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Wildfire Suppressant Rheology:

Mapping Viscosity as a Function of Product Mix Ratios

PROJECT NUMBER: 301014177

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The USDA Forest Service's Qualified Product List (QPL) provides guidance on the range of permissible mix ratios for water-enhancer products. Due to the proprietary nature of water-enhancer products, there are several unknowns about the rheology of the permissible mix ratios.

This study focused on mapping the viscosity of various suppressant products as a function of their mix ratios. The results revealed a wide range of viscosities across products, with each product showing a different non-linear relationship with different mix ratios.

The results from this study can help understand the optimum viscosity range to achieve desired drop characteristics during aerial operations.

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Background

Wildfire management agencies use several methods and strategies to suppress wildland fires. Among the various methods and strategies, aerial suppression may be considered as one of the more effective tools at agencies' disposal. Aerial suppression's effectiveness at fighting wildland fires comes with a significant financial cost. Any efforts to optimize and improve aerial suppression activities will therefore result in considerable cost savings.

In recent decades, there has been an increase in the commercial availability of products that have aimed to replace water and foam in wildfire suppression activities. These products, referred to as *water-enhancers*, are often proprietary, and their chemical composition is undisclosed. Water-enhancers increase the viscosity of water when the concentrate product (solute) is mixed with water (solvent). Manufacturers of these products claim that this increase in viscosity is what improves performance when dropped from an aircraft.

Because water-enhancer products are proprietary, wildfire agencies have been unable to obtain sufficient information regarding two important questions: (1) does an increase in viscosity improve the performance of a drop; and (2) what the rheological properties of these products are.

This study focused on the rheological attributes of water-enhancer products—specifically, how does viscosity change with different mix ratios. Understanding the rheological attributes of these products should allow researchers to determine the optimal viscosity range to obtain intended drop characteristics. Viscosity data also offers value in aircraft safety where high viscosity products may resist flow and fail to drop out of an aircraft.

To execute this study, FPInnovations collaborated with the Tsai Lab of Fluids and Interfaces, a fluid dynamics laboratory that is part of the Department of Mechanical Engineering at the University of Alberta. All data presented in this study was collected by members of the Tsai Lab and redistributed in this report for an audience of wildfire practitioners.

Methods

Equipment

To determine how viscosity of various suppressants change based on their mix ratios, sample solutions were tested with a rheometer in the lab (Figure 1). A rheometer can facilitate gathering information on:

- **Viscosity**
  This is a liquid's resistance to flow.
- **First normal stress difference**

This is a calculated metric that describes the reproducibility of fluid to exhibit normal shear stress when sheared tangentially. For the purposes of this study, this tells us that the products are well mixed and exhibit the same properties in all directions (i.e., isotropic).

- **Storage and loss modulus**
  These metrics describe the viscoelastic behaviour of a fluid. The storage modulus describes the elastic component of a fluid, while the loss modulus describes how plastic the fluid is when deformed.

Figure 1. Anton Paar MCR 302 with a particle image velocimetry cell and a concentric cylinder.

Details regarding the following aspects of this study are not discussed in this report but are provided in the original technical report (Yang and Tsai 2020). See appendix.

- how a rheometer works
- how viscosity, first normal stress difference, and storage and loss modulus is measured.
- data pertaining to first normal stress difference and storage and loss modulus.

This information can be found in the original technical report (Yang and Tsai 2020).

Sample preparation

Six suppressant products were tested in this study:

- BlazeTamer 380
- Firewall II
- FireIce 561
- Thermo-Gel 200L
- Phoschek LC 95A
- WD881C

Although this study focused on water-enhancer products (i.e., BlazeTamer 380, Firewall II, FireIce 561, Thermo-Gel 200L), samples of Phoschek LC 95A (a long-term retardant) and

WD881C (a foam product) were included to provide a reference. Phoschek LC95A and WD881C are currently the most commonly used products in wildfire aerial operations.

Table 1 presents the mix ratios that were tested in this study. Products that had liquid concentrates were mixed by volume, whereas products that had solid (powdered) concentrates were mixed by weight.

Table 1. Mix ratios for the various suppressant products tested in this study.

Product	QPL Mix-Ratio Range*	Mix Ratios Tested				
BlazeTamer 380	0.65%	0.3%	0.4%	0.5%	0.6%	0.65%
Firewall II	0.25% – 3%	0.25%	0.9%	1.6%	2.3%	3.0%
FireIce 561	1.4% – 2.1%	1.4%	1.6%	1.8%	2.0%	2.1%
Thermo-Gel 200L	0.5% - 3.0%	0.5%	1.1%	1.7%	2.4%	3.0%
Phoschek LC 95A	5.5: 1	5.5:1				
WD881C	0.1% - 1.0%	0.3%	0.5%	0.7%	1.0%	1.1%

**Mix-ratio range as determined by the qualified products list (QPL) from the USDA Forest Service (2020).*

The rheometer requires only a small amount of working fluid, thus a 10 mL mixed solution was prepared for each product at each mix ratio. An ambient temperature of 20ºC was maintained throughout the tests. The shear rate range was capped at 0.1 to 100 (1/s). Each sample was tested three times.

Water hardness is known to influence viscosity. To control for this, the same water was used to prepare all test samples—tap water from E.L. Smith Zone (Edmonton, Alberta) with a measured hardness of approximately 170 ppm. A separate study is investigating how the variability in water hardness influences the rheology of these products.

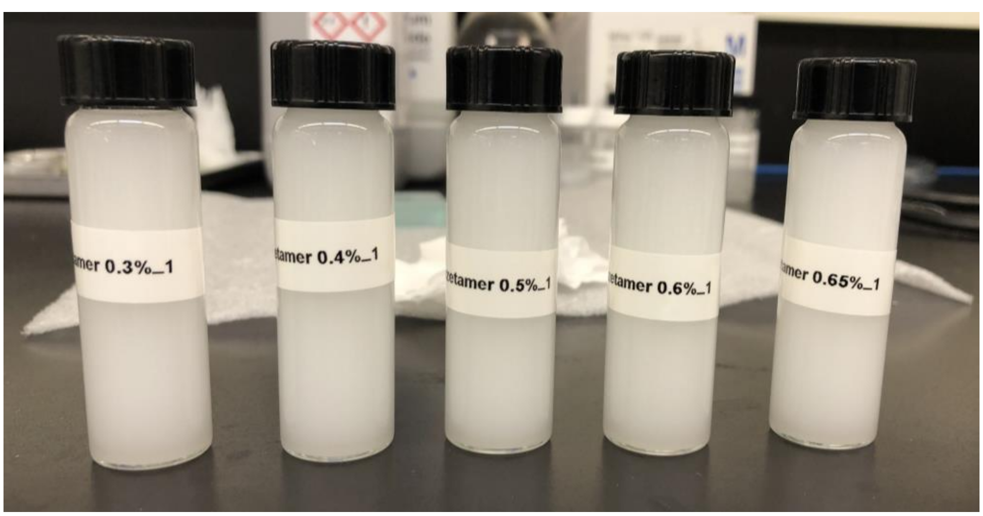

Figure 2. BlazeTamer 380 samples of various mix ratios.

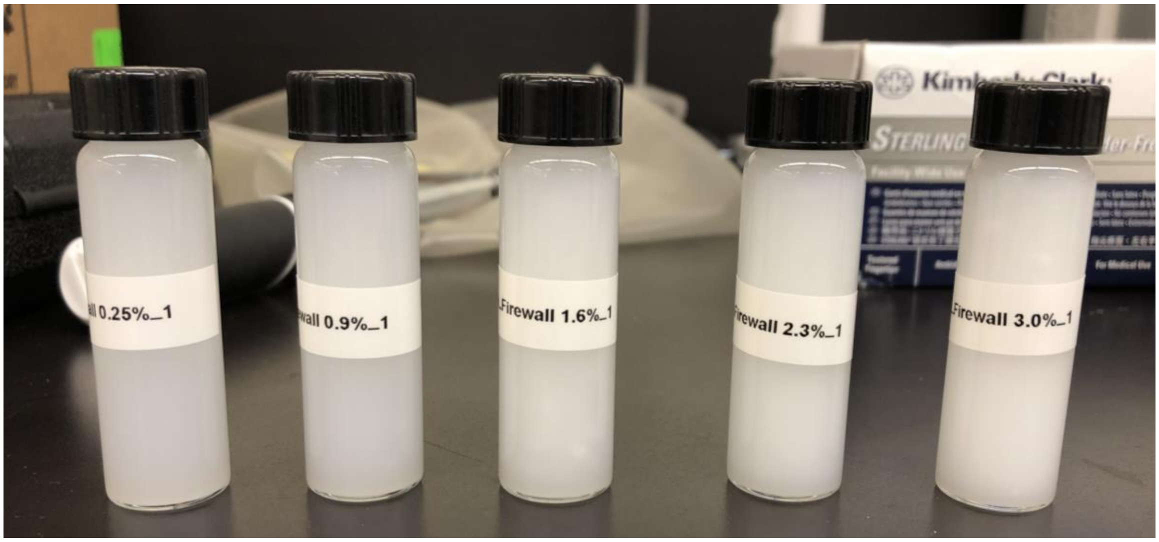

Figure 3. Firewall II samples of various mix ratios.

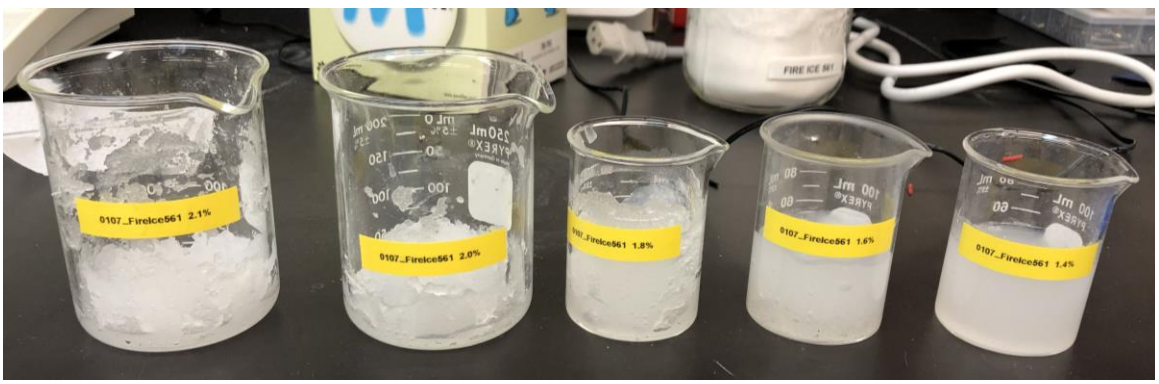

Figure 4. FireIce 561 samples of various mix ratios.

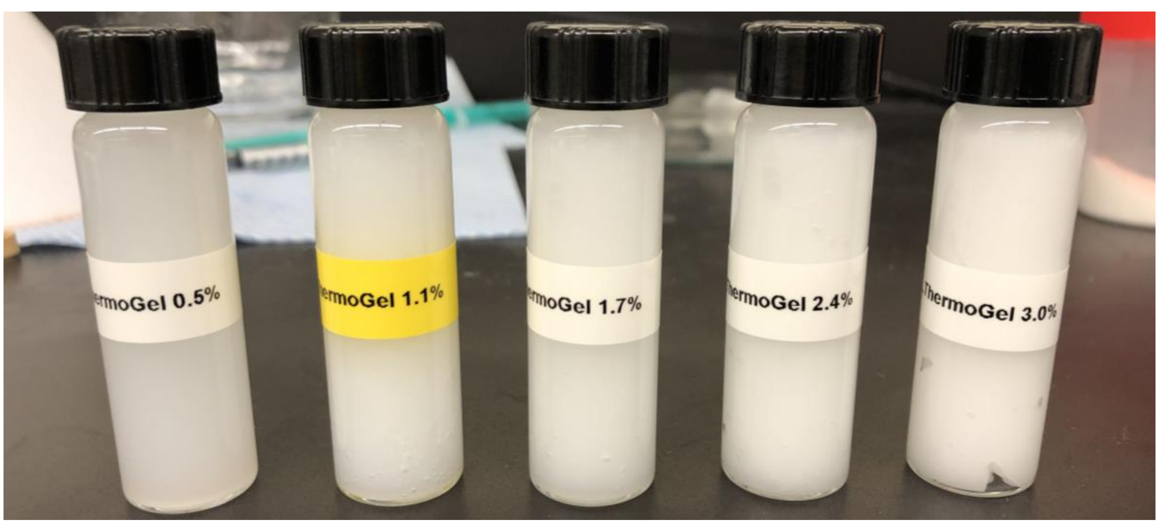

Figure 5. Thermo-Gel 200L samples of various mix ratios.

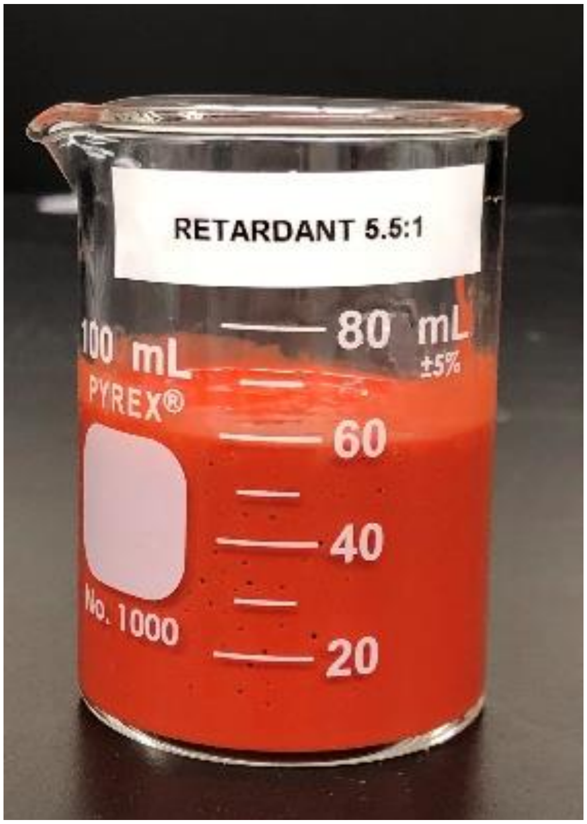

Figure 6. Phoschek LC 95A sample at a set mix ratio.

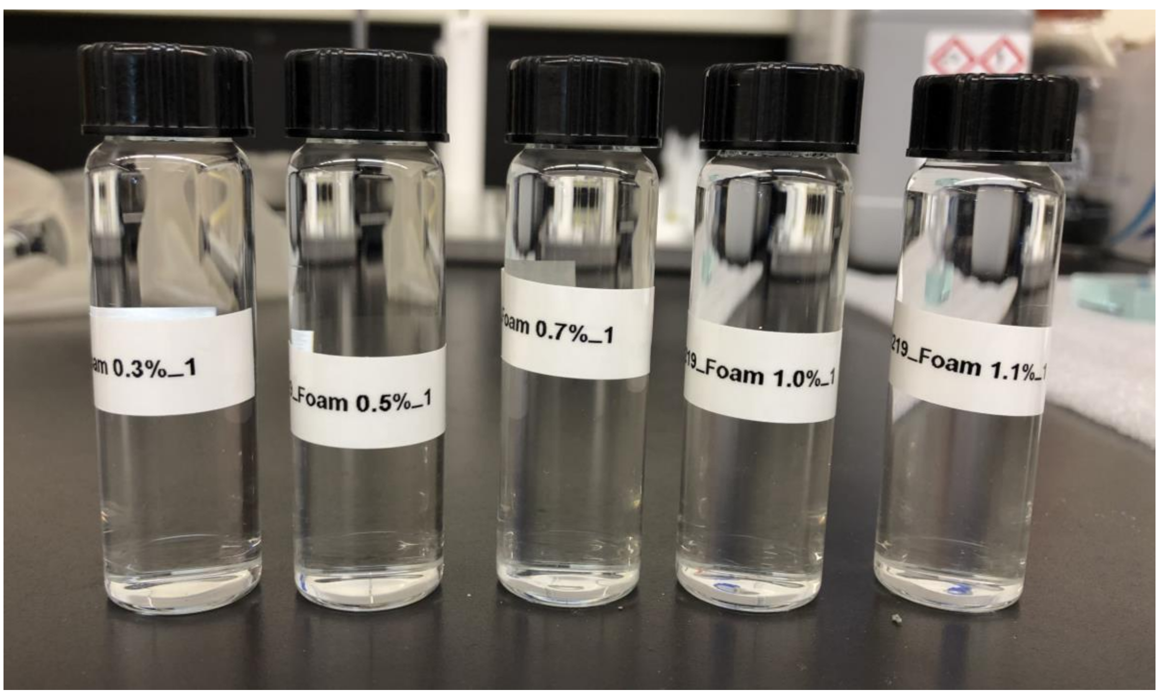

Figure 7. WD881C samples of various mix ratios.

Results

The findings from the viscosity tests for each product at various mix ratios are presented below. A few notes about the graphical representations in Figures 8 to 13:

- Viscosity values (on the y-axis) were found to range tremendously; therefore, a logarithmic scale base 10 was used, and the lower and upper bounds were adjusted for each product. This allowed for a more accurate representation of the data for each product but made it difficult to use the graphs to directly compare the products.
- The lines in each graph represent the average of three replicates. Only the averages are presented to improve the readability of the graph. For detailed information about individual tests and standard deviation values, please refer to Yang and Tsai (2020).
- Each graph has a shear rate range from 0.1 to 100 (1/s). This range was chosen based on standard rheometric practice. These numbers do not have any bearing on the design of mixing systems for these products.

It is well understood among wildfire practitioners that viscosity increases as mix ratio increases; therefore, those trends are not presented here. Of more interest is the spread between the lowest and highest mix ratio, and the differences in viscosity between those bounds.

Viscosity is measured in centipoise (cP). To give context to this measurement, Table 2 provides the viscosity values in cP for several common materials.

Table 2. Viscosities of common materials.

Material	Viscosity (cP)
Water at 21°C	1-5
Blood or kerosene	10
Antifreeze or ethylene glycol	15
Motor oil SAE 10 or corn syrup	50 - 100
Motor oil SAE 30 or maple syrup	150 - 200
Motor oil SAE 40 or castor oil	250 - 500
Motor oil SAE 60 or glycerin	1,000 – 2,000
Karo corn syrup or honey	2,000 – 3,000
Blackstrap molasses	5,000 – 10,000
Hershey's chocolate syrup	10,000 – 25,000
Heinz ketchup or French's	50,000 – 70,000
Tomato paste or peanut butter	150,000 – 2,000,000
Crisco shortening or lard	1,000,000 – 2,000,000
Caulking compound	5,000,000 – 10,000,000
Window putty	100,000,000

**Viscosity comparison chart retrieved from http://www.cstsales.com/viscosity.html*

BlazeTamer 380

Figure 8 presents the average viscosity curves for different mix ratios of BlazeTamer 380.

Viscosity range

Figure 8 has a y-axis range between 3 and 30 cP wherein all curves for the different mix ratios fall. BlazeTamer 380 was found to have the lowest viscosity of all water-enhancer products tested in this study for any given mix ratio. Variation in mix ratios of BlazeTamer 380 yielded minimal changes in viscosity.

Fluid properties

Different mix ratios of BlazeTamer 380 exhibited minimal thinning with an increase in shear rate. mostly amplified by the scale on the y-axis. Each of the different mix ratios produced a solution that could be considered a Newtonian fluid (i.e., viscosity is independent of shear rate).

NOTE: *Not all the mix ratios presented in Figure 8 are permissible as per the QPL (USDA 2020). At the time of writing, only a mix ratio of 0.65% has been approved for use in aircraft application.*

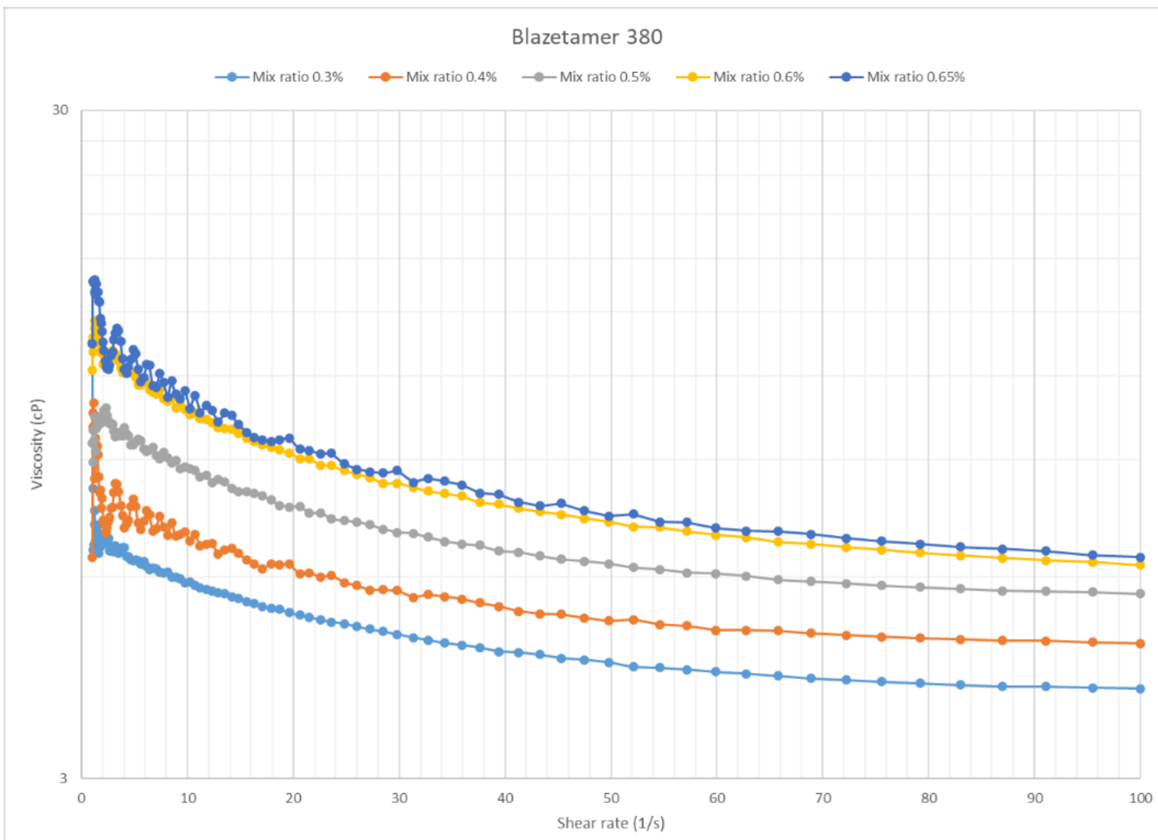

Figure 8. Viscosity versus shear rate for different mix ratios of BlazeTamer 380.

Firewall II

Figure 9 presents the average viscosity curves for different mix ratios of Firewall II.

Viscosity range

Figure 9 has a y-axis range between 1 and 10,000 cP wherein all curves for the different mix ratios fall. These results show that Firewall II's viscosity can vary over a wide range for the different approved mix ratios.

Fluid properties

Firewall II at 0.25% was found to be a Newtonian fluid. However, all other mix ratios exhibited noticeable decreases in viscosity when shear rate was increased, thus exhibiting shear-thinning properties. How shear-thinning properties impact operations is discussed in the *Discussion* section of this report.

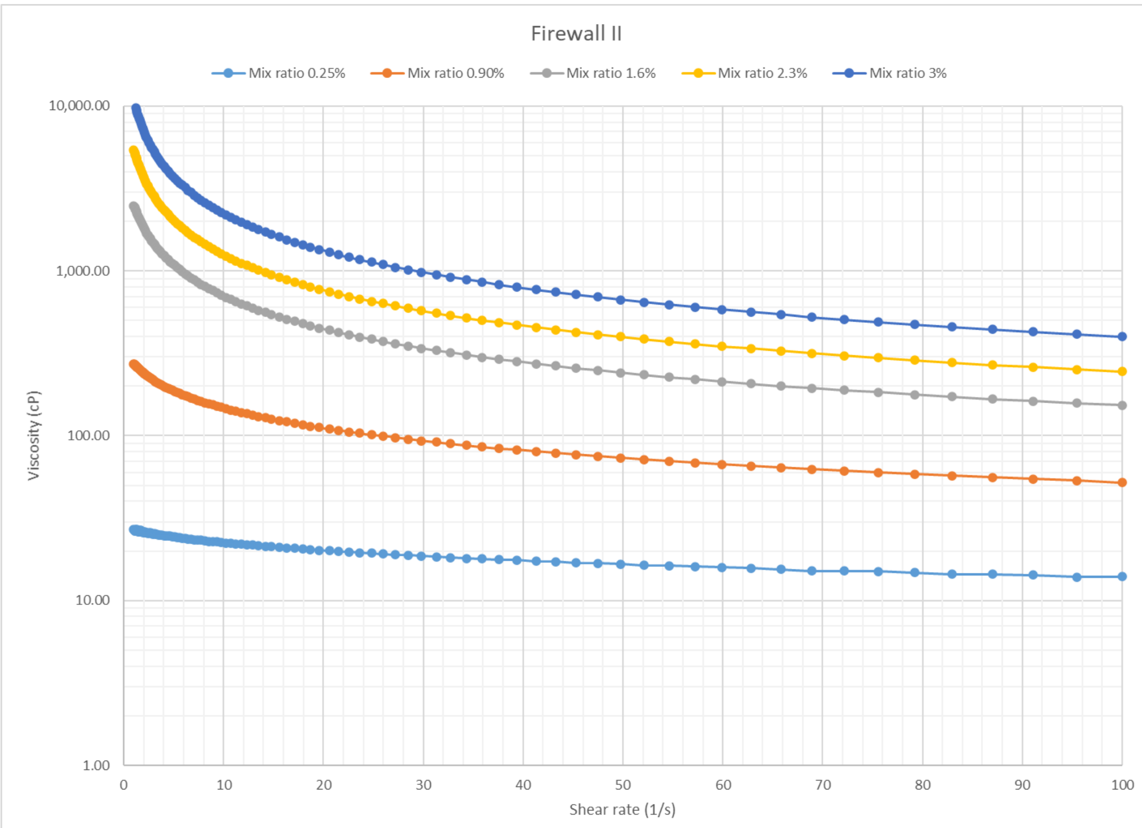

Figure 9. Viscosity versus shear rate for different mix ratios of Firewall II.

FireIce 561

Figure 10 presents the average viscosity curves for different mix ratios of FireIce 561.

Viscosity range

Figure 10 has a y-axis range between 100 and 1,000,000 cP wherein all curves for the different mix ratios fall. These results show that FireIce 561 has very high viscosities across the entire range of approved mix ratios.

Fluid properties

All mix ratios exhibited noticeable decreases in viscosity when shear rate was increased, thus exhibiting shear-thinning properties.

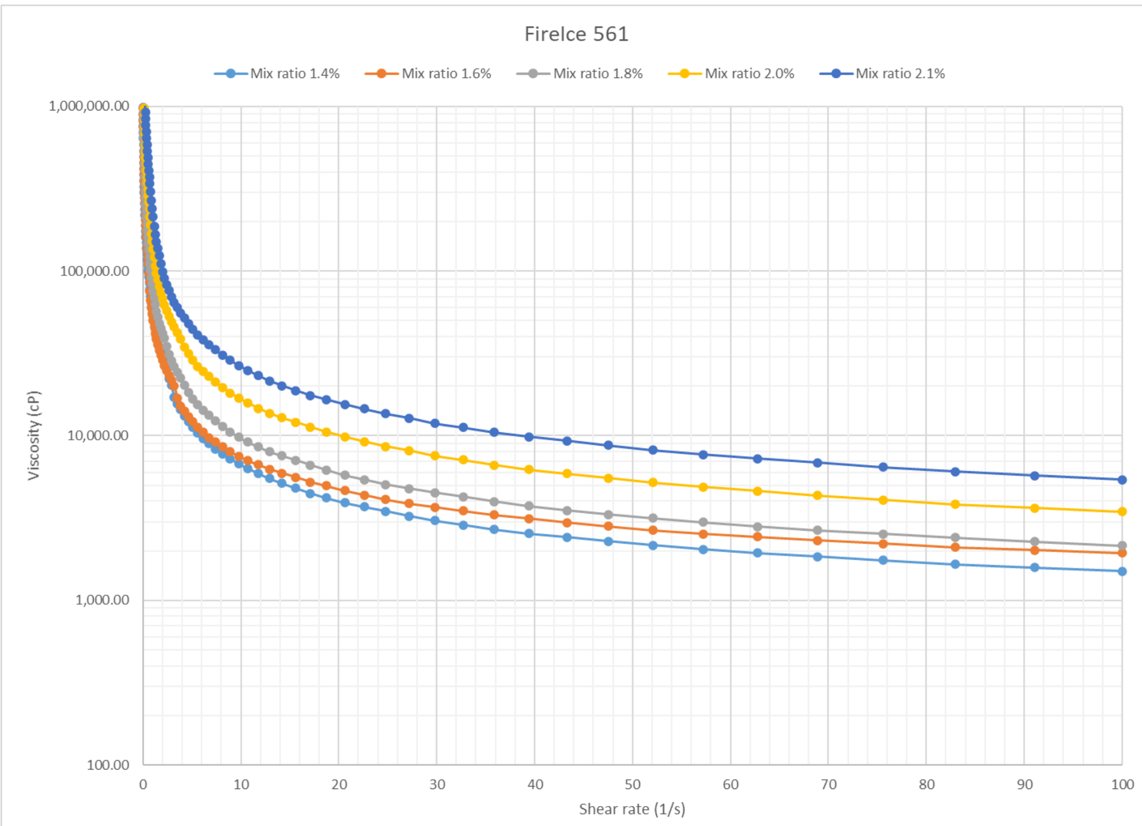

Figure 10. Viscosity versus shear rate for different mix ratios of FireIce 561.

Thermo-Gel 200L

Figure 11 presents the average viscosity curves for different mix ratios of Thermo-Gel 200L.

Viscosity range

Figure 11 has a y-axis range between 1 and 100,000 cP wherein all curves for the different mix ratios fall. These results show that Thermo-Gel 200L has moderate to high viscosities across the range of approved mix ratios. Starting with a mix ratio of 0.5%, the viscosity is relatively moderate; viscosity quickly increases at higher mix ratios.

Fluid properties

Thermo-Gel 200L at 0.5% was found to be a Newtonian fluid. However, all other mix ratios exhibited noticeable decreases in viscosity when shear rate was increased, thus exhibiting shear-thinning properties.

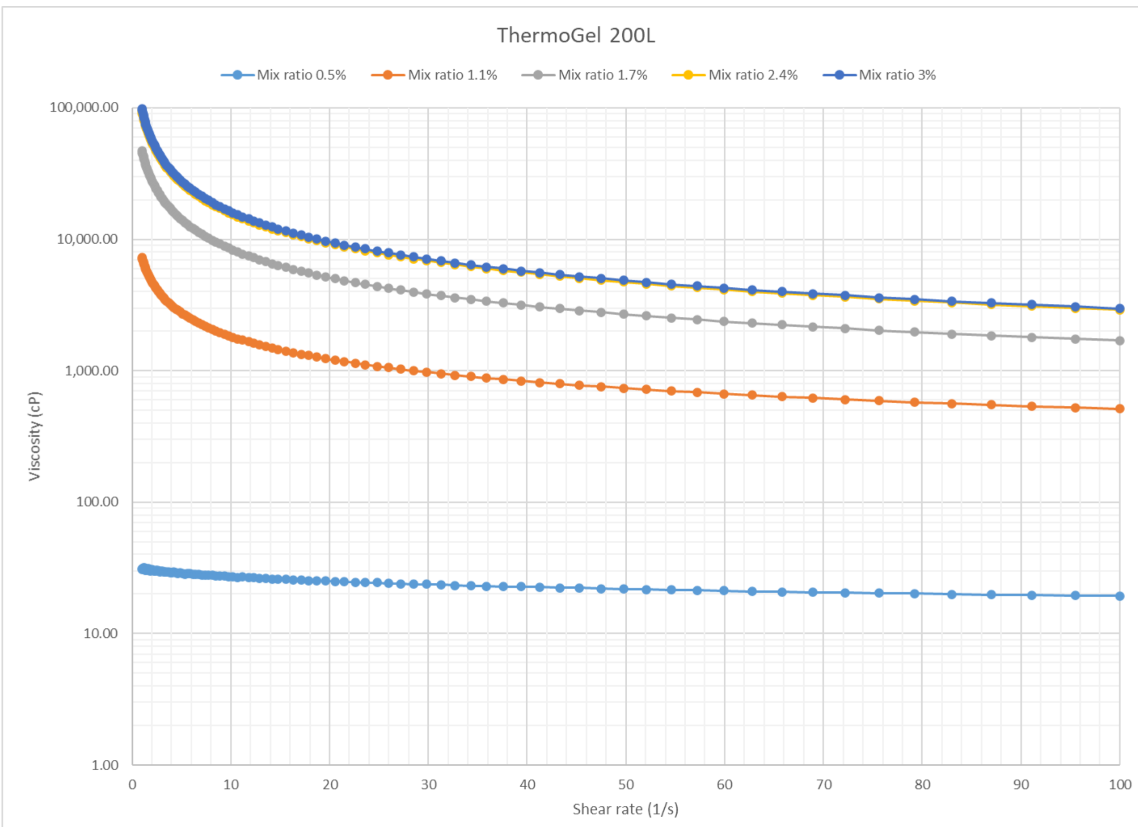

Figure 11. Viscosity versus shear rate for different mix ratios of Thermo-Gel 200L.

Phoschek LC 95A

Figure 12 presents the average viscosity curve for the standardized Canadian mix ratio of Phoschek LC 95A.

Viscosity range

Figure 12 has a y-axis range between 1 and 10,000 cP wherein the curve for the product lies. These results show that Phoschek LC 95A starts off with relatively high viscosity and tapers off in the 100 cP region fairly quickly.

Fluid properties

This mix ratio exhibited a noticeable decrease in viscosity when shear rate was increased, thus exhibiting shear-thinning properties.

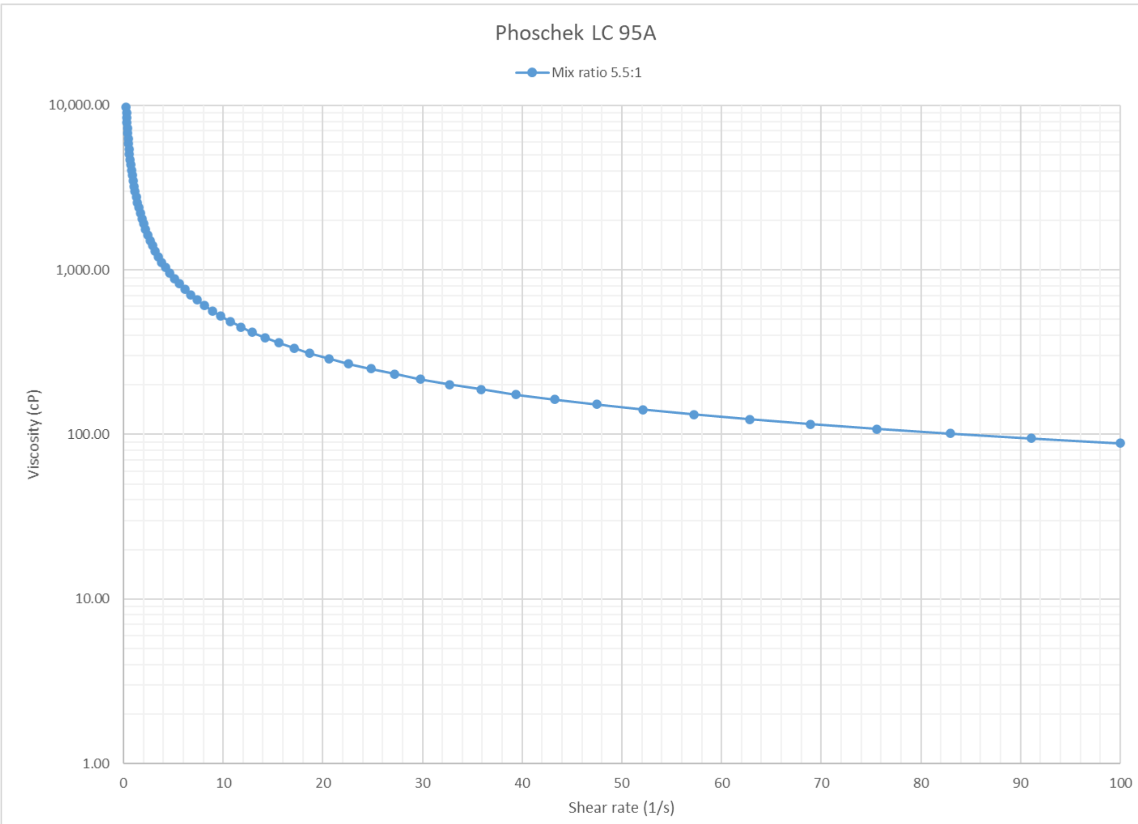

Figure 12. Viscosity versus shear rate for 5.5:1 mix ratio of Phoschek LC 95A.

WD881C

Figure 13 presents the average viscosity curves for different mix ratios of WD881C.

Viscosity range

Figure 13 has a y-axis between 1 and 10 cP wherein all curves for the different mix ratios fall. These results show that WD881C has minimal variation in viscosity, meaning that mix ratio does not influence its viscosity. In addition, the range of viscosities observed is similar to that of water (i.e., 1–5 cP).

Fluid properties

Due to minimal changes in viscosity with an increase in shear rate, WD881C at different mix ratios can be considered a Newtonian fluid.

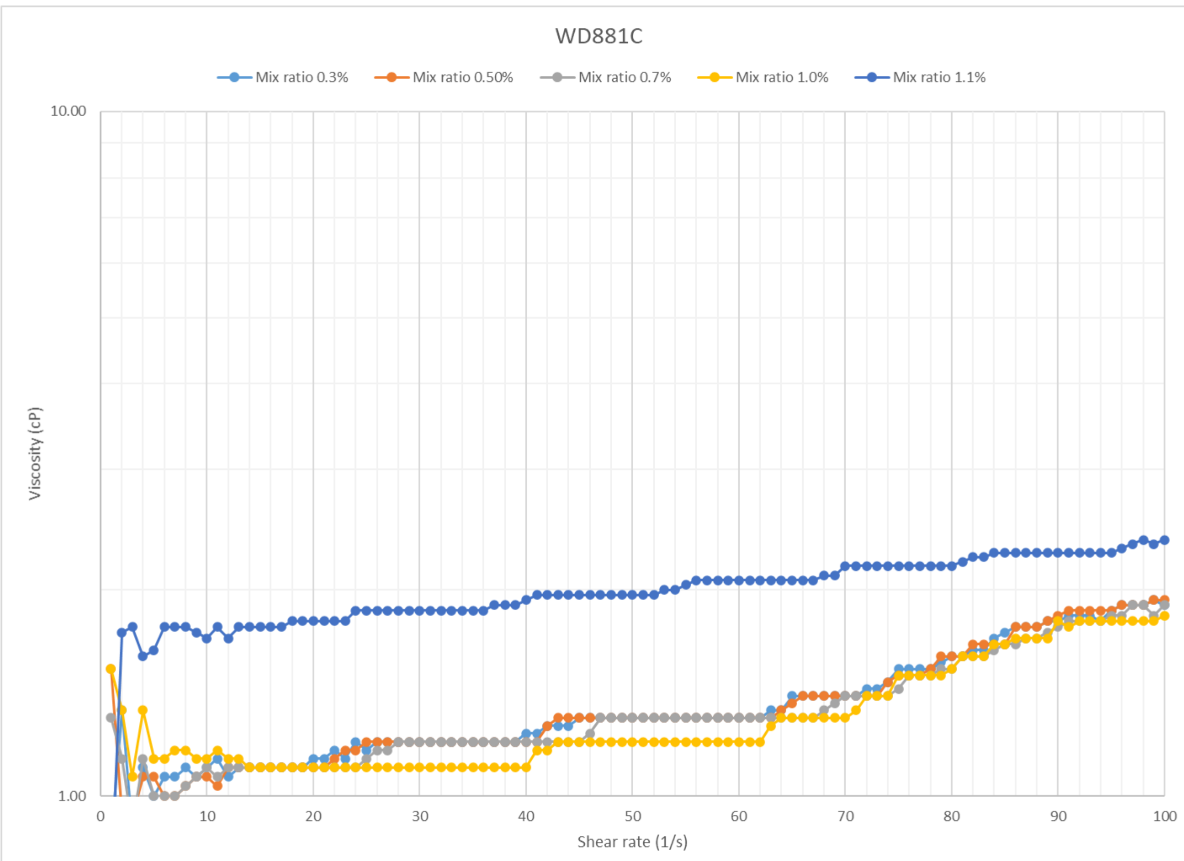

Figure 13. Viscosity versus shear rate for different mix ratios of WD881C.

Discussion

Operational viscosity range

Based on the results of this study, we see that water-enhancer products can produce high viscosities at higher mix ratios. These high viscosities do not necessarily correlate with better performance. If a product has such high viscosity that it does not mix properly or cannot flow out of an aircraft's drop tank, the effectiveness of that product should be questioned. It may be useful to wildfire management agencies to establish an *operational viscosity range* where the minimum and maximum viscosity thresholds for drops are defined. The operational viscosity range should be product-specific and should:

- Be within the bounds of the QPL mix ratio ranges, thereby adhering to environmental standards first and foremost.
- Be a subset of the QPL mix ratio ranges, thereby narrowing the selection for agencies.

An operational viscosity range would offer agencies flexibility in selecting a viscosity suitable to meet their operational objectives.

Potential solution in retardant data

Phoschek LC 95A is a retardant, and it is the most common wildfire chemical used by wildfire management agencies. Retardants contain gum thickeners that increase the viscosity of the mixed solution. Retardants are operationally effective and have been in use for a number of decades. Wildfire agencies are familiar with retardant, both its manageable viscosity and its drop characteristics. Therefore, a good starting point in developing an operational viscosity range for water-enhancer products would be to consider the viscosity data of retardants. For example, if the mix ratios in Table 1 were to be colour-coded such that mix ratios with viscosities similar to retardant are shaded green, and mix ratios with viscosities higher than retardant are shaded red, we would get Table 3.

Table 3. Hypothetical exercise in developing operational viscosity ranges.

Product	QPL Mix-Ratio Range*	Mix Ratios Tested				
BlazeTamer 380	0.65%	0.3%	0.4%	0.5%	0.6%	0.65%
Firewall II	0.25% – 3%	0.25%	0.9%	1.6%	2.3%	3.0%
FireIce 561	1.4% – 2.1%	1.4%	1.6%	1.8%	2.0%	2.1%
Thermo-Gel 200L	0.5% - 3.0%	0.5%	1.1%	1.7%	2.4%	3.0%
Phoschek LC 95A	5.5: 1	5.5:1				
WD881C	0.1% - 1.0%	0.3%	0.5%	0.7%	1.0%	1.1%

**Mix-ratio range as determined by the qualified products list (QPL) from the USDA Forest Service (2020).*

Interestingly, the water-enhancer products shaded red in Table 3 are almost exactly the same products that could not be effectively dropped during the crib tests (Refai and Paskaluk 2021). This suggests that there may be value in pursuing an operational viscosity range and ruling out certain products at certain mix ratios for aircraft use.

Shear thinning fluids

The results from the viscosity tests showed that several suppressant products were shear-thinning fluids—that is, their viscosity decreased when shear rate increased. When a suppressant is dropped from an aircraft, individual drops are formed. Each of these drops experiences drag force equal to its weight when it reaches terminal velocity. This drag force imparts shear. For suppressants that are shear-thinning fluids, this shear will decrease their viscosity. This raises the question: is the goal to achieve a target viscosity in the tank or in the air? The answer has financial implications because more concentrate will be required to achieve a target viscosity in the air for suppressants that are shear-thinning fluids.

Minimal change in viscosity

Two products were found to have minimal changes in viscosity when their mix ratios were increased—BlazeTamer 380 and WD881C. WD881C is a foam, and is therefore not designed to increase in viscosity. BlazeTamer 380, advertised as an elastomer and independent of viscosity changes for its functionality, was found to have marginal increases in viscosity with increases in mix ratio. This raises the question: why use more concentrate when less will result in the same physical properties? It would be worth exploring why lower mix ratios of BlazeTamer 380 are not currently on the QPL.

Conclusion

The objective of this study was to map how viscosity of different suppressant products changed with their mix ratios. FPInnovations collaborated with the Tsai Lab of Fluids and Interfaces to obtain this data. Samples of various wildfire suppressants were prepared and run through a rheometer to obtain viscosity, normal differential stress, and storage and loss modulus data. The products tested were BlazeTamer 380, Firewall II, FireIce 561, Thermo-Gel 200L, Phoschek LC 95A, and WD881C. Five mix ratios were selected for each product (one for Phoschek LC 95A) within the approved mix ratio bounds set by the QPL.

Results from this study showed that viscosity ranges were product-specific and varied widely amongst products. Certain products, such as FireIce 561 and Thermo-Gel 200L, showed a wide range of viscosities, with certain mix ratios likely to be unmanageable for aircraft use. BlazeTamer 380 was found to have minimal increases in viscosity associated with increases in mix ratios. Some suppressant products were found to be shear-thinning fluids (i.e., their viscosity decreased with increasing shear rates).

The benefits of an operational viscosity range were discussed, and the viscosity data of retardant was suggested as a starting point for its development. An operational viscosity range may help agencies identify and rule out products that offer little value to aircraft operations.

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