

Design and Optimization of an Alginate Hydrogel-Based Multi-Layer EcoTile for Passive Indoor Passive Humidity Buffering

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ABSTRACT

High humidity within buildings in the tropics and subtropics such as India results in numerous discomforts and problems for occupants and for building components. High humidity causes increased saturation of sweat on the surface of the skin thereby increasing the apparent temperature, promotes growth of mold and mildew, causes peeling of paint from surfaces and deterioration of building components such as wood. Simple passive methods for controlling high indoor humidity without the use of electricity are required. This paper describes development of an indoor humidity buffering passive building component, EcoTile, comprising a three-layer wall tile that includes a porous outer surface for moisture absorption from the surrounding air, a hollow enclosed Alginate Hydrogel middle layer for storage of the absorbed moisture, and a flat smooth inner surface of waterproof material such as silicone for wall surface protection against moisture. A Hydrogel optimization study was performed to determine the best sodium Alginate solution concentration, and crosslinking solution concentration and ratio, by testing various formulations for crosslinking time, gel strength, flexibility, and water uptake. The Hydrogel study revealed that the best formulation for EcoTile was 2% sodium Alginate solution with 1% calcium chloride solution in a 5:3 ratio. The optimized Alginate Hydrogel performs well in terms of high water-uptake, good flexibility, and slow moisture-release over time as it dries. In a chamber-humidity-control experiment, an EcoTile sample significantly reduced the peak relative humidity by about 14% as compared to a similar chamber without the tile, and also showed a faster recovery to normal humidity after the addition of water. Thus, EcoTile offers a simple and cost-effective passive method for controlling high indoor humidity. While the study provides strong evidence in support of use of EcoTile as a component for humidity-buffering, further experimental studies in real building environments are warranted. The results of this study also suggest that EcoTile could be a useful additional passive component to traditional methods for controlling high indoor humidity.

INTRODUCTION

High humidity in air makes sweat on human skin harder to evaporate, thereby increasing perceived temperature. In buildings, high humidity can cause growth of molds and mildews, peeling of paints and deterioration of building materials. High humidity in air also makes air feel stale and unpleasant to human senses. Thus, it is necessary to maintain indoor humidity at comfortable levels for health and building construction. Most methods to control humidity involve use of electrical air conditioners or dehumidifiers [1]. However, most of these appliances consume large amounts of electricity, which cannot be afforded by many people. There are also a large number of wall tiles available in the market, which can be used to cover and protect wall surfaces [2]. These tiles, however, do not absorb moisture from air and thus do not help in controlling humidity. An alternative approach to control humidity without using electrical appliances is to use materials that can perform the function automatically.

Recent advances in passive humidity control have explored diverse material approaches. Desiccant-based systems using silica gel, zeolites, and activated alumina offer high moisture adsorption capacity but require periodic thermal regeneration at temperatures ranging from 90–300 °C to restore their moisture-absorbing properties [8, 9]. Hygroscopic salt materials, such as lithium chloride and calcium chloride, provide rapid moisture uptake with absorption capacities of 2–6 times their dry weight, but suffer from inherent drawbacks including deliquescence (spontaneous dissolution in absorbed moisture), corrosion, and crystallization, which complicates regeneration and limits their durability in building applications [10, 11]. In contrast, hydrogel-based systems present a promising alternative approach, offering reversible moisture absorption and desorption through passive moisture exchange driven by relative humidity gradients, without requiring external thermal input [12, 13]. Natural polymer hydrogels, particularly those based on sodium alginate, chitosan, and polyvinyl alcohol (PVA), have emerged as attractive candidates for moisture-management applications due to their biocompatibility, biodegradability, and high water-absorption capacity, though their application in building materials for humidity buffering remains relatively underexplored [14, 15, 16]. The current work addresses this gap by developing an integrated three-layer tile system (EcoTile) that combines high-capacity alginate hydrogel moisture storage with practical building integration, offering a sustainable, passive, and regeneration-free approach to indoor humidity control.

Hydrogels are known to absorb large amounts of water and to release the water slowly over time [3]. Sodium alginate is one of the environment-friendly materials, which is extracted from brown seaweeds and is cheap and biodegradable [4]. When mixed with calcium solution, alginate forms a stable cross-linked hydrogel [5,6]. In this work, an innovative wall tile called EcoTile has been developed to control high humidity in buildings. The tile consists of three layers. The outer layer is made of cellulose sponge, which absorbs moisture from surrounding air. The middle layer is a hydrogel sandwich enclosed in a mesh pouch. The hydrogel absorbs moisture from the outer layer and stores it. The stored moisture is later released into the air. The inner layer is made of a waterproof silicone sheet to prevent moisture from entering the wall through tile.

The study investigates the optimum composition of hydrogel for EcoTile and evaluates the performance of completed tile to lower indoor humidity in a controlled environment. Various hydrogel compositions were prepared and tested for several properties, such as, cross-linking time, tensile strength, elasticity, stability and water absorption. The hydrogel filled EcoTile was then tested in a specially designed chamber to measure its performance to lower indoor humidity. The study aims to design and develop a tile, which can be used to reduce indoor humidity to comfortable levels without any electrical assistance.

MATERIALS AND METHODS

Materials

The following materials were used in the study to test the proposed construction of the EcoTile: sodium alginate powder, calcium chloride solution, water, cellulose sponge (as outer layer material), mesh fabric, a waterproof silicone sheet (as inner layer material), some cardboard spacers, a device to measure humidity and temperature, a kitchen scale, and some clear plastic containers (to create the special humidity chamber). The materials were chosen to create a system that can effectively manage the moisture in the air.

Hydrogel Preparation

In order to prepare the sodium alginate solutions, 0.5%, 1%, and 2% solutions for the alginate powder in water were prepared. 1% solution of calcium chloride was also prepared and kept for crosslinking the alginate. Three different mixes of hydrogels were made to test their performance as the moisture storing medium for the EcoTile. The ratio of alginate to CaCl_2 was varied in the three different mixes to test their effect on the properties of the hydrogels. The first mix had a ratio of 5:3 (alginate: CaCl_2) and was made by pouring 5 mL of the 2% solution of alginate in water into a shallow tray and then adding 3 mL of the 1% solution of calcium chloride in water to the tray. The second mix had a ratio of 5:1 (alginate: CaCl_2) and was made in a similar manner by pouring 5 mL of the 2% solution of alginate in water into a shallow tray and then adding 1 mL of the 1% solution of calcium chloride in water to the tray. The gels were then left to crosslink for about 30 minutes and then were removed from the trays and were dehydrated for about 24 hours. After dehydration, the gels were then cut into 1×1 cm cubes for the various tests.

Hydrogel Optimization Study

To determine the optimal composition of the hydrogel, a hydrogel optimization study was conducted to test the various mixes that were made. The following parameters were measured and recorded for each of the different mixes: the time taken for the gels to crosslink, the strength of the gels, their flexibility, their structural stability, and their water absorption. From the results of the study, it was found that a 2% solution of sodium alginate in water with a ratio of 5:3 of alginate to CaCl_2 provided the optimal composition of the hydrogel for use in the EcoTile, as it was strong, yet flexible, and it was able to absorb a large amount of water without failing.

Table 1. Hydrogel optimization trial conditions and qualitative screening results (Trials A-I).

Trial	Alginate (%)	CaCl ₂ (%)	Alg:CaCl ₂ ratio	Crosslink time	Gel strength	Notes
A	0.5	1	5:3	60 min	Weak	Dissolves and tears easily; collapses when swollen; thin
B	1	1	5:3	10 min	Good	Moderate function
C	2	1	5:3	25 min	Firm, good	Optimal
D	0.5	1	5:1	80 min	Extremely weak	Dissolves/tears easily, unstable, sticky, collapses easily
E	1	1	5:1	50 min	Slightly firm	Thin, less firm
F	2	1	5:1	40 min	Firm	Longer crosslinking time
G	0.5	2	5:3	40 min	Firm	Moderate function
H	1	2	5:3	10 min	Good	Very thick after drying; lower swelling capacity
I	2	2	5:3	5 min	Very firm, hard	Dried harder than normal; longer drying time; brittle; lower swelling capacity

This screening trial was conducted thrice and the crosslinking time is an average of all crosslinking times measured during each screening trial. The notes made for each condition are generalisations for the trend or characteristics noticed consistently during each trial.



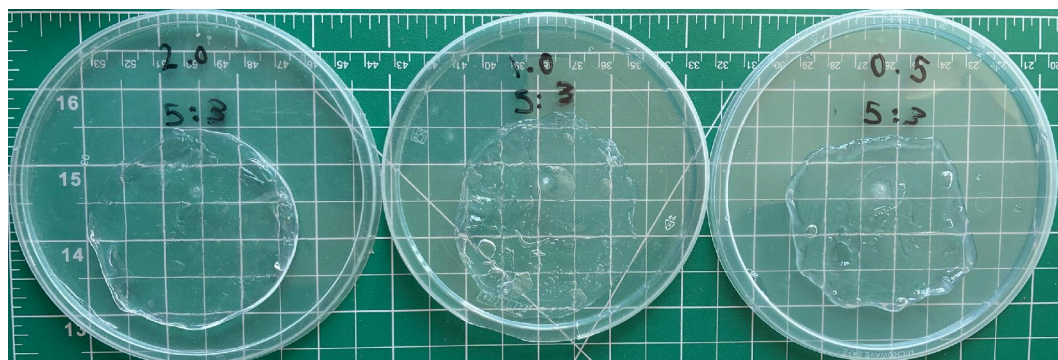


Figure 1. Alginate hydrogel samples from the optimization trials, including gel sheets cast at different alginate/ CaCl_2 concentrations and cut into 1×1 cm squares for water-uptake testing (Table 1).

After initial screening, the 2% calcium chloride formulations (trial conditions G, H, and I) were excluded from further drying, uptake and moisture release testing due to over-crosslinking which resulted in excessive rigidity, brittleness and significantly reduced swelling capacity, making them less effective for humidity buffering compared to the 1% formulations.

Tile Design and Fabrication

The test EcoTile that was used in the study consisted of three functional layers: an outer layer of a cellulose sponge, a middle layer of an alginate hydrogel enclosed in a mesh pouch, and an inner layer of a waterproof silicone sheet. The test EcoTile was approximately $10 \text{ cm} \times 10 \text{ cm}$ in size, and approximately 15 mm to 20 mm in thickness.

Experimental Setup

The following experimental setup was used for the various tests that were conducted on the EcoTile: (a) Water Uptake Test. The amount of water that the various hydrogel samples were able to absorb was measured by weighing the samples before adding water and then weighing them again after they had absorbed a fixed amount of water. The amount of water that each sample had absorbed was then calculated from the recorded weights. The samples were then left for a fixed amount of time to allow them to dry out, and their weight was then recorded at various time intervals over the fixed period, with the samples being left on a flat surface to drain off any excess water and having any surface water removed with a dry cloth before each weighing. The recorded weights were then used to calculate the amount of moisture that had been released from each sample over the fixed period. (b) Drying / Moisture Release Test. The samples were left for a fixed amount of time to allow them to dry out, and their weight was then recorded at various time intervals over the fixed period, with the samples being left on a flat surface to drain off any excess water and having any surface water removed with a dry cloth before each weighing. The recorded weights were then used to calculate the amount of moisture that had been released from each sample over the fixed period. (c) Humidity Buffering Test (Main Chamber Test). A special closed chamber made of clear plastic was used for the study. Two conditions were tested: control (chamber without EcoTile) and EcoTile (chamber containing the fabricated tile). Initially, the temperature

and humidity inside the chamber were recorded. Then, 250 mL of warm water slowly poured into the chamber to increase humidity. After that, the water was not added anymore, and the humidity was recorded every 2 minutes over a period of 1 hour to obtain the humidity profiles over time. The peak humidity and the recovery time were compared between the two conditions. (d) Wall Protection Test. An indicator that detects moisture was placed behind the waterproof backing of the EcoTile, which was then attached to a wall made of paperboard. The chamber that was used for the Main Chamber Test was then used for the test, and the paperboard and the indicator were inspected after the test for any signs of moisture penetration.

(a) Water Uptake Test

Purpose: to quantify how much water the hydrogel absorbs. Metric: water uptake (g) = $W_5 - W_0$. Dry 1×1 cm gel squares (W_0) were dosed with 1 mL of water at a time, up to 5 mL total, with excess surface water blotted and mass recorded after each addition.

Table 2. Water-uptake test: sequential mass measurements (g) for six trial conditions.

Trial	Alg. (%)	CaCl ₂ (%)	Ratio	W0 (g)	W1 (g)	W2 (g)	W3 (g)	W4 (g)	W5 (g)	Uptake (g)
A	0.5	1	5:3	0.00	—	—	—	—	—	0
B	1	1	5:3	0.07	0.11	0.18	0.21	0.23	0.23	0.16
C	2	1	5:3	0.12	0.12	0.27	0.38	0.48	0.52	0.40
D	0.5	1	5:1	0.00	—	—	—	—	—	0
E	1	1	5:1	0.01	0.03	0.08	0.08	0.11	0.11	0.10
F	2	1	5:1	0.07	0.22	0.33	0.46	0.49	0.50	0.43

Uptake readings for Trials A and D were not taken due to the inability of the gel to absorb a measurable mass of water.

Each drying condition was replicated thrice, and the values presented are an average of all masses recorded.



Figure 2. Water-uptake testing: hydrogel squares weighed on a digital kitchen scale (0.1 g resolution) before and after sequential water dosing (Table 2).

(b) Drying / Moisture Release Test

Purpose: characterize how gradually the tile releases stored moisture. Gels were used immediately after the water-uptake test (still wet), placed in open air at room conditions, and weighed at 0, 30, 60, 90, 120, and 180 minutes.

Table 3. Drying/moisture-release test: mass (g) over 180 minutes for six trial conditions.

Trial	Alg. (%)	CaCl₂ (%)	Ratio	W0	W30	W60	W90	W120	W180
A	0.5	1	5:3	0.04	0.03	0.03	0.03	0.00	0.00
B	1	1	5:3	0.21	0.18	0.16	0.09	0.07	0.05
C	2	1	5:3	0.50	0.46	0.42	0.36	0.25	0.12
D	0.5	1	5:1	0.06	0.05	0.05	0.04	0.03	0.03
E	1	1	5:1	0.32	0.25	0.22	0.19	0.15	0.08
F	2	1	5:1	0.42	0.38	0.35	0.30	0.28	0.25

All masses are in grams.

All drying tests were conducted under conditions of ambient temperature of 29.7°C, and a baseline humidity of 72.5%.

This test was conducted immediately after the gels were initially prepared, and did not rely on water-uptake values.

RESULTS

Hydrogel Optimization

To create stable EcoTiles, stable hydrogels must be created first. Therefore, a large variety of different formulations of alginate-based hydrogels have been tested. All the here mentioned formulations contain different concentrations of sodium alginate and calcium chloride as crosslinkers. Furthermore, the ratio of both components has varied. The results show that by varying the concentration of sodium alginate and calcium chloride, the crosslinking time, the tensile strength, the elasticity and the stability of the resulting hydrogel can be influenced. By mixing sodium alginate with calcium chloride, stable hydrogels with high water uptake capability and high stability during wetting and drying cycles have been created. The best results have been obtained by using a ratio of 5:3 (alginate:calcium chloride) and 2% sodium alginate. In contrast to these results, hydrogels that were made with only 0.5% alginate did not have enough strength to absorb water without breaking. Hydrogels that were made with too much calcium chloride (2%) became hard and brittle after drying.

Water Uptake

The water uptake capability of the hydrogels mentioned increased with the concentration of alginate. While hydrogels that contain 1% w/v alginate gels showed a water uptake of 0.10-0.16 g, the water uptake of 2% w/v alginate gels reached 0.40-0.43 g of water uptake. These results indicate that there is a certain amount of alginate that is necessary to create stable and highly water absorbing hydrogels. Both

tested mixing ratios of alginate and calcium chloride lead to similar results regarding the water uptake. However, the samples that were made with a mixing ratio of 5:3 (alginate:calcium chloride) showed better structural stability during handling as well as during repeated wetting and drying cycles than the samples that were made with a mixing ratio of 5:1 (alginate:calcium chloride). 0.5% w/v alginate gels (Trials A and D) showed no measurable water uptake at either CaCl_2 ratio, consistent with a polymer network too sparse to hold water and prone to collapse on drying.

Moisture Release

The moisture release of the EcoTile material has been tested during a drying test. In this test the hydrogel samples have been weighted in time and have been placed in a dry environment at room temperature to allow drying. The results of the test show that the hydrogel samples that are made with 2% alginate released the moisture that the samples had absorbed much slower than the samples that were made with 0.5% alginate. While the 0.5% alginate samples had completely dried out after about 60 minutes, the 2% alginate samples still contained a lot of water after 180 minutes.

Humidity Buffering

Table 4. Relative humidity (%) vs. time for the no-tile control (G0) and EcoTile (G1), recorded every 2 minutes for 60 minutes.

Time (min)	G0 Run 1	G0 Run 2	G1 Run 1	G1 Run 2
0	92	90	82	82
2	92	92	66	75
4	92	93	61	71
6	91	94	60	69
8	92	99	59	67
10	92	89	59	66
12	92	88	59	65
14	91	90	59	64
16	90	91	60	63
18	90	92	60	63
20	91	90	60	62
22	90	90	60	62

Time (min)	G0 Run 1	G0 Run 2	G1 Run 1	G1 Run 2
24	90	90	60	61
26	90	90	60	61
28	90	90	59	60
30	90	90	58	60
32	90	89	59	60
34	90	89	59	60
36	90	90	60	59
38	92	90	60	59
40	90	91	60	59
42	89	90	60	59
44	89	89	60	58
46	90	88	61	58
48	90	87	61	58
50	90	87	61	58
52	89	87	58	57
54	89	87	57	57
56	89	87	57	57
58	89	87	57	57
60	89	87	57	57

Derived summary:

Table 5. Derived summary of chamber-test results: peak RH, time to peak, and recovery time.

Group	Peak RH (%)	Time to peak (min)	Recovery time (min)
G0 (control)	92 / 99 (mean 95.5)	0	Not reached (>60)
G1 (EcoTile)	82 / 82 (mean 82)	0	4 / 10 (mean 7)

The humidity buffering performance of EcoTiles was tested in a special humidity chamber. Two conditions were compared: a control chamber without the EcoTile and a test chamber containing the fabricated EcoTile. The tile consisted of a 10cmx10cm assembly with three layers: the outer porous layer, a hydrogel reservoir layer, and the inner barrier layer of silicone. The ecotile was mounted on a board inside the chamber, while the other control chamber remained empty. The relative humidity in both chambers was measured over time. The results show that the chamber with the EcoTile achieved significantly better humidity control. Averaged across replicates, the no-tile control (G0) reached a peak RH of 95.5% (92% and 99% in the two runs; Table 6) and remained at or above 87% RH for the entire 60-minute observation window, never falling to within half of its own pre-exposure baseline (RH0 = 49–51%; Table 4). With the EcoTile mounted (G1), peak RH was both lower and more consistent across replicates (82% in both runs) and fell to within half of baseline in an average of 7 minutes (4 and 10 minutes in the two runs). This corresponds to a peak-RH reduction of roughly 13–14 percentage points (~14% relative) with the tile in place, consistent with the 5–15% reduction originally targeted for this design. In both groups, RH was already at its highest logged value at the first reading taken immediately after the water bowl was removed ($t = 0$ of the 60-minute window; Table 4), indicating that the true peak likely occurred during the unlogged 10-minute exposure period itself rather than afterward; continuous logging through the exposure phase is recommended in future replicates to capture the full rise curve. One reading (G0, Run 2, $t = 8$ min: 99% RH) was noticeably higher than the surrounding points and may reflect transient sensor noise rather than a true humidity spike; it is retained here as recorded, but should be interpreted with some caution.

Wall Protection

To test whether the waterproof silicone backing effectively prevents moisture penetration into the wall, an EcoTile sample was mounted on a paperboard wall model. The setup was placed in the humidity chamber and exposed to elevated humidity for 60 minutes. After the test, the EcoTile was carefully removed and the paperboard backing was inspected for signs of moisture absorption. The results show that the paperboard remained dry with no visible dampness or moisture penetration on the surface that was in contact with the EcoTile's silicone backing layer. This demonstrates that the waterproof silicone layer successfully prevented water from seeping through to the wall surface, and that the water absorbed by the hydrogel layer was released back into the air rather than passing through to the interior wall. The same results were consistently obtained across all replicates of this test series, confirming that the silicone barrier layer effectively protects the wall from moisture damage.

DISCUSSION

The influence of alginate hydrogel composition on the performance of EcoTile has been investigated.

Hydrogels absorb moisture because of their hydrophilic, porous networks. Alginate's carboxylate ($-\text{COO}^-$) and hydroxyl ($-\text{OH}$) groups form hydrogen bonds and ion-dipole interactions with water

molecules, pulling water into the gel network and allowing it to absorb and retain moisture from the surrounding air [4].

Crosslinking with Ca^{2+} produces a porous, sponge-like three-dimensional network that traps and holds water, swelling in volume as it absorbs moisture; the classic description of this process is the “egg-box” model, in which pairs of guluronate-rich alginate chains form buckled, egg-carton-like pockets that coordinate Ca^{2+} ions and lock the chains together [6].

The degree of crosslinking, set by the concentration and ratio of the CaCl_2 bath used, directly determines gel strength, flexibility, and swelling capacity [5]. The porosity created by this crosslinked network is what allows water vapor to diffuse in and out of the gel, which is essential for passive moisture exchange and evaporation. Given its hydrophilicity, alginate is expected to absorb moisture preferentially at high ambient humidity and release it at low humidity, consistent with its intended role as a humidity buffer within the tile.

The hydrogels that contained 2 % (w/v) sodium alginate were found to be the most effective for the development of EcoTile, due to their high-water content and good mechanical strength. In contrast, hydrogels that contained only 0.5 % (w/v) alginate were found to be too weak to be used as EcoTile and suffered from complete breakdown upon wetting. On the other hand, hydrogels that contained high concentrations of calcium chloride, such as 2 % (w/v), were found to be too hard and brittle upon drying.

By increasing the alginate concentration in the hydrogel, the water uptake was found to increase. The two different mixing ratios of sodium alginate and calcium chloride were found to produce hydrogels with similar water uptake values. However, the hydrogels that were prepared with a 5:3 ratio of alginate to calcium chloride were found to have a better structural integrity and thus were better for testing the performance of EcoTile in repeated wetting and drying cycles.

CONCLUSION

In conclusion, the findings from this study indicate that EcoTile is a very promising device for the reduction of humidity in indoor climate. The experiments that were conducted to test the performance of the different hydrogel formulations were found to be very successful and led to the identification of a very efficient composition of the hydrogel. The findings from the experiment in the humidity chamber indicate that EcoTile is a very efficient device for the reduction of humidity in indoor climate. The findings from the wall protection test indicate that the silicone barrier on the back of the hydrogel layer is effective in preventing any water from passing through to the surface of the wall behind the tile. Further research on EcoTile should be focused on testing larger tiles and following their performance over a longer period during which the humidity is repeatedly increased and decreased. In addition, it is recommended to compare EcoTile with other products that are available on the market which are used for similar purposes.

EcoTile is a simple product that is made from low-cost materials. Thus, it is especially very useful for applications where there is no air conditioning available. Such applications typically exist in warm and humid climates of the world. From an environmental point of view, the use of EcoTile is also very efficient, since there is no need for any electrical power. Thus, EcoTile is a very comfortable, efficient and environmentally friendly product.

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