)

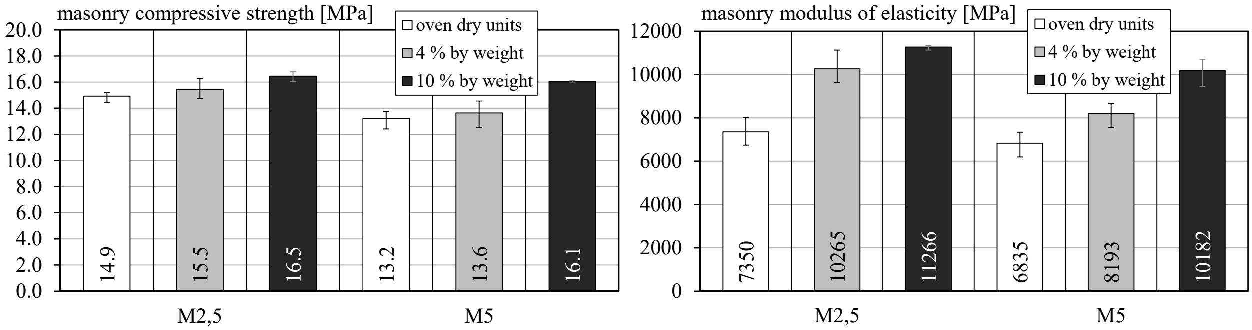

Figure 11: Masonry compressive strength (left) and modulus of elasticity (right)

The results illustrated in Figures 10 and 11 show that the suction of the units, which is different depending on the initial moisture contents, also has a significant influence on the load bearing and deformation behaviour of the masonry pillars. With both mortars, the compressive strength as well as the modulus of elasticity of the masonry pillars increases with rising moisture of the masonry units. This was also observed for the joint compressive strength. The masonry pillars manufactured using oven dry units feature the lowest compressive strength values for both mortars. The use of masonry units conditioned to 4 % by weight increases the masonry compressive strength with mortar M2.5 as well as with mortar M5 only by about 3 %. Units with a still higher moisture content of 10 % by weight lead to an increase in the masonry compressive strength by 10.2 % for mortar M2.5 and for mortar M5 to a significant increase by 21.4 %. However, without exception, masonry pillars with mortar M2.5 reach higher compressive strength values than specimens produced with mortar M5, although the joint compressive strength of mortar M5 is considerably higher after getting into contact with the calcium silicate units than that of mortar M2.5. The same applies to the moduli of elasticity of the masonry. This, however, can probably be ascribed to a completely different lateral deformation behaviour of both mortars in the masonry.

CONCLUSIONS

Numerous tests were conducted to examine the influence of the suction behaviour of calcium silicate units on the properties of the joint mortar and on masonry under compressive load.

Based on the results presented in this paper, it could be shown that the suction behaviour of the units and the degree of the resulting influence on the examined properties of the joint mortar and the masonry clearly depend on the initial moisture content of the masonry units during placing.

For the examined materials, firstly it can be stated that the strength properties of the joint mortar, and hence also of the masonry, improve with increasing moisture content of the masonry units during placing up to a moisture content of 10 % by weight.

To which extent, however, the masonry is eventually influenced by the water absorption of the units varies strongly, depending on the chosen material combination.

In the present studies, the contact to the CS units influences the masonry properties much stronger when the weaker mortar M2.5 is used than when specimens are manufactured with mortar M5.

ACKNOWLEDGEMENTS

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