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The influence of natural reinforcement fibers, gypsum and cement on compressive strength of earth bricks materials

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HIGHLIGHTS

- Un-fired earth bricks were made from biocomposites.
- The compression and flexural test were done for different samples.
- Fibers have greater effect on compression and flexural strength than cement and gypsum.

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ABSTRACT

This paper presents an experimental work on the compressive strength of earth bricks in particular the influence of additives. In total 21 different test series are carried out with different composition of earth, cement, gypsum, hemp and flax fibers. The earth material is characterized by geotechnical laboratory tests. The test results indicated that the compressive strength is highly dependent on the density of the bricks. The fibers hemp and flax have rather low impact on the compressive strength of earth bricks, but they have strong influence on the breaking behavior. Cement and gypsum as additive, as they seem to reduce the binding force of the clay minerals, lead to a highly decreased strength.

1. Introduction

The promotion of sustainable development has put pressure on all industries, including the construction industry to adopt and implement proper methods to protect the environment. Due to current global concerns for sustainable development that have arisen from extensive environmental problems such as climate change and the impoverishment of resources coupled with the rapid pace of technological advancement within the building sector, interest in alternative building materials such as earth has developed. Most building regulations have increasingly strict criteria for the thermal performance of buildings, including building ecology and sustainability. Soil as a building material has good physical properties when considering energy conscious and ecological design, and also fulfills all strength [1,2]. In developed countries, a new consciousness arises for organic and healthy building materials. The concept of sustainability is gaining importance. Earth as a natural building material is being received increasing attention. Compared with industrial building materials like concrete, earth material requires approximately 99% less energy in the production process. Moreover, earth as building material is recyclable, cost effective and regionally available making long transport routes unnecessary. Reuse the agricultural by-products presents clear advantages from economic (cost-reducing) and ecological (resource-saving) perspectives [3,4]. Natural fibers offer an attractive alternative to many synthetic materials building with natural fibers presents diverse markets for farmers, reduces the emission of carbon dioxide and minimize the volume

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of waste in landfill. Furthermore, natural fiber source is renewable and considered being green and environmentally friendly [5–7]. On the other hand the relation between earth bricks reinforced by agricultural wastes and environment conditions were studied. They found that, the equilibrium moisture content (EMC) for bricks under different conditions was less than 7% and it has a good physical and mechanical properties for different materials [8–13]. The use of natural fibers and in particular hemp fibers as reinforcing agents in composite materials offers many advantages such as low density and biodegradability [14–16]. On the other hand, faced with the worldwide shortage of forest resources, the industry is showing increased interest in the production of particle board from agricultural residues [17].

For unstabilized soils, the compressive strength between 0.60 and 2.25 MPa was shown by Delgado and Guerrero [18]. According to the Spanish Standards [19], Morel et al. [20] summarized the mechanical behavior of unstabilized rammed earth, where the compressed earth blocks produced with manual press usually possess compressive strengths in a range of 1.5–3.0 MPa and densities from 1763 to 2160 kg/m^3. Higher strengths can be achieved using hydraulic press and/or higher cement contents with typical compressive strengths in the range 2–3 MPa. Some in-situ measurements were reported by Bui et al. [21] in a rammed earth house erected near Thiers (France). The densities obtained were about 1980 kg/m^3 and compressive strengths about 1.65 MPa. Stabilizers such as lime, cement or bitumen, were added to improve the earth properties [22]. In some countries such as Papua New Guinea clayey soils are stabilized with native materials, e.g. volcanic ash, finely ground natural lime, cement and their combinations. The influence of stabilizers was studied by Hossain et al. [22]. The compressive strength in this case varies between 0.39 and 3.10 MPa. According to Ngowi [23], the strength of cement stabilized bricks is about 70% higher than the bricks stabilized with lime, as the strength of lime mortar is only a third of the cement mortar. Atzeni et al. [24] added stabilizers such as hydraulic cements, hydrated lime and polymers (acrylic latex and an aqueous solution of naphthalene–sulfonate) and increased the compressive strength from 0.9 MPa (unstabilized) to 5.1 MPa (polymer impregnated) [25].

Minke [26] suggested that for dry building elements made of earth the compressive strength of 2–5 MPa should be used. Note that poor earth materials may have strength as low as 1 MPa while optimum loam products can have strength as high as 10 MPa. According to Schröder [27] there are numerous influence factors on the dry compressive strength of earthen building materials, such as grain distribution, grain quality, quality of clay minerals, quantity of clay minerals, binding strength of the clay minerals, preparation, amount of water used in production, compaction work, surcharges and additives. Ashour et al. [28] showed that fiber has positive effect on both the strength and ductility of earth plaster materials. While the fiber has remarkable effect on the strength and ductility of plasters, its effect on the elastic modulus of plasters is relatively small. Cook [29] showed that the chemical composition and morphological properties of coir fiber provide better protection against decomposition than sisal fiber. Guimaraes [30] reported that the impregnation of sisal fiber with 0.375% polyvinylalcohol (PVA) aqueous solution heated for 60 min led to tensile strength about 78% higher than unimpregnated sisal fibers after 140 days under lime solution exposure. On the other hand, Agopyan [31] showed that subjecting the coir fibers to tap water followed by drying at laboratory environment or oven at 105 °C caused significant reduction in the tensile strength and in elongation. This can be attributed to biodeterioration [32], but the leaching of extractive may also be considered Our paper represents a systematic investigation on the influence of hemp and flax fibers as reinforcement materials for earth bricks. Moreover, the effect of stabilization materials such as cement and gypsum on the compressive strength of earth bricks is discussed.

2. Materials and methods

2.1. Materials tested

Five different materials are used, i.e. cohesive soil, flax, hemp, gypsum and cement. The fibers were selected because of their positive impact on the thermal properties of earth building materials and the mineral binders because of their strength properties. The composition of the cohesive soil texture is as follows: 26% clay (<2 μm), 66% silt (20–63 μm), 5% sand (63–2000 μm) and 3% gravel.

The Atterberg limits were determined in a geotechnical laboratory with W_L = 32% (liquid limit), W_P = 17.3% (plastic limit) and I_P = 14.7% (plasticity index). According to the unified soil classification system the soil can be defined as low plastic clay. To analyze the composition of clay minerals, X-ray diffraction clay mineral analysis was performed. Type and amount of these clay minerals have large influence on the binding force and therefore also on the bending and compressive strength. The content of clay minerals can be given as follows: 50% smectite (low binding force), 30% illite (high binding force), 10% kaolinite (high binding force) and 10% vermiculite (medium binding force). Fig. 1 shows the grain size distribution of the tested soil.

2.2. Sample preparation

At first, the oversized gravels were removed from soil. The soil was then moistened to the liquid limit, a state in which you can squeeze the earth through the fingers by pressing it. During mixing the consistence of the earth needs to be carefully

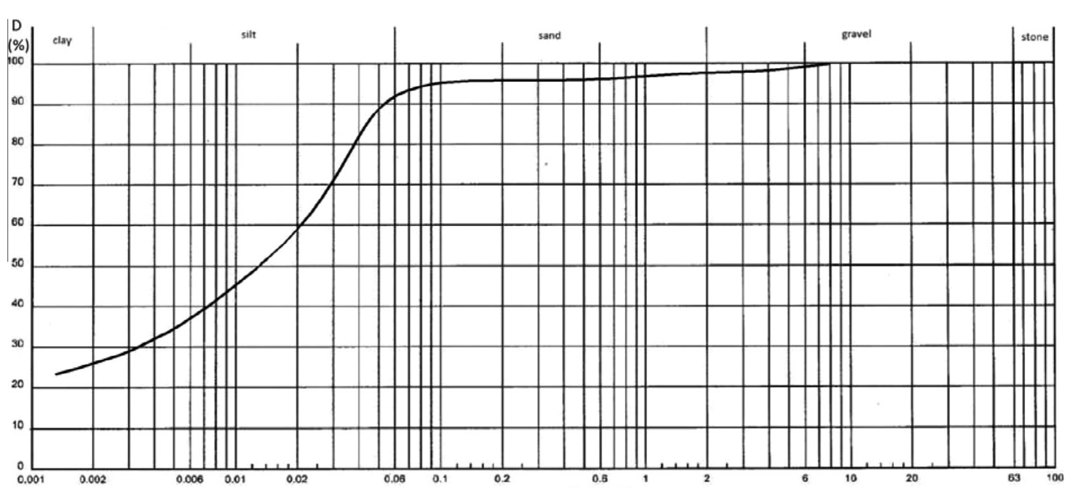

Fig. 1. Grain size distribution of soil.

Fig. 2. Mixing machine for composite preparation.

controlled. The amounts of materials were determined as dry weights. Afterwards the raw materials of soil, cement, gypsum, and fiber were placed in a mechanical mixer (Fig. 2).

An optimum water content for filling in a formwork is achieved when the earth is formed into one large clump, which adheres on the inner surface of the mixer and falls down inside of it during each rotation. Through this process the earth gets kneaded like dough, which further activates the binding forces of the clays as they bind water and accumulate on the larger soil particles and the additives. The mixer machine is working until materials become homogeneously combined and then the content of the mixer is dumped in the formwork and evenly distributed. Fig. 3 shows the produced bricks, while Fig. 3a illustrated the bricks without reinforcement fibers and Fig. 3b the bricks reinforced with hemp fibers.

The standard EN 1015-11 [33] used to measure the compressive strength of some mortars is adopted to measure the strength of earth bricks. This standard regulates the sample production and testing of the bending tensile and compression strength. The specimens are prisms with the dimensions of 160 $\times$ 40 $\times$ 40 mm.

For each group three samples were produced as replicates. For compressive strength the prisms broken in flexure are used to get six half prisms. Mixing materials for different recipes are listed in Table 1.

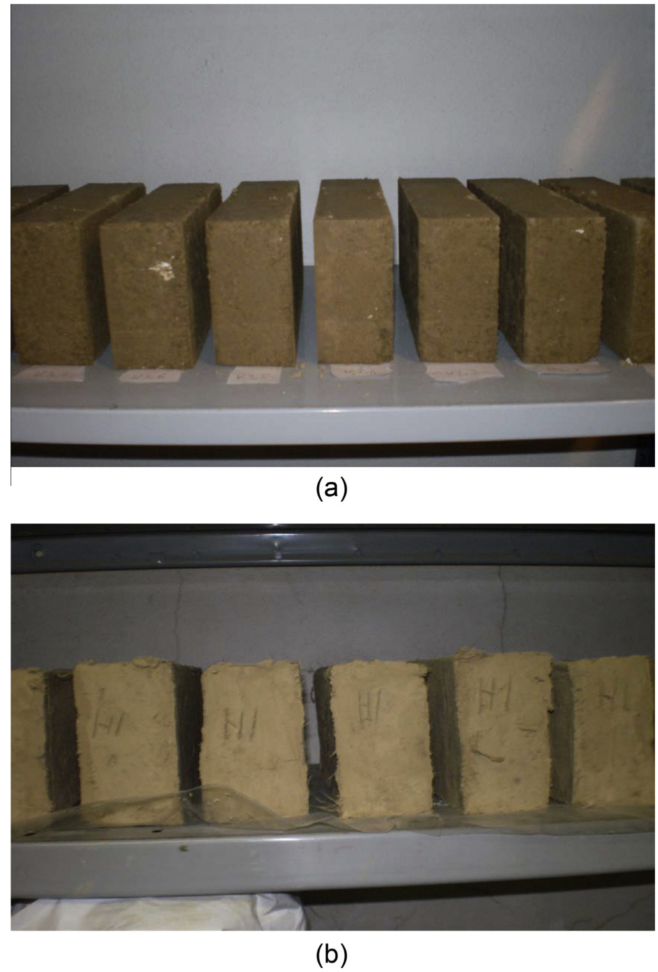

Fig. 3. Produced bricks through drying process, (a) bricks without fibers, (b) bricks reinforced with hemp fibers.

2.3. Testing apparatus and procedure

A DOLI testing machine with the extern digital controller EDC580 was used to determine the compressive strength. For the load transfer, two plates of steels with a dimensions of 40 $\times$ 40 mm and a height of 10 mm are used. The specimen is placed in the center of these plates. The load is increased at a rate of about 50 Newton per second. Fig. 4 illustrates the failure progress of a test specimen.

The uniaxial compressive strength is the compressive strength of soil samples with free lateral expansion. It is the maximum value of the uniaxial compressive stress.

$$q_u = \sigma_{max}\ (\mathrm{N/mm^2}) \tag{1}$$

The uniaxial compressive stress is defined by the ratio of the axial force F (N) and the cross section area A (mm^2).

$$\sigma = F/A\ (\mathrm{N/mm^2}) \tag{2}$$

3. Results and discussion

3.1. Influence of fibers on the compressive strength

Fibers act as reinforcement in earth bricks. Fibers have a lower compressive strength than the earth but it can hinder the lateral strain during the compression thereby increase compressive strength. This requires that the fibers have an adequate bond with the binding clay in the material. If the bond is too weak, the tensile forces cannot be transferred to the fibers (Fig. 5).

The stability of the fiber itself is also very important. If the fibers have a lower tensile strength than the soil material, they may reduce the compressive strength of the composite not only by replacing the stronger material but also by inducing stress peaks around the fibers, which can lead to earlier failure. To absorb the lateral strain the fibers should be arranged uniformly in the direction of tension.

3.1.1. Flax fibers

The presence of flax fibers may have some negative effect on the strength. Flax fibers as additive reduce the density because of the lower fiber density itself and because of the higher water content to reach plastic state compared to soil without fibers. The force transmission between the soil particles is disturbed by the presence of flax fibers and the bond of the clay aggregates is interrupted. Despite these negative influences of flax, however, the tests do not show any negative effect on the compressive strength. It seems that the flax fibers exert some confinement to compensate the strength. The fracture pattern of the specimens differs substantially to the specimens without additives. Pure earth specimens show brittle behavior, while specimens with flax fibers show ductile behavior (Fig. 6). After the maximum load is reached, samples with flax can still sustain further deformation before final failure. Apparently, this more gentle strain softening behavior is due to the flax fibers. Note that some samples show steadily increasing strength with deformation, which is ascribed to the large compaction of the samples. Since the force–displacement curve does not show a peak in this case, the compressive strength is assumed at the end of the linear regime. The addition of flax fibers would reduce the compressive strength of the composite, regardless of

Table 1
Tested soil mixtures.

Recipe symbols	Recipes definition
N	Soil without additives
F1	Soil with 1 mass-percent flax fibers
F3	Soil with 3 mass-percent flax fibers
H1	Soil with 1 mass-percent hemp fibers
H3	Soil with 3 mass-percent hemp fibers
F1G5	Soil with 1 mass-percent flax fibers and 5 mass-percent gypsum
F1G10	Soil with 3 mass-percent flax fibers and 5 mass-percent gypsum
F3G5	Soil with 3 mass-percent flax fibers and 5 mass-percent gypsum
F3G10	Soil with 3 mass-percent flax fibers and 10 mass-percent gypsum
H1G5	Soil with 1 mass-percent hemp fibers and 5 mass-percent gypsum
H1G10	Soil with 3 mass-percent hemp fibers and 5 mass-percent gypsum
H3G5	Soil with 3 mass-percent hemp fibers and 5 mass-percent gypsum
H3G10	Soil with 3 mass-percent hemp fibers and 10 mass-percent gypsum
F1Z5	Soil with 1 mass-percent flax fibers and 5 mass-percent cement
F1Z10	Soil with 3 mass-percent flax fibers and 5 mass-percent cement
F3Z5	Soil with 3 mass-percent flax fibers and 5 mass-percent cement
F3Z10	Soil with 3 mass-percent flax fibers and 10 mass-percent cement
H1Z5	Soil with 1 mass-percent hemp fibers and 5 mass-percent cement
H1Z10	Soil with 3 mass-percent hemp fibers and 5 mass-percent cement
H3Z5	Soil with 3 mass-percent hemp fibers and 5 mass-percent cement
H3Z10	Soil with 3 mass-percent hemp fibers and 10 mass-percent cement

the mixing method. The increased porosity of the composite material as a result of fiber addition is the major factor responsible for the reduction in compressive strength, which agrees with some previous findings [34,35]. Moreover, in the case of coir fiber reinforced mortar slabs, fiber pull-out was observed at ultimate failure, whereas, tensile failure of fibers was observed in all other slab specimens. The above compressive strength mechanism is typical of natural fiber reinforced composites, as observed by other investigators [36–38].

3.1.2. Hemp fibers

Hemp as well as flax requires higher water content in the production, which leads to lower density and reduced compressive strength. The hemp fibers cannot compensate this behavior by reducing the transverse expansion. The fibers of hemp are thinner and weaker than flax fibers, which gives rise to somewhat lower compressive strength than pure earth bricks or bricks with flax. Although the fibers weaken the strength they have at the same time some positive effect on the fracture behavior by increasing ductility. After the breakage the samples can still resist certain load, which decreases gradually with increasing deformation. The more hemp is added to the earth the more force it is able to resist after fracture. Fig. 6 shows the breaking behavior of bricks samples with different fibers. The mechanical properties of the cement composite depend mainly on the content of fibers, their orientation, and on the quality of load transfer between the reinforcement and matrix. The positive effect of fibers was observed mainly visually; the samples with fibers remained relatively compact at large strain [39]. While fibers alone cannot resist axial compressive load and as such do not contribute to the compressive strength of the composite. Rather, under compressive loading the fibers may be viewed as filler in the mortar matrix thus, introducing voids and discontinuity in the matrix with consequent reduction of strength. The reduction in compressive strength increases with increase in volume fraction of fiber [40].

3.2. Influence of gypsum on the compressive strength

Gypsum used as mortar has, according to DIN EN 13279-1 [41], compressive strengths between 2 and 6 N/mm^2. If gypsum is used

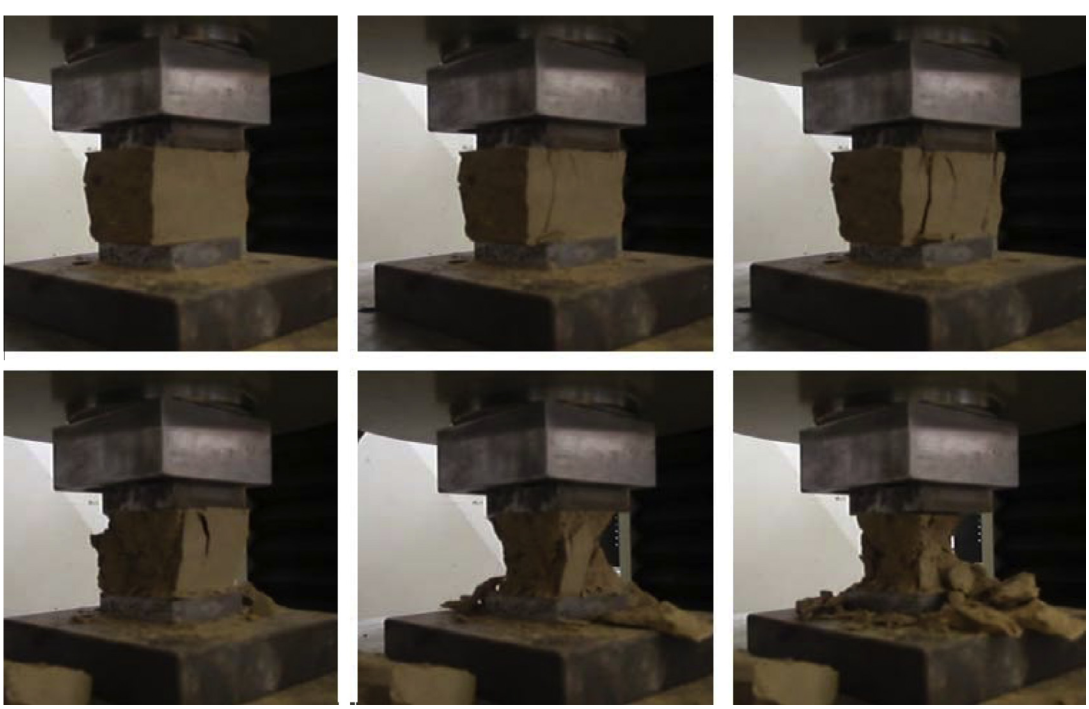

Fig. 4. Breaking process of earth bricks without additives.

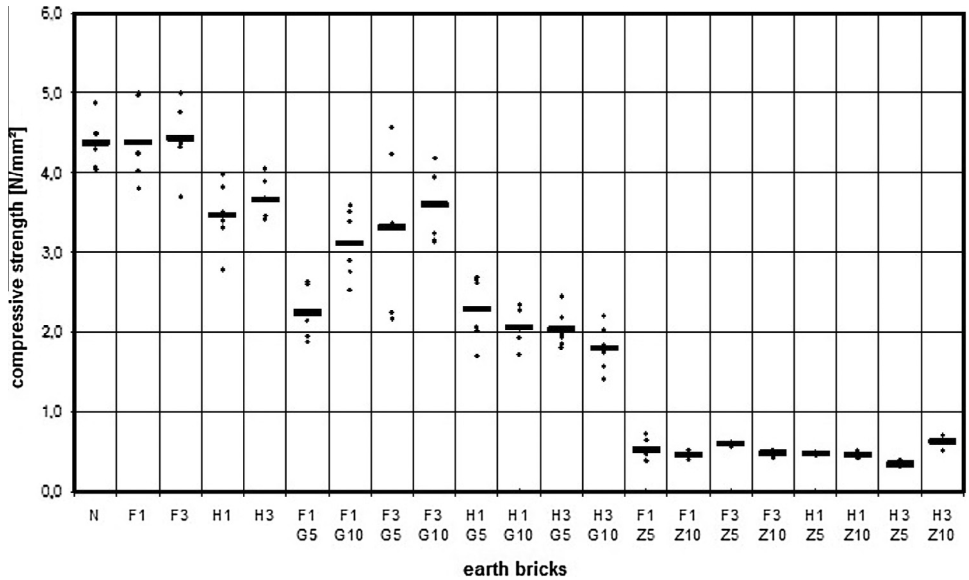

Fig. 5. Compressive strength of bricks made from different materials.

for screed mixed with sand, the strengths can be as high as 40 N/mm^2 [42]. The strength properties of gypsum materials are influenced by the crystal formation and above all by the water–gypsum ratio. The higher the water-binder value, the lower is the achievable strength. During our brick production the gypsum had too much water to reach optimal strength values, since the water in soil and fibers is easy available for gypsum. In addition, the required consistency for adding the gips-water suspension in the mixture requires water contents that are far above the optimum. The mixtures with gypsum result in reduction of the compressive strength due to several factors, such as the high water content. A high water–gypsum ratio leads to low strength and to low interconnection between the gypsum crystals. By building up crystal framework, gypsum may expand into the pores. It is possible that gypsum has negative influence on the binding force of clay. Another factor for the strength reduction could be the high binding speed of gypsum. If gypsum solidifies fast during the mixing process, the formed gypsum crystals could be interrupted in their connections or they could be destroyed. The fracture behavior of earth with gypsum is similar to the behavior of pure earth. The force–displacement diagrams show that the influence of the fibers is dominant (Fig. 7). The compressed soil bricks stabilized with gypsum show better compressive strength than that with no or low stabilization with gypsum. This improvement can be attributed to the crystal formation between soil and gypsum. Also, there is a similar effect on flexural strength [43].

3.3. Influence of cement on the compressive strength

It is well known that concrete with cement can achieve high compressive strength. Concrete is a mixture of cement, aggregates (grains) and water. The grain structures and the cement around the grains form a matrix. The compressive strength of concrete is almost exclusively dependent on the strength of cement, as the strength of the grains is significantly higher than the cement binder. The strength of the cement depends on its composition and on the water–cement ratio. The compressive strength of the tested earth bricks with cement is very low compared to concrete. Considering that the earth bricks with cement can be regarded as a concrete under modified production conditions, the cause of the strength reduction can be explained as follows:

3.3.1. Cement content

Concrete has a mean mixing ratio of cement and aggregates of about 1:6.5. However, the tested bricks are produced with mixing ratios of 5% (1:20) and 10% (1:10). The low mixing ratios mean that the soil grains are not completely enclosed with cement.

3.3.2. Aggregate sizes

A well-compacted concrete with a maximum aggregate size of 32 mm has an air pore content of 1–2 vol%. Fine-grained mixtures have higher air contents of about 6 vol%. The compressive strength decreases by about 8% for each percent of pore content. Concrete needs certain amount of fines to improve workability and to form coherent microstructure. However, if the fine content is too high, more water is needed for workability. Depending on the usage of the concrete the fine-grained constituents smaller than 0.25 mm should be less than 150–200 kg/m^3 [42]. The soil used for the tests consists mainly of silt and clay, resulting in a fine-grain content of about 1700 kg/m^3.

3.3.3. Water–cement ratio

The fine particles of the soil require high water content to reach workable consistency. The water is physically bound on the soil particles making it easy available for the cement. When cement binds, it forms rod shaped crystals that expand and interlink with each other. However, if more water is available between the hydrating crystals, the space between them results in loss of connections with each other. The excess water between the crystals evaporates after hardening, leaving pore spaces with air, which reduces the strength of the composite.

3.3.4. Prevented shrinkage

The strength of earth bricks depends on the attractive forces between the clay minerals and the water molecules. To enhance these forces, the soil particles need direct contact to each other. Clay minerals are attracted closer together during shrinkage and generate hydrogen bridges, which gives rise to increased strength. The process of shrinkage takes, depending on the drying conditions, several weeks until it is completed. In comparison, the crystal lattice of the cement is completed after about 1 day preventing the shrinkage due to their rod-shaped crystals. The clay minerals are not able to interconnect and lose their cohesion.

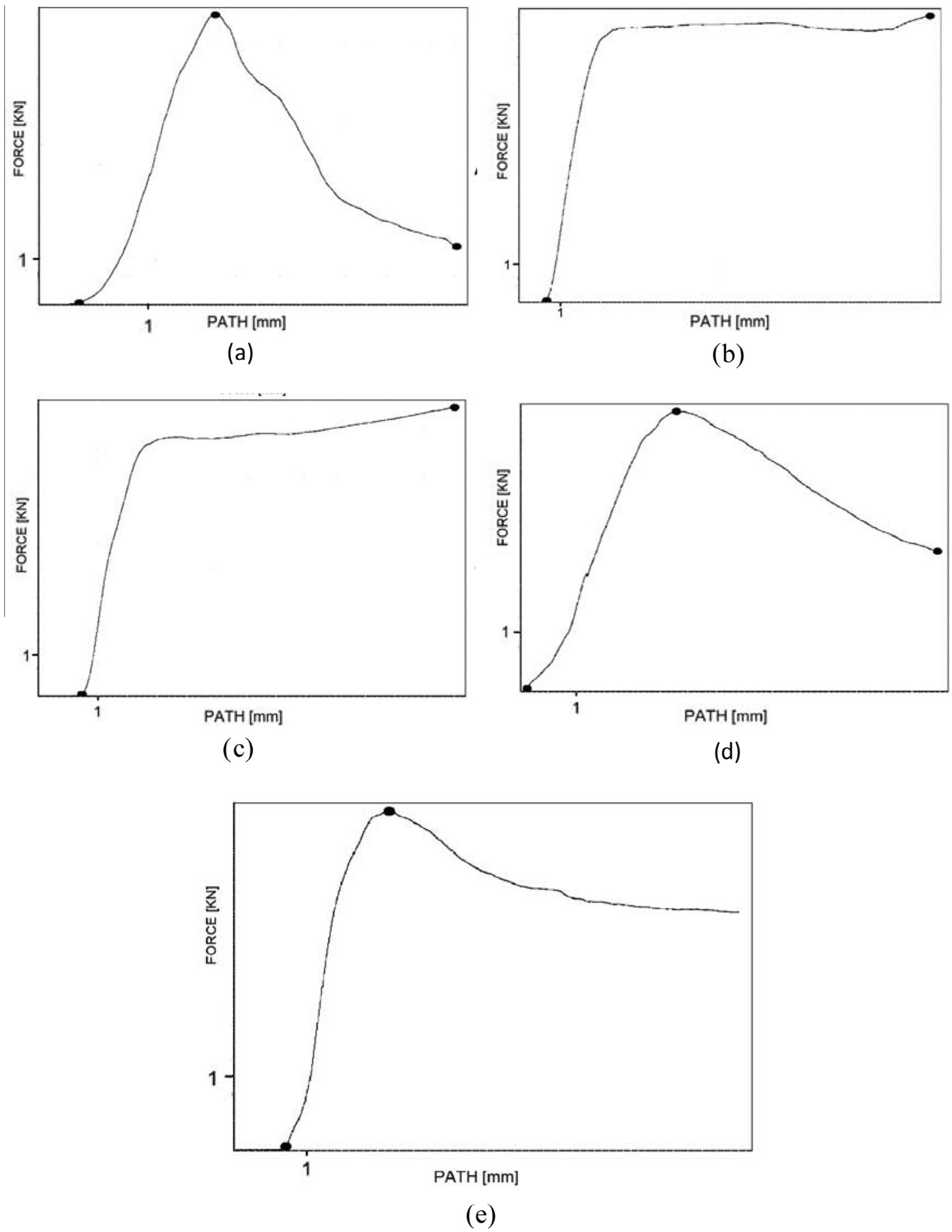

Fig. 6. Force–path diagrams of bricks with different fibers type and contents, (a) without additives, (b) flax 1%, (c) flax 3%, (d) hemp 1%, (e) hemp 3%.

3.3.5. Chemical interaction between soil and cement

Soils vary in their chemistry making it very difficult to analyze the interactions between soil and cement. It is possible that these interactions affect the binding force of the clay minerals and the crystallization of cement.

3.3.6. Fracture behavior

The mixtures with cement have an elastic limit of about 0.5 N/mm^2. A further increase of stress leads to plastic deformation and the samples start to consolidate. As a result of consolidation, the pore cavities collapse and the compressive strength increases. Fig. 8 illustrated force–path diagrams earth bricks stabilized by cement mixture.

Fiber petrifaction can also cause composite embrittlement [34]. In a similar study on air-cured fiber-cements, Bentur and Akers [44] observed that, the fiber petrifaction can take place under ambient carbonating conditions, probably due to lower pH and greater solubility of the hydration products. However, carbonation should be expected to reduce the incidence of $Ca(OH)_2$ and to avoid the alkali attack on the non-cellulose components of the fiber (lignin, e.g.) [45]. But this phenomenon did not appear to have significant effect on the prevention of ductility drop for the studied composites. The other mechanisms of degradation continue to act in similar form. John et al. [46] pointed out that generalized interfacial damage could be progressively generated by hygroscopic volume change of fibers inside the cement and clay matrix hence contributing to the

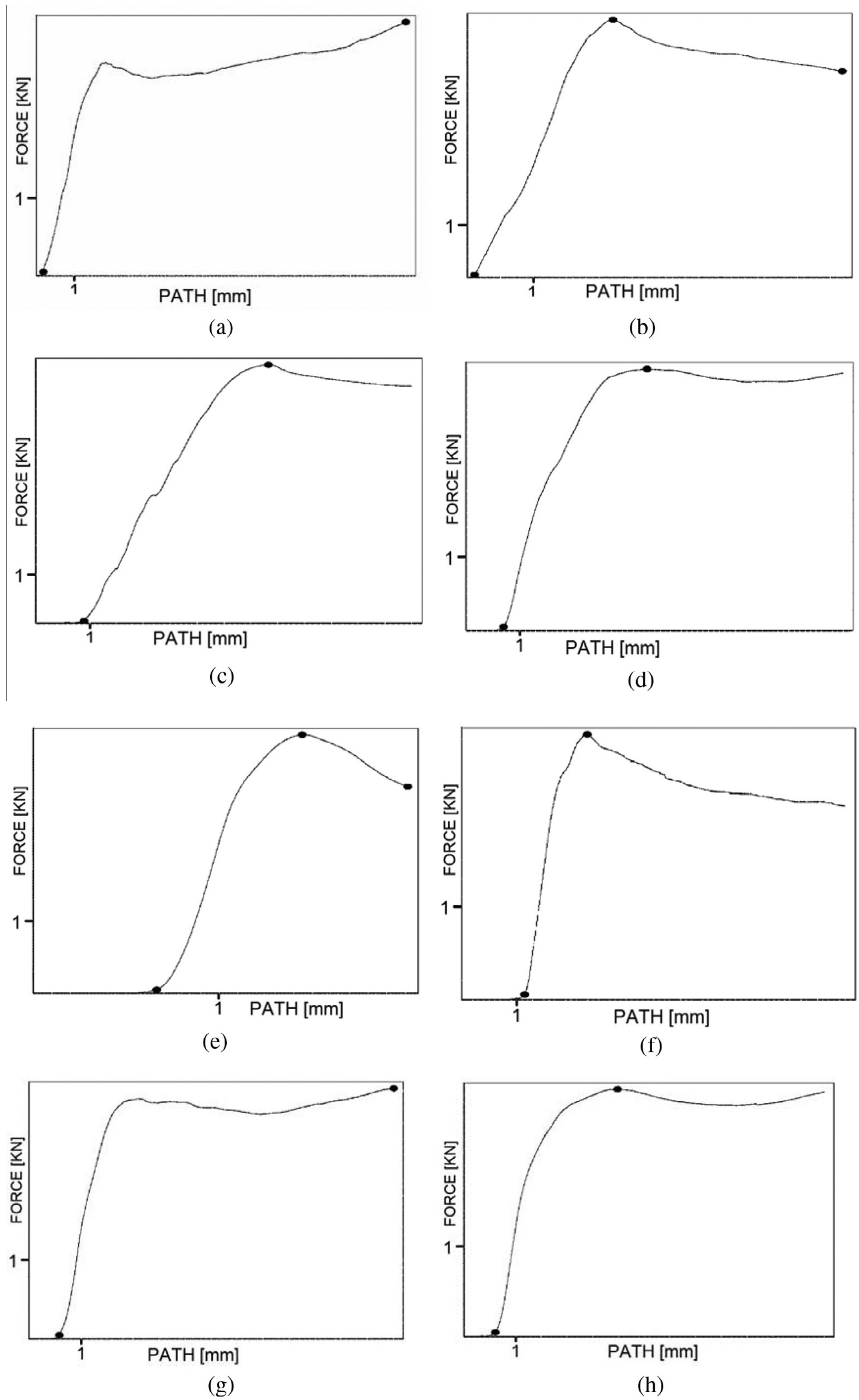

Fig. 7. Force–path diagrams of bricks made from gypsum mixtures and other materials, (a) flax 1% and gypsum 5%, (b) flax 1% and gypsum 10%, (c) flax 3% and gypsum 5%, (d) flax 3% and gypsum 10%, (e) hemp 1% and gypsum 5%, (f) hemp 1% and gypsum 10%, (g) hemp 3% and gypsum 5%, (h) hemp 3% and gypsum 10%.

deterioration of composite mechanical behavior in the long run. Moreover, composite with vegetable fibers showed poor bonding between both phases with high porosity and increased microcracking in the fiber-matrix transition zone [47–49].

3.4. Influence of density on the compressive strength

Density of building material is known to have significant impact on its properties. Fig. 9 shows the correlation between density and

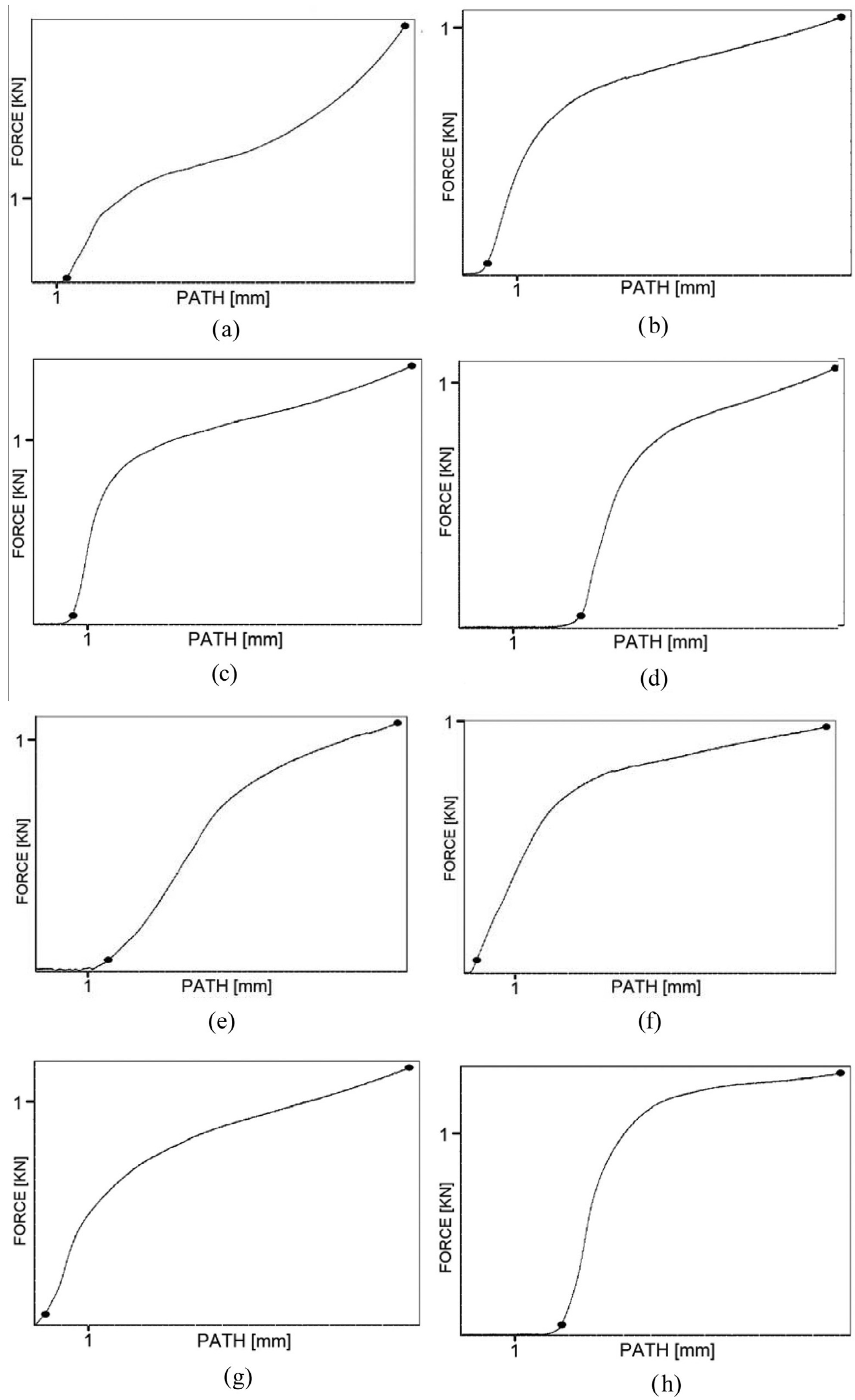

Fig. 8. Force–path diagrams of bricks made from cement mixtures and other materials, (a) flax 1% and cement 5%, (b) flax 1% and cement 10%, (c) flax 3% and cement 5%, (d) flax 3% and cement 10%, (e) hemp 1% and cement 5%, (f) hemp 1% and cement 10%, (g) hemp 3% and cement 5%, (h) hemp 3% and cement 10%.

compression strength. In general, increasing the fiber content in the composites decreased the specimen weights. Replacement of cement or gypsum (dense materials) with hemp or flax fibers (light materials) resulted in a total volume increase. The increase in compacted mix volume resulted in a decrease in specimens' weights and densities. As might be expected, lower densities due to light additives and higher water contents in production lead to reduced resistance.

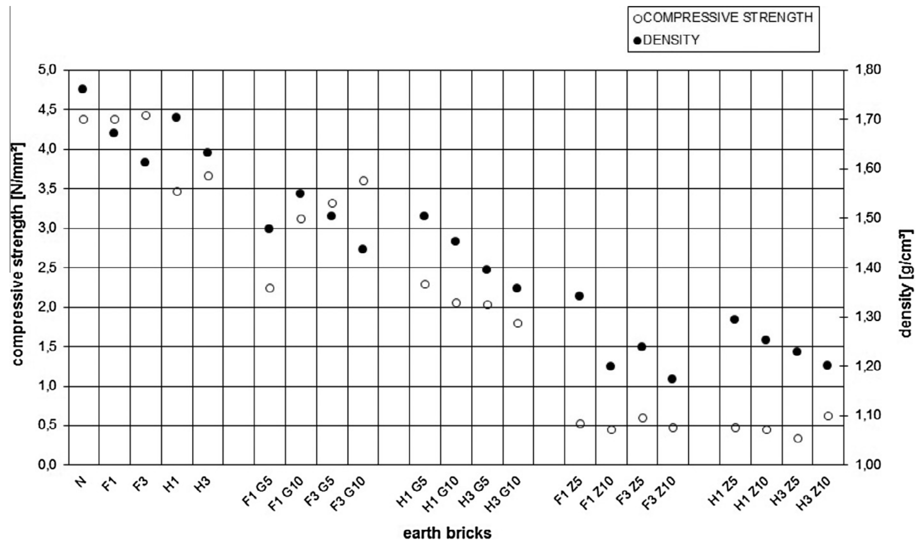

Fig. 9. Influence of density on compression strength of earth bricks.

4. Conclusion and recommendations

The stabilisation of earth with cement to increase the compressive strength is a common method in earth building construction and geotechnical engineering. However, our tests show that cement can be detrimental to the stability of soil. When stabilizing earth with cement, special attention should be paid to the water content in soil. High water contents can lead to more porous structure. The produced bricks with cement are not applicable for load bearing walls due to their low compressive strength. Nevertheless, when used as infill, the soil-cement composite is thought to be strong enough to resist the load of 25 m high wall.

Flax fibers do not significant change the compressive strength but reduce the brittle breaking behavior of the material. Hemp fibers lead to slightly reduced compressive strength compared with the pure earth bricks. This is mainly due to the strength loss of the fibers and the reduced density. Mixing earth with gypsum has no favorable influence on the compressive strength. Also the production with gypsum is rather difficult as it binds very fast compared to cement.

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