

# Turbulent Drag Reduction by Polymer-Fiber Mixtures

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## Synopsis

The turbulent drag reduction studies by asbestos fiber mixtures with purified guar gum, purified xanthan gum, and their graft copolymers have been conducted at low concentration and  $Re$  14000 using turbulent flow rheometer designed by Hoyt. A method for making stock suspension of asbestos fibers is also suggested which gives better drag reduction. It has been found from the present studies that purified guar gum-asbestos fiber mixtures give positive synergistic effect even at low concentration and synergism in drag reduction may be caused by a mixture when its constituents are rigid. A simple mixture rule equation having interaction parameter may be used for the prediction of drag reduction by the mixture.

## INTRODUCTION

The polymer-fiber mixtures cause high turbulent drag reduction, however, very limited work has been reported on polymer-fiber mixtures. Lee, Vaseleski, and Metzner<sup>1</sup> have reported drag reduction in aqueous solutions of polymers containing suspended fibers. They observed that both the additives together provide far more than linearly additive effect in drag reduction. They also speculated that the susceptibility to degradation of polymer in the mixtures is greatly reduced and suggested that highly effective mixture systems might be developed which are resistant to degradation. They have further observed that the concept of maximum drag reduction asymptote<sup>2</sup> does not hold good in polymer-fiber mixtures, but needs moderate reworking. The drag reduction obtained by Lee et al.<sup>1</sup> is more than that predicted by maximum drag reduction asymptote.

Kale and Metzner<sup>3</sup> and Metzner<sup>4</sup> explained reasons for the synergism in drag reduction by polymer-fiber solutions. Metzner<sup>4</sup> suggested that if the polymer solution containing suspended fibers is subjected to extensional deformation, the solution will be sheared as well as stretched, as the fluid elements move axially along the fiber particles. Metzner<sup>4</sup> contends that, under steady state conditions, the presence of shearing deformation rate of magnitude  $\Gamma_s$  imposed upon a steady extension rate of magnitude  $\Gamma_e$  increases stresses in sheet of deforming fluid by a ratio

$$\eta_{es}/\eta_e = 1 + (\theta_e/2)(\Gamma_s/\Gamma_e)^2 \quad (1)$$

Here  $\eta_{es}$  denotes the ratio of stress to strain rate (extensional viscosity) in an element subjected to both extensional and shearing deformation, while  $\eta_e$  is

the corresponding extensional viscosity in the same material element when it is extended only.  $\theta_e$  is the time constant of the fluid. Using the cell model of the system containing suspended fibers, the ratio  $(\Gamma_s/\Gamma_e)$  in eq. (1) has been related to the concentration of the fibers and their geometry as

$$\Gamma_s/\Gamma_e = 2\sqrt{C}\Gamma_e(L/D) \quad (2)$$

where  $(L/D)$  is the length to diameter ratio of the fiber and  $c$  is the concentration of the fibers in the suspension (volume fraction). Combining eqs. (1) and (2), one gets

$$(\eta_e)_{pf}/(\eta_0)_p = 1 + 2\theta\Gamma_e c(L/D)^2 \quad (3)$$

where the subscripts  $pf$  and  $p$  refer to polymer-fiber and polymer solutions, respectively.

Again Metzner<sup>4</sup> proposed that in polymer-fiber mixtures, which are of interest in drag reducing flows, the viscosity in eq. (3) may be very large and its effects may be carried over to the unsteady state of the system. The presence of fibers in the solution ensures that the latter is subjected to continuous shearing and stretching. This would reduce radical momentum transport rates by reducing the intensity of the Townsend-Backwell roll waves, thereby explaining the nonlinear synergism of some of the studied additives. Sharma, Sheshadri, and Malhotra<sup>5</sup> conducted experiments with polymer-fiber mixed systems. Methafos, a cellulose derivative, is mixed with asbestos fibers. The fibers were injected into 300 ppm polymer solution, and synergism was observed at Reynolds number of  $2 \times 10^4$ . They observed that the synergism in the mixed polymer-fiber system is due to the decrease in radial momentum transport.

Reddy<sup>6</sup> and Reddy and Singh<sup>7</sup> have studied the drag reduction by guar-gum-asbestos fibers and xanthangum-asbestos fibers mixtures as drag reducing agents, as the total concentration of 200 ppm between Re 20,000 and 56,000. The percentage drag reduction vs. composition behavior has been studied, which shows a clear synergistic effect. It has been shown that the following single phase equation with interaction parameter predicts the percentage drag reduction by the mixture, instead of the two-phase mixture law equations:

$$DR_M = DR_1 \times W_1 + DR_2 \times W_2 + IW_1 \times W_2 \quad (4)$$

where  $DR_M$  is the percentage drag reduction by the mixture,  $DR_1$ ,  $DR_2$  and  $W_1$ ,  $W_2$  are the percentage drag reductions and weight fractions of components 1 and 2, respectively, in the mixtures. It is to be noted that

$$W_1 + W_2 = 1 \quad (5)$$

and  $I$  is the interaction parameter believed to depend upon the interaction between the constituents of the mixture. McComb and Chan<sup>8</sup> have pointed out that the fibers when degraded behave like polymers in drag reducing flows. Due to this reason the gum-fiber mixtures under the present study

behave like polymer-polymer mixtures; therefore, eq. (4), applicable to the single phase system, is also applicable in this case. Reddy and Singh<sup>7</sup> further pointed out that this behavior may be due to a very low concentration of the fibers in polymer solution.

The synergism in the drag reduction has been ascribed to the cumulative effect of molecular and mechanistic processes.<sup>4,7</sup> It has been pointed out that there is an increase in random coil dimensions of the polymer molecules. Both the guar gum and xanthan gum have relatively rigid molecules and asbestos fibers are more rigid. Hence, good synergism has been observed in both the mixtures. However, Reddy and Singh<sup>7</sup> have conducted their drag reduction studies in a recirculatory turbulence flow system using a stainless steel centrifugal pump which is known to cause the degradation of polymers and fibers. Further, Reddy and Singh have used commercial samples of guar and xanthan gums at higher concentrations. The present paper reports the results of a study on turbulent drag reduction by asbestos fibers with more efficient purified and grafted guar and xanthangums<sup>9-11</sup> at very low concentrations by turbulent flow rheometer supplied by Hoyt.<sup>12</sup>

## EXPERIMENTAL

### Materials

The following materials were used in the present study:

- (i) Guargum (GG) (Hindustan Gums and Chemicals, Bhiwani, India).
- (ii) Purified guargum (PGG): The commercial guargum was purified by using a method given by Whitcomb et al.<sup>13</sup>
- (iii) Xanthangum (XG) (Kelco, USA).
- (iv) Purified xanthangum (PXG): The commercial xanthangum was also purified by Whitcomb method.<sup>13</sup>
- (v) Polyacrylamide (PPM) (Hoechst, France; trade name Bozofloc N-46BT; average molecular weight  $6 \times 10^6$ ).
- (vi) Surfactant sodium dioctyl sulfosuccinate (Manoxol OT, TBA Industrial Products Ltd., U.K.).
- (vii) Asbestos fibers Cassiar A65 (AF) (Cryotile, TBA Industrial Products Ltd., U.K.; diameter 30-40 nm and aspect ratio  $4 \times 10^4$ ).
- (viii) Grafted guargum ( $Gm_3$ ) was synthesized by Deshmukh et al.<sup>9,10</sup> Intrinsic viscosity of  $Gm_3$  is 408.7 mL/g in 1 M  $NaNO_3$  solution at 30°C.
- (ix) Grafted xanthangum ( $XGm_3$ ) was synthesized by Deshmukh and Singh.<sup>11</sup>

### Fiber Suspension Preparation

As the asbestos fibers were not supplied in the form of suspension by the manufacturer, a 1.8% (by weight) stock suspension of A65 Cassiar asbestos fibers was, therefore, prepared in 0.8% (by weight) solution of surfactant (Manoxol OT). Both the materials were supplied by TBA-Industrial Products Ltd., U.K. For making stock suspension, first, the required quantity of surfactant was dissolved in a known quantity of water in a container, and the contents were aged for 24 h so that dissolution of surfactant was complete. In between, a magnetic stirrer was used for stirring the solution. The required

amount of asbestos fiber was added into the surfactant solution. The contents were stirred for about 20 min 4–5 times a day, at medium speed, using a laboratory magnetic stirrer. The process is repeated for 5–6 days, and then the suspension was transferred into a flat bottom bucket with a tight lid. The suspension was aged for about 1 month. While handling the fibers and fiber-suspension, care should be taken to avoid inhalation and skin contact with fibers. Hand gloves were used while working with them because asbestos fibers are carcinogenic.

For making the suspensions of lower concentrations, a fiber suspension of 500 ppm (by weight) was used. A 0.5% solution of surfactant was used for making suspensions of 500 ppm and other lower concentrations. For making 500 ppm fiber suspension, again the surfactant was dissolved in water to obtain 0.5% solution, and aged for 24 h. The stirrer was used, for uniform mixing. The required amount of 1.8% (by weight) of stock suspension was added into the known quantity of 0.5% surfactant solution, in order to make 500 ppm fiber suspension. The contents were stirred slowly till dispersion of the fibers in the solution was complete. All other fiber suspensions of lower concentrations were prepared by diluting the exact amount of 500 ppm suspension with 0.5% surfactant solution to make suspension of the desired concentration. It needs little shaking or stirring to get the suspension ready for use.

The percentage drag reduction was measured by a turbulent flow rheometer supplied by Hoyt.<sup>12</sup> The apparatus operates at the Reynolds number of 14,000. The percentage drag reduction (DR) is calculated using the following formula:

$$DR = \frac{\Delta h_s - \Delta h_p}{\Delta h_s} \times 100 \quad (6)$$

where  $\Delta h$  is the pressure loss in test section and  $s$  and  $p$  refer to the solvent and polymer solution, respectively.

## EXPERIMENTAL RESULTS

In the present study very low concentrations, i.e., 20 and 50 ppm, of the mixtures have been taken. Before conducting the drag reduction experiments in each case, the drag reduction by fibers alone has been measured, and the results have been plotted in Figure 1. Earlier drag reduction by fibers was studied by Lee, Vaseleski, and Metzner,<sup>1</sup> Radin, Zakin, and Patterson,<sup>14</sup> Hoyt,<sup>15</sup> McComb and Chan,<sup>16</sup> and Sharma, Seshadri, and Malhotra.<sup>5</sup> In most of the cases, drag reduction has been measured in a large diameter pipe, higher  $Re$ , and higher concentrations. However, the values of the percentage drag reduction obtained are lower than the present results. Hoyt<sup>15</sup> has measured percentage drag reduction by asbestos fibers by using the same kind of instrument, having the same pipe diameter, and at the same  $Re$ . His experimental values of drag reduction are lower than the values obtained in the present investigation.

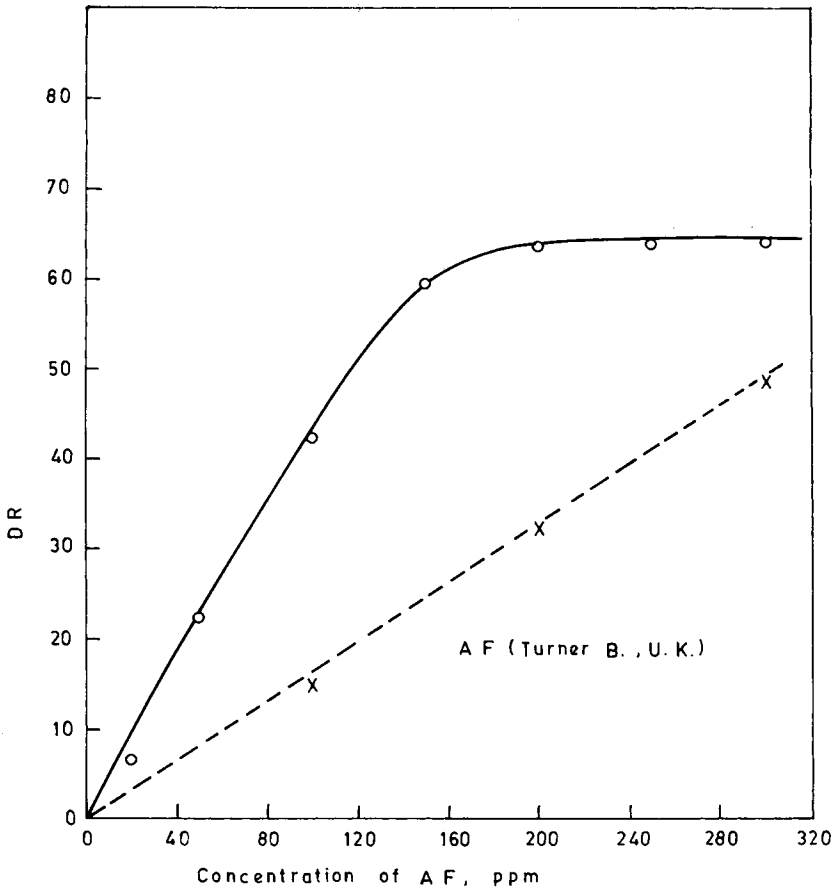


Fig. 1. DR vs. concentration (ppm) for two samples of asbestos fibers in the same turbulent-flow rheometer: (O) asbestos fibers used in our laboratory (TBA, U.K.); (X) asbestos fibers used by Hoyt.<sup>15</sup>

Figure 2 indicates the drag reduction vs. concentration in case of PAM (Bozofloc). It has been observed that the concentration profile goes on shifting toward the higher concentration side with the passage of time, which may be due to the highly hygroscopic nature of PAM and its aging. Hence, before each set of experiments, the drag reduction vs. concentration profile for PAM was measured.

### Polyacrylamide-Asbestos Fiber Mixtures

PAM and asbestos fiber mixtures were first studied by Lee, Vaseleski, and Metzner,<sup>1</sup> in a 2.4 cm diameter tube using 150 ppm of PAM and 200 ppm asbestos fibers at a Reynolds number in the range of  $2 \times 10^5$ . It has been observed that both additives used together provide far more than a linearly additive effect. They have studied two fiber systems, i.e., John's-Mauville and Turner Brothers. By the first system, synergistic effects have been obtained; however, by the latter system, though a high level of drag reduction has been obtained, the drag reduction is less than linearly additive effects.

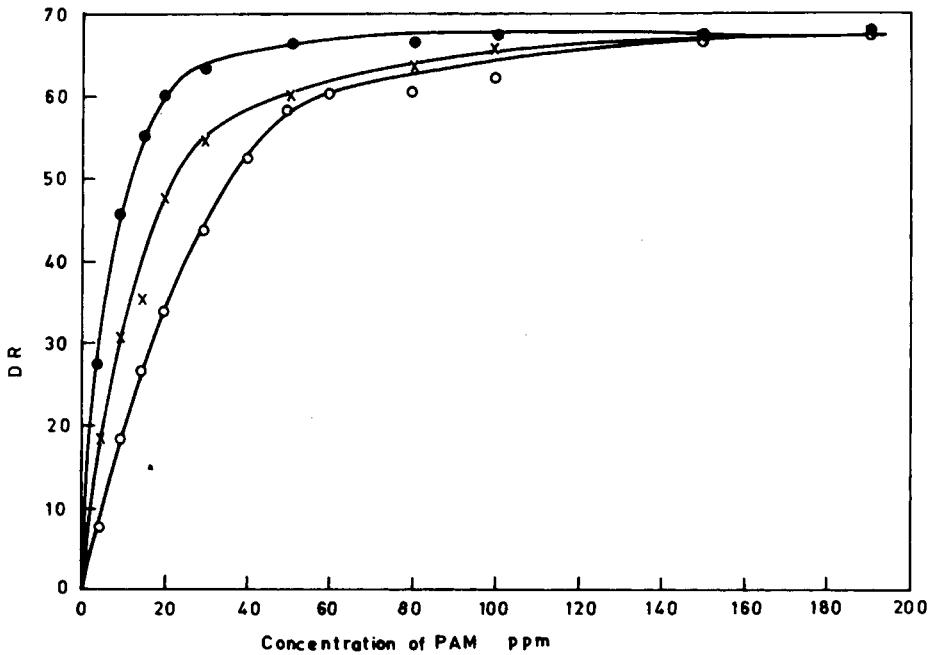


Fig. 2. DR vs. concentration (ppm) for polyacrylamide showing effect of aging on drag reduction effectiveness. Tests were conducted on the following dates: (○) 11/27/84, 10 AM; (×) 10/18/84, 10 AM; (●) 9/5/84, 10 AM.

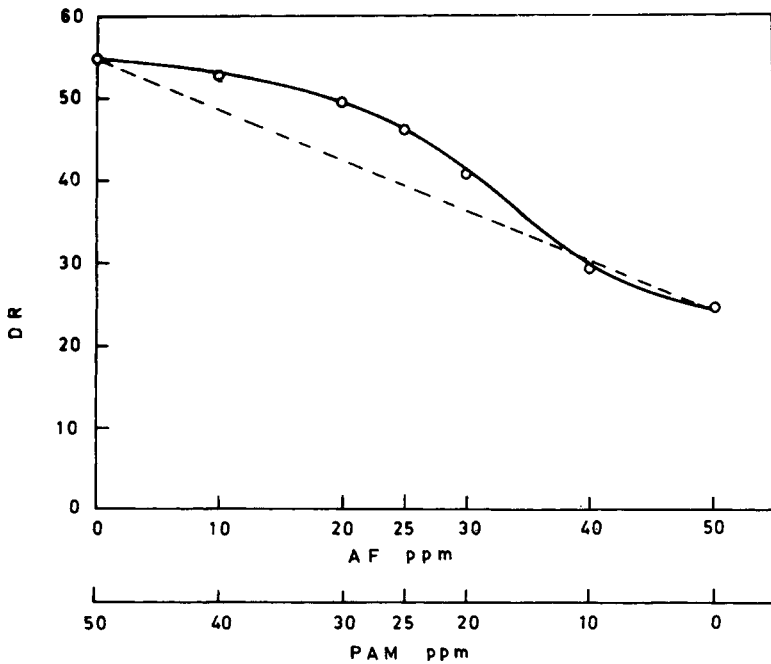


Fig. 3. DR vs. composition of mixtures of asbestos fibers and polyacrylamide at total concentration of 50 ppm and Reynolds no. 14,000.

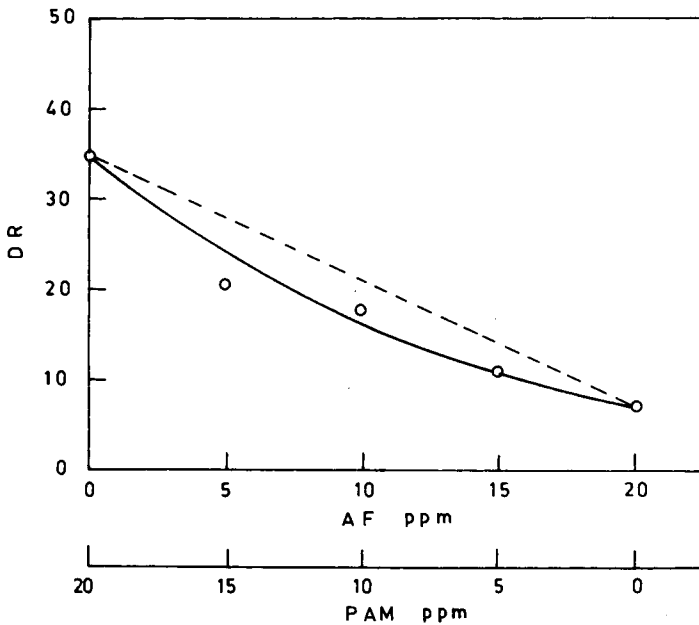


Fig. 4. DR vs. composition of mixtures of asbestos fibers and polyacrylamide at total concentration of 20 ppm and Reynolds no. 14,000.

TABLE IA  
Drag Reduction Effectiveness in AF + PAM Mixtures at Total Concentration of 50 ppm

Concn of AF (ppm)	Concn of PAM (ppm)	DR by AF	DR by PAM	Additive DR	DR by mixture
50	0	25.00	0.0	25.00	25.00
40	10	19.00	19.0	38.00	30.00
30	20	14.00	34.0	48.00	41.50
25	25	11.50	39.0	50.50	46.25
20	30	9.00	44.0	53.00	50.00
10	40	4.25	52.0	56.25	53.00
0	50	0.00	55.0	55.00	55.00

TABLE IB  
Drag Reduction Effectiveness in AF + PAM Mixtures at Total Concentration of 20 ppm

Concn of AF (ppm)	Concn of PAM (ppm)	DR by AF	DR by PAM	Additive DR	DR of mixture
20	0	7.0	0.0	7.0	7.0
15	5	6.5	9.5	16.0	11.0
10	10	4.0	18.5	22.5	14.1
5	15	2.2	27.0	29.2	24.0
0	20	0.0	35.0	35.0	35.0

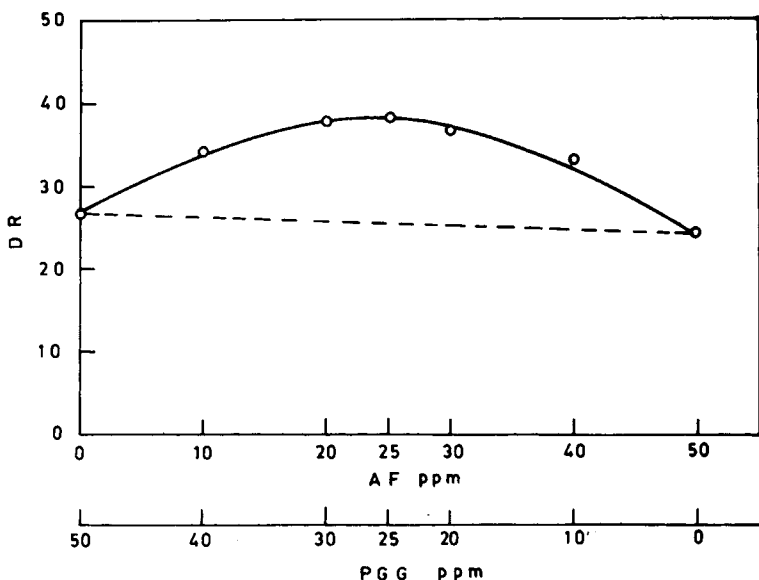


Fig. 5. DR vs. composition of mixtures of asbestos fibers and purified guar gum at total concentration of 50 ppm and Reynolds no. 14,000.

Figures 3 and 4 depict the drag reduction caused by PAM-AF mixtures at the total concentrations 50 and 20 ppm, respectively, at various compositions of the mixtures. At the concentration of 50 ppm, the drag reduction caused by mixtures is higher than the drag reduction caused by PAM alone, almost over all the compositions, although the drag reduction caused by the mixture is less than the linearly additive effect. As the concentration goes down to 20 ppm, the drag reduction caused by the mixtures is less than that caused by PAM, for the compositions containing asbestos fibers below the 15 ppm level. But it is clear from Tables IA and IB that the drag reduction caused by the mixtures is less than the drag reduction obtained by the addition of drag reduction caused by the constituents of the mixture at all compositions.

#### Guar gum-Asbestos Fiber Mixtures

As mentioned earlier AF and commercial guar gum mixtures were studied by Reddy and Singh<sup>7</sup> at a concentration of 200 ppm. The guar gum on purification and grafting becomes a better drag reducing agent; hence the drag reduction caused by AF-PGG and AF-Gm<sub>3</sub> mixtures were studied at the total concentration of 50 ppm and Re 14,000. The results are shown in Figures 5 and 6. It is evident from Figure 5 that the mixture having the composition of 25 ppm AF and 25 ppm PGG is the most efficient drag reducing agent and the drag reduction caused by the mixtures at all compositions is higher than that caused by constituent polymers. In conformity with the observation made by Reddy and Singh,<sup>7</sup> the synergistic effect is quite prominent in this case even at lower concentration and Re. This effect is further confirmed by the fact that the drag reduction caused by the mixture at all compositions is greater than the additive value of the drag reduction caused by the constituents of



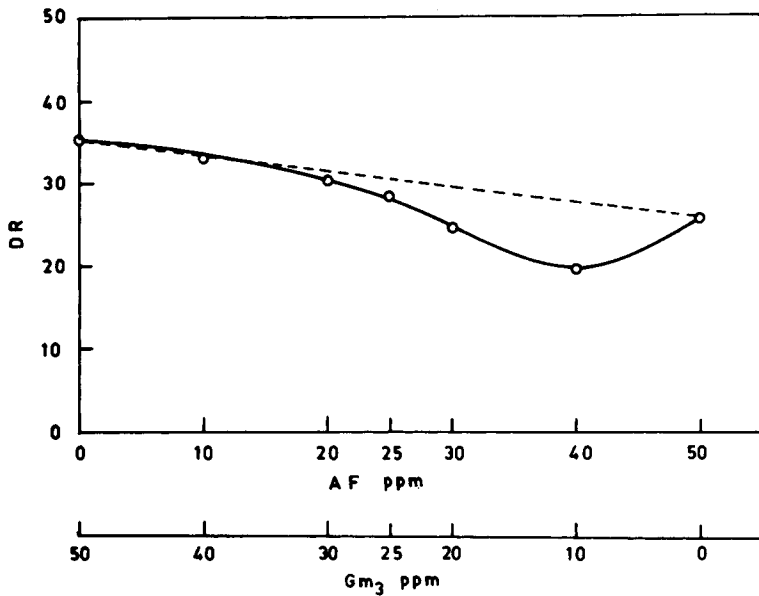


Fig. 6. DR vs. composition of mixtures of asbestos fibers and graft copolymer of guar gum (Gm<sub>3</sub>) at total concentration of 50 ppm and Reynolds no. 14,000.

TABLE IIA  
Drag Reduction Effectiveness in AF + PPG Mixtures

Concn of AF (ppm)	Concn of PPG (ppm)	DR AF	DR by PPG	Additive DR	DR by mixture
50	0	25.00	0	25.00	25.0
40	10	19.00	8.66	27.66	32.5
30	20	14.00	16.00	30.00	37.5
25	25	11.50	19.00	30.50	38.5
20	30	9.00	21.33	30.33	38.0
10	40	4.25	24.00	38.25	34.0
0	50	0.00	27.00	27.00	27.0

TABLE IIB  
Drag Reduction Effectiveness in AF + Gm<sub>3</sub> Mixtures

Concn of AF (ppm)	Concn of Gm <sub>3</sub> (ppm)	DR by AF	DR by Gm <sub>3</sub>	Additive DR	DR by mixture
50	0	25.00	0.00	25.00	25.0
40	10	19.00	13.50	32.50	19.7
30	20	14.00	21.66	35.66	24.5
25	25	11.50	24.50	36.00	28.5
20	30	9.00	26.90	35.90	30.5
10	40	4.25	31.50	35.75	33.5
0	50	0.00	35.00	35.00	35.0

the mixtures (Table IIA). The mixture having the composition of 25 ppm PGG + 25 AF gives maximum drag reduction.

The drag reduction caused by AF-Gm<sub>3</sub> mixtures (Fig. 6) is lower than the 50 ppm value of Gm<sub>3</sub> at all compositions and lower than the 50 ppm AF value at 40 ppm AF + 10 ppm Gm<sub>3</sub>. At other compositions, the drag reduction is higher than the 50 ppm AF value. It appears that grafted PAM chain brings down the synergistic ability of the guar gum main chain. In this case, the drag reduction caused by the mixture is less than the additive value of the drag reduction caused by the constituents of the mixtures (Table IIB).

### Xanthangum-Asbestos Fiber Mixtures

The AF and commercial xanthangum at 200 ppm were studied by Reddy and Singh.<sup>7</sup> In the present case, the mixtures of AF, purified xanthan, and grafted xanthangum have been studied at the total concentration of 50 ppm and Re 14,000, over a wide composition range. The results of present study are depicted in Figures 7 and 8. Here, in both cases, the drag reduction at all compositions is less than that caused by 50 ppm concentration of PXG and XGm<sub>3</sub>. At the compositions of 40 ppm of AF + 10 ppm of PXG or XGm<sub>3</sub>, the drag reduction values are lower than its value at 50 ppm concentration of AF. The results indicate the presence of negative synergism. Here again the drag reduction caused by the mixture is less than the additive value of the drag reduction caused by the constituents of the mixture (Tables IIIA and IIIB).

The following general features are apparent from the study of drag reduction caused by polymer-fiber mixtures.

1. From the study of the drag reduction caused by AF and PAM (Bozofloc) mixtures at low concentrations of 50 and 20 ppm, it is obvious that the positive deviation from linearly additive straight line and synergism are

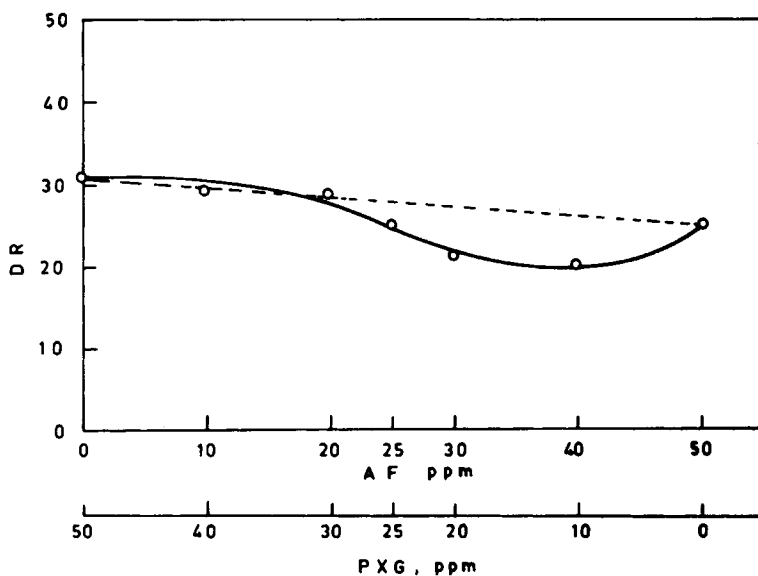


Fig. 7. DR vs. composition of mixtures of asbestos fibers and purified xanthangum at total concentration of 50 ppm and Reynolds no. 14,000.

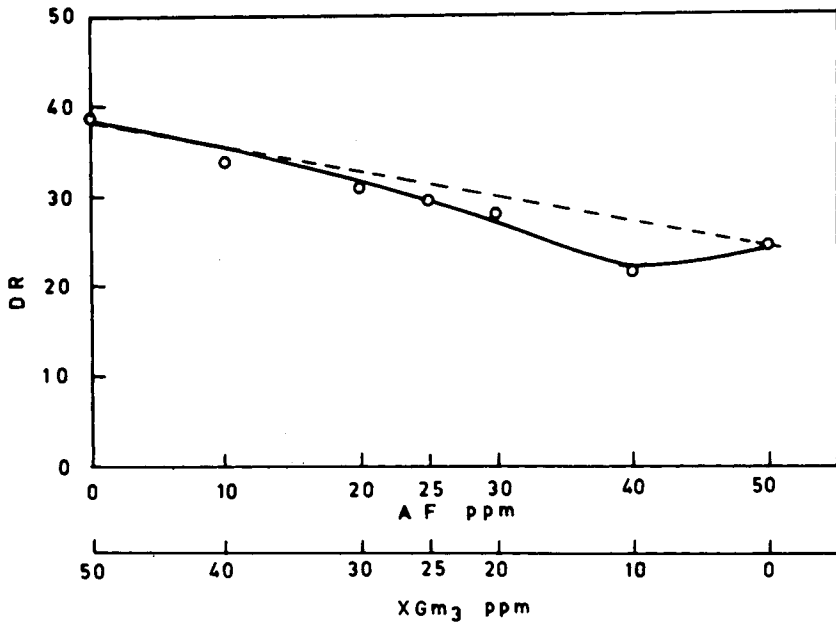


Fig. 8. DR vs. composition of mixtures of asbestos fibers and graft copolymer of xanthangum (XGm<sub>3</sub>) at total concentration of 50 ppm and Reynolds no. 14,000.

TABLE IIIA  
Drag Reduction Effectiveness in AF + PXG Mixtures

Concn of AF (ppm)	Concn of PXG (ppm)	DR by AF	DR by PXG	Additive DR	DR by mixture
50	0	25.00	0.00	25.00	25.0
40	10	19.00	8.66	27.66	20.0
30	20	14.00	15.00	29.00	21.0
25	25	11.50	18.33	24.83	24.5
20	30	9.00	21.10	30.10	27.5
10	40	4.25	26.33	30.58	30.5
0	50	0.00	30.50	30.50	30.5

TABLE IIIB  
Drag Reduction Effectiveness in AF + XGm<sub>3</sub> Mixtures

Concn of AF (ppm)	Concn of XGm <sub>3</sub> (ppm)	DR by AF	DR by XGm <sub>3</sub>	Additive DR	DR by mixture
50	0	25.0	0	25.00	25.0
40	10	19.0	12.66	31.66	22.5
30	20	14.0	22.0	36.00	27.5
25	25	11.5	26.0	37.50	29.5
20	30	9.0	29.2	38.20	31.0
10	40	4.25	34.66	38.91	35.0
0	50	0	39.0	39.00	39.0

strongly dependent upon the concentration of the mixture. Here from 20 ppm concentration to 50 ppm concentration, the negative deviation becomes positive. The difference between the drag reduction caused by the mixture and sum of the drag reductions caused by constituents is higher in former case and lower in latter case. When concentrations are taken at much higher level, the positive synergism has been obtained by Lee, Vaseleski, and Metzner.<sup>1</sup>

2. The positive synergism is obtained in the case of PGG-AF mixtures even at a low concentration of 50 ppm. It is a unique system in which the synergism starts appearing at very low concentration and Re. It may be due to cumulative molecular and mechanistic effects observed in the polymer-fiber systems. Grafted guar gum ( $Gm_3$ ) has a lower intrinsic viscosity in comparison with the PGG and has flexible PAM chain grafted on it. Due to the loss of rigidity of the chain, its mixtures with rigid AF are giving negative deviation and synergism.

3. From the studies of drag reduction, by AF-PXG and AF-XGm<sub>3</sub>, it appears that their concentrations are too low to give positive deviation and synergism, observed at higher concentrations and Re.

## CONCLUSIONS

The drag reduction and synergism in drag reduction are functions of concentration and flow rate. Synergism in drag reduction is caused by a mixture when both the constituents are rigid.

The positive synergism can be obtained in the case of PGG-AF mixtures even at a low concentration, but in many other mixtures synergism may be obtained at higher concentrations.

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Received June 11, 1986

Accepted September 23, 1986