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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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ENTITLED VARIANCES OF SHEAR RATE AND STRESS AS A FUNCTION OF ELECTRICAL FIELD STRENGTH ON ELECTRORHEOLOGICAL FLUIDS

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE

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O-1364

Variances of Shear Rate and Stress as a Function of Electrical Field Strength on Electrorheological Fluids

by

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Thesis

for the
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in
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Introduction

Previous studies show that fluids composed of dielectric particles and a nonconducting fluid show an electrical field squared increase in viscosity with increasing applied voltage of 3 KV/mm. This fluid returns to its original value when the field is removed. The purpose of this thesis is to establish the effects of shear rate and electric field on stress for the electrorheological fluids (ER).

Survey of Literature

Fluids composed of dielectric particles and a nonconducting fluid, when exposed to an electric field, show a reversible increase in viscosity. The field strength required is usually on the order of .5-1 KV/mm,[1] supporting the use of a nonconducting fluid to keep current flow zero. Most of the theory utilized in this study is found in an article by D. L. Klass and T. W. Martinek.[2] The response time for these fluids is characterized by stress which increases with field strength, but which decreases with shear rate. Characteristic relaxation times are on the order of magnitude of a millisecond,[3] with field strengths of .5-1 KV/mm. The varying stress is related to the fact that the high dielectric particles align themselves parallel to the electric field. This phemonenon occurs any time the particles have a different dielectric constant than the suspending solvent, and gives rise to strings or chains of particles spanning the electrode gap. The viscosity is also dependent on this gap distance.

Many fluids have been studied for electrorheological applications. These fluids are characterized by chemical stability, nonabrasiveness, and lubricity. Also, the fluid must be an excellent electrical insulator and the solids must be highly dielectric compared to the liquid.

Applications for ER fluids are clutches, valves, shock absorbers, pumps, digital control systems, and robot actuators. The potential market worth has been estimated at $20 billion annually within a decade.

Apparatus

The apparatus used was a clutch-like system with a circular aluminum bob concentrically placed inside an aluminum well. The bob is 3.153-inches in diameter and 3.153 inches long, and is driven by a down-geared 1/40-horse power laboratory stirrer. The well has an inner diameter of 3.341 inches and a depth of 4.525 inches. It is connected to a shaft and pulley, with the pulley being connected to a spring scale. The gap formed on the sides is .094 inches and on the bottom it is 1.372 inches if the bob is flush with the well. The electric field is created by an electrical contact touching the bob and another contact in touch with the outside of the well. The support bracket for the system is completely insulated from the electrical contacts.

Auxiliary equipment includes a variable-voltage transformer, which produces 0-3300 V DC, a voltameter to monitor volage output, a controller for the variable speed motor, and a stopwatch to determine the shear rate.

Procedure - Polyaniline

The syntehsis of polyaniline (PAn) from aniline is simple but very time consuming. For a yield of approximately 30 g PAn, combine 171.1 g of Ammonium Persulfate, 122.94 ml of 37.7% HCl, 274.46 ml of aniline, and enough water to make the total batch volume 3000 ml. The reaction is almost instantaneous but is should be left stirring over-night. Large green cyrstals will be formed and caution should be taken when handling PAn since aniline is a known carcenegentic. The crystals have to be spun down at 10,000 RPM for 45 minutes. The liquid should be drained off. The crystals need to be washed and spun with 1 M HCl twice and washed and spun with .1 M twice. Water is then added and the solution is titrated until the pH is above 8.5. The solution needs to remain at this pH for a 24-hour period. The crystals are now highly polar blue crystals. Again they should be washed and spun twice in pure water, and finally placed in a 50°C dry oven until crystals are very brittle. The dried crystals are nonconducting, but if exposed to air or moisture for extended periods, they will become somewhat conductive and worthless as an ER fluid. The final step is to grind the crystals into a fine powder and dissolve them in an appropriate nonconducting fluid.

Procedure - Flour and Oil

A .500 mass fraction of flour and corn oil was made using 167.043 g of each component. After mixing thoroughly by hand, the solution was poured into the apparatus well. Enough liquid was used so that the liquid level was just below the top of the bob when it was set into the well, and the top of the bob was even with the top of the well. This quantity equaled almost 240 ml.

Data was collected on this solution by three different methods to ensure reproducability. Data for trials 1 and 2 were determined by fixing the voltage and varying the shear rate beginning at the highest stress rate. The voltage was measured by a voltameter.

The shear rate was determined by using a Helix stop-watch to measure the amount of time the bob took to revolve ten times. The hand timing was done 3 times and averaged for each run. Stress was determined by reading a spring scale. The power was not shut off at any time, but the scale was physically forced back to the 0 gram region after decreasing the shear rate for each run. In trials 3 and 4 the voltage was fixed again, except this time the scale was read with the power off (0 volt/mm) with constant shear rate starting at the highest rate. The power was then switched on, instantly producing the set voltage. As before, the scale was forced back to the 0 grams region and slowly released. The stress rate was then checked and scale readings were made. The power was switched off and shear rate decreased. The cycle was repeated. Data from trials 5-7 were taken starting at the lowest shear rate. The rate was determined in the same manner as before, and was fixed for each run. The voltage was varied to 0, 710.3, 1423, 2105.9, 2503.4, and 2848.4 volts for the same rate. The voltage was turned off after each scale reading. All trial data scale readings were taken after a 1 minute wait to allow equilibrium. Sixty grams of flour was added in Trial 7 to make a mass fraction solution of .600.

Results

Because experimental error is approximately 10 N/m^2, there is probably no effect at the 424.5 V/mm field in either figure 1 or figure 2. But the 626.2 V/mm in figure 1 did exhibit the expected ΔV^2 relationship to stress in the lower shear rates. The stress at 424.5 V/mm was 12.98 and at a similar shear the 626.2 V/mm read 28.56, meaning a magnitude change of 2.2 where a 2.25 was predicted.

Figures 3 and 4 show two very graphs, but both are at nearly the same electrical field strength. Besides proving the procedure for trials 3 and 4 causes large error. It does prove the 0 V/mm was reproducable.

Figures 5 and 6 from trial 5 and 6 showed the largest range of electrical fields and therefore stresses. The stresses do seem to begin converging at the higher shear rates. We expect this because once the shear rate is large enough the particles will have no time to form even simple two-particle chains and at that shear rate the fluid will behave the same as the 0 V/mm solution. The other more obvious pattern is at 47 Sec^{-1} there is a significant decrease in the stress but then begins to rise again. This is shown in figure 5, but even more clearly in figure 6. The cause for this is not totally know. It may be because small broken chains are tumbling through the center of the gap and becoming parallel with the field, causing the viscosity to decrease and thereby decreasing the stress. The 60 wt % flour solution also exhibited this decrease, reinforcing the possibility of it being a phenomena and not an error. Figure 7 was very similar in magnitude changes to figures 5 and 6. All were below the expected V^2 magnitude change. Tables 11-13 show the shear rate divided by this voltage squared for trials 5-7. Also, in tables 8-10 the collected data is shown as viscosity in poise.

Figures 8 and 9 show plots of ciscosity vs. shear rate and figures 10 and 11 show plots of viscosity vs. shear rate divided by electrical field squared. The data plots in figures 10 and 11 should be very close to each other.

Conclusions - Polyaniline

Polyaniline showed some promise, but unfortunately there was not enough time to make a significantly high wt % solution. But at the 30 wt % we currently have there is some effect, although not enough to collect data from.

Conclusions - Flour and Oil

1) There was some correlation with the stress change and the voltage change, but only at low shear rates.
2) There was a reproducible shear rate which created a drop in stress in the 50 wt % and 60 wt % flour solutions.
3) The second way of data collection is very inaccurate and should be avoided.

4) All data showed the possibility of convergence at a high enough shear rate.

Recommendations

1) Generate enough PAn so data could be gathered.
2) Determine what is occuring within fluid at the 47 sec^{-1} shear rate.
3) Try to increase range of shear rates.
4) Purchase means to measure shear rate and stress more accurately.
5) Power supply needs a built-in voltameter.

Acknowledgements

I would like to thank Dr. Zukoski for his patience and more patience, but more for his support and enthusiasm.

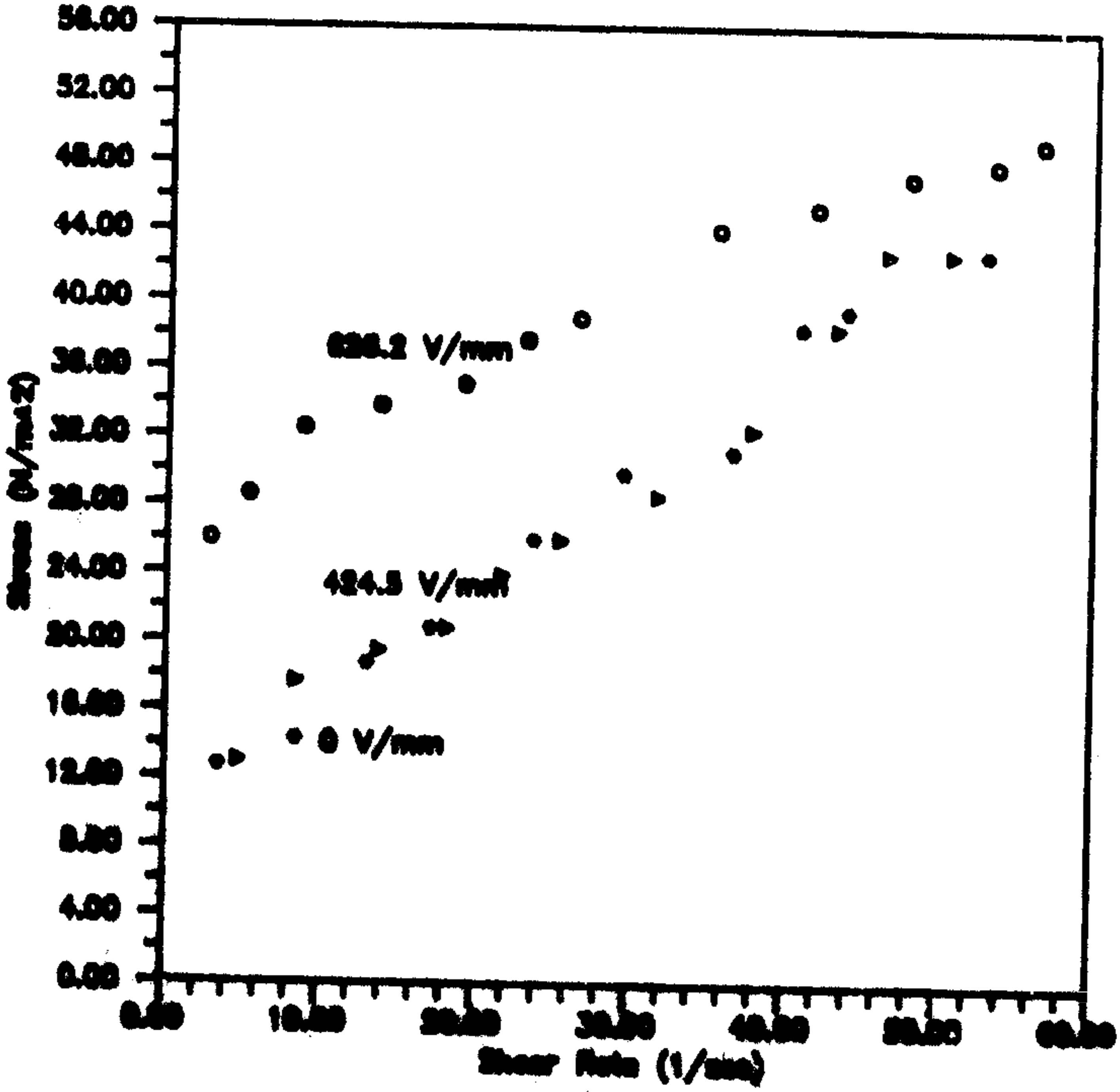
Also, the grad students for their help and guidance.

References

1. Zuckoski IV, C.F., and Goodwin, J.W., "Towards the Electrical Control of Viscosity: Optimization of Electrorheological Fluids,"

2) Klass, D.L., and Martinek, T.W., Journal of Applied Physics, p. 38, 67.

Appendices



[illegible] 20 wt.% Flour and Corn Oil at 0, 424.5, [illegible] V/mm

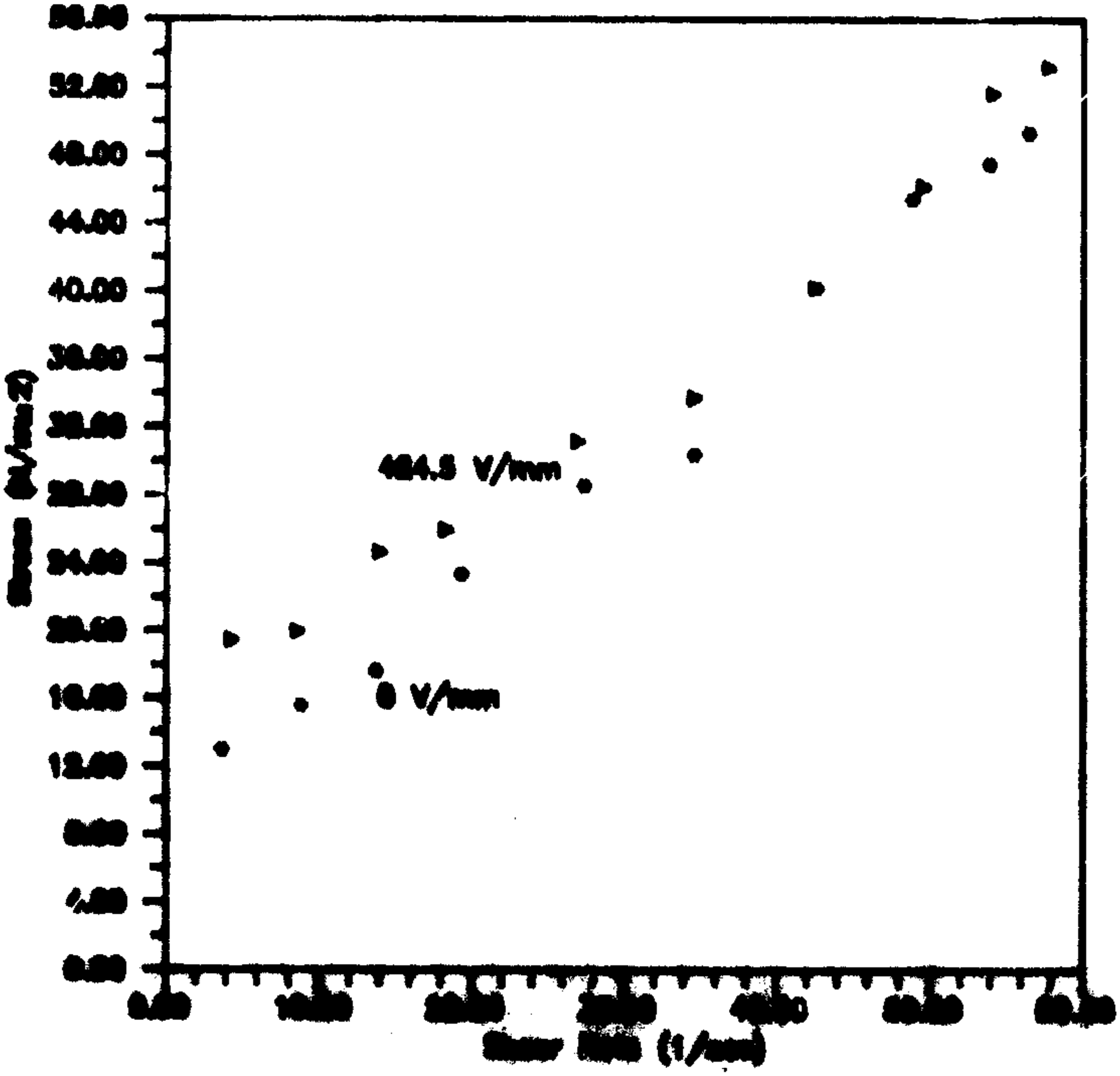
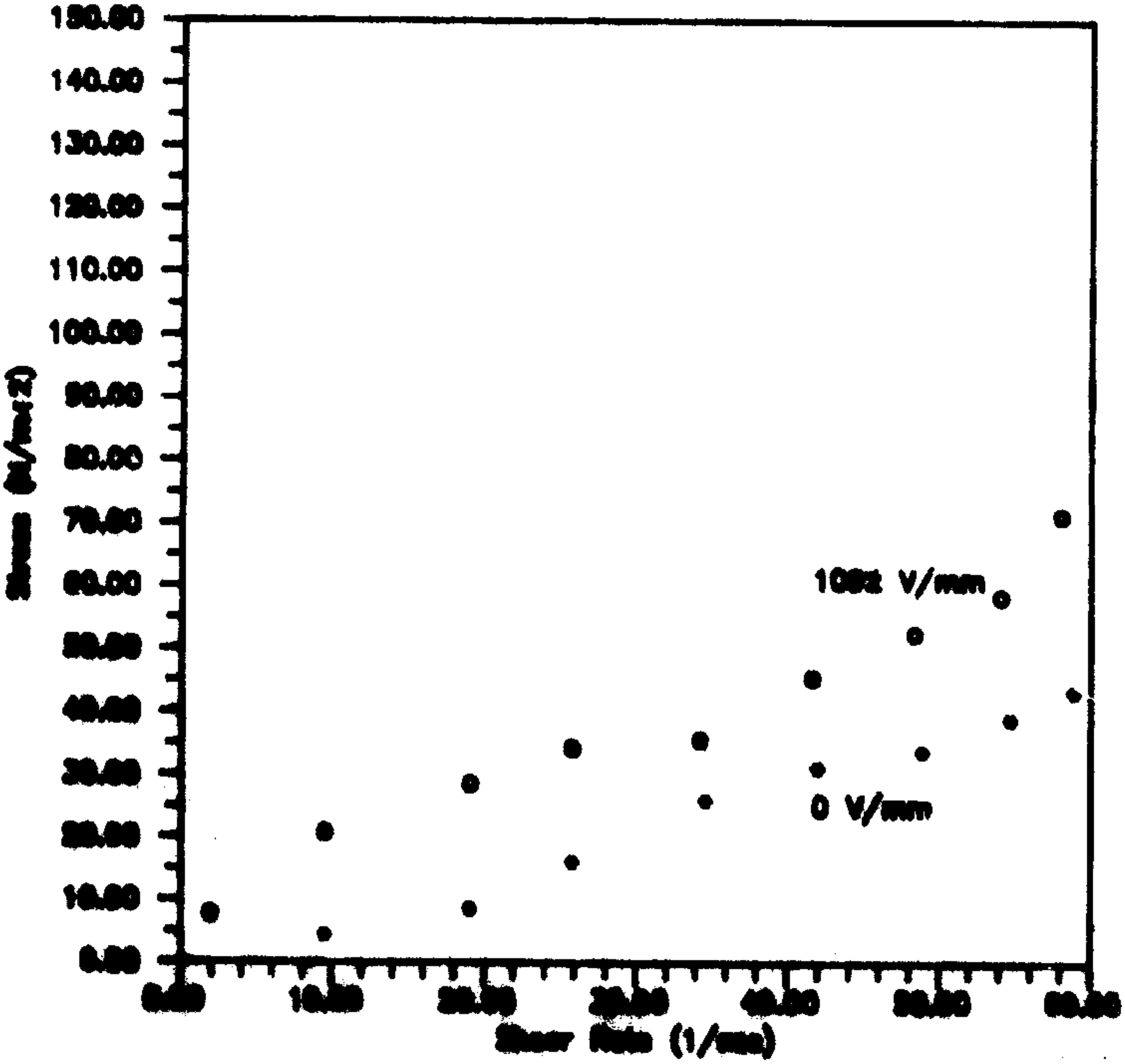


Figure 2: [illegible]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130.00
110.00
100.00
0 V/mm

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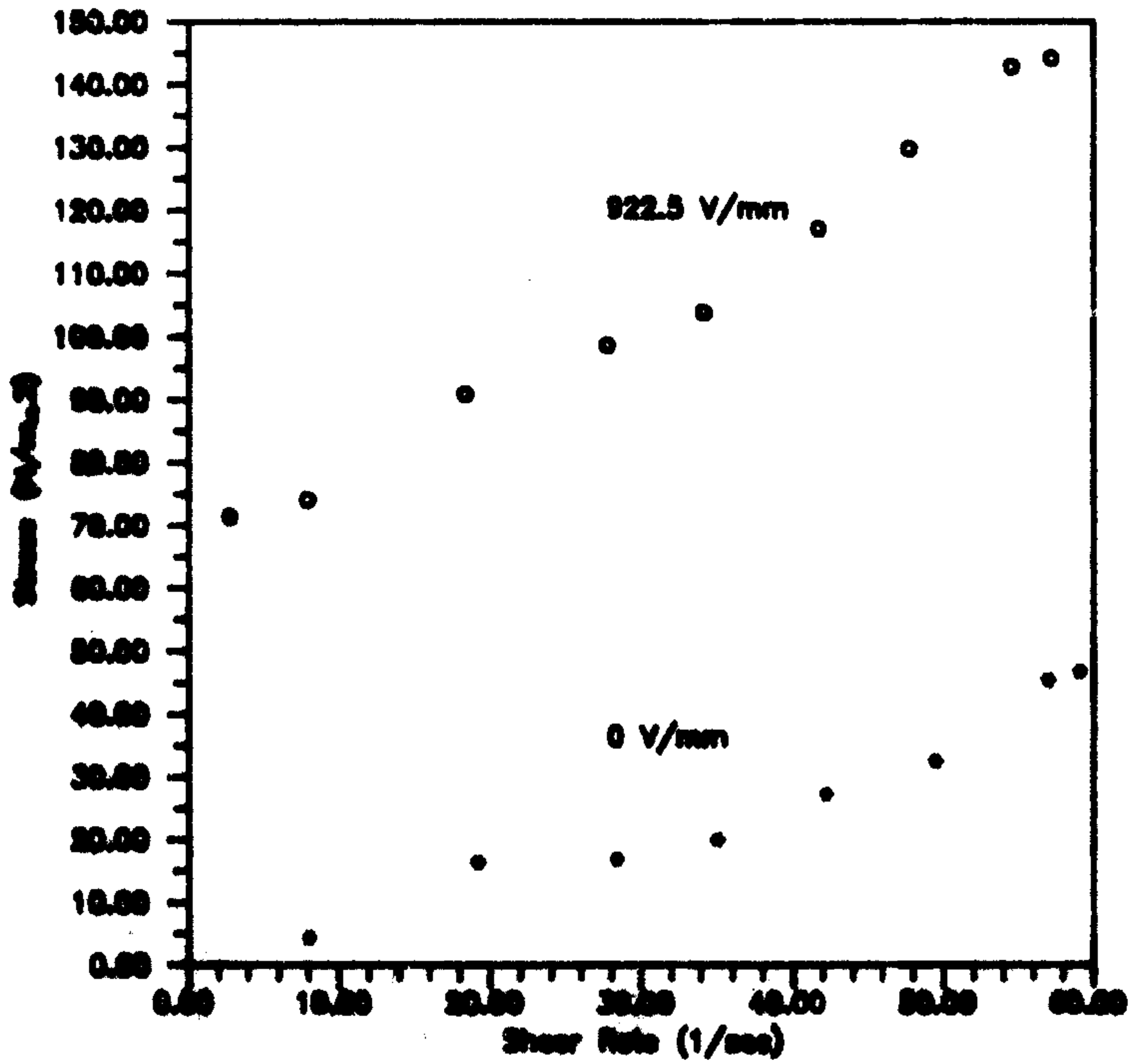


[redacted] 4: Trial 4-- 50 wt % Flour and Corn Oil at 0 and [redacted] V/mm

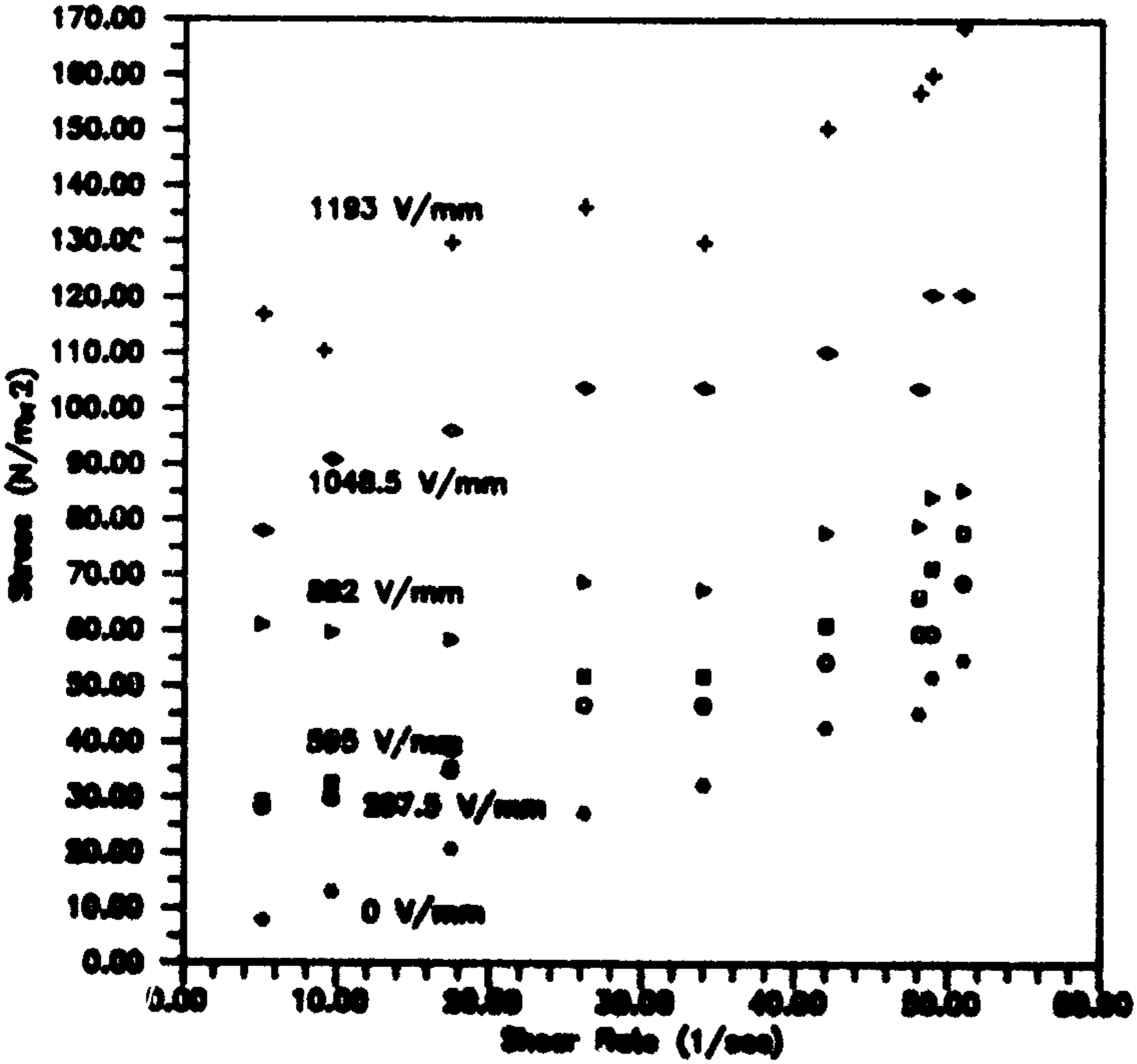
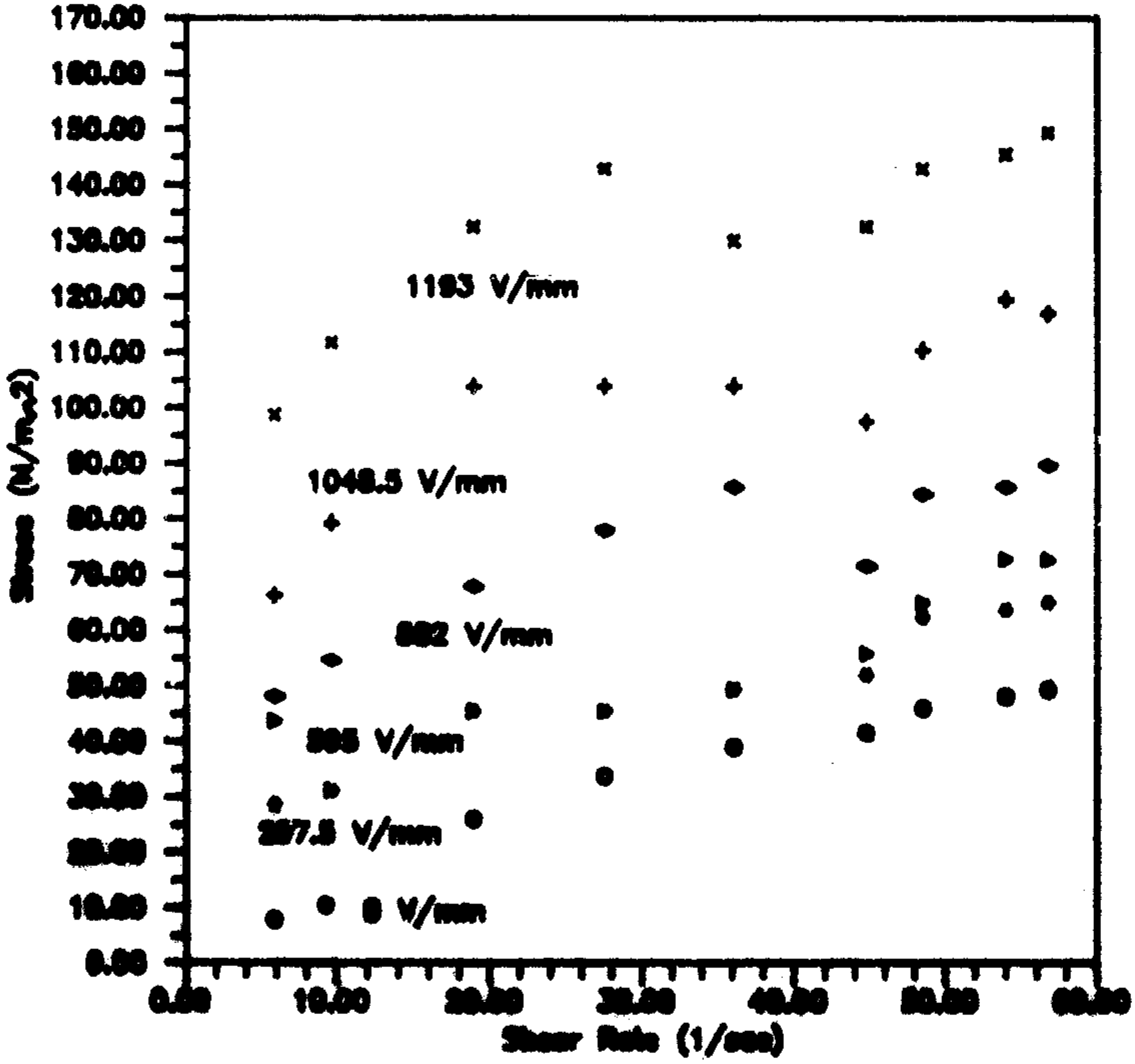


Figure [illegible]: Trial [illegible]-60 wt % at 0, 297.5, 595, 892, 1048.5, and 1193 V/mm



[illegible] 50 wt % at 0, 297.5, 595, 892, 1048.5, [illegible]

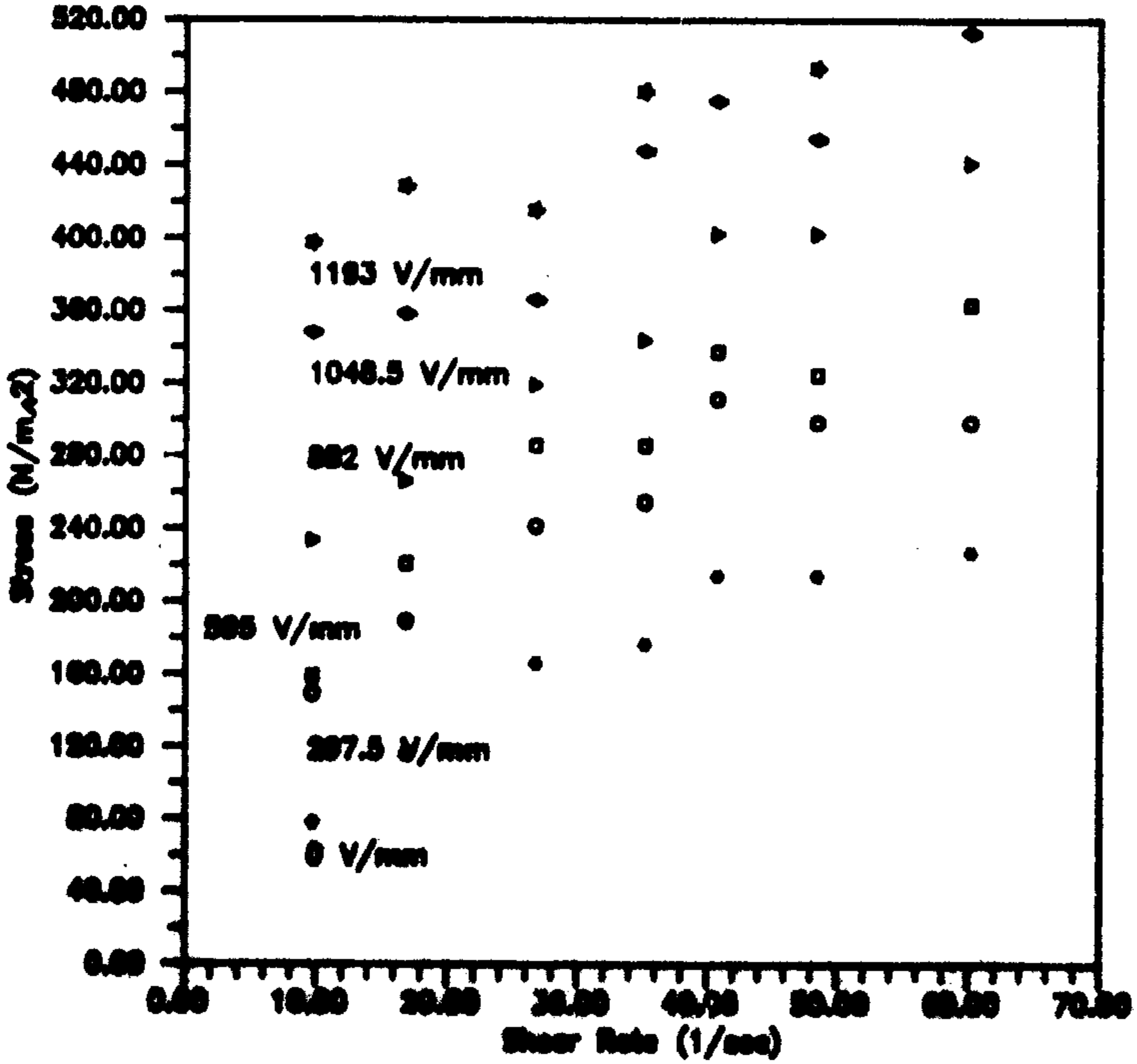
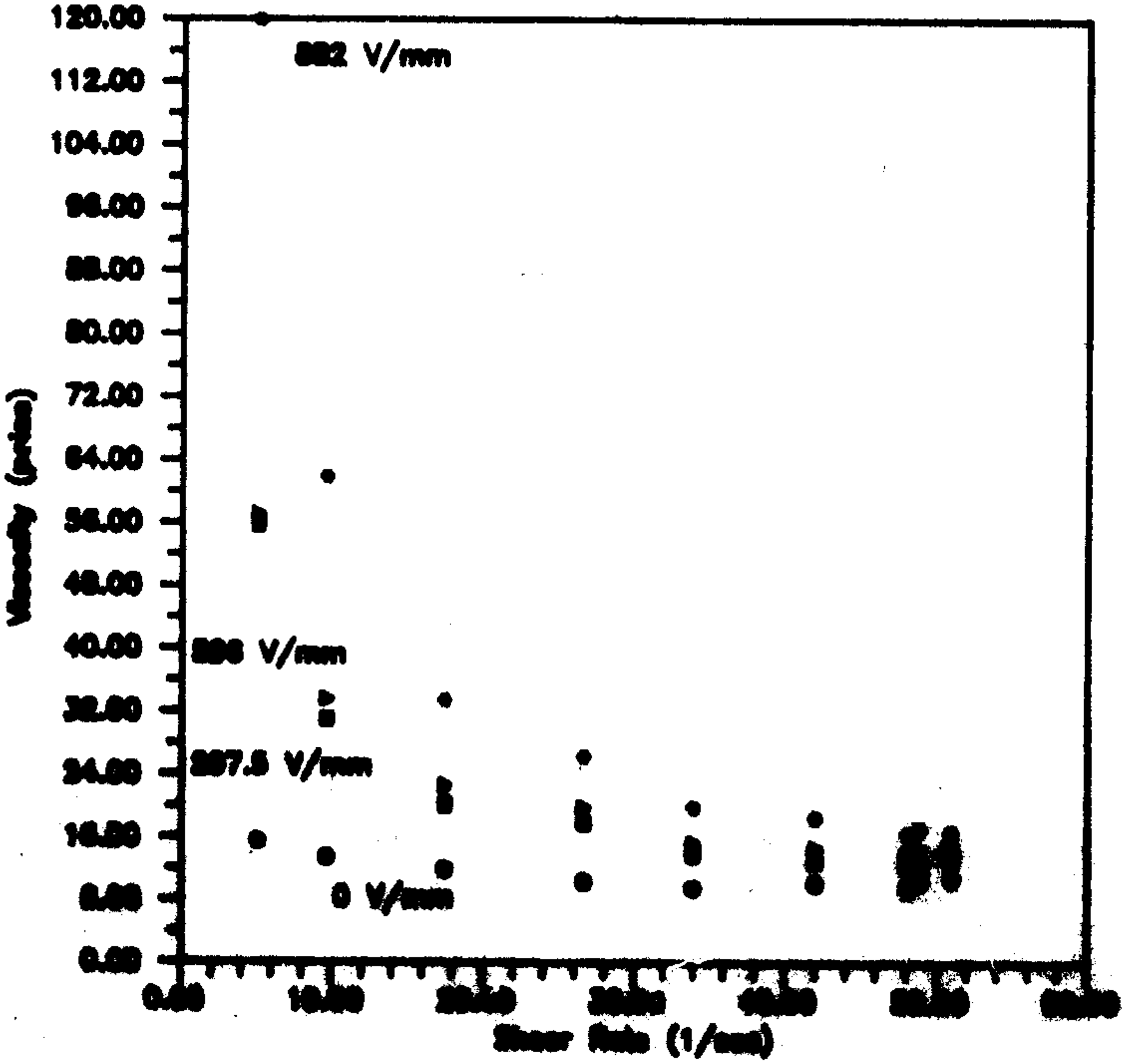
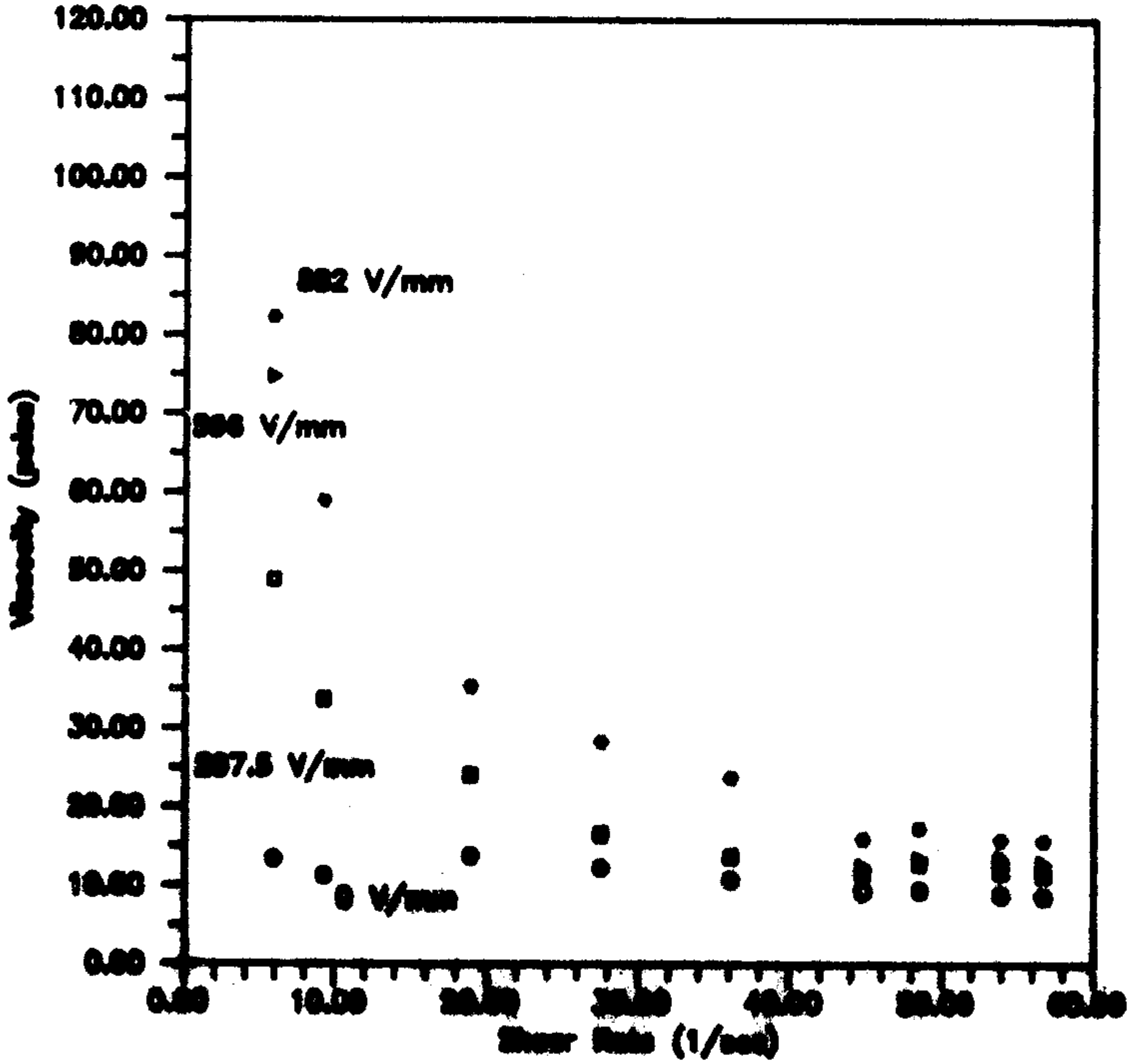


Figure 7: Trial 7-- [illegible] at [illegible] at 0, 297.5, 595, 892, 1046.5, and 1193 V/mm


120.00
112.00
104.00
80.00
72.00
40.00
882 V/mm
586 V/mm
287.5 V/mm
0 V/mm

[illegible]



[illegible] 50 wt % Flour and Corn Oil at 0, 287.5, 585, [illegible]

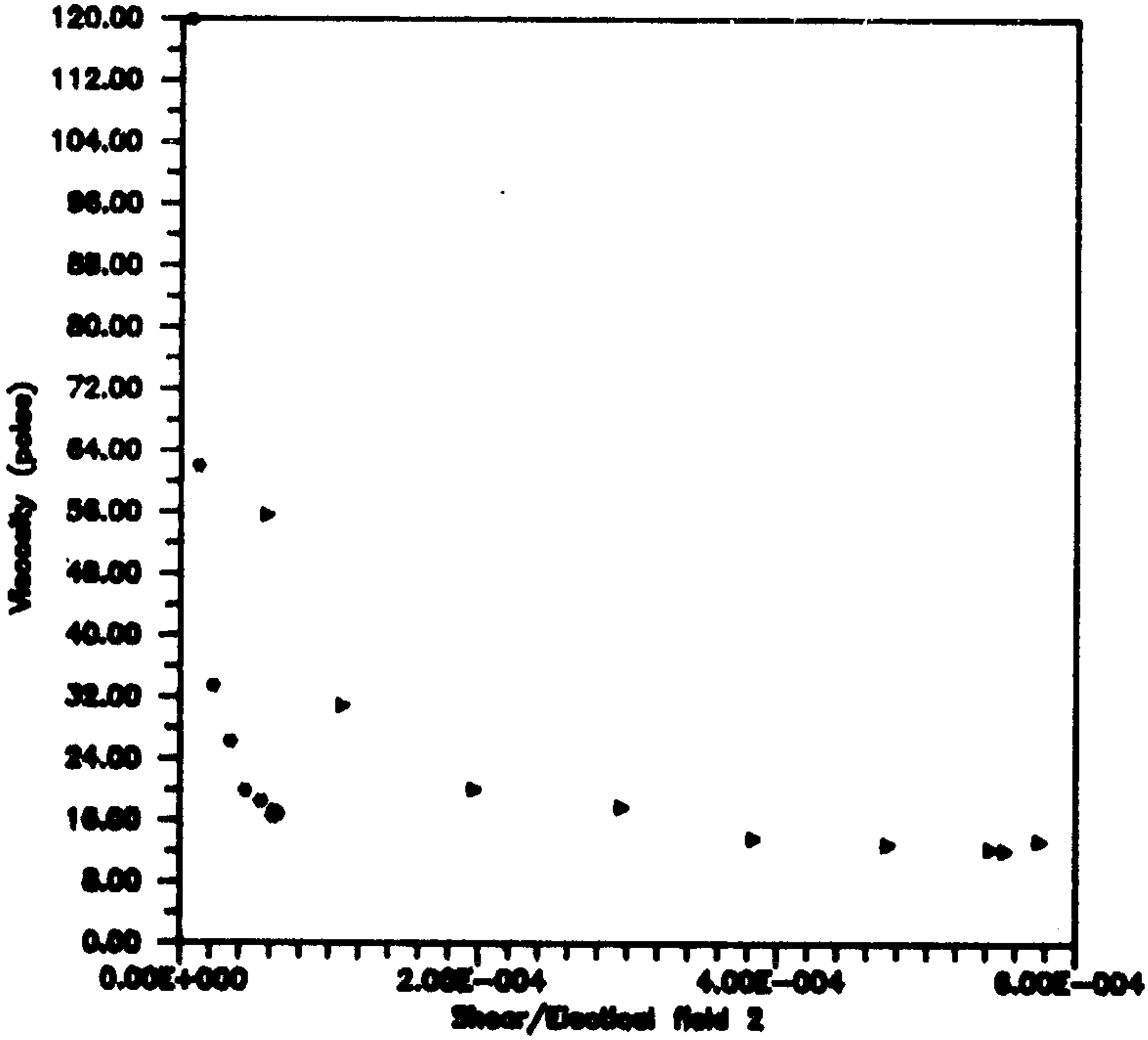


Figure 10: Trial 5 at 287.5 and 682 V/mm

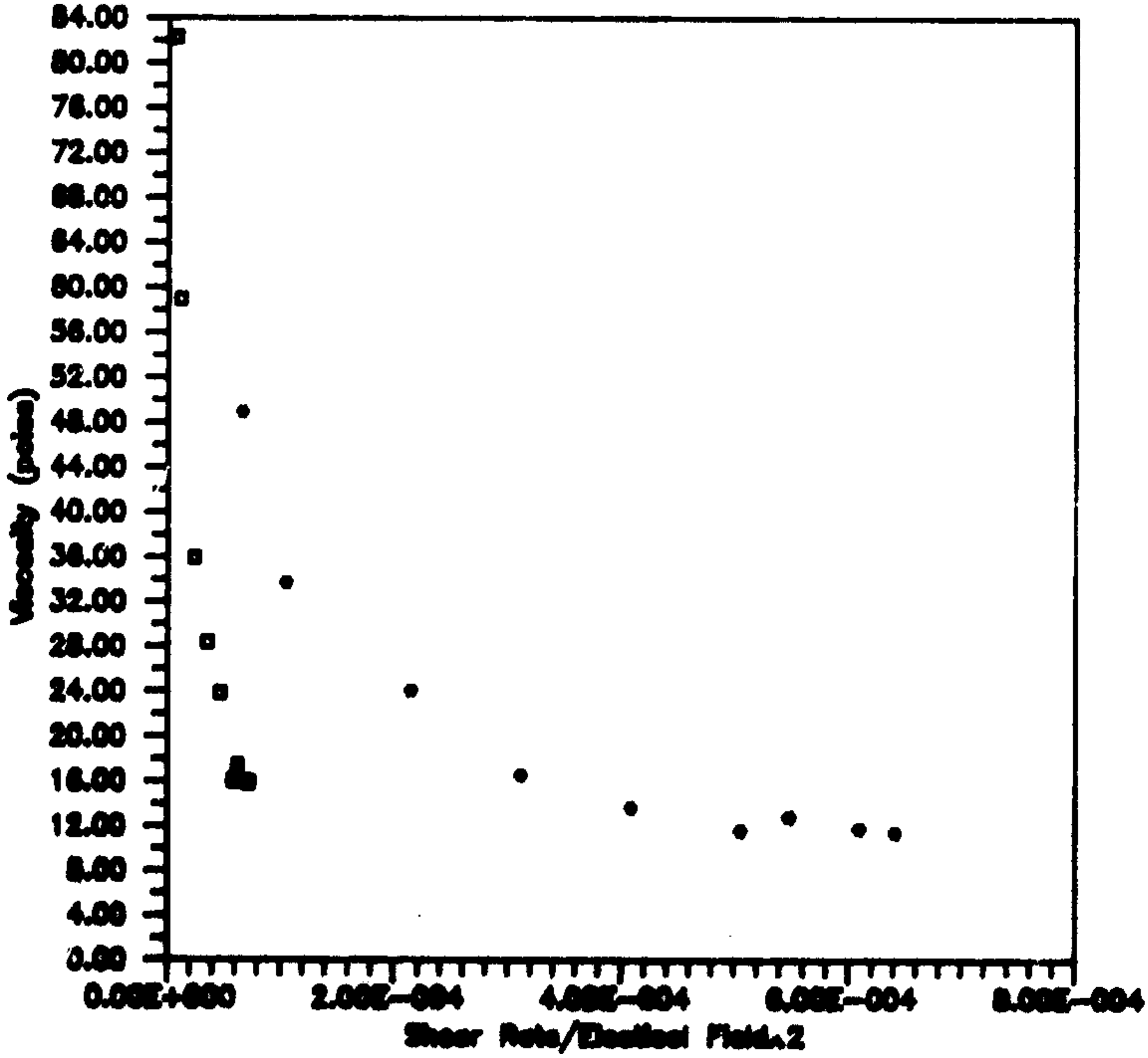


Figure 11: Trial 6 287.5 and [illegible] V/mm

TABLE 1:

Trial 1 (50 wt %)					
0 V/mm		424.5 V/mm		626.2 V/mm	
Shear Rate(1/sec)	Stress (N/m^2)	Shear Rate(1/sec)	Stress (N/m^2)	Shear Rate(1/sec)	Stress (N/m^2)
3.45	12.72	4.80	12.98	2.80	25.97
8.50	14.28	8.46	17.66	5.27	28.56
12.97	18.69	13.74	19.47	8.84	32.45
17.04	20.77	18.10	20.77	13.72	33.75
23.70	25.96	21.66	23.89	19.13	35.05
29.46	29.86	25.42	25.96	23.15	37.65
36.58	31.16	31.68	28.56	26.51	38.94
40.90	38.43	37.82	32.45	35.50	44.14
43.84	39.46	43.20	38.43	41.82	45.44
52.90	42.84	46.48	42.84	47.98	47.25
		50.70	42.84	53.49	48.03
				56.51	49.33

TABLE 2:

Trial 2 (50 wt %)			
0 V/mm		424.5 V/mm	
Shear Rate(1/sec)	Stress (N/m^2)	Shear Rate(1/sec)	Stress (N/m^2)
3.68	12.98	4.29	19.47
8.78	15.58	8.53	19.99
13.74	17.66	13.94	24.67
19.27	23.37	18.25	25.96
27.35	28.56	26.90	31.16
34.60	30.38	34.59	33.75
42.56	40.24	42.46	40.24
48.77	45.44	49.47	46.21
53.80	47.51	54.07	51.67
56.42	49.33	57.73	53.22

TABLE 3:

Trial 3 (50 wt %)			
0 V/mm		1092 V/mm	
Shear Rate(1/sec)	Stress (N/m^^)	Shear Rate(1/sec)	Stress (N/m^2)
9.47	4.41	1.89	7.79
18.97	8.57	9.48	20.77
25.80	16.10	19.00	28.56
34.58	25.96	25.80	34.27
41.91	31.16	34.21	35.57
48.81	33.75	41.55	45.44
54.66	38.94	48.28	52.45
58.84	43.36	54.04	58.42
		58.00	71.40

TABLE 4:

Trial 4 (50 wt %)			
0 V/mm		922.5 V/mm	
Shear Rate(1/sec)	Stress (N/m^2)	Shear Rate(1/sec)	Stress (N/m^2)
8.03	4.41	2.72	71.40
18.13	16.36	7.91	74.00
28.33	18.88	18.35	90.87
35.01	19.99	27.69	98.66
42.21	27.26	34.16	103.85
48.47	32.45	41.68	117.09
56.98	45.44	47.71	128.82
58.06	48.73	54.52	142.88
		57.16	144.10

TABLE 5:

Trial 5 (50 wt %)						
	0 V/mm	297.5 V/mm	596.0 V/mm	882.0 V/mm	1048.5 V/mm	1193.0 V/mm
Shear Rate(1/sec)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)
5.09	7.89	28.30	29.08	61.01	77.89	116.83
9.65	12.98	29.86	32.45	59.72	90.87	110.34
17.46	20.77	35.05	38.94	58.42	96.06	129.82
26.20	27.26	46.73	51.93	68.80	103.85	136.31
33.96	32.45	46.73	51.93	67.50	103.85	129.82
41.99	42.84	54.52	61.04	77.89	110.34	150.59
48.05	45.44	59.72	66.21	79.19	103.85	157.08
48.90	51.93	59.72	71.40	84.38	120.73	160.19
50.94	55.04	68.80	77.89	85.68	120.73	168.76

TABLE 6:

Trial 6 (50 wt %)						
	0 V/mm	297.5 V/mm	596.0 V/mm	882.0 V/mm	1048.5 V/mm	1193.0 V/mm
Shear Rate(1/sec)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)
5.04	7.79	28.56	43.62	48.03	66.21	98.66
9.26	10.39	31.16	31.16	54.52	79.19	111.64
18.98	25.96	45.44	45.44	67.76	103.85	132.41
27.51	33.75	45.44	45.44	77.89	103.85	142.80
36.07	38.94	49.33	49.33	85.68	103.85	129.82
44.72	41.54	51.93	55.82	71.40	97.36	132.41
48.48	45.85	62.31	64.91	84.38	110.34	142.80
53.93	48.03	63.61	72.70	86.98	119.43	145.30
56.71	49.33	64.91	72.70	89.57	116.83	149.29

TABLE 7:

Trial 7 (60 wt %)						
	0 V/mm	297.5 V/mm	596.0 V/mm	882.0 V/mm	1048.5 V/mm	1193.0 V/mm
Shear Rate(1/sec)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)	Stress (N/m^2)
9.67	77.89	149.29	156.33	233.67	347.91	397.24
16.85	115.54	189.01	220.69	266.12	358.29	428.39
26.70	166.16	241.46	285.60	319.35	366.08	415.41
35.15	176.55	254.44	285.60	344.31	447.87	480.32
40.75	214.20	311.56	337.52	402.43	475.13	
48.47	214.20	298.58	324.54	402.43	454.36	
60.12	227.18	298.58	363.49	441.37	512.77	493.30

TABLE 8:

Trial 5 (50 wt %)						
	0 V/mm	297.5 V/mm	596.0 V/mm	882.0 V/mm	1048.5 V/mm	1193.0 V/mm
Shear Rate(1/sec)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)
5.09	15.50	55.60	57.13	119.86	153.03	229.53
9.65	13.45	30.94	33.63	61.89	94.17	114.34
17.46	11.90	20.07	22.30	33.46	55.02	74.35
26.20	10.40	17.84	19.82	26.26	39.64	52.03
33.96	9.56	13.76	15.29	19.88	30.58	38.23
41.99	10.20	12.98	14.54	18.55	26.28	35.86
48.05	9.46	12.43	13.78	16.48	21.61	32.69
48.90	10.62	12.21	14.60	17.26	24.69	32.76
50.94	10.80	13.51	15.29	16.82	23.70	33.13

TABLE 9:

Trial 6 (50 wt %)						
	0 V/mm	297.5 V/mm	596.0 V/mm	882.0 V/mm	1048.5 V/mm	1193.0 V/mm
Shear Rate(1/sec)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)
5.84	13.34	48.90	74.69	82.24	113.37	168.94
9.26	11.22	33.65	33.65	58.08	85.52	120.56
18.90	13.74	24.04	24.04	35.05	54.95	70.06
27.51	12.27	16.52	16.52	28.31	37.75	51.91
36.07	10.80	13.68	13.68	23.75	28.79	35.99
44.72	9.29	11.61	12.48	15.97	21.77	29.61
48.48	9.48	12.85	13.39	17.41	22.76	29.46
53.93	8.91	11.79	13.48	15.89	22.15	26.96
56.71	8.70	11.45	12.82	15.79	20.60	28.33

TABLE 10:

Trial 7 (60 wt %)						
	0 V/mm	297.5 V/mm	596.0 V/mm	882.0 V/mm	1048.5 V/mm	1193.[illegible]
Shear Rate(1/sec)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)	Viscosity (Poise)
9.67	80.55	154 [illegible]8	163.78	241.64	359.78	410.80
16.85	68.57	112.17	130.97	157.93	212.64	254.24
26.70	62.23	90.43	106.97	119.61	137.11	155.58
35.15	50.23	72.39	81.25	97.87	127.42	136.65
40.75	52.56	76.46	82.83	98.76	116.60	0.00
48.47	44.19	61.60	66.96	83.03	93.74	0.00
60.12	37.79	49.66	60.46	73.41	85.[illegible]9	82.05

TABLE 11:

Trial 5 (50 wt %)						
	0 V/mm	297.5 V/mm	596.0 V/mm	882.0 V/mm	1048.5 V/mm	1193.0 V/mm
Shear Rate(1/sec)	Shear/E^2	Shear/E^2	Shear/E^2	Shear/E^2	Shear/E^2	Shear/E^2
5.09	ERR	5.75E-05	1.43E-05	6.54E-06	4.63E-06	3.58E-06
9.65	ERR	1.09E-04	2.72E-05	1.24E-05	8.78E-06	6.78E-06
17.46	ERR	1.97E-04	4.92E-05	2.24E-05	1.59E-05	1.23E-05
26.20	ERR	2.96E-04	7.38E-05	3.37E-05	2.38E-05	1.84E-05
33.96	ERR	3.84E-04	9.56E-05	4.37E-05	3.09E-05	2.39E-05
41.99	ERR	4.74E-04	1.18E-04	5.40E-05	3.82E-05	2.95E-05
48.05	ERR	5.43E-04	1.35E-04	6.18E-05	4.37E-05	3.38E-05
48.90	ERR	5.53E-04	1.38E-04	6.29E-05	4.45E-05	3.44E-05
50.94	ERR	5.76E-04	1.43E-04	6.55E-05	4.63E-05	3.58E-05

TABLE 12:

Trial 6 (50 wt %)						
	0 V/mm	297.5 V/mm	596.0 V/mm	882.0 V/mm	1048.5 V/mm	1193.0 V/mm
Shear Rate(1/sec)	Shear/E^2	Shear/E^2	Shear/E^2	Shear/E^2	Shear/E^2	Shear/E^2
5.04	ERR	6.60E-05	1.64E-05	7.51E-06	5.31E-06	4.10E-06
9.26	ERR	1.05E-04	2.61E-05	1.19E-05	8.42E-06	6.51E-06
18.90	ERR	2.14E-04	5.32E-05	2.43E-05	1.72E-05	1.33E-05
27.51	ERR	3.11E-04	7.74E-05	3.54E-05	2.50E-05	1.93E-05
36.07	ERR	4.08E-04	1.02E-04	4.64E-05	3.28E-05	2.53E-05
44.72	ERR	5.05E-04	1.20E-04	5.75E-05	4.07E-05	3.14E-05
48.48	ERR	5.48E-04	1.36E-04	6.23E-05	4.41E-05	3.41E-05
53.93	ERR	6.09E-04	1.52E-04	6.93E-05	4.91E-05	3.79E-05
56.71	ERR	6.41E-04	1.60E-04	7.29E-05	5.16E-05	3.98E-05

TABLE 13:

Trial 7 (60 wt %)						
	0 V/mm	297.5 V/mm	596.0 V/mm	882.0 V/mm	1048.5 V/mm	1193.0 V/mm
Shear Rate(1/sec)	Shear/E^2	Shear/E^2	Shear/E^2	Shear/E^2	Shear/E^2	Shear/E^2
9.67	ERR	1.09E-04	2.72E-05	1.24E-05	8.80E-06	6.79E-06
16.85	ERR	1.90E-04	4.74E-05	2.17E-05	1.53E-05	1.18E-05
26.70	ERR	3.02E-04	7.52E-05	3.43E-05	2.43E-05	1.88E-05
35.15	ERR	3.97E-04	9.90E-05	4.52E-05	3.20E-05	2.47E-05
40.75	ERR	4.60E-04	1.15E-04	5.24E-05	3.71E-05	2.86E-05
48.47	ERR	5.48E-04	1.36E-04	6.23E-05	4.41E-05	3.41E-05
60.12	ERR	6.79E-04	1.69E-04	7.73E-05	5.47E-05	4.22E-05
0.00	ERR	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.00	ERR	0.00F+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Calculations

Shear rate $= \dot{\gamma} = \frac{2\pi r}{\Delta r}\left(\omega \frac{cycles}{sec}\right)$

From Trial 1 run 1 $\omega = .046\ sec^{-1}$

$\dot{\gamma} = \frac{2\pi(3.152\ in)}{.18\ in}(.046\ sec^{-1}) = 5.09\ sec^{-1}$

Stress $= \tau = m(g) \times \frac{kg}{1000g} \times \frac{9.8066\,m}{s^2} \times \frac{1}{Surface\ Area\,(m^2)} = N/m^2$

For trial 1 run 1 $m = 49g$

$\tau = 49g \times \frac{9.806\,m}{s^2} \times \frac{kg}{1000g} \times \frac{1}{2\pi(3.152\ in \times .0254\ m/in)(2.956 \times .0254\ m/in)}$

$= 12.72\ N/m^2$

Viscosity $= \tau / \dot{\gamma}$