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OPTIMIZING THE MECHANICAL STRENGTH OF ADOBE BRICKS

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Abstract—Ecologic building materials such as adobe bricks have become of greater economic importance in recent years. In the present work, the addition of selected materials to improve the compressive and bending strengths of adobe bricks was tested. The raw material (loam UD) was analyzed for its mineralogical and chemical composition. The loam studied consisted of quartz, feldspar, and the clay minerals chlorite, vermiculite, illite, and kaolinite. Prerequisites for using this loam for brick making were its grain-size distribution and the absence of expandable clay minerals.

To optimize the compressive and bending strengths of the adobe bricks, seven natural and 'eco-friendly' synthetic additives were admixed with the raw material and homogenized.

From this material, small adobe bricks and bars were made. One series of bricks and bars was made without additives but instead was coated with a hydrophobic impregnation cream. The bricks were stored for up to 20 days at 100 and 75% relative humidity (RH). After 1, 5, and 20 days, the compressive and bending strengths were measured to identify the critical humidity level for brick strength. The compressive and bending strengths of loam UD at dry conditions without additives showed values of 9 N/mm^2 and 4.8 N/mm^2, respectively. With some of the additives, the strength improved by up to 30%. The greatest increases in strength were achieved by mixing the loam with Acronal S650. Finely ground trass and diatomite also increased the dry strength. After storage at high levels of RH, these mixtures lost >50% strength. In contrast, the loam mixed with blast-furnace slag has a small initial strength but showed the smallest decreases in strength after exposure to high levels of RH.

Key Words—Adobe Bricks, Bending Strength, Compressive Strength, Industrial Application of Clay, Load Capacity.

INTRODUCTION

The need for energy- and cost-saving building materials (Berge, 2009) is increasing. Loam is one of the materials fulfilling this need; it has been utilized as a building material for more than 9000 y. In hot, dry countries, it has been used to build houses, forts, and places of worship. In Europe, loam has been used as a filling material for palisades and as a flame retardant for straw roofs until the 19th century. In addition, loam is widely used as raw material in brick making.

Natural loam soil has many advantages as a building material: enhancing the indoor climate by regulating the relative humidity (RH), binding pollutants, and storing heat (Minke, 2004). Loam is, therefore, much in demand as an ecologic product, since it is recyclable. A major disadvantage is that it is not resistant to water and shrinks when dried. Loam also swells when it comes in contact with water, but not when it comes in contact with vapor. To prepare loam for brick-making, however, it must be mixed with water and, hence, during the subsequent drying stage, the volume decreases. Deformation may occur, especially desiccation cracks, and, as a result, buildings in which adobe bricks have been used lose strength. For this reason, the amount of expandable clay minerals within brick loam should be as small as possible (Minke, 2004). In cases where the clay mineral content of the loam is too great, the loam must be 'shortened' with sand, silt, or gravel.

To improve the properties of loam bricks for construction, loam can be mixed with a range of other substances. Soluble glass, soda, humic acid, and tannic acid have commonly been added to dilute the clay without enhancing the formation of cracks. Materials such as ox blood, urine, faeces, casein, whey, and bone glue have also been added, in the past, to the loam to improve the weathering resistance. To reduce the linear dry shrinkage of the loam, animal and human hair as well as coco-, cannabis-, flax-, and bamboo fibers were also added (Minke, 2004).

Dondi *et al.* (2002) added fly ash in amounts of up to 6% to adobe bricks and tested the technological properties of the material. Difficulties in mixing the clay with ash were encountered because the ash is very hygroscopic and tended to form agglomerates. In addition, the fly ash caused some detrimental changes to the technological properties of the unfired products. Lee *et al.* (2008) improved the compressive and flexural strength as well as the water resistance by adding small amounts (up to 1.5%) of polymeric binders. Pineda-Piñón *et al.* (2007) added cationic amine to the raw material which increased the hydrophobicity of the loam.

Previous studies on behalf of Wienerberger Ziegelindustrie GmbH concerning the optimization of

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adobe bricks were carried out by A. Schmidmair (pers. comm., 2008) and M. Trojan (pers. comm., 2005). Additives such as fiber glass, charcoal, brick split, ash, cannabis fibers, sawdust, glass granulate, and casein (A. Schmidmair, pers. comm., 2008) were mixed with the loam, as well as brick-dust (M. Trojan, pers. comm., 2005). Ash and brick-dust improved the compressive and bending strength under both dry and wet conditions. M. Trojan (pers. comm., 2005) suggested further investigations with bentonite, hydraulic and calcareous materials such as finely-ground trass, blast-furnace slag, and fly ash.

Some of these suggestions were taken up in the present study, with the objective of finding additives which improved the mechanical strength of adobe bricks. Seven different additives were mixed with a specific loam to find mixtures which could potentially improve the properties of adobe bricks for construction. The additives were finely ground trass, diatomite, brick-dust, blast-furnace slag, AcronalS650 (a hydrous dispersion of a copolymer based on styrol and acrylic ester) (BASF, Ludwigshafen, Germany), sawdust, and a clay mineral-rich (heavy) loam. In addition, one set of bricks without additives was coated with Funcosil®IC (Remmers, Lönningen, Germany), a hydrophobic impregnation cream. The mechanical properties of the mixtures were tested.

MATERIALS AND METHODS

Wienerberger Ziegelindustrie GmbH provided the raw material for the study, an Upper Pleistocene loam from a clay pit in Uttendorf (UD), as they are interested in optimizing this loam for the production of adobe bricks. Uttendorf is situated in the Upper Austrian Molasse Zone; the clay pit covers an area of 1600 m^2, the loam is 4–6 m thick (Wimmer-Frey *et al.*, 1992).

70 g of the sample was sieved according to ÖNORM B 4412 (1974) for grain-size analysis; the <63 μm fraction was analysed using a Sedigraph 5100 instrument from Micromeritics. For the separation of the clay fraction, samples were treated with a 400 W ultrasonic probe for 3 min causing disaggregation. Subsequently, the <2 μm fraction was separated by sedimentation (DIN 51033, 1962).

The mineralogy was determined using a PHILIPS PW 3710 X-ray powder diffractometer (CuKα radiation, 45 kV, 35 mA, step scan, step size 0.02°2θ, 1 s per step). Semiquantitative mineral estimates of the bulk sample were made using the method of Schultz (1964), which has error limits of ±10%.

Oriented samples of the <2 μm fraction for X-ray diffraction (XRD) were made by dispersing 8 mg of clay in 1 mL of water, pipetting 1 mL of suspension onto circular glass slides, and drying at room temperature. The oriented XRD mounts were analyzed in an air-dried state, and when saturated with Mg and K ions, and after vapor solvation with ethylene glycol, glycerol, and DMSO at 60°C for 12 h (Moore and Reynolds, 1997), and at 550°C.

The chemical composition (major and trace elements) of the raw loam and the blast-furnace slag was measured using a Philips PW 2400 X-ray fluorescence spectrometer.

The cation exchange capacity (CEC) was measured by the Cu-trien method (Meier and Kahr, 1999), using smectite SAz-1 as a standard, which has a large CEC (122.0 mmol/100 g). For the analysis, 200 mg of the sample was mixed with 10 mL of Cu(II)-trien, centrifuged for 5 min at 2000 rpm and the supernatant solution was measured with a photometer.

The loam (UD) was homogenized then admixed with the finely ground trass, diatomite, brick-dust, blast-furnace slag, AcronalS650, sawdust, or clay mineral-rich (heavy) loam (Table 1).

Trass is a hydrothermal, altered volcanic tuff which consists of compacted pumiceous dust. The altered tuff was ground to a fine powder which should act as a hydraulic binder between the silt and sand component of the loam.

Diatomite is a highly porous sediment with 75 to 95% porosity (Füchtbauer, 1988). The granulometric distribution can be compared to that of a well sorted silt. Diatomite consists of fossilized remains of diatoms which are composed of opaline silica (Tucker, 2001).

Brick dust came from fired bricks which were broken and crushed to coarse sand-grain size. As fired bricks have greater strengths, adding them to the loam should have had a positive effect on the strength of the unfired adobe bricks.

Blast-furnace slag is a high quality by-product in the manufacture of pig iron. After grinding, the powder has latent hydraulic properties (Grosse, 2007). Chemical analysis of the blast-furnace slag (Table 2) showed that it consisted mainly of CaO (32.95 wt.%), SiO_2 (30.12 wt.%), and Al_2O_3 (12.64 wt.%).

AcronalS650 is a hydrous dispersion of a copolymer based on styrol and acrylic ester (information from

Table 1. Different additives and mixing ratios of the loam samples. Funcosil is a hydrophobic impregnation cream so it was not mixed with the loam but a coating was added to the top of the adobe bricks and bars.

Additives	Mixing ratio (vol.%)
UD	100
UD + trass (TM)	90 + 10
UD + diatomite (DM)	90 + 10
UD + brick dust (BD)	90 + 10
UD + blast-furnace slag (SL)	90 + 10
UD + Acronal (A)	97.5 + 2.5
UD + sawdust (S)	90 + 10
UD + Funcosil (F)	100
UD + heavy loam (HL)	80 + 20

manufacturer). Acronal S650 was supposed to improve the water resistance and strength of adobe bricks by forming polymer bridges between the loam particles.

Sawdust is commonly added to fired bricks. During the firing process the sawdust combusts and secondary porosity is produced in the fired bricks. The porosity has a positive effect on the strength of the fired bricks. Fabric such as cannabis fibers or animal hair is also known to improve the bending strength of unfired bricks (Binici *et al.*, 2005).

Funcosil®IC is a hydrophobic cream based on silane used for impregnation into concrete and ferroconcrete (information from manufacturer). The adobe bricks were coated with the cream in an attempt to protect them from RH. The silane component intrudes deeply under the surface of the adobe brick and reacts to form silicone resin.

The heavy loam was a clay mineral-rich loam which contained >30% clay-sized particles (Minke, 2004).

The powder density of the additives was measured (DIN 4226-1/2, 2002) to calculate the relative proportions of loam and additive (Table 1) . For each mixture, 14 kg of loam was mixed with an additive. To achieve the defined wetness, water was added to the dry loam until a defined height (30 mm, 25 mm, 20 mm) was reached, in accord with Pfefferkorn (Salmang and Scholze, 1983) where a 1192 g weight drops down on a ready-made test cylinder from a height of 18.6 cm. Through graphical comparison of the compression height, the water demand of the loam can be estimated (Salmang and Scholze, 1983).

Adobe bricks (52 mm × 25 mm × 22 mm) and bars (120 mm × 30 mm × 14 mm) were produced under vacuum conditions. They were air dried at ambient temperature for 1 day and then for 2 further days at 110ºC and afterwards abraded to achieve planar and parallel upper and lower surfaces. The samples were stored in plastic boxes for 20 days under 100% and 75% RH and a temperature of 22–23ºC. To achieve 100% RH, a beaker filled with distilled water was placed in the boxes; for 75% RH, a saturated NaCl solution was used (Lide, 2009).

To determine the robustness of the adobe bricks and bars, tests on compressive strength and bending strength were performed after 1, 5, and 20 days of storage in the humidity boxes. The analyses were carried out four times on each mixture for the compressive strength and three times each for the bending strength.

The compressive-strength experiments were carried out on loam bricks according to ÖNORM 772-1 (2000) in which the planarity of the surface area is very important. The influence of the geometrical features of adobe bricks on the compressive strength was discussed at some length by Morel *et al.* (2007).

The bending strength (flexibility) of the material was measured (ÖNORM EN 1052-2, 1999) on adobe bars which were placed in a sample holder and a single-point stress applied in the middle.

RESULTS

Mineralogical, chemical, and granulometrical properties of the loam

Semi-quantitative mineral analysis (Schultz, 1964) gave a composition of 44% clay minerals, 45% quartz, 8% plagioclase, and 3% K-feldspar for the bulk loam (Figure 1). In the clay fraction, chlorite, vermiculite, illite, and kaolinite were present. The layer spacing of vermiculite remained at 14 Å when saturated with Mg and glycerol, contracted to 10 Å when saturated with K, and did not re-expand with K + ethylene glycol. It collapsed to 10 Å when heated to 550ºC (Moore and Reynolds, 1997). Only minor amounts of chlorite were found in the sample. Kaolinite expanded when saturated with DMSO to 11.2 Å.

Chemically, the loam consisted of a large amount of SiO_2 (68.25 wt.%), lesser amounts of Al_2O_3 (15.16 wt.%), Fe_2O_3 (5.92 wt.%), K_2O (2.10 wt.%), and MgO (1.30 wt.%) (Table 2), in accord with the mineralogical composition.

Granulometric analysis (Figure 2) showed that the loam UD contained 67% of silt-sized particles

Table 2. Chemical composition of loam UD and the blast-furnace slag (SL).

	Loam UD	Blast-furnace slag
Major elements (wt.%)		
SiO_2	68.25	30.12
TiO_2	0.99	0.43
Al_2O_3	15.16	12.64
Fe_2O_3	5.92	0.56
MnO	0.09	1.19
MgO	1.30	8.71
CaO	0.66	32.95
Na_2O	1.05	0.55
K_2O	2.10	1.55
P_2O_5	0.14	0.04
LOI	4.60	1.91
Total	100.24	90.65
Trace elements (ppm)		
Nb	23	13
Zr	394	281
Y	46	76
Sr	87	1447
Rb	110	62
Pb	39	20
Ga	23	11
Zn	65	30
Cu	29	17
Ni	47	15
Co	18	n.d.
Cr	98	14
Sc	17	11
V	107	18
Ce	83	143
Ba	485	1601
La	46	74

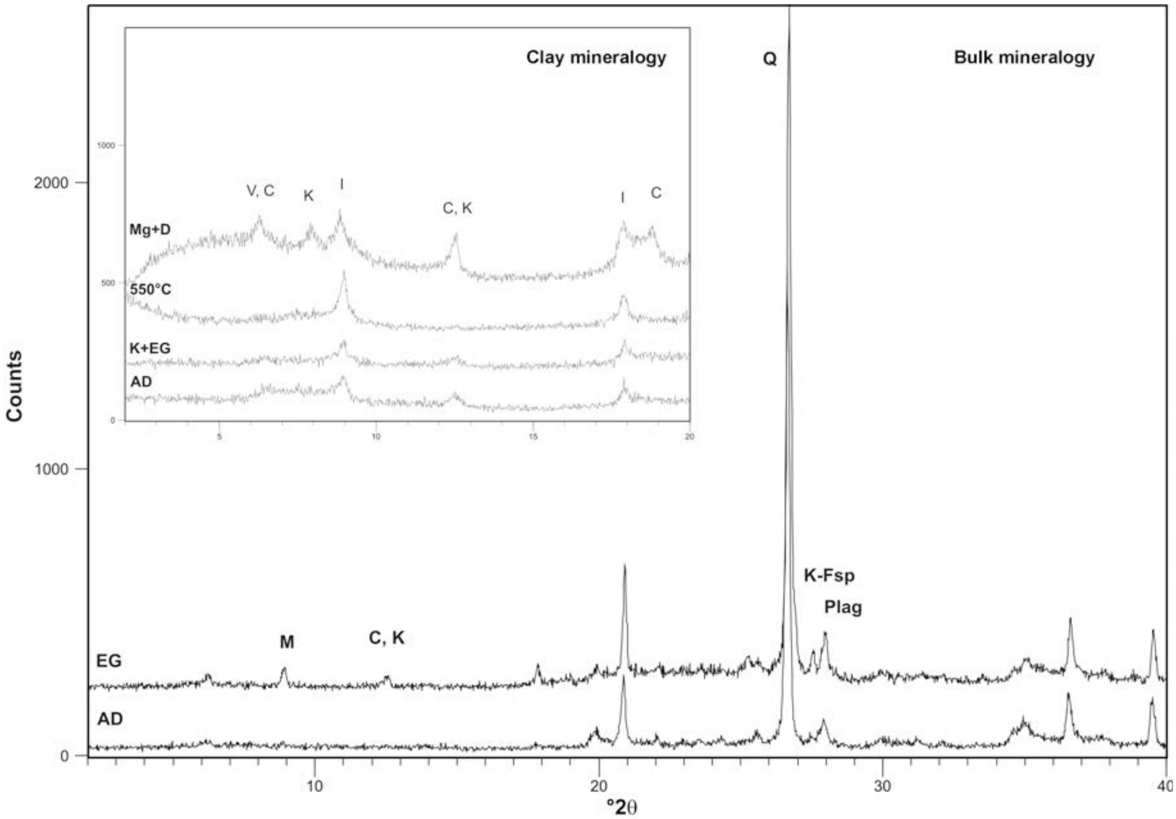

Figure 1. Bulk and clay mineralogy of loam UD (AD: air-dried, unoriented; K + EG: potassium + ethylene glycol; Mg + D: magnesium + DMSO; 550ºC: heated to 550ºC; M: mica, C: chlorite, Q: quartz, K-Fsp: K-feldspar, Plag: plagioclase; K: kaolinite, V: vermiculite, C: chlorite, I: illite).

(2−63 μm), 26% clay-sized particles (<2 μm), and 7% sand-sized particles (63 μm−2mm).

The CEC of the loam UD is 6.8 mmol/100 g, a very small value compared to the 122.0 mmol/100 g value for smectite SAz-1.

Mechanical properties

The compressive strengths of the different loam-additive mixtures at dry conditions and after storage at 100% RH (Figure 3) revealed that the greatest dry strength, which is measured after drying at 110ºC (before exposure, in this case, to relative humidities of 100% and 75%), was >10 N/mm^2 with loam UD+Acronal S650 (UD+A). UD+finely ground trass (UD+TM), UD+diatomite (UD+DM), UD without additives (UD), and UD+heavy loam (UD+HL) had values of >8 N/mm^2 (Figure 3). After 1 day of storage in boxes with 100% RH, all the adobe bricks lost more than 50% of their strength. The greatest strength was achieved with UD+Acronal S650 which had a compressive strength of >2 N/mm^2 after exposure to 100% RH for 20 days. The compressive strength of UD+blast-furnace slag (UD+SL) dropped below 2 N/mm^2 after the first day of storage in the humidity box.

The loss of compressive strength of the adobe bricks was less if stored at a RH of 75% than if stored at 100% (Figure 4). UD+Acronal S650 still had a compressive strength of >5 N/mm^2 after 20 days of storage at 75% RH. Loam UD, UD+trass (UD+TM), UD+diatomite (UD+DM), UD+brick dust (UD+BD), and UD+heavy loam (UD+HL) showed compressive strengths of ~4 N/mm^2 after storage at 75% RH. The mixtures UD+blast-furnace slag (UD+SL), UD+sawdust (UD+S), and UD+Funcosil®IC (UD+F) had the smallest dry strength values (3−4 N/mm^2), but also showed the smallest losses in strength at relative humidities of 75%. Generally, after 5 days of exposure to 75% RH, an equilibrium formed between the loam mixture and the RH, such that the compressive strengths stopped decreasing.

The bending strength of the loam with the various additives at a RH of 100% (Figure 5) revealed that sample UD+Acronal S650 had the greatest bending strength under dry conditions (7 N/mm^2) and after 1 day of storage in boxes with 100% RH (2.5 N/mm^2). However, UD+Acronal S650 lost >60% of its strength after the first day of storage. UD+blast-furnace slag had the smallest dry strength (2 N/mm^2) compared to the other mixtures, but this mixture showed the smallest losses in strength after storage.

The bending-strength behavior at 75% RH (Figure 6) was similar to the compressive-strength behavior at 75%

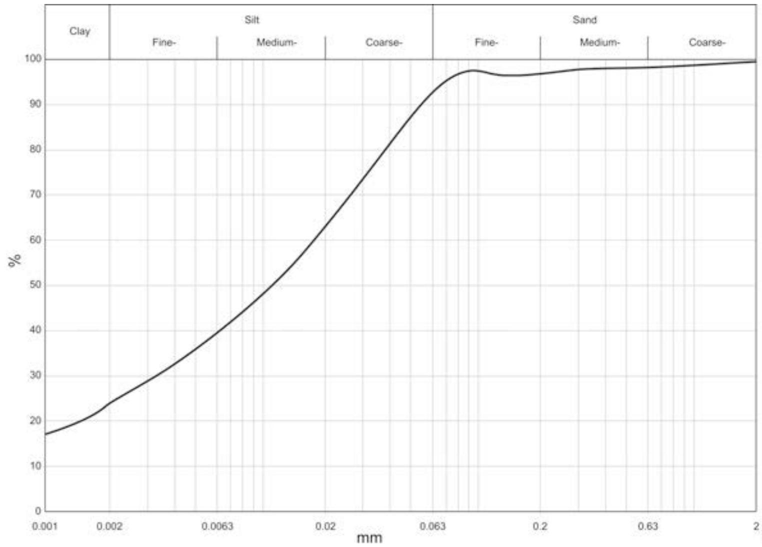

Figure 2. Grain-size distribution of loam UD.

RH (Figure 4). An equilibrium formed between the loam and the RH and bending strengths did not change significantly after 1 day of storage in boxes with 75% RH. UD+Acronal S650 showed the best results, with a bending strength between 3.3 and 2.9 N/mm^2 after storage (Figure 6). UD+blast-furnace slag showed very small strength at dry conditions (2 N/mm^2) but did not lose as much strength as UD+Acronal S650.

DISCUSSION

The absence of expandable clay minerals make loam UD an ideal raw material for the production of adobe bricks. The granulometric properties are also ideal because the grain-size distribution of the loam is dominated by silt-size grains. The strength of loam UD without additives was good in terms of compressive and bending strength but with additives it improved.

The various other additives only improved the compressive and bending strengths slightly. By adding finely ground trass, diatomite, Acronal S650, or heavy loam, the dry strength increased compared to the original sample.

Finely ground trass acted as a hydraulic binder between the components of the loam, and thus improved the strength in dry conditions (Figures 3–6). The mixture did lose strength after the RH storage, however, possibly implying that the finely ground trass had the same properties as clay and silt, *i.e.* it took up too much water, thereby decreasing the stability. The compressive strength decreased as the moisture content increased due to the softening of binders by water (Morel *et al.*, 2007).

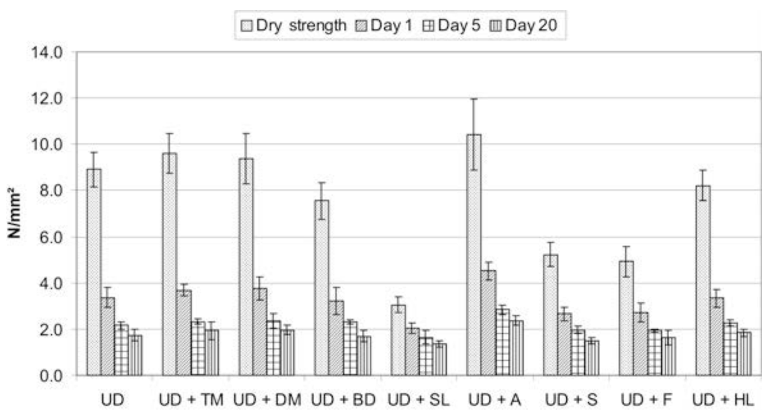

Figure 3. Compressive strengths of the loam mixture at dry conditions (dry strengths) and after 1, 5, and 20 days of storage at 100% relative humidity (UD: loam without additives; TM: trass; DM: diatomite; BD: brick dust; SL: blast-furnace slag; A: Acronal S650; S: sawdust; F: Funcosil; HL: heavy loam). Four tests were carried out for each mixture.

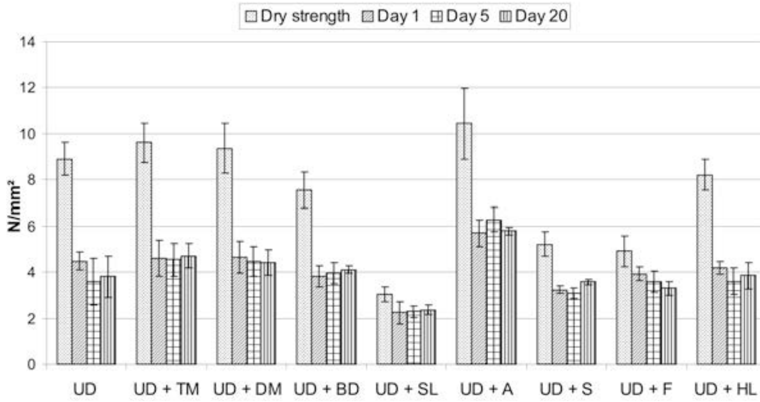

Figure 4. Compressive strengths of the loam mixtures at dry conditions (dry strengths) and after 1, 5, and 20 days of storage at 75% relative humidity (UD: loam without additives, TM: trass, DM: diatomite, BD: brick dust, SL: blast-furnace slag, A: Acronal S650, S: sawdust, F: Funcosil, HL: heavy loam). Four tests were accomplished for each mixture.

Compared to the raw material, the compressive and bending strengths of the mixture UD+diatomite at dry conditions improved slightly as did they under storage at 100% RH. Diatomite consists of large amounts of opaline silica and is a highly porous material which also had a positive influence on the strength of the loam.

The greatest increase in strength was achieved from mixing the loam with Acronal S650. Under the influence of 100% and 75% RH, the mixture lost strength indicating that Acronal S650 is very adsorptive and that the polymer bridges, which should 'glue' the loam particles together, broke under the influence of RH (Figures 3–6). Lee *et al.* (2008) suggested that hydrogen bonds could be formed between the clay and the polymer, and they added water-based polymers such as polyvinyl alcohol, polyvinyl pyrrolidone, and carboxymethyl cellulose which are 'eco-friendly' and thought to improve the stabilities of the adobe bricks. The best results were achieved with polyvinyl alcohol because of the hydrogen bonds.

At dry conditions, the bending strength of UD improved slightly with the admixture of heavy loam. On the other hand the compressive strength of UD+heavy loam did not improve compared to the blank sample. Heavy loam contains >30% clay minerals which can adsorb water. During storage under 100% RH, the clay adsorbed the water, and the compressive and bending strengths decreased markedly (Figures 3, 5).

None of the additives brick dust (BD), blast furnace slag (SL), sawdust (S), or Funcosil®IC (F) improved the compressive or bending strengths of the adobe bricks compared to the original, unaltered sample.

Addition of brick dust to the loam was probably unsuccessful because the particles were too large and the degree of cohesion between the clay particles of the loam and the fired brick components was insufficient.

The mixture of loam UD with blast-furnace slag decreased the dry strength of the material by >50%. After storage under 100% RH conditions the mixture UD+blast-furnace slag was the weakest material of all

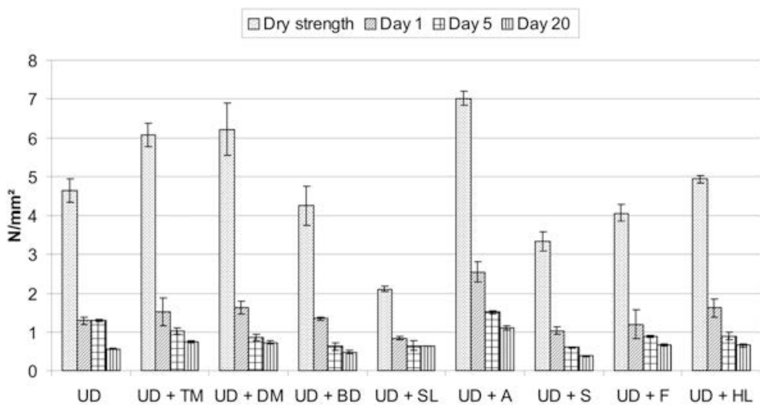

Figure 5. Bending strengths of the loam mixtures at dry conditions (dry strengths) and after 1, 5, and 20 days of storage at 100% relative humidity (UD: loam without additives; TM: trass; DM: diatomite; BD: brick dust; SL: blast-furnace slag; A: Acronal S650; S: sawdust; F: Funcosil; HL: heavy loam). Three tests were carried out for each mixture.

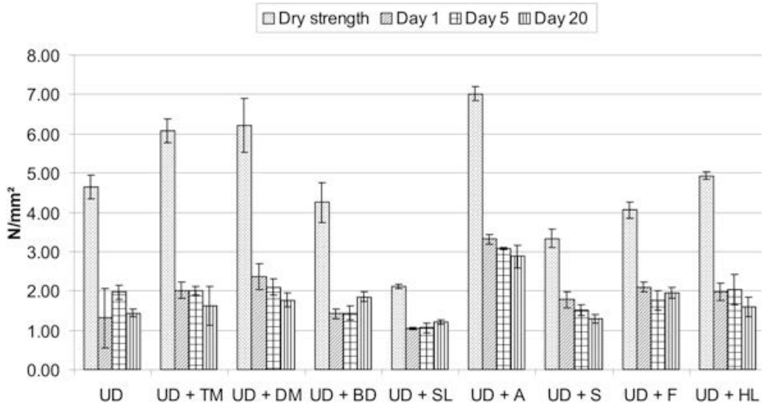

Figure 6. Bending strengths of the loam mixtures at dry conditions (dry strengths) and after 1, 5, and 20 days of storage at 75% relative humidity (UD: loam without additives; TM: trass; DM: diatomite; BD: brick dust; SL: blast-furnace slag; A: Acronal S650; S: sawdust; F: Funcosil; HL: heavy loam). Three tests were carried out for each mixture.

the samples, although it does not lose as much of the original strength as the other mixtures, possibly implying that the blast-furnace slag decreased the hygroscopicity of the loam, a point also demonstrated by the small amount of dry shrinkage. Chemical analysis of the slag showed that it consisted of 33% CaO which acts as a hydraulic binder. An ongoing pozzolanic reaction might be occurring which could even cause an increase in strength with time, and might be the reason for the small losses in strength. Larger amounts of blast-furnace slag (>10%) might increase the stabilities of the loam.

Though the addition of fibers clearly improves the strength behavior of adobe bricks (Binici *et al.*, 2005), the sawdust did not (Figures 3–6). The adobe bricks and bars started to mold in the humidity boxes with a negative influence on the strength. Also, the sawdust particles, at up to 0.50 cm in length, may not have been long and thin enough. According to Binici *et al.* (2005), fibers provide a better coherence between the mud layers; those authors added plastic fiber, straw, and polystyrene fabric to improve the compressive strength of adobe bricks.

By covering the adobe bricks and bars with the hydrophobic impregnation cream, the RH resistance should have been improved; this was not the case. During storage under 100% RH conditions, the adobe bricks took up more water than the blank sample.

CONCLUSIONS

Bricks made from loam amended with Acronal S650 had the greatest compressive and bending strengths but lost stability after exposure to high RH. Adding more than 2.5% Acronal S650 might improve the stabilities.

Bricks made from loam amended with blast-furnace slag (SL), had poor stabilities under dry conditions compared to the unamended sample but, after the storage under high RH conditions, failed to become much less stable. An increase in the amount of blast-furnce slag (to >10%) mixed with the loam might improve the stabilities. Further investigations are required to determine whether increasing the amounts of these additives would enhance the properties of loam UD. Tests with other additives, or combinations of additives, are also required to establish how greater improvements in the strength can be achieved.

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