Absorbency Behaviour of Vertically Positioned Nonwoven Glass Fiber Mats in Case of Two Different Resin Viscosities

Zoltán Gombos,[*1] Veronika Nagy,[1] Eva Košťáková,[2] László Mihály Vas[1]*

Summary: The resin absorbency of vertically positioned chopped strand mat samples was examined as a function of time with a microtensiometer type Krüss K12. With the help of a theoretical model the results of this measurement can be interpreted and evaluated. The samples of different structure (mats bonded with powder or emulsion) were compared and the impact of resin viscosity was studied and conclusions were drawn about the pore and capillary sizes in the mats. The results verified the applicability of the method and revealed the typical pore characteristics of mats and this way estimations can be made on the properties of composites.

Keywords: absorption; glass fiber mat; Lukas–Washburn equation; resins; viscosity

Introduction

Composites are applied in a wider and wider range as engineering materials. They are made up of reinforcing material of high strength (usually in a fibrous form) and the embedding matrix of high toughness (usually resin). The most commonly used and cheapest reinforcement is still glass fiber or glass fiber mat (GFM), which is usually processed with unsaturated polyester resin. The adhesion between the matrix and the reinforcement determines the mechanical properties of composites mostly; hence the resin impregnation of glass fibers is a key factor when producing this kind of composite structures. Hence the absorption properties of the applied product has to be known in order to be able to determine the mechanical properties such as tensile and bending strength, as well as modulus of the final product. On the other hand, porosity and absorbency of fibrous structures has been studied for a long time, mostly in case of textile materials. [1–4] Hence the methods for testing absorbency are already known but have not been applied for studying resin absorbency. [5]

This paper aims to reveal that this method of microtensiometry, basically used for textile testing, can be applied for the fibrous reinforcement of composites. The other objective is to compare the effect of two different resin viscosities.

Theoretical Background

The absorption process in a fibrous structure can be described by the Lukas–Washburn equation, the general formula of which for a monocapillary system is [6,7]:

$$\frac{dh}{dt} = \dot{h} = \frac{b}{h} - a \tag{1}$$

where h is the height of the meniscus (which is in correlation with the absorbed weight of resin), t denotes time and a and b are constants defined in the following expressions:

$$a = \frac{r^2 \rho g}{8\eta} \quad b = \frac{r\gamma \cos\theta}{4\eta} \tag{2}$$

where r is the radius of pore or capillary, g is gravitational acceleration ($g = 9.81$ m/s^2), γ is the surface tension of resin, ρ and η are the density and viscosity of the resin,

[1] Department of Polymer Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3, H-1111 Budapest, Hungary
Fax: (+36) 1 4631527
E-mail: gombos@pt.bme.hu
[2] Department of Nonwovens, Technical University of Liberec, Hálkova 6, 46117 Liberec, Czech Republic

respectively while θ is the contact angle between the resin and the GFM.

If the mass (m) of the absorbed resin is measured, it is proportional to meniscus height:

$$m = hA\rho \tag{3}$$

where A is the approximate free cross section area of the sample. In our case the absorbed mass was measured as a function of time. Then Eq. (1) can be transformed into the following formula:

$$\frac{dm}{dt} = \dot{m} = \frac{b_m}{m} - a_m \tag{4}$$

$$b_m = bA^2\rho^2 \quad a_m = aA\rho \tag{5}$$

The absorption process in the initial phase can be described by the following simplified Lukas–Washburn equation:

$$\frac{dm}{dt} = \frac{b_m}{m} \tag{6}$$

In case of zero initial condition, the solution of Eq. (6) is as follows:

$$m(t) = \sqrt{2b_m t} = k_{0m}\sqrt{t} \tag{7}$$

where $k_{0m}[g/\sqrt{s}]$ is a coefficient of the dynamics of resin absorption in the initial state of the process and corresponds to the steepness of the curve (see Fig. 1).[8]

This means that the absorbed mass of resin as a function of the square root of time is linear but only in the initial part. Afterwards the curve can be described with the following equation:

$$m(t) = m_\infty \left[1 - e^{-\left(\frac{2a_m \cdot t}{m_\infty}\right)^p}\right]^q \tag{8}$$

In this equation m_∞ is the maximum absorbed mass of resin in equilibrium (see also Fig. 1). Eq. (8) provides a good approximation in the sense of the asymptotic behavior as well if:

$$p \cdot q = \frac{1}{2} \tag{9}$$

while

$$\begin{array}{ll} m(t) \sim \sqrt{2\mathrm{b_m}t}, & t \to 0 \\ m(t) \to m_\infty, & t \to \infty \end{array} \tag{10}$$

The above mentioned equations are only valid in case of one single capillary (monocapillary). However, in reality there are always more capillaries of different sizes, i.e. a multicapillary system should be taken into consideration. In this case the system is stochastic because the radii of capillaries and the quantities of resin in one capillary are stochastic variables. If the solution of Eq. (1) is extended for statistical multicapillary systems where the following formula is obtained for the mean capillary pore size:

$$r_{P,hydr} \approx \left[\frac{k_{0m} 2\sqrt{2\eta\gamma\cos\theta}}{m_\infty \rho g\left(1 + \frac{15}{8}V_r^2\right)}\right]^{2/3} \tag{11}$$

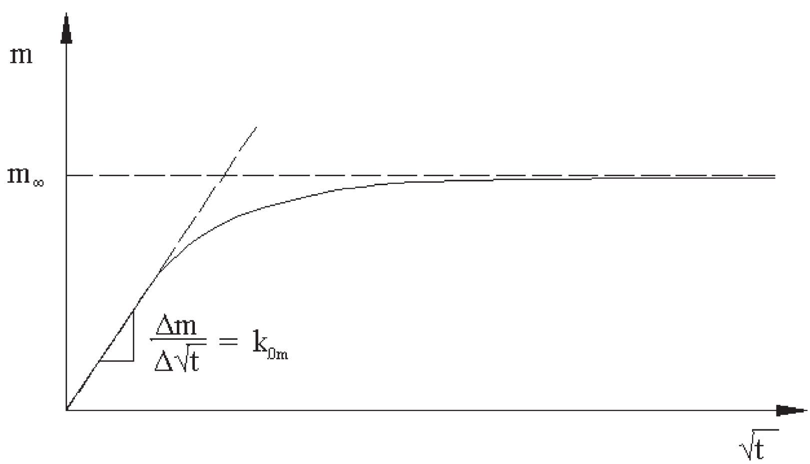

Figure 1.
The absorbed mass of resin as a function of the square root of time.

where $r_{p,hydr}$ is hydraulic pore radius, and V_r is the variation coefficient of the hydraulic pore (capillary) radius.

Based on a statistical fiber mat model [9] the expected value of the geometrical pore radius can be calculated as an upper estimation as follows:

$$r_{P,geo} \leq \frac{1}{2Kl} \tag{12}$$

$$K = \frac{Q_\infty}{q_0 nl} \tag{13}$$

where K is the average number of fiber bundle centers in a designated area, l is the mean length of the fiber bundles, Q_∞ is the mean surface mass of the mat, q_0 is the linear density of fibers, n is the mean number of fibers in the fiber bundle.

Making the mean hydraulic pore radius equal with the mean geometrical one the variation coefficient of pore radius (V_r) can be estimated.

Materials and Method

The GFMs used in the experiments are denoted and classified. The main properties of these GFMs are the same: the nominal fiber diameter is 12 μm, the linear density of the rovings is 30 tex, the length of the chopped roving is around 50 mm, the surface mass of the mat is 450 g/m^2 and the density of glass is 2.6 g/cm^3. The difference among them lies in the bonding agent (powder-P and emulsion-E) and the producer (Johns Manville-1, Scottbader-2, Ahlstrom-3). Two types of unsaturated polyester (UP) resins of different viscosities measured according to standard Brookfield LVF 2/12 at 23 °C at 20 1/s shear rate were used: *VIAPAL VUP 4627 BEMT/56* ($\rho_1 = 1060$ kg/m^3; $\eta_1 = 0.45$ Pas; $\gamma_1 = 0.035$ N/m; $\cos\theta_1 = 0.95$) and *ChS Polyester Lamit109* ($\rho_2 = 1140$ kg/m^3; $\eta_2 = 0.30$ Pas; $\gamma_2 = 0.033$ N/m; $\cos\theta_2 = 0.95$).

A relatively small sample (30 mm × 40 mm) was hung vertically in a micro-tensiometer type Krüss K12. The principle of this measurement is the following (see Fig. 2): the sample of GFM is hung vertically in the microtensiometer, the sensitivity of which is 0.0001 g. A beaker filled with liquid (in this case polyester

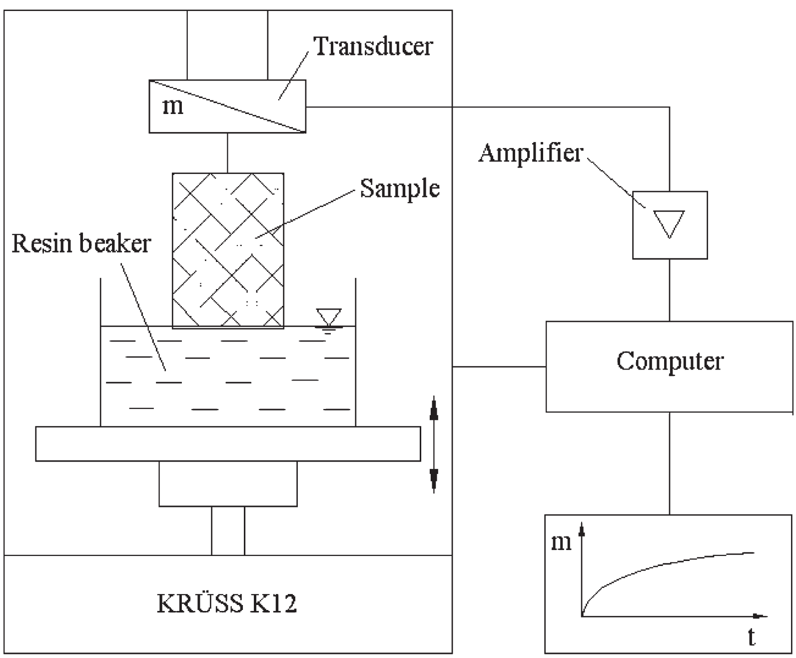

Figure 2.
Schematic arrangement of measurement (device KRÜSS K12).

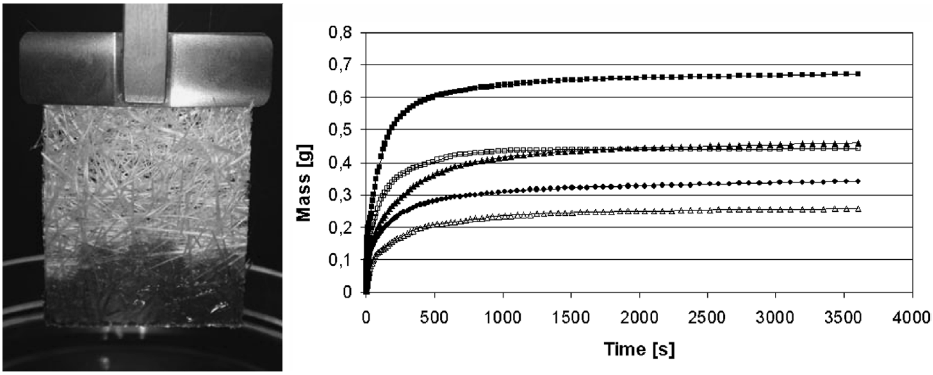

Figure 3.
Lower viscosity case: sample measured (left); and the absorbed resin mass as a function of time (right) ■ = GFM1P, ▲ = GFM2P, ● = GFM3P, □ = GFM1E, △ = GFM2E.

resin) approaches the vertical sample slowly and when the first change of mass is registered, the beaker stops and the measurement of weight increase starts in this position. The schematic arrangement of the measurement is shown in Fig. 2.

Results and Discussion

The samples that were hung in the resin of lower viscosity obviously absorbed more resin, hence the height of absorbed resin was also higher in this case as revealed by Figs. 3 and 4, the images of which were taken after 1 hour of measurement. Figs. 3 and 4 also show the absorbed resin mass as a function of time for both kinds of resin.

The comparison of these two graphs reveals the difference between the two kinds of resin, i.e. the process of absorption in case of the resin of lower viscosity is less dynamic, meaning that the value of k_{0m} is smaller. On the other hand, if the resin has lower viscosity, the GFM sample absorbs higher amount of it, as expected, but the front of flow is not so homogenous in this case.

Variation coefficient of hydraulic pore radius, V_r was of lower value (revealed in Fig. 5 by the steepness of lines) if the resin had lower viscosity. This means that the distribution of capillary radii is more uniform in this case. The value of V_r is obtained

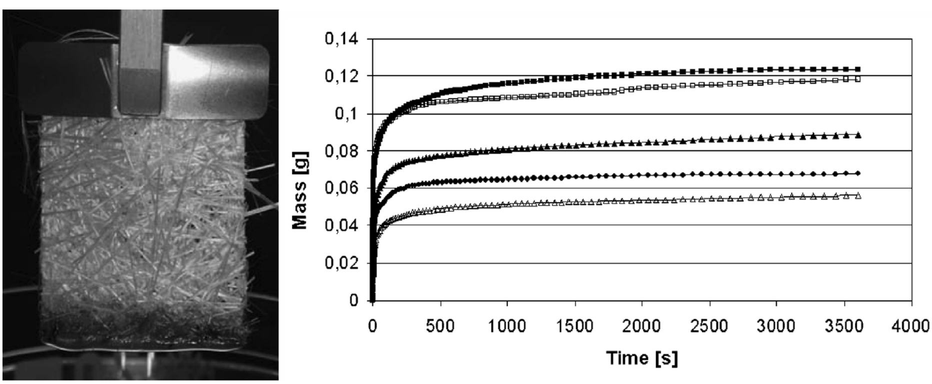

Figure 4.
Higher viscosity case: sample measured (left); and the absorbed resin mass as a function of time (right) ■ = GFM1P, ▲ = GFM2P, ● = GFM3P, □ = GFM1E, △ = GFM2E.

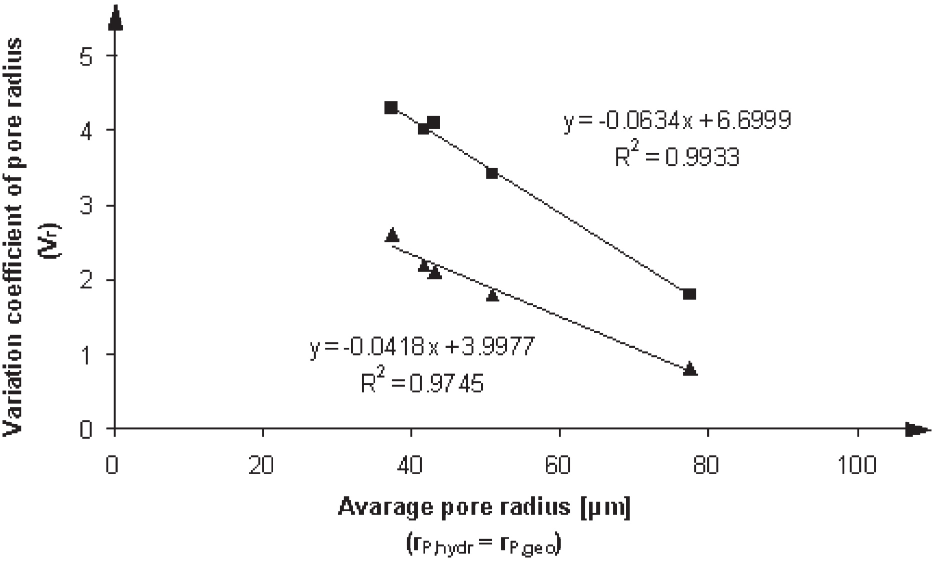

Figure 5.
Variation coefficient of pore radius V_r as a function of the average pore radius in case of $r_{P,hydr} = r_{P,geo}$; condition of the absorption process: T = 23 °C; ■ = unsaturated polyester resin with higher viscosity *VIAPAL VUP 4627 BEMT/56*, ▲ = unsaturated polyester resin with lower viscosity *ChS Polyester Lamit109*.

if the mean geometrical pore size measured and determined on the basis of a statistical fiber mat model were considered to be equal to the hydraulic pore size, and the mat properties [9] are substituted into Eq. (10). It is visible in Fig. 5 that the variation coefficient of pore radius (V_r) decreases with the increase of the average pore radius.

Conclusion

The conclusions that the resin of lower viscosity is absorbed in greater amount than that of higher viscosity but more slowly can be drawn from these measurements. If resin viscosity is lower, the calculated variation coefficient of pore radius (V_r) was also found to be of lower value. Another conclusion is that the variation coefficient (V_r) of differently bonded GFMs versus the mean pore radius relationship can be estimated by a linear trend line for both examined resin viscosities. This process using a microtensiometer turned out to be applicable in examining the interaction of fiber and resin and should be studied with other fiber types due to the simplicity of the method.

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