Equilibrium moisture content of earth bricks biocomposites stabilized with cement and gypsum

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ABSTRACT

In recent years, energy efficient and ecologically friendly buildings have been important in the housing and construction sector. One of the major barriers to producing good and useful products is the lack of detailed information about natural materials, in particular their moisture related properties, as these materials are hygroscopic and sensitive to moisture. This research aimed to determine the equilibrium moisture content of earth block materials, as an extremely important characteristic variable for all physical simulations. Earth bricks with different compositions were fabricated from cohesive soil, cement, and gypsum combined with two kinds of natural fibers. Wheat and barley straw were used as reinforcing fibers and materials were treated at various temperatures (10–40 °C) and relative humidity (33–95%). The moisture content was considered in dynamic equilibrium with the environmental conditions and the effects of relative humidity and temperature were investigated. The effect of relative humidity was observed more pronounced than that of temperature. The test results are discussed with reference to the relevance of the earth bricks as an ecologically friendly building material that is directly associated with the moisture related properties of buildings. The results also showed significant improvement in the durability.

1. Introduction

Recycling of agricultural wastes present clear advantages from an economical point of view; the reduction of costs related to use of alternative raw materials; the reduction in consumption of virgin raw materials [1,2]. Natural fibers form alternatives for most widely applied synthetic fibers in composites technology and manufacturing. The interest in natural fibers comes about because they are cheap, light (providing better stiffness per weight), give more diverse markets for farmers, and reduce emissions of carbon dioxide and wastes going to landfill. Furthermore, natural fibers sources are renewable, they are green and environmentally friendly [3–5].

The deterioration of porous building materials is mainly due to the interactions between their structures and water. Depending on the material characteristics, physical state of water (liquid or vapor) and environmental conditions, the quantity of water absorption and sorption mechanisms may be different [6]. In particular, the absorption of humidity from air, the capillary rise, the rain penetration, and water condensation phenomenon can lead to the formation of superficial moisture [7,8]. Earth bricks are experiencing a renaissance in sustainable buildings. When a hygroscopic material is placed in air, water molecules are constantly absorbed and desorbed to and from its surface depending on the air relative humidity. If the same number of water molecules are absorbed and desorbed, an equilibrium condition is reached. Because the material is neither gaining nor losing water, it is said to have reached equilibrium moisture content (EMC). When air remains in contact with the material for sufficient time, the partial pressure of the water vapor in the air reaches equilibrium with the partial pressure of the water vapor in the material. The EMC is a dynamic equilibrium and changes with relative humidity and temperature of the surrounding atmosphere.

Ashour [9] reported that the EMC value of wheat straw increases with increasing relative humidity and decreases with rising temperature. The relative humidity has greater effect on

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the EMC of straw bales than temperature. For straw bale, an EMC value of 15% seems to be safe, which corresponds to the water activity level or equilibrium relative humidity [10]. Ashour et al. [11] studied the EMC of earth plaster for straw bale buildings. The earth plaster was reinforced by wheat straw, barley straw and wood shavings. He found that, the maximum EMC was as less than 7% for different materials. The EMC value of a biological material can be reliably determined after exposing to an environment with constant temperature and relative humidity for an infinitely long period of time [12]. Damp crop stems are also more difficult to process due to their significant friction resistance force [13]. Moreover, moisture content above 18% promotes growth of fungi, which are present in wood and straw as spores, and may degenerate cellulose. When the moisture content is below 18%, fungi become dormant and when the moisture content exceeds a certain value, fungi may exponentially grow [14].

Furthermore, the deterioration of straw can also be due to microbial activities, such as growth, survival, death, sporulation, and toxin production of microorganisms. These activities are dependent on the environmental variables of temperature, pH, oxygen, radiation, and moisture. Moisture for microbial activity is measured as water activity, which is numerically equal to the equilibrium relative humidity. When the equilibrium relative humidity is kept below 70%, the microbial activity is largely suppressed and the straw remains stable [15]. Hydrophilic materials, such as wood, paper, and cotton stabilize the atmosphere against the changes in relative humidity through temperature variation and exchange of air with the surroundings [16]. The influence of temperature and humidity on the permeability is mainly determined by hygroscopic properties of materials, permeability to air flow, and their capillary transfer ability [17]. All building materials tested were susceptible to mold growth in humidity values of above 90% relative humidity at temperature above 15 °C [18]. In general, adsorption rate is dependent on both temperature and relative humidity [19,20].

There are several methods to determine the EMC. The most commonly used methods are static and dynamic gravimetric techniques [21]. In the static method, the sample reaches the EMC in still air moistened using various salt solutions, whereas in the dynamic one, the air is mechanically moving and often moistened with air conditioning units [22].

We conducted this research because of the shortage of information about the relation between earth bricks and the environmental conditions, particularly temperature and relative humidity. The moisture immigration from the environment into the earth bricks greatly affects the performance of the building elements, mainly walls. Reinforcement fibers were used to improve the strength and thermal insulation of the blocks. Cement and gypsum were used to improve the mechanical characterization of the blocks. So, the main objective of the current study was the establishment of the relationships between moisture contents of earth bricks and environmental conditions to obtain the sorption curves of earth bricks stabilized with cement and gypsum and reinforced with wheat and barley straw.

2. Materials and methods

2.1. Materials

In this investigation, four different materials were used, including cohesive soil, cement, gypsum, and agro fibers. The composition of the cohesive soil texture was 28.7% clay, 63.3% silt, 3% gravel, and 5% sand. The particles sizes were <0.002, 0.0033, 0.172, and >2 mm for clay, silt, sand, and gravel, respectively. Two different types of fiber, wheat and barley straw, were used as reinforcement. The average straw length was approximately 4 cm.

2.2. Sample preparation

Initially, oversized gravels and organic matters (grass roots) were removed from the natural cohesive soil. The soil samples were dried at a temperature of 105 °C to obtain the dry constant weight. The natural fibers were also oven dried at 105 °C to a constant weight.

A variety of earth brick samples with various compositions containing cohesive soil, cement, gypsum, and fiber were fabricated. The amounts of materials were determined as their dry weights. The raw materials of soil, cement, gypsum, and fiber were placed in a mechanical mixer and dry blended for about 20 min until they were homogeneously combined. Afterwards, water was sprayed over the mixture until 24% moisture content level was achieved. The materials were again blended using an electric mixer for approximately 30 min until a homogenous mixture was obtained (Fig. 1).

Earth bricks from different mixtures combined with two types of natural fibers used in the sorption tests are listed in Table 1. The material compositions in Table 1 are given as a percentage of dry weight for earth ingredient.

The soil-fiber mixture was then poured into a wooden mold. The wood mold dimensions were $4 \times 4 \times 2$ cm. The surface was leveled and compressed using a loading plate under a force of about 50 kgf. After pressing, the samples were allowed to dry slowly to avoid cracking. The samples were dried under controlled room conditions for 60 days. The average temperature and relative humidity inside the laboratory room throughout the drying process were 21.7 °C and 56.1%, respectively.

2.3. Examination method

The EMC test was conducted according to DIN EN ISO 12271 standard method [23]. The samples were placed on a wire mesh over a plastic box containing various saturated salt solutions, as presented in Table 2. The samples together with the wire mesh and box were put in a closed box. These boxes were placed inside a climate chamber at various temperatures (10, 22, 30, and 40 °C) and relative humidity levels (33%, 51%, 75%, and 90%). For each recipe and humidity level, three samples of the same materials were used as replicates. In total, 54 samples for each material were fabricated and examined.

The climate conditions inside the box were monitored with combined T/RH sensors. After 3 to 4 weeks, when constant relative humidity inside the box was achieved, the samples were weighed and the moisture contents were calculated.

A climate chamber was used for the storage of the baskets under controlled temperature. The measured signals were directly

Fig. 1. Electrical mixer used for mixing different materials.

Table 1
Recipes of earth bricks.

Materials	Clay (%)	Barley (%)	Wheat (%)	Cement (%)	Gypsum (%)
Clay	100	–	–	–	–
B_1	99	1	–	–	–
W_1	99	–	1	–	–
B_3	97	3	–	–	–
W_3	97	–	3	–	–
B_1C_5	94	1	–	5	–
W_1C_5	94	–	1	5	–
B_1C_{10}	89	1	–	10	–
W_1C_{10}	89	–	1	10	–
B_3C_5	92	3	–	5	–
W_3C_5	92	–	3	5	–
B_3C_{10}	87	3	–	10	–
W_3C_{10}	87	–	3	10	–
B_1G_5	94	1	–	–	5
W_1G_5	94	–	1	–	5
B_1G_{10}	89	1	–	–	10
W_1G_{10}	89	–	1	–	10
B_3G_5	92	3	–	–	5
W_3G_5	92	–	3	–	5
B_3G_{10}	87	3	–	–	10
W_3G_{10}	87	–	3	–	10

proportional to the relative humidity and independent of the atmospheric pressure (Fig. 2).

2.4. Moisture content examination

To obtain different relative humidity conditions, some chemical substances were used (Table 2). The materials were dried according to DIN EN ISO 12570 standard method [24]. Moisture content (MC,%) was obtained using Eq. (1)

$$MC = \frac{W_m - W_d}{W_d} \cdot 100 \qquad (1)$$

where W_m and W_d are the moist and dry sample weight, respectively. The average of replicates was taken for further statistical analysis.

3. Results and discussion

3.1. Density

Fig. 3 shows the relationship between various sample compositions and the dry densities of unfired wheat straw reinforced earth products stabilized with cement and gypsum. The effects of fiber content on density are shown in Fig. 3a. The dry density decreased when the fiber content increased. The samples density were varying in the range of 1530–1222 kg/m^3 for 1% and 3% fiber contents in comparison with the density of control sample (0% fiber) as 1869 kg/m^3. This corresponds to a decrease of about 18–34% relative to the non-fibrous clay bricks.

For bricks reinforced with barley straw, it was observed that the density decreased from 1539 to 1227 kg/m^3, which means that the density decreased from 17.6% to 34% when the fiber content increased from 1% to 3%. It could be noticed that there is small difference between samples reinforced with wheat and barley straw fibers. The average densities of wheat straw samples containing cement were 1318 and 1331 kg/m^3 for 5% and 10% cement contents at 1% fiber. Densities of brick reinforced with barley straw

Table 2
Chemical substances used for adjusting different relative humidity values.

Name	Materials	Relative humidity (%)
Sodium sulfate	$Na_2SO_4 \cdot 10\ H_2O$	90
Sodium chloride	$NaCl$	75
Magnesium nitrate	$Mg\ NO_3 \cdot 6\ H_2O$	53
Potassium carbonate	$K_2CO_3 \cdot 2\ H_2O$	33

Fig. 2. EMC test sample boxes inside climate chamber.

were determined as 1239 and 1270 kg/m^3 at 5% and 10% cement contents, as shown in Fig. 3b. The average densities of wheat straw bricks stabilized with cement were 998 and 1138 kg/m^3 for samples with 5% and 10% cement and 3% fibers, respectively, whereas bricks containing barley straw revealed density values of 1088 and 1155 kg/m^3 at 5% and 10% cement at the same fiber content. Fig. 3c illustrates the dry density of the samples stabilized with gypsum at 1% fiber content. A similar trend was observed in bricks stabilized with gypsum at 3% fiber content, as shown in Fig. 3d.

In general, increasing the fiber content in the composites decreased the specimen weights. Replacement of cement or gypsum (dense materials) with wheat or barley straw fibers (light materials) resulted in a total volume increase. The increase in compacted mix volume resulted in a decrease in specimens' weights and densities.

3.2. Microstructure of earth bricks

The morphology and microstructure of the residues were examined using scanning electron microscopy (SEM). Fig. 4a shows the cross section of the distribution of fibers, whereas Fig. 4b illustrates typical SEM micrographs taken at the top surface of the blocks. It reveals a uniform distribution of fibers inside the brick samples. The micrographs clearly show that the straw fibers were randomly oriented within the samples. The distribution of fibers in the brick are shown in Fig. 4a and b. Additionally, the moisture equilibrium is mainly influenced by the pore size, with pore-specific surface and the percentage of micropores playing a fundamental role in promoting the structure/water interactions.

3.3. Equilibrium moisture content

3.3.1. Earth bricks without additions

Fig. 5 illustrates the EMC values of bricks without fibers. The results revealed that, when the relative humidity increased to
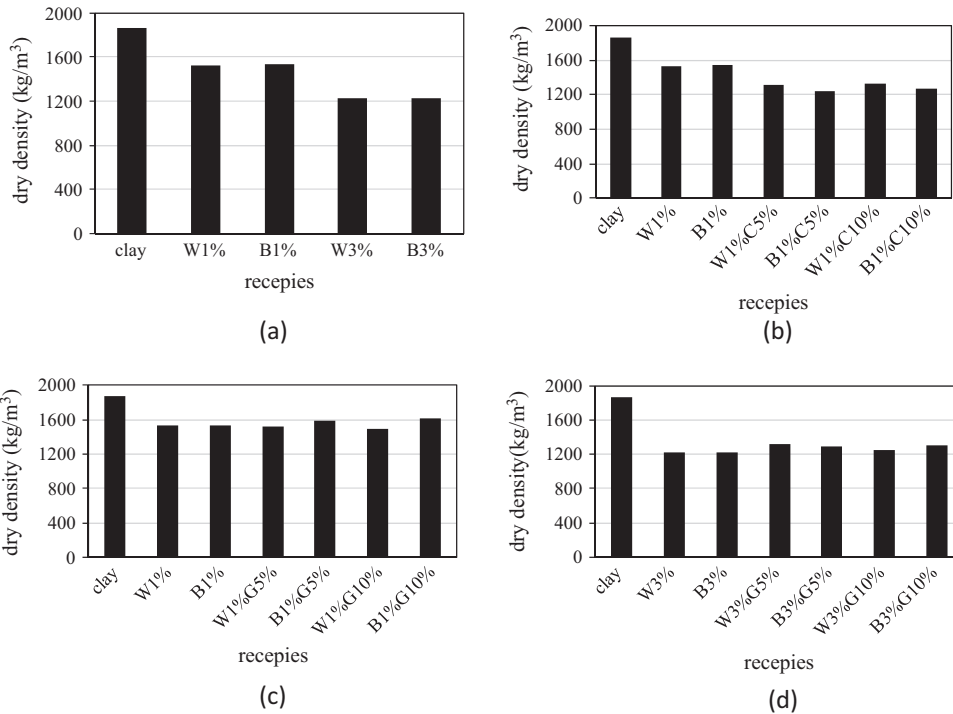
Fig. 3. The effect of fibers, cement, and gypsum content on the bricks densities. (a) Fiber content, (b) cement content at 1% fiber, (c) gypsum content at 1% fiber, and (d) gypsum content at 3% fibers.
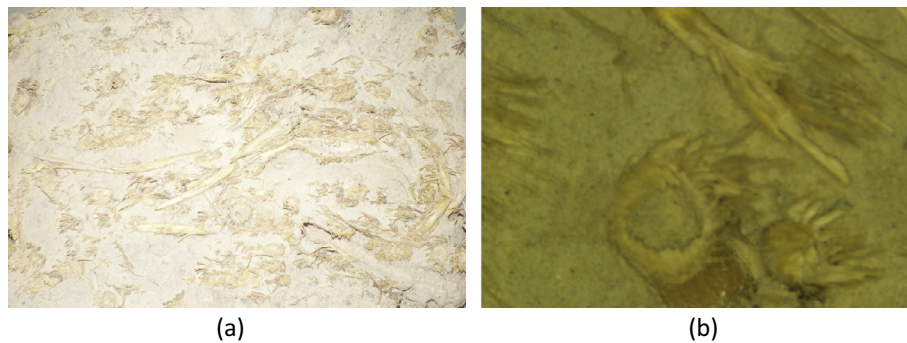

Fig. 4. Fibers distribution inside the bricks. (a) Cross section showing fibers distribution, and (b) SEM micrographs of fibers distribution inside the earth bricks.

90%, the EMC value reaches to 5.35% and 4.99% at 10 and 40 °C. Increasing temperatures from 10 to 40 °C leads to a decrease in the average EMC value from 3.45% ± 1.07% to 2.90% ± 1.12% (0.55% decrease). On the other hand, the main difference with sorption isotherms of bricks was that the equilibrium moisture content of all studied systems decreased with temperature increase. This may be ascribed to a reduction in a total sorption ability of the materials, which may reflect physical and chemical modifications by temperature [25].

3.3.2. Influences of fiber content

Fig. 6 presents the EMC variations of bricks containing two types of fibers at various relative humidity and temperature conditions. The samples were placed under 33–90% relative humidity at 10–40 °C. The results revealed that the EMC values of bricks increase with increasing relative humidity but decrease with increasing temperature. It seems that the relative humidity has greater effect on the EMC than temperature. The EMC values of the bricks were 3.4% to 3.7% for 1% and 3% wheat straw at 10 °C. But, at 40 °C, the EMC values were 3.2% to 3.3% for bricks
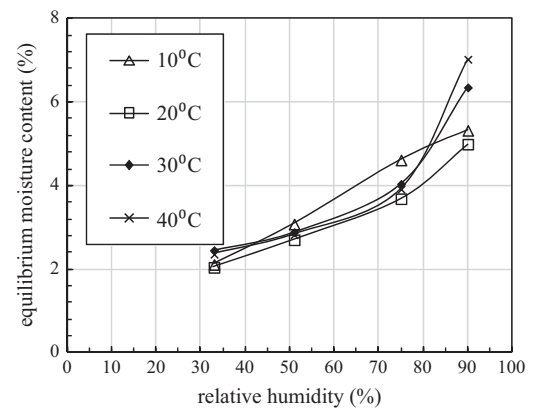

Fig. 5. EMC of earth recipe without any additives.

containing 1% and 3% wheat straw, respectively. The EMC values for bricks containing 1% and 3% barley straw were 3.4% and 3.5%, respectively, at the same temperature of 10 °C. At 40 °C, EMC
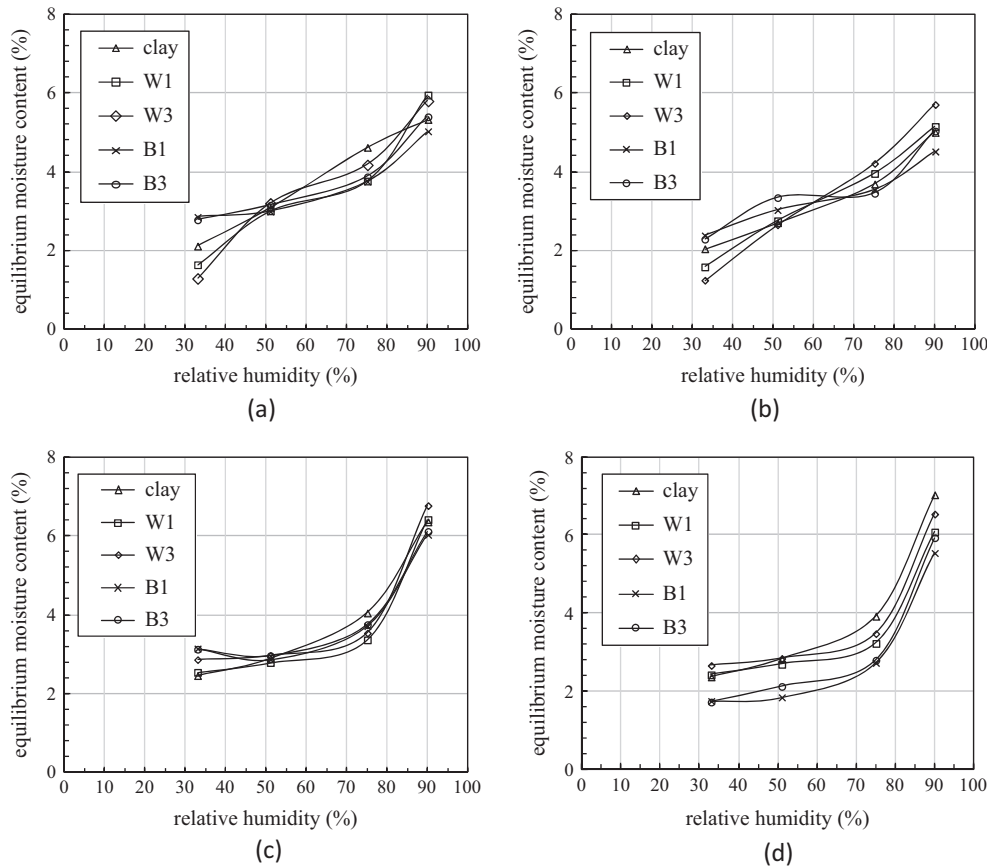
Fig. 6. The influence of reinforcement fibers on EMC at various temperatures of: (a) 10 °C, (b) 20 °C, (c) 30 °C, (d) 40 °C.

values were determined as 3.3% to 3.4% for 1% and 3% barley straw fibers, respectively.

Additionally, the averages of EMC values at 10 °C for wheat straw bricks were 3.9% ± 1.5% and 4.19% ± 1.66% for samples containing 1% and 3% straw, respectively. Whereas, at 40 °C, the EMC values were 3.5% ± 1.55% and 3.7% ± 1.52% for samples containing 1% and 3% straw, respectively. On the other hand, the averages of EMC values at 10 °C for barley straw bricks were 3.39% ± 1.76% and 3.65% ± 1.78% for 1% and 3% straw, respectively. The observations on the same samples at 40 °C were 2.83% ± 1.53% and 3.01% ± 1.65% for 1% and 3% fibers, respectively. Fig. 6a–d shows the variations of EMC for different fiber materials and other ingredients at temperatures from 10 to 40 °C.

3.3.3. Effects of cement content

Fig. 7a illustrates the relationship between the EMC of various cement bricks and the relative humidity at 10 °C. It may be noticed that the EMC gradually increased with increasing relative humidity up to 65% and then the increasing trend slows down between 65% and 80% relative humidity and gradually increases again above 80% for all materials. Our observations indicate that, the EMC values of manufactured bricks decreased with increasing the cement content. At 10 °C, the EMC values of the bricks were 4.22%, 4.21%, and 3.65% for 1% wheat straw and stabilized by 0%, 5%, and 10% cement, respectively. Whereas, at 40 °C, moisture content values were 3.52%, 3.36%, and 3.12% for samples with 0%, 5%, and 10% cement. When temperature varied to 10 °C, the average of EMC values were observed as 4.19% ± 1.46%, 3.89% ± 1.36%, and 3.61% ± 1.23% for samples including 0%, 5%, and 10% cement, respectively.

On the other hand, for the bricks containing 1% barley straw, the average of EMC values at 10 °C were 3.78% ± 0.88%, 3.59% ± 0.98%, and 3.25% ± 0.94% for samples with 0%, 5%, and 10% cement, respectively. At 40 °C, the average values of EMC were determined as 2.83% ± 1.1%, 2.83% ± 1.09%, and 2.66% ± 0.93% for 0%, 5% and 10% cement content, respectively. Finally, at 10 °C, EMC values were 2.68%, 2.87%, and 3.054% for cement contents of 0%, 5%, and 10%, respectively. Whereas, at elevated temperature of 40 °C, EMC values were determined as 3.28%, 3.128%, and 2.73% for cement contents of 0%, 5%, and 10%. Fig. 7a–d shows the EMC variations for different fiber materials and formulations at 10–40 °C.

The results indicated that the EMC values of bricks decrease with increasing cement content. It was also observed that the relative humidity has greater effect on the EMC than temperature.

Additionally, the average values of EMC at 10 °C for wheat straw bricks were 4.19% ± 1.46%, 3.89% ± 1.36%, and 3.61% ± 1.23% for 0%, 5%, and 10% cement, respectively. For bricks reinforced with 3% fibers and stabilized with cement, the EMC value gradually increased with increasing relative humidity up to 65% and then slowed down between 65% and 80% relative humidity. The increasing trend continued again at relative humidity above 80% for all brick samples.

3.3.4. Influences of gypsum content

We observed that the EMC values of bricks decrease with increasing the gypsum content. The environment relative humidity revealed greater effect on the EMC than temperature. At 10 °C, EMC values were determined as 3.43%, 3.37%, and 3.32% for wheat straw bricks (1%) stabilized with 0%, 5%, and 10% gypsum, respectively. At the same conditions but 40 °C, increasing the relative humidity
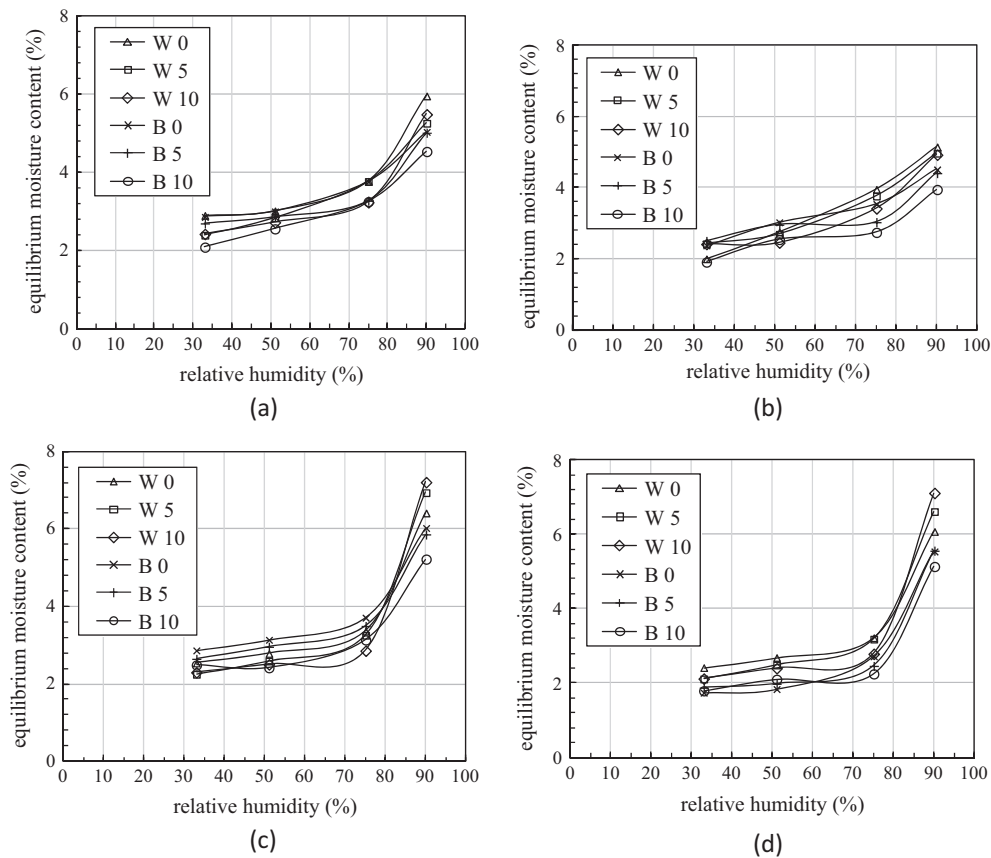
Fig. 7. Effects of cement content on EMC at various temperatures of: (a) 10 °C, (b) 20 °C, (c) 30 °C, (d) 40 °C.

from 33% to 95% increased the EMC value to 3.33%, 3.09%, and 3.03% for bricks containing 0%, 5%, and 10% gypsum, respectively.

The average of EMC for bricks containing wheat straw at 10 °C were found as 4.88% ± 1.00%, 4.37% ± 0.95%, and 3.62% ± 1.3% for 0%, 5%, and 10% gypsum contents, respectively. When temperature was increased to 40 °C, the average of EMC were 4.24% ± 1.02%, 3.68% ± 1.13%, and 3.54% ± 1.15% for 0%, 5%, and 10% gypsum contents, respectively. On the other hand, EMC values for barley bricks were 3.52%, 3.30% and 3.16% the gypsum contents were 0%, 5%, and 10%, respectively, while at 40 °C, increasing the relative humidity caused an increase in EMC value.

Additionally, the average values of EMC at 10 °C for gypsum bricks were 4.32% ± 1.06%, 3.99% ± 1.08%, and 3.64% ± 0.95% for mixing ratios 0%, 5% and 10%, respectively. But, at 40 °C, the average of EMC decreased to 4.13% ± 0.90%, 3.86% ± 0.97%, and 2.83% ± 1.10% for mixing ratios of 0%, 5%, and 10%, respectively.

Fig. 8 illustrates the sorption curves for earth bricks containing gypsum and 3% straw. The results showed a decrease in the EMC values of manufactured bricks with increasing gypsum content. The EMC values of bricks were determined as 3.85% and 3.59% for wheat straw bricks with gypsum contents of 0%, 5%, and 10%, respectively.

Moreover, the EMC values for barley bricks were 3.58%, 3.17%, and 2.35% for gypsum contents of 0%, 5%, and 10% respectively. Whereas, at 40 °C, the EMC values were 3.15%, 3.03%, and 2.19% for gypsum contents of 0%, 5% and 10%, respectively.

Additionally, the average values of EMC at 10 °C for gypsum bricks were 4.99% ± 0.64%, 4.26% ± 0.94%, and 3.93% ± 1.00% for mixing ratios of 0%, 5%, and 10%, respectively. At 40 °C, the average of EMC were observed as 3.40% ± 1.58%, 3.49% ± 1.08%, and 3.58% ± 0.91% for mixing ratios of 0%, 5%, and 10%, respectively.

Fig. 8a–d shows variations of EMC values for different straws and mixing ratios at temperatures from 10 to 40 °C.

The moisture contents in the bricks made of composite materials are strongly related to the sorption isotherms in which water is absorbed from the vapor existing in the ambient air. Therefore, the moisture content in the material is in equilibrium with the ambient relative humidity. There are two mechanisms for the sorption phenomenon. At low relative humidity, water molecules are attached to the pore walls, forming a thin water film. As the relative humidity increases, this water film becomes thicker and capillary condensation occurs in the narrow pores. The two mechanisms overlap each other, but at high relative humidity, the capillary condensation becomes the dominant mechanism [21,30,31]. The greater number of micropores (or larger specific surface area) results in an increase in the amount of humidity that can be absorbed [32,33,37].

The EMC value of brick material increases with the rise of relative humidity at the same temperature. That is because the vapor pressure deficit (VPD) decreases with increasing relative humidity, producing an atmosphere close to saturation conditions and increasing the ability of material to absorb additional moisture from the ambient atmosphere. This behavior is due to the fact that VPD increases at elevated temperatures, which is thought to be the main factor of moisture movement from or into the wheat straw. Fig. 9 shows that the VPD increased by more than 6 times when temperature was increased from 10 to 40 °C. The EMC value decreased and reached a level lower than the initial moisture content of the material. Apparently, the material lost some of its moisture to the ambient.

On the other hand, the VPD values at lower temperatures under different relative humidity levels revealed little change. This
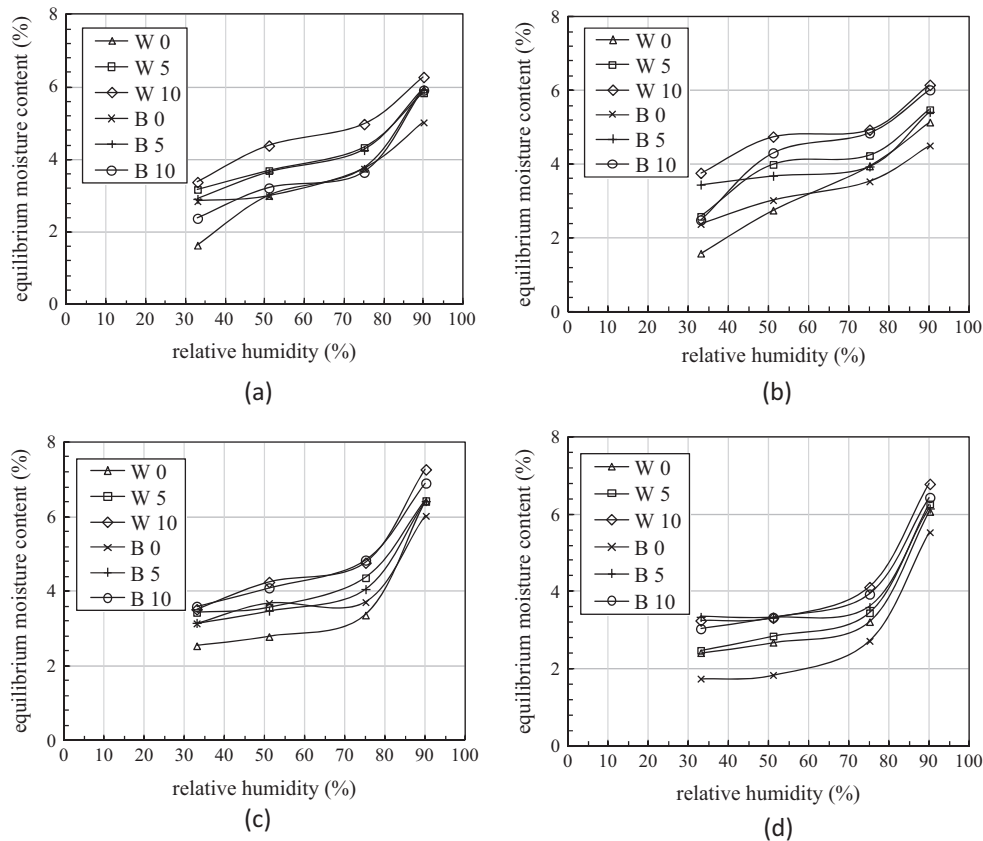
Fig. 8. The influence of gypsum content on EMC at various temperatures of: (a) 10 °C, (b) 20 °C, (c) 30 °C, (d) 40 °C.

means that the relative humidity at lower temperature has only minor influence on the VPD. The apparent increase in vapor diffusion at high relative humidity is due to liquid flow on the surface of the pore walls and the surface diffusion, which are controlled by the vapor pressure gradient [26–28]. It is widely accepted that an increase in temperature results in a decrease in equilibrium moisture content, as proposed by Hill and Rizvi [34], Karoglou et al. [35], and Moreira et al. [36].

The results showed that the adsorption rate is dependent on both temperature and relative humidity [19,20,29]. The EMC value gradually increased with increasing relative humidity up to 65% and then slowed down between 65% and 80% relative humidity. It continues to increase at relative humidity above 80% for bricks

Fig. 9. Vapor pressure deficit at different environmental conditions.

manufactured from different materials. Moreover, the EMC values of bricks containing wheat straw were more than those containing the other materials. This behavior is due to the pores in the structure of wheat straw, which take up more moisture. The moisture storage capacity is influenced by the variable surface charge of the clay particles and their size [38].

Finally, the water absorption increases with clay content, as a greater proportion of water is absorbed by the clay minerals and reduces with cement and gypsum content, as the porosity increased as clay content increased and decreased with cement and gypsum increased. However, suction rates tend to increase with soil plasticity, which may in part be attributed to the moisture-attracting characteristics of increasing clay mineral content [39,40]. Moreover, EMC for the composites is around 7% for earth bricks reinforced with wheat and barley straw fibers and without cement and gypsum, while for bricks stabilized with cement and gypsum under the same fiber contents, the average of EMC was 4%.

Moreover, the recent studies showed that the unsafe moisture content is more than 15%. So, experimental results of the composite showed significant improvement in the brick durability.

4. Conclusions and recommendations

Our experimental results revealed that, the EMC of brick materials increases with increasing relative humidity and decreases with increasing temperature. The EMC values of bricks reinforced with barley straw were observed to be greater than bricks reinforced with wheat straw. The relative humidity revealed greater effect on the change of moisture content than temperature. The moisture content was observed in the range of 1.74–7.2% for all materials under different conditions. The EMC was found to increase gradually for relative humidity up to 65%, slow down in
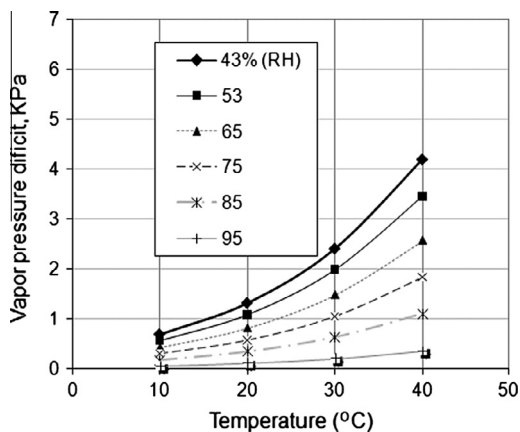
the range of 65–80% relative humidity and then continue to increase at a faster rate at relative humidity above 80%.

Increasing the straw content from 1% to 3% increased the EMC value for different materials. The EMC decreased with increasing the gypsum and cement contents. The straw fibers revealed greater effects on the EMC value than cement and gypsum. It is therefore possible for the planned building use (wet production) to manufacture and apply the appropriate earth bricks stabilized with natural fibers. The low levels of relative humidity do not necessarily make a problem when the right constructions are chosen. The composite results also showed a significant improvement in the brick durability.

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