Rice sacks against earthquakes

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SUMMARY
Masonry reinforcement using natural fibres was investigated systematically for the first time at the University of Kassel. Based on small masonry investigations, it was possible to achieve high levels of strength and deformation behaviour. The results indicate a promising method for retrospective reinforcement of masonry. In particular, the methods prove suitable for "weak" masonry with low stone and mortar stability classes. In a pilot project to rebuild Arg-é-Bam, 'Recovery Project of Bam's Cultural Heritage', supported by UNESCO and Sika Schweiz AG under the supervision of the Iranian Commission for Monument Conservation, the method of building reinforcement with natural fibres was used for the first time. Bam is in the province of Kerman in S.E. Iran. It is an oasis city on the southern edge of the Lut desert.

Keywords: Masonry reinforcement, retrofitting, natural fibre composite, earthquake, external strengthening

1. GENERAL INSTRUCTIONS

The building of brick walls has a long tradition in the history of mankind. The simplicity and low expense of masonry help to preserve the interest in this technology. Due to its excellent physical properties the importance of masonry will be undiminished in the future. Disadvantages of buildings made of non-reinforced walls are small tension and shear force resisting capacities. Low building quality in countries with weak economies which are suffering from earthquakes entails massive damage including the complete failure of buildings. Especially in rural areas, use is made of bricks and mortar of low tensile strength classes that are hardly used any longer in Europe. A common kind of external strengthening of masonry structures is the use of carbon fibres (CFRP) and glass fibre-reinforced synthetic materials (GFRP), see Schwegler (1994) and Nani (2000). These materials in combination with synthetic resins systems are already common but because of their high cost and low availability are hardly used in earthquake regions with economic problems. At the University of Kassel we have developed a simple and cost effective method to reinforce existing walls by covering them with jute fibre mats. With this treatment the stiffness as well as the deformability of the wall could be improved considerably. It was successfully used for the first time on the World Cultural Heritage site „Arg-é Bam" with the support of UNESCO. Natural fibres in combination with filler compound of an epoxy resin base or epoxy resin enriched fine filler on a cement base can, for both cost and compatibility reasons, provide a very attractive alternative. The developed strengthening method of masonry structures with natural fibres is characterized by its easy practicability ("like wallpapering a room") in addition to the mentioned advantages.

2. Experimental program

2.1. Investigation of natural fibres

During the first phase of the research project selected types of natural fibres were investigated. In the preselection great importance was attached to the economy and sustainability of the materials. Jute fibres are mostly used as packaging material. Jute ranks second after cotton in the world production of natural fibres and is among the least expensive ones. In particular jute is easy to obtain in most earthquake threatened countries, for example in the Near and Middle East. For this reason the research focuses mainly on jute fibres as a material to reinforce masonry. In the first step of the investigation the behaviour of single jute fibre strands, fibre mats and single strands within a mat, was analysed, see Fig. 1.

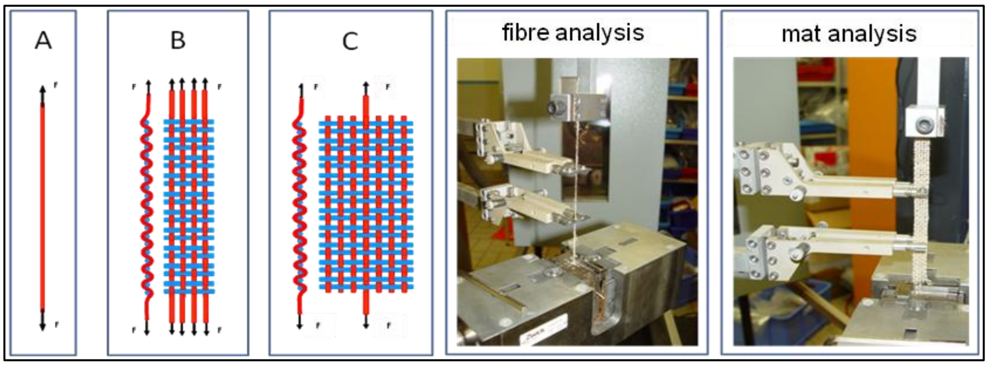

Figure 1. Investigations of single jute fibre strands, fibre mats and single strands within a mat

Fig. 2 shows the comparison of three test variants (single jute fibre strands, fibre mats and single strands within a mat) with respect to their stress-strain behaviour. A comparison of the graphs of the average values reveals that fibre strands outside the mat display considerably less distortion, see Fig. 2-right (A)). The mat in contrast displays considerably more distortion which results from the ondulation of the weave (see Fig. 2-right (B)). This can be demonstrated using the fibre strands within the mat (see Fig. 2-right (C)). The natural ondulation can play an important role for the deformability of masonry.

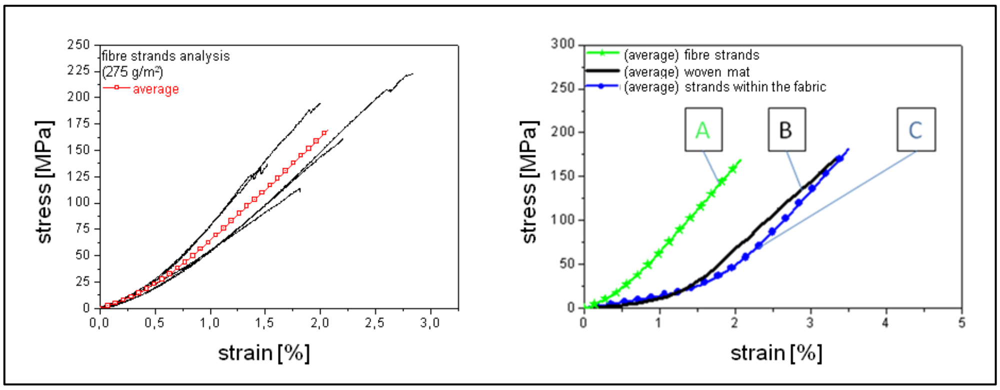

Figure 2. Test of single fibre strands (left), Comparison of stress-strain behaviour of single jute fibre strands (right), fibre mats and single strands within a mat (jute mat - 275 g/m^2)

2.2. Behaviour of composite materials

The behaviour of composite materials depends on the modulus of elasticity and the breaking elongation of the respective materials. Accordingly, the tensile strength of fibres composite materials depends on the properties of the individual components and the fibre volume content. When strains exceed the failure threshold of one of the two components initial damage occurs. In order to determine their properties within composite materials, jute mats were tested in combination with brittle and ductile matrices. The influence of fibre orientation in relation to the main stress axis was tested as well, see Fig.3.

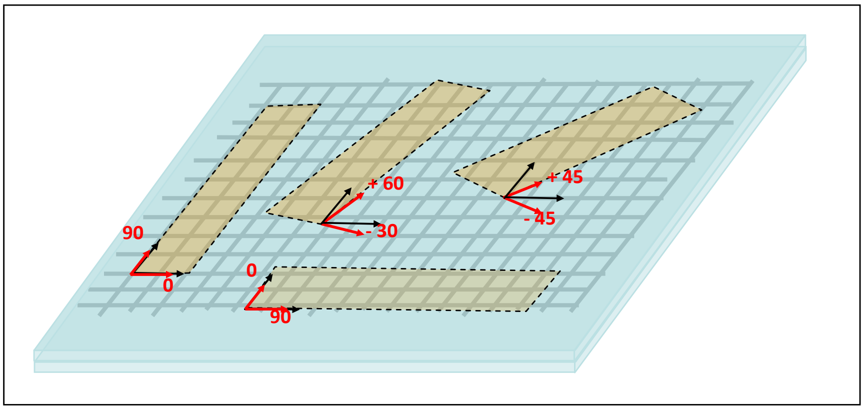

Figure 3. Schematic illustration of test strips for the determination of mechanical properties

Furthermore, two principal methods are available to reinforce buildings. One is the production of composite materials on the building site. This means that trained workers stick the reinforcing material directly onto the substrate. The advantage of this method is that the production does not involve specialized machinery and that basically any practically adept person is able to do it after a short training period. The second method involves the prefabrication of composite materials under laboratory conditions. The composite boards are then taken to the building site and the expenditure in terms of time and materials on the site itself is reduced. The principal advantage of prefabricating composite boards is with respect to quality considerations. With prefabrication the variability of quality can be reduced and production costs can be optimized. Two different tests were conducted in order to address related questions. The first production method follows the conventional way of manual lamination. For the second the composite material was produced using temperature and pressure. This method is similar to the manual lamination procedure with the exception that the hardening takes place under controlled temperature and pressure conditions. The objective here is to achieve better bonding between glue and fibre mat (increase of fibre volume content). The comparison of the force-displacement graph of the untreated woven jute mat with those of the composites produced by the different methods shows clearly that the samples produced by manual lamination have a higher ductility, see Fig.4. In the composites which are produced using temperature and pressure the natural ondulation of the mat was eliminated by the pressure. For the reinforcement of masonry the ductile behaviour of the composite material plays an important role.

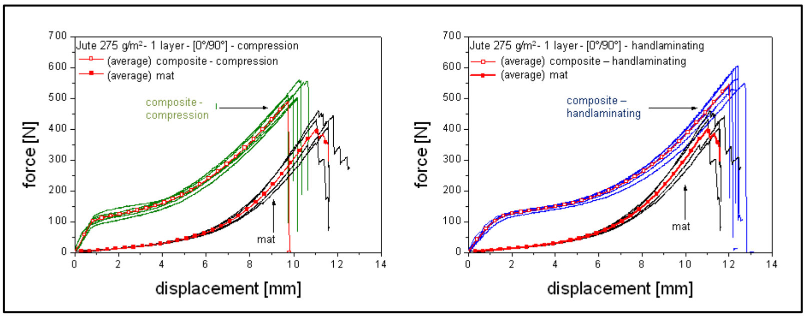

Figure 4. Force-displacement graph of the jute composite material 275g/m^2 compared to untreated jute mat with fibre orientations at an angle of 0°/90° against the main stress axis for different production methods

2.3. Masonry construction analysis

The combination of horizontal and vertical force within the plane of the masonry wall produce different forms of wear and failure. To determine the influence of reinforcing several different tests were conducted on small bodies of masonry. Wear caused by tension, shear, a combination of shear with pressure and brick tension was investigated in small bodies of unreinforced masonry as a reference point and in small bodies of masonry reinforced with natural fibres. For the reinforced masonry the tests were conducted once using a brace (Styrofoam) instead of mortar and then repeated with mortar.

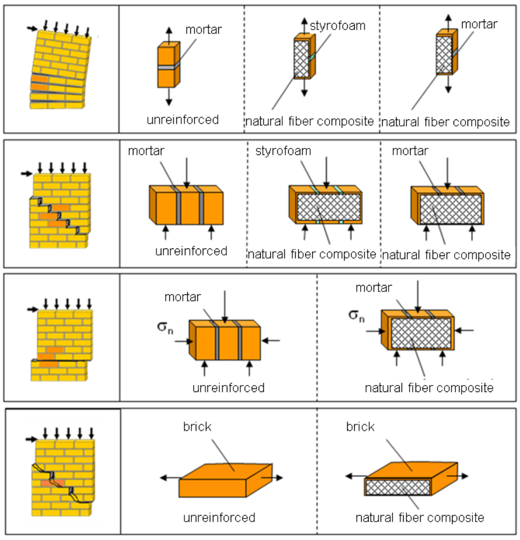

Figure 5. Different models of small masonry for the simulation of wear resulting from forces within the plane of the masonry with and without reinforcement

In this tests different failure modes were observed. The fracture behaviour depended on the adhesion and composite properties. In figure below, the most commonly occurring fracture behaviours are shown.

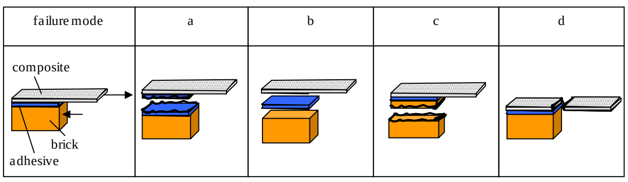

Figure 6. Different failure modes with natural fibre composite

In addition to the different loadings illustrated in Fig.7 two fibre orientations were compared for the reinforced small bodies of masonry. A horizontal/vertical orientation [0°/90°] and a diagonal fibre orientation [+45°/-45°] against the main stress axis were tested. Fig.7 displays the shear stress dependent on the joint displacement for unreinforced and reinforced small bodies of masonry and different fibre orientations. For the horizontal/vertical reinforcement [0°/90°] a more ductile behaviour could be observed compared to the diagonal reinforcement. Within the bond shear tests for reinforced masonry, both fibre orientations improved the stiffness approximately by factor 4, see Fig. 7.

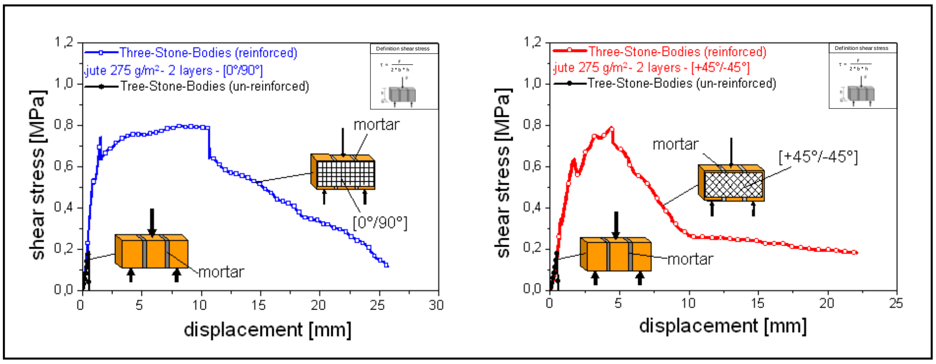

Figure 7. Graphs of mean values of shear strength - joint displacement, left: Comparison of Three-Stone-Bodies with and without reinforcement and fibre orientation of [0°/90°], right: Comparison of Three-Stone-Bodies with and without reinforcement and fibre orientation of [+45°/-45°]

For clarification the experimental results are summarized in a main-stress- and in a τ-σ-diagram. In the representation the one-axis and the combined test results can be compared with each other in a diagram. The experimental results are subdivided into a linear-elastic boundary stress and the stress maximums are calculated from the median values of the various test series, see Fig. 8.

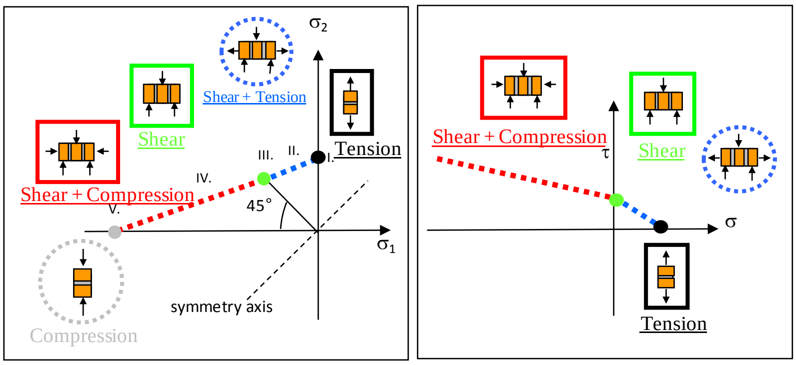

Figure 8. Representation of the experimental results in main-stress and τ-σ-diagram for liner-elastic boundary stress and stress maximum

In Fig. 9 and Fig. 13 the unreinforced results are compared with the reinforced results. Both for the diagonal and horizontal/vertical reinforcement it can be seen that even the results of the linear-elastic boundary stress with reinforcement are above the stress maximums of the unreinforced samples. The representation of the results in the τ-σ-diagram reveals a clear increase of strength for both reinforcements compared with the unreinforced variants.

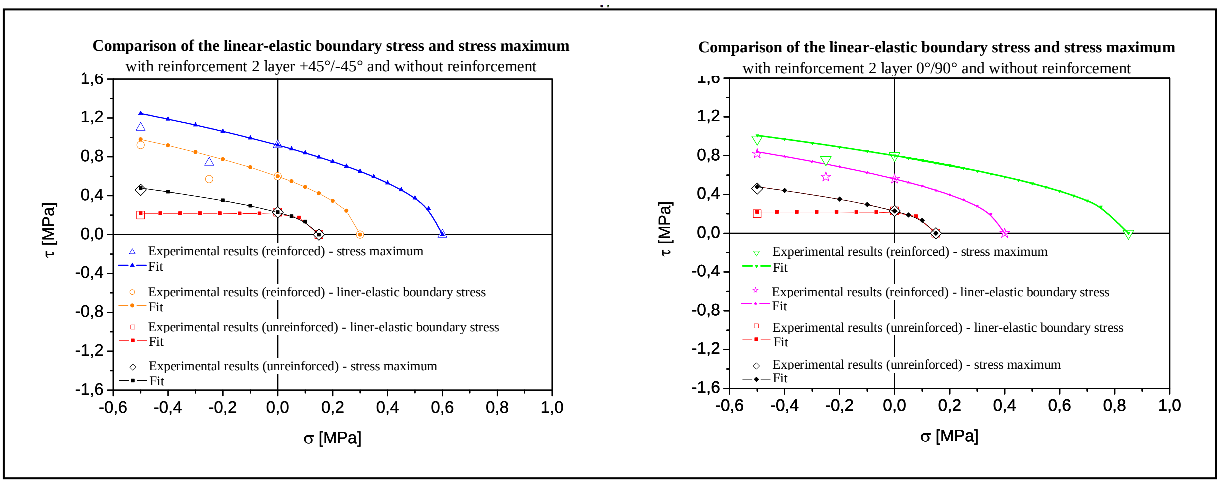

Figure 9. Comparison of the linear-elastic boundary stress and stress maximum for unreinforced and reinforced sample with 2 layers - Left: fibre orientation of [+45°/-45°], right: fibre orientation of [0°/90°]

In addition to the tests on small samples, the behaviour of masonry walls reinforced by jute fibre composites has been tested under cyclic loading in full scale at the laboratory of the Institute of Structural Engineering of the University of Kassel, see Stürz (2009) and Emami (2010). The first experiments conducted so far have proven a significant increase of lateral force capacity and high ductility. However, a complete investigation still has to follow.

Figure 10. Reinforcement of masonry wall with jute fibre mats

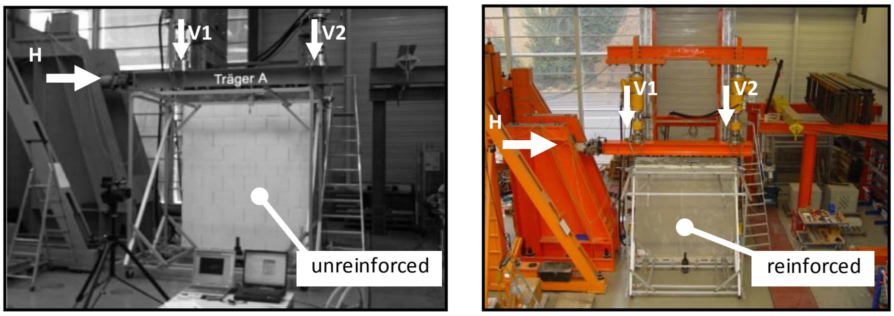

Figure 11. Schematic representation of masonry test

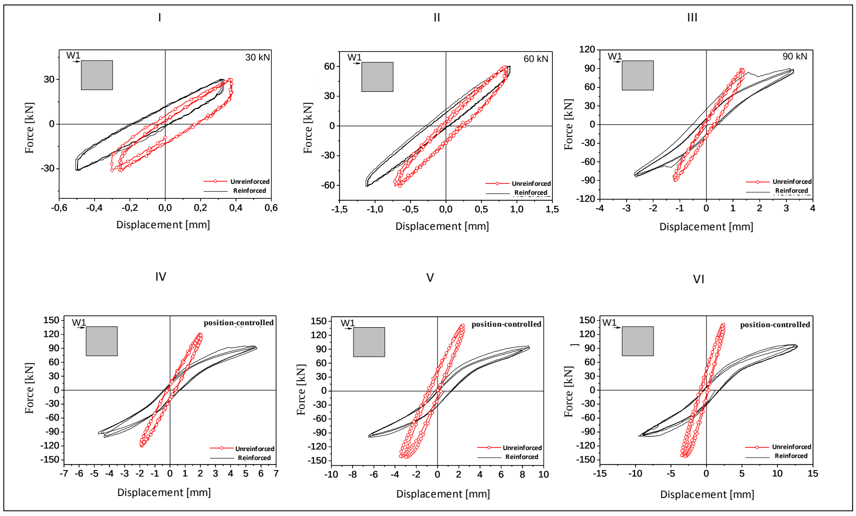

Figure 12. Horizontal Force-Displacement behaviour of reinforced in comparison to unreinforced wall

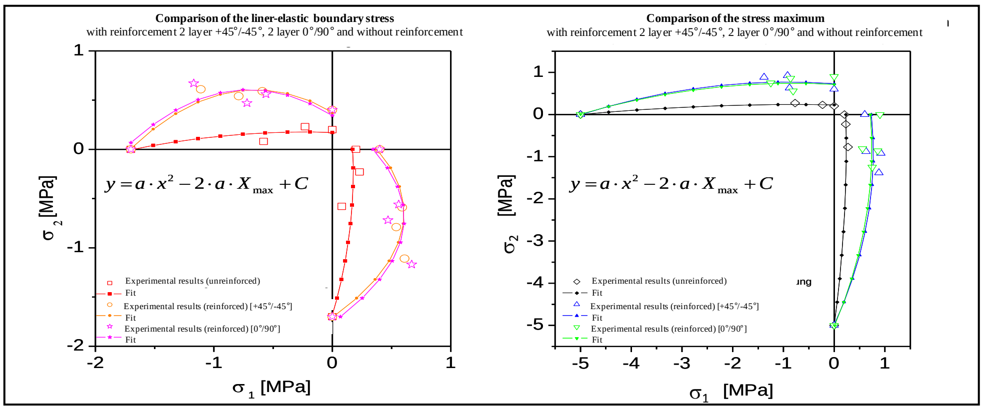

Figure 13. Comparison of the linear-elastic boundary stress and stress maximum for unreinforced and reinforced sample with 2 layers - Left: fibre orientation of [+45°/-45°], right: fibre orientation of [0°/90°]

3. Application in World Cultural Heritage

Within the framework of a pilot project supported by UNESCO and Sika Schweiz AG the method of reinforcing buildings using natural fibres was applied for the first time on the Arg-é Bam project which is lead by the "Iranian Cultural Heritage Organization". Two prototype structures were created: the first was created using sun-dried mud bricks and pure mud as a mortar; the second with burnt bricks (greater stiffness) and cement mixture as a mortar.

Before reinforcing the prototype building the necessary working materials will be prepared. The simple preparatory works include mixing the adhesive, cutting the mat to shape and cleaning the working surface with a brush.

Figure 14. Mixing the two-component adhesive with a mixer (left) and cutting the jute mat to reinforce the walls

In the second stage the adhesive is applied to the wall surface using a trowel, see Fig. 15. In this stage a small quantity of adhesive can make the networking of the mat difficult. Similarly, too much adhesive at unwanted undulations in the matting can make laminating very difficult. On the application of the first adhesive layer care should be taken in particular. The superfluous quantity of adhesive then has to be pressed out to the edges of the matting, which requires a lot of time and effort. For this reason the job should be carried out by a skilled expert. Fig.15- left shows an expert applying the first layer of the adhesive to the wall surface with a trowel. Next the mat is applied to the wall surface in the correct position using simply the flat hand in order to even out the surface. Fig.15-rights shows the expert positioning and smoothing the mat.

Figure 15. Application of the first adhesive layer with a trowel

In the next stage the laminating of the mat on the adhesive layer is carried out. This is done with a simple plastic roller. The last stage is the covering of the mat with a sealing adhesive layer. By covering the natural fibre with adhesive, the natural fibre is protected from environmental influences.

Figure 16. The Lamination of the matting onto the adhesive layer and Application of the adhesive layer on the matting

After several hours the adhesive is clearly hardened. In Fig.17 the already reinforced buildings are represented. The buildings have been in the World Cultural Heritage for over a year and have been visited by many experts and non-experts. So far no delamination or other negative effects have been observed.

Figure 17. With natural fibre reinforced burnt brick (left) and with natural fibre reinforced mud brick (right)

4. Conclusion

It has been possible to demonstrate that the subsequent reinforcement of small masonry structures by natural fibre composites (jute) leads to an increase in stability and ductility properties. The advantage of this method is that the level of stability or ductility can be varied by the variation of the number of layers or fibre orientation. The number of layers is to be determined according to the stability of the brick surface, type of masonry and mortar properties. The method is very simple and practical that can also be done by local workers. This has been proved by the work in Arg-é Bam. The examples in Bam made it possible to observe and document the long-term behaviour. However, a systematic investigation with regard to the long-term behaviour is urgently necessary. Further extraordinarily important points of investigation are the requirements of construction physics and fire protection that have not been taken into account in this study.

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