Shrinkage characteristics of cement stabilized rammed earth

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Abstract. Among the most commonly studied properties of building materials, their strength and physical properties should be mentioned. There is, however, one more feature that exist at the border of these two areas and not taking it into account during the design process of a given building can lead to negative results. This is the susceptibility of the material to the phenomenon of shrinkage. The purpose of the research was to get to know the phenomenon of shrinkage of cement stabilized rammed earth in the context of its composition and changing environmental conditions, by examining such factors as: aggregate content, water/binding materials ratio, relative humidity of the environment RH [%]. For the purpose of the research four groups of samples were made that differed in mixture composition and curing conditions. Based on the results obtained, it was found that the shrinkage of rammed earth is larger than commonly used mineral composites. In addition, it is very sensitive to changes in composition, so it is recommended to continue research on composition optimization, taking into account not only strength and durability but also the phenomenon of shrinkage.

1 Introduction

Earth-based construction is one of the oldest types of technology used to construct buildings. Its beginnings stretch out to prehistory and its development, depending on the region and the climate, lasted until the 20th century. It is estimated that about one third of the human population live in buildings built from earth [1]. There are many methods of using earth in constructing buildings. Technologies changed over time and under the influence of local conditions in which they were used. During this time raw earth was used in masonry, plastering, furnace construction, constructing bearing and partition walls, constructing ceilings, making bricks or even waterproof roof tiles. Today attempts are being made to find an use for raw earth in construction of vertical support elements and multi-storey residential buildings.

For this purpose, two techniques of building made of raw earth are used. The first of these assumes the erection of walls from pre-formed (manually or mechanically) blocks. This technology may resemble making bricks but it differs when it comes to heat treatment. This type of product does not undergo the firing process. The second technique involves the

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construction of walls by compacting the raw earth in the formwork. As in the moulding of blocks, in the same way, the elements can be made in a non-mechanized manner as well as using modern construction equipment. In this method, called rammed earth, the mixture is compacted in layers. After compacting one layer the next one is laid on top and this done until the desired height of the element is achieved.

2 Rammed earth shrinkage

Although there are numerous publications dedicated to the usage of earth as a construction material, the results of shrinkage tests of rammed earth are rarely presented. The acceptable values of linear shrinkage according to different documents are featured in Table 1.

Table 1. Acceptable values of rammed earth shrinkage

Country / Author	Document / Publication	Source	Acceptable value of linear shrinkage [%]
Germany	Lehmbau Regeln	[2]	≤ 2
New Zealand	NZS 4298:1998	[3]	≤ 0.5
Poland	BN-62/6738-02	[4]	1.5 - 2.0
Australia/Walker P.	HB 195-2002	[5]	< 2.5
United Kingdom /Keable J.	Rammed Earth Structures. A code of Practice (1996)	[6]	< 2

Unfortunately the analysis of publications does not give a satisfactory answer concerning the method of testing of rammed earth shrinkage. The New Zealand standard NZS 4298: 1998 [3] assumes testing rammed earth shrinkage on samples rammed in steel or wooden moulds with a square cross-section 5cm x 5cm and length 60cm. According to the specification the moulds should be covered with paper so that the samples do not stick to mould. After ramming the samples remain in their moulds. Together they undergo 7 days of conditioning under a plastic covering and after this they are dried for 21 days in the sun, without any cover. The measurement of the deformation is therefore done at least 28 days after forming the samples. It is done using the feeler gauge that is inserted between the smaller wall of the mould and the sample itself. Unfortunately the method of moulding and studying the samples presented in the NZS 4298:1998 standard cannot be accepted. The accuracy of the measurement itself is also doubtful.

Rammed earth stabilized by cement is a material technologically similar to low cement concrete that has a dry consistency, therefore it seems reasonable to adopt the Amsler method during the research. This method is used successfully in testing concretes [7], that is the standard procedure according to Polish standard PN-84/B-06714/23 [8], further supported by the recommendations contained in the ITB instruction no. 194 [9].

3 Materials used in the research

The purpose of the research was to investigate the phenomenon of shrinkage of cement stabilized rammed earth in the context of its composition and changes of environmental conditions. On the basis of the analysis of publications regarding the researched material [10,11,12] and the phenomenon of shrinkage in technologically similar materials [13,14,15] the most important factors determining the shrinkage characteristics of the material were selected as follows:

– aggregate content,
– mineralogical and chemical composition of the used loam,
– water/binding materials ratio,
– relative humidity of the environment [%].

The research was performed using two soil mixtures. Each mixture contained 70% of aggregate and 30% of loam. The mixtures granular composition of the aggregate differed from each other as far as the 703 mixture contained only 70% of sand fraction and the 433 mixture contained 40% of the sand fraction and 30% of the 2-4mm gravel fraction (Fig. 1). The mineralogical and chemical compositions of the loam used in the research is in Table 2 and Table 3, respectively.

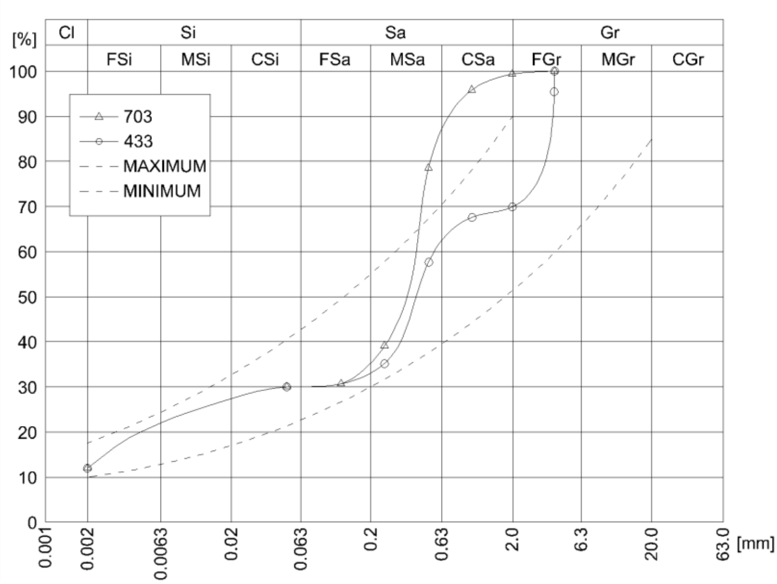

Fig. 1. The granular composition curves of soil mixtures used in the research. The dotted lines mark the recommended range of soil granular composition used in the rammed earth technique [16].

Table 1. The mineralogical composition of the loam [%]

Clay minerals				goethite	siderite	Calcareous minerals	Organic substance	quartz and others
total	beidellite	kaolinite	illite					
43,7	8,9	8,6	26,2	-	6,0	-	-	50,3

Table 2. The chemical composition of the loam [%]

SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	TiO_2	Other oxides
61,78	19,63	10,65	3,18	0,66	0,89	0,33

Before moulding the samples the optimum moisture content was determined for both of the soil mixtures that had the addition of the stabilizing agent in the form of Portland cement CEM I 42,5R in amount of the 9% of dry mass of the soil mixture. The optimum moisture content was determined using the 6,5 kg rammer that was then used to mould the samples for shrinkage testing. For the soil-cement mixture marked as 703, the optimum moisture content of 10% of mass was determined and for the soil-cement mixture 433 it was 9% of mass (a mixture with 1% lower moisture was also examined, ie. 8% of moisture). The shrinkage was tested from the moment of demoulding (after 24 hours) till about 1 year. In order to investigate the effect of the given factors on shrinkage, the study included four groups of samples, differing in composition and curing conditions (Table 3).

Table 3. Group of rammed earth samples tested in the research

Symbol of the group of rammed earth samples	Composition of the soil mixtures [% of mass]			Amount of Portland cement ([%] of mass of soil mixture)	Amount of water ([%] of mass of soil mixture with cement)	Curing conditions [%] RH
	Sand	Gravel	Loam			
703-9C-10W 35%RH	70	0	30	9	10	35
433-9C-8W 35% RH	40	30	30		8	35
433-9C-9W 35%RH	40	30	30		9	35
433-9C-9W 95%RH	40	30	30		9	95

Samples used in the research had the dimensions of 100x100x500mm. The samples were rammed in steel moulds superimposed with a profile, that was used as a guide for the 6,5 kg rammer that ensures vertical movement trajectory. The samples were rammed in three equal thickness layers that had 3.33 cm in height. The detailed ramming process of samples was described in [17].

4 Research results

The shrinkage test results are shown in Fig. 2, which also includes the shrinkage curve for C25/30 concrete with low proportion of CEM I cement - that is slightly below 300kg/m3 and gravel aggregate to 8mm.

The shrinkage of rammed earth is much larger than the shrinkage of concrete, which is confirmed even by the most rigorous NZS 4298: 1998 [3] standard which allows shrinkage after 28 days at 5 ‰. The increase in shrinkage in concrete is also different from that of cement stabilized rammed earth, where it is much more dynamic in the initial phase than in the case of concrete. The highest shrinkage - at the 3.5‰ level - was recorded in samples made from soil without any gravel aggregate. The shrinkage value in this case is approximately 2 times that of samples made of a mixture of similar composition and stored under the same conditions but containing 2/4 mm gravel fractions.

Samples stored in 95% relative humidity are characterized by a total shrinkage of nearly 20% less than samples from the same mixture and the same moisture, but stored in an environment with a relative humidity of 35%.

After 28 days the mixture tested at 35% humidity reached a similar percentage of maximum shrinkage (about 85% of its value), showing that shrinkage growth is similar regardless of differences in soil composition, if it is under the same environmental conditions.

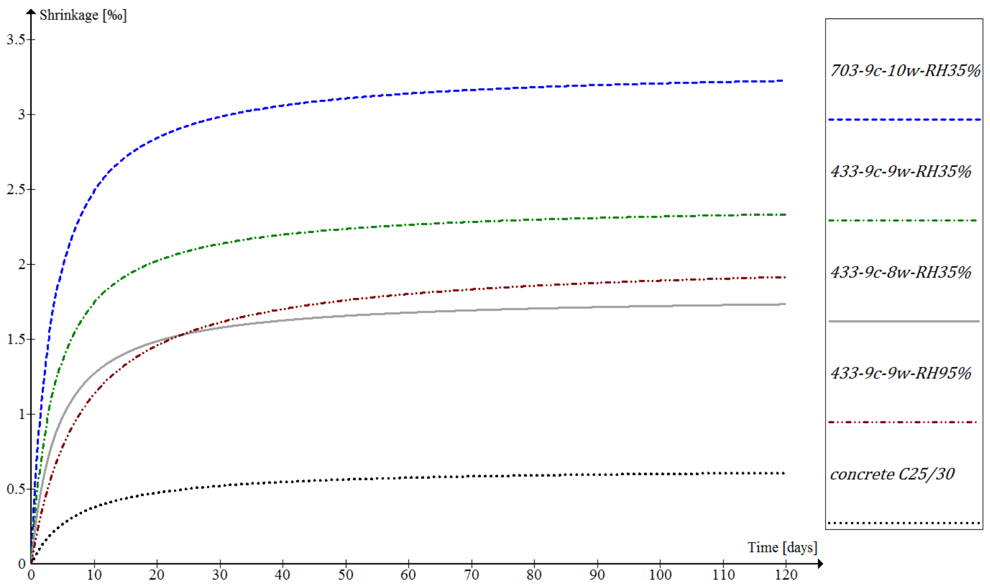

Fig. 2. Overview of the process of shrinkage of rammed earth and concrete

Using the principles of regression analysis, the empirical mathematical model of the curve was determined using the "curve fitting" method, statistically best suited to the results obtained. Parabolic, logarithmic, hyperbolic models were tested, but the best compatibility, measured by the R^2 coefficient of determination was achieved in the case of the curve known as “saturation growth rate” in the form of a hyperbole:

$$S = \frac{a \cdot t}{b+t} \tag{1}$$

where:
S - linear shrinkage [‰]
t - time [days]
a,b - coefficients of the model

The shrinkage model (Fig. 3, Fig. 4, Fig. 5, Fig. 6) in the form of a hyperbolic curve that has a horizontal asymptote means that the ordinate of this asymptote is the hypothetical maximum shrinkage value of the material being tested under accepted environmental conditions. Table 4 provides these values for 4 tested cases.

Table 4. Maximum shrinkage values according to mathematical models

Symbol of the group of rammed earth samples	Mathematical model	Coefficients of the model		Maximum shrinkage value [‰]	Coefficient of determination R^2
		a	b		
433-9C-9W 35%RH	2.4068·x/(3.8169+x)	2.4068	3.8169	2.4	0.9822
433-9C-8W 35% RH	1.7924·x/(4.1279+x)	1.7924	4.1279	1.8	0.9962
703-9C-10W 35%RH	3.3126·x/(3.3242+x)	3.3126	3.3242	3.3	0.9940
433-9C-9W 95%RH	2.0427·x/(8.0376+x)	2.0427	8.0376	2.0	0.9951

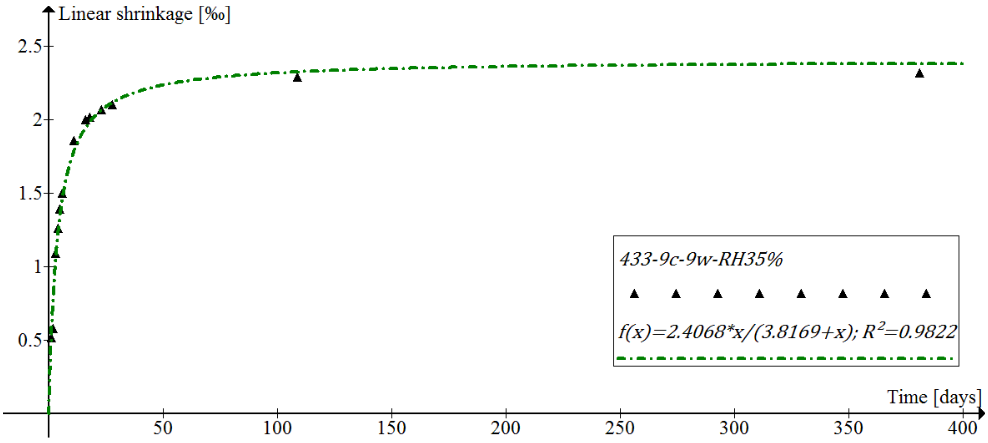

Fig. 3. Shrinkage model of the 433-9C-9W-RH35% mixture

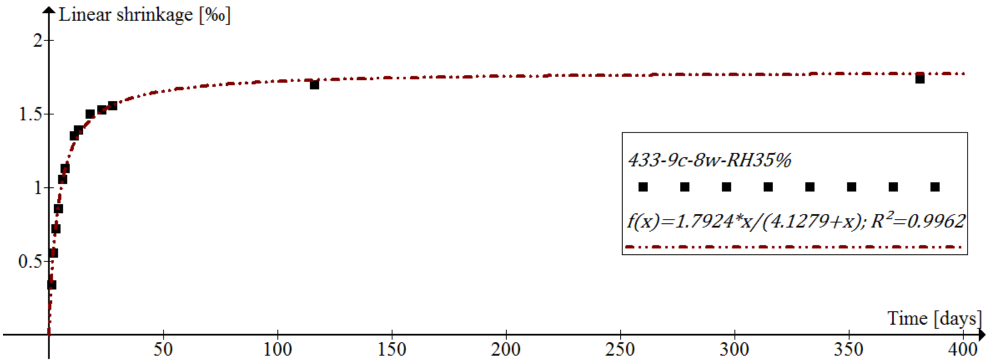

Fig. 4. Shrinkage model of the 433-9C-8W-RH35% mixture

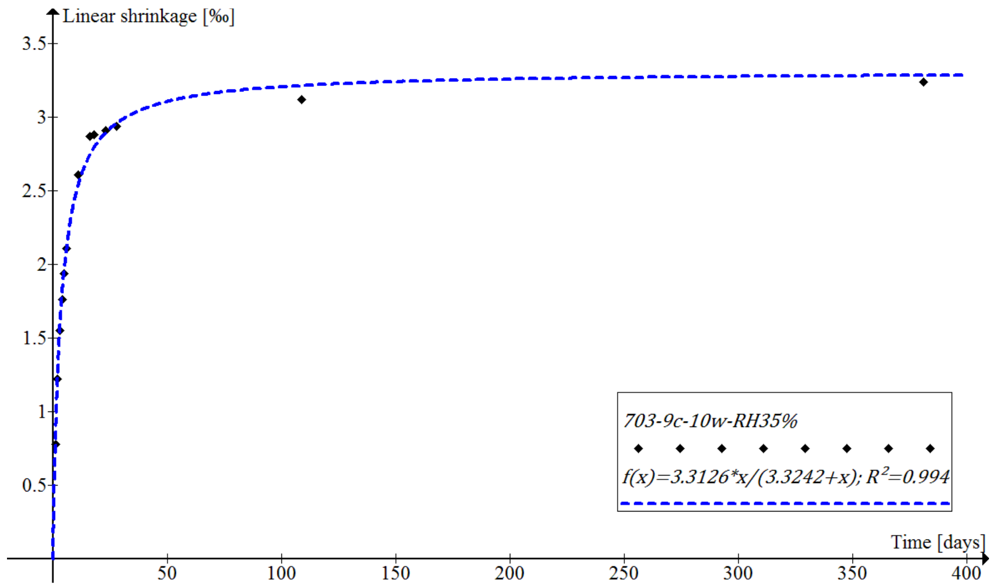

Fig. 5. Shrinkage model of the 703-9C-10W-RH35% mixture

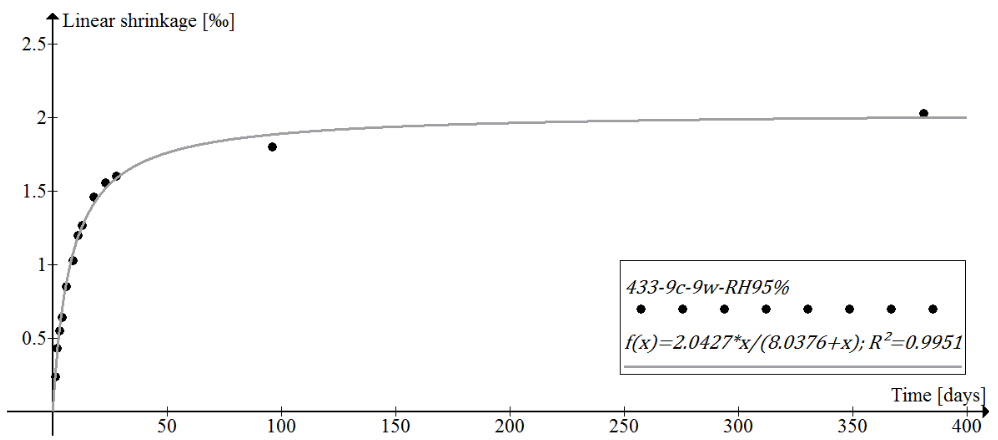

Fig. 6. Shrinkage model of the 433-9C-9W-RH95% mixture

5 Conclusions

All of the tested earth mixtures met the shrinkage requirements but forward in the New Zealand standard NZS 4298:1998 [2]. The maximum total shrinkage value that was the result of testing is significantly lower than the 28 days shrinkage that is given as acceptable in the standard.

As predicted, the shrinkage of “rammed earth" is significantly greater than the shrinkage of commonly used mineral composites. The maximum shrinkage value determined on the basis of the tests carried out is nearly 7 times higher than for medium strength concretes. This demonstrates additional restrictions of the use of “rammed earth" technology in larger engineering constructions.

The characteristics of the cement stabilized rammed earth shrinkage are also different from the popular mineral composite that is the C25/30 concrete. The shrinkage characteristics of the material under investigation are characterized by extremely dynamic incremental shrinkage in the initial phase. Within the first 28 days of hardening in low humidity, 85% of total shrinkage was recorded. Such a dynamic course of the phenomenon causes a significant part of the shrinkage to occur during the erection of the object, and thus deformation in the use stage will not be so large, despite the high total shrinkage.

Research has shown that the greatest impact on the effective shrinkage reduction of rammed earth has the presence of the gravel aggregate. The samples made of the mixtures that did not contain this type of aggregate were characterized by even two times higher shrinkage than mixtures having 30% of 2-4 mm aggregate. This means that when using local earth mixture it is advisable to enrich them with gravel fraction aggregate.

Differences in the total shrinkage value of rammed earth resulting from changes in the composition of the mixtures are large (even twice the value) and greater than for other mineral composites used in construction. This demonstrates the high sensitivity of the material to changes in composition and confirms the need to maintain a technological regime on the construction site to obtain the assumed parameters. At the same time, this confirms the great potential for the development of this technology and confirms the validity of further research aimed at optimization.

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