International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 6, Issue 7, pp 31-42, July-2022

https://doi.org/10.47001/IRJIET/2022.607006

Calculating the Effective Moisture Diffusivity during Drying Process of Gypsum Board

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Abstract **- Gypsum (CaSO4.2H2O) is a type of materials which can be used as a precursor to manufacture insulating building materials. The manufacture process of gypsum board usually is comprised of two steps: (1) preparing the samples by adding water to the gypsum, and (2) drying. Aging (or drying) in wet gypsum board is a complex transport process that involves evaporation due to the difference in liquid concentration between the surrounding air and the sample surface and drainage that is induced by gravity. A full understanding of the aging process may help the researches to choose efficient steps parameters (e.g. the required aging time). Also, it collects the input data for manufacturing numerical models. In the current study, the researcher provided data experimentally (end of aging time, moisture content, and effective moisture diffusivity) on aging of gypsum board under controlled conditions, (i.e. temperature and relative humidity).**

Aging curves were tested for different samples with three different concentrations of the gypsum material on substrates with two values of contact angles (hydrophilic and super- hydrophobic). In addition, the effects of gypsum particles size were tested under all aging conditions. Transport of moisture is represented by estimating the moisture diffusivity utilizing slope method.

The study concluded that the moisture diffusivity reversed change with the average moisture content where, the moisture diffusivity increased during the aging as the decrease in the average moisture content for all trials. Gypsum concentrations had the strongest effect on the drying time and effective moisture diffusivity where is, the gypsum particles size did not affect strongly on them for both types of substrates (super-hydrophobic and hydrophilic). Such information may be useful in using the gypsum as material to fabricate insulating building materials.

Keywords: Drying, gypsum, Concertation, the effective moisture diffusivity, particles size.

I. INTRODUCTION

Gypsum is one of the oldest building materials in the word.[1]. Natural gypsum (calcium sulfate) exists in various forms in nature. It is mainly (CaSO4.2H2O). In Iraq, gypsum is one of the important building materials. It is used as gypsum boards, bonding materials, and plastering materials. [2] Some properties of this material are given below:

- Light in weight,
- Heat resistant,
- Has very good formability,
- Sound insulation,
- Fine fire resistance; and
- High level of performance and aesthetics.

On the other hand, gypsum resistance to liquids "such as water" is low. The thermal behavior of gypsum is greatly affected by its moisture content.[3]

In general, drying is complex process that transfers mass and heat between the material and the surrounding fluid. Transferring moisture from the inside to the outside removing moisture from the surface by evaporation. The moisture in the surface is removed depending on the external conditions such as humidity, temperature, surrounding air velocity, and the available surface area for drying. On the other hand, moisture diffusion inside the material is function of instantaneous moisture content, temperature, and the physical nature of the material. [4] Moreover, drying may cause change in shape and dimensions.

The development methods and strategies for understanding, predicting, and controlling drying have become essential to a successful manufacturing and construction process. One of the characteristics of the transport methods used in porous materials is the diffusion of moisture by means of moisture gradient, porosity gradient, and temperature gradient.[5][6][7] In such complex systems the prediction of moisture diffusion is not clear, and the need for practical measurements arises.[8] The appropriate method for the purpose of presenting the results of practical drying

ISSN (online): 2581-3048
Volume 6, Issue 7, pp 31-42, July-2022
https://doi.org/10.47001/IRJIET/2022.607006

experiments is to plot the moisture content (moisture content over time).

Moisture transport can be described by Fick's second law of diffusion equation for the unstable state which relates to the temporal and spatial changes of moisture content Y (kg liquid / kg dry solid) via moisture-dependent diffusivity, $\boldsymbol{D_{eff}}$(m^2/h) in the dry state. It can be estimated by analyzing the drying data and then applying the slope method [9]-[12]. The research aims to calculating the effective moisture diffusivity, during drying prose's we stored the drying data and analyze it through the (Matlab) program, and calculate the diffusivity based on an equation of Fick's second law of diffusion for the unsteady state.

II. MATERIALS AND METHODS

The commercial gypsum available in the Iraqi market was used and distilled water. Three different gypsum constrictions ($\boldsymbol{C_g}$) [(gypsum / D-water) (g of gypsum / g of D-water)] $\boldsymbol{C_g}$ = 1, 1.33 and 1.66. PVC mold, with diameter (D = 34.25 mm) and thickness of (t = 7.6 mm) were used for all samples. Two substrates with different wet ability were used: hydrophilic glass substrate with contact angle of θ ≈ 30°, and modified glass super-hydrophobic substrate with contact angle of θ ≈ 160°.

First, gypsum with different particles sizes (normal size, 75, 150, 350, 500 microns) were sieved using mechanical sifting device available in the laboratory of the Department of Mechanical Engineering. Using water then acetone, mold and substrate (hydrophilic) were cleaned then nitrogen was compressed to dry them. The gypsum was weighed on the accurate scale, the D-water was weighed, and then D-water was added to the gypsum and mixed well for the mixture.

The time for adding gypsum to the D-water was 30 sec, and the time to mixing D-water with gypsum was 30 sec. according to the recommendations of the Iraqi specification for all trials.[13] The waiting time for the mixture inside the mold for $\mathbf{C_g}$ = 1 which was for both substrates (5-10 min.), $\mathbf{C_g}$ = 1.33 both substrates are (3-6 min.), and $\mathbf{C_g}$ = 1.66 both substrates are (2min). PVC mold, with diameter (D = 34.25 mm) and thickness (t = 7.6 mm) were used for all samples. The super-hydrophobic substrates were prepared by spraying glass substrates with thin non-stick coating (Rust-Oleum).

The coated surface remained super-hydrophobic for the duration of the experiments. After placing the gypsum sample in the mold placed on the substrate, the mold removed from the sample, and then placed the collection inside digital scale (Mettler Toledo, PB303-SRS) in an air-tight transparent acrylic chamber with dimensions (length = 18 cm, depth= 15 cm, width = 17 cm). The scale was connected to data logger (RS232, Eltima) to record the decreasing sample mass over time. A digital thermometer and hygrometer (Ink bird) were placed near the sample for continuous recording of chamber temperature and relative humidity. To keep the relative humidity constant silica gel was placed inside the chamber during drying. To determine changes in dimensions, side and top view images of the samples were recorded at regular intervals using digital camera (Infinity, Lumenera) Figure (1). Before placing the sample on the scale silica gel was placed in oven about 30 min. at temperature of 50 - 80° to make sure that it was free of moisture. All experiments were done at room temperature. After the end of the experiment, the contact angles for substrates were measured using an in-house goniometer.

III. EFFECTIVE MOISTURE DIFFUSIVITY

To describe the drying process, effective moisture diffusivity was collected based on the drying data. The derived slope method was used based on the solution of Fick's second law of diffusion.

From the first hour (when we removed the mold) it was assumed that the moisture transfer one-dimensional across the sample thickness Z-direction (Fick's second law for unsteady state in cylindrical coordinates)[14][4] ;

$$\frac{\partial C_w}{\partial t} = D_{eff}\,\frac{\partial^2 C_w}{\partial Z^2} \qquad (1)$$

where, C_w was the moisture concentration rate (kg/m^3), C_w was the mass of the liquid (i.e. D-water) used in preparing the sample (kg) divided by the sample volume (m^3), t was the time (h), D_{eff}. was the effective moisture diffusivity (m^2/h), which was the function of moisture concentration, and Z was the coordinate thickness

Multiplying both sides of eq. (1) by ($1/C_g$) where C_g was the solid (i.e. gypsum) concentration (kg/m^3)

$$\frac{\partial\left(\frac{C_w}{C_g}\right)}{\partial t} = D_{eff}\,\frac{\partial^2\left(\frac{C_w}{C_g}\right)}{\partial Z^2} (2)$$

Substituting:

$$Y = \frac{C_w}{C_g} (3)$$

Eq. (4. 2) becomes:

$$\frac{\partial Y}{\partial t} = D_{eff}\,\frac{\partial^2 Y}{\partial Z^2} (4);$$

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ISSN (online): 2581-3048

Volume 6, Issue 7, pp 31-42, July-2022

https://doi.org/10.47001/IRJIET/2022.607006

Where Y is the average moisture content (g D-water / g dry gypsum). Y is related to the measured sample mass during drying.

$$Y = \frac{m_w}{m_g} = \frac{m}{m_g} - 1 \quad (5);$$

Where m_w is D-water mass, m_g is gypsum mass, and m is mass sample at any time.

IV. MATHEMATICAL SIMPLIFICATION

Applying initial and boundary conditions in equations. (6-8), the solution was described in eq. (9)

$$t = 0 \qquad 0 \le Z \le Zo \qquad Y = Y_o \quad (6)$$

$$t > 0 Z = 0 \frac{\partial_Y}{\partial_Z} = 0 \qquad (7)$$

$$t > 0 Z = Z_o Y = Y_e \qquad (8)$$

$$U = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \left(\frac{1}{(2n+1)^2} exp[- \frac{(2n+1)^2 \pi^2 D_{eff}\ t}{4 Z_o{}^2}] \right)$$
(9)

Where;

$$U = \frac{Y - Ye}{Yo - Ye} (10)$$

U is dimensionless moisture content or fractional average moisture content Y is average moisture content at any time, Y_e is final average moisture content, and Y_o initial average moisture content.

$$Y_e = \frac{m_{we}}{m_g} = \frac{m_e}{m_g} - 1 (11)$$

$$Y_o = \frac{m_{wo}}{m_g} = \frac{m_o}{m_g} - 1 (12)$$

Eq. (11) m_{we} is final mass of water, and m_g is mass of gypsum used to prepare the sample (this quantity stays constant during drying), m_{wo} is the initial water mass the liquid used to prepare the sample.

In the current work, $Ye = 0$ and $0 \le U \le 1$. For long drying times, eq. (9) simplified it taking n = 0 to give:

$$U = \frac{8}{\pi^2} exp[- \frac{\pi^2 D_{eff}\ t}{4 Zo^2}] (13)$$

By taking the logarithm and subsequently the time derivative on both sides of eq. (13), arrive at :

$$\frac{\partial log U}{\partial t} = - \frac{\pi^2 D_{eff}}{4 Z_o{}^2} \qquad (14)$$

Now, plotting $log\ U$ versus time, the effective diffusivity, D_{eff}.Was calculated as :

$$D_{eff} = - \left(\frac{4 Z_o{}^2}{\pi^2} \right) * \ \text{(slope of line)} \qquad (15)$$

V. RESULTS AND DISCUSSION

5.1 Drying curves: changes in sample mass

Figures (2–4) show the changing in sample mass with time for gypsum dries out on two different substrates (i.e. θ ≈ 30°, and 160°), three of gypsum concentrations (C_g), and different gypsum particles sizes.

As expected, sample mass decreased due to the combination of discharge caused by gravity and surface evaporation eventually reaching the end of drying point where is defined as the point after which any change in the sample mass is negligible, as shown in the Figure (5).

When conducting practical experiments, it was found that gypsum concentrations C_g= 1 took longer time to dry, followed by C_g = 1.33 and finally C_g = 1.66. This difference may be caused by the high percentage of gypsum when mixing with D-water. For the used substrates, the sample on the super-hydrophobic substrate took longer than the hydrophilic substrate when dried for C_g= 1, and 1.33, this is because:

The increase in the contact angle between the sample and the substrate forced the water to stay inside the sample, meaning that the mechanism of water exit from the sample occurred from the surface evaporation only.

For C_g= 1.66, the time varied between the two substrates. For gypsum particles size, with hydrophilic substrate, increases in the particles size, led to decreases drying time of the samples, maybe due to few of permeability between the particles slows the water to exit outside the sample, for the super-hydrophobic, the time was varies. C_g= 1.66, with hydrophilic substrate θ ≈ 30° and normal gypsum particles size give better result (minimum drying time). Moreover, constant drying rate period was absent under drying process in all trials. [15] All trials are done in laboratory conditions (temperature, and relative humidity).

For all trials no cracks, occurred during drying process. No dimensions change (shrinkage), occurred during drying process.

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The gypsum concentrations (C_g) had the greatest effect on the drying process followed by the effect of the gypsum particles size.

5.2 Moisture Transport and Effective Moisture Diffusivity

The change for the average moisture content Y, and fractional average moisture content U, over time were plotted in Figures (6-11), for a gypsum dries out on two different substrates, (i.e. $\theta \approx 30°, 160°$), and three gypsum concentration and different gypsum particles sizes where U was normalized by changing in sample moisture content and varies from one to zero.

The slope method was adopted to calculate the effective moisture diffusivity for samples noted that the decrease in average moisture content caused increase in effective moisture diffusivity for all experimental samples as shown in Figures (12– 14). This may due to an increase (porosity and permeability) during drying. For example, the permeability of the sample initially was close to zero but over time it increased as the excess water left the sample. The same behavior of effective moisture diffusivity was concluded in drying of Pickering foam [4],and different systems (such as some types of food) conducted by previous studies, which also focused on the effective moisture diffusivity during the drying process, show the same behavior for the results. [10][16][17][18] The increase in permeability lead to an increase in effective moisture diffusivity during drying.

VI. CONCLUSIONS

In gypsum drying system under controlled conditions, drying curves and required drying time (end-drying point) were determined for all gypsum samples. Drying curves and using the slope method, the effective moisture diffusivity was calculated. Generally, the rate of fall continuously i.e. absence of constant rate period.

1. In conclusion, the values of effective moisture diffusivity increased as the average moisture content decreased due to the increase of samples (porosity and permeability).
2. For both substrates (hydrophobic and hydrophilic) the gypsum concentrations had the strongest effect, increasing the gypsum in mixture (gypsum/D-water) led to a decrease in the drying time.
3. Increasing the gypsum particles size led to reducing drying time.
4. For all trials no cracks, occurred during drying process, may be because the cohesion force between the gypsum particles was greater than the adhesion force between the sample and the substrate.
5. No dimensions change (shrinkage), occurred during drying process due to the capillary stresses.

ACKNOWLEDGMENTS

We would like to acknowledge the support received from the College of Engineering, University of Mosul, Iraq.

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APPENDIX-I

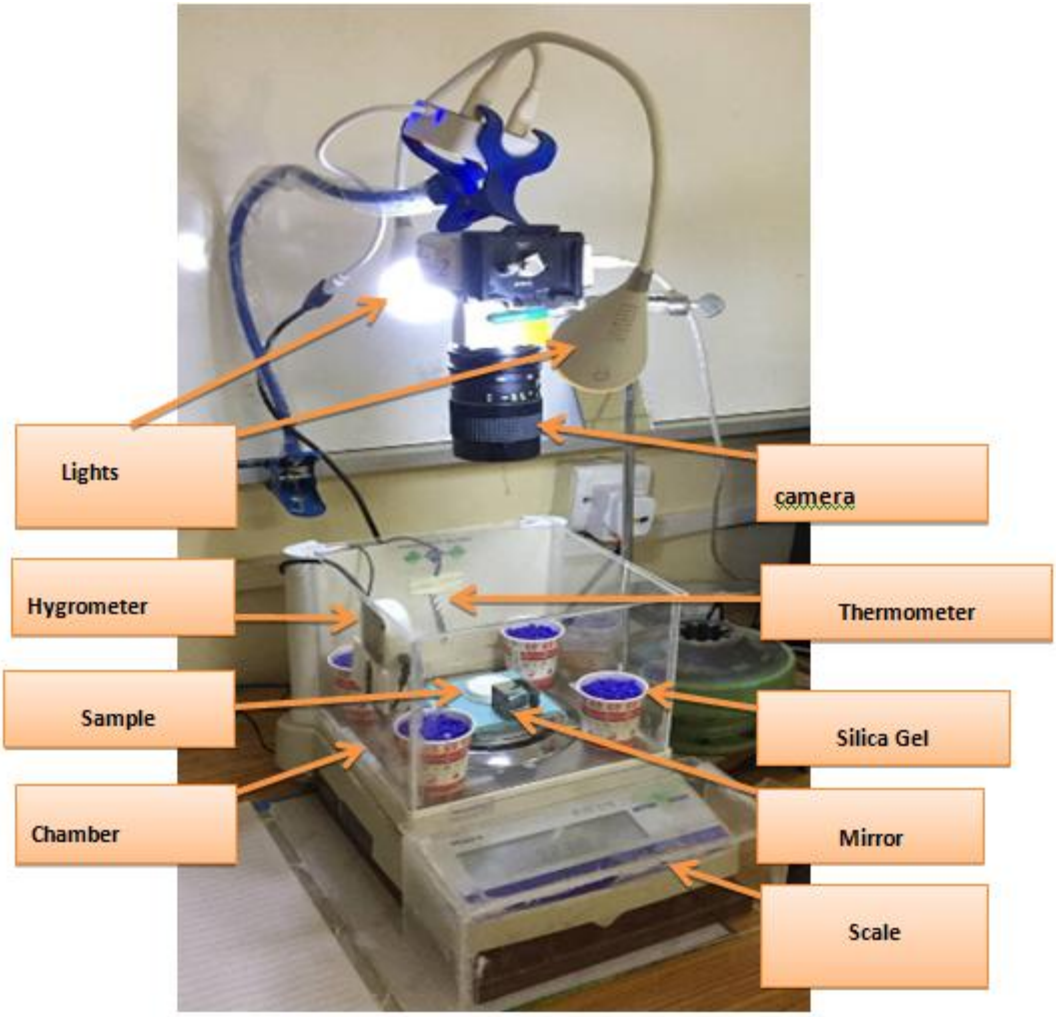

Figure (1): Experimental setup

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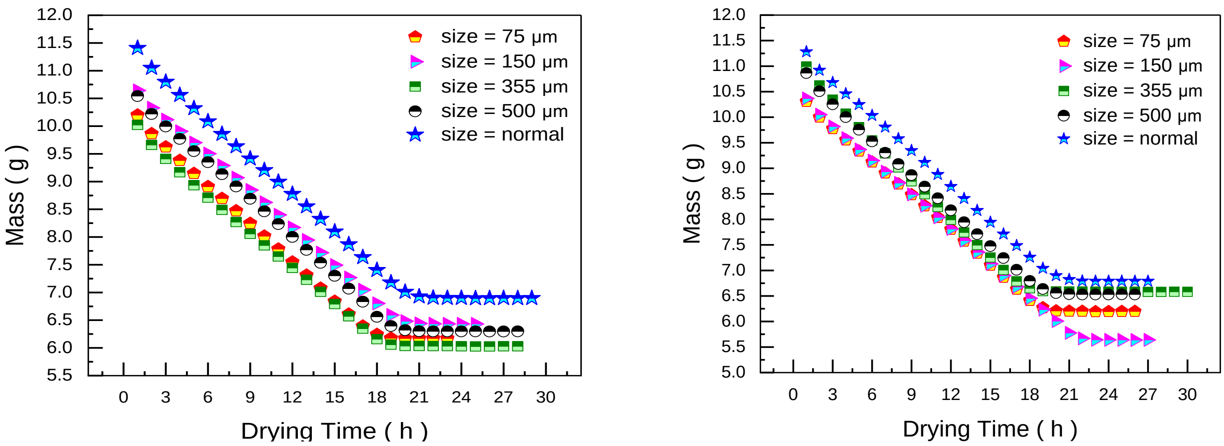
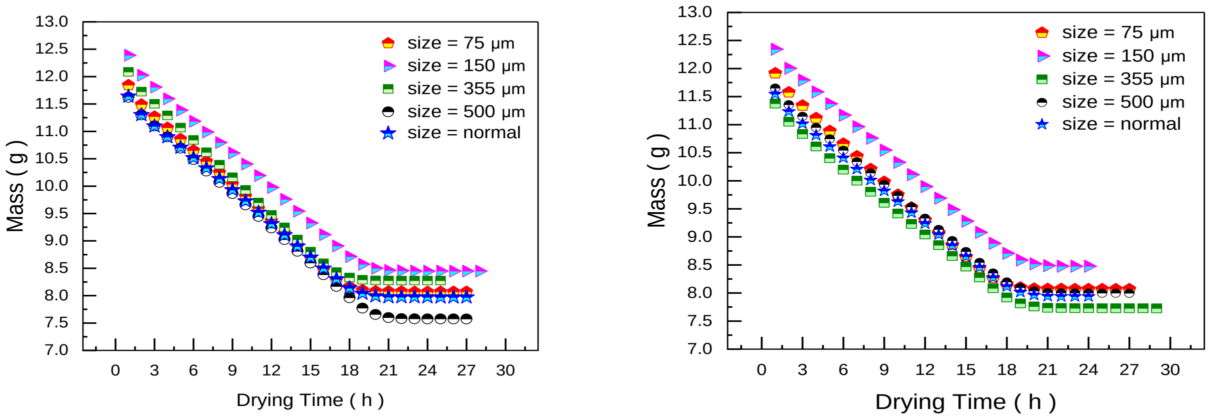


(a) **(b)**

Figure (2): Mass change during drying for gypsum concentration (C_g= 1) and gypsum with different particles size, for (a)glasshydrophilic substrate θ ≈ 30° and (b) modified glass super-hydrophobic substrate θ ≈ 160°.



(a) **(b)**

Figure (3): Mass change during drying for gypsum concentration (C_g= 1.33) and gypsum with different particles size, for (a) glasshydrophilic substrate θ ≈ 30° and (b) modified glass super-hydrophobic substrate θ ≈ 160°.

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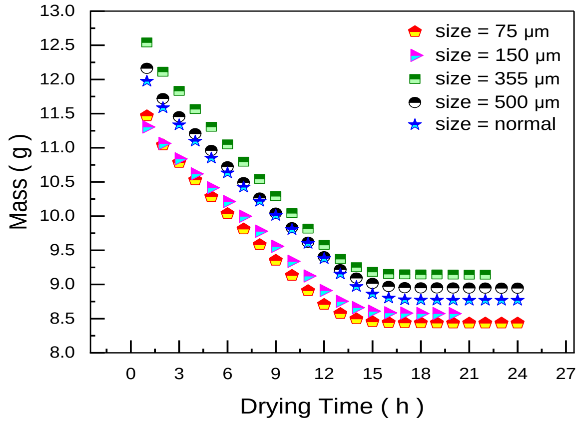
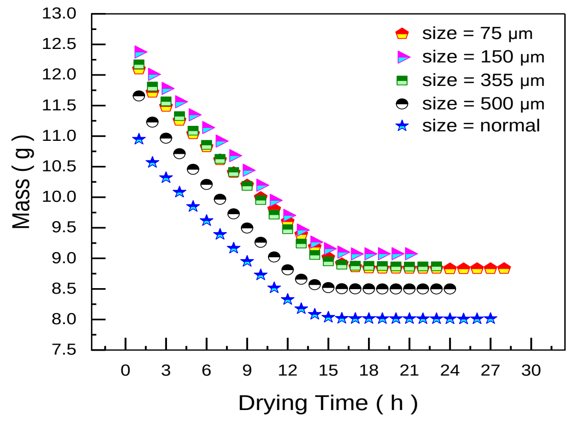


(a)



(b)

Figure (4): Mass change during drying for gypsum concentration (C_g= 1.66) and gypsum with different particles size, for (a)glass hydrophilic substrate θ ≈ 30° and (b) modified glass super-hydrophobic substrate θ ≈ 160°.

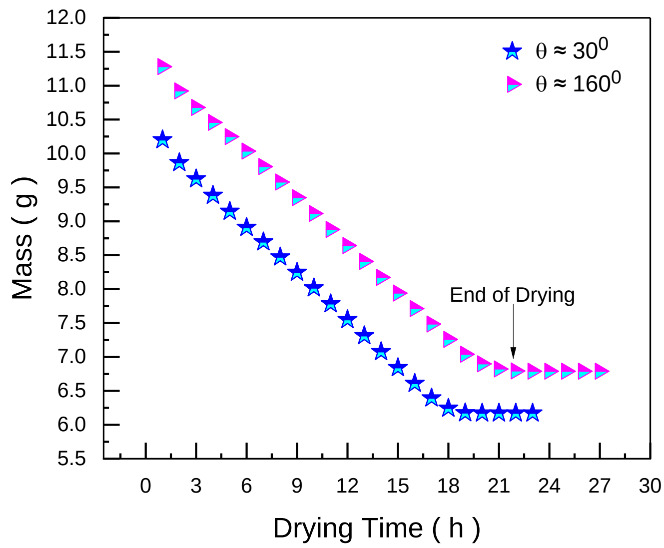


Figure (5): End of drying time for gypsum normal size, and (C_g= 1) with two substrate1- glass hydrophilic substrate θ ≈ 30°, 2- modified glass super-hydrophobic substrate θ ≈ 160°.

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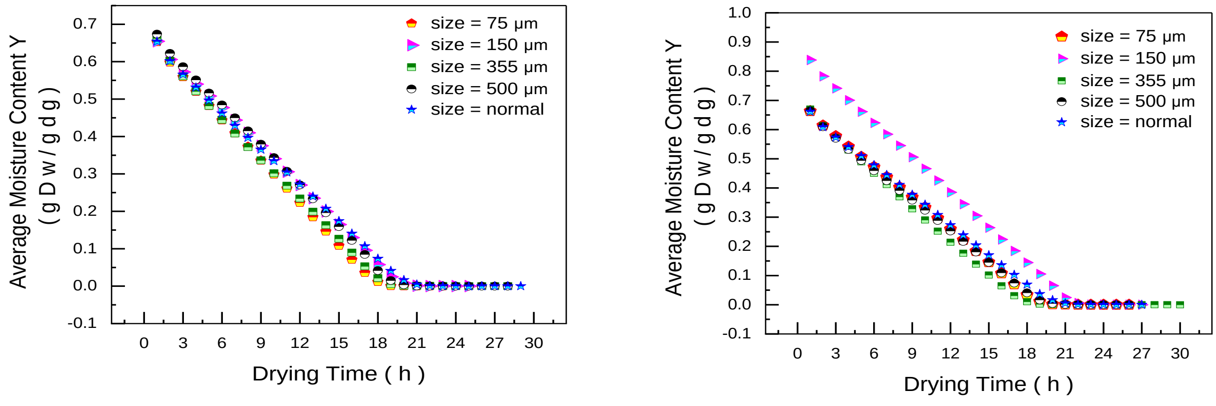
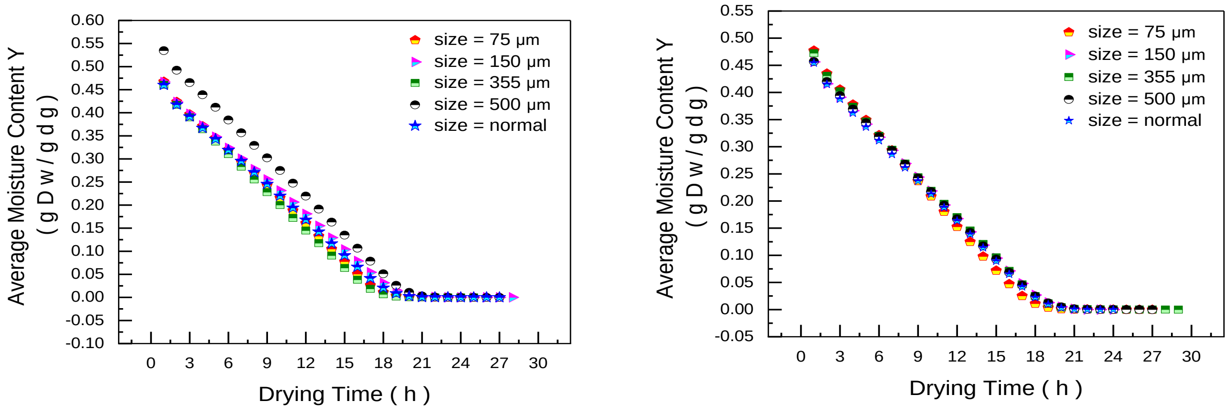


(a) (b)

Figure (6): Average moisture content change with time during drying for gypsum concentration (C_g= 1), and gypsum with deferent particles size, for (a) glass hydrophilic substrate with θ ≈ 30°, and (b)modified glass super-hydrophobic substrate with θ ≈ 160°.



(a) (b)

Figure (7): Average moisture content change with time during drying for gypsum concentration (C_g= 1.33), and gypsum with deferent particles size, for (a)glass hydrophilic substrate with θ ≈ 30°,and (b) modified glass super-hydrophobic substrate with θ ≈ 160°.

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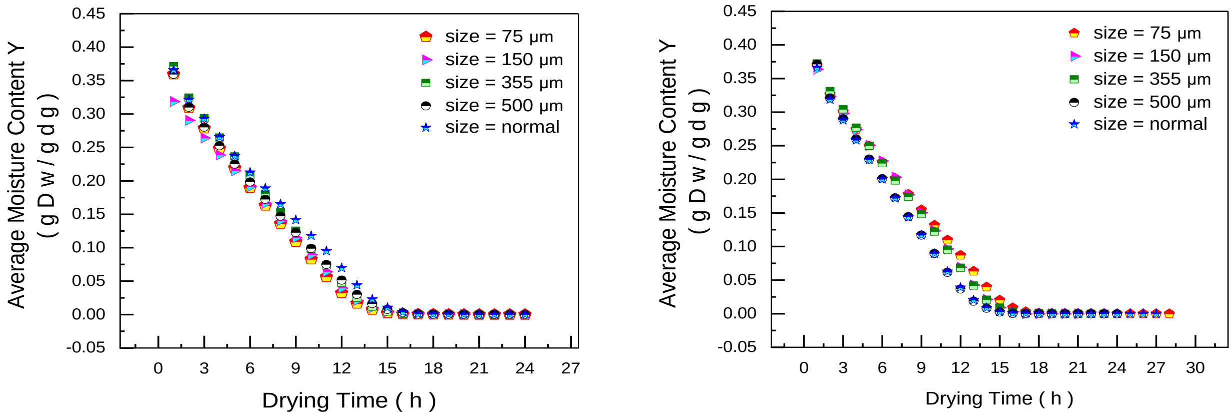
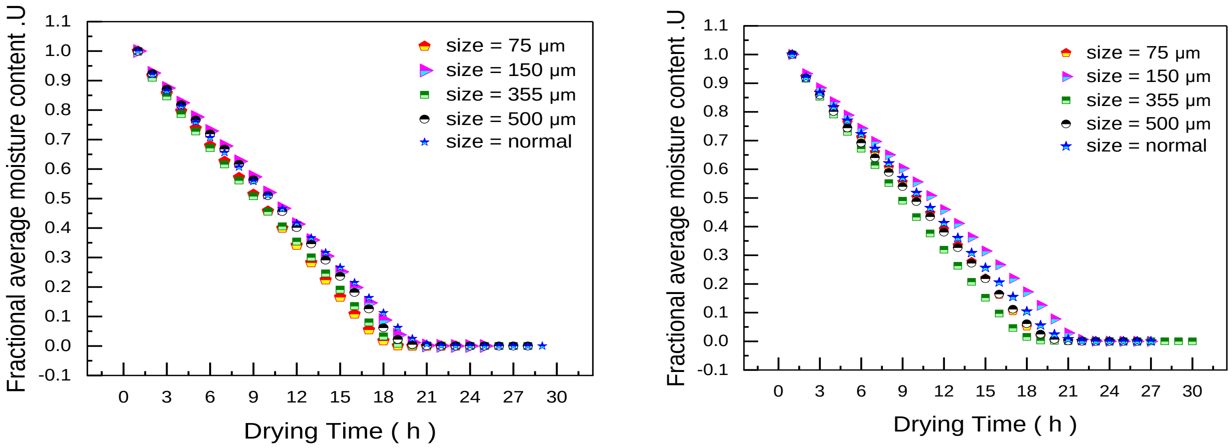


(a) (b)

Figure (8): Average moisture content change with time during drying for gypsum concentration (C_g= 1.66), and gypsum with deferent particles size, for (a)glass hydrophilic substrate with θ ≈ 30°,and (b) modified glass super-hydrophobic substrate with θ ≈ 160°.



(a) (b)

Figure (9): Fractional average moisture content change with time during drying for gypsum concentration (C_g= 1), and gypsum with deferent particles size, for (a)glass hydrophilic substrate with θ ≈ 30°,and (b) modified glass super-hydrophobic substrate with θ ≈ 160°.

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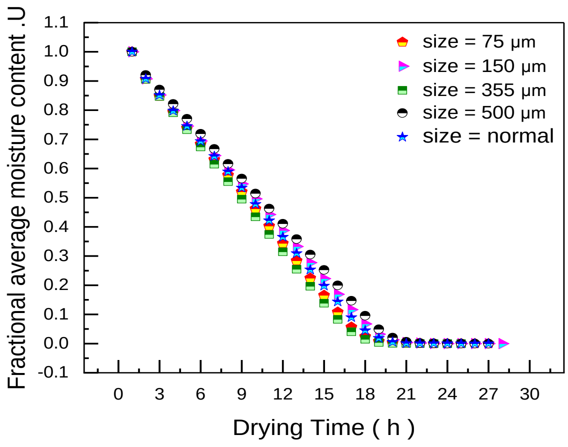
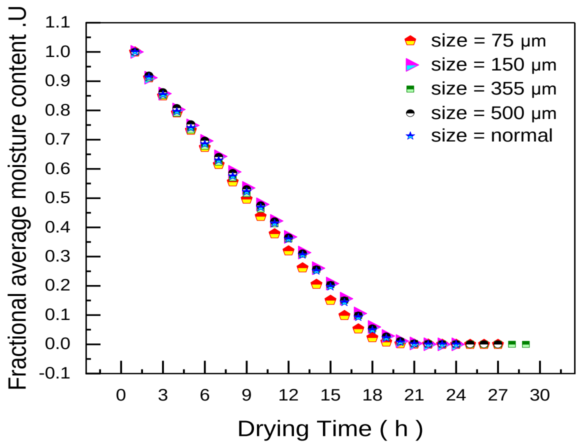
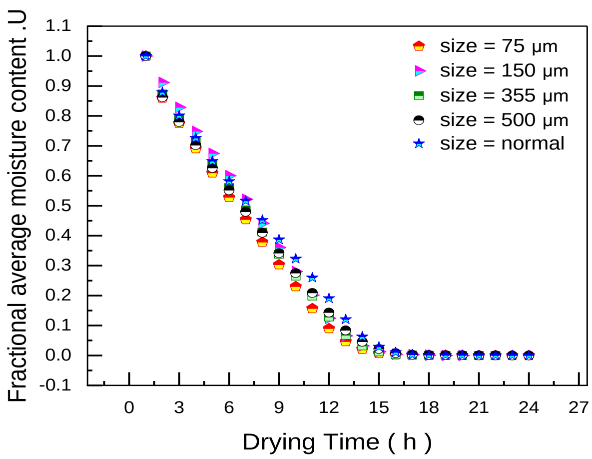


(a)

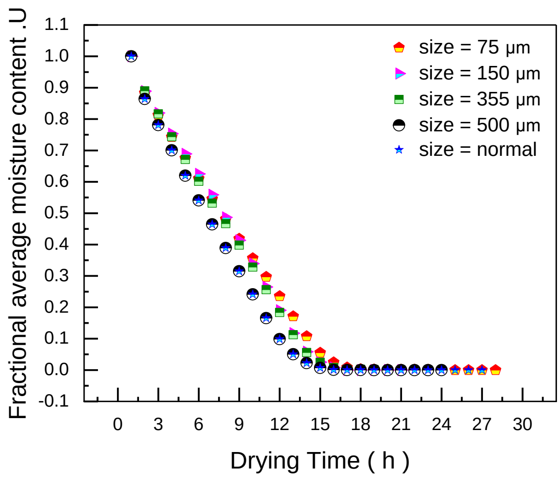


(b)

Figure (10): Fractional average moisture content change with time during drying for gypsum concentration (C_g= 1.33), and gypsum with deferent particles size, for (a)glass hydrophilic substrate with θ ≈ 30°, and (b) modified glass super-hydrophobic substrate with θ ≈ 160°.



(a)



(b)

Figure (11): Fractional average moisture content change with time during drying for gypsum concentration (C_g= 1.66), and gypsum with deferent particles size, for (a)glass hydrophilic substrate θ ≈ 30°, and (b)modified glass super-hydrophobic substrate with θ ≈ 160°.

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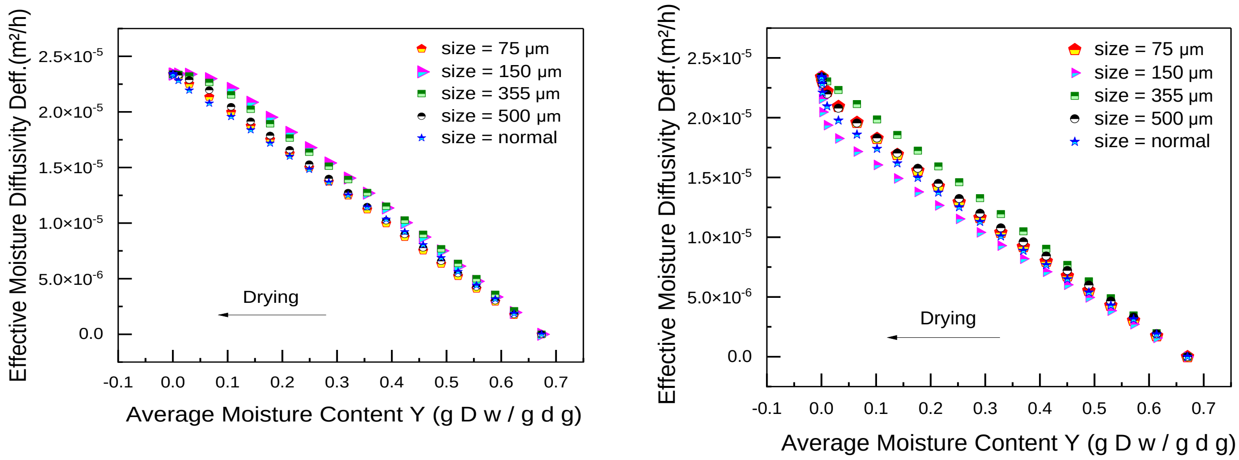
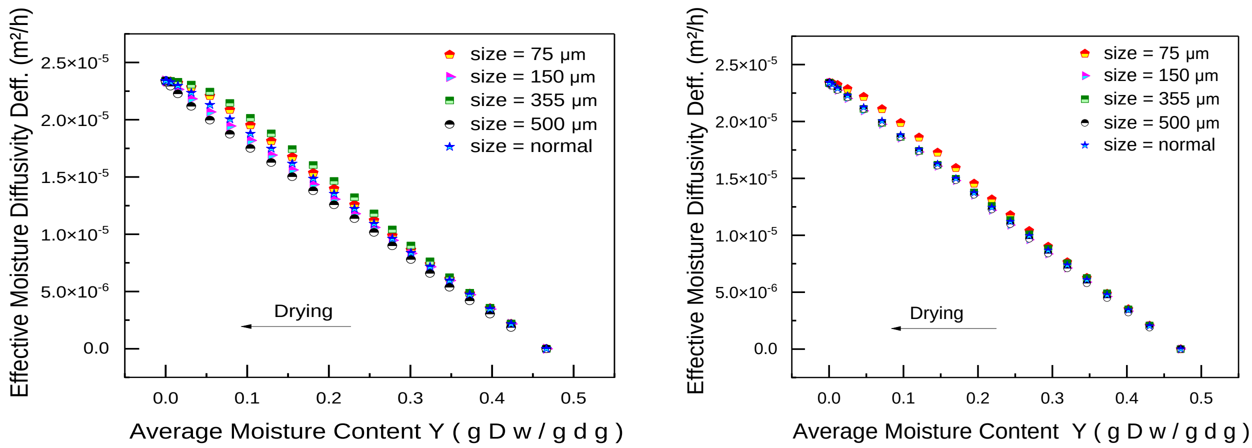
Volume 6, Issue 7, pp 31-42, July-2022

https://doi.org/10.47001/IRJIET/2022.607006



(a) **(b)**

Figure (12): Effective moisture diffusivity change with average moisture content(Y) during drying for gypsum concentration (C_g= 1), and gypsum different particles size, for (a)glass hydrophilic substrate with θ ≈ 30°, and (b)modified glass super-hydrophobic substrate with θ ≈ 160°.



(a) **(b)**

Figure (13): Effective moisture diffusivity change with average moisture content (Y) during drying for gypsum concentration(C_g= 1.33), and gypsum with different particles size, for (a)glass hydrophilic substrate with θ ≈ 30°, and (b) modified glass super-hydrophobic substrate with θ ≈ 160°.

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 6, Issue 7, pp 31-42, July-2022

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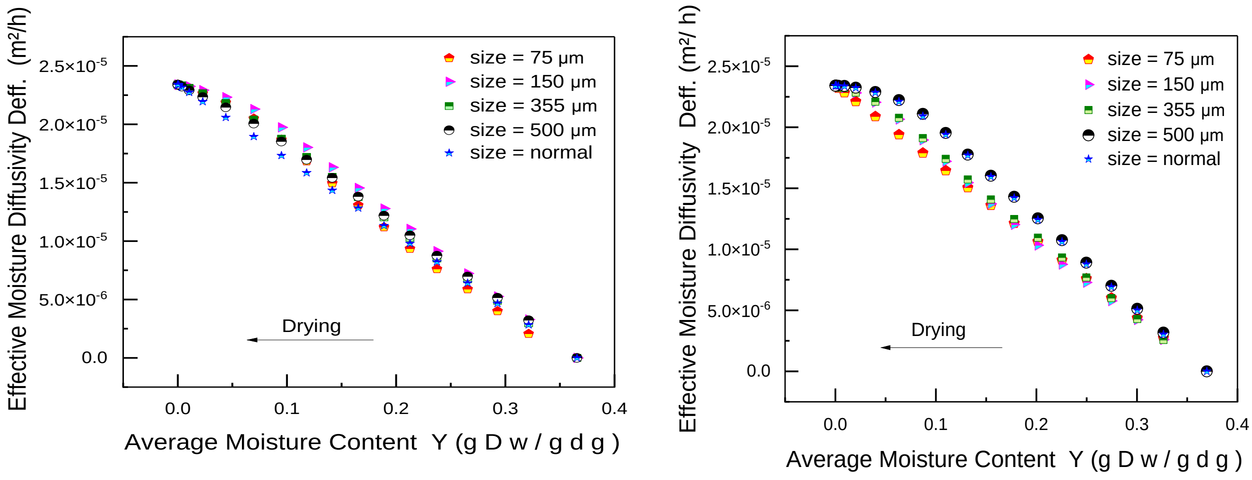

(a) **(b)**

Figure (14): Effective moisture diffusivity change with average moisture content(Y) during drying for gypsum concentration(C_g= 1.66), and gypsum with different particles size, for (a)glass hydrophilic substrate with $\theta \approx 30°$, and (b) modified glass super-hydrophobic substrate with $\theta \approx 160°$.

Citation of this Article:

Waleed M. Najm, Omer S. Alabidalkreem, Awadhalosh, "Calculating the Effective Moisture Diffusivity during Drying Process of Gypsum Board" Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 6, Issue 7, pp 31-42, July 2022. Article DOI https://doi.org/10.47001/IRJIET/2022.607006

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