NRL Report 6486

Use of the Hysteresis Loop Method to Study Thixotropic Suspensions

Part 1 - Ben-a-Gel/Water System

J. T. LEONARD AND R. N. HAZLETT

Fuels Branch
Chemistry Division

January 24, 1967

NAVAL RESEARCH LABORATORY
Washington, D.C.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

CONTENTS

Abstract 1

INTRODUCTION 1

EXPERIMENTAL DETAILS 2

Material 2
Sample Preparation 2
Flow Curves 2

RESULTS AND DISCUSSION 2

Analysis of Flow Curves 2
Plastic Viscosity 3
Evaluation of Constants 5
Yield Points 6

CONCLUSIONS 8

REFERENCES 8

APPENDIX A—Calibration of the Viscometer and Use of the Recorder 9

APPENDIX B—Preparation of Flow Curves 10

APPENDIX C—Time Required for Gels to Develop Maximum Properties 11

APPENDIX D—Reproducibility of Rheograms 12

Use of the Hysteresis Loop Method to Study Thixotropic Suspensions

Part 1 — Ben-a-Gel/Water System

JOSEPH T. LEONARD AND ROBERT N. HAZLETT

Fuels Branch
Chemistry Division

Abstract: The rheological behavior of aqueous suspensions of Ben-a-gel, a highly purified magnesium montmorillonite, was studied by the hysteresis loop method. It was found that the plastic viscosities of these suspensions could be related to concentration by Arrhenius' law at low concentrations or Weltmann and Green's equation at higher concentrations. The transition from one exponential law to the other occurs at about 1.1 vol-% of Ben-a-gel, the concentration at which the gel strength is sufficiently developed so that the suspension no longer flows from an inverted container. The values for the various yield points characterizing the hysteresis loop also bear exponential relationships to concentration and show similar transitions at about 1.1 vol-% of Ben-a-gel. The results of this study indicate that Arrhenius' law may be used in conjunction with Weltmann and Green's equation to describe the rheological behavior of an ideal thixotropic suspension over a concentration range covering both the pregelation and postgelation regions.

INTRODUCTION

Liquid-fueled rockets and missiles have been considered for fleet use, but a major objection is that the handling and storage of such weapons aboard ship can involve dangerous operations. It has been suggested that the hazards involved can be greatly minimized by converting the propellants to thixotropic gels (1). Ideally, such gels would combine the advantages of both liquid and solid fuels. If a tank ruptured, the gelled propellant would behave as a solid and would not leak out. On the other hand, such gels would retain the pumping and throttling characteristics of liquid fuels without sacrificing much of the advantage in specific impulse that liquids have over solids.

The present study was initiated to investigate the nature of gels and to determine how factors responsible for gel formation might be applied later to gelled propellant systems. In order to attain a better understanding of the more complex gelled propellants, a preliminary investigation was made on the behavior of a much simpler thixotropic system, namely, an aqueous suspension of magnesium montmorillonite.

A thixotropic system may be defined as a suspension which experiences a decrease in viscosity when subjected to shear but which regains its initially higher viscosity upon resting (2). According to this definition, paints, printing inks, suspensions of pigments, gelatin sols, and clay pastes are all thixotropic substances.

When an ideal thixotropic suspension is placed in a cup-and-bob-type viscometer and the shear rate is increased rapidly from zero to a preselected maximum and then decreased rapidly to zero, a plot of the shear stresses encountered along this route reveals a hysteresis loop as shown in Fig. 1. This loop, which results from the breakdown in structure with shear, is characteristic of thixotropic substances (2-4). Since the structure also breaks down with time under shear, the upcurve and downcurve must be made as rapidly as possible.

A hysteresis loop in the flow curves (rheograms) of thixotropic substances was noted earlier (5,6) and a method of studying gels based on their hysteresis loops was proposed by Weltmann and Green (2, 7-12). This method has been applied to many dispersions such as printing inks (7), pigment suspensions (10), cosmetics (13), and aqueous

NRL Problem C01-05; Projects RR 010-01-44-5851. This is an interim report on this phase of the problem; a final report will follow. Manuscript submitted September 2, 1966.

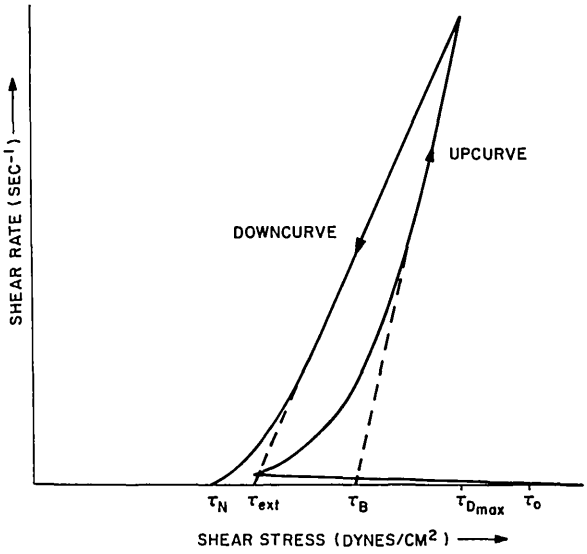

Fig. 1 – Idealized flow curve (rheogram) for a thixotropic suspension

suspensions of attapulgite (3) and bentonite (14). In the present study, the hysteresis loop method was used to investigate the flow behavior of aqueous dispersions of Ben-a-gel, a highly purified magnesium montmorillonite.

EXPERIMENTAL DETAILS

Material

Ben-a-gel, a product of the National Lead Co., is a highly beneficiated, hydrous, magnesium silicate derived from montmorillonite. When properly dispersed, the ultimate particle size of the platelets is less than 1 micron.

Sample Preparation

Samples containing 0.42 to 2.15 vol-% of Ben-a-gel were dispersed in distilled water using a Waring blendor at low speed for 2 minutes, followed by 2 minutes of shearing at high speed. Certain samples, depending on gellant concentration, set up as gels in the blender during the low speed shearing, while others set up only at high speed. A sample that gelled during low speed shearing was shaken down into the path of the blades and then sheared at high speed until it set up again. A sample that set up under high shear conditions before the 2-minute period was up, was shaken down again into the path of the blades and stirred at high speed until the gel set up again. This usually took a few seconds. The shaking-down and stirring procedure was repeated five times to ensure maximum dispersion. This sample preparation technique gave reproducible, uniformly dispersed gels as indicated by flow properties.

Flow Curves

Flow curves were obtained using a Haake Rotovisco rotating bob viscometer coupled to a Sargent recorder. With the Rotovisco, the shear rate for a given cup and bob combination is controlled by a ten-speed, manually operated gear shift. The corresponding shear stress data are obtained from the recorder tracing. Details on the calibration of the viscometer and the use of the recorder are given in Appendix A. The preparation of flow curves is described in Appendix B. The time required to obtain a flow curve generally was between 40 and 120 seconds, depending on the concentration of the suspension. However, the sample was not sheared throughout this entire period, since the bob stopped rotating momentarily while the instrument was shifted to the next speed.

In this study, two cup and bob combinations were employed which had the characteristics shown in Table 1. The cups were held in a bath, controlled at 25.00° ± 0.02°C.

TABLE 1
Viscometer Characteristics

Designation	Dimensions of Cup, $L \times D$ (mm)	Dimensions of Bob, $L \times D$ (mm)	Shear Rate Range (sec^{-1})
MVI	92.0 × 42.0	60.0 × 40.1	8-1370
MVIIP	92.0 × 42.0*	60.0 × 36.8*	3-497

*Effective diameter. MVIIP cup and bob have fluted surfaces to minimize slippage.

RESULTS AND DISCUSSION

Analysis of Flow Curves

A typical flow curve, as idealized in Fig. 1, affords the following data points:

τ_0 = experimental yield stress, a measure of the minimum yield stress that must be overcome before flow will commence. Not all thixotropic substances have τ_0 lying beyond the lower limit of the upcurve as shown in Fig. 1. In some cases τ_0 is not detected.

τ_B = Bingham yield value, obtained by extrapolating the straight-line portion of the upcurve

$\tau_{D_{max}}$ = shear stress at maximum shear rate

τ_{ext} = extrapolated yield stress, obtained by extrapolating the straight-line portion of the downcurve

τ_N = residual gel strength, a measure of the amount of structure remaining in the gel after it has undergone the shear history as given by the upcurve and downcurve.

For a given suspension, the position of the hysteresis loop along the stress axes can be described by these five points.

Flow curves were made for each sample, using both the low-shear and high-shear cup and bob arrangements. A composite flow curve showing data obtained with both cup and bob arrangements is presented in Fig. 2. The agreement between the data for low and high shear was good.

Gels appeared to reach their maximum strength within 24 hours after preparation (Appendix C). For a given concentration of gelling agent, the flow curves were found to be reproducible (Appendix D) and unaffected by standing for 9 days (Appendix C).

Plastic Viscosity

The plastic viscosity of each suspension was calculated from the flow curve data using the following expression (10):

$$\eta_{pl} = \frac{\tau_{D_{max}} - \tau_{ext}}{D_{max}} \tag{1}$$

where

η_{pl} = plastic viscosity, poises

D_{max} = maximum shear rate, sec^{-1}.

The plastic viscosity is plotted on a logarithmic scale as a function of concentration of Ben-a-gel for both the low-shear and high-shear data in Fig. 3. It is evident that the flow behavior of

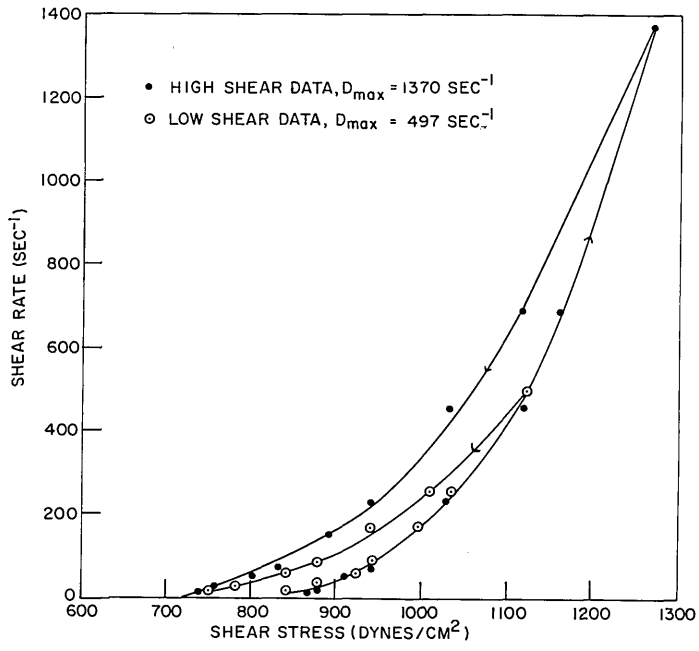

Fig. 2 — Experimental flow curves for Ben-a-gel suspensions showing agreement between low and high shear data

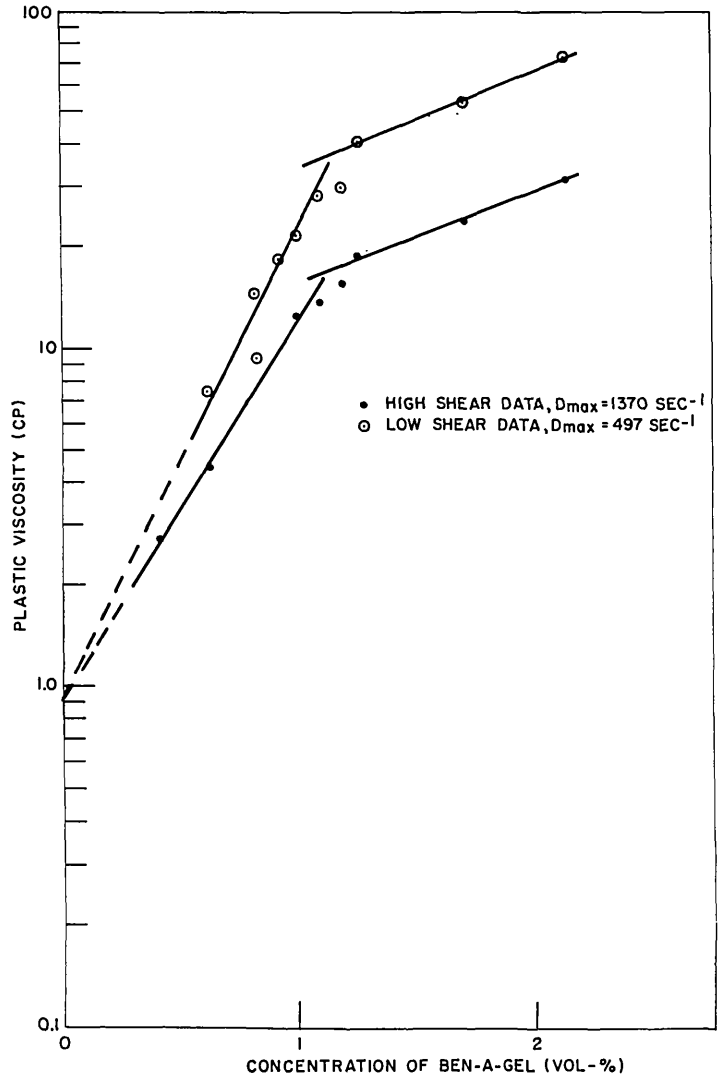

Fig. 3 – Change in the exponential function relating the plastic viscosity of Ben-a-gel suspensions to concentration

Ben-a-gel suspensions is governed by two exponential laws. This behavior was predicted by Weltmann and Green (10), who sought to explain why similar plots of plastic viscosities of pigment suspensions did not extrapolate at zero concentration to the viscosity of the suspending liquid as predicted by Arrhenius' law but appeared to follow another exponential law.

According to Arrhenius' law, the viscosity of a colloidal suspension is given by

$$\eta = \eta_0 \, e^{\kappa C} \qquad (2)$$

where

η = viscosity of the suspension, poises

η_0 = viscosity of the suspending liquid, poises

κ = a constant characterized by the solid, suspending liquid, and temperature

C = concentration, vol-%.

Weltmann and Green (10) found that their suspensions did not adhere to Arrhenius' law but appeared to be governed by

$$\eta_{pl} = (\eta_0 + A)e^{BC} \quad (3)$$

where

B = slope

A = a constant.

The difference between the two laws is illustrated in Fig. 4 (10). As shown, Weltmann and Green's equation does not hold at low concentrations, since this equation predicts that the viscosity of the pure liquid is $\eta_0 + A$, which obviously cannot be the case. On the other hand, extrapolation of the curve plotted from Arrhenius' law does give the viscosity of the pure liquid at zero concentration of solid. Since Weltmann and Green were working with suspensions containing 10 to 50 vol-% of solids, it appears that they were operating in a region where Arrhenius' law did not apply.

These authors (10) suggest that the change from one exponential law to another may be explained if one considers that suspensions are Newtonian liquids up to a certain solid content, and that a higher percentage of solid causes a rather sudden change to plastic flow behavior. However, they offered no experimental evidence to support this contention.

In the present study, it was found that if plastic viscosity is substituted for η in Eq. 2, Arrhenius' law is obeyed for concentrations of Ben-a-gel up to about 1.10 vol-% (Fig. 3). At higher concentrations, Weltmann and Green's equation is followed. Thus these two equations can be used in conjunction to describe the flow behavior of Ben-a-gel suspensions. The physical phenomena associated with the transition from one law to another can best be described by dividing the gelation process into three regions.

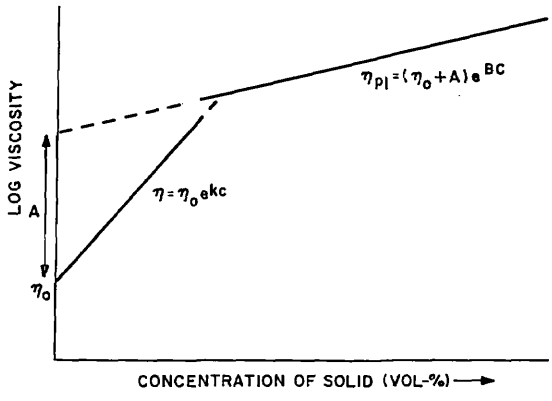

Fig. 4 – Explanation of Fig. 3, showing the applicability of Arrhenius' law at low concentrations and Weltmann and Green's equation at higher concentrations.

Pregelation Region (0.42 to 1.10 vol-% of Ben-a-gel)—Ben-a-gel suspensions behave as thixotropic liquids and exhibit a large increase in viscosity upon the addition of small amounts of gelling agent. Such behavior indicates that structure is building up rapidly. Although no attempt was made in the present study to determine the lowest concentration at which thixotropic behavior could be observed in Ben-a-gel suspensions, there were indications that such behavior exists below 0.42%. Hauser (15) found evidence of gel structure at concentrations as low as 0.05 wt-% for fine fractions of natural bentonite.

Transition Zone (1.10 to 1.27 vol-% of Ben-a-gel)—There is a change in the behavior of the suspension which coincides with the break in the curve in Fig. 3. Thus, by the time the concentration of Ben-a-gel reaches 1.10 vol-%, the structure is developed to the point where the dispersion will set up as a gel in the blendor during high shear mixing. Also, the yield point is sufficiently high at this concentration that the suspension will no longer flow from an inverted container. For the Ben-a-gel/water system, this behavior marks the transition from thixotropic liquid to gel and gives rise to the break in the curve as shown in Fig. 3.

Postgelation Region (above 1.27 vol-% of Ben-a-gel)—When the concentration of Ben-a-gel reaches 1.27 vol-%, the gel structure can be considered to be completely built up. Additional amounts of gelling agent do not affect the plastic viscosity as much as in the pregelation region.

Evaluation of Constants

The values for the constants in Eqs. 2 and 3 as determined from the experimental data are given in Table 2. Since Ben-a-gel suspensions are thixotropic even at low concentrations, the plastic viscosities decrease with increasing shear rate. This behavior is demonstrated by the fact that the value for κ, the slope in Eq. 2, was twice as high with the low-shear cup and bob.

TABLE 2
Values for Constants in Eqs. 2 and 3 for Ben-a-gel Suspensions

Cup and Bob	Eq. 2*	Eq. 3*	
	κ	A	B
MVI	12.7	7.5	0.63
MVIIP	25.7	16.9	0.65

*η_0 for H_2O at 25°C = 0.8937 cp.

In the postgelation region, where Eq. 3 holds, the difference in the plastic viscosities at the two shear rates is given approximately by the difference in the values for the constant A, since the value of the other term which comprises the ordinate-axis intercept, η_0, is less than 1.

In Table 2, the value of A is shown to be about twice as high at the lower shear rate, indicating that, at a given concentration of gelling agent, the plastic viscosity would also be about twice as high at the lower shear rate. The values of B, the slope in Eq. 3, are the same at both shear rates. This means that in the postgelation region, the curves are parallel straight lines and B is a material constant, characteristic of the liquid-gellant combination and independent of shear rate.

Yield Points

In Figs. 5 and 6 the values for the various yield points, τ_{ext}, τ_B, and τ_N, are plotted as a function of concentration. As in the case of the plastic viscosity, two flow regimes are observed for each yield point: the first covering the pregelation region and the second, the postgelation region. In either region, the data follow the equation set forth by Weltmann and Green (10):

$$\tau = Me^{NC} \tag{4}$$

where

τ = yield stress, dynes/cm²

M = yield stress intercept

N = slope

C = concentration, vol-%.

Within the range of experimental accuracy, the values of τ_{ext}, τ_B, and τ_N depend only on concentration of the gelling agent and are indpendent of the shear rate. This means that, for a given concentration of Ben-a-gel, the upcurves coincide, the extrapolated downcurves meet at a common point, and the amount of structure remaining in the gel after the hysteresis loops are obtained is the same at both the low and high shear rates.

The significant fact about the data in Figs. 5 and 6 is that the break in the curve at about 1.10 vol-% of Ben-a-gel coincides with the break indicated in Fig. 3 for plastic viscosity. As shown above, this break in the curve marks the transition in behavior from thixotropic liquid to gel.

The values for the constants in Eq. 4 are given in Table 3. The slopes N for each flow regime are practically constant, indicating that in both the pregelation and postgelation regions the curves are parallel. Hence, the position of each curve is distinguished by the value of M, the shear stress intercept. By definition, M is the yield stress at zero concentration. Since the dispersion medium, water, is a Newtonian liquid, there can be no yield stress in the absence of a gelling agent. Hence, the values of M in Table 3 have no physical significance but merely indicate the magnitude of the separation among the various curves.

In practice, a certain concentration of gelling agent is required before a continuous network can be established which will give rise to a yield point. Therefore, at some concentration below 0.42 vol-% of Ben-a-gel, Eq. 4 will no longer be valid and the curve will bend toward the concentration axis, as noted by Weltmann and Green (10).

The values for τ_0, the experimental yield stress, are not shown. In general, τ_0 increased

TABLE 3
Values for Constants in Eq. 4 for Ben-a-gel Suspensions

Yield Point	Constants in Pregelation Region		Constants in Postgelation Region	
	N	M	N	M
τ_B	3.82	9.33	0.537	400
τ_{ext}	3.80	7.95	0.547	350
τ_N	3.46	6.58	0.539	225

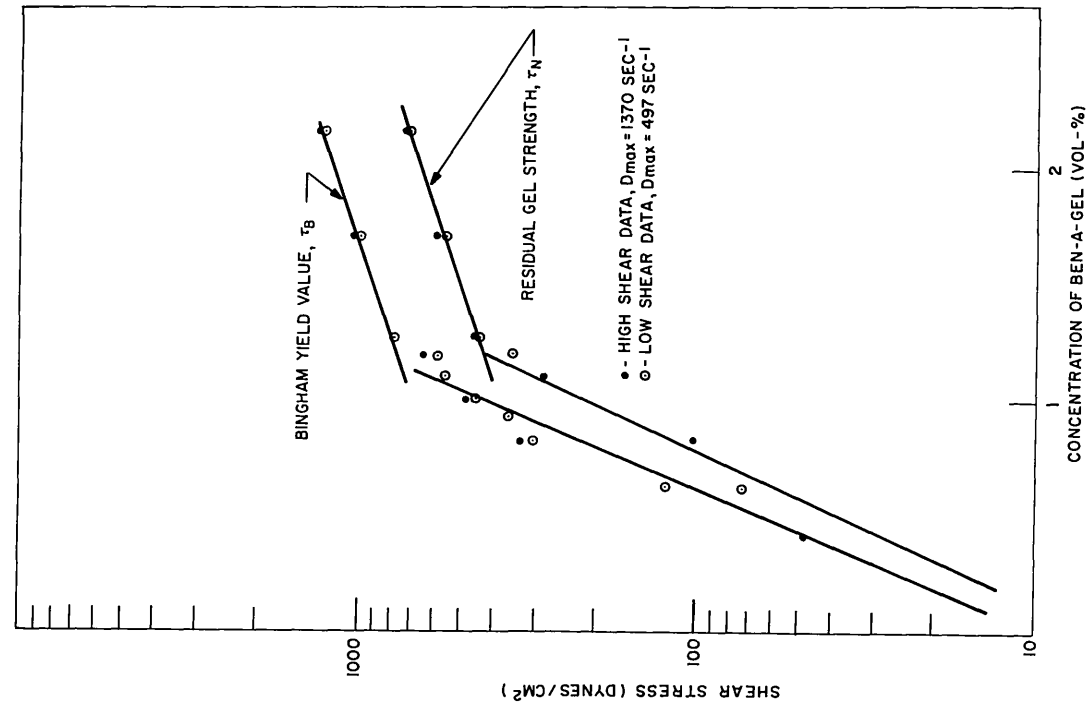

Fig. 6 — Plots of two of the yield points, showing breaks in the curve at the same concentration as that in Fig. 3

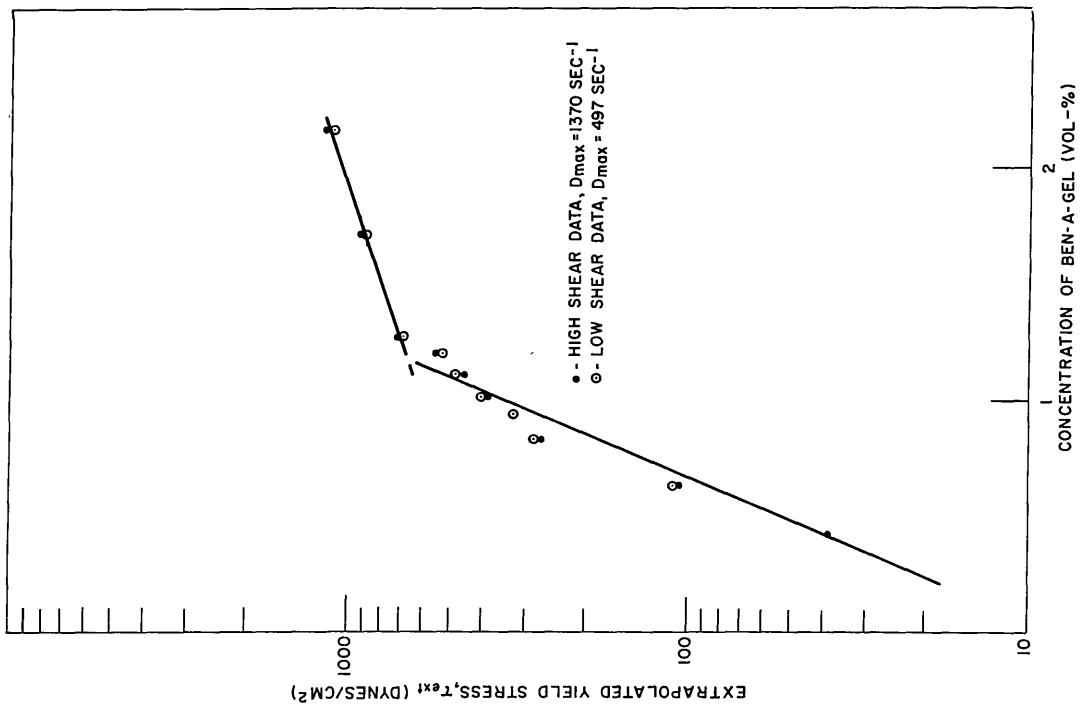

Fig. 5 — Plot of one of the yield points, showing a break in the curve at the same concentration as that in Fig. 3

exponentially with concentration, but in the postgelation region these values were not reproducible.

CONCLUSIONS

The plastic viscosity of aqueous Ben-a-gel suspensions can be related to concentration by Arrhenius' law at low concentrations or Weltmann and Green's equation at high concentrations. In the region where Arrhenius' law applies, the addition of small amounts of gelling agent increases plastic viscosity much more than at higher concentrations. This behavior suggests that the transition from one exponential law to the other may occur at the concentration at which a three-dimensional gel structure is achieved, since one would expect the plastic viscosity to increase at a much greater rate before the three-dimensional structure is reached than after. The fact that plots of the logs of the various yield points *vs* concentration show a transition occurring at the same concentration as for the plastic viscosity-concentration relationship, lends support to this view.

Although Arrhenius' law and Weltmann and Green's equation have been used individually to describe the flow behavior of various colloidal suspensions, the present work demonstrates that both equations can be applied to a single system to cover two separate flow regimes. This must be taken into account in any study and use of practical gelled fuel systems.

REFERENCES

1. Aeroprojects Incorporated, "Research and Development Program on Thixotropic Propellants," RR-61-38 on Navy Contract NOas-60-6122C final report (Confidential), June 1961
2. Weltmann, R.N., *Ind. Eng. Chem., Anal. ed.* **15**:424 (1943)
3. Gabrysh, A.F., Ree, T., Eyring, H., McKee, N., and Cutler, I., *Trans. Soc. Rheol.* **5**:67 (1961)
4. Hahn, S.J., Ree, T., and Eyring, H., *Ind. Eng. Chem.* **51**: 856 (1959)
5. Reiner, M., *Physics* **5**:321 (1934)
6. Pryce-Jones, J., *J. Oil Colour Chemists Assoc.* **19**:295 (1936)
7. Green, H., and Weltmann, R.N., *Ind. Eng. Chem., Anal. ed.* **15**:201 (1943)
8. Green, H., and Weltmann, R.N., *Ind. Eng. Chem., Anal. ed.* **18**:167 (1946)
9. Weltmann, R.N., *J. Appl. Phys.* **14**:343 (1943)
10. Weltmann, R.N., and Green, H., *J. Appl. Phys.* **14**:569 (1943)
11. Green, H., and Weltmann, R.N., *J. Appl. Phys.* **15**:414 (1944)
12. Green, H., "Industrial Rheology and Rheological Structures," New York:Wiley, p. 50, 1949
13. Heinrich, H., and Clements, J.E., Proc. Sci. Sect. Toilet Goods Assoc., No. 33 (1960)
14. Gabrysh, A.F., Cutler, I., Utsugi, H., Ree, T., and Eyring, H., Division of Colloid Chemistry, 137th Meeting ACS, Cleveland, Ohio, Apr. 6, 1960
15. Hauser, E.A., and Reed, C.E., *J. Phys. Chem.* **41**:911 (1937)

Appendix A

CALIBRATION OF THE VISCOMETER AND USE OF THE RECORDER

Flow curves were obtained using a Haake Rotovisco rotating bob viscometer in conjunction with a Sargent multirange recorder. The accuracy of the viscometer was checked with Bureau of Standards standard viscosity oils and found to be within 1%.

The efficiency of the constant temperature apparatus in removing the heat built up in the sample during prolonged shearing was also determined. For this purpose, a sample of Bureau of Standards standard viscosity oil was sheared at a rate of 685 sec^{-1} for 4 minutes. The decrease in the recorded shear stress during the 4-minute period corresponded to a decrease in viscosity of 0.61% or to a calculated temperature rise of 0.01°C.

The input circuit of the recorder was modified to match the impedance of the viscometer with that of the recorder by placing a 10,000-ohm resistor in parallel with the input of the recorder. Later, a circuit diagram for a variable resistance recorder adapter was provided by the viscometer manufacturer. The adapter was built and installed in place of the resistor.

Normally, the shear stress data from the Rotovisco are obtained by multiplying the viscometer scale reading by a constant for the particular cup and bob combination being used. However, to use the viscometer with a recorder it was necessary to calibrate the recorder: A sample of standard viscosity oil was placed in the cup and sheared momentarily to provide a reading on the viscometer scale. Then, the shearing was interrupted, the recorder switch activated, and the sample sheared again to give the corresponding point on the recorder. The procedure was repeated four times at each shear rate and the average viscometer and recorder readings taken. By using a combination of four Bureau of Standards standard viscosity oils and by employing different shear rates the recorder was calibrated over the entire range of the viscometer scale as shown in Fig. A1. From the data in this figure, a conversion of factor of 4.72 viscometer scale divisions per recorder scale division was established.

Shear stress data were obtained from the following formula:

$$\text{shear stress} = \text{recorder reading} \times 4.72 \times \text{cup and bob constant.}$$

The cup and bob constants are provided by the manufacturer. Since the shear stress depends on the dimensions of the bob, there is a different constant for each cup and bob combination.

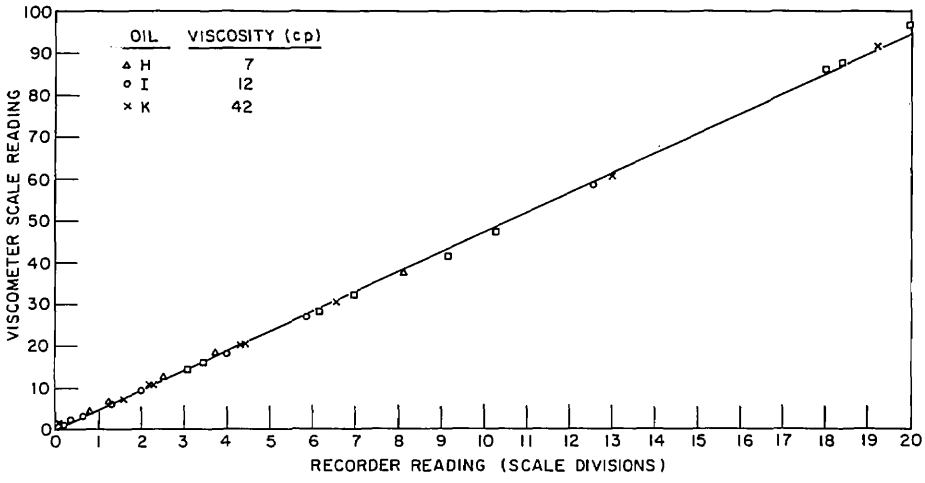

Fig. A1 — Calibration of the Sargent multirange recorder

Appendix B
PREPARATION OF FLOW CURVES

To prepare a flow curve, a sample of the gel is placed in the annulus between the cup and bob. After waiting 20 minutes for the temperature to equilibrate, the instrument is shifted into its lowest speed and the recorder engaged. Since the material in the annulus is a gel, the bob does not move until the shear stress at the surface of the bob exceeds the yield stress for the gel. Consequently, the shear stress builds up rapidly. This is shown in Fig. B1, which is a recorder trace of the shear stress data obtained when a sample containing 0.83 vol-% of Ben-a-gel was sheared in the MVIIP cup and bob arrangement. When the shear stress reaches τ_0, the experimental yield stress, the bob begins to move and the shear stress settles down to a constant value for the particular shear rate. The shear rate is then increased progressively to the maximum value for the cup and bob combination thereby forming the upcurve. The numbers under the steps are the shear rates.* Then, the shear rate is decreased in a stepwise fashion to give the shear stresses for the downcurve. Finally, the instrument is shifted into neutral and the amount of structure remaining in the sample (τ_N) is found.

*In the preparation of Fig. B1, the sample was sheared for a longer time than usual for clarity of presentation. In practice, the instrument is shifted to the next speed as soon as a reading is obtained at a given shear rate.

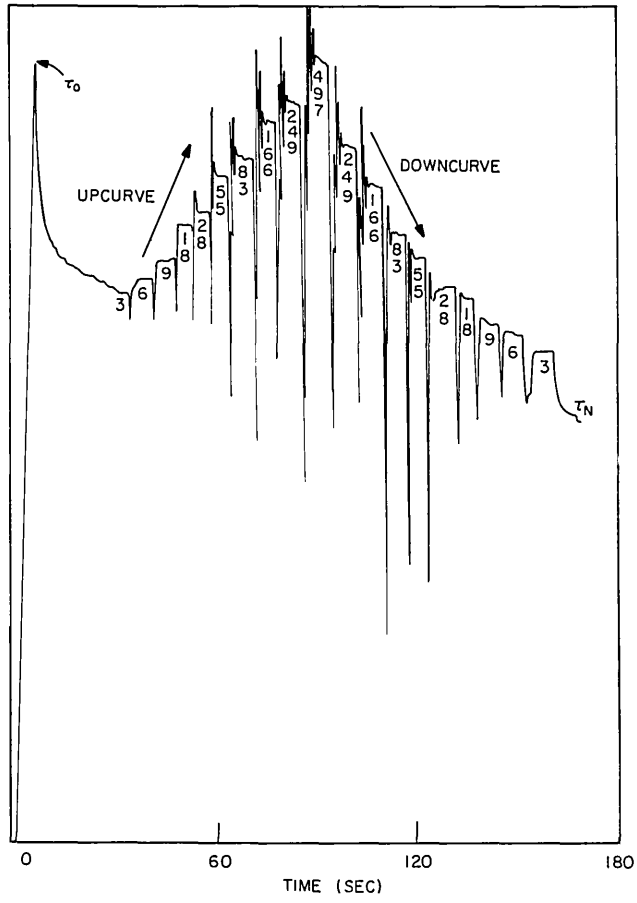

Fig. B1 – Recorder tracing of the shear stresses obtained while preparing a flow curve (0.83 vol-% of Ben-a-gel; MVIIP cup and bob)

Appendix C

TIME REQUIRED FOR GELS TO DEVELOP MAXIMUM PROPERTIES

A comparison of flow curves obtained 1, 2, 24, 48, and 96 hours after sample preparation was made to determine the time required for gels to develop their maximum properties. In Table C1 the shear stress data at maximum shear rates ($\tau_{D_{max}}$) are used as a basis for detecting changes in gel strength over the 96-hour period. Since the change in $\tau_{D_{max}}$ was so slight, it was considered that samples used 24 hours after preparation had certainly achieved their maximum gel strength, and that data obtained with them would be valid.

In another study, a comparison was made of the flow curves obtained 9 days after sample preparation with those obtained after the first day. The results of this comparison, as shown in Fig. C1, showed no significant change in the size or shape of the rheogram on standing for 9 days.

TABLE C1
Effect of Storage on Gel Strength

Storage Time (hr)	$\tau_{D_{max}}$ (dynes/cm²)	
	1.27 vol-% of Ben-a-gel	1.71 vol-% of Ben-a-gel
1	810	1123
2	840	1116
24	860	1133
48	860	1204
96	864	1221

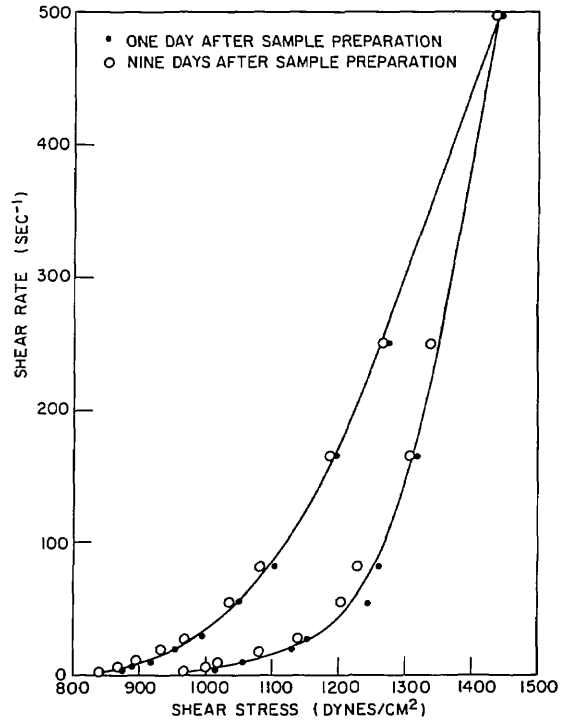

Fig. C1 — Effect of time on the shape of a flow curve (2.15 vol-% of Ben-a-gel)

Appendix D

REPRODUCIBILITY OF RHEOGRAMS

A number of flow curves were prepared for samples containing 0.83-2.15 vol-% of Ben-a-gel in order to determine if rheograms at a particular concentration are reproducible and characteristic of the sample. Since the size, shape, and position of the flow curve along the shear stress axis is determined by the various shear stress terms, τ_B, $\tau_{D_{max}}$, τ_{ext}, and τ_N, these terms were used as a basis for comparing the flow curves. The average values for these shear stress terms are shown in Table D1 together with the average deviations. Three samples were run at 0.83 vol-%, seven at 1.27 vol-%, and five each at 1.71 and 2.15 vol-%. The data in Table D1 show that the reproducibility of the flow curves as described by the shear stress values is satisfactory.

TABLE D1
Average Values for Shear Stress Terms for Ben-a-gel Suspensions and the Average Deviations

Concentration of Ben-a-gel (vol-%)	Average Shear Stress and Average Deviation (dynes/cm²)			
	τ_B	$\tau_{D_{max}}$	τ_{ext}	τ_N
0.83	306±3	343±2	265±2	N.D.*
1.27	792±52	889±64	686±41	453±16
1.71	994±61	1160±61	898±42	555±33
2.15	1274±55	1478±61	1116±51	708±31

*Not detected.

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Research Laboratory Washington, D.C. 20390	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

USE OF THE HYSTERESIS LOOP METHOD TO STUDY THIXOTROPIC SUSPENSIONS, PART 1—BEN-A-GEL/WATER SYSTEM

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

An interim report on one phase of the problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

J. T. Leonard and R. N. Hazlett

6. REPORT DATE January 24, 1967	7a. TOTAL NO. OF PAGES 14	7b. NO. OF REFS 15
8a. CONTRACT OR GRANT NO. NRL Problem C01-05 b. PROJECT NO. RR 010-01-44-5851 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 6486 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*	

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy (Office of Naval Research), Washington, D.C. 20360

13. ABSTRACT

The rheological behavior of aqueous suspensions of Ben-a-gel, a highly purified magnesium montmorillonite, was studied by the hysteresis loop method. It was found that the plastic viscosities of these suspensions could be related to concentration by Arrhenius' law at low concentrations or Weltmann and Green's equation at higher concentrations. The transition from one exponential law to the other occurs at about 1.1 vol-% of Ben-a-gel, the concentration at which the gel strength is sufficiently developed so that the suspension no longer flows from an inverted container. The values for the various yield points characterizing the hysteresis loop also bear exponential relationships to concentration and show similar transitions at about 1.1 vol-% of Ben-a-gel. The results of this study indicate that Arrhenius' law may be used in conjunction with Weltmann and Green's equation to describe the rheological behavior of an ideal thixotropic suspension over a concentration range covering both the pregelation and postgelation regions.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Guided missiles						
Rockets						
Fuels						
Storage						
Fluid flow						
Viscoelasticity						
Water						
Magnesium compounds						
Silicates						
Gels						
Shear stresses						
Viscosity						
Thixotropic gels						
Thixotropic rocket propellants						
Safety						
Rheological properties						