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Effect of Surface Temperature on Water Absorption Coefficient of Building Materials

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Abstract

Water absorption coefficient of a material governs the liquid moisture movement into it. In the case of various components of a building envelope, in particular exterior claddings, this is one of the most important hygrothermal material properties that needs to be assessed to determine the overall moisture management strategy. In different geographical locations, components of the building envelope, in particular the surface of the exterior cladding, are exposed to various temperature regimes. However, the effect of various temperature regimes on the water absorption coefficient of common building materials has not been adequately investigated. This study looks at the water absorption characteristic, determined through water absorption test, of three commonly used building materials (i.e., eastern white pine, red clay brick and concrete) at four temperature levels at the surface of the material, ranging from 3°C to 35°C. A clear surface temperature effect on water absorption coefficient and derived liquid diffusivity value is shown in eastern white pine whereas changing the surface temperature shows no effect on the water absorption characteristic of red clay brick and concrete.

Introduction

Building envelopes in North America are exposed to extreme weather fluctuations with variations in temperature of between –30°C and +50°C being realistic. Temperature is a major driving force for moisture movement and influences sorption characteristics of many building materials. Quite naturally, temperature variations have distinct effects on the moisture management strategy of building envelopes. Increases in temperature induce greater mobility in the water molecules in any form of moisture. However, the extent of this influence of temperature on the liquid moisture movement into the material is not adequately understood.

Increasingly, in recent years, numerical models have been used to predict the moisture response of a building envelope (Mukhopadhyaya and Kumaran 2001; Mukhopadhyaya et al. 2001; Kumaran et al. 2002b; Nofal et al. 2001). These models invariably need well-defined moisture transport properties. However, at this moment, moisture transport properties are generally assumed to be independent of the temperature. One main reason for such an assumption is the unavailability of data that would define the moisture transport properties of common building materials as a function of temperature. However, it is quite logical to suggest the next generation of numerical models would need such data for more realistic predictions and understanding of the hygrothermal response of the building envelope in different climatic conditions.

One of the moisture transport properties is water absorption coefficient. Its relation to moisture/liquid diffusivity has also been researched (Krus and Künzel 1993; de Wit and van Schindel 1993). These two properties together define the moisture transport into a material when it is in direct contact with a source of liquid water (Figure 1) and the redistribution of moisture in materials. Hence, water absorption coefficient is a property that would directly govern wind-driven rain penetration through the surface of exterior cladding materials in a building envelope. Numerical simulation results show that the variation of the liquid diffusivity and hence, the water absorption coefficient of exterior cladding materials can influence the moisture response of the building envelope considerably (Mukhopadhyaya et al. 2002). Therefore, it is important for building scientists to understand how water absorption coefficient of a building material responds to different temperature regimes.

Research Background

Water Absorption Coefficient

A material that allows liquid moisture diffusion through its boundary surface would change its weight with time when it is brought in contact with liquid water (Figure 1). A schematic plot (Kumaran 1999) of the increase in weight of the test specimen versus the square root of the time indicates that the specimen weight increases linearly (Figure 2) before it comes close to the saturation limit. The slope of this linear variation is called the water absorption coefficient (A_w) and can be mathematically written as:

$$A_w = \left(\frac{M_t - M_i}{A\sqrt{t}} \right) \qquad [1]$$

where
M_t = weight of the specimen after time 't'
M_i = initial mass of the specimen
A = liquid contact area of the specimen
t = time.

Liquid Diffusivity

According to Fick's law of diffusion (Crank and Park 1968), for isotropic materials, the rate of transfer, measured normal to the section, of diffusing moisture through a unit area of a section is proportional to the gradient of moisture concentration. Hence, the liquid moisture transport phenomenon through isotropic building materials can be expressed with the following relationship:

$$F = - D_{w}.\ ¶C/¶x \qquad [2]$$

where

F = rate of liquid transfer per unit area of section [$kg.m^{-2}.s^{-1}$]

D_w = material specific liquid diffusion coefficient [$m^{2}.s^{-1}$]

C = volumetric moisture concentration [$kg.m^{-3}$]

x = space co-ordinate measured normal to the section [m].

In equation 2, when the volumetric moisture content C [$kg.m^{-3}$] is expressed in terms of the mass moisture content U [$kg.kg^{-1}$], the equation can be rewritten as:

$$F = - (?_0\ D_w)\ .\ ¶U/¶x\ = - (?_0\ D_w).\ grad\ U \qquad [3]$$

where

$?_0$ = dry density of material [$kg.m^{-3}$]

U = mass of moisture per unit mass of dry material [$kg.kg^{-1}$].

While the mathematical relationship depicting the liquid transport phenomenon remains unquestionable, up until now, several experimental methods have existed (Krus 1996), along with different analytical procedures, to determine liquid diffusivity (D_w). In all these experimental methods, liquid diffusivity is determined by conducting a free water intake test as shown in Figure 1. This test simulates the water absorption caused by wind-driven rain on the façade or exterior cladding of a building envelope or any material (except for loose fill materials). However, this test does not mimic the water absorption by materials under water or in permanent contact with saturated ground, where a complete or full immersion test is considered more appropriate. In the past, either gamma-ray attenuation (Kumaran and Bomberg 1985; Kumaran et al. 1989) or nuclear magnetic resonance (Krus 1996) was used to measure liquid diffusivity (D_w) of a material from a free water intake test (Figure 1). These techniques generally indicate that liquid diffusivity is a function of local moisture content. However, these techniques are expensive and require well-trained personnel to maintain and operate. Hence, they are impractical for routine quality control assignments. Moreover, these methods do not always reach a unique value of liquid diffusivity (Kumaran 1999). While discussions on this issue are ongoing, it has been suggested that water absorption coefficients together with capillary saturation moisture content can be used to calculate an average liquid diffusivity (Krus and Künzel 1993; de Wit and van Schindel 1993). This average liquid diffusivity can be used in moisture transport equation 3 as Dw. The usefulness of this simplified method has already been established and confirmed through a series of laboratory measurements using the gamma-ray attenuation technique (Kumaran 1999). In the present study, the average liquid diffusivity values at different temperatures are determined from the water absorption coefficients as described in the following paragraphs.

Water Absorption Coefficient and Liquid Diffusivity

To calculate the average liquid diffusivity from the water absorption coefficient (A_w), it is necessary to establish the relationship between the A_w value and the average liquid diffusivity. Using equation 3, with the assumption of a constant value of *Dw*, the average value of liquid diffusivity can be expressed as (Krus and Künzel 1993):

$$D_w \approx \left(\frac{A_w}{w_c} \right)^2 \qquad [4]$$

where

'w_c' = the saturated volumetric moisture content of the material.

Taking the progressive moisture front (i.e. profile of the advancing moisture front) into account (Krus and Künzel 1993), equation 4 can be modified as:

$$D_w = \frac{\pi}{4} \left(\frac{A_w}{w_c} \right)^2 \qquad [5]$$

Equation 5 is used in this study to derive the average liquid diffusivity (D_w) from the water absorption coefficient (A_w).

Experimental Work

In general, the experiments conducted in this study are guided by the outline of the partial immersion method as explained in the European Standard 'Thermal performance of buildings and building components - Determination of water absorption coefficient' (CEN/TC 89/WG10 N70 (1994). More specific details regarding the materials, test conditions, test set-up, equipment and specimens are given in the follow paragraphs.

Materials

To generate enough information for a basic understanding of the effects of temperature on the water absorption characteristic of materials, three commonly used building materials were selected: eastern white pine, red clay brick and concrete. The selected properties of these materials required for this study are shown in Table 1.

Table 1: Material properties

Material	Average density ($kg.m^{-3}$)	Average capillary saturated volumetric moisture content ($kg.m^{-3}$)
Eastern white pine	375	622
Red clay brick	1980	188
Concrete	2130	117

Temperature Range

The tests for each material were conducted at 3°C, 12°C, 21°C and 35°C. These temperatures are very much within the minimum and maximum range expected in North America. The temperature levels were obtained by raising and maintaining the temperature of the liquid water in contact with the surface of the specimens. Hence, it implies that while the specimen remained at ambient room temperature (≈23°C), the surface area of the specimen in contact with water had been exposed to different temperature regimes.

Test Set-Up and Equipment

Three basic components are required for this simple test: a circulation bath or water tank, a balance for weighing specimens and a stopwatch.

The schematic diagram of the circulation bath or water tank is shown in Figure 3a and the picture of the system used in this study is shown in Figure 3b. The set up is fitted with an inlet-outlet system that keeps the water level constant to ±1 mm. It is also fixed with a device (specimen holder) that allows the specimens to hang, move up and down, and stay fixed in a position just touching the surface of the water (Figure 3c).

The balance or weighing system is capable of determining the weight of the specimen to an accuracy of ±0.1% of the weight of the specimen.

The stopwatch can record the time to the nearest second.

Test Specimens

Six specimens of each material, each with a surface area ≈25 cm^2 (Figure 4), were tested for each of the selected surface temperature levels. Hence, 24 specimens were cut from each material to be tested at four temperatures.

Preparation of Test Specimens

Specimens were cut to the specific size (Figure 4) from the middle of a material block to ensure they did not include any edge of the material block. The specimens were stored at room temperature (≈23°C) and 50 ± 5% relative humidity until the weight of each specimen has reached a steady state (i.e., variation ±0.1% of its weight). The exact weight and size of the specimens were recorded at this stage. The side surfaces of the specimens were then sealed with an impermeable vapour-tight sealant (epoxy) that would not significantly penetrate into the pore of the material or modify the structure or chemical composition of the material (Figure 4). In the case of eastern white pine, the specimens were prepared and surfaces were coated in such a way that the water intake direction coincided with the longitudinal direction of the wood fibre.

Test Procedure

Specimens were placed in the specimen holder (Figure 3c). The initial weight of the specimen with the detachable specimen holder was recorded. The circulation bath or water tank was filled with water. The temperature of the water was adjusted with a thermostat, and the system was allowed to stabilize. The specimens were then clamped in position, above the water, in such a way that one free surface (the base) is in continuous contact with the water. The water level was kept constant during the test at 5 ±2 mm above the specimen surface in contact with the water. Care was taken to ensure that no air bubbles were entrapped at the interface between the water and the specimen surface.

The stopwatch was started immediately after the specimen surface came in contact with the water. At periodic intervals, each specimen, with the specimen hanger, was removed from the water. The wet surface was then pressed against multiple layers of highly absorptive tissue paper to dry it. Each specimen with the specimen hanger was then weighed to the nearest 0.1% of its weight. Specimens were returned to the circulation bath or water tank and the procedure was repeated at increasing time intervals such as 5, 10, 20 minutes, 1, 2, 4 hours etc. after immersion to generate a series of data indicating the change in mass with time. The procedure was repeated for all three materials at 3°C, 12°C, 21°C and 35°C.

Results and Discussion

Typical plots of mass gain versus the square root of time (water intake curves), at 35°C, are shown in Figure 5. The calculated water absorption coefficient (A_w) (using equation 1) and derived liquid diffusivity (D_w) (using equation 5) at four different temperature levels for all three materials are shown in tables 2 to 4.

However, before looking into the effects of various temperatures on the water absorption coefficients of the materials, a few fundamental observations can be made on the water intake characteristics of the selected materials from the plots in Figure 5 and numbers shown in tables 2 to 4.

(1) The shape of the curves obtained from red clay brick and concrete (figures 5b and 5c) show two distinct stages in the water intake process. A sloped straight line defines the first stage and a relatively flat line defines the second stage. In the first stage, the water, from the circulation bath or water tank, gradually approaches the opposite side of the specimen. Capillary and viscous forces control this process. The water absorption coefficient is calculated from the slope of this line in the first stage, ignoring the initial irregularities. During the second stage, the further slow increase of the moisture content is due to the dissolution of entrapped air in the water after the establishment of capillary saturation.

(2) In the case of the eastern white pine, unlike the red clay brick and concrete, the second stage of the curve is not yet reached (Figure 5a), though the exposure period was the longest. This indicates the first stage of water intake is continuing at a steady rate. The water intake in eastern white pine was the slowest but the process continued for the longest period of time, because it has the lowest water absorption coefficient (tables 2a, 3a and 4a). Also note that eastern white pine specimens had a higher thickness (Figure 4). The tests were discontinued for eastern white pine, before the water intake curve reached the second stage, because enough data had been collected for the calculation of the water absorption coefficient (A_w).

(3) In the case of concrete, the water intake was very fast (Figure 5c). The capillary saturation was very rapid, and the initial linear part is not very well defined as in red clay brick or eastern white pine. Therefore, the possibility of minor deviation from the real slope of the water intake curve cannot be ruled out. The existence of such deviation in the results of this study, if any, would be consistent at all surface temperatures. Nevertheless, for rapid water-absorbing materials, a shorter time gap for the initial reading may be desirable.

(4) The variability of the water intake curve, within the six specimens tested in this study, is much less in the eastern white pine than in the red clay brick or the concrete. This may be due to the inherent degree of homogeneity associated with the materials. However, this variation pattern was consistent at all four temperature levels considered in this study.

(5) It is evident from the tabulated results (tables 2 to 4), that concrete has the highest, and the eastern white pine has the lowest water absorption coefficient and derived liquid diffusivity values. However, the following information, from an extensive material database (Kumaran et al. 2002a), can be a useful guideline for understanding the physical significance of the tabulated liquid diffusivity (D_w) values in tables 2b, 3b and 4b.

- 10^{-7} → 25mm thick specimen come close to complete saturation within hours while constantly in touch with liquid water.
- 10^{-8} → 25mm thick specimen come close to complete saturation within a day while constantly in touch with liquid water.
- 10^{-9} → 25mm thick specimen come close to complete saturation within a few days while constantly in touch with liquid water.
- 10^{-10} → 25mm thick specimen come close to complete saturation within a few weeks while constantly in touch with liquid water.
- 10^{-11} and less → High resistance to liquid diffusion.

Effect of Surface Temperature on Water Absorption Coefficient

The effects of temperature on the water absorption coefficient and liquid diffusivity, derived from the six specimens of each of the three materials considered in this study, are shown in Figure 6 and 7 respectively. It is clear from Figure 6a that the water absorption coefficient of eastern white pine, in the longitudinal direction of the fibre, changes linearly with the variation of temperature. That is not the case for red clay brick (Figure 6b) where there seems to be no consistent pattern of variation observed in the test results (Figure 6b). Though the fluctuations of the water absorption coefficient values at various temperature levels appear to be relatively small, such fluctuations may be due to the inherent material property variation at different locations of the red clay brick considered in this study. A more definitive reason requires further study, involving more test specimens. The results obtained from the concrete specimens (Figure 6c) undoubtedly indicate that temperature variation has no significant effect on the water absorption coefficient of concrete.

In looking at the liquid diffusivity values of all the three materials at different temperatures (Figure 7), it is evident that eastern white pine has the most distinctively visible and consistent change in liquid moisture transport property variation with the variation of temperature. Eastern white pine also has the lowest density (Table 1) and average liquid diffusivity values (tables 2b, 3b and 4b) of the three materials considered in this study. Conversely, temperature variation has virtually no effect on the average liquid diffusivity of concrete (Figure 7), which has the highest density (Table 1) and liquid diffusivity (tables 2b, 3b and 4b).

Hence, despite acknowledging the need for further investigations, this study suggests that lower water absorption coefficient or liquid diffusivity (D_w) values would be more susceptible to temperature variations. Further studies on this issue are in the planning stage at the Institute for Research in Construction (IRC) of the National Research Council (NRC), Canada.

Table 2a: Water absorption coefficient ($kg.m^{-2}.s^{-1/2}$) of eastern white pine

Specimen ID	Water Absorp. Coef.	Specimen ID	Water Absorp. Coef.	Specimen ID	Water Absorp. Coef.	Specimen ID	Water Absorp. Coef.
Temp. = 3°C		Temp. = 12°C		Temp. = 21°C		Temp. = 35°C	
WD-T2-1	0.0068	WD-T3-1	0.0099	WD-T1-1	0.0114	WD-T4-1	0.0151
WD-T2-2	0.0078	WD-T3-2	0.0089	WD-T1-2	0.0116	WD-T4-2	0.0139
WD-T2-3	0.0075	WD-T3-3	0.0088	WD-T1-3	0.0112	WD-T4-3	0.0136
WD-T2-4	0.0077	WD-T3-4	0.0092	WD-T1-4	0.0109	WD-T4-4	0.0132
WD-T2-5	0.0080	WD-T3-5	0.0096	WD-T1-5	0.0111	WD-T4-5	0.0144
WD-T2-6	0.0076	WD-T3-6	0.0099	WD-T1-6	0.0112	WD-T4-6	0.0142
Average	0.0075	Average	0.0094	Average	0.0112	Average	0.0142
Standard deviation	0.0004	Standard deviation	0.0005	Standard deviation	0.0002	Standard deviation	0.0007

Table 2b: Liquid diffusivity ($m^2.s^{-1}$) of eastern white pine

Specimen ID	Liquid Diffusivity	Specimen ID	Liquid Diffusivity	Specimen ID	Liquid Diffusivity	Specimen ID	Liquid Diffusivity
Temp. = 3°C		Temp. = 12°C		Temp. = 21°C		Temp. = 35°C	
WD-T2-1	9.26E-11	WD-T3-1	1.97E-10	WD-T1-1	2.61E-10	WD-T4-1	4.59E-10
WD-T2-2	1.23E-10	WD-T3-2	1.62E-10	WD-T1-2	2.73E-10	WD-T4-2	3.91E-10
WD-T2-3	1.14E-10	WD-T3-3	1.57E-10	WD-T1-3	2.55E-10	WD-T4-3	3.76E-10
WD-T2-4	1.20E-10	WD-T3-4	1.71E-10	WD-T1-4	2.40E-10	WD-T4-4	3.55E-10
WD-T2-5	1.28E-10	WD-T3-5	1.87E-10	WD-T1-5	2.48E-10	WD-T4-5	4.23E-10
WD-T2-6	1.17E-10	WD-T3-6	2.00E-10	WD-T1-6	2.54E-10	WD-T4-6	4.11E-10
Average	1.16E-10	Average	1.79E-10	Average	2.55E-10	Average	4.02E-10
Standard deviation	1.23E-11	Standard deviation	1.83E-11	Standard deviation	1.13E-11	Standard deviation	3.68E-11

Table 3a: Water absorption coefficient ($kg.m^{-2}.s^{-1/2}$) of red clay brick

Specimen ID	Water Absorp. Coef.	Specimen ID	Water Absorp. Coef.	Specimen ID	Water Absorp. Coef.	Specimen ID	Water Absorp. Coef.
Temp. = 3°C		Temp. = 12°C		Temp. = 21°C		Temp. = 35°C	
BR-T2-1	0.064	BR-T3-1	0.064	BR-T1-1	0.094	BR-T4-1	0.067
BR-T2-2	0.073	BR-T3-2	0.069	BR-T1-2	0.095	BR-T4-2	0.096
BR-T2-3	0.075	BR-T3-3	0.068	BR-T1-3	0.075	BR-T4-3	0.061
BR-T2-4	0.066	BR-T3-4	0.065	BR-T1-4	0.077	BR-T4-4	0.053
BR-T2-5	0.066	BR-T3-5	0.062	BR-T1-5	0.080	BR-T4-5	0.064
BR-T2-6	0.065	BR-T3-6	0.065	BR-T1-6	0.083	BR-T4-6	0.051
Average	0.068	Average	0.066	Average	0.084	Average	0.065
Standard deviation	4.67E-03	Standard deviation	2.52E-03	Standard deviation	8.64E-03	Standard deviation	1.62E-02

Table 3b: Liquid diffusivity ($m^2.s^{-1}$) of red clay brick

Specimen ID	Liquid Diffusivity	Specimen ID	Liquid Diffusivity	Specimen ID	Liquid Diffusivity	Specimen ID	Liquid Diffusivity
Temp. = 3°C		Temp. = 12°C		Temp. = 21°C		Temp. = 35°C	
BR-T2-1	9.11E-08	BR-T3-1	9.13E-08	BR-T1-1	1.95E-07	BR-T4-1	9.98E-08
BR-T2-2	1.20E-07	BR-T3-2	1.06E-07	BR-T1-2	2.00E-07	BR-T4-2	1.06E-07
BR-T2-3	1.26E-07	BR-T3-3	1.02E-07	BR-T1-3	1.23E-07	BR-T4-3	8.38E-08
BR-T2-4	9.80E-08	BR-T3-4	9.51E-08	BR-T1-4	1.31E-07	BR-T4-4	6.32E-08
BR-T2-5	9.61E-08	BR-T3-5	8.55E-08	BR-T1-5	1.42E-07	BR-T4-5	9.02E-08
BR-T2-6	9.49E-08	BR-T3-6	9.38E-08	BR-T1-6	1.52E-07	BR-T4-6	5.84E-08
Average	1.04E-07	Average	9.55E-08	Average	1.56E-07	Average	8.26E-08
Standard deviation	1.47E-08	Standard deviation	7.39E-09	Standard deviation	3.28E-08	Standard deviation	1.93E-08

Table 4a: Water absorption coefficient ($kg.m^{-2}.s^{-1/2}$) of concrete

Specimen ID	Water Absorp. Coef.	Specimen ID	Water Absorp. Coef.	Specimen ID	Water Absorp. Coef.	Specimen ID	Water Absorp. Coef.
Temp. = 3°C		Temp. = 12°C		Temp. = 21°C		Temp. = 35°C	
CO-T2-1	0.135	CO-T3-1	0.228	CO-T1-1	0.163	CO-T4-1	0.188
CO-T2-2	0.145	CO-T3-2	0.122	CO-T1-2	0.172	CO-T4-2	0.201
CO-T2-3	0.191	CO-T3-3	0.179	CO-T1-3	0.211	CO-T4-3	0.146
CO-T2-4	0.194	CO-T3-4	0.114	CO-T1-4	0.215	CO-T4-4	0.188
CO-T2-5	0.164	CO-T3-5	0.205	CO-T1-5	0.141	CO-T4-5	0.158
CO-T2-6	0.217	CO-T3-6	0.203	CO-T1-6	0.203	CO-T4-6	0.188
Average	0.174	Average	0.175	Average	0.184	Average	0.178
Standard deviation	3.19E-02	Standard deviation	4.70E-02	Standard deviation	2.96E-02	Standard deviation	2.15E-02

Table 4b: Liquid diffusivity ($m^2.s^{-1}$) of concrete

Specimen ID	Liquid Diffusivity	Specimen ID	Liquid Diffusivity	Specimen ID	Liquid Diffusivity	Specimen ID	Liquid Diffusivity
Temp. = 3°C		Temp. = 12°C		Temp. = 21°C		Temp. = 35°C	
CO-T2-1	1.04E-06	CO-T3-1	2.97E-06	CO-T1-1	1.53E-06	CO-T4-1	2.02E-06
CO-T2-2	1.20E-06	CO-T3-2	8.51E-07	CO-T1-2	1.70E-06	CO-T4-2	2.32E-06
CO-T2-3	2.09E-06	CO-T3-3	1.84E-06	CO-T1-3	2.54E-06	CO-T4-3	1.21E-06
CO-T2-4	2.16E-06	CO-T3-4	7.44E-07	CO-T1-4	2.64E-06	CO-T4-4	2.03E-06
CO-T2-5	1.54E-06	CO-T3-5	2.42E-06	CO-T1-5	1.14E-06	CO-T4-5	1.42E-06
CO-T2-6	2.70E-06	CO-T3-6	2.36E-06	CO-T1-6	2.35E-06	CO-T4-6	2.03E-06
Average	1.79E-06	Average	1.86E-06	Average	1.98E-06	Average	1.84E-06
Standard deviation	6.37E-07	Standard deviation	9.01E-07	Standard deviation	6.12E-07	Standard deviation	4.26E-07

Conclusions

Though further studies are required, a number of conclusions can be made from the results of this study.

(1) Temperature at the surface of the material does have an effect on the water absorption coefficient of some building materials.

(2) There are indications that the extent of the effect of surface temperature on the water absorption coefficient of building materials could be related to the inherent physical or transport properties of the materials.

(3) Lower water absorption coefficient or liquid diffusivity values (i.e., as found in this study, liquid diffusivity in the order of 10^{-10} $m^2.s^{-1}$ or around) could be more susceptible to the effect of surface temperature variation.

(4) Higher water absorption coefficient or liquid diffusivity values (i.e., as found in this study, liquid diffusivity in the order of 10^{-6} $m^2.s^{-1}$ or around) could be less or not at all susceptible to the effect of temperature variation.

(5) Simple water absorption tests done carefully in the laboratory can identify the effect of surface temperature on the water absorption coefficient of building materials.

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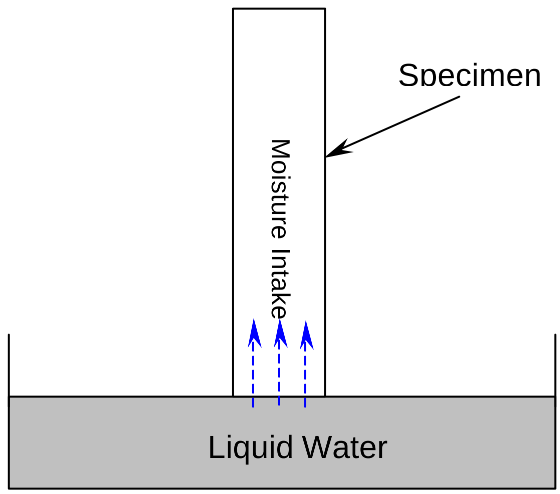


Figure 1: Moisture movement into the material from surface contact with liquid water

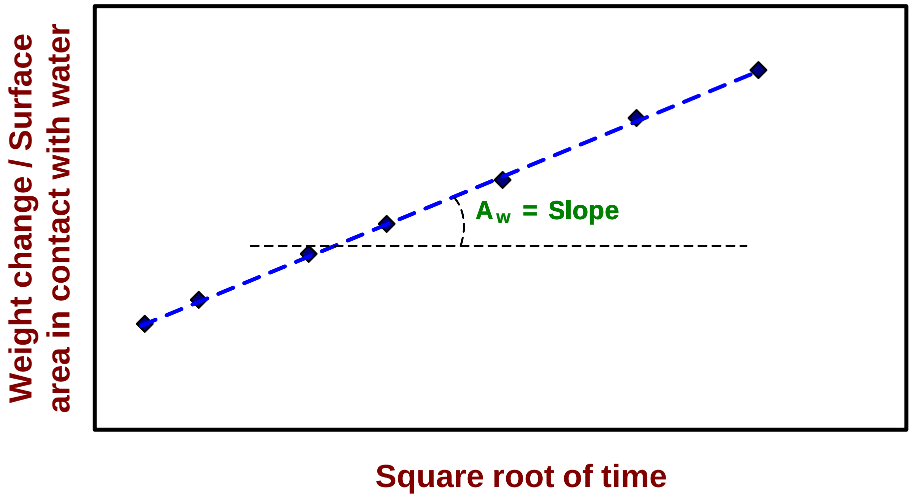


Figure 2: Results from water absorption test

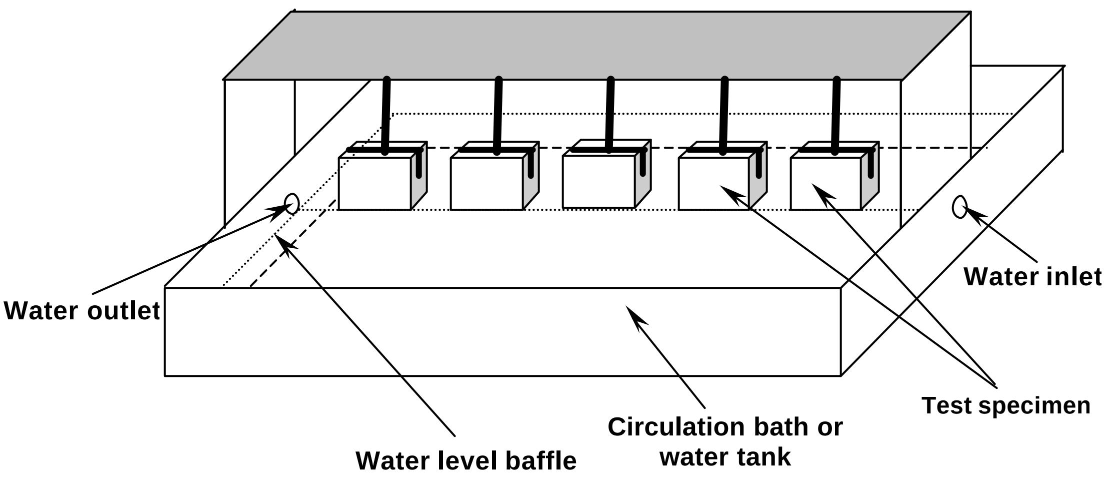


Figure 3a: Schematic diagram of the circulation bath/water tank

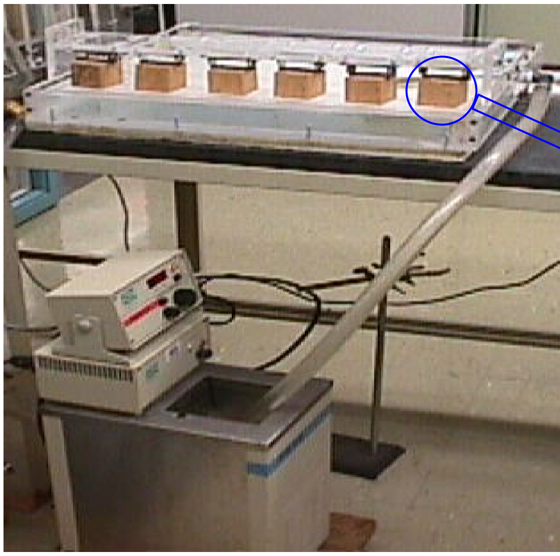


Figure 3b: Circulation bath / water tank

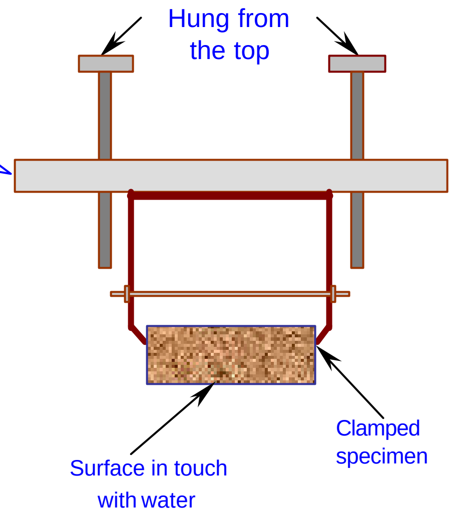


Figure 3c: Specimen holder

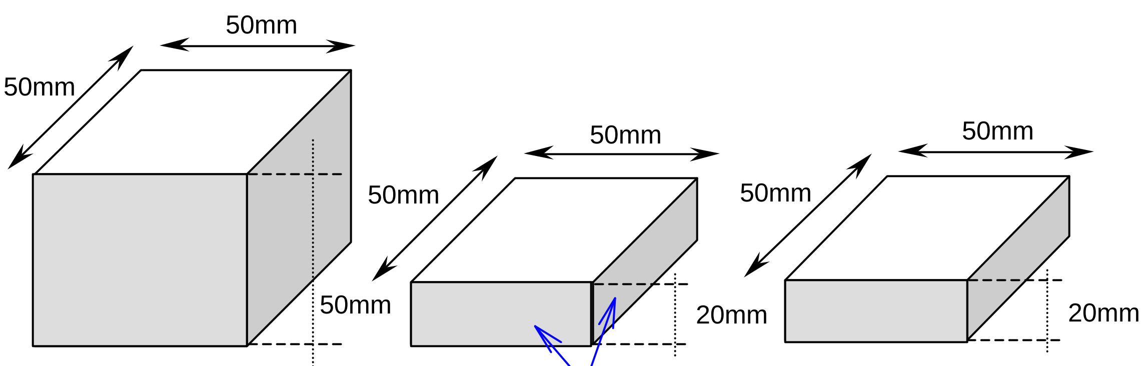
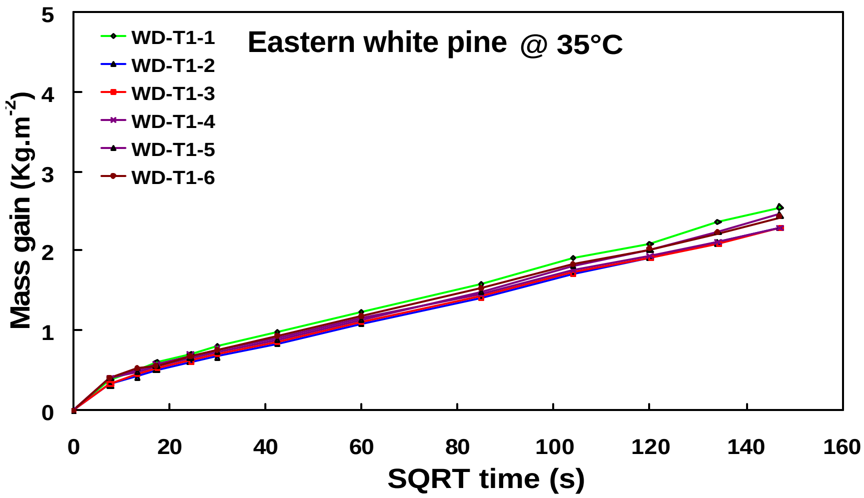
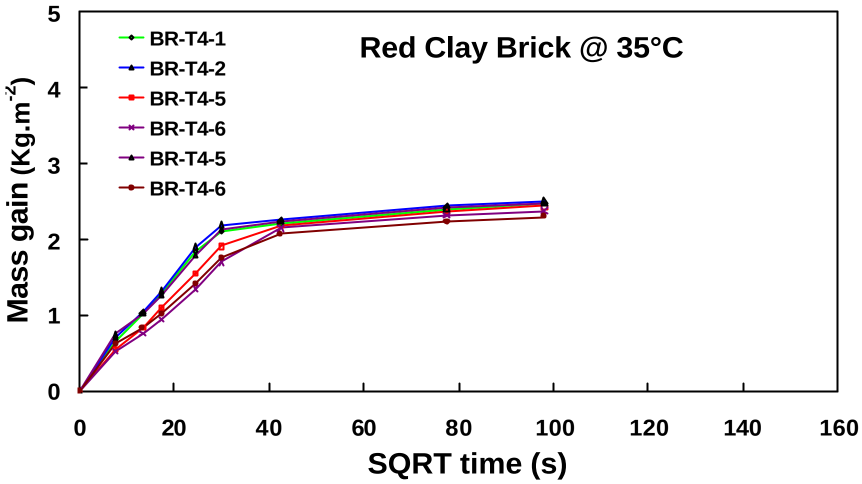


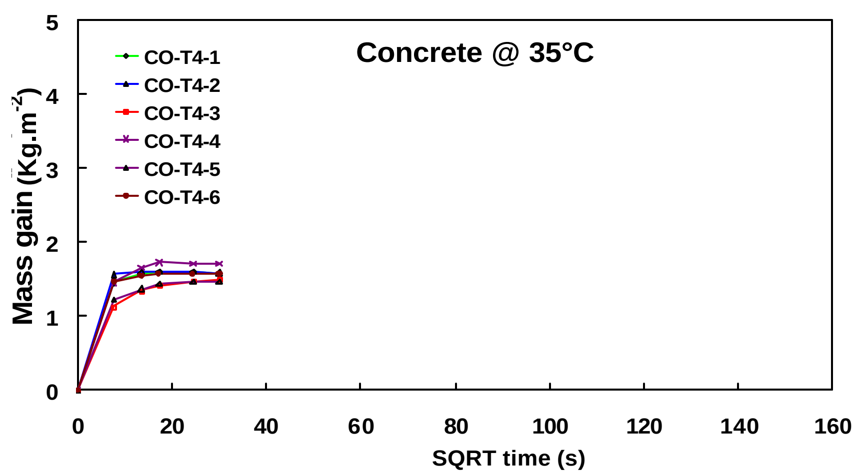
Figure 4: Test specimens



(a)

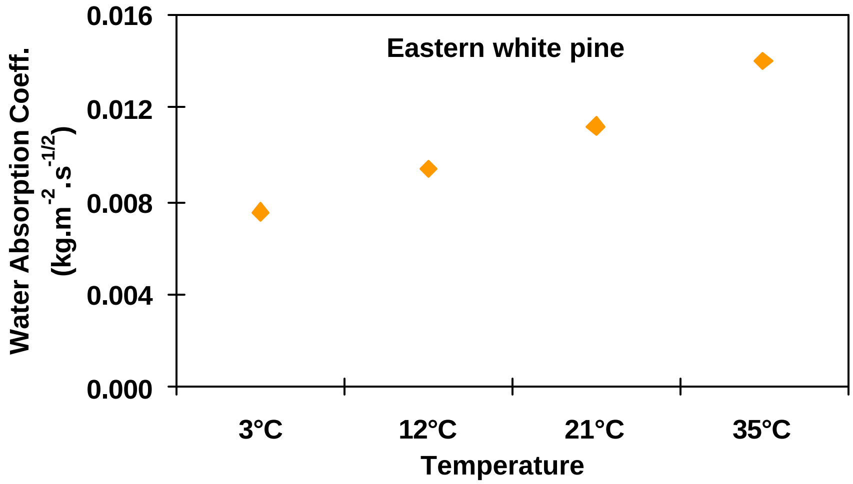


(b)



(c)

Figure 5: Typical water intake (mass gain) versus square root of time plots



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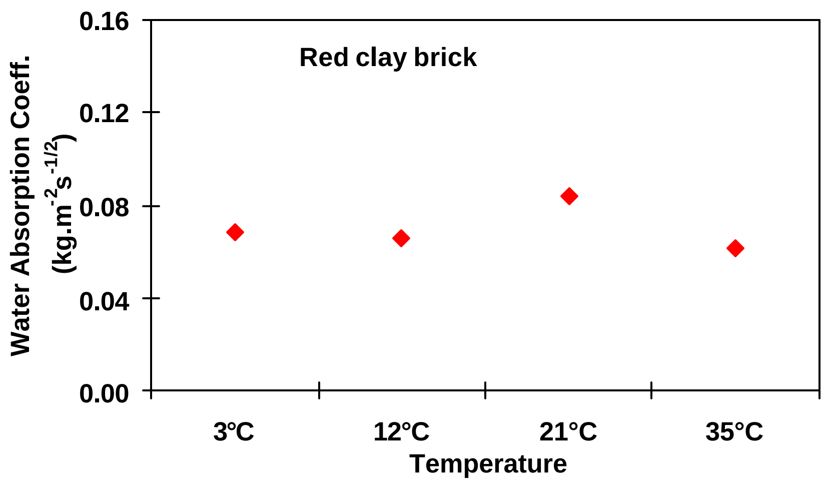

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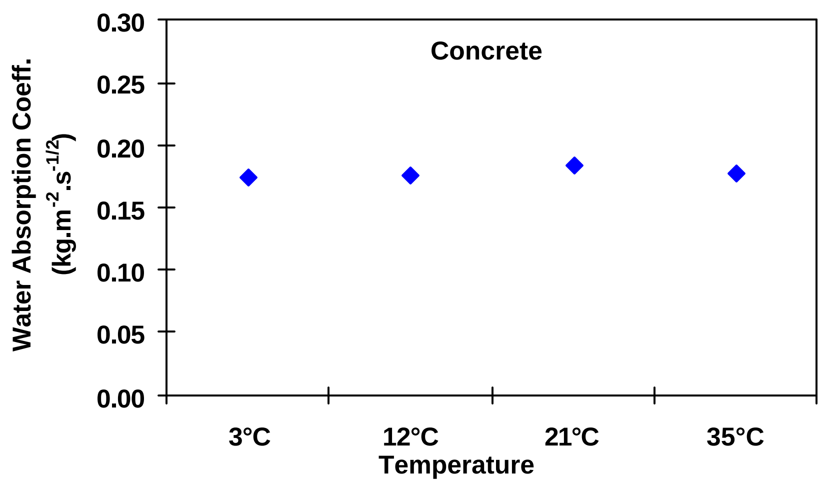

(c)

Figure 6: Water absorption coefficients at various temperatures

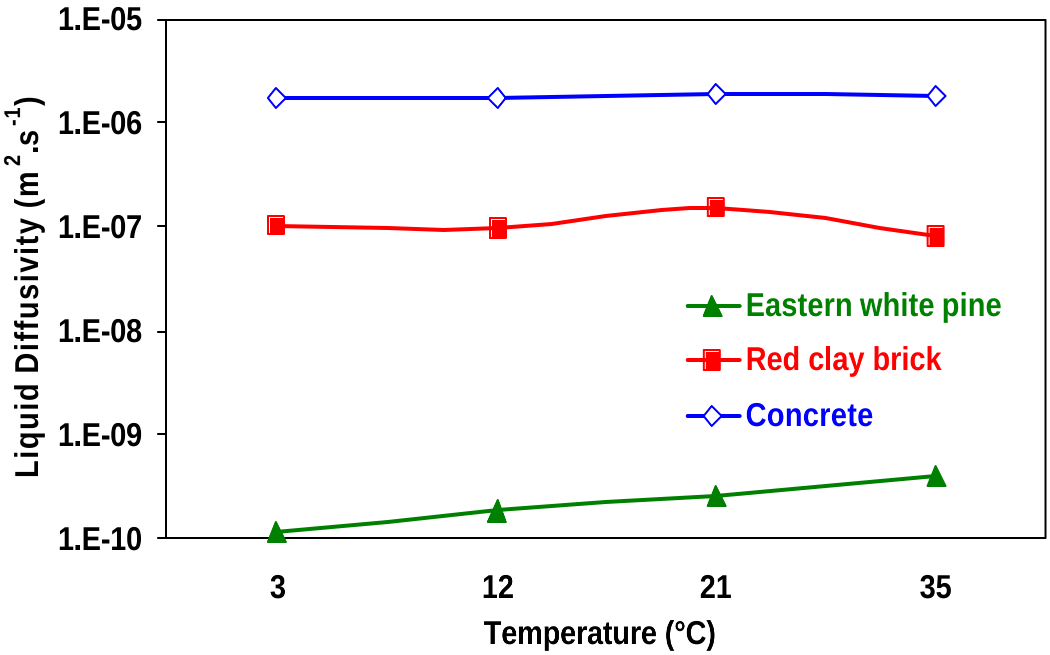

Figure 7: Effects of temperature on liquid diffusivity