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Water and Air Permeability of Wet Sheets

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Abstract

The water and air permeabilities of wet sheets as functions of sheet porosity and solids were experimentally studied. The purpose was to identify the basic trends and possible correlations between water and air permeability.

Air permeability of wet sheets was found to be not unique and not a monotonic function of porosity. Air permeability may significantly vary at the same porosity depending on the compressive history of the sheet. Water permeability was unique and a monotonic function of porosity. The sheets at different initial solids had similar water permeabilities at equal porosities. Since water and air permeability determine performance in the pressing and drying section, the information obtained has practical implications for optimal design of pressing and drying sections of paper machines.

Experimental results for water and air permeability measurements as functions of sheet porosity were compared. In general, a discrepancy between water and air permeability was observed. However, there were regions of the correlation that indicate similarity of porous structure for water and air flow.

It appeared that air permeability of the dry sheets and water permeability of the wet sheets at different porosity values approximately fall on the same curve. This could be used for predicting a water permeability curve based on air permeability data.

Introduction

Permeabilities of the wet sheet to water and air flow are parameters which to a great extent determine water removal in the pressing and drying section of a paper machine. Permeability to water flow (water permeability) impacts water removal in the pressing section, especially in a flow-controlled nip. Permeability to air flow (air permeability) is close to vapor permeability because the dynamic viscosities of the vapor and air are close. Sheet permeability determines vapor flow rate during drying. Therefore, air permeability may be a factor in evaporative water removal occurring in the dryer section of a paper machine.

Information about dependence of permeability on sheet porosity and solids may be critical for selecting optimal configuration of pressing and drying section. As both permeabilities are influenced by a degree of sheet openness, the question about their possible correlation arises.

Permeability to air flow (air permeability) can be measured by standard laboratory equipment. The test is rapid. Any moisture loss during the test and its possible effect on the air permeability can be easily accounted for.

To measure permeability to water flow (water permeability), specially designed equipment must be used. In order to obtain reproducible measurements, the sheet is brought to a saturated state prior to the test. After application of the driving pressure, there is a waiting period during which steady-state flow is established. The test is time consuming. Hence, the potential benefits of using air permeability for predicting water permeability are unquestionable.

Permeability is determined by the sheet compression. In general, a more compressed sheet has smaller pores and more tortuous paths for the fluid flow and is less permeable. Water permeability measurements are conducted at different compressive loads, which change the initial state of the sheet prior to the test. Additionally, the sheet is saturated before the test. Hence, the chances to observe the effect of the compressive history (applied load value and load rate) before the test on the sheet porosity and permeability measured during the test are slim.

Testing of the sheets at various ingoing solids may result in slightly different sheet thickness at the same load applied to the sheet during a permeability test. Minor effects of the sheet solids, with a slight increase in water permeability within the range of solids 30-50% at higher ingoing solids, was observed. In steady-state water permeability measurements, the sheets subjected to higher compression showed lower porosity and lower permeability [3, 10].

In air permeability measurements, the state of the sheet is not likely to be affected by the test. Some minor changes in the sheet solids can be taken into account. Thus, the effect of compression history on the permeability can be examined. It is not completely clear as to how porosity of the sheet determined as a void volume changes with increased sheet compression. It is obvious, however, that the way in which the sheet is compressed affects changes of porosity and permeability.

If the sheet is subjected to low and moderate compression and compression is accompanied by significant water removal, an increase of the sheet compression may result in higher sheet porosity and higher permeability. On the other hand, rapid compression at high loads, which is not coupled with significant water removal, may result in a decrease of sheet porosity and air permeability.

Comparison between the water and air permeability as functions of sheet porosity would allow better understanding of the link between the water and air permeabilities.

Experimental

The water and air permeabilities of wet sheets as functions of sheet porosity and solids were experimentally studied. For the water permeability test, no change of compressive mode was made. Some sheets were tested at different ingoing solids. For the air permeability test, the sheets made from various furnishes were brought to different porosity and solids by applying different compressive loads.

Two extreme pressing conditions were employed to bring sheets to various solids for air permeability measurements. Under one set of pressing conditions, which was termed hard pressing, the sheet was pressed at high pressures. Under another set of pressing conditions, which was termed soft pressing, low applied pressures were used.

Air permeability was measured by Gurley Densometer, which indicates the time required for 100 cm^3 of air to pass through the sheet. Water permeability measurements were conducted on the Carver press [3]. The sheets were brought to different porosity levels by applying different compressive loads during the test.

Calculation of permeability and porosity

Permeability

According to Darcy's equation, permeability

$$K = \mu \; U L / \Delta P, \qquad (1)$$

where

K is permeability;
μ is dynamic viscosity of the fluid, kg/(m s);
U is flow velocity;
L is sheet thickness;
ΔP is the pressure differential.

Since Darcy's equation only accounts for viscous resistance and neglects inertial resistance, the above approach for the calculation of sheet permeability is valid only when the inertial resistance is low, that is, at low Reynolds numbers ($Re \approx < 1$ according to [5,6]). Validity of Darcy's equation can be verified experimentally by plotting driving pressure as a function of flow velocity. Linearity of this function indicates applicability of Darcy's equation.

Reynolds number is defined as follows:

$$Re = \rho \, U / (\mu \, S_V), \qquad (2)$$

where

ρ is the density of fluid, kg/m^3;
S_V is surface area of fibers per unit volume of the paper material, m^2/m^3.

To calculate Re from (2) it is necessary to know S_V. However, S_v can be found only after experimentally determining the sheet permeability and making some assumptions with regard to the Kozeny factor, k.

Use of the Kozeny-Carman Equation for Calculation of Permeability

Among the different permeability models that correlate the permeability of a porous medium with parameters of its porous structure, the Kozeny-Carman approach was found to be particularly popular in permeability studies of paper sheets. It is often called the "hydraulic radius theory".

The Kozeny-Carman equation has the form:

$$K = \varepsilon^3 / [k\, S_v{}^2(1 - \varepsilon)^2], \qquad (3)$$

where

ε is flow porosity;
k is the Kozeny factor.

The Kozeny factor is used to account for the pore size distribution, pore branching, pore interconnections, pore shape, particle shape, pore constrictions, tortuosity of porous structure, etc. Carman recommended $k = 5$. However, it was found that it can be substantially higher [7, 8]. It is frequently claimed that anomalously high sample tortuosities may be the main reason for the disagreement between results predicted by the Kozeny-Carman equation and experimental results.

The Kozeny factor can be experimentally determined from permeability measurements of the flow through a porous medium that has known geometry and orientation of the particles. Then S_v can be calculated and Equation (3) can be solved for k.

When using the Kozeny-Carman equation for water and air flow through the wet paper sheets, some differences between the water and air permeabilities are to be taken into account.

Water Permeability

It is well known that the wet paper sheet contains free water that is basically located in the interfiber volume and water that is located in intrafiber wall volume. Free water does not obstruct water flow. Only the fibers and intrafiber water obstruct water flow. If there is no intrafiber water, then only the fibers obstruct the water flow. As in the wet sheet, the water acts as both the obstructing medium and the flowing medium; two porosities must be defined: volume porosity and flow porosity.

Volume porosity, ε_v, determines part of the volume occupied by the water and air only:

$\varepsilon_v = 1 - m_f / (\rho_f A L)$,

where

m_f is the mass of dry fibers;
ρ_f is the density of the wood fibers, which is usually assumed to be 1.55 g/cm^3.

Introducing apparent density of the wet sheet,

$c = m_f / (A L)$,

and specific volume of the dry fibers

$v_f = 1/\rho_f$,

volume porosity may be written down as follows:

$\varepsilon_v = 1 - c\, v_f$.

Similarly, flow porosity can be presented

$$\varepsilon = 1 - c\, v \qquad (4)$$

where

v is specific volume of obstructing volume consisting of the dry fibers and intrafiber water.

Replacing ε in (3) with ε from (4) yields the following expression for the Kozeny-Carman equation:

$$(K\, c^2)^{1/3} = (k\, S^2)^{-1/3} (1 - v\, c), \qquad (5)$$

where

$S = S_v\, v$

is the specific surface area per unit mass exposed to water flow, m^2/kg.

Expression (5) and K and c measured from a water permeability test are used for the calculation of specific surface and specific volume. The determination requires that the quantity $k\,S^2$ be assumed constant. Using a linear plot

$(K\,c^2)^{1/3} = a - b*c$

where

a and b are coefficients of regression, the values of v and S can be calculated as:

$$v = b/a; \quad S = (k\,a^3)^{-1/2}.$$

After this, flow porosity can be calculated using Equation (4). To obtain the linear regression, permeability must be measured at two different sheet thicknesses, that is, compression loads. The Kozeny factor is usually assumed to be $k = 5.55$ for paper mats.

Air Permeability

For the air flow through the sheet, the obstructing volume is the sum of the water volume and the fiber volume. It is assumed that no trapped air is in the sheet. Therefore, volume and flow porosities are identical and are given by

$\varepsilon_a = 1 - (m_f/\rho_f + m_w/\rho_w)/(A\,L)$,

where

ρ_w is density of water;
m_w is mass of water.

Using a concept of apparent density for the air flow

$c_a = (m_f + m_w)/(A\,L)$,

the expression for porosity to the air flow can be written down in the form similar to that for water flow

$\varepsilon_a = 1 - c_a\,v_a$

The specific volume of obstructing water and fibers, v_a is:

$v_a = (m_f/\rho_f + m_w/\rho_w)/(m_f + m_w) = s/\rho_f + (1 - s)/\rho_w$,

where

$s = m_f/(m_f + m_w)$ is the solids.

As opposed to water permeability test, v_a can be calculated at a known solids prior to the permeability test. Specific volume decreases with solids. Once air permeability is measured, the specific surface can be calculated directly from the Kozeny-Carman equation,

$$K_a = \varepsilon^3 v_a^2 / [k S_a^2 (1 - \varepsilon)^2]$$

if the Kozeny factor, k, is assumed to be known.

Results and discussion

Air Permeability

1. Air permeability was not a unique function of porosity (see Figure 1). At a given level of sheet solids, air permeability was significantly affected by pressing history of the sheet. Over the wide range of the sheet solids, hard pressing resulted in significantly lower permeabilities as compared with the soft pressing. The ratio of air permeability at soft pressing to that at hard pressing may be 5-10 and more.

2. Air permeability was not a monotonic function of porosity and may increase or decrease with increased solids depending on pressing history and sheet. It appeared that at low solids levels when compression produced significant water removal, an increase in sheet porosity resulted in an increase in air permeability. Further increase in sheet compression resulted in low water removal and led to a decrease of the air permeability.

3. In the case of hard pressing, air permeability changed insignificantly within the range of 20-40% solids and substantially dropped in the solids range of 40-75%. At the solids level above 75%, a slight decrease of permeability or no change was observed with increased solids. In the case of soft pressing, air permeability increased in the range of 20 to 35-40% solids and then decreased slightly.

4. An increase in the solids, in general, resulted in an increase in porosity with both hard and soft pressing (see Figure 2). However, in both cases of compression history there was some region of the solids where an increase of the sheet solids produced almost no increase and sometimes even a reduction of sheet porosity. Further increase of the solids after this point resulted in a much lower increase of the sheet porosity.

This "discontinuity" in porosity as a function of solids most likely signifies that the water is removed from larger pores. Further compression brings about some sheet compression but minimum water removal, which produces a decrease in sheet porosity and permeability.

If the sheets had the same porosities and apparent densities, then it was likely that air permeabilities would also be close even if the sheets were pressed differently (see Figure 2). Closeness of the sheets porosities and apparent densities, however, did not guarantee that air permeabilities would be the same (Figure 2). The discrepancy was more likely to occur for sheets of higher basis weights when, at the same porosity, more tortuous paths for air flow could exist. Thus, it can be stated that an equality of wet sheet porosities and apparent densities is a necessary but insufficient condition for their air permeabilities to be equal.

Water Permeability

Water permeability was found to be a monotonic function of sheet flow porosity. An example is given in Figure 3 for the unbleached sheets used for air permeability testing (see Figure 1). Flow porosity was determined as a fraction of volume available to water flow. A decrease of sheet porosity to water flow induced a significant decrease in the sheet water permeability. The sheets with different initial solids had similar values of permeability at the same porosity. An increase of the basis weight resulted in a decrease of permeability, which was expected.

Due to creep of the wet paper during compression, particularly in its initial phase, and permeability decay with time, measurement of water permeability was not a trivial task.

Comparison of Air and Water Permeability

Plots of water and air permeability for hard and soft pressing as functions of porosity are shown in Figure 4 for the case 450 mL CSF, 100 gsm. There is a significant discrepancy between the water and air permeability. At the same time, water and air permeabilities approach each other at porosities of about 0.5-0.6 and sometimes at porosities of about 0.2. Closeness between water permeability at low compressive loads and sheet air permeability at high solids was found to exist. On the other hand, sheet water permeability at high compressive loads tended to approach air permeability at low levels of solids. Similar trends were also observed for other cases.

The Kozeny-Carman equation

$$K = \varepsilon^3 / [k\, S_v{}^2 (1 - \varepsilon)^2]\,, \qquad (3)$$

shows that if permeability is plotted as a function of $E = \varepsilon^3 / [(1 - \varepsilon)^2]$ the slope of the straight line is $1 / (k\, S_v{}^2)$ and should be positive. The plot is shown in Figure 5. It is similar to that in Figure 4 because E, which may be termed the porosity factor, increases with the increase of ε. The slope of the air permeability curves at the porosities above 0.35 (or E=0.1) for the case of hard pressing and at porosities above 0.45 (or E=0.3) for the case of soft pressing is negative. It means that Kozeny-Carman equation in form (3) is not applicable for correlating permeability and porosity. Other functions used sometimes for correlating permeability and porosity [4] are also not applicable as permeability is an increasing function of porosity in all equations proposed.

Reduction of permeability with increased porosity is induced by more tortuous porous structure formed in the sheet pressed to high solids.

An important observation is that air permeabilities of the dry sheets at different porosity factors (thicknesses) appear to fall approximately on the same curve as the water permeability curve. The curves for different cases are shown in Figure 6. Closeness of the air permeability function of the dry sheets and the water permeability function of the wet sheets prompts a simple approach for evaluating water permeability function based on the air permeability function for the sheet of given furnish and basis weight.

First, the air permeability function of dried sheet is plotted as a function of porosity. To construct this dependence the sheet must be pressed at different loads and dried. Second, the resultant function is extended for plotting water permeability as a function of porosity. Third, the obtained function should be replotted for predicting water permeability as a function of the sheet thickness (apparent density) because, as follows from Equation (4), porosity depends on specific volume that is not known. One of the ways to solve this issue is to set specific volume v and determine specific surface S from Equation (5). As the slope $dK/dE = v^2 / (k S_v^2)$ is known from the plot K(E), specific volume is specified after each iteration until set and specified specific volume match.

It should be noted that in the suggested procedure water permeability is evaluated by extrapolating the air permeability curve, which may negatively affect the accuracy of the estimate. There are indications that calculated and measured water permeability curves match better for the sheets of low basis weight and lower specific volume.

Conclusions

Air permeability of a wet sheet was found to be not unique and not a monotonic function of porosity. Air permeability may significantly vary at the same porosity depending on the compressive history of the sheet. Reduction of permeability with an increase in sheet porosity at high solids evidences that the Kozeny-Carman equation is not applicable for correlating permeability and porosity.

Water permeability was unique and a monotonic function of porosity. The sheets at different initial solids had similar permeabilities at equal flow porosities.

Comparison of experimental results for water and air permeability measurements indicated significant discrepancy between water and air permeability. However, there were regions of the correlation that indicate similarity of porous structure for water and air flow.

Air permeabilities of the dry sheets at different porosities (thicknesses) appear to fall on the same curve as the water permeability data. Closeness of the air permeability function of the dry sheets and the water permeability function of the wet sheets prompts a simple approach for evaluating the water permeability function based on the air permeability function for a sheet of given furnish and basis weight. This result is of great importance as it avoids the time-consuming water permeability test, which requires specially designed testing equipment.

Since water and air permeability determine performance in the pressing and drying section, the information obtained has practical implications for selecting optimal strategies of water removal in pressing and drying sections of paper machines.

Figure 1. Effect of Pressing Mode on the Air Permeability as a Function of Solids. Freeness - 450, 540, and 560 mL CSF. Basis Weight - 100 and 75 gsm.

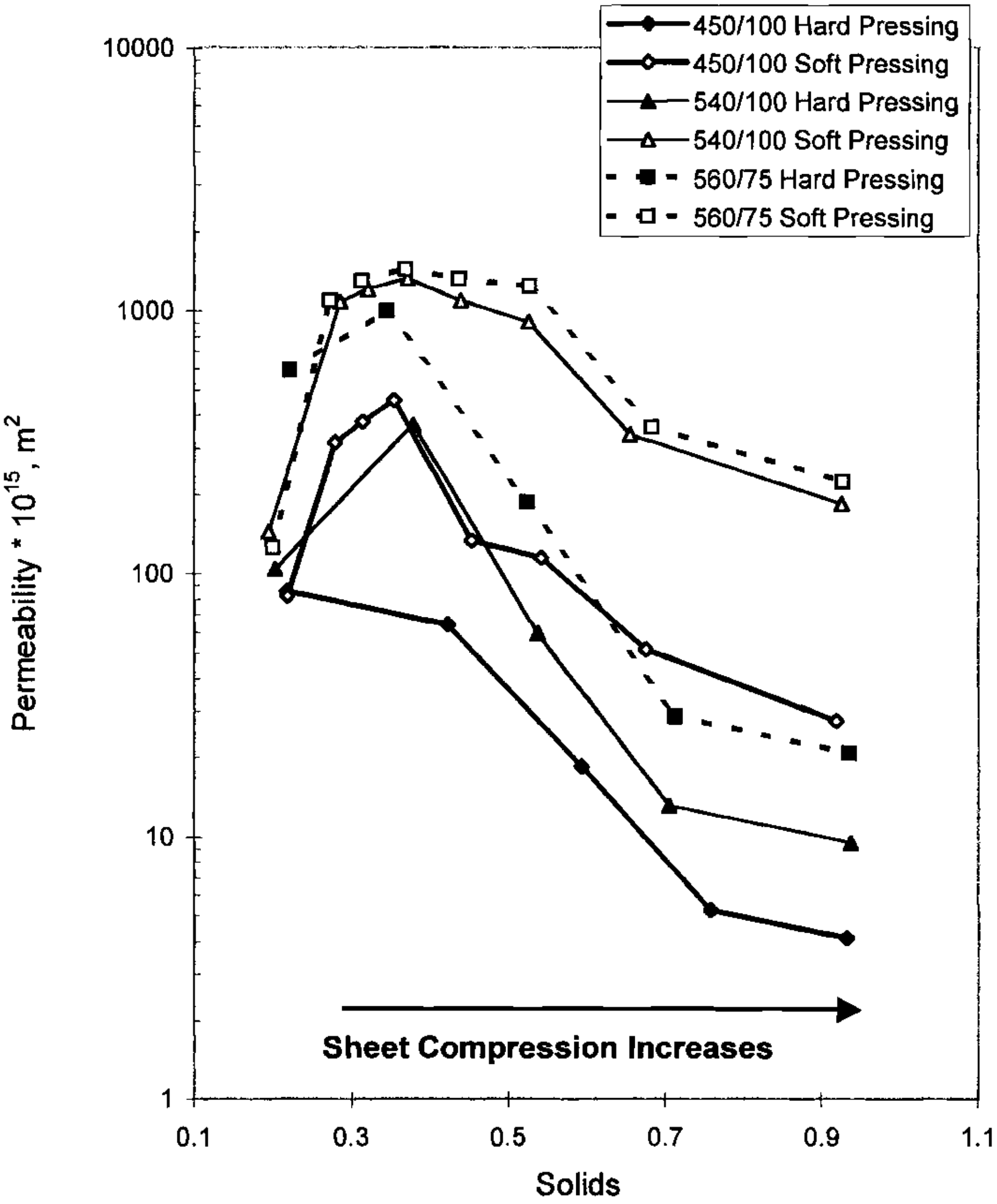


Figure 2. Effect of Pressing on Dependence of Air Permeability, Porosity, and Apparent Density vs. Solids for the Case 450 mL CSF, 100 gsm

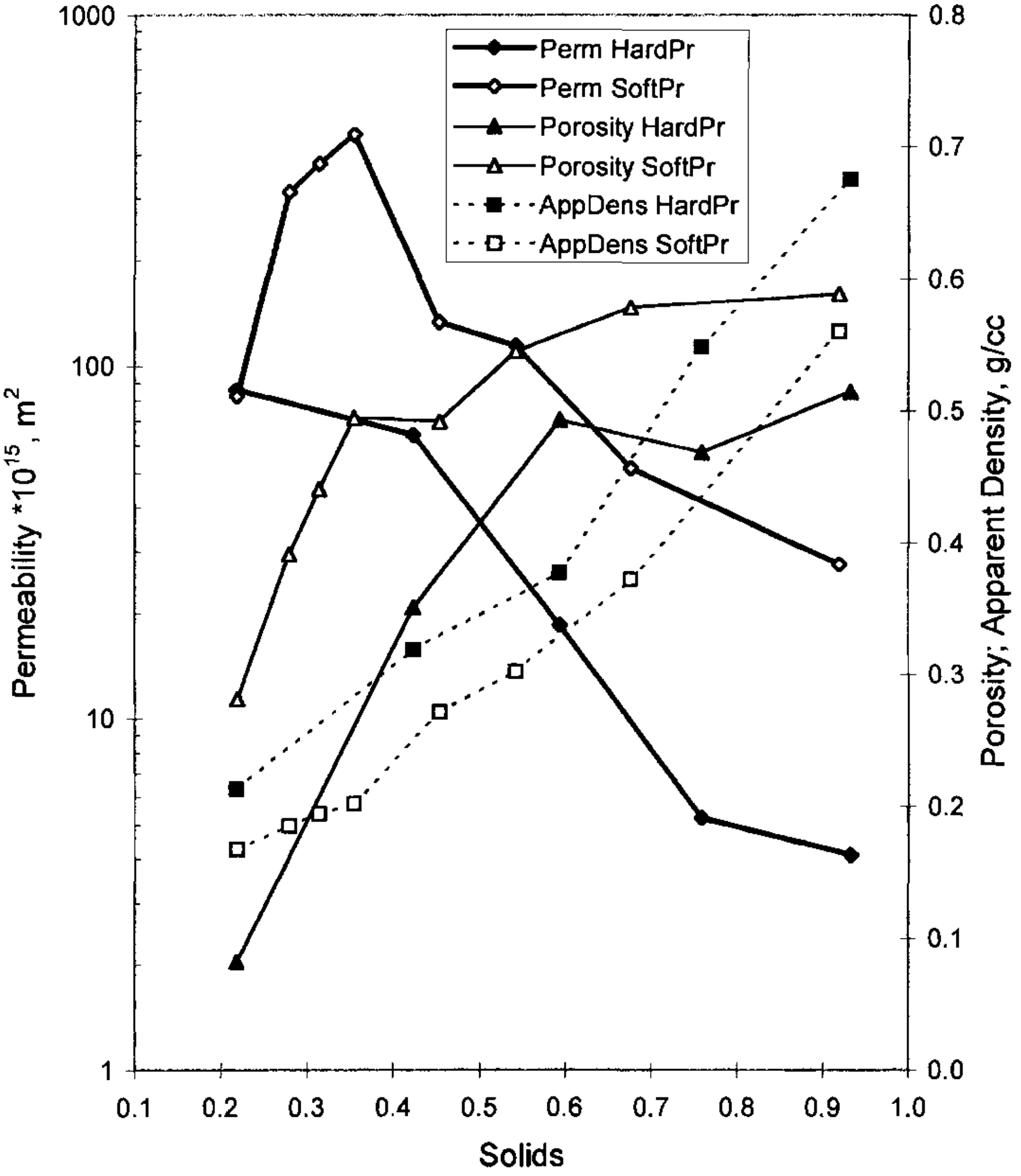
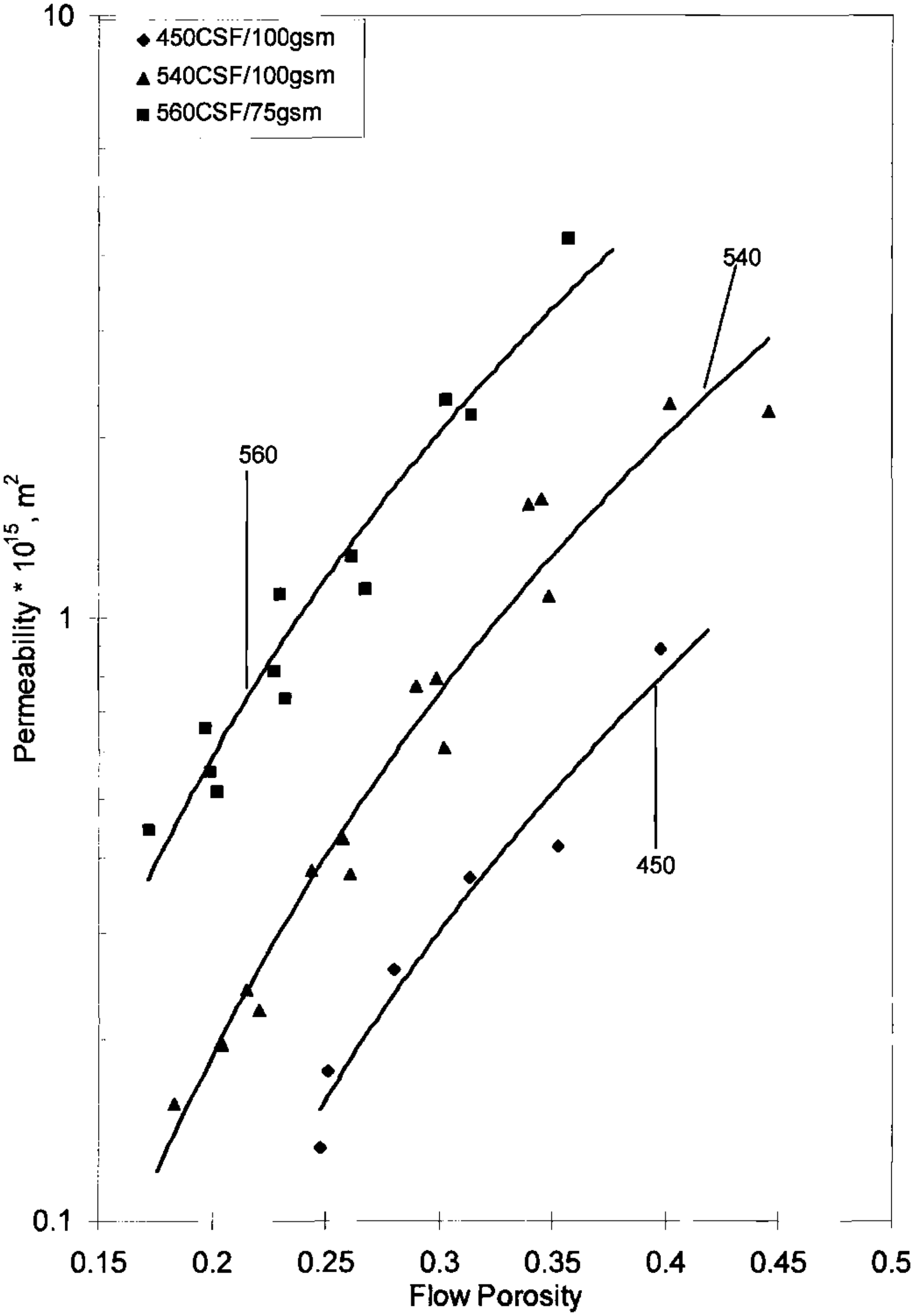


Figure 3. Effect of Flow Porosity on the Water Permeability for Unbleached Sheets



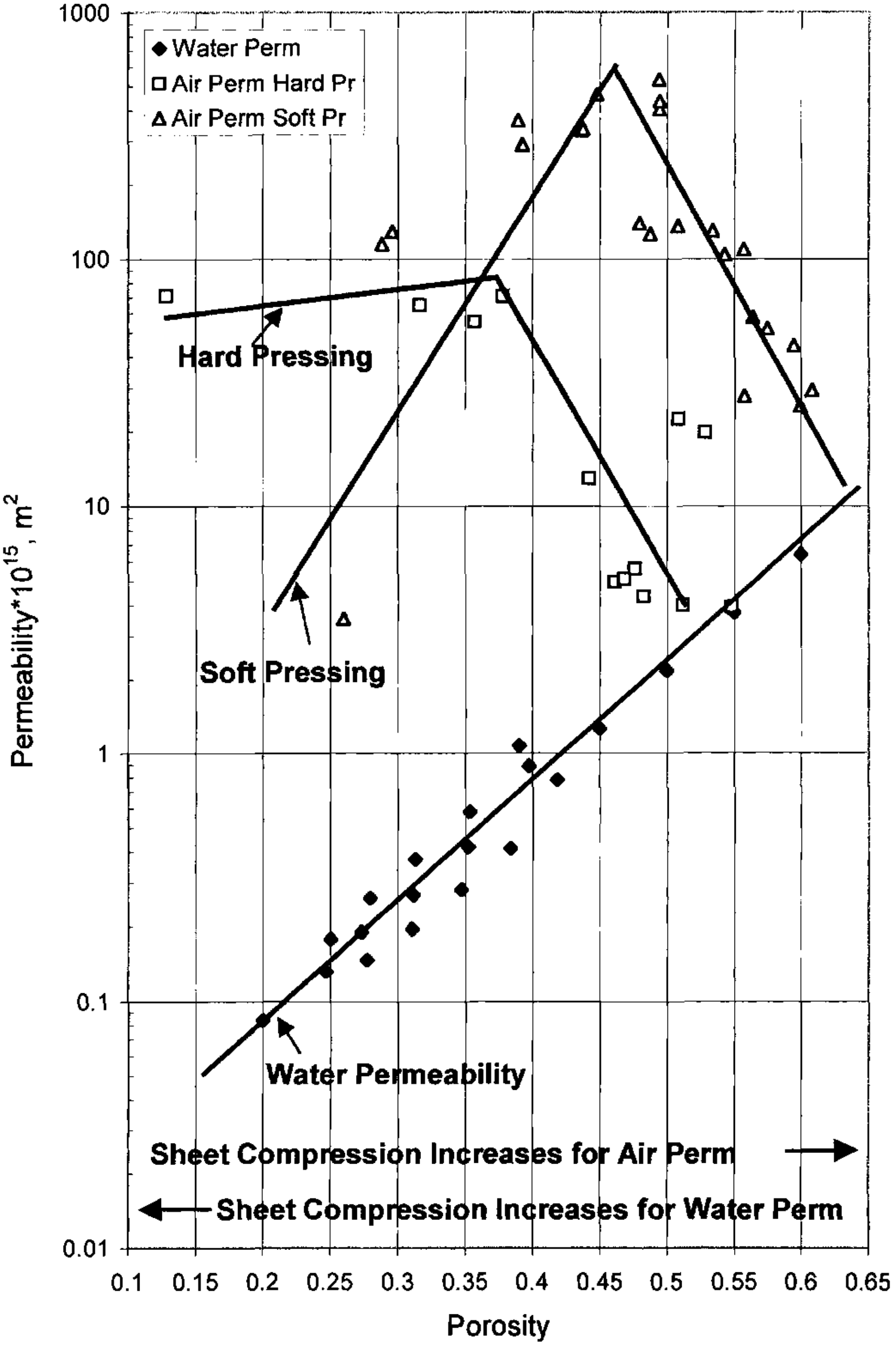
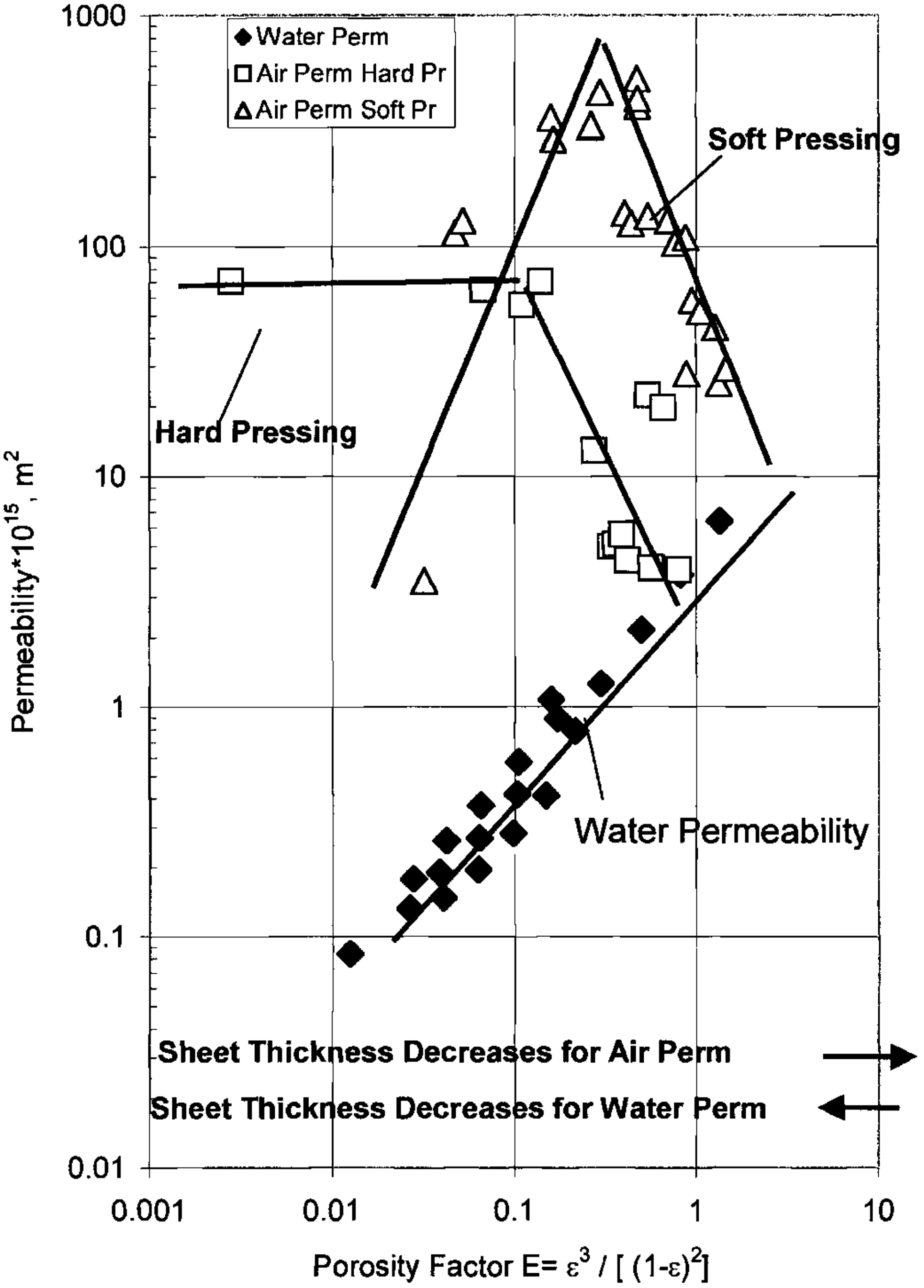


Figure 4. Water and Air Permeability vs. Porosity for the Case 450 mL CSF, 100 gsm

Figure 5. Water and Air Permeability vs. Porosity Factor for the Case 450 mL CSF, 100 gsm



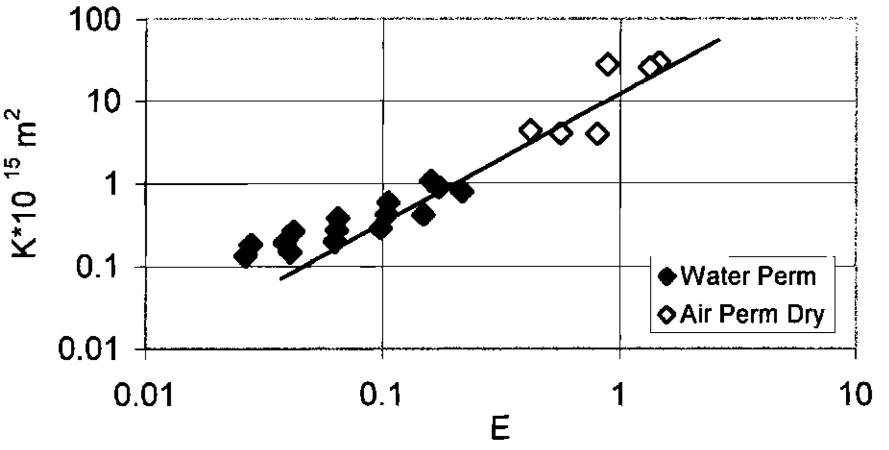


Figure 6a. K vs. E for 450 CSF / 100 gsm

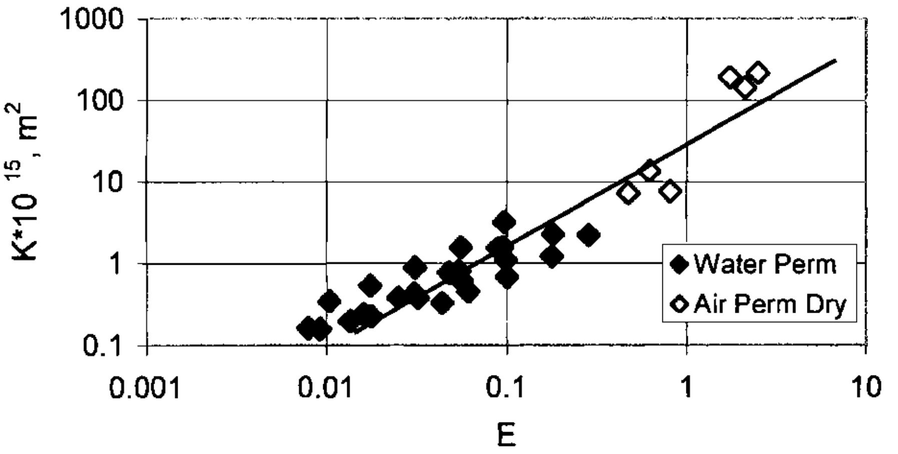


Figure 6b. K vs. E for 540 CSF / 100 gsm

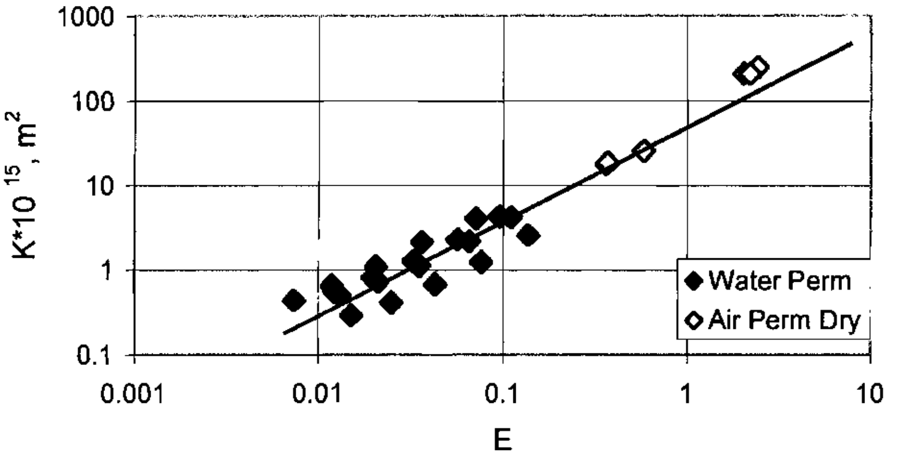


Figure 6c. K vs. E for 560 CSF / 75 gsm

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