WATER AND AIR PERMEABILITY OF WET SHEETS

Project F002

Report 6

to the

MEMBER COMPANIES OF THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

September 1998

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

Atlanta, Georgia

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By

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1. Summary

The permeability of a paper web is a physical parameter that characterizes the degree of web resistance to fluid flow. Permeability to water flow can be used to predict sheet performance in the press section of a paper machine. The water permeability is used to calculate the specific surface of the sheet exposed to water flow and the specific volume of the swollen fibers. These parameters are related to the development of sheet mechanical strength [1]. A number of authors [1-3], describe the apparatus and procedures for conducting water permeability measurements. The water permeability test is time-consuming and performing the test requires some skill from the test apparatus operator. Sheet permeability to air flow can be measured using standard Gurley or Bendtsen porosimeters [4]. Usually, air permeability measurements are performed on dry sheets. However, wet paper sheets may also be tested. The air permeability of wet sheets can potentially be used to predict through-air drying efficiency in the dryer section and depth of steam penetration in the press section.

The primary objectives of this work were to determine if there is a relationship between the water and air permeability of wet paper sheets and to investigate the properties that affect these two measurements. Specifically, an analogy between flow in a channel and flow in a porous medium was used as a means of developing a relationship between water and air permeability. This made it possible to develop a non-dimensional relationship based on an analogy between flow in channels and flow in porous media. The work encompassed some basic theoretical developments and experimental investigations of water and air permeability for several sheet types.

The analogy between channel and porous media flow was experimentally shown to be invalid in the manner used. The primary reason was the use of the same Kozeny factor for all permeability calculations. The Kozeny factor is determined by the pore structure, its value depends on such factors as: the pore size distribution, pore branching, pore interconnections, pore shape, porous tortuosity, pore specific surface, etc. Despite this result, the non-dimensional analogy showed some regions of correspondence between water and air permeability. When expressed in non-dimensional terms, the sheet water permeability at low compressive loads approached the sheet air permeability at high solids levels. Also, sheet water permeabilities at high compressive loads tended to approach air permeabilities at low solids levels.

This paper is divided into the following sections. First, the water and air permeability of wet sheets, as functions of porosity and solids, are reviewed. The review is somewhat basic, but is included for completeness. The next section, Section 3 reviews the theory behind the flow in a channel and flow in a porous medium analogy. The fourth section presents the experimental data. Significant differences as to the effect of porosity on the water and air permeability are observed. Water permeability tends to be a simple and unique function of porosity. The basic pore structure (as represented by the Kozeny factor) is modified, but does not undergo fundamental changes as the porosity changes. The data shows that air permeability is not a unique function of porosity. At low solids levels (20-45%), both porosity and permeability increase rapidly with solids content. At higher solids levels (> 45%), porosity increases slightly or not at all and permeability decreases. These results indicate that porosity has a significant effect on air permeability at low solids levels (< 40%) while at high solids levels (> 45%) other pore structure characteristics affect the permeability. This suggests that the basic pore structure changes and that the Kozeny factor is not constant. Section 5, the final section presents, the conclusions. The primary conclusion is: Equality of solids levels, porosities, and apparent densities is a necessary but insufficient condition for air permeabilities of wet sheets to be equal.

2. Determination of Air and Water Permeability

2.1 Porosity and Air Permeability

The permeability of a paper web is a physical parameter that characterizes the degree of web resistance to fluid flow. The permeability of a porous media is partially dependent on the porosity of the media. Porosity is a non-dimensional quantity which represents the volume fraction of the porous media that is not occupied by the porous media. For the purposes of this work it was assumed that the volume not occupied by the porous media is "open space", all of which is accessible to a fluid flowing through the porous media. This assumption requires that all the open spaces are connected by other open spaces and together the spaces form continuous, but not necessarily direct, pathways through the sample. Fluid can flow along the pathways completely through the porous media.

A wet paper sheet presents a complicating factor, the fibers which make up the sheet change shape as the amount of water in the sheet changes. The shape changes because some of the water in the sheet is contained within the fibers (intra-fiber water). Some of the intra-fiber water is bonded to the fiber. As the amount of water in the sheet is increased, the amount of intra-fiber water increases and the fibers swell. Fiber swelling also causes dimensional changes in the pore spaces between the fibers. As a result, the porosity changes. Eventually a point is reached where the fibers are saturated and the additional water begins to fill the inter-fiber pore spaces. The inter-fiber water is referred to as free water.

In the case of air flow through the sheet, the obstructing volume is the sum of the total water volume and the fiber volume. Both the water and fiber masses are used because all the water in the sheet (bonded/intra-fiber and free) and all the fibers combine to obstruct the flow of air.

The porosity for the air permeability test is given by

$$\varepsilon_a = \text{(open space volume)/(total volume)}$$

$$\varepsilon_a = \text{(total volume - fiber volume - water volume)/(total volume)}$$

$$\varepsilon_a = 1 - \text{(volume fiber)/(total volume)} - \text{(volume water)/(total volume)}$$

$$\varepsilon_a = 1 - (m_f/\rho_f)/(AL) - (m_w/\rho_w)/(AL) \qquad (1)$$

where m_w is the mass of fiber, ρ_f is the fiber density, m_w is the mass of all the water in the sheet (bound and free), ρ_w is the water density, A is the area, and L is the caliper (thickness).

An alternative definition of porosity is given by,

$$\varepsilon = 1 - c\,v \qquad (2)$$

where c is the apparent density, kg/m^3, and v is the specific volume, m^3/kg. By definition, the apparent density for air permeability is given by

$$c_a = (m_f + m_w)/(AL) \qquad (3)$$

An expression for the specific volume can be found by substituting ε from (2) into (1), which yields

$$c_a v_a = m_f/(\rho_f AL) + m_w/(\rho_w AL) \qquad (4)$$

Algebraic manipulation of (4) gives the following expression

$$c_a v_a = [(m_f + m_w)/AL][m_f/\rho_f + m_w/\rho_w][1/(m_f + m_w)] \qquad (5)$$

Since the first term on the right hand side of (5) is equivalent to c_a, an expression for v_a is given by

$$v_a = [m_f/\rho_f + m_w/\rho_w][1/(m_f + m_w)] \tag{6}$$

which can be restated as

$$v_a = [1/\rho_f + MR/\rho_w][1/(1 + MR)] \tag{7}$$

The specific volume can be calculated at a known solids level prior to the permeability test. Specific volume decreases with solids.

Using (7) and (3), the air porosity can be stated as

$$\varepsilon_a = 1 - (m_f/AL)(1/\rho_f + MR/\rho_w) \tag{8}$$

2.2 Porosity and Water Permeability

Water permeability is also partially determined by the sheet porosity. However, the flow medium and the obstructing media are different than those for air permeability. Therefore, there are differences in the representations of specific volume, apparent density, and porosity.

Free water does not present resistance to the flowing water. Only the fibers and the bonded/intrafiber water in the swollen fibers obstruct the flow. If there is no bonded water, then only the fibers obstruct the water flow (this condition is not realistic because when a paper fiber is exposed to water, some of the water always becomes bound to the fiber). Thus, in the wet sheet, the water acts as both the obstructing medium and the flowing medium.

The porosity, apparent density, and specific volume for the water permeability test are more difficult to define than for the air permeability test. This is because there is invariably a difference between the amount of bound water in the sample prior to the test and the amount of bound water in the sample during the test. Prior to the test, the bound water is dependent on the solids level and the previous processing of the sample. The amount of bound water may or may not be the maximum possible for the given sample. During the water permeability test, the sample is exposed to an excess of water. Therefore, the fibers absorb as much water as is possible and the bound water is at a maximum.

The porosity for a water permeability test is defined as

$$\varepsilon_w = \text{(open space volume)/(total volume)}$$

$$\varepsilon_w = \text{(total volume - fiber volume - bound water volume)/(total volume)}$$

$$\varepsilon_w = 1 - \text{(fiber volume)/(total volume)} - \text{(bound water volume)/(total volume)}$$

$$\varepsilon_w = 1 - (m_f/\rho_f)/(AL) - (m_{wb}/\rho_w)/(AL) \tag{9}$$

where m_{wb} is the mass of the water which is bound to the fibers (prior to the test). As with air permeability, an alternative expression for porosity is given by

$$\varepsilon = 1 - c\,v \tag{10}$$

where c is the apparent density, kg/m^3, and v is the specific volume, m^3/kg. By definition, the apparent density for water permeability is given by

$$c_w = m_f /(AL) \tag{11}$$

Note the difference between the expressions for air and water permeability.

An expression for the specific volume can be derived in the same manner as for air porosity,

$$c_w v_w = m_f /(\rho_f AL) + m_{wb} /(\rho_w AL) \tag{12}$$

$$c_w v_w = (m_f /AL)[m_f /\rho_f + m_{wb} /\rho_w][1/m_f] \tag{13}$$

Canceling c_w gives

$$v_w = [m_f /\rho_f + m_{wb} /\rho_w][1/m_f] \tag{14}$$

which can be rewritten as

$$v_w = 1 /\rho_f + MR_{wb} /\rho_w \tag{15}$$

In (14) and (15), m_{wb} is not known prior to the water permeability test. An upper bound on $v_{w\text{-}max}$ is found by setting $m_{wb} = m_w$, where m_w is the mass of water in the sheet prior to the water permeability test. The data collected during the test allows the calculation of the estimated actual m_{wb}. If v_w produced by the permeability test exceeds $v_{w\text{-max}}$, then the test data is considered erroneous. Similarly, a calculation of the lower limit of $v_{w\text{-}min}$ can be made by assuming $m_{wb} = 0$. If the v_w produced by the test is less than that value, the test data is also considered erroneous.

Since

$$MR = m_w / m_f$$

$$MR = (1/ s) -1$$

where s is the solids level, (15) can also be stated as

$$v_{w\text{-}max} = 1 /\rho_f + (1 /\rho_w)(1/s - 1) \tag{16}$$

Using (11) and (15) an expression for the water porosity is

$$\varepsilon_w = 1 - (m_f / AL)(1 /\rho_f + MR_{wb} /\rho_w) \tag{17}$$

2.3 Permeability and Specific Surface

Permeability, either air or water, is determined using Darcy's equation

$$K = \mu \ Q L / (A \Delta P) \tag{18}$$

where μ is the dynamic viscosity of the moving fluid, kg/(m s), Q is the volume flow rate of the fluid m^3/s, L is the thickness of the porous medium, m, A is the area, m^2, and ΔP is the pressure drop across the porous medium, Pa. The units for K are m^2.

The air permeability is determined using the TAPPI Gurley Porosity Test, T460 om-88. In this test the pressure differential (drop), ΔP, is 1.21 kPa and flow area, A, is 6.47 cm^2; both are characteristics of the instrument. The sheet caliper, L, is measured just prior to the test and the volume flow rate, Q, is inversely proportional to the Gurley tester reading, g,

$$Q = 100/g,$$

where g is the number of seconds required for 100 cm^3 of air to flow through the sheet. By substituting the above values into Darcy's equation, and assuming the dynamic viscosity of air is $\mu = 18.21 \times 10^{-6}$ (kg/(m s)) at 20°C, the following formula for converting the Gurley Porosity reading into air permeability is obtained

$$K = 2.326 * 10^{-15} * L / g,$$

where the units for L are microns (μm) and the units for K are m^2.

The permeability is related to the hydraulic resistance, R, by the equation

$$R = \mu\ L / K = 7829\ g \tag{19}$$

where the units for R are kg/s m^2.

Darcy's equation only accounts for viscous resistance; it neglects inertial resistance. Therefore, the above approach for the calculation of sheet permeability to air is valid only when the inertial resistance is low, that is, at low Reynolds numbers, Re. In [5,6], it is stated that the Darcy's equation is valid if $Re < 2$.

Reynolds number is defined as

$$Re = \rho\ U/(\mu\ S_v), \tag{20}$$

where S_v is the surface area of fibers per unit volume of the paper material, m^2/m^3, and

$$U = Q/A \tag{21}$$

is superficial velocity of the fluid, m/s. To calculate Re from (20) it is necessary to know S_v. However, S_v can be found only after experimentally determining the sheet permeability. Gurley Porosimeter measurements generally produce flows with Reynolds Numbers significantly less than 2.

In the case of water permeability there is no standardized test instrument. The instrument used for the work reported here produced flow rates that were significantly less than that for the air permeability test. Given the relative viscosities of air and water, the Reynolds Number for the water permeability test was also significantly less than 2.

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 for permeability has the form

$$K = \varepsilon^3 / [k\ S_v{}^2(1 - \varepsilon)^2], \tag{22}$$

where ε is the flow porosity, and k is the Kozeny factor. The reciprocal of S_v is proportional to the average hydraulic radius of the pores.

The Kozeny factor accounts 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, k can be substantially higher [7, 8]. It is frequently claimed that anomalously high sample tortuosities may be the reason for the disagreement between results predicted by the Kozeny-Carman equation and results obtained experimentally.

The Kozeny factor can be experimentally determined from permeability measurements of the flow through a porous medium which has fibers or particles of a known geometry and orientation. Given an experimentally determined K, and an S_v calculated from a known geometry, equation (22) can be solved for k. In the case of paper webs, a media containing fibers of non-uniform geometry and unknown orientation, the value of k is usually assumed ($k = 5.55$).

In the case of air permeability, specific surface can be calculated directly from the Kozeny-Carman equation. Once air permeability is measured the specific surface is calculated using

$$K_a = \varepsilon^3 \nu_a^2 / [k S^2 (1 - \varepsilon)^2] \tag{23}$$

where

$$S = S_v \nu \tag{24}$$

is the specific surface area per unit mass exposed to the flow, m^2/kg, and the Kozeny factor, k, is assumed to be known ($k = 5.55$).

In the case of water permeability the specific surface is found using the following procedure. Replacing ε in (22) with ε from (10) yields the following expression for the Kozeny-Carman equation:

$$(K c^2)^{1/3} = (k S^2)^{-1/3} (1 - \nu c), \tag{25}$$

Expression (25), along with 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 of

$$(K c^2)^{1/3} = a - b*c \tag{26}$$

where a and b are coefficients of regression, the values of ν and S can be calculated as

$$\nu = b/a \quad S = (k a^3)^{-1/2}. \tag{27}$$

The porosity can then be calculated using equation (10). To obtain the linear regression, the permeability must be measured at a minimum of two different sheet thicknesses or compression loads.

3. Analogy Between Laminar Channel Flow and Porous Medium Flow

Both water and air permeability characterize the degree of the sheet openness. Usually a sheet that has low water permeability also has low air permeability and vice versa. It would be useful to determine whether a correlation exists between these two permeabilities in the range of standard paper making processes. Given the difficulty of measuring water permeability and the ease of measuring air permeability, such a correlation would potentially save considerable time.

It is well known that for flow in a channel the interrelation between pressure differential and flow velocity is the same for both laminar and turbulent flows regardless of flowing medium. Although flow in a porous structure is a more complicated phenomenon than that in a channel, it appears that there is an analogy between laminar flow in a channel and laminar flow in a porous medium as described by the Darcy's equation. The analogy is developed in the following sections.

3.1 Laminar Flow in Channels and in Porous Media

In hydraulics for straight channels the pressure drop for flow along the channel is given by

$$\Delta P = (C_h\ L / D_h)\ (\rho\ U^2/2), \tag{28}$$

where C_h is the coefficient of hydraulic resistance, L is the length of the channel, D_h is the hydraulic diameter, and ρ is the density of the flowing medium. For laminar flow

$$C_h = B/Re, \tag{29}$$

where B is a coefficient that depends on the channel geometry, for instance, B = 64 for a round channel, and Re is the Reynolds number as given by $Re = \rho\ U\ D_h / \mu$. Substitution of the expressions for C_h and Re into (28), yields

$$\Delta P = U\ \mu\ L / (2\ D_h^2/64). \tag{30}$$

Combining Darcy's equation (18) with (21)

$$\Delta P = U\ \mu\ L / K \tag{31}$$

shows that it has a form similar to (30).

This similarity is exploited by introducing the Euler number, $Eu = \Delta P / (\rho\ U^2)$ for channel flow. It expresses the ratio of pressure differential to inertial resistance. Using (28), Eu can be rewritten as

$$Eu = [B\ L / (2\ D_h)] / Re. \tag{32}$$

If the flow is laminar, expression (32) can be used with any fluid.

For a porous medium there is a similar equation for Eu. It has the form

$$Eu = [L/(K\ S_v)] / Re \tag{33}$$

or

$$Eu = (C_e\ L / K^{1/2}) / Re, \tag{34}$$

where

$$C_e = \varepsilon^{-3/2}\ (1 - \varepsilon)\ k^{1/2} \tag{35}$$

which depends on the porous structure as defined by the porosity and the Kozeny factor.

Since K and S_v are not readily measurable, (34) is of little practical use. However, the equation does show that if a change in the thickness of a porous medium due to its compression causes a significant change in the parameters characterizing the porous structure, the interaction between Eu and Re is not unique. This is not the case with flow in channels (compare (34) and 32)).

Note that (32) and (34) have similar forms, with each term having a similar purpose. C_e and B describe the geometry of the medium. D_h and K are related to the hydraulic radius, K through the internal S_v term. If the channel flow-porous media flow analogy is valid, alternative means of calculating S_v could be developed.

3.2 Choice of Non-dimensional Terms

An attempt to develop a correlation between water and air flow in wet paper sheet using the analogy between the flow in a channel and a porous medium was described in [9]. It was shown that a linear correlation exists between the products of Eu*Re for water and Eu*Re for air flow in the overlapping range of Re numbers. However, in an expression for a quantity $Eu*Re = C_e L / K^{1/2}$, the coefficient C_e was assumed to be 5.66 based on an analogy with the laminar fluid flow in a channel. When making such an assumption, the change in porous structure of the sheet under compression is ignored, which is incorrect.

If a direct anaolgy between channel and porous media flow is valid, then if a plot of f(Eu) vs. f(Re) is made for a given sheet, the function should be similar for any fluid. If the function is different for different fluids, the analogy cannot be applied directly, but it may provide some insight into the interaction between the porous structure and the fluids. A direct plot of Eu vs. Re is only of limited interest, since both Eu and Re depend on K.

Using the Kozeny-Carman equation (22) and the Darcy formula, the following expressions for Eu and Re numbers in porous media can be obtained:

$$Re = (K^{3/2} \rho \Delta P) / (L \mu^2) C_e \tag{36}$$

$$Eu = \mu^2 L^2 / (\rho \Delta P K^2). \tag{37}$$

For convenience, it would be preferable to select the abscissa, X, as a non-dimensional quantity that did not contain permeability. It would be also convenient if the ordinate, Y, did not contain the coefficient C_e which includes the Kozeny factor. Based on these considerations, X and Y were selected using the following combinations of Eu and Re:

$$X = Eu^{3/4} * Re = C_e \rho^{1/4} \Delta P^{1/4} L^{1/2} \mu^{-1/2} \tag{38}$$

and

$$Y = Eu^{-1/4} = \rho^{1/4} \Delta P^{1/4} L^{-1/2} K^{1/2} \mu^{-1/2}. \tag{39}$$

As the quantity X is proportional to the coefficient C_e, it can be termed porosity index. The quantity Y which is proportional to the permeability can be termed permeability index.

Some further insight into the relationship between X and Y can be gained if one examines

$$f(Eu, Re) = Y/X = (Eu * Re)^{-1} \tag{40}$$

Substituting for X and Y yields

$$Y/X = [\rho^{1/4} \Delta P^{1/4} L^{-1/2} K^{1/2} \mu^{-1/2}] / [Ce \rho^{1/4} \Delta P^{1/4} L^{1/2} \mu^{-1/2}] \tag{41}$$

which simplifies to

$$Y/X = K^{1/2} / [Ce L] \tag{42}$$

Recalling that

$$Ce = \varepsilon^{-3/2} (1 - \varepsilon) k^{1/2}$$

$$K = \mu Q L / (A \Delta P)$$

and substituting into (42) and simplifying gives

$$Y/X = [\mu\, U / (\Delta\, P)] / [\varepsilon^{-3/2}/(1-\varepsilon)\, k^{1/2}] \tag{43}$$

where once again it is assumed $k = 5.55$.

If one were to plot Y/X for air and water permeability and there were common points, at those points one could write

$$\{[\mu\, U / (\Delta\, P)] / [\varepsilon^{-3/2}/(1-\varepsilon)\, k^{1/2}]\}_{\text{water}} = \{[\mu\, U / (\Delta\, P)] / [\varepsilon^{-3/2}/(1-\varepsilon)\, k^{1/2}]\}_{\text{air}} \tag{44}$$

An experimental investigation was pursued to investigate the existence of such points.

4. Experimental Results and Discussion

4.1 Experimental Conditions

The relationship between air and water permeability was explored using sheets made from two different pulps. The first group of test sheets were made from once dried unbleached softwood kraft pulp that was refined to three different levels of freeness. The sheet types made were: 100 gsm - 450 ml CSF, 100 gsm - 540 ml CSF, and 75 gsm - 560 ml CSF. Each sheet was prepressed to a solids level of about 20%. Water permeability was measured at 5 compression loads in the range of 28-92 psi using the Carver hydraulic press [3]. After the specific volume was determined, the values X and Y were calculated at $k = 5.55$.

In addition to the water permeability measurements, similar sheets were pressed to several solids levels and Gurley porosity and sheet caliper were measured. Pressing was conducted using two methods. One method used higher loads and shorter pressing times – hard pressing, while the other method used lower loads and longer pressing times – soft pressing. At each level of solids, values of X and Y as well as porosities and permeabilities were calculated using $k = 5.55$.

The sheets in the second group were made from bleached softwood kraft dry lap. The sheet types made were: 100 gsm - 450 ml CSF and 200 gsm - 450 ml CSF. These sheets were prepressed to about 20 and 40% solids. The 40% solids sheets were pressed on a laboratory low speed roll press while the 20% solids sheets were pressed in a hand operated vertical press. Water and air permeability measurements were made for the sheets at solids of 20 and 40%. After each pressing, air permeability measurements were performed.

4.2 Water Permeability

Water permeability is determined by the condition of the fiber mat structure. The structure is at least partly described by the porosity. Factors which alter the fiber mat structure, and which in turn affect the porosity and permeability, generally include any factor which changes fiber geometry, how the fibers are packed, or the pathways through the sheet. Some of these factors are,

1. Refining – alters fiber geometry and fiber packing.
2. Prior pressing – alters fiber geometry and fiber packing.
3. Basis Weight – alters path length and path tortuosity through the sheet.
4. Furnish – fiber geometry.

The interaction of these parameters with sheet water permeability was investigated by observing changes in the permeability vs porosity relationship. Water permeability of the unbleached sheets as a function of porosity is plotted in Figure A-1 and water permeability of the bleached sheets as a function of porosity is plotted in Figure

A-2. In these figures, the condition of high porosity-high permeability corresponds to the lowest load case and the condition of low porosity-low permeability corresponds to the highest load case. In all cases permeability increases exponentially with porosity

$$K = a\, e^{\varepsilon b} \tag{45}$$

where $7 < b > 12$. The permeabilities were calculated with an assumed constant Kozeny factor of $k = 5.55$.

4.2.1 Refining

Sheets with high refining levels had lower maximum permeabilities and reduced rates of increase in permeability. Figure A-1 shows this trend for unbleached sheets. Only one refining level was used for the bleached pulp. However, the same trend should be expected with the bleached pulp. Regardless of furnish, refining causes fibrillation of the fibers. This would tend to increase the fines content and reduce permeability.

4.2.2 Prior Pressing

Figure A-2 shows the results from samples prepared using two different pressing conditions, one in which the sheets were pressed to 20% solids and the other in which the sheets were pressed to 40% solids. In the case of the 100 gsm sample, prepressing to 40% solids resulted in greater total permeability and a higher rate of increase in permeability than was produced for the sample prepressed to 20% solids. There was little difference between the two pressing cases with the samples at 200 gsm. The permeabilities were less than those for the 100 gsm sheets. The result may be an indication that at lower basis weights, both pressing and basis weight affect permeability while at higher basis weights, pressing is not a factor.

4.2.3 Basis Weight

Figure A-2 shows the effect of increasing basis weight on the permeability vs. porosity relationship. As noted above, the effect of pressing appears reduced at higher basis weights. Also given the same prepressing, increasing basis weight significantly decreases the total permeability and the rate of increase of permeability. This is consistent with observations made in [7].

4.2.4 Furnish

The effect of furnish can be seen by comparing the 450 CSF, 100 gsm, unbleached sheet from Figure A-1 with the 450 CSF, 100 gsm, bleached sheet from Figure A-2. The unbleached sample reaches a greater permeability at a lower porosity. The unbleached fibers having been processed to a lesser extent should more readily resist flattening or other shape changes. Undeformed fibers would produce wider pores which could lead to higher permeability.

4.2.5 Solids

The level of solids has a minor effect on the water permeability. This was to be expected as the sheets tested in the Carver hydraulic press were pressed to different thicknesses. There was an overlapping thickness zone for low and high solids sheets. The closer the level of solids, the wider the overlapping range of the sheet thicknesses and the less the influence of solids on permeability.

4.2.6 Pore Structure – Kozeny Factor and Specific Surface

The data from the water permeability test indicate that, in the range of compressive loads tested (30-100 psi), altering the condition of the sheet (i.e., changing the applied compression load) does not produce a significant fundamental change in the basic pore structure of each type of sheet. There is, therefore, probably little change in the Kozeny factor. This conclusion is primarily supported by the simple and unique relationship between permeability and porosity throughout the compression ranges used. It is secondarily supported by the relationship between specific surface and porosity shown in Figure A-3. For each furnish, there is relatively little change in specific surface for the change in porosity. Specific surface is a calculated value; the calculation assumes a constant $k = 5.55$. It is only a measure of the surface area exposed to the flow. However, the Kozeny factor is a measure of pore size distribution, pore branching, pore interconnections, pore shape, particle shape, pore constrictions, tortuosity of porous structure, etc. and specific surface is one of the factors which would influence it. Given that there are apparently variations in both k and S, a more in depth study of pore structure changes would benefit from graphing the quantity $k S^2$.

4.3 Air Permeability

As with water permeability, air permeability is determined by the condition of the fiber mat structure. In the case of air permeability, the amount of water in the pore spaces of the fiber mat must be considered as part of the mat structure. Despite this difference, the structure is still at least partly described by the porosity. However, the porosity and permeability change as the amount of water in the pore spaces changes. This results in trends that are different than those for water permeability. The other factors that affected water permeability also affect air permeability. The interaction of these parameters with sheet water permeability was investigated by plotting permeability vs. porosity as was done for water permeability. In addition, permeability vs. solids, porosity vs. solids, apparent density vs. solids, permeability vs. porosity, and specific surface vs. solids were also plotted.

4.3.1 Porosity and Apparent Density vs. Solids

In general, as solids content increased, sheet porosity and apparent density increased (Figures A-12, A-13, A-14, A-15, and A-16). Apparent density increased in either a linear or slightly greater than linear manner as solids increased. Porosity increased linearly with solids up to a solids level of 30 - 40%. Above 40% the rate of increase in porosity was reduced, in some cases to zero at the given experimental conditions. The bleached sheets showed the most linear behavior, both in apparent density and porosity. In the case of the unbleached sheets, the rate of change in porosity approached zero at the higher solids levels.

4.3.2 Permeability vs Porosity

At equal porosity levels, permeability produced by soft pressing was higher than that produced by hard pressing. This indicates that pore branching in the hard-pressed sheet is more tortuous. Increased refining, increasing basis weight, bleaching, and more vigorous pressing reduced the maximum permeability.

Air permeability of the wet sheets is not a unique function of porosity. Figures A-4 and A-5 show the relationship for the sheets tested. The permeability tends to increase and then decrease as the porosity increases. The non-unique relationship between permeability and porosity indicates that the Kozeny factor does not remain constant as the porosity changes.

The peak permeability occurred in the range of 35-40% solids. In this solids range it is expected that most of the water in the sheet is bound water and little or no water remains in the inter-fiber pores. Under these conditions the fibers are still swollen with water and have maximum or close to maximum cross sectional area. Thus, the fibers are not packed as densely as possible and the pore spaces have large cross-sectional areas. The pore spaces contain little or no water, providing an unobstructed path for air flow. At lower solids levels the pore spaces are filled with greater amounts of water, reducing the air permeability. At higher solids levels, water is removed from the fibers, reducing the cross-sectional area and making it possible for the fibers to be packed more closely. The pore spaces are correspondingly smaller, reducing the air permeability. Fiber surface area also changes. Given these sheet structure changes, one could expect the Kozeny factor to change as well. As stated previously, since there are apparently variations in both k and S, a more in depth study of pore structure changes would benefit from graphing the quantity $k S^2$.

As with the water permeability, specific surface is a secondary indicator of the sheet structure changes that have an effect on the Kozeny factor. The specific surface for the air permeability of each of the sheet types was calculated using (23). Once again, this calculation was performed using an assumed constant Kozeny factor of $k = 5.55$. The results are plotted in Figures A-10 and A-11. The variation in specific surface with solids tends to follow second order polynomial function with a high degree of correlation. The trend is the opposite of what was found for porosity vs. solids. The specific surface remains relatively constant for solids levels between 20 and 40%. At solids levels above 40%, the specific surface increases with solids content, indicating a possible sheet structure change that would alter the Kozeny factor. The rate of increase is greatest at high refining levels, higher pressing intensities, and higher basis weights.

Figures A-8 and A-9 show the relationship between specific surface and porosity. The trend is similar to that for solids, but there is not a high correlation with a second order polynomial.

4.3.3 Permeability vs. Solids

As Figures A-6 and A-7 show, air permeability is also not a unique function of solids level. Permeability increased and then decreased as the solids level increased.

The effect of the solids level on air permeability at different pressing histories for the sheets made of unbleached pulp is demonstrated in Figure A-6. Permeability is significantly affected by the pressing history of the sheet. The plots indicate that at the same solids level, hard pressing produces a significantly lower air permeability when compared to soft pressing. This corresponds with the effect of pressing history on porosity and specific surface.

Pressing history affects air permeability because different pressing histories produce different fiber and mat structure deformations at the same solids level. The different deformation results in different porosities and apparent densities or thicknesses, which in turn can alter the permeability (see Figures A-7 through A-9).

4.3.4 Summary

The following observation are made regarding the results:

There is a substantial difference between the effect of porosity on water and on air permeability. Water permeability is a monotonic unique function of porosity. An increase in sheet porosity induces an increase in water permeability (see Figures A-1, A-2). This is an indication of little or no change in Kozeny factor over the range of compression loads used. Air permeability is more complicated. It is not a monotonic function of porosity. At low solids levels, an increase in sheet porosity results in an increase in air permeability. This is apparently because an increase in solids generally corresponds with a decrease in free water and more open pore spaces. Further increases in solids beyond 35-40%, which is accompanied by the removal of intrafiber water, apparently produce a more tortuous porous structure that decreases the sheet air permeability. The non-unique relationship between permeability and porosity indicates that for air permeability the Kozeny factor changes with solids content. This is supported by the relationship between specific surface and solids at solids levels above 40%, specific surface increases with solids content. The increase is greatest in those sheet types that show the lowest permeabilities.

The variability of the air permeability of the wet sheet at low levels of solids is significant. At the same value of solids and compression history, air permeability of the wet sheets may differ by the factor of 2-3. This is a reflection of the fact that the interconnectedness and orientation of the pores has the random nature which is emphasized in statistical models of a porous medium [10]. In a wet sheet, the nonuniform porous structure consists of larger pores that are connected by smaller pores which form a random network. From probability considerations, it is obvious that the likelihood of partial pore blockage is higher for the wet sheets of higher basis weight and lower freeness. Additionally, partial pore blockage may occur under certain pressing conditions.

If sheets have the same porosities and apparent densities, then it is possible that air permeabilities will also be close even if the sheets were pressed differently. This is demonstrated in Figures A-5, A-7, and A-15 which show the relationships for 100-gsm bleached sheets. Closeness of the sheets porosities and apparent densities, however, does not guarantee that air permeabilities will be the same. This is demonstrated in Figures A-6, A-8, and A-16 which show the plot for 200-gsm sheets. Thus, it can be stated that an equality of wet sheets porosities and apparent densities (thicknesses) is a necessary but insufficient condition for the air permeabilities to be equal.

The above findings are very important, for instance, for the design of the press section with steam shower. It can be shown that permeability to z-direction steam flow determines the depth of the steam penetration into the sheet and an average increase of the sheet temperature due to steaming. Therefore, the effect of pressing history and solids level on the permeability of a given sheet are parameters to be considered when using steam for web preheating in the press section. An additional parameter is the effect of steam preheating on sheet permeability, which is briefly discussed in [12].

The above results indicate that air permeability may vary significantly at the same level of the solids. This is one of the possible explanations as to why the information related to the efficiency of the steaming in the press section is so contradictory [11].

4.4 Non-Dimensional Relationship between Water and Air Permeability

The non-dimensional parameters Y and X were calculated for the water and air permeability tests and were plotted in Figures A-17 through A-21. According to the analogy between the laminar flow in a channel and porous medium, $f(\mathrm{Eu})$ vs. $f(\mathrm{Re})$ should not depend on the flowing medium. The experimental results show that the non-dimensional factor does depend on the flowing medium; the results for air and water permeability followed different trends. However, at extreme values of X, values of Y for water and air flow tended to approach each other.

The reason for the observed discrepancy in non-dimensional correlations for the wet sheet water and air permeability is that the interactions of the water and air flow with the porous structure of the wet sheet are essentially different in the wide intermediate range of X. Eliminating the discrepancy in the non-dimensional correlations necessitates the use of different Kozeny factors for water and air flow. In the case of air flow the actual Kozeny factor probably changes with solids, this is indicated by the changes in porosity and specific surface as the solids content changes. In the Kozeny-Carman equation, the Kozeny factor is the only parameter that accounts for all the specifics of the porous structure: the shape of pores, pore size distribution, interconnectedness of the pores, etc. The Kozeny factor was assumed to be the same for both types of flow ($k = 5.55$). An experimental measurement or theoretical calculation of the Kozeny factor based on different pore network models [10] are outside the scope of this paper. The assumption of $k = 5.55$ is standard in the literature addressing paper webs.

If the appropriate Kozeny factors were used for calculation of Y vs. X, Y(X) should be the same for the water and air permeability. The question may be posed: "Under which circumstances does the porous structure of the sheet function in a similar manner for both water and air flow, or, in other words, at what value of X will the values of Y be the same for water and air flow?" It is obvious that this can take place when Kozeny factors and porosities for water and air flow are close.

The case of high porosity (low X) for water permeability corresponds to the lightly compressed sheet, while for air permeability it corresponds to the sheet pressed to high level of solids, up to 0.8-0.95. The equality of Y at the same X signifies that the Kozeny factors are close for water and air flow which, in turn, means that their porous structure have similar effects on the flowing medium. In the case of water flow, there is a minimum of fiber geometry distortion and a minimum resistance to flow. In the case of air flow, there is a minimum of free water in the pore spaces and a minimum of blocked pore spaces. The unbleached, hard pressed sheets demonstrated the greatest correspondence.

The case of low porosity (high X) for water permeability corresponds to highly compressed sheet, while for air permeability it corresponds to the sheet at low level of solids. In the case of water permeability there is a maximum of fiber deformation and a maximum of flow resistance. In the case of air permeability there is a maximum of free water in the pore spaces and a maximum flow resistance. The unbleached lightly pressed sheets show the greatest correspondence.

If the Kozeny factor is measured or calculated, for example, for water flow, the correlation Y(X) developed for water permeability is applicable for air permeability. This correlation can be used for determination of the Kozeny factor for air flow in the wet sheet, provided that the wet sheet air permeability is also measured and the value of Y is calculated for air flow.

5. Conclusions

1. The trends in behavior of air permeability of wet sheets were observed at different modes of pressing. While air permeability of the wet sheet may be significantly affected by the sheet porosity and solids, it is not a unique function of porosity and solids. It depends strongly on the branching of the porous structure network as accounted for by the Kozeny factor in Kozeny-Carman equation. This suggests that the Kozeny factor changes as the sheet solids changes. This is supported by the relationship between specific surface (air) and both solids and porosity. The data indicate that in the case of water permeability, the Kozeny factor does not change appreciably over the range of conditions tested.

2. Experimental results for water and air permeability measurements were translated into non-dimensional form. The relationship between non-dimensional water and air permeability was considered. In general, there is a substantial discrepancy between non-dimensional water and air permeability due to significantly different porous structures of the wet paper to water and air flow. However, at extreme values of the non-dimensional parameters, there is a trend toward a correspondence between the flows.

3. At given experimental conditions, non-dimensional water permeability is rather insensitive to the change of the freeness at the same basis weight which is an indication that the Kozeny factor does not change. Alteration of the basis weight changes non-dimensional correlation which is evidence that the Kozeny factor is affected by the basis weight.

6. Literature Cited

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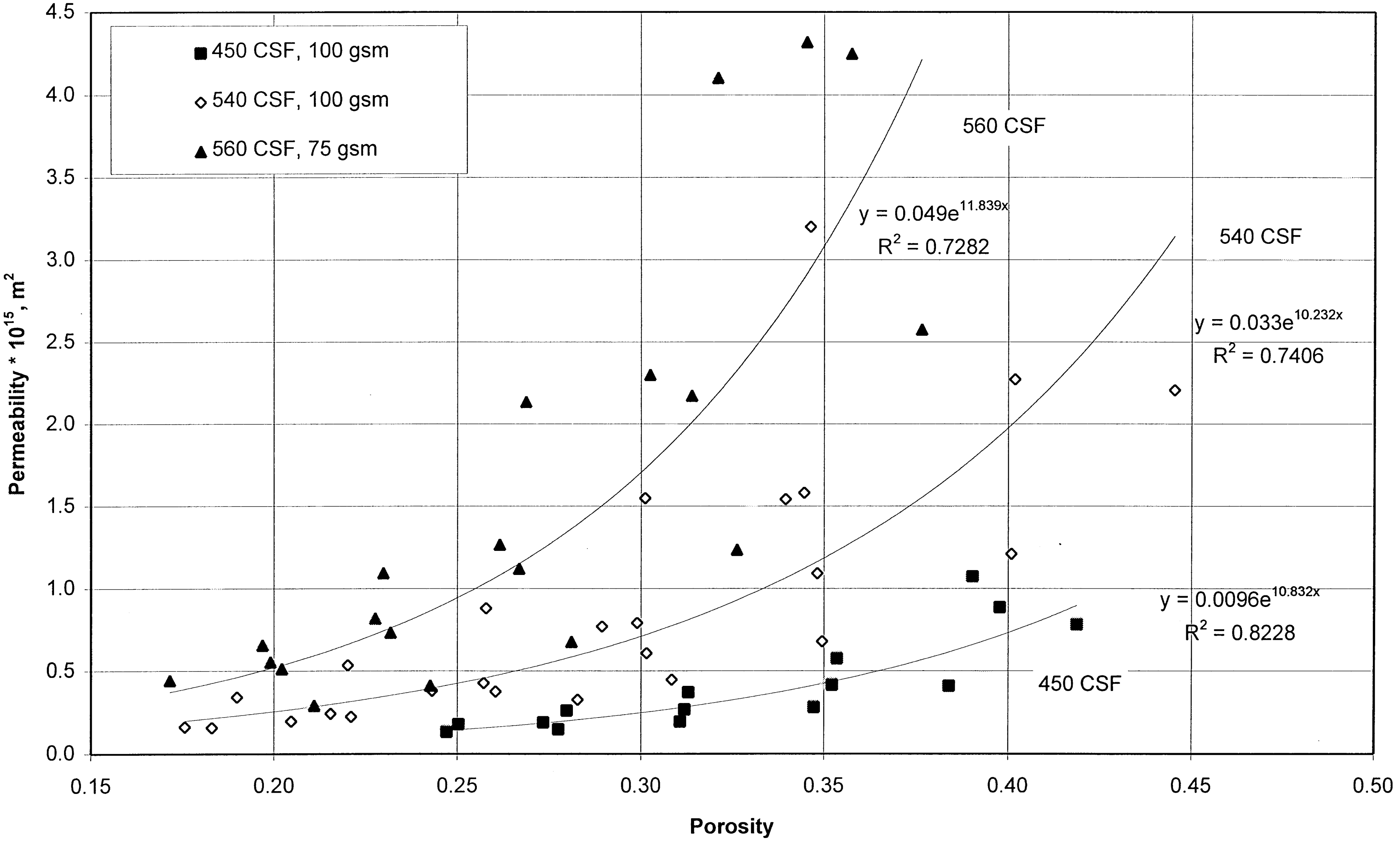
12. Patterson, T. and Rudman, I. IPST Member Report, Project F002 Report 5, March 1998.

Appendix Graphs

Figure 1. Water Permeability vs. Porosity - Unbleached Sheets



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WPerm UB F1

Figure 2. Water Permeability vs. Porosity - Bleached Sheets

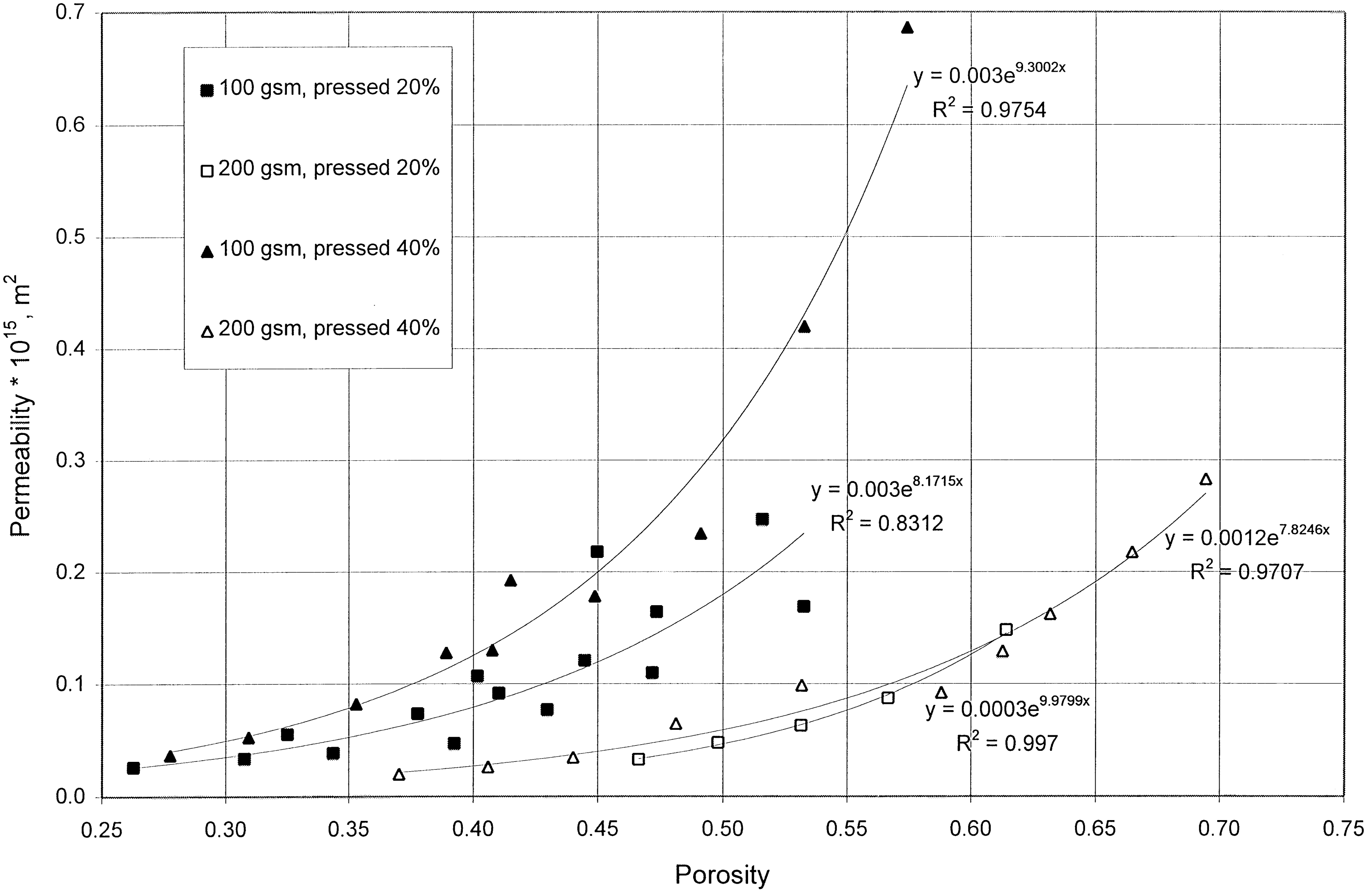

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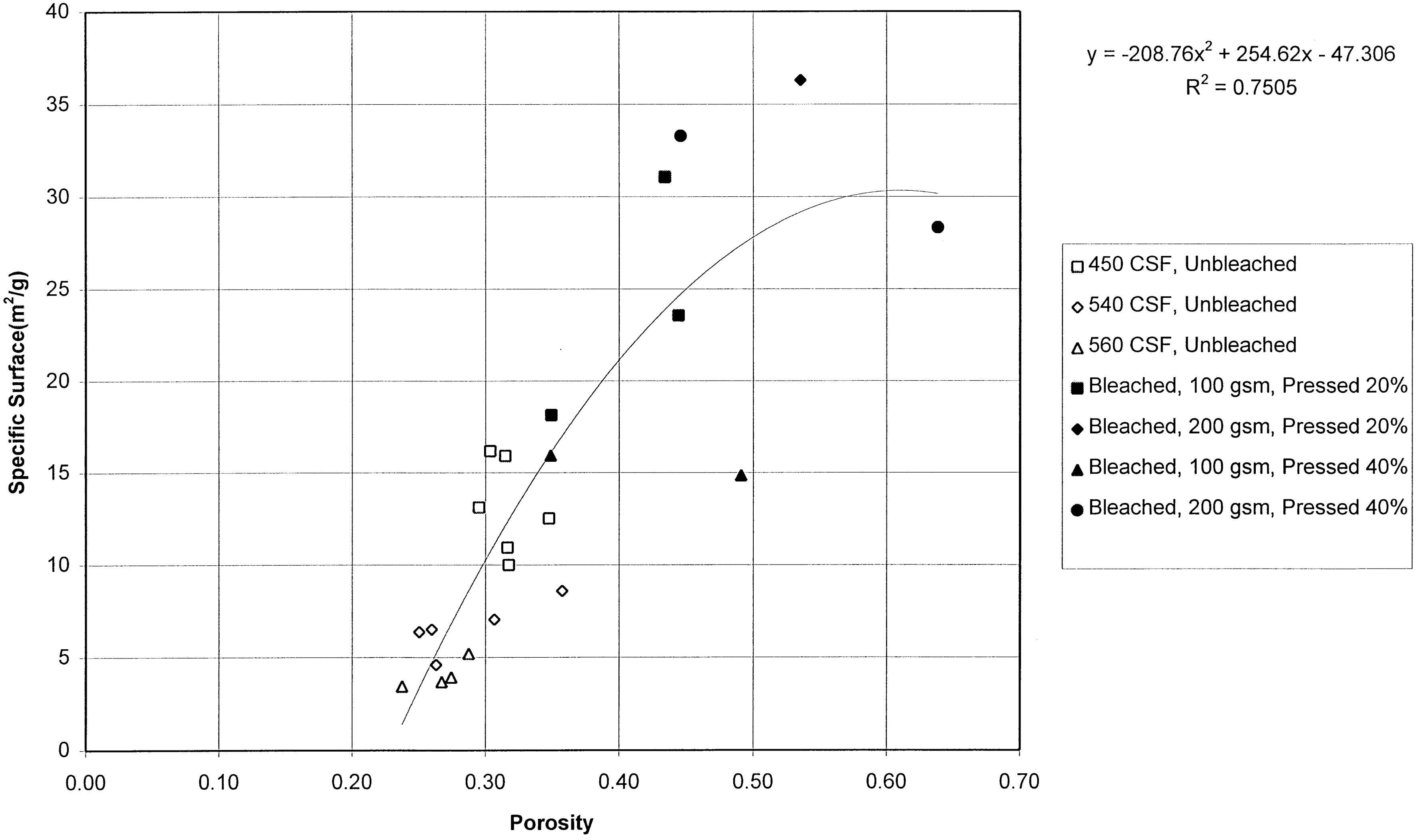
Figure 3. Specific Surface (Water) vs. Porosity



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SpSurf-Por F3

Figure 4. Air Permeability vs. Porosity - Unbleached Sheets

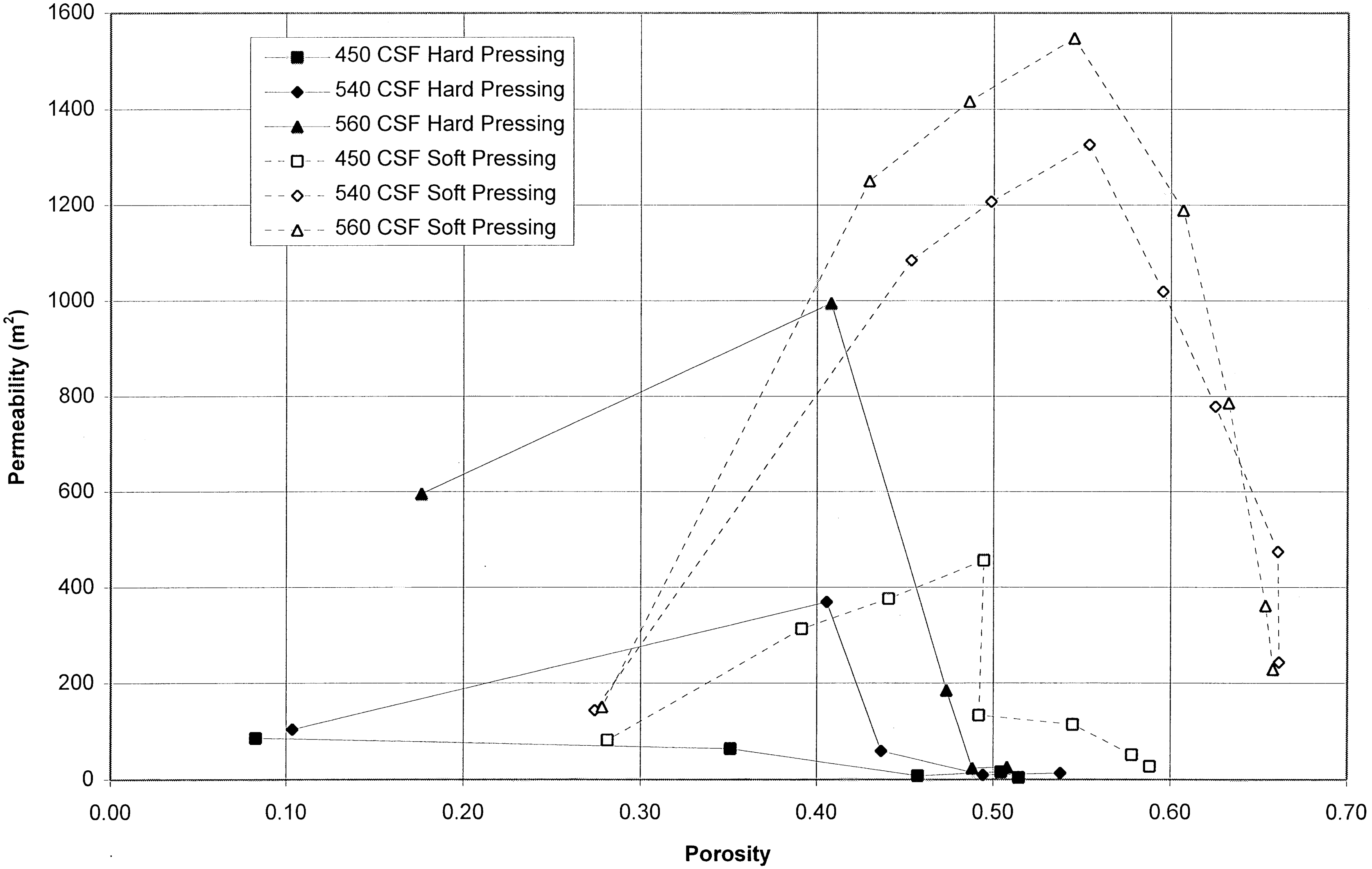
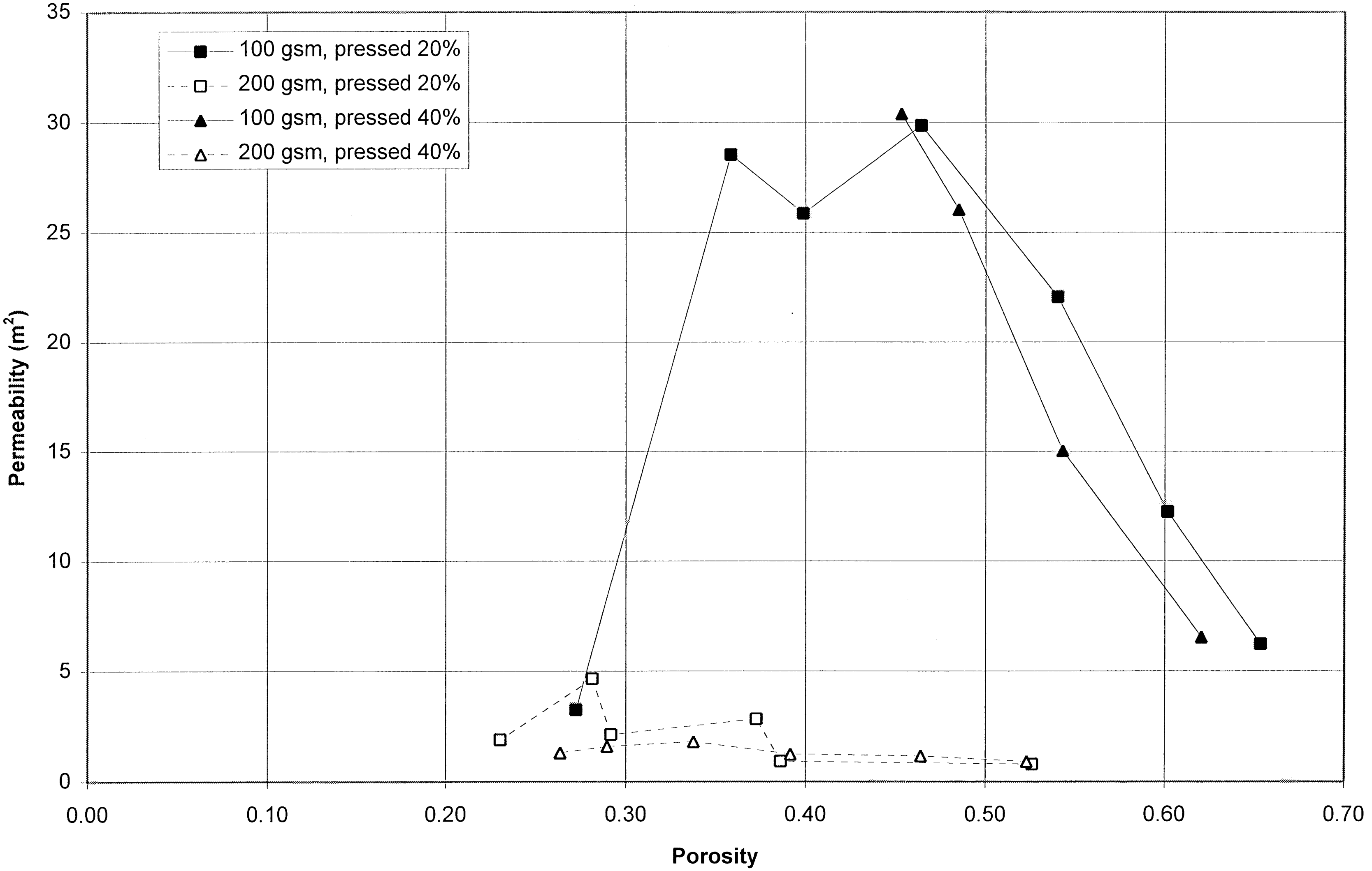


Figure 5. Air Permeability vs. Porosity - Bleached Sheets



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APerm B F5

Figure 6. Air Permeability vs. Solids - Unbleached Sheets

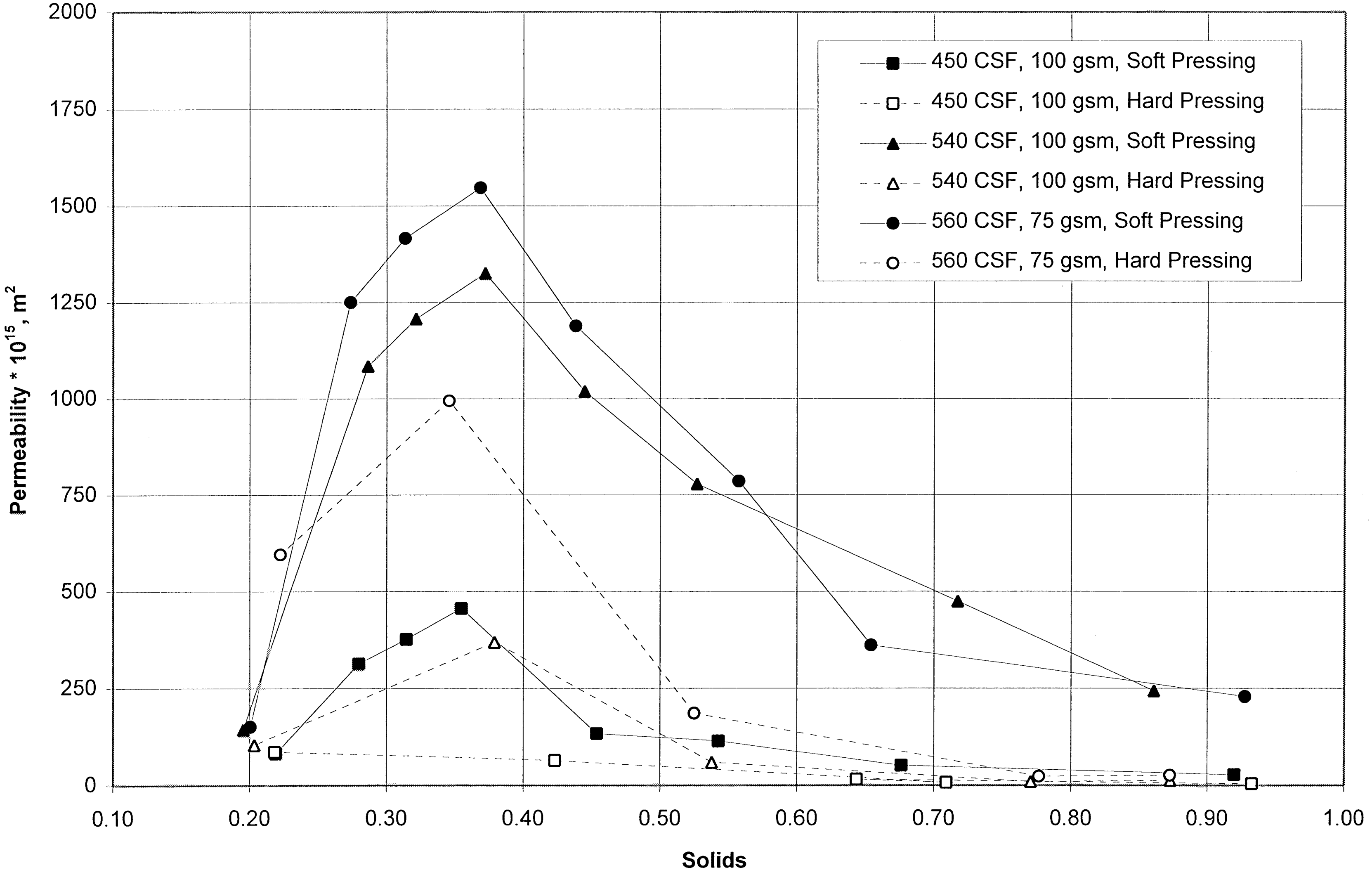

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Figure 7. Air Permeability vs. Porosity - Bleached Sheets

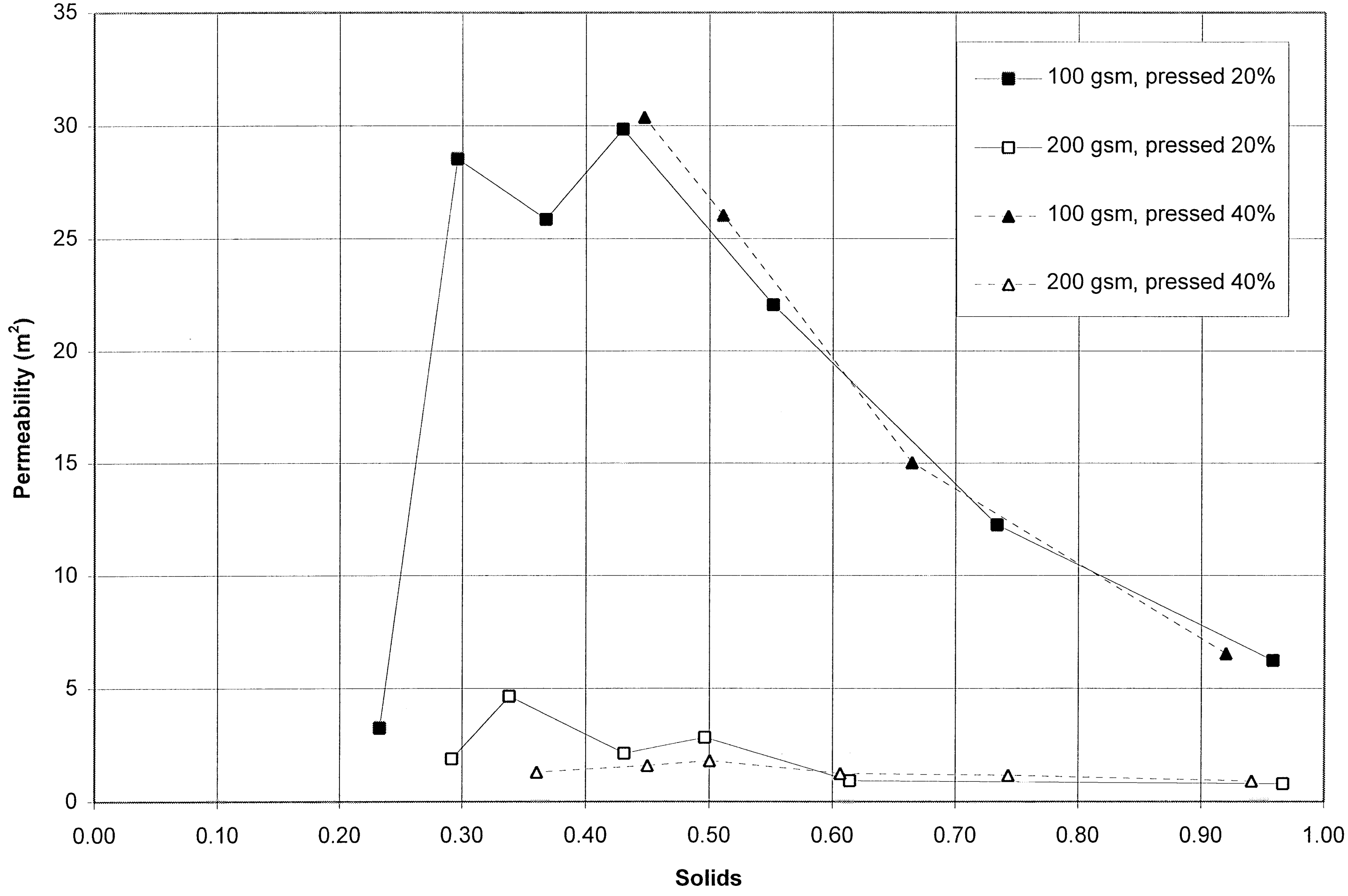

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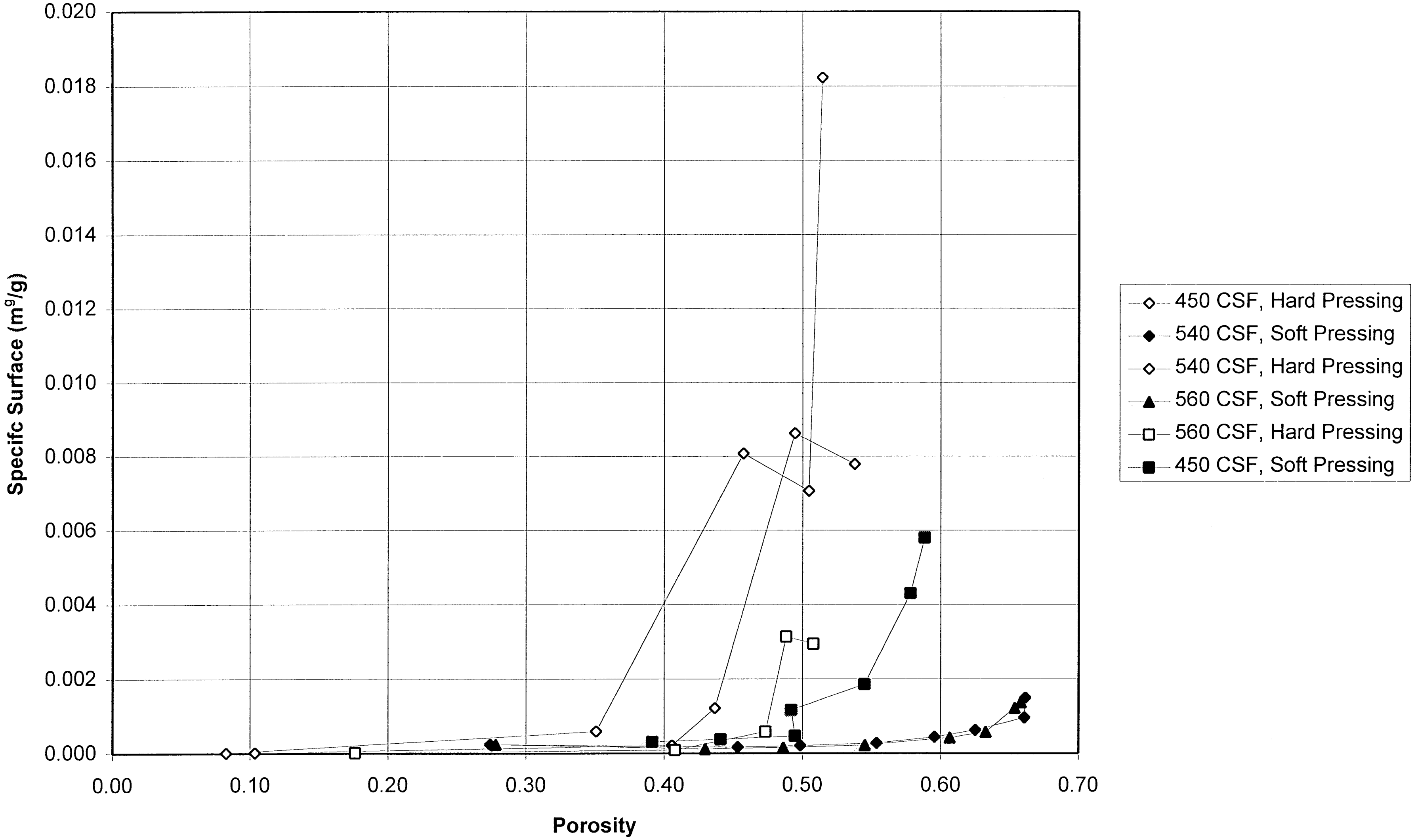
Figure 8. Specific Surface (Air) vs. Porosity
Unbleached Sheets



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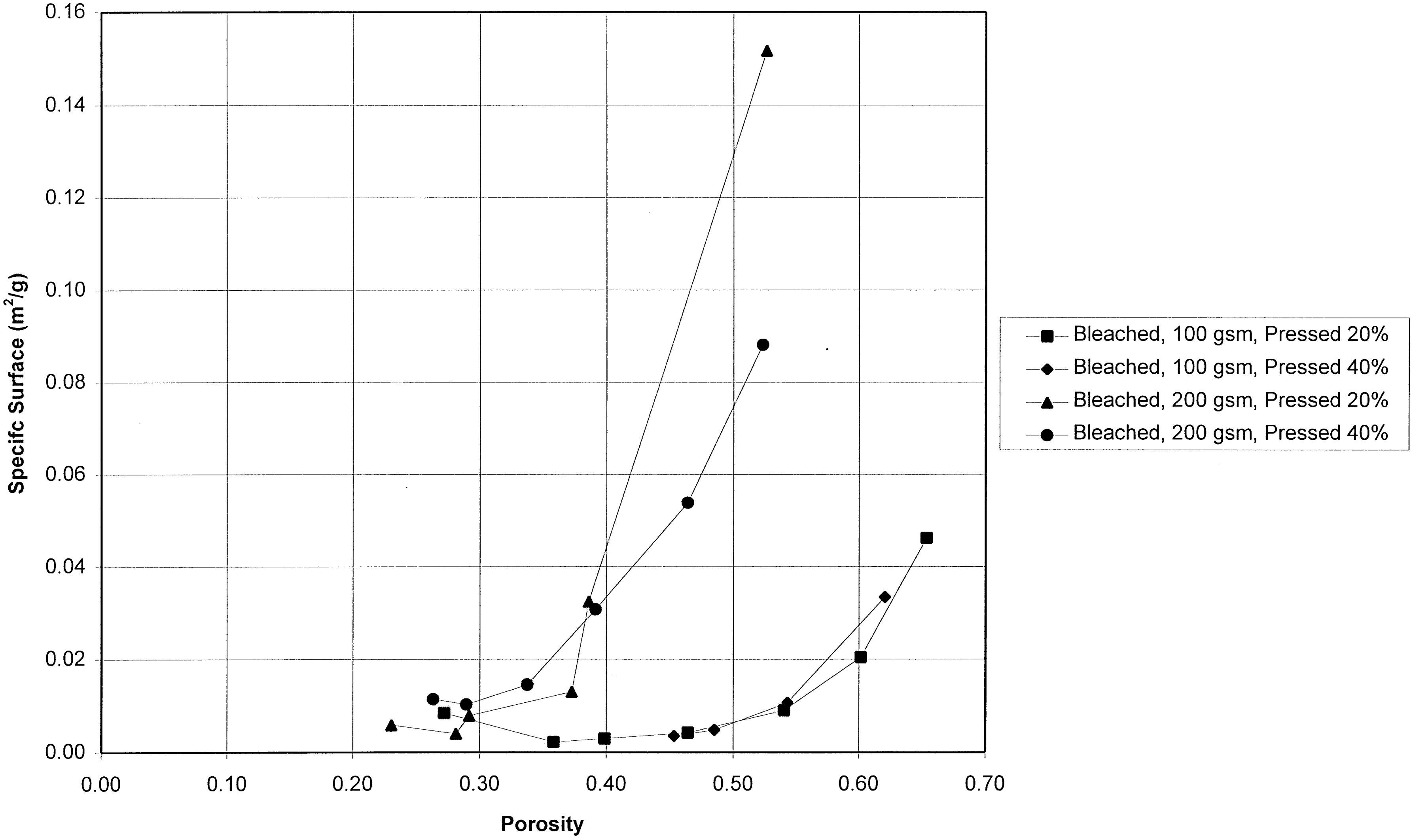
SpSurf-PorUB F8

Figure 9. Specific Surface (Air) vs. Porosity
Bleached Sheets



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SpSruf-PorB F9

Figure 10. Specific Surface (Air) vs. Solids
Unbleached Sheets

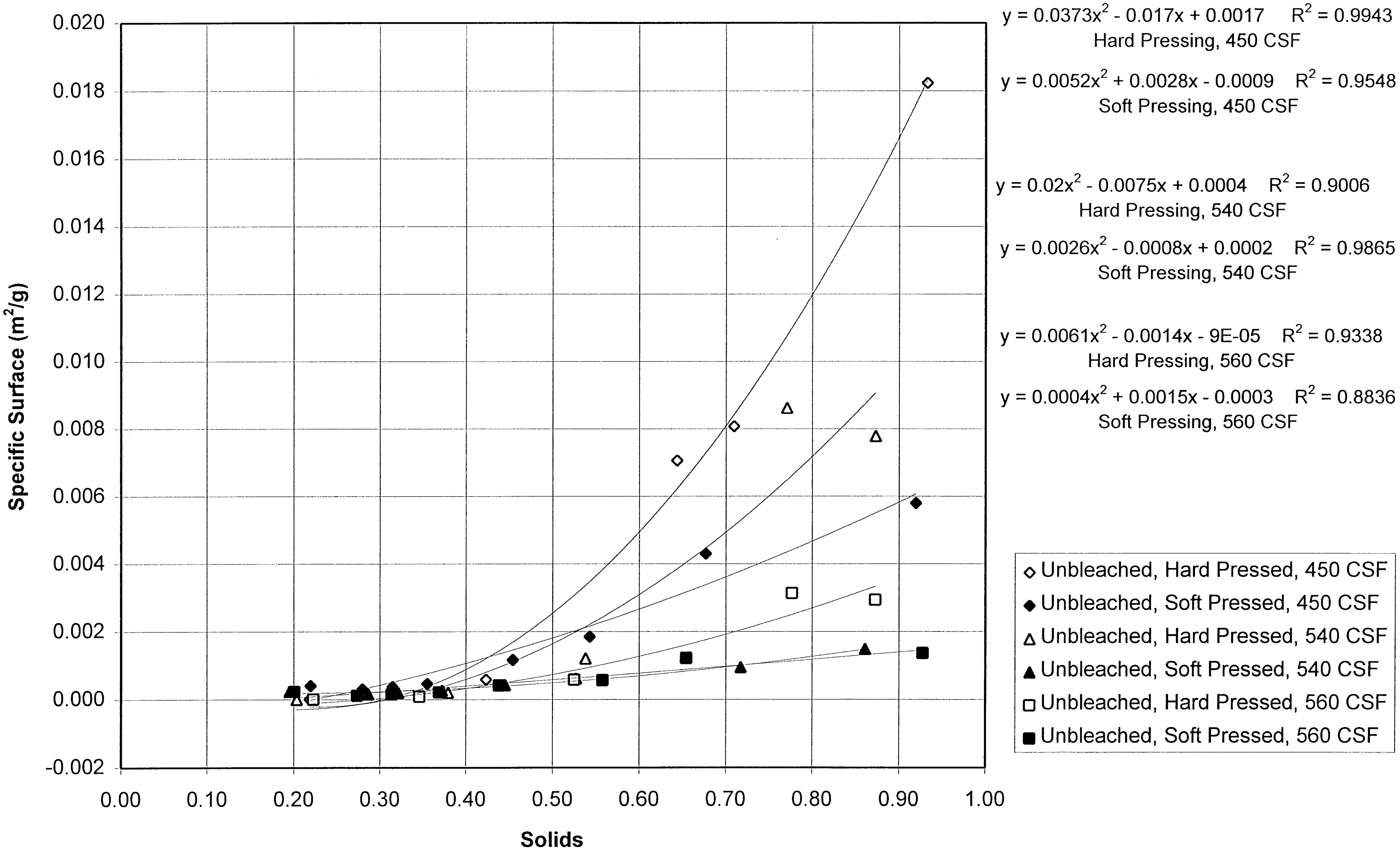

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Figure 11. Specific Surface (Air) vs. Solids
Bleached Sheets

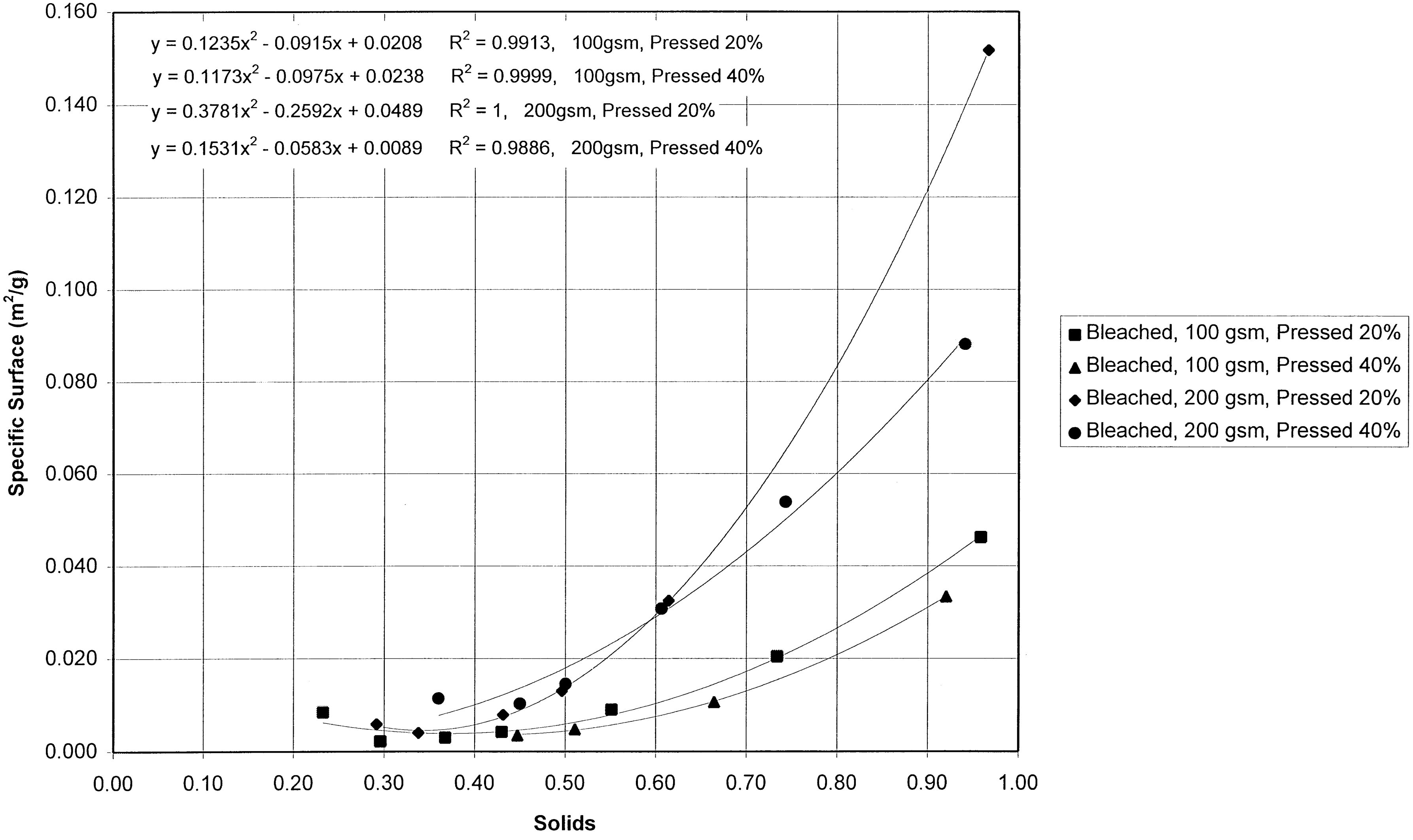
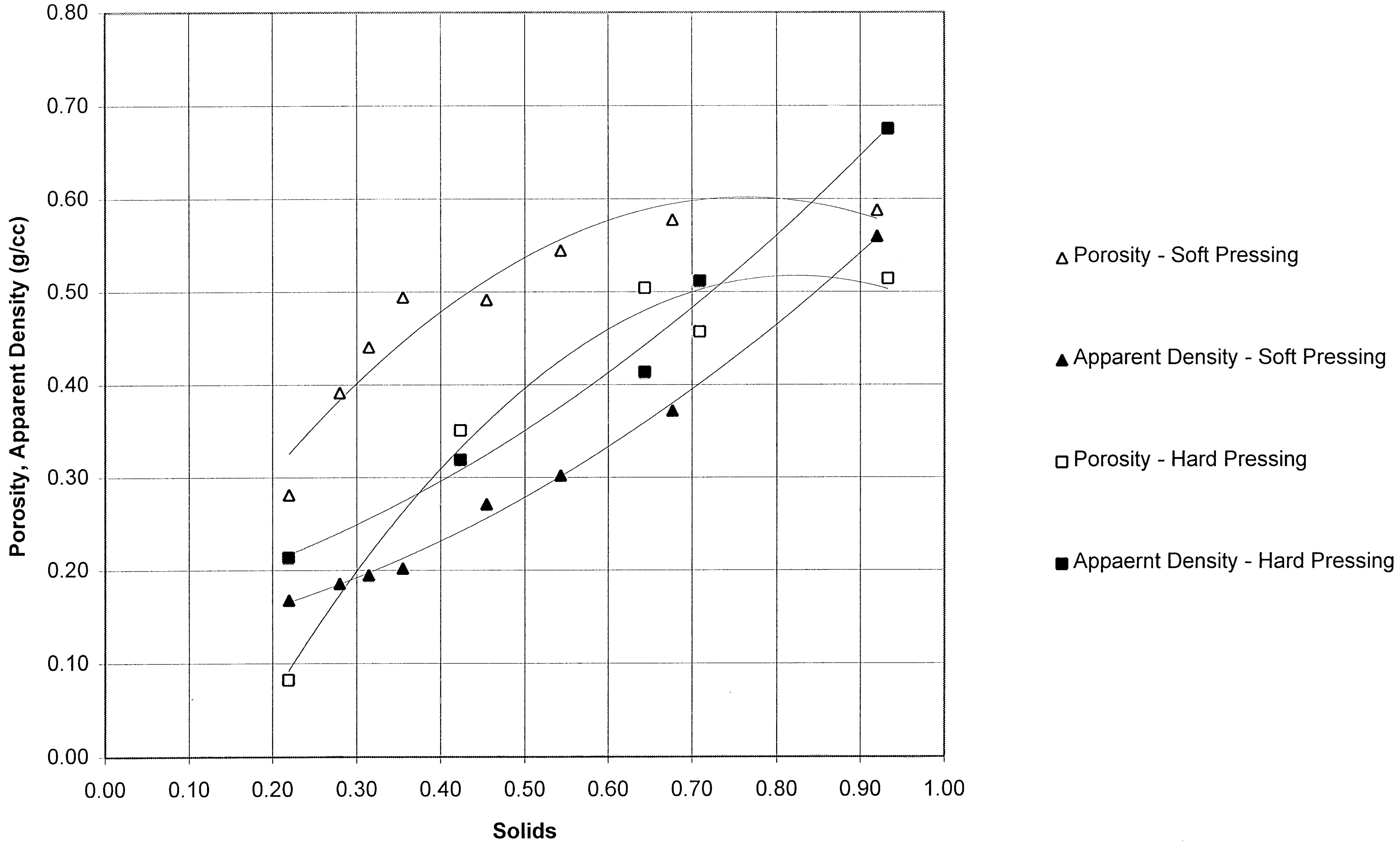


Figure 12. Porosity and Apparent Density vs. Solids
Case 450 CSF, 100 gsm



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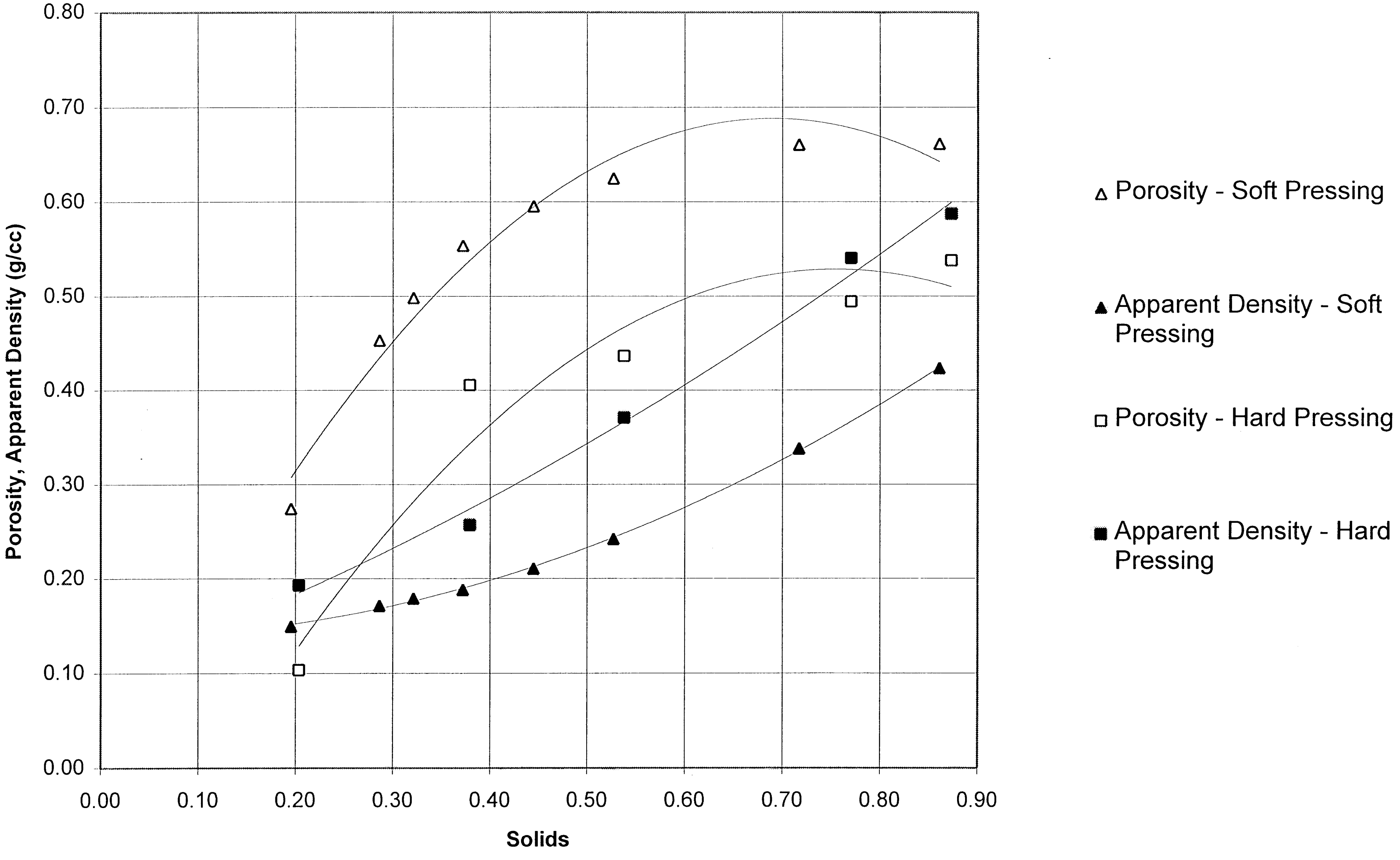
450PorSolids F12

Figure 13. Porosity and Apparent Density vs. Solids
Case 540 CSF, 100 gsm



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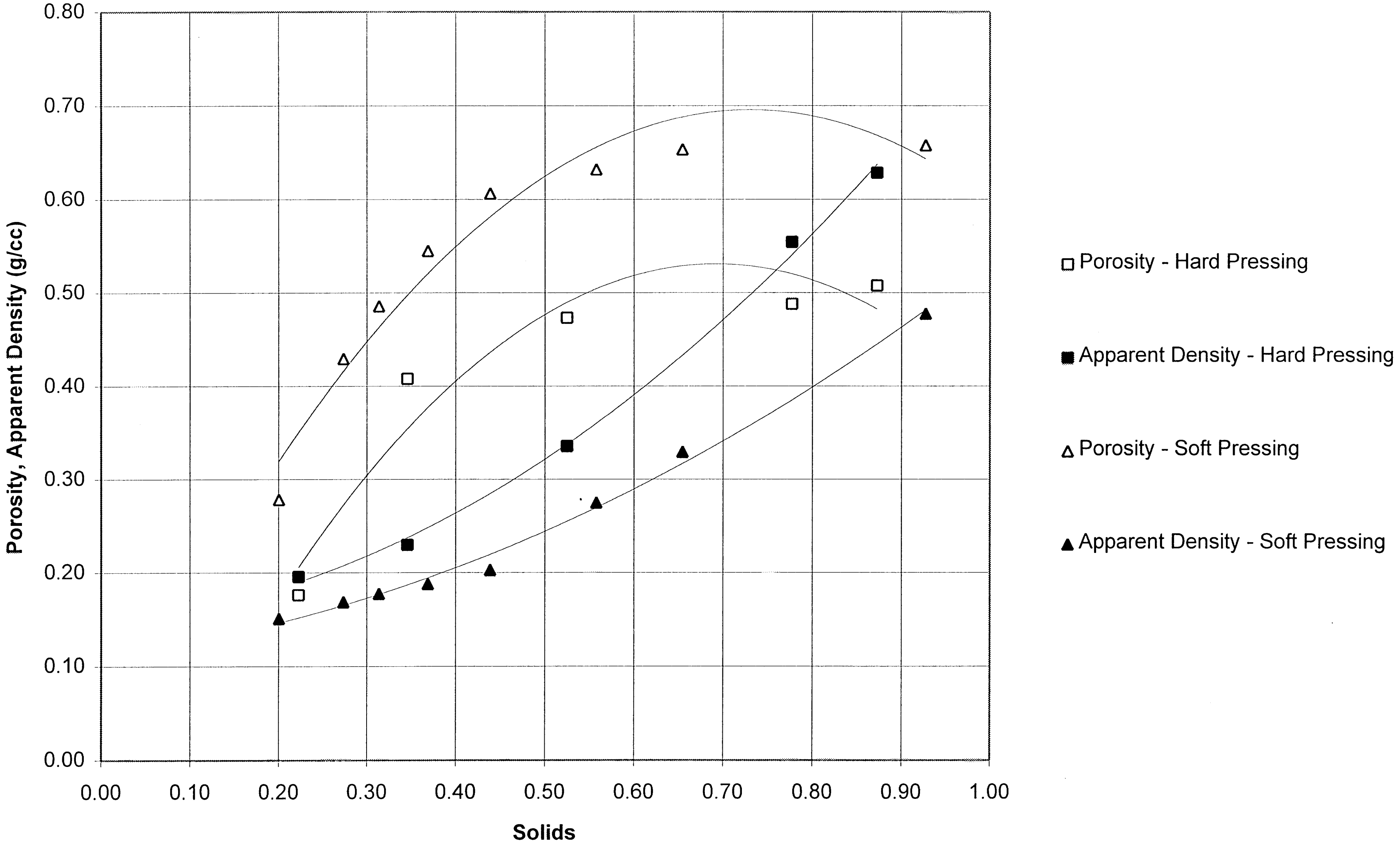
540Por Solids F13

Figure 14. Porosity and Apparent Density vs. Solids
Case 560 CSF, 75 gsm



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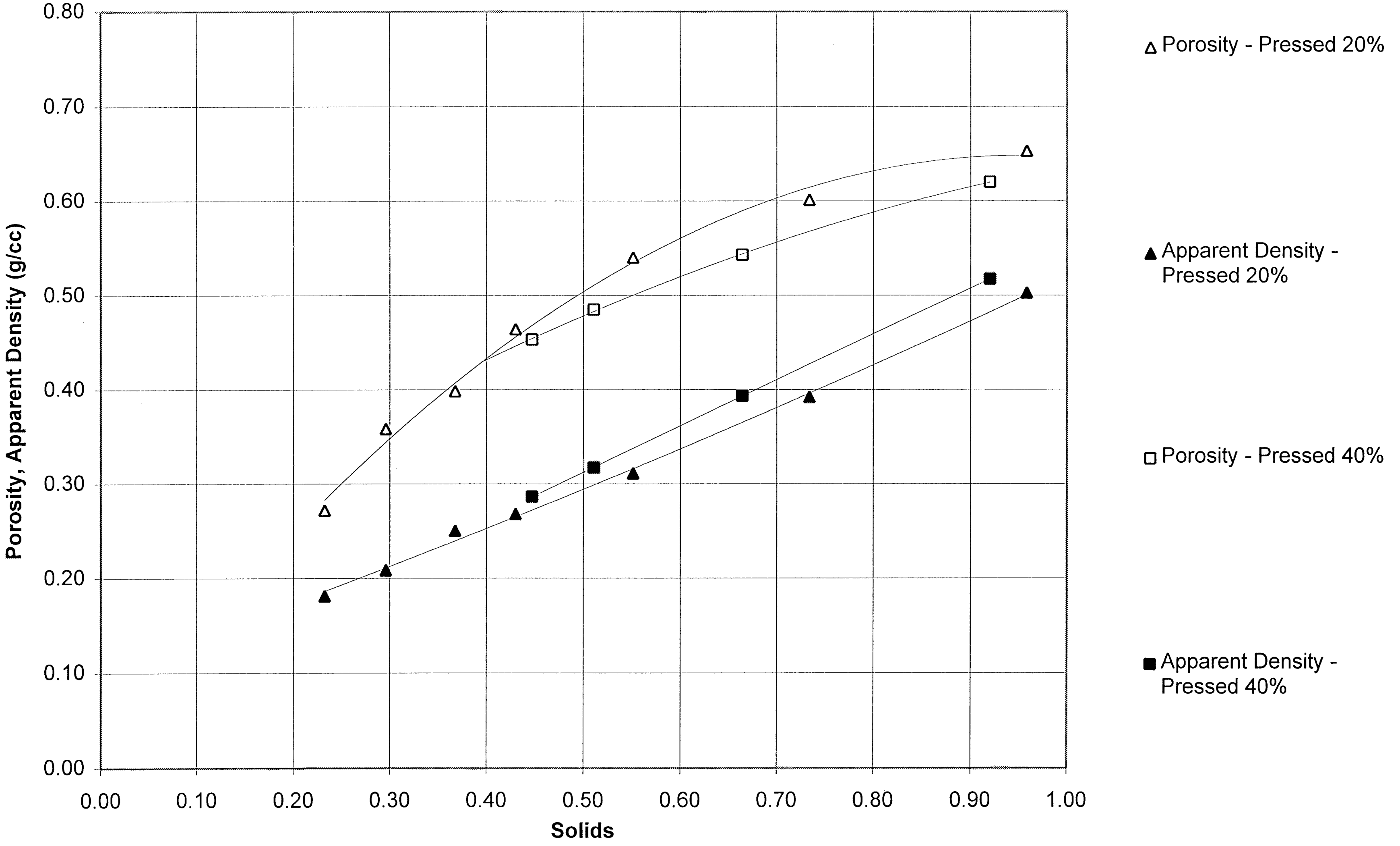
560PorSolids F14

Figure 15. Air Permeability, Porosity and Apparent Density vs Solids
100 gsm Bleached Sheets



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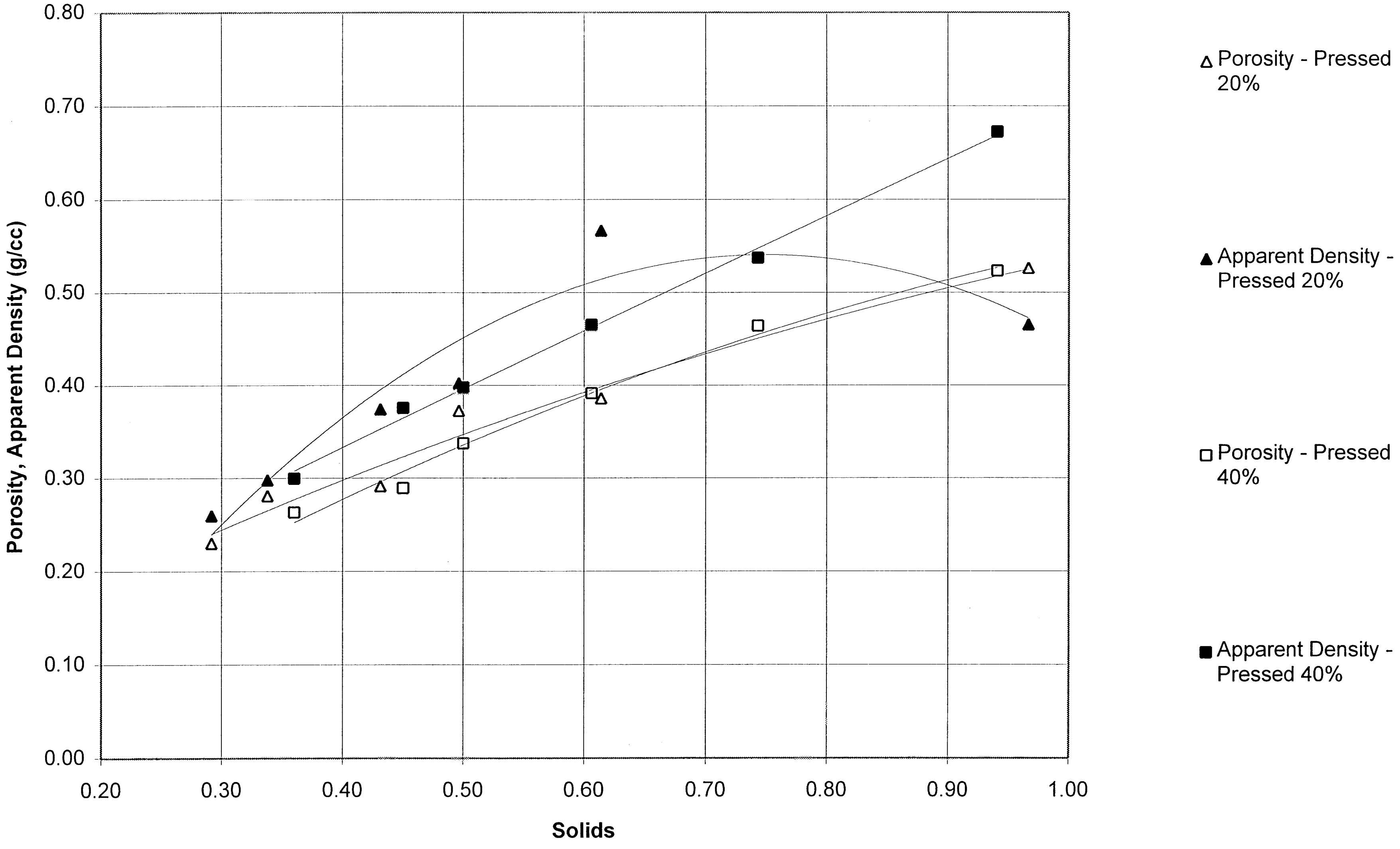
1bPorSolids F15

**Figure 16. Air Permeability, Porosity and Apparent Density vs. Solids
200 gsm Bleached Sheets**



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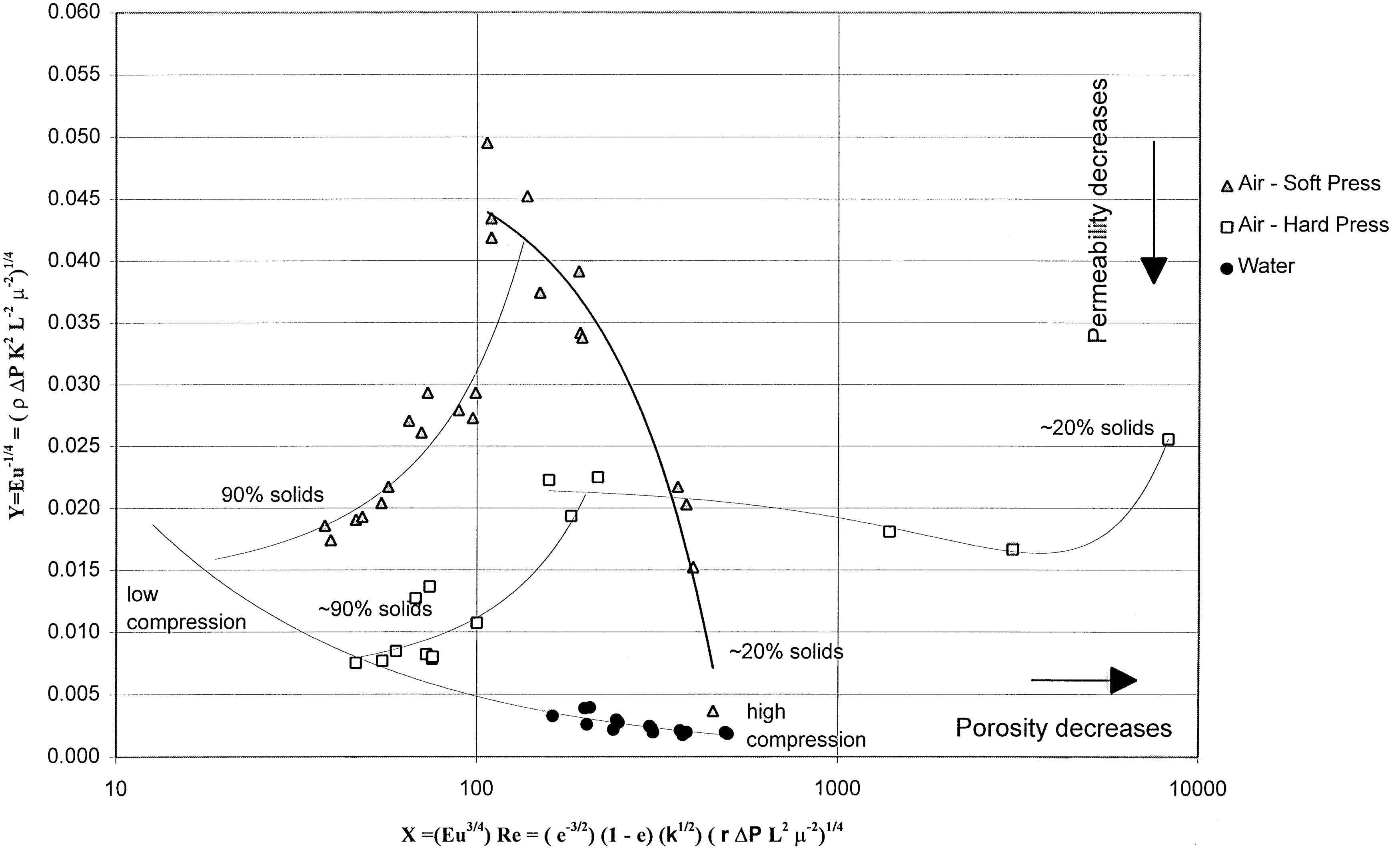
2bPorSolids F16

Figure 17. Y vs. X - Case 450 CSF, 100 gsm, Unbleached



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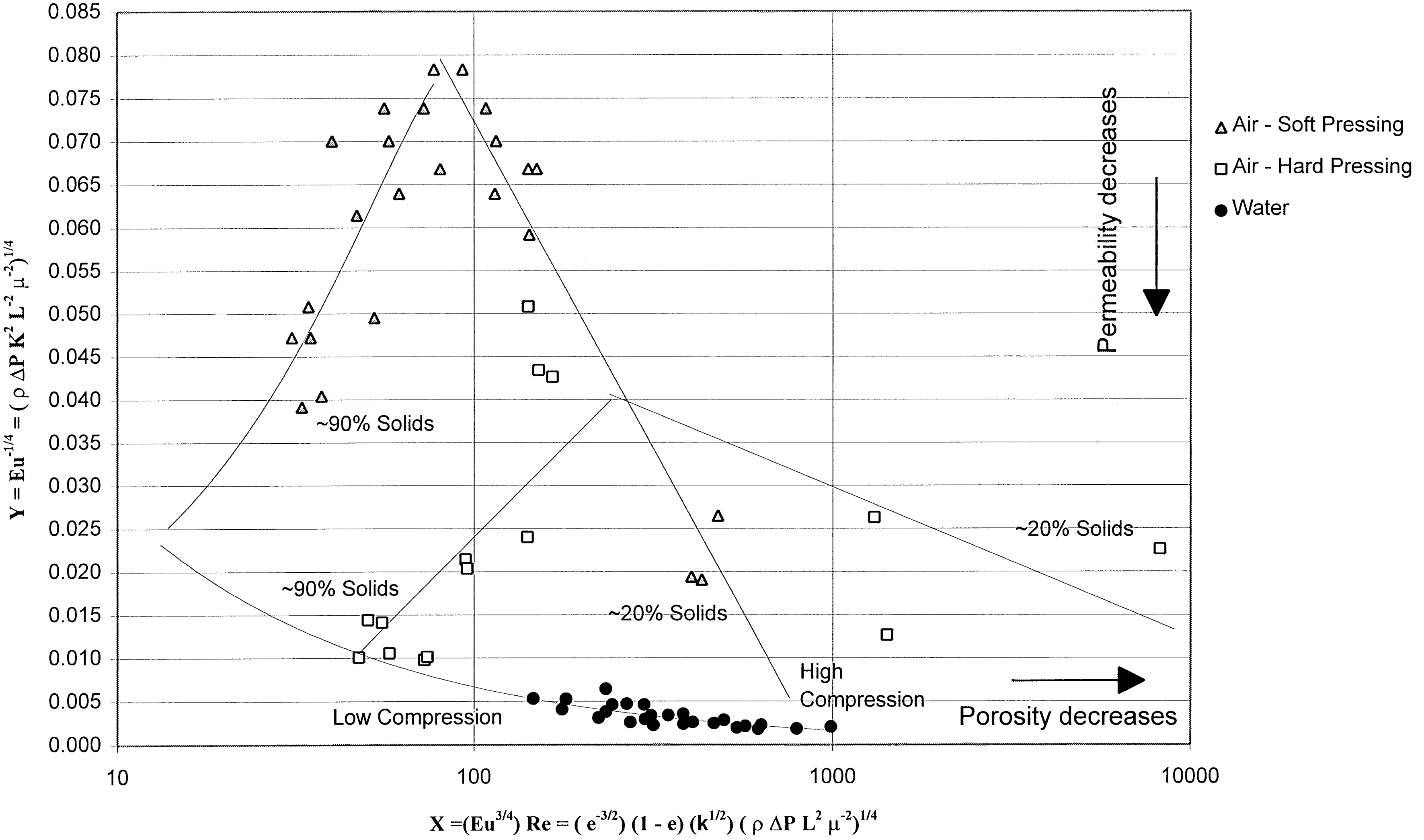
450XvsY F17

Figure 18. Y vs. X - Case 540 CSF, 100 gsm, Unbleached



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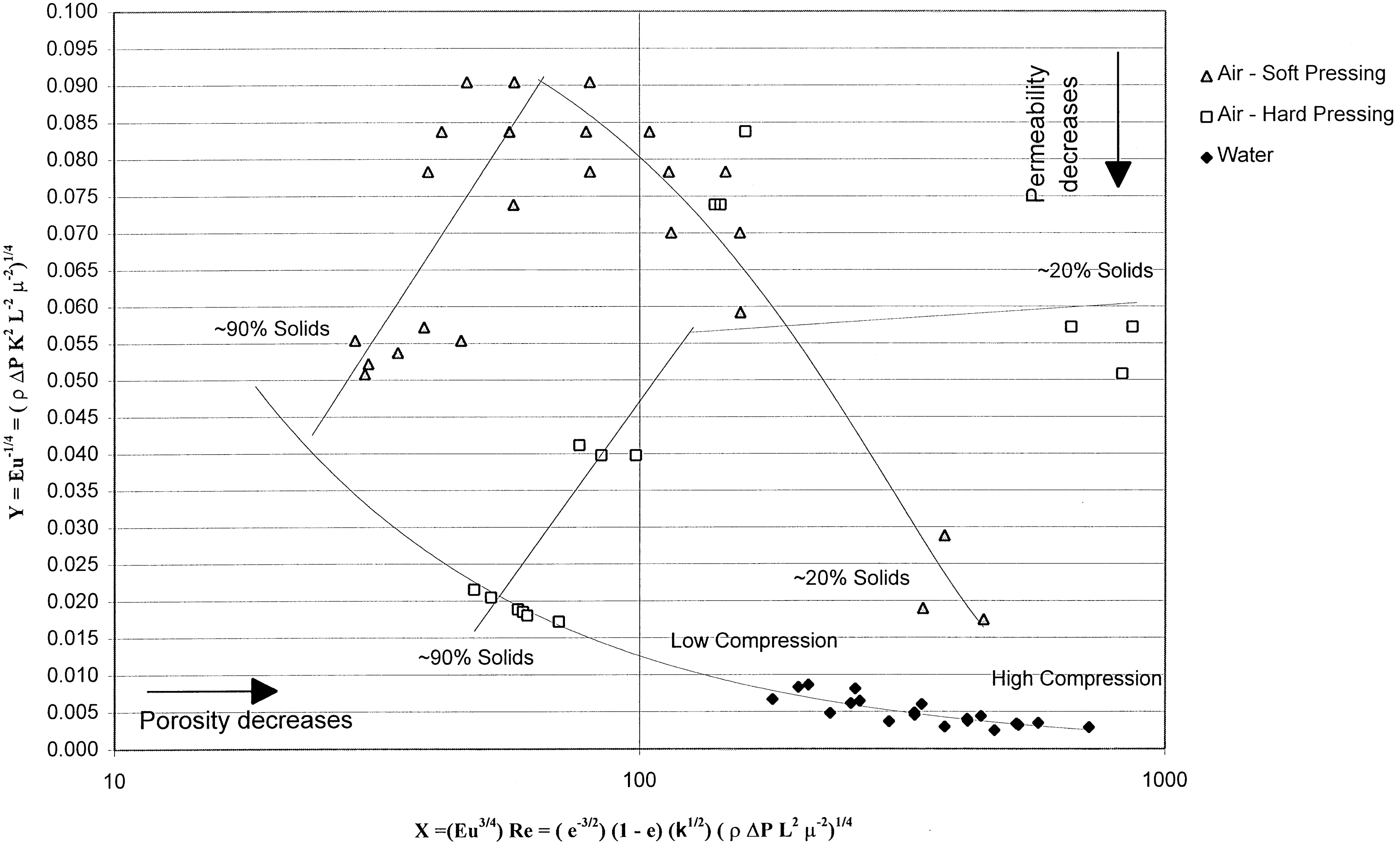
540XvsY F18

Figure 19. Y vs. X - Case 560 CSF, 75 gsm, Unbleached



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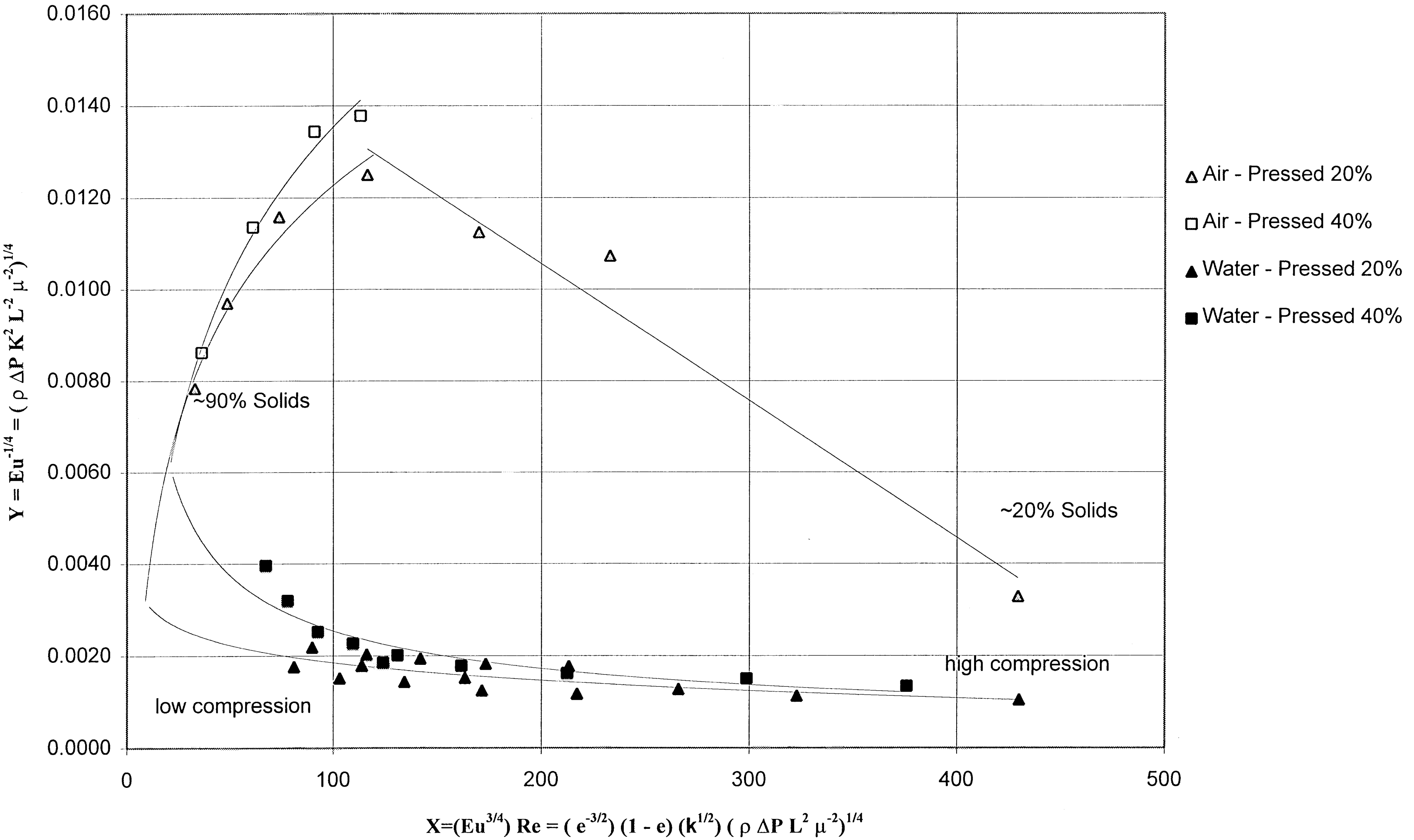
560XvsY F19

Figure 20. Y vs. X - 100 gsm, Bleached Sheets



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1bXvsY F20

Figure 21. Y vs. X - 200 gsm, Bleached Sheets