THE TRANSPORT OF WATER IN WET-FORMED NETWORKS OF CELLULOSE FIBERS AND POWDERED SUPERABSORBENT

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ABSTRACT

The wicking behavior of water into wet-formed paper strips consisting of cellulose fibers and varying proportions of powdered carboxymethyl cellulose superabsorbent is investigated and contrasted with the performance of similar composites made with the superabsorbent in fiber form. The degree of pore blocking caused by the swelling of the powdered superabsorbent is found to be significantly greater than that produced by the fibrous form, at the same superabsorbent loading.

Keywords: Wicking, absorbency, superabsorbents, fiber swelling, Lucas-Washburn theory, gel blocking.

INTRODUCTION

Composite media consisting of wood pulp fibers and superabsorbent material have become important components of a variety of absorbent products. In their design, investigators have attempted to achieve both rapid liquid uptake as well as high liquid retentivity under pressure, a property to be obtained through the use of superabsorbent. The designs, however, have always involved compromises between these two attributes. The rapid swelling of the superabsorbent particles often leads to a partial or sometimes total blockage of the pore spaces through which the imbibing liquid must travel. The latter condition is a form of "gel blocking." The present work seeks to quantitate the gel blocking tendency in a model system in which the swelling properties of the individual components are determined independently. An earlier study (Schuchardt and Berg 1991) investigated the wicking of water into random composite networks consisting of cellulose and carboxymethyl cellulose superabsorbent (CMC) fibers of approximately the same size and shape in the dry state. The extent, morphology, and kinetics of the swelling of both the cellulose fibers and the CMC fibers were determined independently by a Wilhelmy technique (single fiber microtensiometry) described in detail elsewhere (Berg 1986; Hodgson and Berg 1988; Schuchardt and Berg 1991). Both fibers displayed substantial circumferential but negligible axial swelling. The perimeter increase of the cellulose fibers averaged approximately 10% (volumetric swelling: 20%) and was achieved both effectively and instantly (usually within five seconds of contact with water). The CMC fibers, on the other hand, showed an average perimeter increase of approximately 120% (volumetric swelling: 400%), with roughly 80% of the increase achieved at a constant rate over times ranging from 30 to 60 seconds. The balance of the increase required two to five minutes. The wicking behavior of water into composites of various ratios of CMC to cellulose fibers was determined for two different structures: strips cut from wet-formed handsheets and air-laid pads. Both displayed a progressive decrease in water permeability with superabsorbent content, but with a notable exception. For short times or wicking distances at 15% or less CMC content in the handsheet strips, there was actually an *increase* in the permeability relative to that obtained in the equivalent strip of pure cellulose. Decreases in initial permeability were not observed until the CMC content exceeded 20%. This effect was attributed to the existence of open channels, paralleling the CMC fibers, created when the wet-formed strips were subsequently dried before the wicking trials.

Many absorbent products consisting of cellulose fibers and superabsorbent material contain the latter in the form of particulates, i.e., powders or pellets. The present work seeks to determine the wicking characteristics of cellulose fiber—CMC strips in which the superabsorbent is distributed throughout the strip in powder form. The same materials as used in the earlier study of Schuchardt and Berg (1990), and fully characterized with respect to their swelling characteristics, are to be used in the present work. We wish in particular to compare the performance of strips containing the same proportion of superabsorbent and therefore to isolate the effect of the shape (powder vs. fiber) of the superabsorbent particles on the wicking performance.

MATERIALS AND METHODS

The cellulose fibers used were obtained from Whatman #4 filter paper, and consisted of fully hydrophilic bleached wood pulp. The superabsorbent used was obtained from Aquasorb FC fibers, Hercules Chemical Company, Wilmington, DE. It consisted of a highly swellable, cross-linked sodium salt of carboxymethylated wood pulp fibers, with a degree of substitution of 0.7. The latter fibers were chopped into powder form using a Thomas-Wiley mill (Model ED-5), Arthur Thomas Co., Philadelphia, PA. The fibers were broken into lengths ranging from one to ten diameters (average aspect ratio 3 to 4), as determined by optical microscopy. The volumetric swelling characteristics of the powder particles were assumed to be the same as those of the original fibers.

The wicking media were 1-cm-wide paper strips cut from handsheets prepared from various proportions of cellulose fibers and powdered superabsorbent. The handsheets were prepared using the methods (modified as described below) and equipment described in TAPPI Method T205 OM81. After initial formation of the wet sheet of cellulose fibers, the CMC powder was deposited evenly over its surface using a shaker. Then a dry sheet of filter paper was placed over the top and compressed with the roller in the usual manner. After drying, the filter paper oversheet was removed. This procedure was found to distribute the powder fairly evenly throughout the sheet with only minimal loss. The distribution of powder was verified by optical microscopy, and the fact that nearly all of the powder remained in the sheet was verified at least qualitatively by the comparison shown in Fig. 1. This compares the wet weight of the composite sheet as a function of the nominal percent superabsorbent in powdered form against that obtained when the superabsorbent was in fibrous form. The water retention, and hence the amount of superabsorbent retained, was found to be comparable in the two cases. The resulting sheets had a dry weight of 1.3–1.4 g. Handsheets were prepared at 0, 10, 20, and 30% superabsorbent by weight, above which sufficient structural strength could not be maintained.

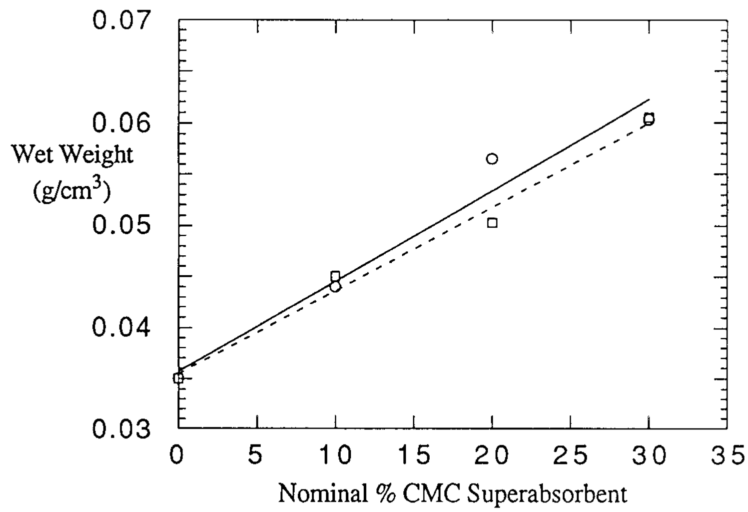

FIG. 1. Wet weight of composite strips of cellulose and CMC superabsorbent as a function of the nominal weight % CMC. (○) powder form of CMC, (□) fibrous form of CMC.

The liquids used were purified water (triply distilled in an all-quartz apparatus) and *n*-octane (Reagent grade), used as a fully wetting, nonswelling reference liquid.

Wicking measurements were carried out by hanging 10-cm-long paper strips, pre-marked at 1-cm intervals, inside an enclosed, vapor-saturated, glass chamber (to prevent evaporation during wicking), where they were contacted at the bottom with the wicking liquid. The course of wicking was monitored visually as a function of time. A timer was touched as the advancing liquid front passed each of the markers.

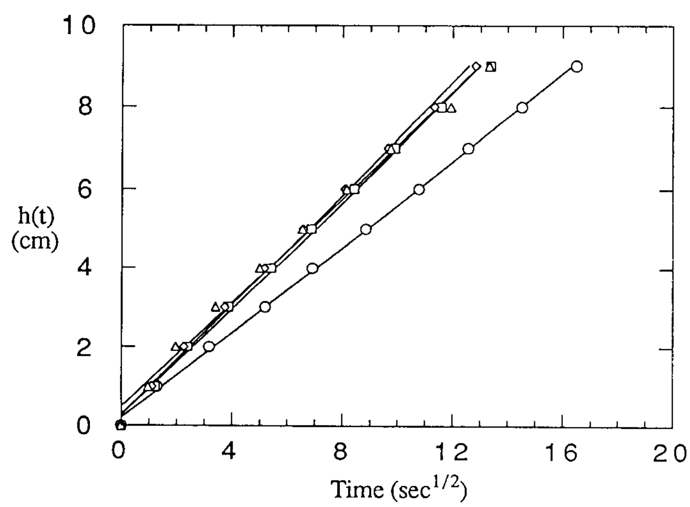

FIG. 2. Wicking distance vs. time$^{1/2}$ for the reference liquid, *n*-octane into cellulose-CMC composite strips, with CMC in powder form. (○) 0% CMC; (□) 10% CMC; (◇) 20% CMC; (△) 30% CMC.

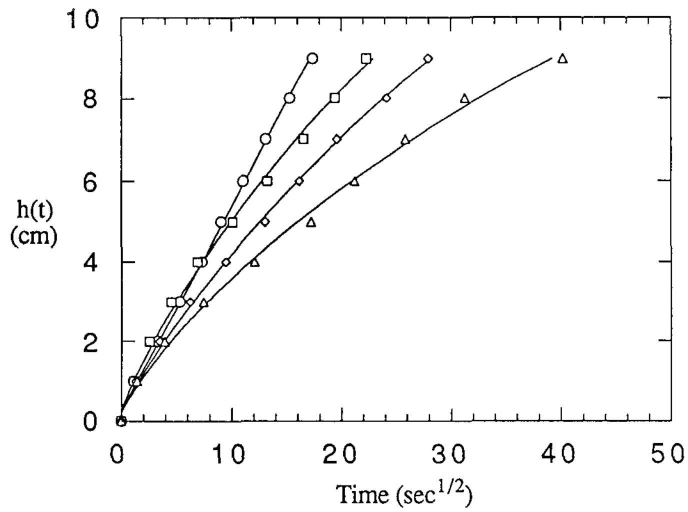

FIG. 3. Wicking distance vs. time$^{1/2}$ for water into cellulose-CMC composite strips, with CMC in powder form. (○) 0% CMC; (□) 10% CMC; (◇) 20% CMC; (△) 30% CMC.

Wicking data were analyzed with reference to Lucas-Washburn theory, which gives:

$$h(t) = \left[\frac{\sigma r_e \cos\theta}{2\mu}\right]^{1/2} t^{1/2} = kt^{1/2}, \tag{1}$$

where h(t) is the wicking distance as a function of time, t; σ is the surface tension of the liquid; r_e is the wicking-equivalent pore radius of the structure; θ is the contact angle of the wicking liquid against the solid (0° for both the water and the reference liquid, *n*-octane, so that $\cos\theta = 1$); and μ is the liquid viscosity. The slope k is referred to as the Lucas-Washburn constant. For situations in which neither structural nor chemical changes occur during the course of imbibition, Eq. (1) is obeyed, and plots of wicking distance vs. $t^{1/2}$ are straight lines. Experimental plots of this type may be used to evaluate the wicking-equivalent pore radius, r_e, in a given structure when the other factors in k are known independently. The use of *n*-octane as a nonswelling reference liquid permitted determination of r_e in the absence of any cellulose fiber or superabsorbent swelling. The zero-degree contact angle of *n*-octane against the fibers was verified by the fact that the liquid yielded mirror-image force traces in the advancing and receding modes. The specific effects of swelling (pore blocking) obtained with water were then quantified in terms of a permeability factor, P_f, defined as the ratio of the local wicking-equivalent radius to that obtained with the reference liquid in pure cellulose strips, viz.

$$P_f = \frac{r_{e,swollen}}{r_{e,ref}} = \left[\frac{k}{k_{ref}}\right]^2 \left[\frac{\sigma_{ref}}{\sigma}\right]\left[\frac{\mu}{\mu_{ref}}\right]. \tag{2}$$

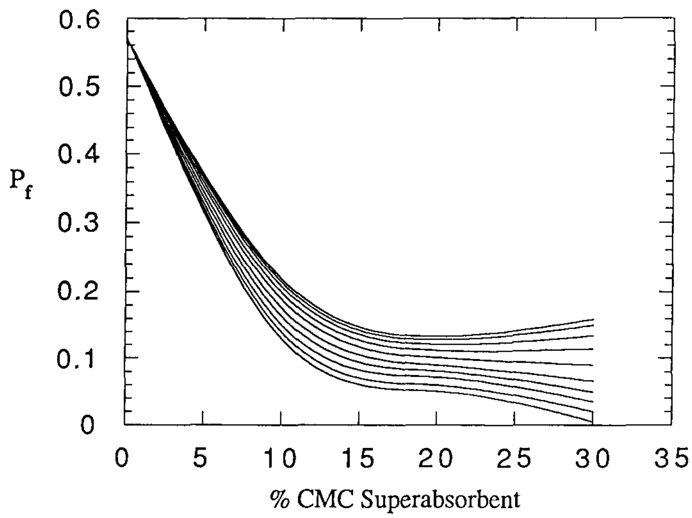

FIG. 4. Permeability factor for water in cellulose-CMC composite strips as a function of superabsorbent content. Curves from top to bottom correspond to wicking distances of 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9 cm.

The ratio of $\cos \theta_{ref}/\cos \theta$ is omitted from Eq. (2) since $\theta = 0°$ for both water and the reference liquid.

RESULTS AND DISCUSSION

Lucas-Washburn plots of the wicking results obtained with the reference liquid, *n*-octane for paper strips consisting of 0 to 30% superabsorbent powder, are shown in Fig. 2. Straight lines were obtained in all cases, and the slopes obtained were approximately 20% larger when the superabsorbent was present. Thus the wicking-equivalent radii were increased by approximately 44%, an effect not significantly different in the range of 10 to 30% superabsorbent. This contrasted with the effective pore enlargement of approximately 70% obtained with the same CMC superabsorbent in fibrous form (Schuchardt and Berg 1991).

Figure 3 shows Lucas-Washburn plots obtained with water in a pure cellulose strip and for composite strips of 10, 20, and 30% superabsorbent. As in previous observations, the wicking of water into pure cellulose strips followed Lucas-Washburn kinetics, even though the cellulose fibers were known to swell, and the computed permeability was only approximately 57% of that indicated in the wicking tests with *n*-octane. Since the swelling of the cellulose fibers is effectively instantaneous, the straight-line Lucas-Washburn behavior is maintained. The composite strips displayed increasing deviation from Lucas-Washburn kinetics in proportion to superabsorbent content. Deviations occurred because the time scale for the swelling of the superabsorbent was equivalent to the time scale of the wicking itself. Thus the pore spaces were gradually closing as the wicking proceeded. The extent of the deviations is shown in greater detail in Figs. 4 and 5 in terms of the permeability factor, P_f, defined in Eq. (2). *Local* values of P_f were computed at each centimeter of wicking distance for each of the composite strips investigated and are shown as a function of superabsorbent content at

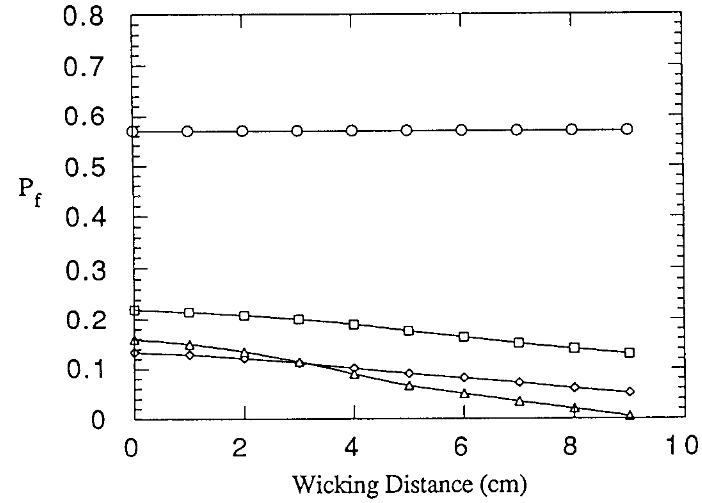

FIG. 5. Permeability factor for water in cellulose-CMC composite strips as a function of wicking distance. (○) 0% CMC; (□) 10% CMC; (◇) 20% CMC; (△) 30% CMC.

various wicking distances in Fig. 4 and as a function of wicking distance for various superabsorbent contents in Fig. 5. Quite extensive pore blocking was evident even at only 10% superabsorbent content, and only slight increases in the effect were observed as the content increased to 30%. As expected, the effects of pore blocking were greater at the larger wicking distances.

The specific objective of the present work was to compare the behavior of composite strips containing superabsorbent in powdered form with that obtained using the same superabsorbent in fiber form. This comparison is shown in Figs. 6 and 7 at wicking distances of 0 and 8 cm, respectively. Figure 6 shows the

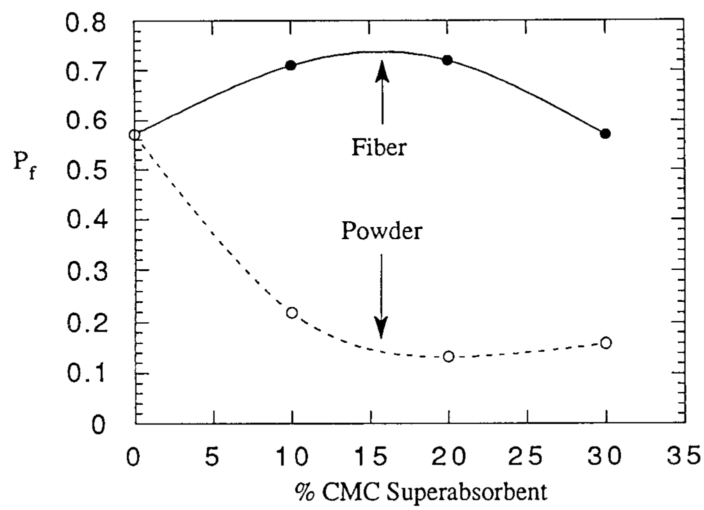

FIG. 6. Comparison of permeability factors at zero wicking distance for water in cellulose-CMC superabsorbent composite strips with the superabsorbent in powder vs. fibrous form.

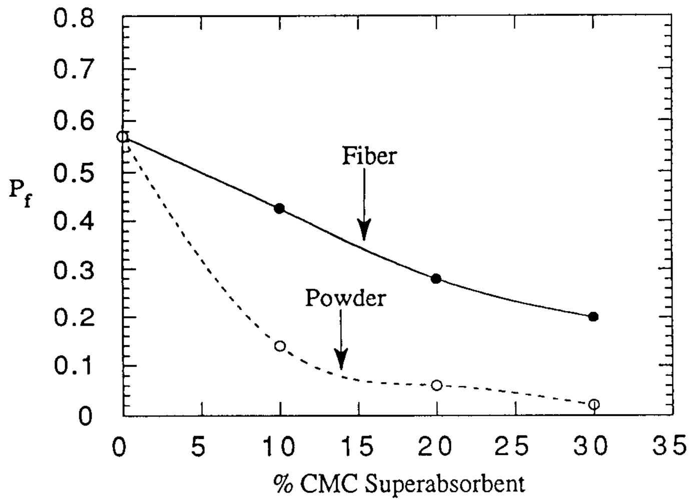

FIG. 7. Comparison of permeability factors at a wicking distance of 8 cm for water in cellulose-CMC superabsorbent composite strips with the superabsorbent in powder vs. fibrous form.

increase in permeability obtained at low superabsorbent contents with the superabsorbent in fibrous form, attributed earlier to the open channels created in the structure as the wet-formed strips were dried. The powdered superabsorbent produced no such enhancement in permeability. This may be explained by the fact that the pore spaces created during drying of the powder-containing composites were more likely in the form of isolated cells than long channels along which rapid wicking could occur. Thus with the powder superabsorbent, the compensatory opening of the pore spaces due to the presence of the superabsorbent was not as effective as in the case of the fibrous material. The fact that increasing the powder superabsorbent content from 10% to 30% produces only a minor deterioration in the permeability suggests that at the higher superabsorbent levels, the particles may be lining up to some extent to form channel-like openings. The overall results suggest that while especially effective absorbent structures may be constructed from wet-formed superabsorbent-containing composites in fibrous form, similar results may not be obtainable using superabsorbent in powdered form.

CONCLUSIONS

The wicking behavior of wet-formed composite materials of cellulose fibers and superabsorbent depends significantly on the geometric form of the superabsorbent. Specifically, when superabsorbent is in the form of powder rather than fibers, significant pore blocking occurs at lower superabsorbent levels and at shorter wicking distances. These observations are attributed to the differences in the shapes of the open spaces created when the composite materials are dried. The channel-like pore spaces created by the dried superabsorbent fibers are more effective in promoting rapid wicking and compensating for the ultimate effects of the re-swelling than are the isolated cell-like openings created by the dried superabsorbent in powdered form.

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