Proposing a new type of DPC to control moisture movements in brick walls

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Abstract. This paper reviews several traditional and modern damp-proof courses (DPCs) techniques that have been used worldwide and show the limitation(s) of each technique. It also presents a new waterproofing technique employing the principles of capillary breaking layers (CBLs) used widely in earth structures. The paper presents the results of a study on rising damp based upon a practical one-year-long tests. The short and the long term hygrothermal behavior of the proposed technique was also investigated numerically using WUFI simulation program. It has been found that a capillary breaking layer can be successfully utilized to create a capillary barrier that is capable of blocking moisture rise in a brick wall and enhancing wall breathability at the level of treatment.

1. Introduction

Water is a crucial element in the process of brick and mortar manufacturing [1]. In brick manufacture, the wet clay is moulded and fired to yield a hard, silicate bound structure with a network of pores. These pores are the remaining volume that the evaporating water has left [2]. Similarly, in cement mortar, a considerable quantity of unreacted water evaporates in the mortar curing process, leaving a network of pores [1]. These networks consequently turn out to be the pathways through which water can rise in brick walls. Rising and damp can be defined as the vertical movement of moisture by capillary action through pores and voids or via small slits or cracks or as water vapour [3]. Depending on the severity of dampness, buildings may become inhabitable due to paint blistering, mound growth, plaster crumbling and wallpaper separation [1,19]. To protect the structural safety, increase life span, eliminate the size of the defect and reduce maintenance cost, buildings must be adequately waterproofed against dampness. Damp-proof courses (DPC) or damp proof membrane DPM have been used for this purpose. They are simply defined as a physical or chemical layer placed at the interface between the wall and the footing to prevent the intrusion of water into the wall utilizing capillary action [4]. It is, however, considered that chemical DPC controls rather than stops moisture rise [5]. Hollis [6] expresses doubt concerning whether a chemical injection DPC can work. Several traditional and modern damp-proof courses have been used worldwide. Copper, lead, and aluminium sheets have also been used as a DPC. Nonetheless, if aggressive salts are present, corrosion takes place unless the metallic membrane is covered with a protective coat. Lead sheets, for instance, are attacked by the lime presented in the mortar while they...
are being carbonated and should be protected with a protective coat [7]. Polyethylene sheets, on the other hands, have been used as a DPC. While corrosion is not an issue for polyethylene sheets, they can be punctured or torn during installation [7]. Besides, as they do not bond well with mortar, polyethylene may cause stability issues if the wall is being loaded laterally. Moreover, a thin layer of plain or lightly reinforced concrete is also used to prevent the rise and damp in walls. Nevertheless, this layer does not flex or move with the structure over the years due to its rigidity. Consequently, they can crack and fracture, allowing moisture to rise in the wall [8]. Additionally, cement hydration that occurs during the curing process inevitably produces some calcium hydroxide [9]. The amount produced relies on the composition of the cement. If it dissolved in the rising water and transported to the surface, calcium hydroxide will react with carbon dioxide in the air, creating calcium carbonate, which can appear on the surface as a white deposit [9]. Additives, plasticizers, for instance, can be added to cement mortar to increase water retention and reduce the porosity [1]. Nevertheless, some admixtures for mortars are usually not recommended because of their unidentified ingredients and the absence of data on their effect on bond strength and, consequently, water tightness of masonry walls [10]. Further, plasticized mortar develops a weak bond with highly absorptive bricks [11]. Besides, excessive dosage of plasticizer harms strength, and hence manufacturers’ instructions need to be firmly followed [11]. Other systems based on evaporation increase such as knapen siphons and drying stones have also been used against rising damp. By enhancing evaporation, these methods lead to a reduction in the height reached by the rising damp [12]. However, these systems are incapable of reducing or stopping the ingress of water. Consequently, the accumulation of salts may become higher in the case salts are present [12]. Numerous other materials and technologies have been suggested over last century to eliminate the capillary rise of water from ground in masonry walls [18]. Nonetheless, their actual efficiency in the field are limited and the explanations for their success or failure in real masonry have not been fully explained yet [18]. Upon careful examination of the available literature, no waterproofing method has been found which can be applied with complete success in any situation. Also, no technique was found that is capable of efficiently and ultimately breaking the network of capillaries and potentially enhance aeration at the level of treatment simultaneously. In this paper, the principles of capillary breaking layers have been employed to produce a waterproofing layer. A confined physical layer has been proposed and examined experimentally for one year to achieve the above mentioned two targets.

2. The Proposed Water Proofing Layer

2.1. Waterproofing

The voids in the soil form a complicated network of continuous channels whose size is directly proportional to soil particles. The height to which water rises by capillary in soils and other materials is inversely proportional to the diameter of the pores or tube [13]. According to Terzaghi and Peck [14].

\[ hc = \frac{C}{e} \cdot D_{10} \]  

(1)

Where \( hc \) is the maximum height of capillary rise in mm, \( e \) is the soil void ratio, \( D_{10} \) is the effective particle size of soil, and \( C \) is a constant range from (10-50) mm². According to equation 1, the maximum capillary rise ranges from 10 to 50mm in gravel and from 10000 to 30000 mm in clay [13]. It can be deduced that the capillary rise in clean gravel is almost negligible, whereas, for clays, it is considerable. Capillary Breaking Layers (CBLs), on the other hand, have been used into earth structures to control water transfer from one horizon to another [15]. These layers comprise relatively uniform coarse particles such as gravel or rock fragments. They are capable of performing their functions because the larger pores exist in CBLs are unable to draw water from smaller pores of the protected medium due to significant differences in hydraulic conductivity [13,15]. The principle of capillary breaking layers has been employed in this research to produce a waterproofing layer. Instead of using a uniform soil structure, a well-graded structure has been chosen. This is because well-graded soils possess higher shear strength, more interlocking between the particles and almost zero compressibility. A 30 mm of
well-graded angled gravel layer whose $D_{10}$ is 5mm was sandwiched by cement mortar and used as a waterproofing layer. This thickness of gravel was safe enough to prevent any contact between the top and the bottom mortar covers of the CBL. The layer was confined by a steel frame to provide lateral support and most importantly, to increase the interparticle stresses and keep them elevated under loading conditions. These high stresses make the gravel stronger, so it supports the weight without moving. A line of holes with a diameter of approximately 5mm was made in one side of the frame only to help promote air exchange and encourage the evaporation of the raised moisture if there is any. Besides, gravel aeration is necessary to keep the hydraulic conductivity of the geomaterial always significantly smaller than that of cement mortar beneath it [16].

3. Experimental Work

3.1. Walls Construction

Standard perforated Iraqi clay brick whose dimensions are 240mm x 115mm x 75mm was used in this study to construct two walls: a reference wall without waterproofing and a waterproofed wall. Efflorescence and absorption tests were carried out according to the Iraqi standard IQS No 24/1988 before construction. The results of the efflorescence test showed that 8.6% of the area of the brick had been covered with a thin deposit of salts. The absorption of the brick was found to be 23%. The used mortar comprised ordinary Portland cement type (I) and washed natural sand from Al-Ukhaider region with a maximum size of (4.75mm) in a volumetric ratio of 1:5. The sand was tested according to the Iraqi standard IQS No.45/1984 and it complies with it. This mix proportion was reported to be quite absorbent [3,17]. Each wall contained six courses, and each course consisted of one and a half bricks in a single width. They were constructed in a steel tray and left for a month to allow curing of the cement mortar. At the end of curing time, local tap water was added into the steel tray and allowed to rise into the wall. Water was topped up whenever needed to make up for water losses. A confined layer consisted of well-graded angled gravel-covered from top and bottom with cement mortar was used to waterproof the second wall. A 45mm wide steel strips with a thickness of 3mm were extended along the wall from both sides and placed over the top of the first course, forming a confinement cage. Horizontal steel extensions were welded to the lower edge of the strips. These extensions served as chairs and were embedded in the mortar placed on the top of the first course. To provide additional anchorage, the ends of the extensions were hooked up 90 degrees. In addition to the horizontal extensions, the cage was equipped with vertical extensions. These extensions tie the course below the treatment with the course above, and hence enhancing the stability of the wall. Holes with a diameter of 5mm were made in the front strip only to help promote air exchange and encourage the evaporation of the raised moisture if there is any. The configuration of the confinement cage is illustrated in Figure 1. After constructing the first course of the waterproofed wall, the confinement cage was placed on top of it. Approximately 10 mm of cement mortar was then placed. After that, 30 mm of well-graded angled gravel was distributed and tapped evenly over the cement mortar. A temporary wooden frame was used to close the open sides of the cage. These sides were later sealed with a layer of spray foam. The compacted gravel was covered with approximately 10 mm cement mortar, and then the five courses of bricks were built over it.
3.2. Moisture Content Measurement
Due to brick-to-brick variation and the possibility of existing conducted soluble salts in the bricks, the oven drying method was chosen to make all measurements of moisture content. Cores of bricks were taken using a 14 mm diamond core drill and used to measure the moisture content. It has been shown that the rotation speed of the drill possibly may affect the measured moisture content in case comparatively hard materials with low porosity [20]. However, no critical effect is detected for relatively weak material with high porosity, such as fired clay bricks [20]. Rounds of measurements are summarised in Table 1. In each round, two brick cores from each course were taken. Core samples were placed in the oven and dried at a temperature of 105 °C to the constant weight. The left-behind holes were filled with spray foam.

Table 1. Test Timescale

| Date       | Task                                      |
|------------|-------------------------------------------|
| June 2019  | Wall construction                         |
| July 2019  | Water introduction                        |
| January 2020 | The first round of measurements        |
| July 2020  | The final round of measurements and dismantling |

4. Results and Discussion
4.1. Visual Observation
Upon filling the steel tray with water after the end of curing time, the progression of the rising water could be visually observed in the first course of the walls. After two weeks, the front reached the 3rd course of the reference wall, but was only at the first course for the waterproofed wall. As time elapsed, the progressing water line continued to rise in the reference wall but became less distinct. Efflorescent salts became visible on the reference wall over the course of the first months of wetting. Salt formation increased with time and was noticeable on both the brick and mortar surfaces of the reference wall. Some salts appeared on the top course of the reference wall. Unlike the reference wall, no advancement of water beyond the first course was noticed in the waterproofed wall throughout the study. In other words, no signs of darkening or discolouring were noticed in the courses above the treatment level of the waterproofed wall. Besides, no signs of efflorescent salts were seen on the courses above the treatment level of the waterproofed wall. This is because the presence of the gravel has created a sudden change in pores size and broken the flow paths of the moisture, hence, completely stopping moisture supply to the above courses of the wall.
### 4.2. Moisture Content

Figure 2 shows the walls after the end of the study period. The results of the moisture content obtained from extracting cores of bricks from the walls are shown in Table 2. Significant increase in the moisture content of the reference wall has taken place. This is expected due to the absence of any waterproofing layer that may prevent the moisture supply to the above courses. On the other hands, the courses above the capillary breaking layer are air dry in both rounds of measurements. The small amount of moisture in bricks is believed to be owing to the humidity of air (i.e. hygroscopic moisture). When water pressure is reduced compared to the air pressure in soils, a critical pressure will be touched at which air penetrates the soil, and the interfaces fall back to smaller pore [16]. The reduction in water pressure is directly proportional to the degree of saturation [16].

Besides, the amount of the negative pressure at which desaturation begins is inversely proportional to pore size. Consequently, materials comprising of coarse aggregates desaturase at considerably smaller negative pressures than finer soils [16]. The reduction of soil saturation results in a reduction in the conductivity of soil to water [16]. However, the reduction in conductivity is comparatively much higher than the reduction in saturation [16]. Gravel, for instance, desaturate almost totally at minimal negative pressures, the conductivity becomes practically zero [16]. Hence, the presence of the gravel has created a sudden change in pores size and broken the flow paths of the moisture, hence, completely stopping moisture supply to the above courses of the wall.

![Figure 2. The test walls after 12 months. Left: is the waterproofed wall. Right: is the reference wall.](image)

### Table 2. Results of experimental work

| Waterproofing status | Round No. | First course | Second course | Third course | Fourth course | Fifth course | Sixth course |
|----------------------|-----------|--------------|---------------|-------------|---------------|-------------|-----------|
| waterproofed         | 1st       | 22.61        | 0.44          | 0.44        | 0.42          | 0.41        | 0.41      |
|                      | 2nd       | 22.93        | 0.28          | 0.25        | 0.23          | 0.25        | 0.20      |
| Reference            | 1st       | 22.75        | 15.64         | 13.74       | 9.86          | 5.16        | 3.52      |
|                      | 2nd       | 22.97        | 18.13         | 16.34       | 11.29         | 10.33       | 8.96      |

5. **Hygrothermal simulation model**

5.1. **WUFI**

In this study, the moisture performance simulation model WUFI which is a windows based program for the hygrothermal analysis of building envelope constructions was chosen to validate the experimental program. The WUFI simulation model is a well-known transient heat and mass transfer model that is...
used to evaluate the heat and moisture transfer and distributions for a wide range of building material under different climatic conditions. Besides, the long term behavior of the proposed waterproofing technique was also evaluated for 25 years. Finally, the influence of the thickness of the gravel layer on the performance of the capillary breaking layer was also evaluated. Three thicknesses were analyzed: 30, 60 and 100mm. The corresponding thermal and moisture characteristics are given in Table 3. Some of the input parameters were set as default for both the clay brick and the mortar. The database of the program does not include cement-sand mortar. Therefore, lime cement mortar was used instead in the simulation. Figure 3 shows the simulated and meshed models used in the study. Each model consists of six courses of aerated clay brick. The thickness of each brick is 7.5 cm. A one cm of lime/cement mortar was used in the simulation. As a waterproofing layer, a 3 cm of gravel was used. In the analyses, an air layer was introduced to the gravel layer.

![Simulated meshed model](image)

**Figure 3.** The simulated meshed model. All dimensions are in cm. Top is the reference wall. Bottom is the waterproofed wall.

### Table 3. Thermal and moisture characteristics of the components of the wall.

| Material            | Thickness (cm) | Thermal Conductivity (W/mK) | Heat Capacity (J/kgK) | Diffusion Resistance (m²·s⁻¹) | Initial Water Content (%) | Initial Temperature (°C) | Porosity (m³/m³) |
|---------------------|----------------|-----------------------------|-----------------------|-------------------------------|---------------------------|---------------------------|-----------------|
| Clay brick          | 0.075          | 0.13*                       | 850*                  | 15*                          | 0                         | 20                        | 0.74*           |
| Lime cement mortar  | 0.01           | 0.6*                        | 850*                  | 50*                          | 0                         | 20                        | 0.28*           |
| Gravel              | 0.03           | 0.7*                        | 1000*                 | 1*                           | 0                         | 20                        | 0.3*            |

*Typical values from the database of the program

5.2. Results of the numerical analyses

Figures four and five show the change of moisture content in each course after one year starting from the second course. While the moisture content kept increasing in the reference wall and reached to considerable levels, no significant change has taken place in the moisture content of the courses of the waterproofed wall. From figure five, it can be deduced that the waterproofed wall has remained air dry throughout the analyses, and the variations seen in the moisture content are attributed to the change in the relative humidity of the air which was set to be ranging from 30 to 60%. It can also be deduced that WUFI has succeeded in capturing the overall behavior of both walls. Figure six shows the results of the
long term behavior of the waterproofed wall. Only the results of the second, fourth and sixth courses were shown. The performance of the waterproofed wall was examined for 25 years. As it can be seen that the moisture content is below 1% throughout the 25 years. The fluctuation seen in the curves can be attributed to the variations of the relative humidity of the environment surrounding the wall. Finally, figure seven shows the results of the influence of the gravel layer thickness on the performance of the capillary barrier layer. As can be seen, the influence is negligible. However, this thickness might not be sufficient enough to meet the structural requirements. Hence, further tests are recommended.

![Figure 4](image1.png)

**Figure 4.** Variations of moisture content in each course starting from the second course in the reference wall within a year.

![Figure 5](image2.png)

**Figure 5.** Variations of moisture content in each course in the waterproofed wall within a year.
Figure 6. Variations of moisture content in the waterproofed wall within 25 years.

Figure 7. Influence of thickness of gravel on the variations of moisture content.

6. Conclusions and Recommendations
Dampness is an annoying and persistent problem, resulting from the direct long-term contact of a wall with the ground and the lack of or defected damp insulation. The consequence is a gradual penetration of water and the dissolved salts into the wall. The principles of capillary breaking layer can be utilized to stop dampness or moisture rise in a brick wall. Using well-graded soils that generally have lower void ratios when compared with uniformly graded soils was not a problem due to the absence of fine soil particles. It has been shown that the presence of the gravel has created a sudden change in pores size and broken the flow paths of the moisture, hence, completely stopping moisture supply to the above courses of the wall. While a well-graded gravel layer of 30mm thickness has been capable of stopping dampness, it is recommended that this thickness is examined to meet the structural requirements of non-load and load-bearing walls using a prism test. The influence and the contribution of the confining steel cage on the structural performance of walls should also be examined using a prism test. Finally, this waterproofing technique should also be evaluated under seismic conditions.
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