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Properties and applications of externally impregnated shaped fibers

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Abstract

Polymeric fibers have been produced in an array of geometric cross-sections, all of which possess deep channels along the length of the fiber. These shaped fibers have been made in many different formats including wovens, nonwovens, and parallel arrays. A number of polymeric materials are suitable to retain these nonround cross-sections during spinning; they include polyolefins, polyesters, and polyamides. Specific cross-sections have been observed to capture and tenaciously retain high levels of both liquids and finely divided solids within the channels of the fibers. The liquids are held through capillary forces, while the solids are mechanically entrapped within the channels and do not require adhesives to bond. Their retention is sufficient to allow these impregnated fibers to be used in high-flow applications without experiencing loss of the reagents.

Exploiting this property, one can use this type of fiber to support a host of reagents in a practical format for various applications.

Keywords: Impregnated shaped fibers; A. Polymer textiled fibre

1. Introduction

Fibers of polymeric materials have been made in various cross-sections in order to enhance their physical properties and performance in carpet and textile applications. Usually these applications have centered on their strength, water wicking, or insulating property. The range of cross-sections possible is limited only by the ability of the polymer to retain its shape during the spinning process. This type of fiber can also be looked upon as another member of the much larger family of low-density materials and share in the emerging applications. Many of these applications involve filling the voids with useful reagents. This type of nontraditional composite material is able to combine a wide range of diverse materials and properties.

This paper focuses on the development of a particular fiber cross-section that appears to have a high capacity to entrap both liquids and solids within the longitudinal channels of the fiber. There have been many types of fibrous materials in which reagents have been glued or bound onto the fiber surface. Generally this comes with a diminishment in the ability of the reagent to function. Physically entrapping the reagent within open channels allows the reagent to function and obtain the maximum benefit of the special properties of the reagent chosen.

2. Experimental methods

2.1. Fiber media

The fiber was prepared from polypropylene as a point-bonded nonwoven consisting of individual fibers spun in a triad configuration. The average fiber diameter was 32 μm with a media density of 1.5 oz yd^{-2}.

Wicking fiber media intended for liquid impregnation were first treated with 1% (wt/v) aqueous solution of FC-94 fluorochemical surfactant (3M Specialty Chemicals, St. Paul, MN) and subsequently air dried. A sufficient quantity of the reagent solution to be tested was applied to the pretreated media, and allowed to permeate the entire surface and interior. A 15% (wt/v) solution of sodium permanganate with 10% (wt/v) trisodium phosphate was used for the gas filter testing of acetaldehyde, sulfur dioxide, and hydrogen sulfide.

Powder impregnated media were prepared by coating the virgin media with the desired finely divided solid powder followed by light burnishing of the media. The powders tested included commercially available ultrafine powdered

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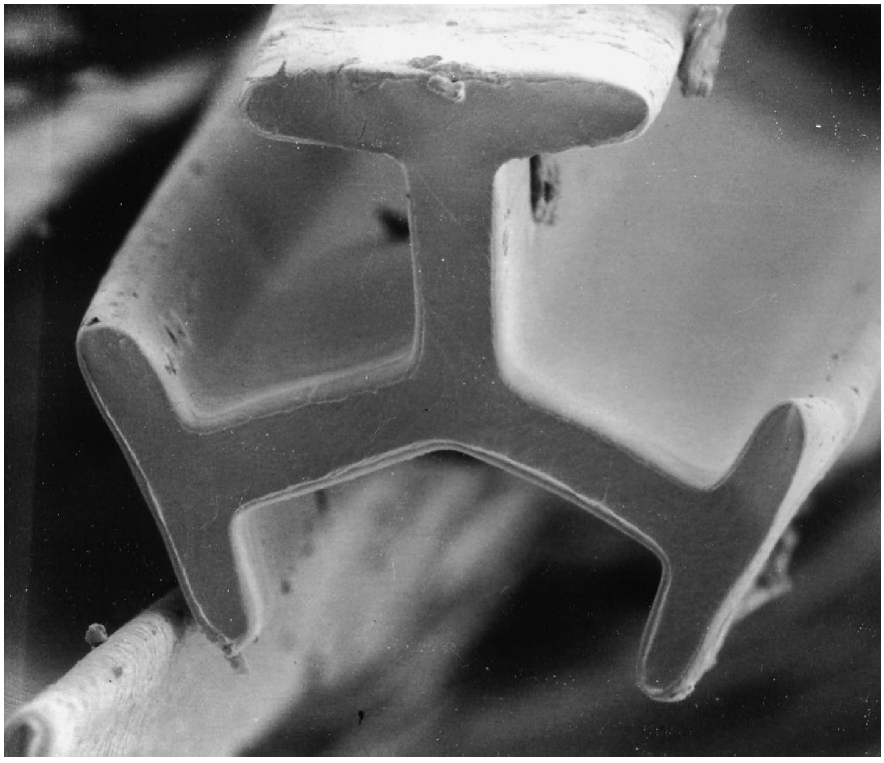

Fig. 1. A scanning electron microscope cross-sectional image of an individual triad polypropylene fiber (32 μm diameter).

PTFE, activated carbon, graphite, alumina, silica, zeolite, agarose, and ferromagnetic powder. The excess powder was removed by agitation and blowing with air using an air gun supplied with 20 psi compressed air. Carbon impregnations used commercially available powder-activated carbon.

2.2. Test apparatus

Several laboratory-scale test stands were used to permit simultaneous analyses of the test gases. The test stands were constructed of stainless and/or PTFE tubing connected by the appropriate stainless steel fittings and valves. All tests were done at ambient room temperature. The compressed air was humidified to 50 ± 5% RH, and concentrated forms of the test gases were introduced into the humidified air stream via flow meters to yield the desired challenge concentrations. The challenge concentration for acetaldehyde was 50 ± 2 ppm, while the diluted H_2S and SO_2 were introduced at concentrations of 10 ± 0.5 ppm and 8 ± 0.4 ppm, respectively. The sources of the acetaldehyde, H_2S, and SO_2 were compressed gas cylinders containing 2500 ppm, 100 ppm, and 200 ppm, respectively, with concentrations certified by Liquid Carbonics (Bethlehem, PA). The gas filter to be tested was secured by an in-house designed holder, and the filter could be tested in either a flat sheet or pleated configuration. Outlet ports on the filter holder were connected to a differential pressure meter, which measured the pressure drop across the filter in inches of water. The circular flat sheet had an outside diameter of 5.1 cm with an area of 11.3 cm^2 being exposed to the test gas. The pleated configuration had dimensions of 5.3 cm × 5.3 cm with a pleat depth of 2.5 cm.

The effluent concentration of the challenge gas was monitored by either a total hydrocarbon analyzer for acetaldehyde or a total sulfur analyzer for H_2S and SO_2. The total hydrocarbon analyzer is a flame ionization detector from Rosemount Analytical (Model 400A) equipped with a sampling pump to deliver the gas to the analyzer. The sulfur analyzer (Columbia Scientific, Model SA260) is a continuous emissions monitor containing a flame photometric detector. The detectors were calibrated by measuring both the compressed air stream and the challenge gas concentration with no filter in place. The progress of the breakthrough was also monitored by a chart recorder.

3. Results

A large number of fibers with various cross-sections have been studied. It was found that the cross-section in Fig. 1, termed the *triad*, demonstrated the greatest capacity to entrap both liquids and solids. After screening many different cross-sections, it was found that the addition of caps on the exterior lobes had a significant affect on the ability to entrap reagents irreversibly.

Graphical analysis of this cross-section reveals that roughly 50% of the volume exists within the channels of

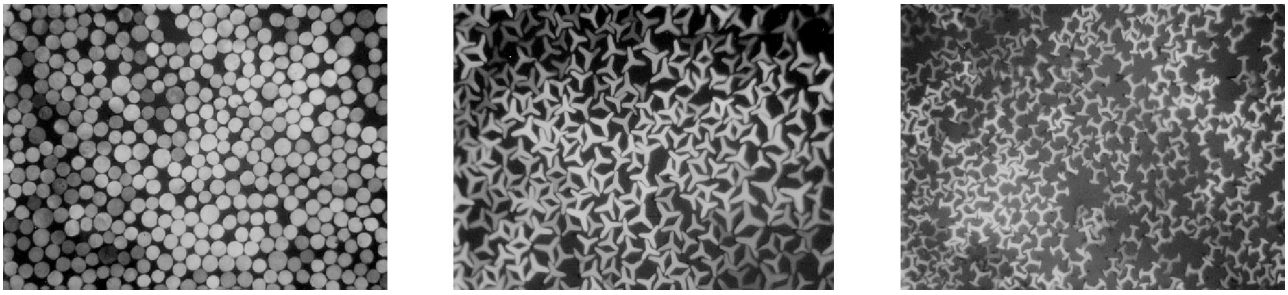

Fig. 2. Carbon loading of various fiber cross-sections.

the fibers. This was experimentally verified with both solids and liquids. Depending on the density of the reagents, one can obtain 100% by weight of reagent loading with liquid reagents and from 25% to 125% with solid reagents such as activated carbon to stainless steel.

With the solid powders, the particle size distribution plays an important role regarding the loading as one might expect.

The data in Fig. 2 demonstrates that solid powders are influenced by the fiber's cross-sectional shape and that the introduction of a cap on the lobes has a significant effect on the powder loading.

Liquids with wetting properties similar to those of the polymer can easily permeate the channels of the fibers, creating a highly dispersing form of the liquid (Fig. 3). As can also be seen, the voids between the fibers remains empty allowing air to permeate and flow through the medium.

In order to determine the stability in which the foreign matter is held within the channels of the fiber, an experiment was undertaken in which a known weight of powder-impregnated media was subjected to progressively higher and higher air flows. Table 1 contains the data from this experiment. As can be seen, very little loss of material was experienced even at face velocities far exceeding those that one might encounter in typical applications, which are 150 to 200 m min^{-1} for air filter applications.

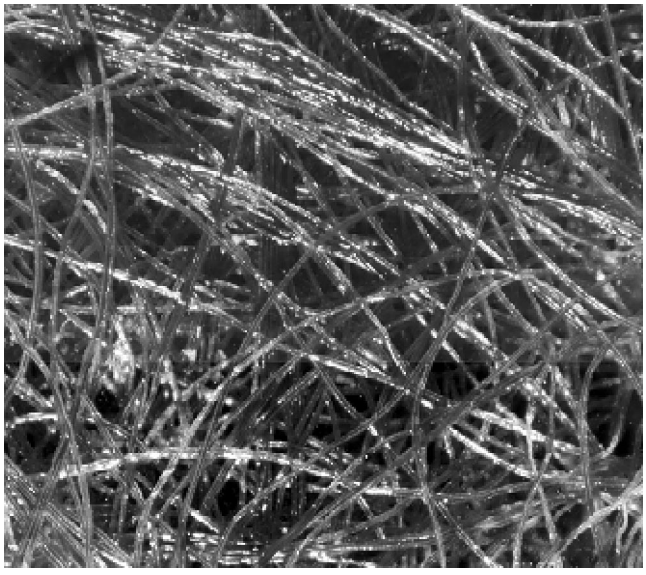

Fig. 3. Triad fibers impregnated with a strong oxidant, sodium permanganate/trisodium phosphate.

Table 2 contains a list of various properties one can introduce into the fiber by choosing the appropriate impregnant. Fibers impregnations with the reagents in Table 2 were prepared and the expected property measured in the triad fibrous matrix and compared to an equivalent matrix prepared with a round cross-section fiber. In all cases, the desired property was conferred to the triad fiber and only marginally with the round cross-section. In several cases very large differences were noted. With a graphite-impregnated triad fiber, the conductivity increased more than two orders of magnitude over that with a round cross-section. The use of a single triad fiber to hold chromatography resin within the channels for micro separations was possible only with the triad cross-section. Electrophoretic separation of a protein mixture could be practically conducted and visualized with only the triad fiber. Empirically, the static charge resulting from the triboelectric effect obtained by a PTFE-impregnated polypropylene triad fiber was significantly higher than that obtained from a round cross-section. All of these enhanced properties described above for the triad fiber over the round cross-section fiber result from the higher loading of the reagent within the triad fiber.

3.1. Breakthrough analysis

Naturally this type of material lends itself to use as a filter medium. A nonwoven form of the triad fiber was produced in a point-bonded configuration at 1.5 oz yd^{-2} and impregnated with both powder-activated carbon and a separate filter with sodium permanganate/sodium phosphate. These two filters were tested and compared to a commercial granular carbon filter specially designed for odor control.

Comparative uptake performance analyses of impregnated wicking fiber media relative to activated carbon for acetaldehyde, hydrogen sulfide and sulfur dioxide are shown in Fig. 4, Fig. 5 and Fig. 6. These gases were chosen as representative of only a partial list of the various chemical classes of gases that one might encounter in air quality applications. In order to rapidly measure the uptake capability of these filters, a high gas challenge level was employed,

Table 1
Tenacity of solids held within the channels of the triad fiber, powder-activated carbon impregnant

Face velocity (m min^{-1})	Exposure time (min)	Weight of fiber and carbon (g)
Experiment 1 — 33% initial loading		
0	0	0.0794 [a]
131	5	0.0792
265	5	0.0790
396	5	0.0789
530	5	0.0786
660	5	0.0784
796	5	0.0779 (31% final loading)
Experiment 2 — 20% initial loading		
0	0	0.0652 [a]
131	5	0.0648
265	5	0.0650
396	5	0.0649
530	5	0.0650
660	5	0.0648
796	5	0.0650 (19.5% final loading)

[a] Initial weight.

higher than one would normally experience under real-world conditions.

The activated carbon tested in these studies was obtained commercially. Carbon filters of this type are currently used for cabin air treatment in automotive applications. The wicking fiber media were impregnated with a reagent package effective for all three gases. The impregnated wicking fiber media were approximately 1.5 mm thick, and the activated carbon material was about 6.3 mm thick. The volume occupied by the activated carbon was, therefore, about 4.2 times that of the wicking fiber media. Because of the thicker carbon bed, the time spent within the activated carbon by the challenge gas is approximately four times longer than in the wicking fiber media, at a given gas velocity.

Fig. 4 shows the percent breakthrough of acetaldehyde in the effluent air of impregnated wicking fiber media and activated carbon as a function of time after the start of the challenge (50 ppm). The challenge gas flow rate in these studies was 14.2 l min^{-1}, or about 12.2 m min^{-1} face velocity. The impregnated wicking fiber demonstrated good acetaldehyde uptake out to the 30 min duration of the study. Despite the longer contact time, however, the carbon media initially rejected nearly half the challenge acetaldehyde and was essentially depleted by 30 min after the start of challenge. In this study, acetaldehyde challenge was terminated at 30 min, and the hydrocarbon content in the effluent gas was measured for an additional 15 min. Considerable hydrocarbon was detected in the effluent gas of the activated carbon for these 15 min post-challenge, indicating that off-gassing of the adsorbed acetaldehyde had occurred. By contrast, however, the hydrocarbon level in the effluent gas of the wicking fiber media had fallen to essentially zero within 1 min post-challenge. This confirms that the uptake of acetaldehyde by the impregnated wicking fiber media is an irreversible phenomenon.

Table 2
Applications and properties resulting from different impregnants

Property	Impregnant
Chemisorptive absorbent-air purification filters	$NaMnO_4/Na_3PO_4$, $Zn(OAc)_2$/alkali
Solid adsorbent filters	PAC, zeolites, alumina
Conductivity	conducting polymer, graphite
Metal extraction	liquid chelating agents
Separation chromatography	agarose, electrophoresis
Electric charge	PTFE powder
Magnetic	ferromagnetic powder
Micromolding	in-situ polymerization

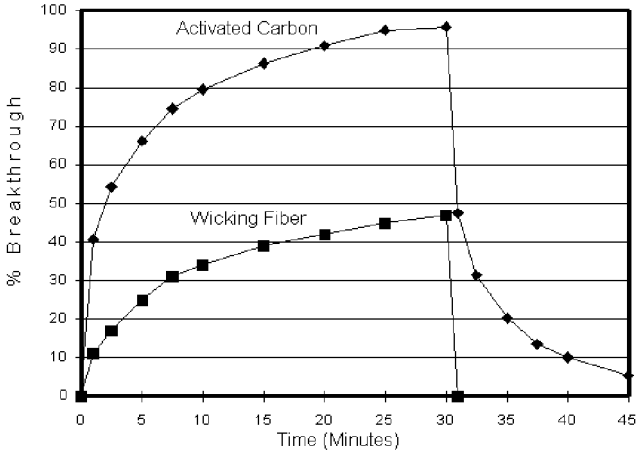

Fig. 4. Comparative acetaldehyde breakthrough performance of activated carbon vs. impregnated wicking fiber. Media were challenged with 50 ppm acetaldehyde in air at a face velocity of 12.2 m min^{-1} at 50 ± 5% relative humidity. The amount of acetaldehyde in the effluent air stream was quantified using total hydrocarbon analysis and plotted vs. time. At 30 min after challenge initiation, acetaldehyde flow was terminated. Hydrocarbon off gassing from the used filters was then monitored for a period of 15 min (from 30 min to 45 min on the figure).

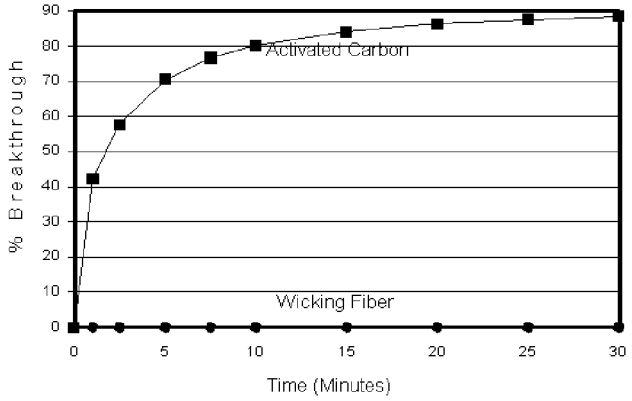

Fig. 5. Comparative hydrogen sulfide breakthrough performance of activated carbon vs. impregnated wicking fiber. Media were challenged with 10 ppm hydrogen sulfide in air at a face velocity of 12.2 m min^{-1} at 50 ± 5% relative humidity. Hydrogen sulfide was quantified in the effluent air stream by flame photometric detection and plotted vs. time.

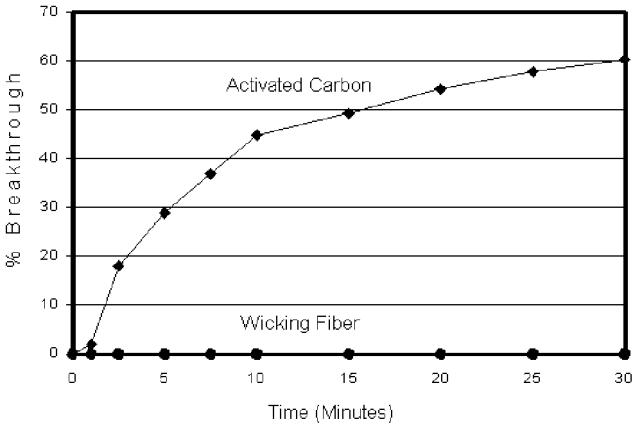

Fig. 6. Comparative sulfur dioxide breakthrough performance of activated carbon vs. impregnated wicking fiber. Media were challenged with 8 ppm sulfur dioxide in air at a face velocity of 12.2 m min^{-1} at 50 ± 5% relative humidity. Sulfur dioxide was quantified in the effluent air stream by flame photometric detection and plotted vs. time.

Fig. 5 compares the relative performance of the impregnated wicking fiber media with that of activated carbon for the removal of hydrogen sulfide. The hydrogen sulfide challenge was 10 ppm, at a face velocity of 12.2 m min^{-1}. The results indicate that the impregnated wicking fiber is capable of superior performance, when compared to the activated carbon media. The concentration of hydrogen sulfide in the effluent air of the wicking fiber media was below the detectable limit for the entire 30-min duration of the test. Initial rejection of hydrogen sulfide by the activated carbon was high, and by 10 min post challenge initiation, the effluent concentration had risen to nearly 80% of the challenge level.

The relative sulfur dioxide uptake performance of impregnated wicking fiber and activated carbon media are shown in Fig. 6. The sulfur dioxide challenge level in these studies was 8 ppm, at a gas face velocity of 12.2 m min^{-1}. The impregnated wicking fiber media removed sulfur dioxide to below the detectable limit for the 30-min duration of the test. Rejection of sulfur dioxide by the activated carbon media was high, and by 15 min, nearly 50% breakthrough was observed.

One can see that the breakthrough behavior of the impregnated triad fiber is significantly greater than conventional carbon for the removal of these gases. This is the result of the combination of high surface area of the reagents resulting from the triad fiber and the use of chemical reagents to chemisorb the various gases.

4. Conclusion

In conclusion, fiber shape plays a significant role in the ability of a fiber to entrap foreign materials within its channels. The end caps on the radial lobes of a multilobal fiber play an important role in enhancing this capacity. Finely divided powders and liquids are entrapped with sufficient strength within these channels to allow them to be used in practical applications such as filtration. The diverse range of materials that one can entrap within the fiber allows one to introduce many new properties into a fibrous matrix.