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Moisture transfer and change in strength during the construction of earthen buildings

La transferencia de humedad y el cambio en la resistencia durante la construcción de edificios de tierra

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SUMMARY

A number of rammed earth projects constructed in recent years in Germany and abroad testify to the high level of architectural interest in this material, not only in our country. Rammed earth has been "rediscovered", in particular by young architects, due to its unique materiality and fascinating and individual surface aesthetics. In connection with the realisation of two rammed earth projects realised in Thuringia, Germany, in 2003/2004 some questions arose concerning the process of moisture transfer and changes in strength properties during construction. The earthen building standards detail only very rough estimates of drying times for rammed earth walls.

The idea arose to develop a test programme for investigating the aspect of drying time with regard to the change in material strength in rammed earth walls, as well as for elaborating general aspects of testing procedures for rammed earth in standards.

The paper presents results of a laboratory programme that attempts to approach this very complex problem. A series of test specimens were produced and the unconfined compressive strength was determined after different drying times varying from 7 to 90 days. The moisture content of the test specimens also was varied: at OMC (Proctor test) and above and below the OMC.

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RESUMEN

Una serie de proyectos de tierra apisonada construidos en los últimos años en Alemania y en el extranjero dan testimonio del alto nivel de interés arquitectónico en este material, no solo en nuestro país. La tierra apisonada ha sido "redescubierta", en particular por los arquitectos jóvenes, debido a su materialidad única y fascinante y la estética singular de su superficie. En relación con la realización de dos proyectos de tierra apisonada realizados en Turingia, Alemania, en el período 2003/2004 surgieron algunas preguntas sobre el proceso de transferencia de la humedad y los cambios en las propiedades de resistencia durante la construcción. Las normas de construcción de tierra indican solamente estimaciones muy aproximadas de los tiempos de secado para muros de tierra apisonada.

Surgió la idea de desarrollar un programa de pruebas para investigar el aspecto del tiempo de secado con respecto al cambio en la resistencia del material en muros de tierra apisonada, así como para establecer los aspectos generales de los procedimientos de ensayo de tierra apisonada en las normas.

El documento presenta los resultados de un programa de laboratorio que intenta abordar este complejo problema. Se elaboró una serie de muestras de análisis y se determinó la resistencia a la compresión no confinada después de diferentes tiempos de secado que variaban de 7 a 90 días. El contenido de humedad de las muestras también era variado: en el método abierto de coordinación (prueba Proctor) y por encima y por debajo de la OMC.

Keywords: moisture transfer, strength, desiccation, test, earth construction.

Palabras clave: *transferencia de humedad, resistencia, secado, ensayo, construcción con tierra.*

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1. INTRODUCTION

A number of rammed earth projects constructed in recent years in Germany and abroad testify to the high level of architectural interest in this material, not only in our country. Rammed earth has been "rediscovered", in particular by young architects, due to its unique materiality and fascinating and individual surface aesthetics. In connection with the realisation of two rammed earth projects realised in Thuringia, Germany, in 2003/2004 (1) (Figures 1, 2) some questions arose concerning the process of moisture transfer and desiccation accompanied by changes in strength properties during construction. The Lehmbau Regeln, the German standard for building with earth (2), detail only very rough estimates for the drying times of rammed earth walls.

1

1. Rammed earth wall project "Stairway to Heaven", Nordhausen, Thuringia, Germany

2

2. Curved rammed earth wall in Suhl Hospital chapel, Thuringia, Germany

The idea arose to develop a test programme for investigating the aspect of drying time with regard to the change in material strength in rammed earth walls, as well as for elaborating general aspects of testing procedures for rammed earth in standards. The general questions were:

1. The design values of compressive strength for rammed earth walls documented in the standards apply to dry material. The process of desiccation influences the strength of a newly built moist rammed earth walls. The maximum load-bearing capacity of the wall will only be achieved once the core of the wall is dry. How long does this take?

2. The recommended moisture content of soils for compaction in foundation building is the Optimum Moisture Content (OMC) according to the PROCTOR test. Is this recommendation also valid for earthen building constructions?

3. Could the bearing capacity of the moist rammed earth material be exceeded at the base of the wall as a result of compaction and the additional weight of the rising wall during construction?

These questions are very complex and it is the aim of the testing programme to contribute at least a little towards their resolution.

A test programme was drawn up as part of student work at the Bauhaus University Weimar (3, 4) to try and find answers to the above questions.

2. THE PREPARATION AND MOULDING PROCESS

Soil has to be prepared and processed for utilisation in earth construction. The preparation process includes the crushing of the excavated soil, sieving, mixing with aggregates (and binders) and wetting (5). Finally the unshaped earth mixture is moulded, compacted and dries. After mixing, the loose and unshaped earth mixture contains voids which must be minimised for building purposes by compaction.

Compaction is the process of increasing the density of the earth mixture filled into a mould under mechanical pressure by expelling the air from the voids. In the compacted state volume changes are minimal as it dries out and the strength increases to a maximum. This is the aim of load-bearing earth constructions. The addition of moisture during the mixing process softens the clay particles ($d < 2\mu m$) which adhere in a thin coat to the coarser particles and facilitate compaction. Thin films of water cover the soil particles. During compaction these films allow the soil particles to slide over each other more easily so that finer particles fill the voids between coarser particles. Up to a certain point the addition of water replaces the air in the voids in the earth mixture while further wetting reduces the effects of compaction. The turning point is known as the "optimum moisture content" of water for a given soil and compaction energy which in turn results in a maximum dry density (MDD) of soil per volume unit (the so-called PROCTOR density). The optimum moisture content (OMC) and density (MDD) for a given soil can be determined using the PROCTOR test.

The aforementioned process works well for coarse-grained soils because the water films are extremely thin in comparison to the grain diameter. Fine-grained soils are clay-rich soils. The clay particles are also covered with water films but they are "thicker" in comparison to those films covering coarse-grained soils. The adhesion of the clay minerals to coarser grains and the water films significantly resist the compaction of fine-grained soils. The attainable maximum dry densities with the same amount of compaction energy are therefore lower than they are for coarse-grained soils.

The moulding process forms an unshaped, wet or plastic earth mixture into a shaped earth building product by compaction depending on the type of earth construction. The moulding process can be broadly divided into two categories:

- Block-sized moulding similar to fired brick production.
- Element-size moulding similar to concrete building.

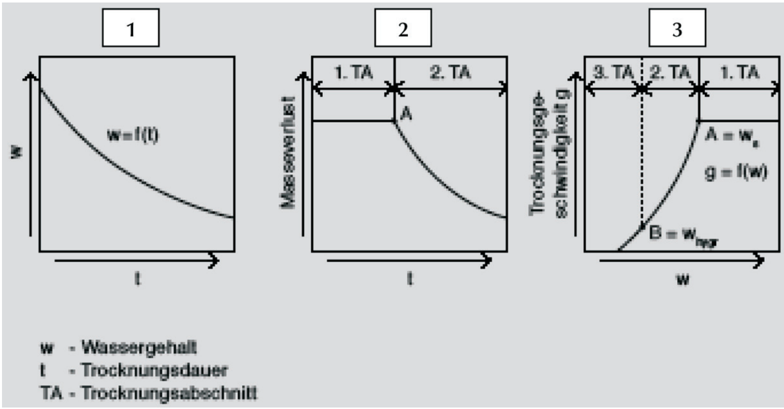
The different types of moulding are determined by the amount of water added. This "preparing" water transforms the earth mixture into different degrees of consistency which can broadly be divided into three levels:

- Semi-dry state: the prepared earth mixture appears dry and crumbly and there is little cohesion between the aggregates. The water content is less than 15% (around the water content at the Plastic Limit, PL, in soil mechanics).
- Plastic state: the prepared earth mixture is a homogeneous mouldable mass. The water content is usually between 15 – 25% (around the Plasticity Index, PI = Liquid Limit, LL – Plastic Limit, PL).
- Liquid state: the prepared earth mixture is a homogeneous pasty/thick liquid mass. The water content is usually between 30 – 40% (above the Liquid Limit, LL).

3. THE DESICCATION PROCESS

The *desiccation* process is the process of dehydration. All earth building products and elements need to be allowed to dry in the air. It is advisable to allow earth building products and elements to dry naturally so that they dissipate moisture slowly to reduce the occurrence of shrinkage cracks. In temperate climates, the natural drying process is not possible in winter. In such cases moist earth building products and element must be wrapped and protected against freezing through the provision of heating and ventilation.

The general course of the desiccation process can be divided into three stages as shown in Figure 3 (5):



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3. Drying sections in moist earth building products / elements

w water content
Masseverlust *loss of mass*
t time of desiccation
g velocity of drying
TA drying section

Stage 1: The pore water at the surface of the earth material or element changes from the liquid into the gaseous state and evaporates into the ambient air by convection. The desiccation starts.

Stage 2: The level of desiccation shifts towards the middle of the earth building element. Capillary moisture transport draws water out of the inner core of the earth building element to the "desiccation level" (point A). The resulting vapour is transported by diffusion through the dry part of the building element. The thickness of the dry part increases as the "desiccation level" moves towards the moist core. Once the moisture reaches the surface of the building element, the vapour escapes into the ambient air by convection.

In Stage 2 the process of a loss of mass starts accompanied by shrinkage and the danger of cracking. In soil mechanics this state is described by the Shrinkage Limit, SL.

Stage 3: The "desiccation level" reaches the core of the earth building element and begins to disappear as it reaches the hygroscopic moisture content w_{hygr} (point B). The drying process is complete. The hygroscopic moisture content w_{hygr} is the level of moisture that is in equilibrium with the ambient air humidity.

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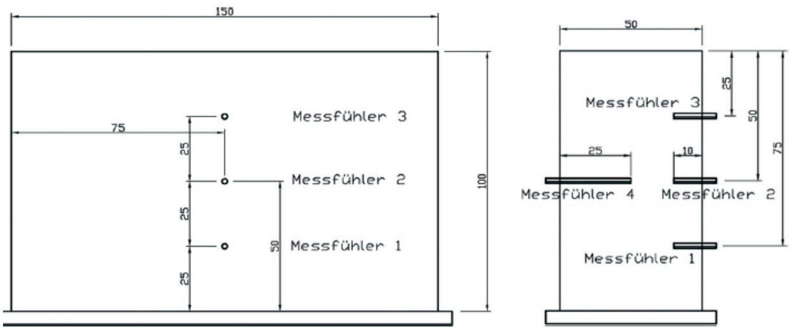


5a

4. Preparation and drying of the soil samples

5a. Size and plan of measuring instrumentation of the rammed earth test wall

4. TESTING PROGRAMME

The testing programme consisted of two parts: In the first part a series of cube samples were produced while varying the parameters of initial water content, drying time, organic fibre and mineral coarse aggregates. The unconfined compressive strength of the samples was tested after different drying periods. The preparation of the samples followed the same procedure as real site conditions.

The second part of the testing programme was the construction of a life-size (true scale) rammed earth wall section. Electronic moisture measuring devices were integrated into the wall to monitor the desiccation process of the wall.

4.1. Materials and methods

The natural raw earth material used for testing was a typical loess-type clay sourced from Kleinfahner in Northern Thuringia, the same kind used for both the aforementioned rammed earth projects. It should be noted that loess is inappropriate for rammed earth and it was therefore necessary to add sand and gravel as well as straw fibres.

4.2. Sample preparation and parameters tested

Test cubes of 20 cm edge length were prepared according to the Lehmbau Regeln (2), varying the parameters tested in the following manner:

– Material composition: raw natural soil, raw soil with coarse aggregates, raw soil with coarse aggregates and straw fibres (as used in the projects “Stairway to Heaven” and “Hospital chapel” (1), (Figures 1, 2).

– Drying period before measuring the unconfined compressive strength: 7, 14, 28, 45, 90 days

– Moisture content during compaction: w at Optimum Moisture Content OMC (PROCTOR), w < OMC (only for mixtures with coarse aggregates and straw fibres), w > OMC.

A total of 105 samples (three for each parameter) were prepared according to this plan. The mean values of the test results were considered.

The manual compaction of all test cubes was carried out in 3 layers of 15 cm which were then compacted to 7 cm using a falling weight of 7.8 kg applied 32 times to each layer from a height of 45 cm. A comparison between this compaction method and those used on site was not provided and this is a general problem.

The compacted cubes were air dried in a room with a climate similar to the real site conditions: air temperature about 12° C, relative air humidity about 68% (Figure 4).

The following parameters of the raw loess-type earth from Kleinfahner were also determined: a mineralogical analysis was conducted using X-ray diffraction, a cohesion test using an 8 shaped sample (NIEMEYER (2)), and the plasticity index and measure of shrinkage (according to DIN 18952).

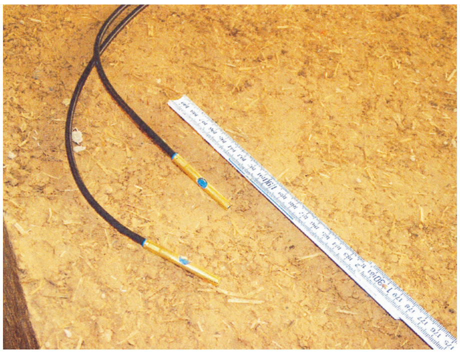
4.3. Preparation of the test wall

In order to simulate the real conditions during compaction and the subsequent drying process in the aforementioned projects (1) a test wall section was built at a scale of 1:1 in the Earth Building Laboratory at the Bauhaus-University Weimar (Figure 5a). The size of the wall section was 1.5 m long, 1.0 m high and 0.5 m thick.

The test wall was made with the same soil mixture used for the aforementioned projects: a loess-type soil from Kleinfahner modified with coarse aggregates and straw fibres. The


5b

5b. Rammed earth test wall with installed measuring instrumentation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5c. Measuring feeler type ALMEMO

moisture content during compaction was near the OMC (12.3 – 13.0%).

To simulate the drying process under environmental conditions the "end" and "top" surfaces of the wall section were covered with plastic film, so that drying could only occur through the exposed sides.

Electronic measuring instruments (type ALMEMO including data logger 2290-8, Figure 5c) were installed in the test wall with the aim of investigating the process of drying from the core to the surface according to Figure 5b. The feelers did not directly measure the humidity of the material but the air humidity in the boreholes closed after installation because the rammed earth material used consisted of soil, coarse aggregate and straw fibres and was very inhomogeneous. Instead, the isothermal sorption line for test samples made of the same rammed earth mixture was calibrated. This line gives a correlation between air and material humidity.

Additionally the degree of shrinkage in both horizontal and vertical directions was measured by measuring the change in distance between two embedded nails in each direction.

5. TEST RESULTS

5.1. Soil parameters

Particle size distribution

The particle size distribution of the raw soil (1) was determined according DIN 18122-1 & -2 and DIN 18123. The mixture used in the real project (2) is very different from (1). It was modified with coarse aggregates to approximate the FULLER-grain distribution (Figure 6) because the raw soil was not optimal for rammed earth.

How can one "compose" an optimal or suitable particle size distribution for rammed earth?

According to a number of references this can be achieved with the help of the model of the "ideal" FULLER-grain distribution, which is also used for foundation design. In this model the pores created by the large grains are completely filled by smaller grains (hence the ideal situation). Another general recommendation is that the proportions sand + gravel to clay + silt should be 70:30. The grain size distribution of the natural raw soil (1) is far from ideal while the grain size distribution of the modified mixture (2) is much better.

The grain distribution of the rammed earth mixture (2) was determined according to the FULLER formula:

$p = 100\ (d/D)^n$

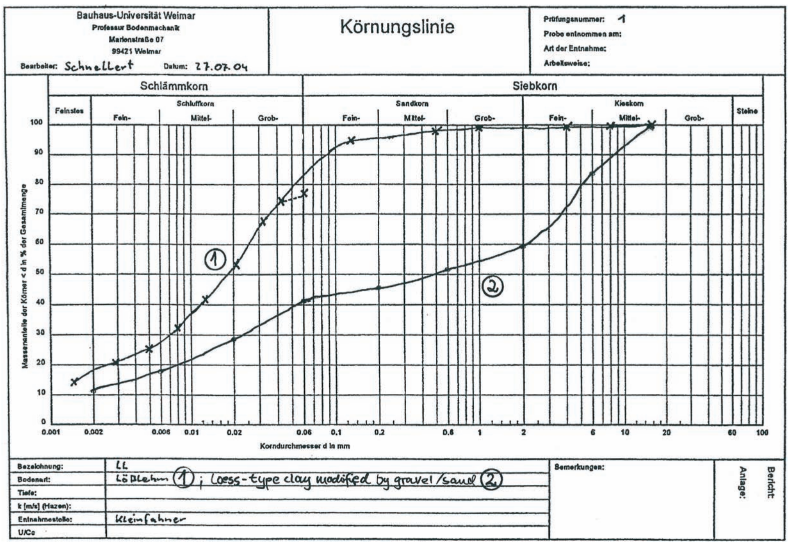
where:

p the proportion of grains of a given diameter

d the diameter of grains for a given value of p

D the largest grain diameter (modified for the rammed earth mixture (2) D = 20 mm)

n the grading coefficient (for spherical grains 0.5)



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6. Grain size distribution of raw and modified test soil

A proportion of 10% of clay (d < 0.002 mm) for the entire mass was defined as a second modification in order to guarantee sufficient plasticity of the rammed earth mixture. According to a modified FULLER formula:

$p = 90\ (d/20)^{0.5} + 10$

The grain distribution of the rammed earth mixture (2) was calculated, and then produced in a mixing plant and delivered to the site.

Plasticity:
The Plasticity Index, PI, of the natural raw soil was determined according DIN 18122-T1:
PI = LL - PL; PI = 0.121, LL = 0.316; PL = 0.195.

According to (6) the Liquid Limit and Plastic Limit for soils used as rammed earth should ideally be as follows: LL = 0.30 – 0.35; PL = 0.12 – 0.22.

Cohesion Test:
The cohesion test (NIEMEYER (2), see also (6)) is a wet tensile test using 8-shaped samples. The cohesion, which in this test is designated as "binding force", is classified into the categories low ("poor") and high ("good").

The cohesion of the natural raw clay was determined and classified according to (2):
100 g/cm²; "poor" 80 – 110 g/cm².

The cohesion or "binding force" of raw soils used for rammed earth must be at least "poor".

Shrinkage Test:
For soils used as raw materials for rammed earth it is also necessary to know their shrinkage parameters in order to avoid or reduce cracking after drying. The shrinkage criteria is < 2% after 72 h air drying using samples with an optimal initial moisture content (OMC). The measure of shrinkage was determined according to DIN 18952.

The shrinkage determined for the natural raw soil was 4.6%. This is far too much, and coarse mineral aggregates as well as straw fibres are necessary to reduce the shrinkage to an acceptable measure.

PROCTOR-Test:
The PROCTOR compaction test was carried out according DIN 18127 and exhibited the following results:

Maximum dry density MDD at optimum moisture content OMC

Raw natural soil

MDD = 1.784 g/cm³; OMC = 0.152

Raw soil with coarse aggregates

MDD = 1.973 g/cm³; OMC = 0.113

Raw soil with coarse aggregates and straw fibres

MDD = 1.804 g/cm³; OMC = 0.134

Mineralogy:
Figure 7 shows the result of the X-ray diffraction analysis of the raw soil. Significant amounts of quartz and calcite are typical for loess soils. Muscovite and chlorite clay minerals were determined in small amounts.

5.2. Cube sample tests

The following moisture contents are used in the discussion of the results of the sample tests:

Table 1
Cube sample test results

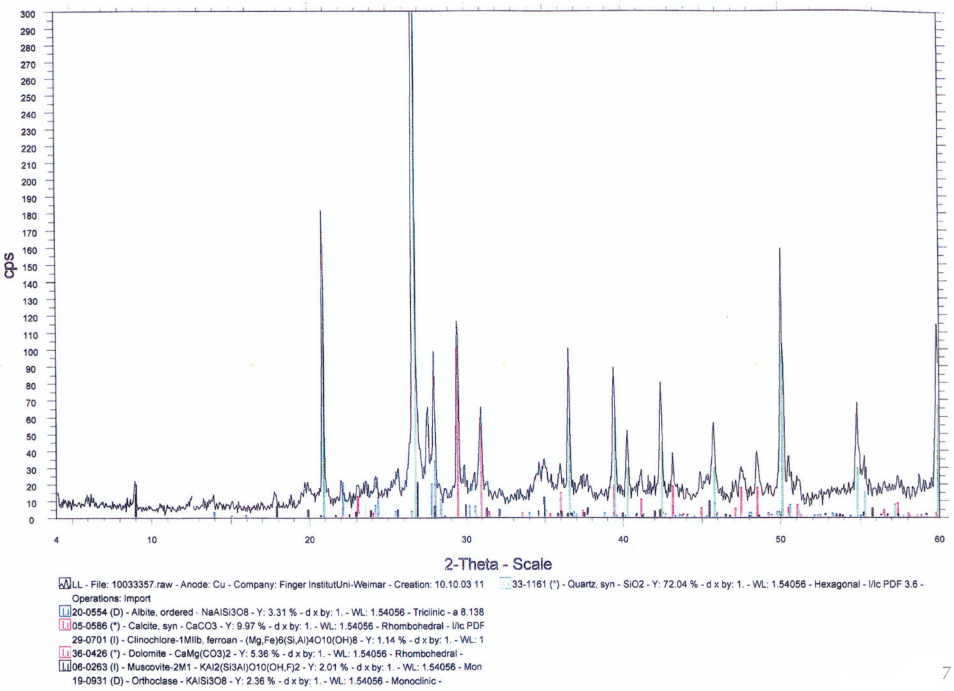
Sample	Soil	Water saturation	Initial moisture content	Moisture content after 7 days drying	Moisture content after 90 days drying
I	raw natural soil	w ~ OMC	0.1472	0.1307	0.0278
II	raw natural soil	w > OMC	0.2032	0.1717	0.0380
III	raw soil with coarse aggregates	w ~ OMC	0.0992	0.0611	0.0071
IV	raw soil with coarse aggregates	w > OMC	0.1242	0.1064	0.0127
V	raw soil with coarse and straw aggregates	w ~ OMC	0.1228	0.1005	0.0137
VI	raw soil with coarse and straw aggregates	w > OMC	0.1552	0.1277	0.0169
VII	raw soil with coarse and straw aggregates	w < OMC	0.0930	0.0880	0.0092

The test results are discussed according to the following topics:

Initial moisture content as a function of drying time.

Figure 8 shows that the moisture content during compaction has an influence on the remaining moisture after 90 days of drying. The range of the absolute values varies between 3.8% for raw soil at w > OMC (II) and 0.71% for raw soil with coarse aggregates at w = OMC (III). The corresponding values for the initial moisture content are 20.32% (II) and 9.9% (III). The values "Initial moisture content" and "Remaining moisture after 90 days of drying" for the samples (III) and (VII) are similar: for III as aforementioned and (VII): 9.3% and 0.92%.

Regarding the three different groups of earth material composition as described in chapter 4.2, all mixtures with above-optimum moisture contents during compaction (w > OMC: II, IV, VI) also exhibit higher absolute values of remaining moisture content after 90 days of drying in comparison to those with an optimum initial moisture content (w ~ OMC: I, III, V). That means that the higher the initial moisture content during compaction, the higher the remaining moisture content after 90 days of drying.



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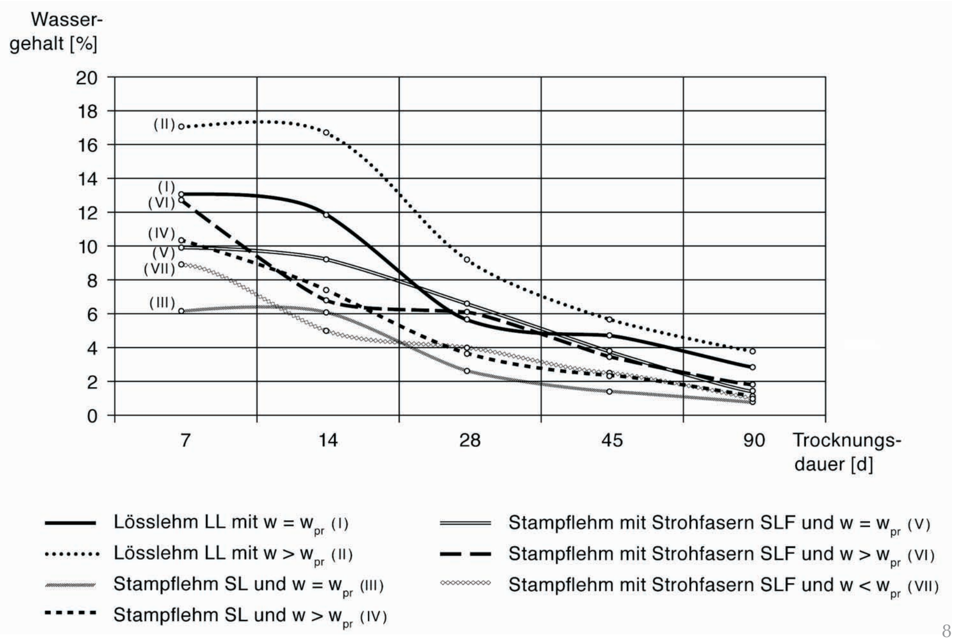

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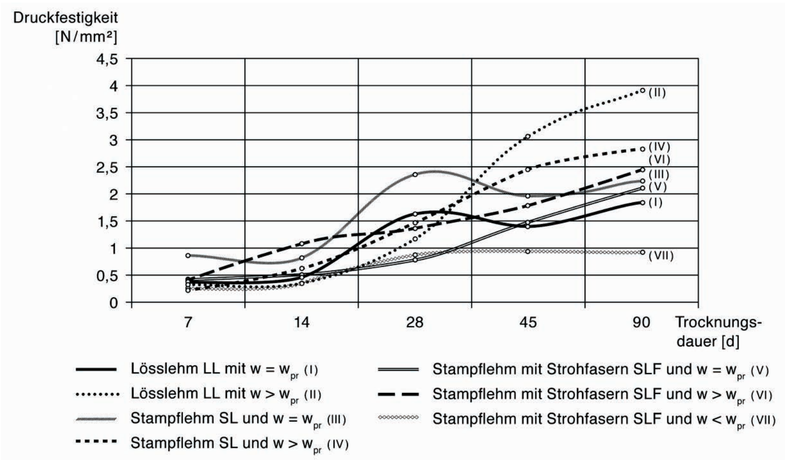
7. Mineralogical analyses using X-ray diffraction

8. Initial moisture content as a function of drying time



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9. Unconfined compressive strength (UCS) as a function of drying time

The speed of drying exhibits similar results for all mixtures: After rapid drying in the first week (with the exception of VII) the process slows in the second week for the mixtures (I), (II), (III), (V) and whilst for the mixtures (VI) and (VII) this slowing of the drying process is offset by a week in the third and fourth week. The drying process of mixture (IV) is continuous without interruption.

Unconfined compressive strength as a function of drying time.

According to Figure 9 all mixtures with an above-optimum moisture content (w > OMC: II, IV, VI) achieve higher unconfined compressive strengths (UCS) than those with an optimal moisture content (w ~ OMC: I, III, V) after 90 days of drying. The highest UCS after 90 days drying time (3.89 N/mm²) is achieved by mixture (II) "natural raw soil, w > OMC", the lowest with mixture (VII) "raw soil with coarse and straw aggregates", w < OMC with 0.9 N/mm².

This difference in strength between the different groups of earth material compositions is most significant for the natural raw soil: 3.89 and 1.83 N/mm² for w > OMC (I) and w ~ OMC (II) respectively (112.6% in relation to the smaller value). The respective differences of the modified mixtures are lower. The lowest difference was observed for the "clay with coarse and straw aggregates" mixtures (V) and (VI) with 2.43 and 2.09 N/mm² (16.3%). For the "dry" mixture (w < OMC: VII) the respective values are 2.43 and 0.9 N/mm² (170%). The respective values for "raw clay with coarse aggregates" (III) and (IV) are 2.8 and 2.21 N/mm² (26.7%).

The compaction effort was constant. The influence of higher or lower compacting energies on the UCS was not considered here.

The speed at which the strength increases is also very different. The natural raw clay at w ~ OMC (I) already achieves 80% of the maximum UCS at 90 days after 28 days of drying. After 28 days the strength decreases, turning into an increase after 45 days again. In the case of w > OMC (II), the mixture achieves only 30.3% of the maximum UCS after 28 days of drying. Both modified mixtures with w > OMC (IV) and (VI) exhibit only a little more than the half (51.4 and 56%) of the maximum value of UCS at 90 days. The "raw soil with coarse aggregates" mixture at w ~ OMC (III) achieves a strength after 90 days that is even 5.9% lower than that measured after 28 days of drying. The function has the same quality as raw soil at w ~ OMC (I) with two turning points. The "dry" mixture (VII) already achieves its maximum UCS (1.0 N/mm²) after 45 days. This value slackens off by about 10% during the next 45 days, the second part of the drying period.

The following densities were determined after 7, 28 and 90 days of desiccation along with the respective values of UCS:

Table 2

Densities after desiccation

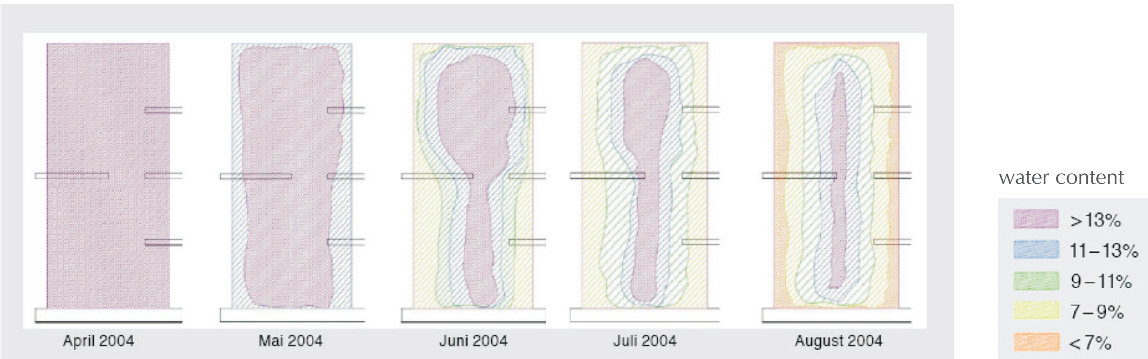
Sample	Soil	Water saturation	Density after 7 / 28 / 90 days of desiccation [g/cm3]	UCS after 7 / 28 / 90 days of desiccation [N/mm2]
I	raw natural soil	w ~ OMC	1.81 / 1.74 / 1.69	0.35 / 1.61 / 1.83
II	raw natural soil	w > OMC	2.04 / 1.97 / 1.92	0.31 / 1.17 / 3.89
III	raw soil with coarse aggregates	w ~ OMC	2.00 / 1.96 / 1.79	0.86 / 2.34 / 2.21
IV	raw soil with coarse aggregates	w > OMC	2.17 / 2.03 / 1.99	0.21 / 1.44 / 2.80
V	raw soil with coarse and straw aggregates	w ~ OMC	1.77 / 1.74 / 1.70	0.42 / 0.77 / 2.09
VI	raw soil with coarse and straw aggregates	w > OMC	1.94 / 1.85 / 1.77	0.39 / 1.36 / 2.43
VII	raw soil with coarse and straw aggregates	w < OMC	1.64 / 1.62 / 1.53	0.39 / 0.99 / 0.90

Shrinkage of tested cube samples:

The shrinkage of the raw natural soil used at w > OMC (3.5%) (I) was higher than the 2% maximum limit criteria (see above). It was therefore also of interest to evaluate the influence of aggregates on possible shrinkage reduction. For this purpose the shrinkage was determined as a percentage reduction of edge lengths in the direction of compaction for all cubic samples before testing the UCS.

The degree of shrinkage measured for the tested cube samples according to the aforementioned mixtures (I) – (VII) differed significantly. After 90 days of drying the maximum shrinkage was measured as 3.51% for raw soil with w > OMC (I). This was to be expected. The lowest values (~0) were exhibited by the "raw soil with coarse aggregates" mixtures at w ~ OMC (III) and w < OMC (VII).

The values of the "raw soil with coarse and straw aggregates" mixture were significantly lower than the raw soil: 0.28% at w ~ OMC (V), 0.6% at w > OMC (VI) and 0.08% at w < OMC (VII).



10. Moisture profile of the test wall section

5.3 Moisture profile of the test wall section

Figure 10 shows the moisture profile of the test wall section over a period of half a year according to the results obtained by electronic measuring.

The drying process of the wall results from a diffusion of the moisture from the core to the surfaces. Figure 10 shows that the moisture level of the core is unchanged after six months drying and the same as the levels during construction of the test wall. By comparison, the drying of the wall surfaces takes only a short time.

It seems that during the first two months the drying of the lower part of the wall is more effective than the upper part. After six months of drying the moisture distribution in the core appears to be homogenous, but now the drying process also spreads from the base in a vertical direction.

The moisture profile in Figure 10 can only show a general trend. Further investigations are necessary to fully understand the drying process of rammed earth walls. Under real conditions the air temperature and relative air moisture as well as the wind velocity influence the drying time and the moisture profile of a rammed earth wall.

6. CONCLUSIONS

Investigations were undertaken to obtain a better understanding of the process of moisture transportation and change in material strength of rammed earth walls after compaction as a function of time, material and initial water content.

The test results can only offer some general conclusions as they are limited to the clay mixtures tested. Further investigations are necessary:

1. The moisture content w ~ OMC during the compaction of cubic samples is not generally the "optimum" level for the rapid drying of rammed earth walls. Initial moisture content levels of w > OMC can accelerate the drying process. Coarse and straw fibre aggregates influence the quality of the drying process: they accelerate the drying process at w > OMC. The most intensive drying is in the first week after compaction with a slowing of the drying process in the following one or two weeks. The remaining moisture after a drying period of 90 days for all tested mixtures depends on the initial moisture content: the higher the water content at compaction, the higher the water content after 90 days of drying.

2. All mixtures with initial moisture contents w > OMC achieve higher unconfined compressive strengths (UCS) as those with w ~ OMC after 90 days of drying. This is most evident for the unmodified raw loess-type soil used which also exhibited the highest and the lowest UCS values with the exception of the "dry" mixture w < OMC (VII) which exhibited the lowest absolute value

of UCS. Coarse and straw aggregates reduce the absolute UCS values compared with unmodified mixtures.

3. The increase in strength over the time is different: The “raw soil” and “raw soil with coarse aggregates” mixtures achieve almost the maximum UCS value after 28 days of drying at w ~ OMC initial moisture content. In the same period, the other mixtures exhibit only around 30 – 56% of their respective maximum UCS after 90 days of drying.

4. Coarse and straw fibre aggregates significantly reduce the measured shrinkage. The addition of coarse and/or straw fibre aggregates to raw soil that is inappropriate for rammed earth can therefore modify its properties such that it becomes appropriate for rammed earth.

5. Based on these tests, the following recommendations can be made:

- For rammed earth the moisture content during compaction should be about 10% higher than w = OMC.
- The determination of the UCS should be carried out for samples of earth mixtures after 90 days of drying because the drying process of earth mixtures for rammed earth takes much more longer than for concrete.

6. The moisture profile determined for a test wall section at 1:1 scale over a period of half a year confirmed the very long drying time necessary for compacted rammed earth constructions. The drying of the surfaces takes place comparatively quickly. However, the gradual drying out of the core to the surface takes a considerable amount of time.

7. Further research programmes investigating the process of moisture transfer and change in strength during desiccation in earth building materials should also investigate the compaction effort as an additional parameter.

BIBLIOGRAPHY

(1) Schroeder, H.; Bieber, A.: “New Rammed Earth Projects in Thuringia”. *LEHM 2004, 4th International Conference on Building with Earth* (2004), pp. 190-201. Dachverband Lehm e.V., Leipzig.
(2) Dachverband Lehm e.V. (ed.): Lehmbau Regeln – Begriffe, Baustoffe, Bauteile, Vieweg+Teubner | GWV Fachverlage, Wiesbaden, 2009, 3rd edition.
(3) Heller, T.; Schnellert, T.; Sowoidnich, T.: “Ermittlung von Parametern zur Bestimmung der Festigkeit von Stampflehm“, *Studienarbeit WS 2003/04* (2004); Bauhaus-Universität Weimar.
(4) Schnellert, T.: Untersuchung von Transportprozessen der Einbaufeuchte in Baukonstruktionen aus Stampflehm während der Austrocknung. Diploma project, Faculty of Civil Engineering, Bauhaus University Weimar, 2004
(5) Schroeder, H.: Lehmbau – Mit Lehm ökologisch planen und bauen. Vieweg+Teubner | GWV Fachverlage, Wiesbaden, 2010.
(6) Houben, H.; Guillaud, H.: Earth construction – A comprehensive guide. IT Publishers, London, 1994.

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