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3 authors:

Lorenzo Miccoli
Xella Technology and Research Centre

Urs Mueller
RISE Research Institutes of Sweden

Patrick Fontana
RISE Research Institutes of Sweden, Stockholm, Sweden

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Mechanical behaviour of earthen materials: a comparison between earth block masonry, rammed earth and cob

Lorenzo Miccoli[1*], Urs Müller[2], Patrick Fontana[1]

[1]BAM Federal Institute for Materials Research and Testing, Division 7.1 - Building Materials, Unter den Eichen 87, 12205 Berlin, Germany

[2]CBI Swedish Cement and Concrete Research Institute, c/o SP, Box 857, Brinellgatan 4, 50462 Borås, Sweden

[*]Corresponding author. Tel. +49 30 8104 3371 Fax +49 30 8104 1717 E-mail address: lorenzo.miccoli@bam.de

Abstract

Earth represents one of the oldest construction materials, which is still utilised both in developed and in developing countries. In this paper a comparison of the mechanical performance of structural elements built in three basic techniques, earth block (adobe) masonry, rammed earth and cob, is presented. In order to gain better knowledge on the structural behaviour under static loads an extensive compression and diagonal compression (shear) test campaign was performed. First compression results showed brittle mechanical behaviour in the case of earth block masonry and rammed earth elements, whereas cob exhibited a very different stress-strain pattern: cob can deform beyond the elastic range with a gradual drop in capacity. Despite its low compressive strength, cob thus presents a relatively good performance within the earthen material range as far as shear behaviour is concerned.

The data here reported represents a base for a further investigation on the dynamic behaviour of the three materials considered. The study was carried out within the framework of the project NIKER funded by the European Commission dealing with improving immovable Cultural Heritage assets against the risk of earthquakes.

Keywords: Earthen materials, compression test, diagonal compression test, initial shear strength

1 Introduction

It is estimated that 30 to 40 % of the world population currently live or work in structures built from earth. Earthen structures require high maintenance as they are prone to erosion under rainfall, spalling and cross-sectional reduction when salts are transported by capillary action. They are also susceptible to cracking both under low tensile and low compressive stresses. When these dwellings are located in regions with high earthquake risk, their intrinsically low resistance to dynamic actions is further worsened by such durability issues.

A number of construction and repair practices negatively affect earthen buildings and make them susceptible to high damage even under low seismic forces [1]. A few typical recurring examples are lack of continuity at corners and at wall junctions, the presence of heavy roofs that are not supported by ring beams, and also roofs often not connected to walls. Some countries where the population, particularly the rural one, still inhabits earthen buildings have been affected by highly destructive earthquakes, for instance Turkey (Erzinkan 1992), Iran (Bam 2003), Peru (Pisco 2007), and Chile (Concepción 2010). Although damage to dwellings and their collapse is usually the cause of human losses, earthquakes are as well devastating to the built cultural heritage in these regions. As a matter of fact, it is often overlooked that a considerable amount of heritage sites, of which many are endangered, are built from earth. Some vernacular earthen building techniques are no longer in practice, and the knowledge of how to build in such materials has been lost. Earthen building techniques considerably differ as far as material composition and construction methods are concerned. While some guidelines and standards for building with earthen materials do exist, e.g. ASTM E2392 / E2393 M [2], IS13827 [3] and NTE E.080 Adobe [4], these often lack design charts. Moreover, values specified do not take the high variability of earthen materials in terms of mechanical properties into consideration, which is dependent on a number of parameters affecting physical and chemical bonds at microstructural level, e.g. granulometry or fibre content [5], compaction and moisture content.

Newly introduced seismic regulations for countries where earthen buildings are still present within the built environment (e.g. Morocco [6], Pakistan [7]) are often based on those of developed countries and exclude earth as a building material. When seismic regulations for earthen buildings do exist (e.g. in New Zealand [8]), these tend to group all earthen materials into one category.

In comparison to recent advances in research on stone and fired brick masonry, knowledge on the material properties and failure mechanisms of earthen materials is limited and scattered [9]. Most of the assembled results have been obtained for earth block masonry [10-12].

The scatter of mechanical property values in the literature as shown in Table 1 can be large. This clearly is not only due to factors such as workmanship and weathering, but also to different testing procedures, for instance in the derivation of the Young´s modulus.

This paper focuses on the determination of material parameters and the behaviour of earthen wallettes and other test specimens under different loading conditions. The study provides an overview of mechanical behaviour of the three basic techniques, earth block masonry, rammed earth and cob. Up today a scientific study comparing mechanical and mineralogical properties of these earthen building techniques is still missing.

Walls made of cob can be regarded as fibre-reinforced monolithic structural elements. With rammed earth, monolithic elements are built as well. But, in general, rammed earth is not reinforced with fibres. In contrast, earth block masonry is considered as a modular construction technique, not as monolithic. In some cases earth blocks are reinforced with fibres to enhance their heat insulation properties and in [13] the positive influence of natural fibres on the mechanical properties of earth blocks is reported. However, fibre-reinforcement of the earth blocks does not change the modular nature of earth block masonry and its general failure mechanisms when subjected to compression and shear loads.

The entire experimental programme was performed in the laboratories of BAM. The types of wall specimens considered in the experiments consisted of one-leaf earth block masonry with earth mortar and of monolithic rammed earth and cob wallettes (Table 2). Investigations were carried out at micro and macro structural levels to acquire the mechanical behaviour of constituent materials as well as that of the structural elements (wallettes). The goal of the experiments was to acquire a basic knowledge of the mechanical properties of the different building techniques and to compare the general failure mechanisms.

The results of the presented study represent an important development of the data partially reported in previous papers [16,17]: Investigations of damage mechanisms via a photogrammetric method and investigation of the influence of pre-wetting of earth blocks on the shear resistance of earth block masonry.

1.1 Earth block masonry

The terms ‘adobe’ and ‘earth block’ will only be used here for the description of building blocks made from air dried earthen materials. Other synonymous terms, such as ‘mud brick’, ‘sun baked brick’ or ‘unfired brick’ often mentioned in literature will not be used.

Earth block masonry consists of earth blocks and mortar, usually an earth mortar. Sometimes stabilising additives, such as lime, cement or gypsum have been/are being used for mortars and blocks. Nowadays earth blocks can have various forms and sizes with or without perforations. In the past, blocks without perforation were usually used in various sizes. These blocks were produced by throwing a handful of a malleable mass of earth into a mould. Due to the higher water content, the plastic earth cannot be compacted. In the last century more and more compressed earth blocks (CEB) were produced, which were mostly stabilised by cement or lime. For CEB a fairly dry earth is used which is mechanically compacted in a mould with a higher pressure producing a material with a higher strength.

Although earth block is a widely utilised building material since prehistoric times, it also represents a type of masonry block that yields the lowest strength values. Typical values for compressive strength of historical unstabilised earth blocks are in a range from 1.0 MPa up to 5.0 MPa [18]. The modulus of elasticity measured on modern earth blocks with similar compressive strength and particle size distribution as historical earth blocks is in the range of 400 MPa to 2000 MPa. Compared to some building stones or fired bricks, earth blocks show a rather moderate to low anisotropic effects towards their mechanical and physical properties.

Within the frame of a programme focusing on strengthening adobe houses, adobe wall specimens in simple compression, diagonal tension and flexure on both, the vertical and horizontal axes of the walls were tested by Hernandez [19]. The same tests were conducted by Tolles [20], Gulkan [21] investigated the behaviour of 1000 x 1000 x 300 mm^3 square adobe wall specimens subjected to constant in plane compression normal and horizontal to the bed joints and to incrementally applied diagonal load for compressive and shear forces. This determined that failure of wall specimens under combined compressive and diagonal loads occurred at joint separation for low magnitude compressive loads and crushing or splitting for higher compressive loads.

Gurumo [22] performed diagonal compression tests on 1200 x 1200 x 250 mm^3 adobe specimens adopting a reinforcement based on soil-cement bond beams with longitudinal pretensioning steel rods. Results indicated that the prestressed specimens carried almost twice the load of the un-reinforced adobe but experiments were carried out with stabilised adobes. Sathiparan [23] conducted diagonal compression tests on non-reinforced and polypropylene mesh reinforced adobe masonry wall specimens. These tests were conducted on stabilised masonry walls, the results of which are not comparable to those of historic adobe masonry. San Bartolome [24] tested four small walls 800 x 800 x 180 mm^3 under diagonal compression to evaluate the shear resistance. Tests were not effective as detachment occurred during the handling prior to the test, resulting in very low values for shear resistance, which are not cited in the publication.

In general, earth reacts much stronger towards different moisture contents than any other porous mineral building material. Earth blocks show a higher strength in a dry state and show a very low strength when saturated with water. A complete de-cohesion of the earth can occur when very high water contents are reached and the earth has a high content of sand and coarse silt sized fractions.

1.2 Monolithic walls

Two types of homogeneous (monolithic) earthen wall constructions are considered in this paper: rammed earth and cob. The structural behaviour depends mostly on the material characteristics of the earth used and the geometry of the wall element. Both terminologies describe not only specific types of materials but also unique construction techniques.

Rammed earth is a special construction technique utilising formwork for the construction. It was/is practiced on all continents and known as ‘pisé’ in French, ‘tapial’ in Spanish, ‘taipa’ in Portuguese, ‘terra battuta’ in Italian and ‘Stampflehm’ in German. Rammed earth shows two significant material characteristics: a fairly low moisture content, usually below the plastic limit of the earth (‘soil-moist’) when filled into the formwork and a wide, poorly sorted particle size distribution ranging from clay to gravel sized (up to 64 mm) fractions. The optimal moisture content for filling the material into the formwork and subsequent compaction depends on the clay and silt content but is usually around 10 mass-%. Both, low moisture content and the specific particle size distribution ideally allow a high compaction of the earth inside the formwork. Size and construction of the formwork for rammed earth depend on local tradition. In the past usually smaller wooden formworks were used because of better handling and lower weight. Continuous formwork, as it is used very often nowadays, was less common. In the course of erecting a wall the formwork was subsequently lifted horizontally for one course then lifted vertically and horizontally again for the next course. Due to the compaction process rammed earth shows a distinctive horizontal layering. Additionally, the single formwork lifts can be visible if the earth used showed high shrinkage. In this case vertical and horizontal shrinkage joints can appear between the lifts. In such a case, a rammed earth wall cannot strictly be considered as ‘monolithic’.

Local traditions also included adding lime to the earth when the clay content of the earth was too low or the grain size distribution was not optimal, as documented with many rammed earth buildings in Spain, Portugal [9,25], Germany or France. This improvement was done by mixing lime and earth beforehand or by filling alternating layers of lime and earth into the formwork. Between the horizontal formwork lifts, often stones or bricks were placed. In some instances straw layers were added in case of earth with a high shrinkage. The straw helped to prevent that shrinkage joints spread into the rammed earth course above. As a consequence of this construction technique rammed earth has a distinctive horizontally layered structure.

The strength values of rammed earth depend on many factors [26]: granulometry of the earth, moisture content, compaction, fibre content and amount of additions. These factors also define the apparent density and porosity, respectively. Typical values for the apparent density of historical rammed earth not stabilised with lime range between 1700 and 2400 kg/m^3. Corresponding compressive strength values lay within a range of 1.5 and 4.0 MPa [18]. Despite the apparent layered structure of rammed earth the mechanical properties seem not to be distinctively anisotropic, although the layered nature has an influence on crack mechanism and must be taken into account when input data on mechanical properties of rammed earth from laboratory is used for design [27]. Laboratory studies showed that compressive strength and modulus of elasticity measured parallel and perpendicular to the layering differed only within a range of 10 % [28]. However, rammed earth with distinctive layers of fibres can show differences in the two directions.

The load behaviour of rammed earth was described by Dierks & Stein [29] analogue to in-situ cast concrete. A comparable stress-strain behaviour was shown by short term compression tests of rammed earth and concrete specimens. However, against a complete analogue speaks the type of binding (clay minerals in case of earth, calcium silicate hydrate phases in the cement paste of concrete) and the shrinkage joints between lifts of rammed earth walls [30].

A parametric study based on simple compression tests carried out by Vargas-Neumann [26], eight shear tests on 2000 x 2000 x 200 mm³ walls were carried out in shear loading. The conclusion of the testing programme was that the clay, water content and compaction are the dominating influences on the shear resistance of rammed earth. His findings indicated that clayey soils with a moisture content of 20 % higher than determined by the standard proctor test and an optimised compaction yielded the best results. Results showed that rammed earth walls were more resistant to earthquakes than adobe masonry walls by 40 %.

Cob is a mixture of earth and plant fibres. The largest particle size of the earth usually does not exceed the sand fraction. The amount of fibres usually is between 20 and 30 kg per m^3 of fresh cob, the fibre length usually is 30 to 50 cm The earth is mixed with water to a plastic consistency and then the straw fibres are worked under (traditionally by the hooves of livestock). The cob material is then stacked to usually 1.0 to 1.2 m high walls and left to dry. When the masses show the right moisture content the wall faces are cut by means of a spade vertically. Due to the high fibre content the material usually has a density below 1500 kg/m^3. Typical density values of historical cob are within a range of 1200 to 1700 kg/m^3 [30,31]. Corresponding compressive strength is between 0.5 to 1.5 MPa. The modulus of elasticity is the lowest of all the earthen materials used for structural elements. Typical values are within 200 to 500 MPa. The original structural behaviour of cob buildings can be impacted by many environmental influences. Increased water content (due to uprising damp or faulty roof) not only lowers material strength but can also initiates putrefaction of the fibres. The high fibre content enables insects or rodents to burrow deeply in cob walls. All these factors impair the overall structural behaviour of cob walls.

In Table 1 a literature review of mechanical performance of earthen materials is presented.

2 Experimental programme

2.1 Materials

Earthen materials for the experiments were sourced from a local manufacturer of prefabricated earthen building products. Although certain material properties were specified by the manufacturer, detailed parameters required for the structural characterisation of the constituent materials were determined in the BAM laboratories. Earth blocks, earth mortar and earth for rammed earth were readymade products from the manufacturer. Solid blocks were produced by a mechanised hand moulding procedure without compression in a plastic phase. Rammed earth wallettes were hand compacted with layers of 10 cm (Figure 7). Cob, however, was prepared at the BAM premises with soil from the manufacturer and straw fibres mixed to a mass of plastic consistency. Mixing was performed in a concrete mixer. After mixing, cob heaps were built following traditional cob building practice. After a drying period of four month, the test specimens (wallettes) were cut out from the blocks by means of a saw. Material specifications and bulk density values obtained according to the new German product standards for earthen building products DIN 18945 [37] and DIN 18946 [38] are listed in Table 2. Mineralogical compositions of the earthen materials are given in Table 3 and Table 4.

For creating earth block masonry usually the same principles were applied as for fired brick masonry. Wallettes were erected in single leaf construction. Structural elements of rammed earth were made from fairly dry earth (moisture content 9-10 %) which was filled in formwork and compacted with a rammer by hand.

The compressive strength and Young's modulus of the earth blocks was determined on a 1 MN universal testing machine. For the measurement of displacements linear variable differential transformers (LVDTs) were used (Fig. 1). The compressive strength tests were carried out according to DIN 18945 [37]. A number of 10 specimens were tested under force-controlled loading. Prior to the test, the specimens were stored at a climate of 23 °C and 50 % relative humidity (RH) for at least 28 days. Fig. 1 shows examples of typical stress-strain curves for the earth block and Table 5 lists the mean and characteristic values of its compressive strength.

Earthen materials' mechanical properties depend on their moisture content. In order to quantify the magnitude of this variation, compressive strength tests on specimen cubes of the earth block exposed to different relative humidity but constant temperature (23 °C) were performed. A strong correlation between compressive strength and moisture content was observed (Fig. 2a). Looking at the graph of relative humidity vs. compressive strength (Fig. 2b), results are aligned along a curve, which is essentially a reversed form of the moisture sorption isotherm of the material (Fig. 2c). The change in strength is quite dramatic at low or high relative humidity. However, within the

40-70 % RH range, strength values are relatively constant. Nevertheless, the dependency of strength from moisture content is even obvious when specimens have merely been exposed to different relative humidity. A more dramatic drop in strength is expected when the material exceeds the water sorption limit by hygroscopic action in case of liquid moisture absorption [39].

Values for the Young's modulus were obtained according to DIN 1048-5 [40]. The specimens (n = 4) were stored at 23 °C and 50 % RH for at least 28 days. Table 5 lists the results of the tests. After the first loading cycle, earth block specimens showed a small residual deformation, which is also observed for other materials but were more pronounced in the case of earth blocks. This behaviour was possibly caused by final settlement of the grain structure of the material, which caused a certain compaction. Thereafter, the material exhibited normal elastic behaviour. The deformation of the specimens was fairly high, which resulted in a relatively low Young's modulus of approx. 2200 MPa.

The tested earth blocks had a fairly high compressive strength of 5.2 MPa. Typical values for historical earth blocks lie between 2 and 4 MPa. However, the chosen earth block showed a limited scatter in results, which is much higher when using handmade earth blocks with lower compressive strength.

The tensile strength of the blocks and of the mortar was determined by means of pull-off tests (Fig. 3). Results from 16 tests can be found in Table 5. The mean value for tensile strength was almost exactly 10 % of the compressive strength. The characteristic strength (5 % quantile), however, is much lower due to the larger scatter in results.

Results for compressive, tensile and flexural strength of the earth mortar are listed in Table 5. The tests were performed on a 10 kN servo mechanical testing machine on mortar prisms of 160 x 40 x 40 mm^3 in size. The mortars were adjusted to a spread flow diameter of 175 mm according to EN 1015-3 [41] and stored for 28 days at 23 °C, 50 % RH after casting. The tests for flexural strength were performed according to EN 1015-11 [42] and EN 18947 [43]. For compressive strength and Young's modulus, prisms were tested instead of cubes (Fig. 4). Results yielded a mean compressive strength of 3.3 MPa. Fig. 4 shows the corresponding stress-strain curves. Values for the mean flexural strength and modulus of elasticity were 1.4 MPa and approx. 1100 MPa respectively. Pull-off tests on a larger mortar block yielded a mean tensile strength of 0.3 MPa.

The initial shear strength of the earth mortar and its bond behaviour to the earth block were found to be of particular interest. Therefore, shear tests according to EN 1052-3 [44], procedure A, were carried out on a 50 kN universal press with a pressure cell in horizontal position to adjust the pre-compression load perpendicular to the bed joints of the specimens (Fig. 5). The specimens consisted of earth blocks, which were laid on each other with earth mortar joints. Shear strength values thus obtained are dependent on sliding at the mortar-block interface. Therefore, two joints are tested simultaneously. The joint width was adjusted to 20 mm, according to the joint width of the masonry wallette (see below). After preparation, the specimens were stored at 23 °C and 50 % RH for at least 14 days until testing.

Tests were performed with four different pre-compression loads: 0.05, 0.10, 0.15 and 0.20 MPa. Chosen pre-compression loads were in the range specified by E DIN 18946 [38] to exceed not the maximum compressive strengths of earth block masonry specified by the German guidelines for construction with earthen materials [45]. Fig. 5b exhibits the shear strength gained for each pre-compression load. The initial shear strength is determined graphically as the intersection point of the trendline between the shear stress values at the corresponding pre-compression loads and the vertical axis of the shear stress.

The initial shear strength and the shear strength values at the respective pre-compression loads were very low compared to masonry with hydraulic mortar (Fig. 5). Failure did not occur at the joints but, instead, in almost all cases, at the mortar-block interface. That means that even though the mortar has a compressive strength equivalent to 2/3 of the earth block's compressive strength, contact between the two materials was a very weak point concerning shear behaviour. This, together with shear behaviour under diagonal compression for wallettes, is discussed below.

2.2 Compression test

2.2.1 Specimen preparation and test setup

For the compression tests, earth block masonry wallettes of size 500 x 500 x 110 mm^3 were produced by laying 6 earthen unit courses in accordance with EN 1052-1 [46]. However, the courses were connected by 20 mm joints, wider than what the standard recommends, since wider joint widths are often observed in historic earth block masonry. Specimens were built without pre-wetting the earth blocks for compression tests. For the shear tests, specimens with non-wetted as well as wetted blocks were built (Fig. 6).

Monolithic wallettes were built in the same size. Rammed earth wallettes were produced with formwork. The premixed material was fairly dry. The earth was then brought into the formwork in 10 to 15 cm layers and then manually compacted with a rammer (Fig. 7). The thickness of the earth layer corresponded to traditional technique since earth layers with more than 15 cm cannot be optimally compacted anymore.

For the basic cob formulation the premixed earth was first mixed with water to plastic consistency (spread flow of 170 mm with flow table test according to DIN EN 196-3 [47]. Afterwards the straw fibres were added and mixed thoroughly in a high performance mixer (Fig. 8). The cob mass was then thrown diagonally onto the cob heap. Throwing the plastic mass was necessary to distribute it on the heap and to minimise voids and air inclusions. With this specific technique first a larger cob heap of ca. 80 x 70 x 110 cm^3 was created. After drying, segments of 420 x 420 x 115 mm^3 in size were cut from the heap, thus preserving the original texture of the cob. The size of the cob specimens was smaller since it was limited by the blade length of the saw (42 cm), with which they were cut out from a larger block.

After production, the wallettes were stored in a climate room at 23 °C and 50 % RH for drying. Specimens were removed from the climate room shortly before strength testing took place.

Prior to the tests, two steel I-girders were attached to the lower and upper side of the wallettes to introduce the compression forces into the specimens. Accurate parallelisation of the girders was achieved by using a low strength cement mortar joint between the girders and the wallette. Five specimens were tested. Compressive tests were carried out under displacement control. The loading speed was adjusted in such a way that failure was reached after 20 to 30 minutes. Deformations were monitored by LVDTs placed parallel and perpendicular to the loading direction on both sides of the specimen (Fig. 9).

2.2.2 Test results

Test set-up and results are shown in Fig. 10. For earth block masonry wallettes, strength values ranged between 2.7 and 3.8 MPa. Ultimate vertical strain varied between 0.5 and 1.2 % and usually exhibited abrupt failure. An example of the failure patterns of the wallettes is depicted in Fig. 10. Failure was visible by vertical or diagonal cracks. On some specimens, a cone-shaped failure pattern was observed.

Rammed earth wallettes reached the highest compressive strength of all three types of earth constructions. The values ranged between 3.4 and 4.0 MPa. The deformations of the earth block masonry and rammed earth wallettes were similar. Failure was abrupt after maximum stress was reached. At failure the rammed earth specimens showed cone shaped cracking pattern, at least on one side, sometimes on both sides. Cob showed a completely different behaviour under compressive load than the other two construction types. Maximum strength ranged from 1.4 to 1.7 MPa. Deformations measured were high reaching up to 6 % vertical strain. Due to the content of straw the material showed a ductile behaviour under compressive load with no distinctive maximum. Crack patterns after the tests were almost random and only in one specimen a cone shaped failure was indicated.

2.2.3 Evaluation and comparison of results

Results obtained from the compression tests are given in Table 6, where $E_{1/3}$ and $\varepsilon_{1/3}$ represent the Young's modulus and vertical strain measured at 1/3 maximum load respectively. The Fig. 11 shows the typical stress-strain curves for each type of construction technique, the scatter of the test results are reported in Table 6. In the case of earth block masonry and rammed earth the stress-strain curves exhibit a short phase of post-peak strain softening under compression, due to its brittle behaviour under uniaxial load.

It is fundamental to underline the strict dependency between the components and the observed material behaviour, as investigated by Quagliarini and Lenci [5], who studied the compressive failure behaviour of earth blocks fabricated with constituent materials in varying proportions. Their results showed that the addition of straw to the mix considerably increased the ductility of the material, while the introduction of sand, particularly in high amounts, tended to significantly lower its compressive strength.

This difference in behavioural pattern was similar to that observed for the different earthen materials investigated, thus giving an indication of the effect of constituent materials on compressive stress-strain behaviour of materials resulting from different construction techniques (Fig. 12).

2.3 Diagonal compression test

2.3.1 Specimen preparation and test setup

Specimens for the diagonal compression test had the same size as for the compression tests as described in section 2.2.1. The tests were performed following ASTM E 519-10 [48]. As specified by the test, wallettes were turned by 45° around the middle axis with one diagonal of the wallette being perpendicular and the other one parallel to the loading direction to induce shear forces (Fig. 13). Stress was applied by means of loading shoes placed between the jack and the corner of the specimen. Particular attention was paid to the problem of load distribution along the corners, since failure of the wallettes was not meant to occur due to excessive localised compression stress at the corners. For earth block masonry six specimens were tested: three with wetted blocks and three with non-wetted blocks. Four to seven wallets were used for the other building types. Monotonic load was applied at a rate of 130 N/s up to failure.

Displacement transducers were used to measure diagonal displacements and were fixed according to the standard, with one pair on the front side and one on the back side of the specimen.

For selected specimens additionally a photogrammetric camera system (ARAMIS) was measuring the two-dimensional deformation during the test. For this a frame of ca. 35 x 25 cm^2 of the centre of the specimen was observed. Prior to the test the specimen were plastered with a thin white gypsum render and sprayed with a marker. The deformation of the specimens was measured by stereographic recording of the movement of the singular marker points and additionally by one set of LVDTs placed on the back side of the specimen.

The test is usually used for masonry but was used in this study also for the pseudo monolithic building elements made of rammed earth and cob. In monolithic materials the diagonal test should introduce compression forces until horizontal strain creates a vertical crack. As shown in the results, this behaviour is true for the beginning of the failure. The actual failure, however, revealed for all earthen materials a strong shear component.

Past and current practice is actually not to wet earth blocks to construct earthen masonry. However, earth blocks generally exhibit high water absorption rates and suck out moisture from fresh mortar, which strongly affects bond between earth blocks and mortar and thus also the shear strength of the masonry. Therefore, as a comparison, two sets of specimen wallettes were prepared: one set with non-wetted and another set with wetted blocks [16,17,49].

2.3.2 Test results

Masonry wallettes with non-wetted blocks showed very low shear strength values, which were in the range of 0.08 to 0.11 MPa. Stress-strain curves usually showed one or several yield points where the blocks began to slide gradually until friction set in and increased stress again until final failure. Masonry wallettes with wetted blocks showed much higher shear strength values than with non-wetted blocks. For the three tests, strength values between 0.25 and 0.40 MPa were reached, which is two to three times higher than in the case of non-wetted blocks. The stress-strain curve for two of the three specimens showed a distinctive yield point, when elasticity of the specimens was exceeded and first cracks appeared. Subsequently, stress increased until the specimen failed. Ultimate strain values were approximately the same for both sets of wallettes. This type of stress-strain response can be linked to the actual failure mode of the specimen. The specimen yields the stress until the first vertical crack appears by exceeding the maximum elastic horizontal strain. The crack ran not only along joints but also through blocks. At the second yield point the specimen failed due to sliding of the blocks along the joints until complete collapse occurred (Fig. 14).

Rammed earth wallettes yielded the highest results for shear strength of all three different construction types. Values ranged between 0.65 and 0.85 MPa. The maximum strain was much higher than with earth block masonry and usually between 1 and 2 % before complete failure.

Almost all the masonry and rammed earth specimen showed a distinctive yield point after the elastic range in the stress-strain curves. Observation from video footage showed the development of failure:

- No visible changes in the elastic range of the strain;
- Appearance of a vertical crack close to the first yield point;
- Development of a system of small parallel running vertical cracks with an increase in load; the cracks usually run diagonally from one end of the upper loading shoe to the other end of the lower one;
- Combination of the single shear cracks to one coherent crack running diagonally through the specimen at the maximum load; sometimes the diagonal shear crack runs partially through the vertical crack;
- Collapse of the specimen;

It is noteworthy that even though a first vertical crack appeared in the wallettes an increase in load was still; possible. Not in every specimen the vertical crack was combined with the diagonal crack system. In two of the seven specimens tested both cracks appeared to be independent. It is probably safe to say that the final failure was not caused by compression but mostly by shear failure as in the earth block masonry wallettes. The photogrammetric analysis by the ARAMIS system essentially confirmed the findings from the stress-strain curves and the analysis of the failure mode. Fig. 15 shows exemplarily the results of one of the rammed earth wallettes tested.

Though only a section of the entire specimen was visualised the development of cracks on the stress-strain curve followed the scheme as described above. Interesting was the appearance of a diagonal deformation (in Fig. 15 indicated by red lines) in the elastic range of the curve. Note the diagonal deformation in the elastic range which is parallel to the rammed earth layers. Some of these deformations became cracks by increasing the load to the maximum value. Even though cob wallettes (Fig. 16) revealed the lowest strength values in the compression tests, the results from the diagonal compression (shear) experiments where much better than that of the earth block masonry wallettes and only slightly below the values for rammed earth wallettes. The strength figures ranged from 0.35 to 0.63 MPa (Fig. 17). The maximum strain was, as in the compression tests, the highest of the three earth construction techniques ranging from 2 to 5 %.

A first yield point on the stress-strain curve, as observed for the masonry and rammed earth wallettes cannot be recognised on the curves of the cob specimen (Fig. 16). The typical course was an elastic range with a low shear modulus followed by a plastic-type deformation of the specimen. Typical vertical cracks due to the compression load as observed with the other two construction types were not identified here. Usually the specimens collapsed after reaching maximum load by shear failure. Cracks were always running diagonally from one end of the upper loading shoe to the other end of the lower shoe (Fig. 15). The results by ARAMIS showed that majority of the cracking occurred not in the end of the elastic range but on the way to the plateau of the maximum load (Fig. 16). However, when the maximum load was reached cracking was prominent and failure followed suit, even though deformation was still possible since the specimen parts were still held together by strings of straw fibre.

2.3.3 Evaluation and comparison of results

Results obtained for diagonal compression tests and calculated according to ASTM E 519-10 [48] are given in Table 7, where $G_{1/3}$ is the shear modulus of elasticity measured at 1/3 maximum load, as well as for the shear strain $\gamma_{1/3}$. The shear strength of the specimens was calculated from the maximum load. Figures 17 and 18 show a comparison of the behaviour between earth block masonry, rammed earth and cob in terms of results for diagonal compression tests. Note the difference in results with earth block masonry, when wetted and dry blocks were used. As in the case under vertical compression, cob presented a marked and significant post-peak strain phase before failure, with a gradual drop in capacity. Rammed earth, as in compressive tests, showed a hardening phase at the beginning with failure starting from compaction planes. It is important to remark that earth block masonry specimens manufactured without wetting the blocks showed a poor bonding with the mortar. This might have caused initial de-bonding when the specimens were handled and prepared for the tests, which has certainly further decreased the shear strength of the masonry specimens.

3 Conclusions

This paper presents an analysis of the mechanical properties of traditional earthen construction materials, based on results obtained from compression and shear tests. Basic parameters concerning mechanical behaviour under static loads were determined, including shear strength, shear modulus and elastic modulus. The values of compressive strengths for the three types of construction techniques cannot be directly compared due to different types of soil used. But, the general material behaviour is depending from the building techniques. In the case of cob a lower bulk density is related to a lower compressive strength. A high ductility is due to the content of fibres.

The compressive tests on wallettes were carried out with displacement control, and it was thus possible to determine post peak strain performance. In the second part of the study, diagonal compression tests were performed under force control.

Results show that building technique practice is one of the crucial parameters affecting performance of earth block masonry. Leaving the earth blocks dry or otherwise wetting them prior to laying the blocks strongly affected results in the shear tests. Wetting of blocks might be in particular effective, if the water retainment of the mortar is poor. Moistening the blocks prevents early water reduction in the mortar, thus improving the bond between mortar and earth block and enabling a two- to three-fold increase in the shear strength of a masonry wallette.

A general conclusion is that cob, which exhibits lower compressive resistance, shows relatively ductile post peak behaviour when compared with the brittle behaviour of the earth block masonry and rammed earth specimens: cob can deform beyond the elastic range with a gradual drop in capacity. This behaviour is strongly influenced by the presence of fibres. Despite its low compressive strength, cob thus presents a relatively good performance within the earthen material range as far as shear behaviour is concerned. This parameter, together with its long post peak plastic phase, is relevant if its utilisation in seismic areas is considered. Buildings in these areas are bound to be subjected to lateral displacements and the ability of a building to deform without collapsing is essential for saving human lives and the repair of a structure.

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Fig. 17. Typical stress-strain curves of earth block masonry, rammed earth and cob. Comparison of behaviour of the three basic techniques under diagonal compression.

Fig. 18. Comparison between earth block masonry, rammed earth and cob under diagonal compression.

Table
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Table 1
Summary of material properties for earthen materials in the literature.

Material	Bulk density [kg/m³]	Compressive strength [MPa]	Tensile strength [MPa]	Young´s modulus [MPa]	Reference
Earth block masonry	1870	2.15	0.021	315	[18]
Rammed earth	2100-2300	2.40-3.00	nd	650	[36]
	1800	1.00	nd	90-105	[28]
	1700-2400	1.50-4.00	nd	750	[18]
	2020-2160	0.75-1.46[a]	nd	nd	[31]
	1870-2170	1-80-2.00	nd	nd	[32]
	nd	0.60-0.70	nd	60	[9]
	1850	3.88	nd	205	[33]
	1850	2.46	nd	160	[34][b]
	1763-2027	0.62.0.97	nd	60-70	[34][c]
Cob	1400-1700	0.45-1.40	0.09-0.34	170-335	[35]

nd = not determined; [a]Value corrected because the very low slenderness; [b]Sample dimensions: d = 10 cm, h = 20 cm; [c]Sample dimensions: 30 x 30 x 60 cm3 cm^3.

Table
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Table 2
Constituent materials of the specimens.

Type of application	Material	Specifications	Bulk density ρ [kg/m^3]
Masonry wallette	Earth block	Solid blocks produced by a mechanised hand moulding procedure (no compression, plastic consistency); size 240 x 115 x 72 mm^3	1863
	Earth mortar	Shrinkage 2 %[a], particle size up to 4 mm.	1885
Rammed earth wallette	Rammed earth	Shrinkage 0.5 %[b], particle size range 0-16 mm	2190
Cob wallette	Cob	Earth, water and straw fibres of 200 to 300 mm in length	1475

Bulk density ρ of earth block masonry is 1870 kg/m^3; [a]according to DIN 18946 [38], length change of mortar prisms 40 x 40 x 160 mm^3; [b]according to Lehmbau Regeln [45], length change of samples 600 x 100 x 50 mm^3.

Table 3
Mineralogical properties of earthen materials measured by X-ray powder diffraction. Quantities: +++ = high, ++ = medium, + = low.

Material	Grain constituents					Clay fraction				
	Quartz	Feldspar	Calcite	Dolomite	Clino-enstatite	Smectite-illite	Smectite	Kaolin	Illite	Chlorite
Earth block	+++	+	+				+++	++	++	
Earth mortar	+++	+	+		+		+	++	+++	++
Rammed earth	++	+	+	+++			+	++	+++	+
Cob	+++	+	-			++		+++	++	

Table 4
Granulometric properties of the used earthen materials (mass-%).

Material	Gravel and Sand > 0.063 mm	Silt = 0.002-0.063 mm	Clay < 0.002 mm
Earth block	43	45	12
Earth mortar	55	37	14
Rammed earth	64	25	11
Cob	18	61	21

Table
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Table 5
Mechanical properties of earth block and earth mortar specimens.

Mechanical parameters		Earth block	Earth mortar
Compressive strength [MPa]	Mean	5.21	3.32
	Characteristic	4.96	2.53
	STD	0.18	0.22
Tensile strength [MPa]	Mean	0.52	0.30
	Characteristic	0.34	0.21
	STD	0.12	0.08
Flexural strength [MPa]	Mean	-	1.39
	Characteristic	-	1.21
	STD	-	0.17
Young's modulus [MPa]	Mean	2197	1067
	STD	71	191
Poisson´s ratio [-]	Mean	0.45	nd
	STD	0.07	nd
Initial shear strength f_{vk0} [MPa] (with earth blocks)	Value	-	0.018
	Characteristic	-	0.014
Angle of internal friction [°]	Value	-	49
	Characteristic	-	39

Characteristic values represent the 5 % quartile of all values measured (except for initial shear strength and angle of internal friction, where they indicate 80 % of the determined value); STD = standard deviation; nd = not determined.

Table
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Table 6
Results from compressive strength tests of wallettes (STD = standard deviation).

	Compressive strength [MPa]		Young's modulus $E_{1/3}$ [MPa]		Vertical strain $\varepsilon_{1/3}$ [%]		Poisson's ratio [-]	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Earth block masonry	3.28	0.40	803	204	0.145	0.045	0.37	0.13
Rammed earth	3.73	0.23	4143	961	0.031	0.007	0.27	0.04
Cob	1.59	0.03	651	441	0.123	0.083	0.15	0.04

Table
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Table 7
Results from diagonal compression tests in comparison (W = earth block, wetted; STD = standard deviation).

	Shear strength τ_u [MPa]		Shear modulus $G_{1/3}$ [MPa]		Shear strain $\gamma_{1/3}$ [%]	
	Mean	STD	Mean	STD	Mean	STD
Earth block masonry	0.09	0.01	41	5	0.074	0.017
Earth block masonry (W)	0.34	0.06	660	277	0.020	0.011
Rammed earth	0.71	0.11	2326	710	0.011	0.003
Cob	0.50	0.10	420	137	0.041	0.006

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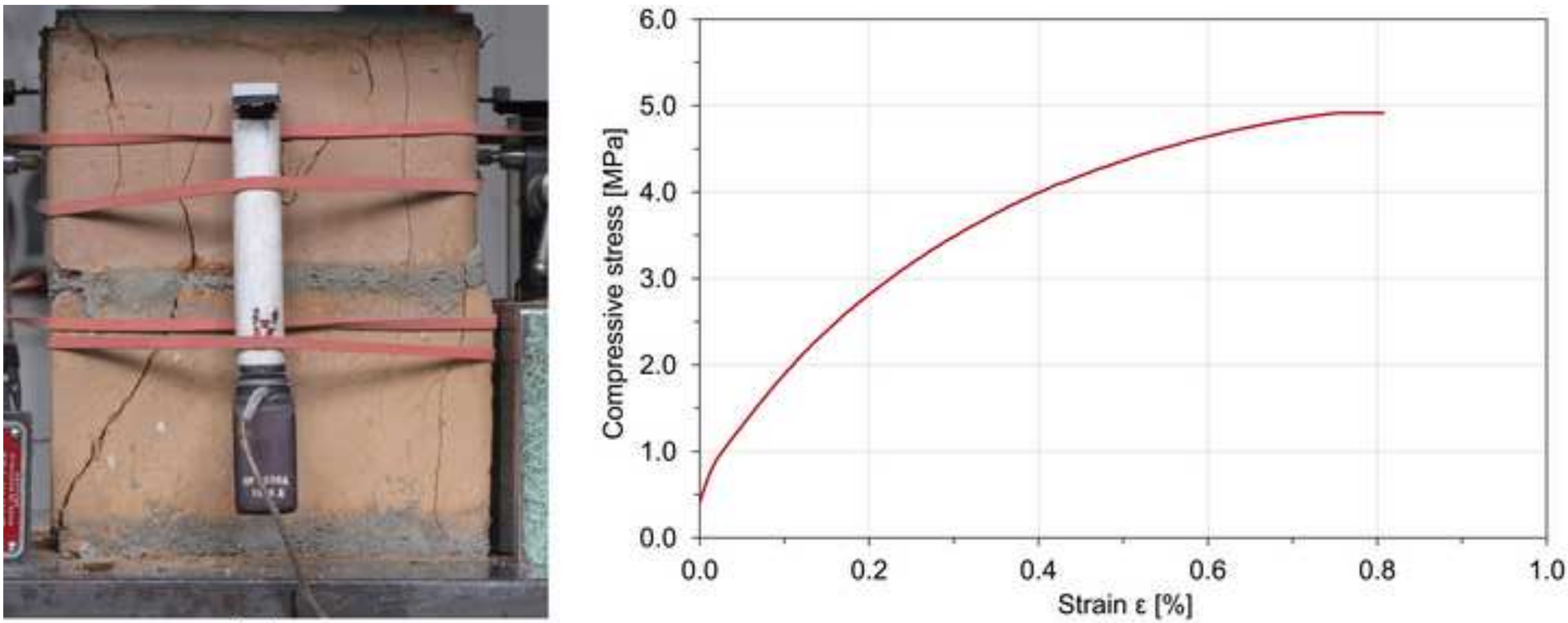

(a) (b)

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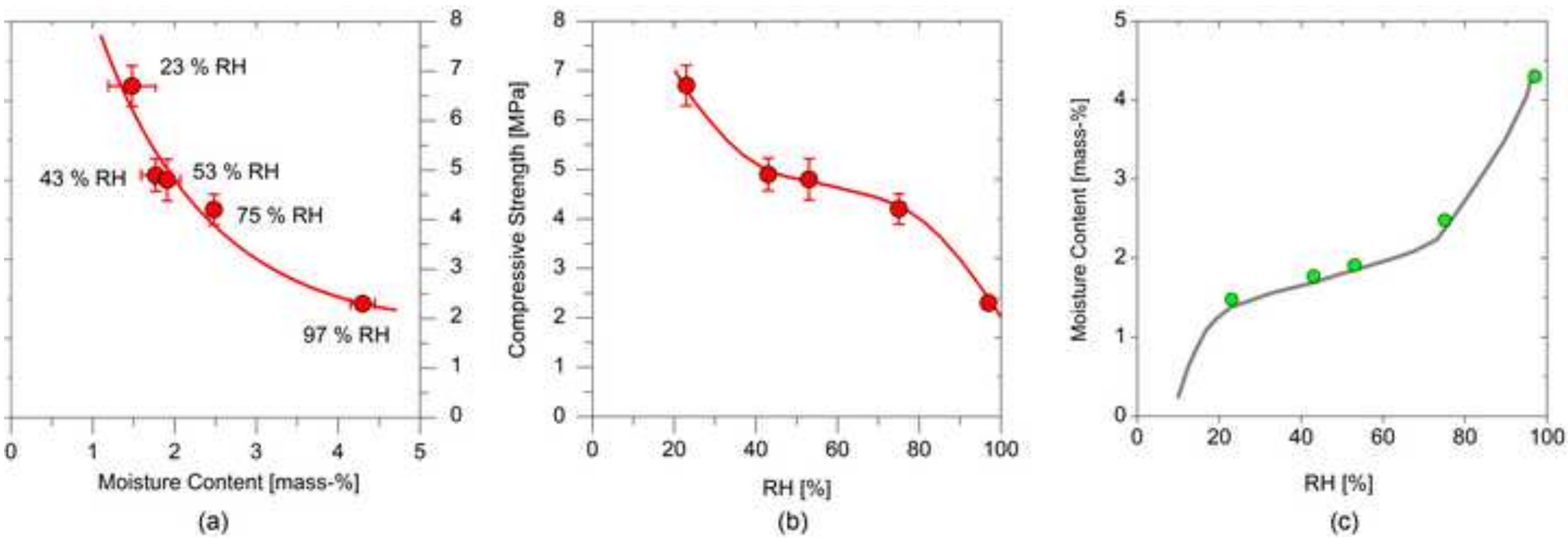

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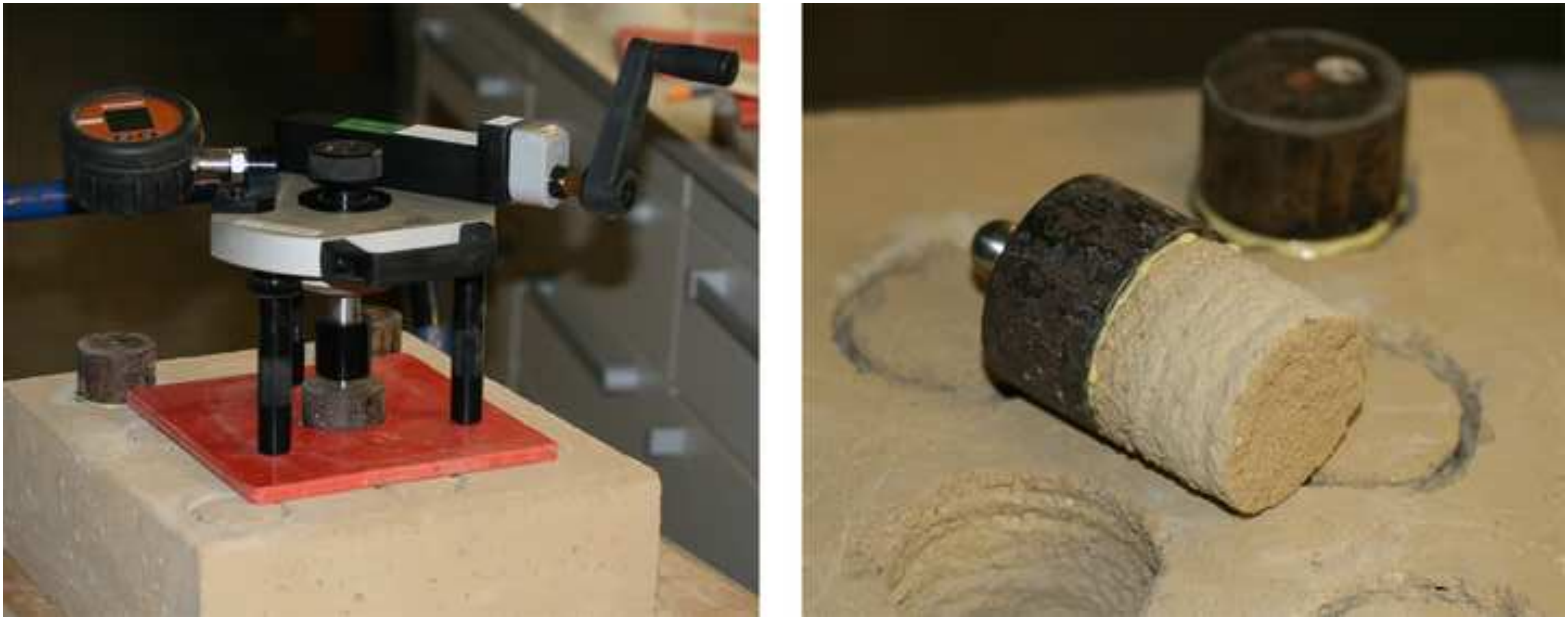

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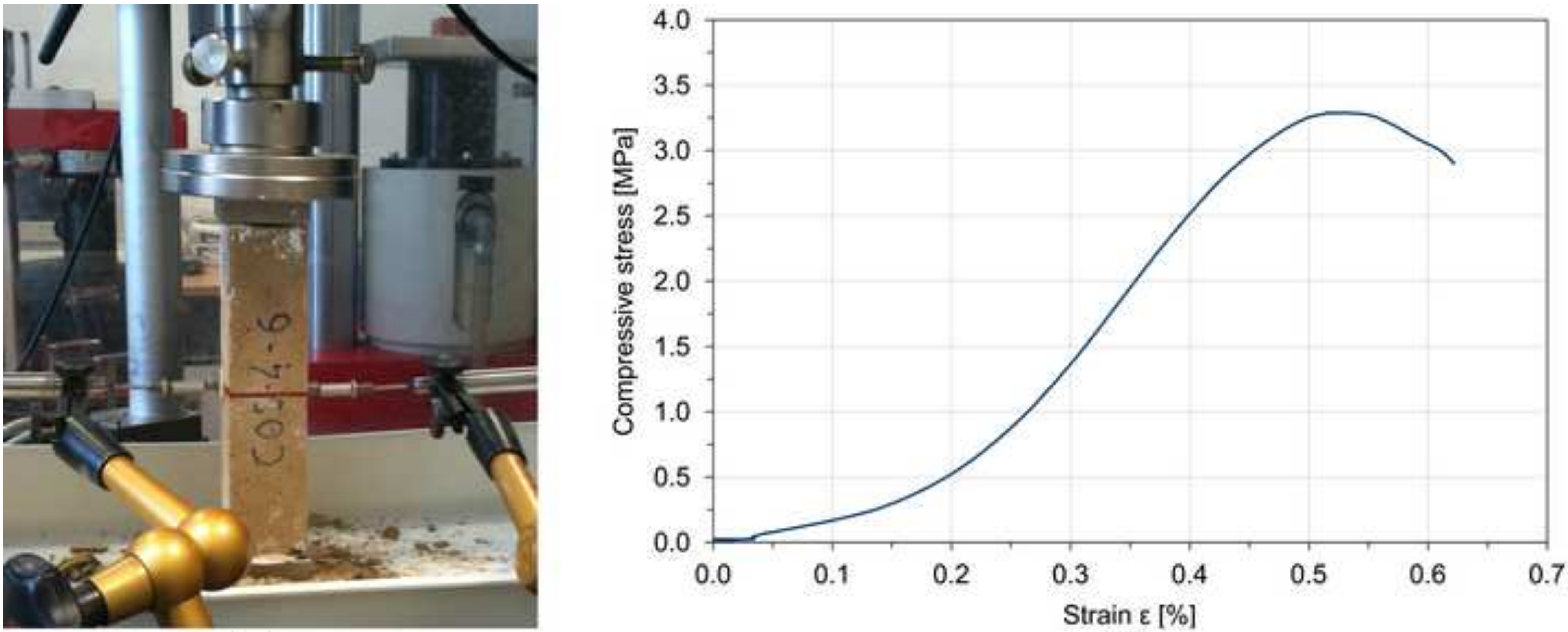

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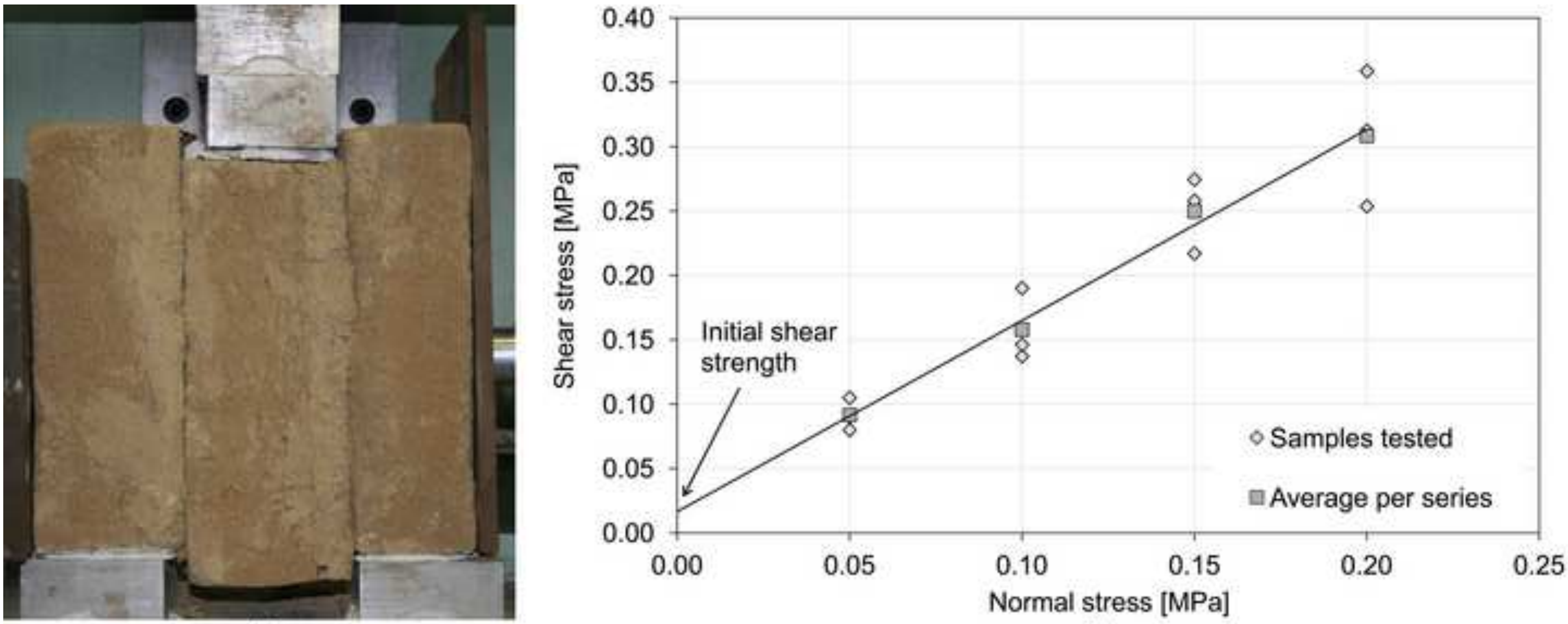

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(a) (b) (c) (d)

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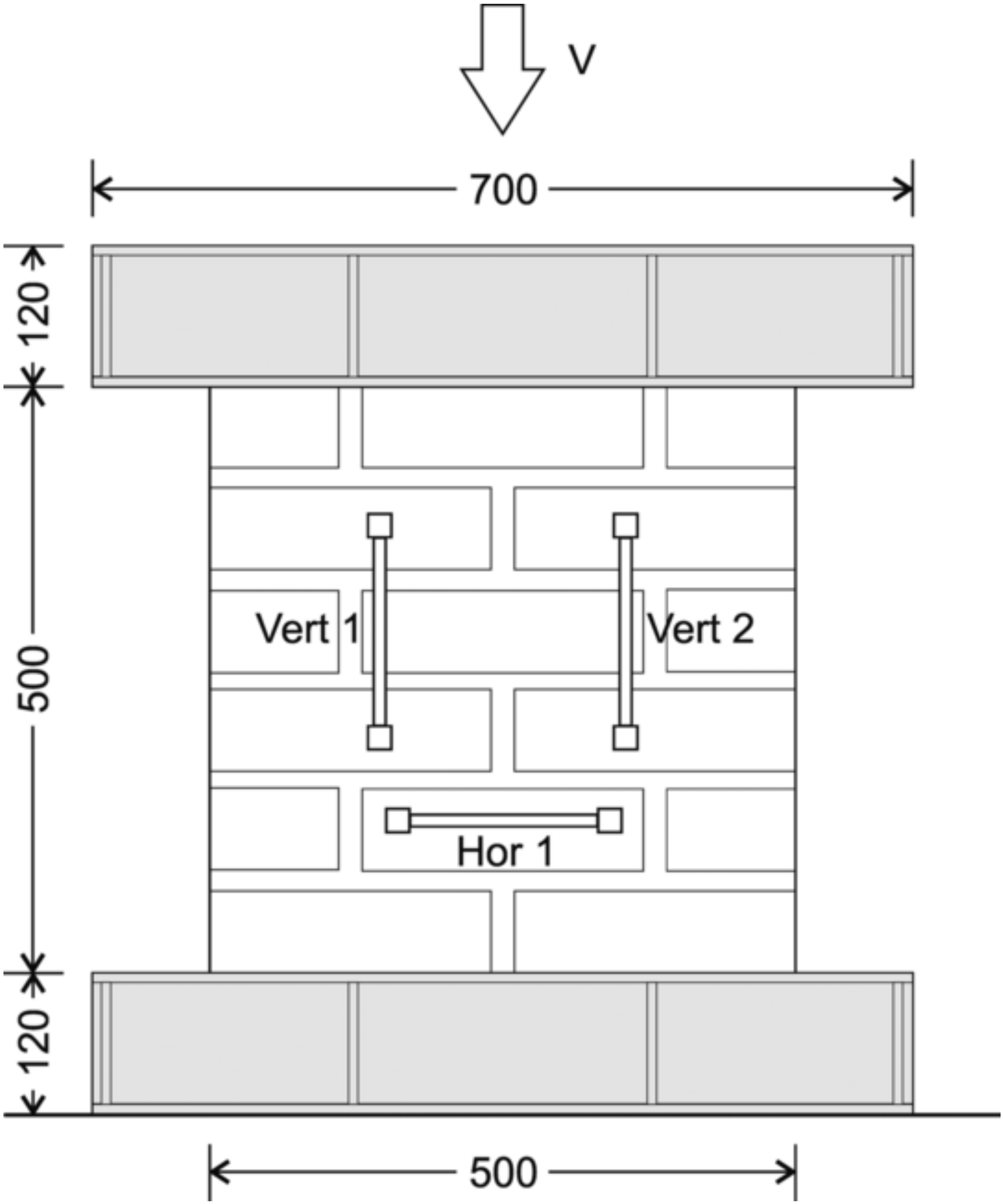

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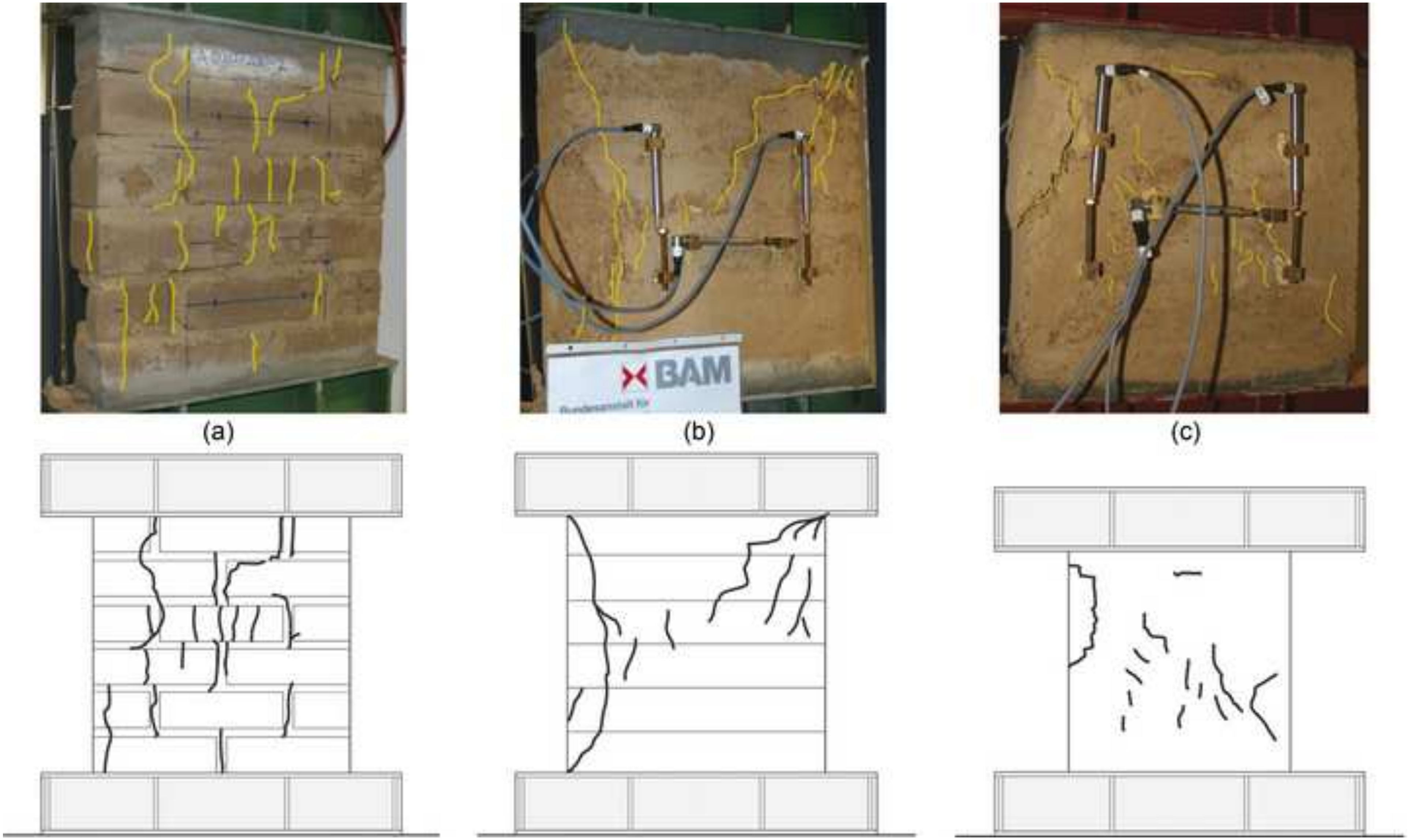

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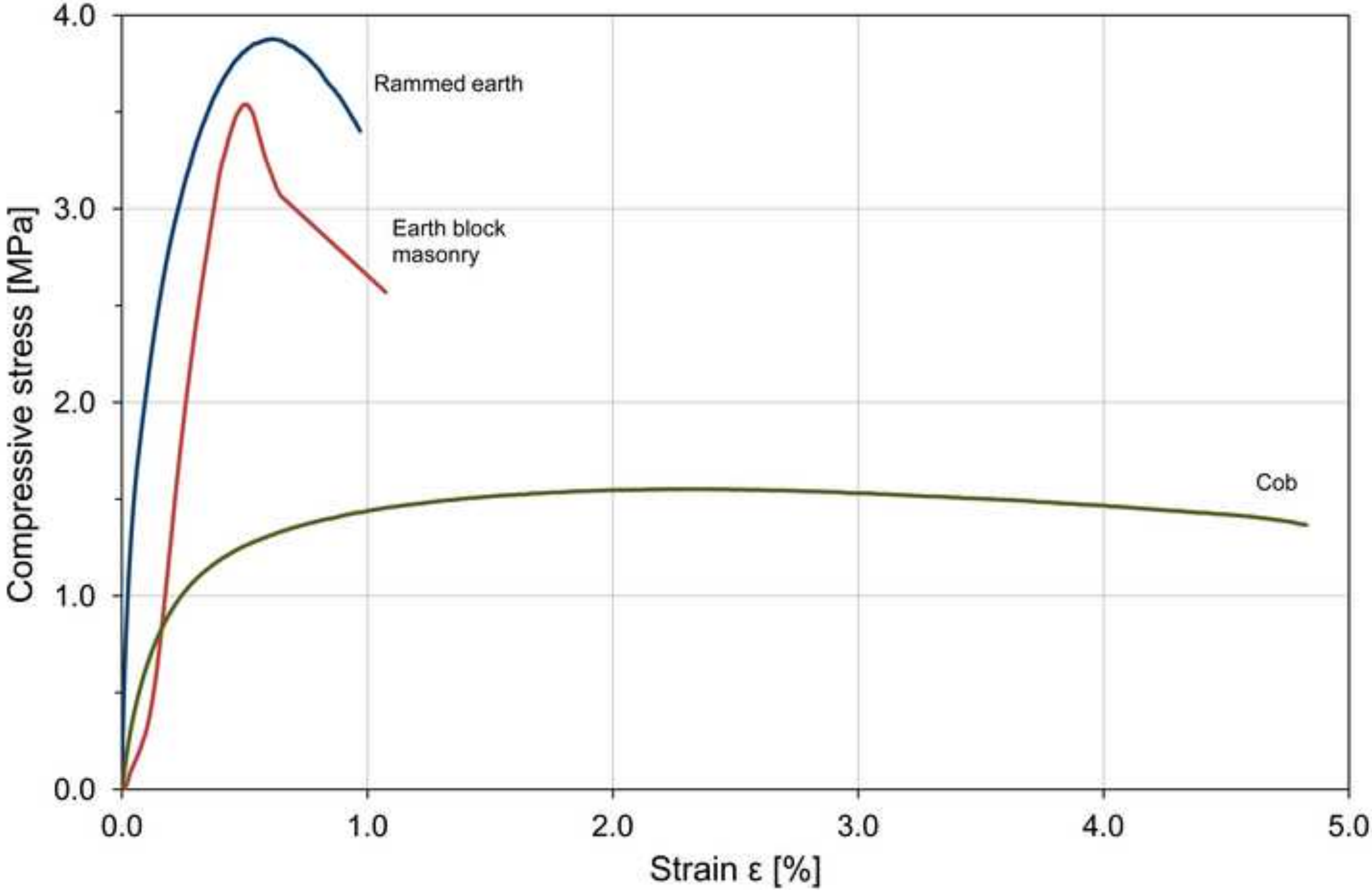

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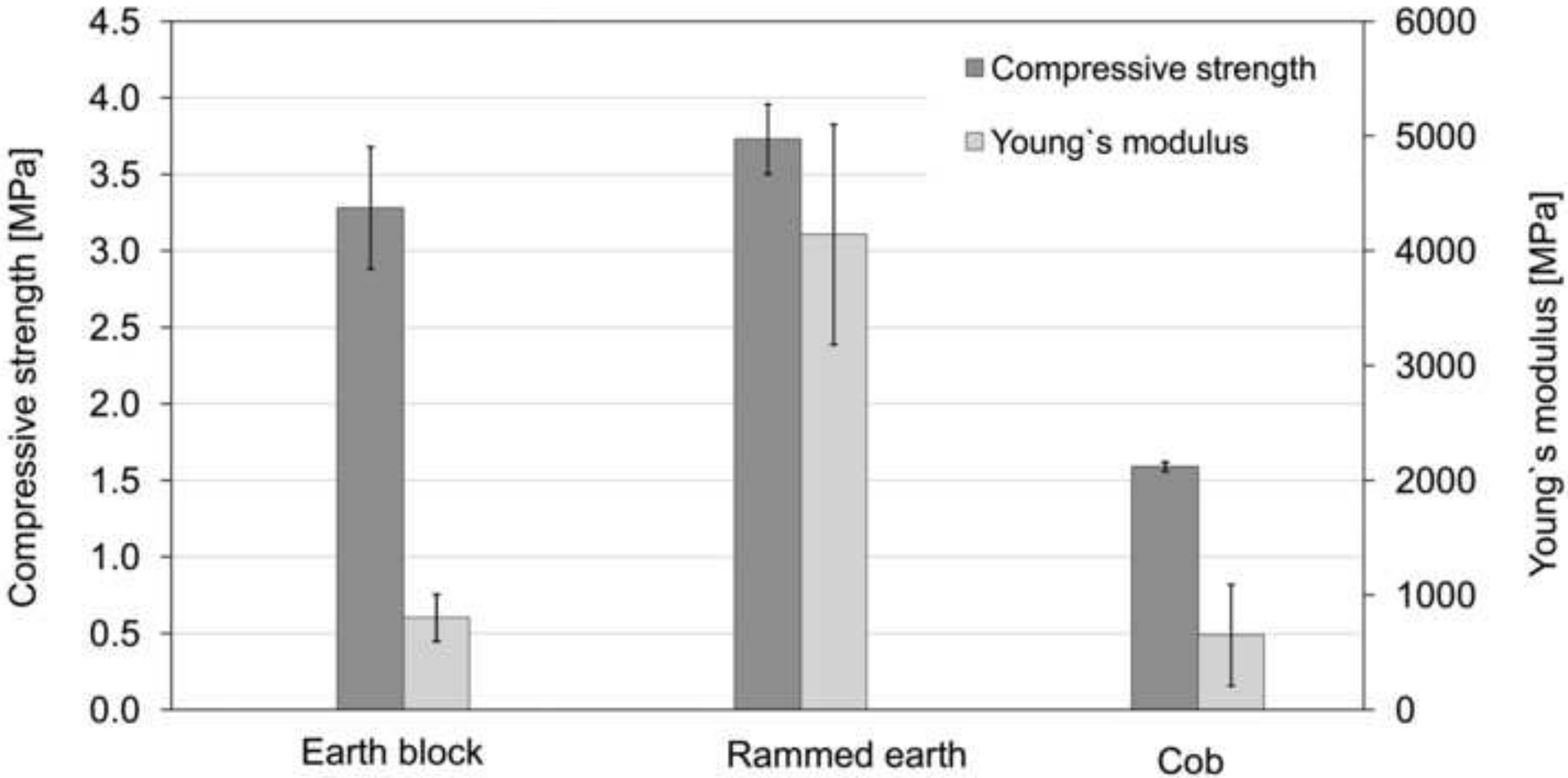

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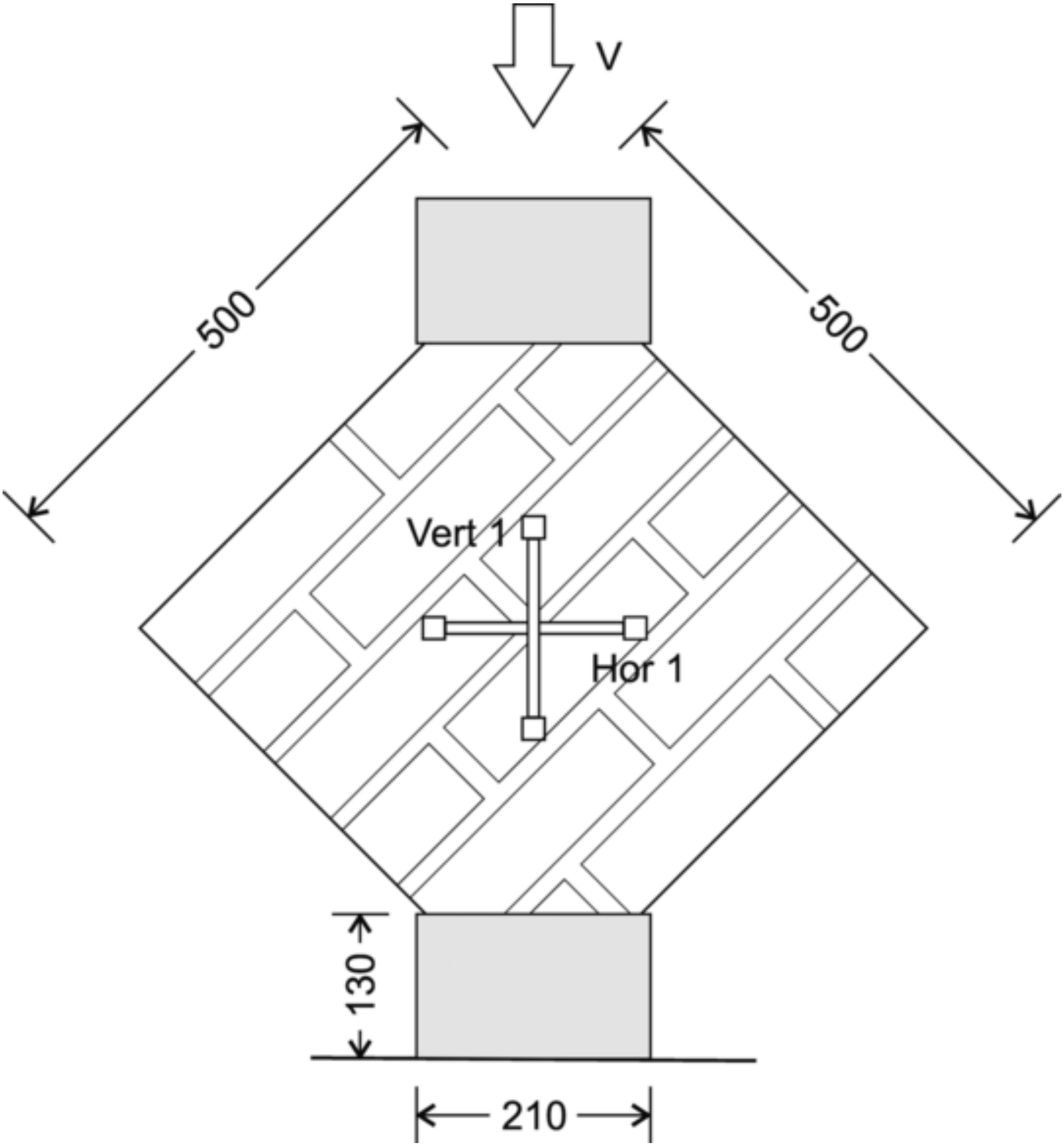

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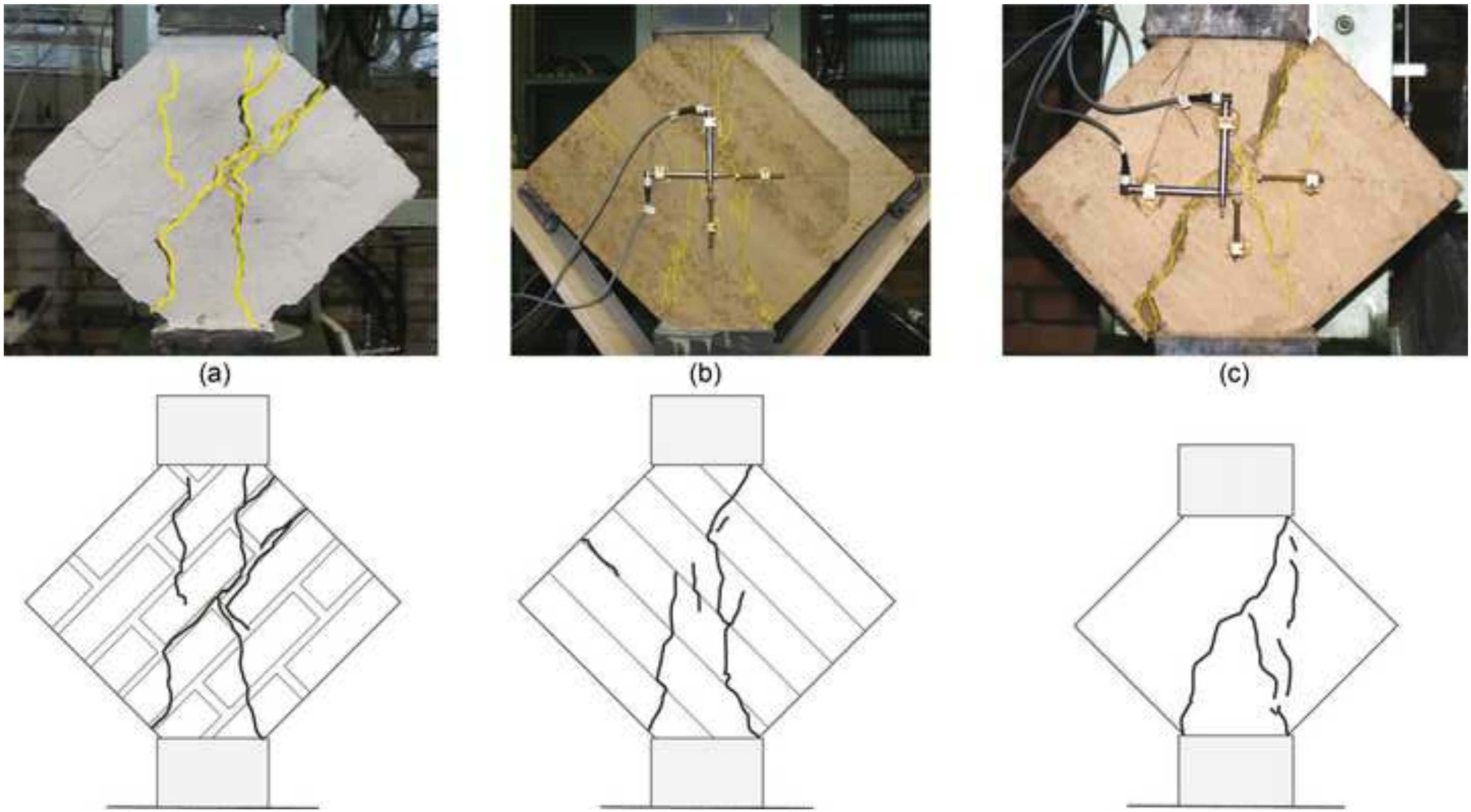

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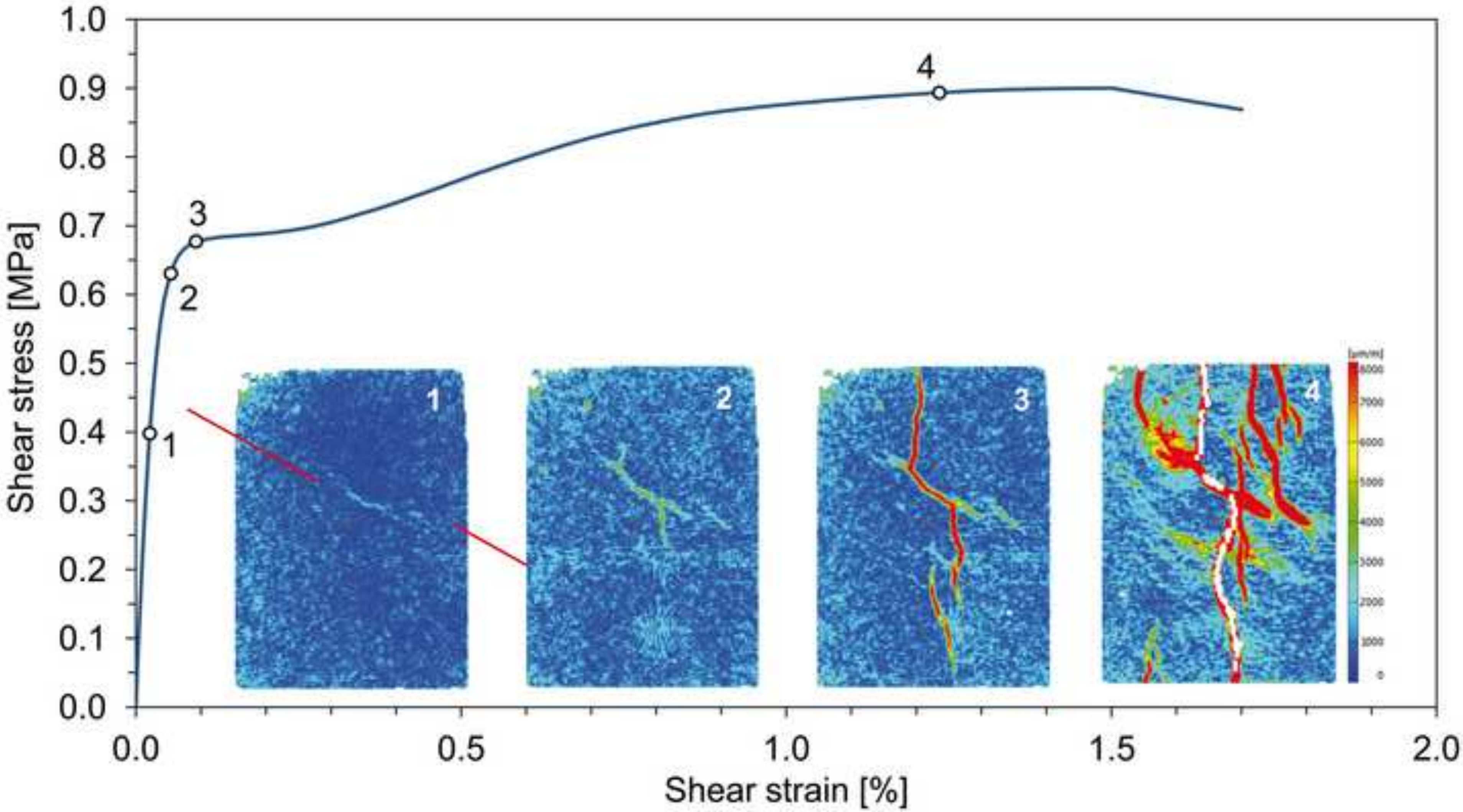

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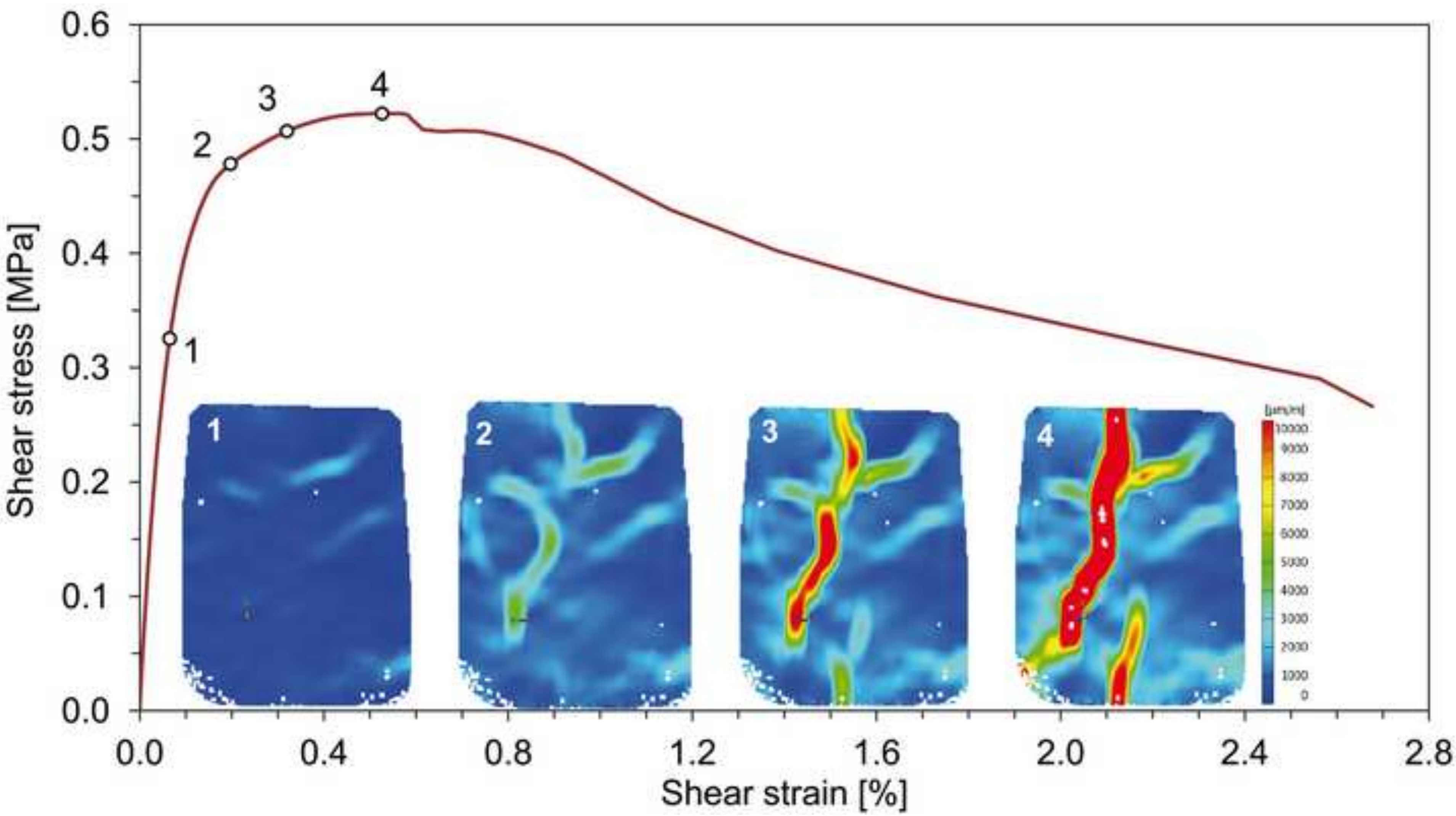

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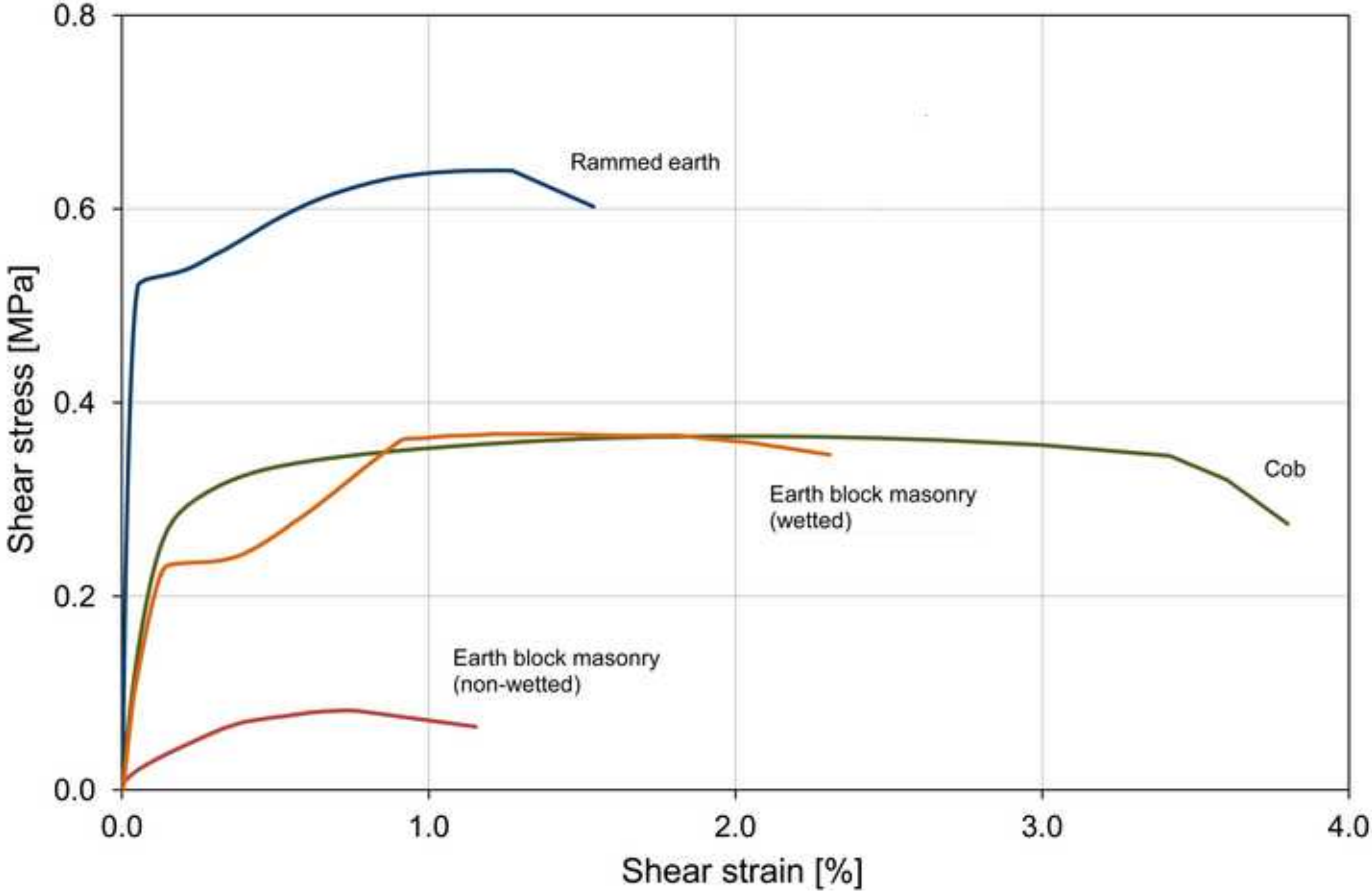

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