

HYGRIC AND THERMAL PROPERTIES OF A GLASS FIBER REINFORCED CEMENT COMPOSITE MATERIAL AFTER THERMAL LOAD

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Abstract

Moisture diffusivity, water vapor diffusion resistance factor, adsorption isotherm, thermal conductivity and specific heat capacity of a glass fiber reinforced cement composite material are studied as functions of thermal load, the loading temperatures being 600⁰C, 800⁰C and 1000⁰C. The decomposition of calcium hydroxide is found to be the most important factor affecting all the studied thermal and hygric properties.

Key words: glass fiber reinforced cement composite, moisture diffusivity, water vapor diffusion coefficient, adsorption isotherm, thermal conductivity, specific heat capacity

1 Introduction

Glass fiber reinforced cement composites (GFC) have found their place as versatile and commercially viable materials for use in construction industry in the beginning of 1970s [1]. Currently, they are frequently applied in wall systems, utilized in form work, pipework, used for surface bonding and rendering, etc. They can also replace asbestos cement products as fire protection materials. More detailed survey of GFC applications can be found e.g. in [1]-[3]. The use of GFC in different technical areas require specific design principles to be employed. However, one condition is common for all applications. A designer should be provided by an exact knowledge of mechanical, thermal and hygric properties of the particular GFC. Otherwise, the assessment of mechanical and hygrothermal performance of GFC in the particular application cannot be done in a serious way.

In this paper, basic hygric and thermal properties of a glass-fiber reinforced cement composite are determined as functions of thermal load.

2 Materials and samples

The measurements were done on a glass fiber reinforced cement composite produced in the laboratories of VUSTAH Brno. The composition of the material was as follows

(calculated among the dry substances only): Portland cement CEM I 52.5 54%, sand 0-1 mm 40%, microsilica 3%, alkali-proof glass fiber 12 mm long 3%. Water in the amount corresponding to the w/c ratio of 0.33 was added to the mixture.

The samples were produced using a successive homogenization procedure. First, sand and microsilica were homogenized in a mixing device, then cement was added and the dry mixture was homogenized again. The dry well homogenized mixture was thoroughly mixed with water. Finally, the glass fibers were added and the mixture shortly mixed again. The prepared mixture was cast into the molds and vibrated. After the time period of 28 days after mixing, the samples were prepared for testing.

In the experimental measurements, four various sample pre-treatment conditions were tested:

- Reference specimen not exposed to any load (denoted as UM in what follows)
- Specimen exposed to a gradual temperature increase up to 600, 800 and 1000°C during two hours, then left for another 2 hours at the final temperature and slowly cooled (denoted as UM-600, UM-800 and UM-1000 according to the loading temperature).

The samples for the measurement of particular thermal and hygric properties had the following dimensions: water absorption coefficient and moisture diffusivity – 50x50x20 mm, water vapor diffusion resistance factor – cylinders with 120 mm diameter and 20 mm height, adsorption isotherms – 30x30x10 mm, thermal conductivity and specific heat capacity – 71x71x71 mm. For every pre-treatment, 3 specimens were used for testing. Before the measurements of all parameters, all specimens were dried in an oven at 110 °C. The measurements on both reference and pre-treated specimens were performed in the laboratory conditions at 24±1 °C and 30-35% relative humidity.

3 Experimental methods

3.1. Basic properties

Among the basic properties, the bulk density, the matrix density and the open porosity were measured. Each sample was dried in a drier to remove majority of the physically bound water. After that the samples were placed into the desiccator with deaired water. During three hours air was evacuated with vacuum pump from the desiccator. The specimen was then kept under water not less than 24 hours.

From the mass of the dry sample m_d , the mass of water saturated sample m_w , and the mass of the immersed water saturated sample m_a , the volume V of the sample was determined from the equation

$$V = \frac{m_w - m_a}{\rho_l}, \quad (1)$$

where ρ_l is the density of water.

The open porosity ψ_0 , the bulk density ρ and the matrix density ρ_{mat} were calculated according to the equations

$$\psi_0 = \frac{m_w - m_d}{V\rho_l} \quad [\text{m}^3\text{m}^{-3}] \quad (2)$$

$$\rho = \frac{m_d}{V} \quad [\text{kgm}^{-3}] \quad (3)$$

$$\rho_{mat} = \frac{m_d}{V(1 - \psi_0)} \quad [\text{kgm}^{-3}] \quad (4)$$

3.2 Water vapor transport properties

Standard cup methods in several configurations were employed in the measurements. In the dry cup method the sealed cup containing silica gel was placed in a controlled climate chamber with 30% relative humidity and weighed periodically. For wet cup method sealed cup containing potassium sulfate creating environment with 97% relative humidity was placed in an environment with the relative humidity of 30%. For the combined wet-dry cup method sealed cup containing silica gel was placed in a controlled climate chamber with 50% relative humidity. In all configurations the steady state values of mass gain or mass loss determined by linear regression for the last five readings were used for the determination of water vapor transport properties.

The water vapor diffusion coefficient D [m^2s^{-1}] was calculated from the measured data according to the equation

$$D = \frac{\Delta m \cdot d \cdot R \cdot T}{S \cdot \tau \cdot M \cdot \Delta p_p}, \quad (5)$$

where Δm the amount of water vapor diffused through the sample [kg], d the sample thickness [m], S the specimen surface [m^2], τ the period of time corresponding to the transport of mass of water vapor Δm [s], Δp_p the difference between partial water vapor pressure in the air under and above specific specimen surface [Pa], R the universal gas constant, M the molar mass of water, T the absolute temperature [K].

The water vapor diffusion permeability δ [s] was calculated as

$$\delta = \frac{\Delta m \cdot d}{S \cdot \tau \cdot \Delta p_p} \quad (6)$$

On the basis of the diffusion coefficient D , the water vapor diffusion resistance factor μ was determined:

$$\mu = \frac{D_a}{D}, \quad (7)$$

where D_a is the diffusion coefficient of water vapor in the air.

3.3 Water transport properties

Standard experimental setup for water sorptivity measurements was used. The specimen was water and vapor-proof insulated on four lateral sides and the face side was immersed 1-2 mm in the water, constant water level in tank was achieved by a Marriott bottle with two capillary tubes. One of them, inside diameter 2 mm, was ducked under the water level, second one, inside diameter 5 mm, was above water level. The automatic balance

allowed recording the increase of mass. The water absorption coefficient A [$\text{kgm}^{-2}\text{s}^{-1/2}$] was then calculated using the formula

$$i = A \cdot \sqrt{t}, \quad (8)$$

where i is the cumulative water absorption [kg/m^2], t is the time from the beginning of the suction experiment. The water absorption coefficient was then employed for the calculation of the apparent moisture diffusivity in the form [4]

$$\kappa_{app} \approx \left(\frac{A}{w_c - w_0} \right)^2, \quad (9)$$

where w_c is the saturated moisture content [kgm^{-3}] and w_0 the initial moisture content [kgm^{-3}].

3.4 Adsorption isotherms

In the measurements of adsorption isotherms the samples were placed into the desiccators with different solutions to simulate different values of relative humidity. The initial state for all the measurements was dry material. The experiment was performed parallel in all desiccators in a common way. The mass of samples was measured in specified periods of time until steady state value of mass was achieved. Then, the moisture content by mass was calculated.

3.5 Thermal conductivity and specific heat capacity

Thermal conductivity and specific heat capacity were measured using the commercial device ISOMET 2104 (Applied Precision, Ltd.). ISOMET 2104 is a multifunctional instrument for measuring thermal conductivity, thermal diffusivity, and volumetric specific heat capacity. It is equipped with various types of optional probes, needle probes are for porous, fibrous or soft materials, and surface probes are suitable for hard materials. The measurement is based on analysis of the temperature response of the analyzed material to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater having a direct thermal contact with the surface of the sample.

4 Experimental results and discussion

Table 1 Basic material parameters

Material	Ψ_0 [%]	w_{sat} [kg m^{-3}]	ρ [kg m^{-3}]	ρ_{mat} [kg m^{-3}]
UM	0.25	247	1872	2491
UM-600	0.35	352	1885	2898
UM-800	0.38	376	1822	2929
UM-1000	0.38	374	1812	2903

Table 1 shows basic parameters of the studied material depending on the loading temperature. The most important change in porosity and saturated water content occurred between the unloaded state and the loading temperature of 600°C where the increase of

porosity was as high as 40%. Later porosity changes were lower than 10%. This is in accordance with the behavior of most Portland cement based composite materials where the most important chemical reaction in the high temperature range is decomposition of calcium hydroxide at about 460-480°C.

Table 2a Water vapor transport properties – dry cup and wet cup methods

Material	97/25-30%			5/25-30%		
	δ [s]	D [m ² s ⁻¹]	μ [-]	δ [s]	D [m ² s ⁻¹]	μ [-]
UM	3.08E-12	4.24E-07	55.2	4.09E-12	5.62E-07	40.9
UM-600	9.15E-12	1.26E-07	18.3	8.53E-12	1.17E-07	19.6
UM-800	2.04E-11	2.81E-06	8.2	1.35E-11	1.85E-06	12.4
UM-1000	3.20E-11	4.39E-06	5.2	1.33E-11	1.82E-06	12.6

Table 2b Water vapor transport properties – dry-wet cup method

Material	5/50%		
	δ [s]	D [m ² /s]	μ [-]
UM	4.51E-12	6.20E-07	37.4
UM-600	1.05E-11	1.45E-06	16.0
UM-800	1.62E-11	2.22E-06	10.4
UM-1000	1.52E-11	2.09E-06	11.0

Tables 2a, b show water vapor transport properties of the studied GFC material. We can see that the values of water vapor diffusion resistance factor decreased very rapidly with the increasing load temperature for all three configurations of the experiment, the most important being the change between the unloaded state and the loading temperature of 600°C. This is in basic agreement with the porosity data. For the loading temperatures of 800°C and higher the wet-cup values of the water vapor diffusion resistance factor were significantly lower than dry-cup data, the dry-wet cup values slightly lower than dry cup data and significantly higher than wet cup data. This is in an agreement with the measurements obtained for many other building materials. A similar behavior was not observed for unloaded specimens and partially even for the specimens subjected to the loading temperature of 600°C. However, for these two cases the values of water vapor diffusion resistance factor were quite high, almost comparable with the sealing materials used in the cup method so that the accuracy of the measurement might be lower.

Tables 3a, b present water transport properties determined for two principal directions of the plate. For unloaded samples, the values of water absorption coefficient and moisture diffusivity in the direction through the plate were significantly lower than in the direction of the plate plane. This is a logical consequence of the higher compactness of the surface layer and of the fiber orientation basically in the plane of the plate surface. However, for thermally loaded samples the differences in water transport parameters measured for different sample orientation were much lower and not systematic. Therefore, it can be

concluded that the decomposition processes at high temperatures were a dominant factor here prevailing the effect of sample orientation.

Table 3a Water transport properties – direction through the plate

Material	A [kg m ⁻² s ^{-1/2}]	κ [m ² s ⁻¹]
UM	0.011	1.95E-09
UM-600	0.114	1.05E-07
UM-800	0.122	1.57E-07
UM-1000	0.229	3.74E-07

Table 3b Water transport properties – direction in the plate plane

Material	A [kg m ⁻² s ^{-1/2}]	κ [m ² s ⁻¹]
UM	0.030	1.85E-08
UM-600	0.102	7.69E-08
UM-800	0.139	3.87E-08
UM-1000	0.269	5.30E-07

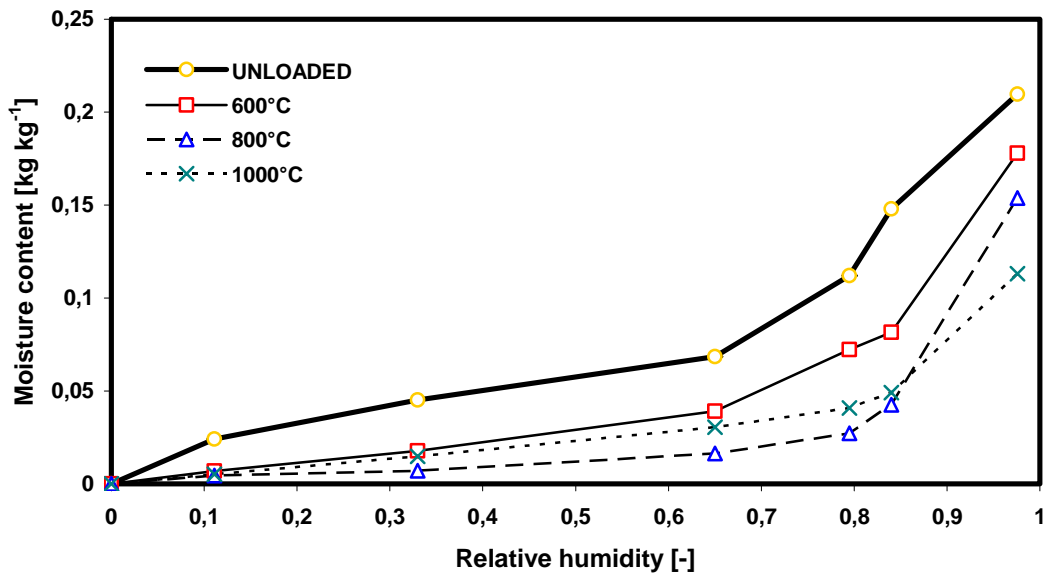


Fig. 1 Adsorption isotherms

Fig. 1 shows that water vapor adsorption capacity of the studied material decreased with increasing loading temperature, the most dramatic decrease being observed between the unloaded state and the loading temperature of 600⁰C again. This behavior is in accordance with the presumed changes of the porous structure after high temperature exposure. The observed increase in porosity (see Table 1) due to the decomposition

reactions was apparently caused by the increase of the amount of larger pores but the amount of smaller pores decreased on that account because of the partial destruction of the cement matrix. As the specific surface (which is the most important parameter for the water vapor adsorption capacity) of smaller pores is much higher than of larger pores, the measured results seem to be quite logical.

Table 4a Thermal properties in dry state

Material	w [kg/kg]	λ (W/mK)	ρc (10^6 J/m ³ K)	a (10^{-6} m ² /s)
UM	0.000	1.226	1.622	0.750
UM-600	0.000	0.615	1.540	0.499
UM-800	0.000	0.559	1.515	0.380
UM-1000	0.000	0.638	1.514	0.422

Table 4b Thermal properties in capillary water saturated state

Material	w [kg/kg]	λ (W/mK)	ρc (10^6 J/m ³ K)	a (10^{-6} m ² /s)
UM	0.11	1.121	1.769	0.633
UM-600	0.18	1.552	1.825	0.851
UM-800	0.20	1.620	1.893	0.857
UM-1000	0.18	1.893	2.007	0.904

Table 4c Thermal properties in wet state

Material	w [kg/kg]	λ (W/mK)	ρc (10^6 J/m ³ K)	a (10^{-6} m ² /s)
UM-600	0.15	1.314	1.738	0.754
UM-800	0.15	1.380	1.803	0.766
UM-1000	0.03	0.879	1.665	0.528
UM-600	0.16	1.525	1.745	0.874
UM-800	0.17	1.500	1.840	0.817
UM-1000	0.17	1.450	1.913	0.794

The results of measurements of thermal parameters showed that thermal conductivity in dry state (see Table 4a) significantly decreased after high temperature loading. This is in qualitative agreement with the increase of porosity due to decomposition reactions in high temperature range leading to an increase of significance of the low thermal conductivity of air in the cement matrix-air system. The principal loading temperature was again 600⁰C where occurred the most dramatic change and thermal conductivity decreased to about one half of the value for unloaded specimens. Further changes were within a 10% range. The volumetric specific heat capacity was affected in much lower range. The changes were only up to 5%, which may reflect the mass loss due to the decomposition reactions. Thermal diffusivity then logically followed the changes of

thermal conductivity which were more remarkable than changes of volumetric specific heat capacity.

Thermal conductivity in capillary water saturated state (see Table 4b) was affected by the presence of water in the most important way, and with the increasing loading temperature it increased by up to 70%. This is in basic accordance with the porosity increase after high temperature loading which has led to the increase of significance of thermal conductivity of water in the three-phase system. A similar effect was also observed for the volumetric specific heat capacity which, however, increased in a lower extent (up to 14%). Therefore, the increase of thermal diffusivity with the loading temperature followed again the changes in thermal conductivity.

Thermal properties in wet state, with moisture content below capillary water saturated state, basically followed similar patterns as the analogous properties in capillary water saturated state (see Table 4c). The presence of water was a dominant factor leading to increase of thermal conductivity and thermal diffusivity.

5 Conclusions

The measurements of hygric and thermal properties of the glass fiber reinforced cement composite after thermal loading in this paper have shown that the decomposition of calcium hydroxide was the principal factor affecting the behavior of thermally loaded specimens. The most important changes in moisture diffusivity, water vapor diffusion resistance factor, adsorption isotherm and thermal conductivity occurred between the unloaded state and the loading temperature of 600⁰C which was safely above the calcium hydroxide decomposition temperature.

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