

**RHEOLOGICAL EXAMINATION OF DOMESTIC SEWAGE SLUDGE**

by

**Robert A. Lemon**

**Thesis submitted to the Graduate Faculty of the**

**Virginia Polytechnic Institute**

**in candidacy for the degree of**

**MASTER OF SCIENCE**

in

**Sanitary Engineering**

**APPROVED:**

Chairman, H. R. Bungay

W. A. Parsons

R. E. Benoit

J. M. Wiggert

**February, 1966**

**Blacksburg, Virginia**

TABLE OF CONTENTS

	Page
I. INTRODUCTION .....	5
II. REVIEW OF LITERATURE .....	7
III. METHODS AND MATERIALS .....	10
IV. EXPERIMENTAL RESULTS	
A. The Rheological Examination of Domestic ..... Digested Sludge	14
B. The Rheological Examination of Domestic ..... Raw Sludge	24
V. DISCUSSION OF RESULTS .....	34
VI. CONCLUSIONS .....	36
VII. SUMMARY .....	37
VIII. ACKNOWLEDGEMENTS .....	38
IX. BIBLIOGRAPHY .....	39
X. VITA .....	41
XI. APPENDICES .....	42

LIST OF FIGURES AND TABLES

	Page
Figure I. Newtonian Curve .....	8
Figure II. Non-Newtonian, Pseudoplastic Curve .....	9
Figure III. Non-Newtonian, Dilatant Curve .....	9
Figure IV. Non-Newtonian, Plastic Curve .....	9
Figure V. Brookfield Viscosimeter .....	12
Table I. Deflection Readings of The Brookfield .....	14
Viscosimeter Using Domestic Digested Sludge	
Table II. Values of $dN/d\theta$ at Various Settling Times .....	15
Figure VI. Spring Deflection Versus Spindle Speed of .....	16
Digested Sludge at $t = 0.0$ minutes	
Table III. Shear Stress for Domestic Digested Sludge .....	17
Table IV. Velocity Gradients for Domestic Digested .....	17
Sludge	
Figure VII. Shear Stress Versus Velocity Gradient for .....	19
Domestic Digested Sludge at $t = 0.0$ minutes	
Figure VIII. Shear Stress Versus Velocity Gradient for .....	20
Domestic Digested Sludge at $t = 5.0$ minutes	
Figure IX. Shear Stress Versus Velocity Gradient for .....	21
Domestic Digested Sludge at $t = 10.0$ minutes	
Figure X. Shear Stress Versus Velocity Gradient for .....	22
Domestic Digested Sludge at $t = 15.0$ minutes	
Figure XI. Shear Stress Versus Velocity Gradient for .....	23
Domestic Digested Sludge at $t = 20.0$ minutes	
Table V. Deflection Readings of the Brookfield .....	24
Viscosimeter Using Domestic Raw Sludge	

LIST OF FIGURES AND TABLES (continued)

	Page
Table VI. Values of $dN/d\theta$ at Various Settling Times .....	25
Figure XII. Spring Deflection Versus Spindle Speed of .....	26
Raw Sludge at $t = 0.0$ minutes	
Table VII. Shear Stress for Domestic Raw Sludge .....	27
Table VIII. Velocity Gradients for Domestic Raw Sludge .....	27
Figure XIII. Shear Stress Versus Velocity Gradient for .....	29
Domestic Raw Sludge at $t = 0.0$ minutes	
Figure XIV. Shear Stress Versus Velocity Gradient for .....	30
Domestic Raw Sludge at $t = 5.0$ minutes	
Figure XV. Shear Stress Versus Velocity Gradient for .....	31
Domestic Raw Sludge at $t = 10.0$ minutes	
Figure XVI. Shear Stress Versus Velocity Gradient for .....	32
Domestic Raw Sludge at $t = 15.0$ minutes	
Figure XVII. Shear Stress Versus Velocity Gradient for .....	33
Domestic Raw Sludge at $t = 20.0$ minutes	

## I. INTRODUCTION

Biological waste treatment plays a very important role in our everyday living. Without treatment of our wastes, streams, lakes, and even our oceans would become polluted. Swimming, fishing, boating, and many other recreational uses of water would have to cease. Our health can be adversely affected if our waters are not kept relatively pure.

Biological waste treatment is a fairly satisfactory means of treating our wastes, both domestic and industrial. In the biological treatment processes microorganisms utilize the organic matter in the wastes. In so doing, the biochemical oxygen demand (BOD) of the waste is reduced prior to discharging to the receiving stream. During the process the larger pieces of solid material including flocs of microorganisms are removed in primary and secondary settling tanks. The solids that settle to the bottom and are collected in hoppers are called raw sludge. The raw sludge is pumped to a digester and undergoes anaerobic decomposition. The solid fraction after a period of time in the anaerobic digester is termed digested sludge.

Raw sludge is generally very heterogeneous and contains pieces of paper and undigested fragments of waste material. Digested sludge is more homogeneous and contains little undigested waste material.

The raw and digested sludge are transported through

pipelines by pumps. Because of the nature of the sludge, it is not customary to incorporate a gravity flow system. The viscous characteristics of the sludge make it necessary that the pumps transporting the sludge be chosen carefully keeping in mind the basic engineering rule of economy.

In sanitary engineering, properties of fluids have recently begun to attract considerable research interest. Thus the formation of sludge flocs, their mechanical resistance properties, the diffusion of gases through them, and oxygen supply and demand are all phenomena in which the engineer needs a greater understanding.

To aid the engineer in his understanding of fluids and in his design of pumps and pipelines it is necessary that the flow characteristics of the sludges be known. It is the purpose of this thesis to investigate the flow parameters of some typical sewage sludges by using a rheological approach. The investigation attempted to characterize the sludges as Newtonian or non-Newtonian sludge and to define non-Newtonian behavior as plastic, pseudoplastic or dilatant.

## II. REVIEW OF LITERATURE

Strictly speaking, all flow measurements, including those on normal liquids, come within the scope of rheology, but in practice the rheologists' main interest lies in those materials, mainly of industrial importance, which show a behavior intermediate between those of solids and liquids and consequently are no longer simple liquids.

A great deal of rheological work has been done in the past pertaining to paints, asphalts, fermentation broths, etc., but the use of rheology by sanitary engineers is at present, just becoming a reality.

F. H. Deindoerfer and J. M. West(1) in 1960 used rheology in the examination of some important fermentation broths. They found that the broths used in industrial fermentation are too complex to be described adequately by a single property such as viscosity, especially in fermentation broths employing filamentous microorganisms where deviations from Newtonian behavior are appreciable. Of the broths investigated the majority of them showed non-Newtonian characteristics, being either pseudoplastic or plastic. Also it was found that the rheological properties of most of the fermentation broths changed appreciably during the course of fermentation. Fermentation broths are somewhat similar to sewage sludges and therefore it is expected that a similarity of rheological properties exists. The sewage sludges will change with respect to time just as the fermentation broths. Sewage sludges contain many types of organisms, unicellular, multicellular and filamentous. Therefore,

it is expected that sludge behaves very much like fermentation broths when examined rheologically.

The laminar behavior of any fluid is defined by the relationship between shearing stress  $\tau$ , and velocity gradient or shear rate  $\frac{dy}{dy}$ . All fluids which exhibit direct proportionality between shear stress and shear rate as shown in Figure I are classed as Newtonian fluids.

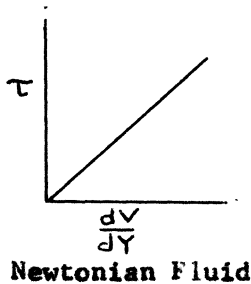
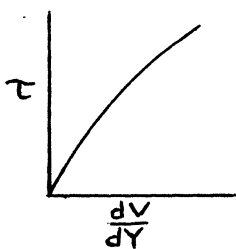


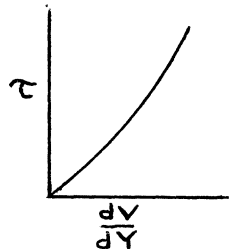
Figure I

Fluids that do not exhibit Newtonian behavior are classified as non-Newtonian. A non-Newtonian fluid can be classified as a pseudoplastic, plastic or dilatant fluid. Figures II and III show the pseudoplastic and dilatant behavior of fluids. In both types there is no linearity between shear stress and velocity gradient.



Pseudoplastic Fluid

Figure II

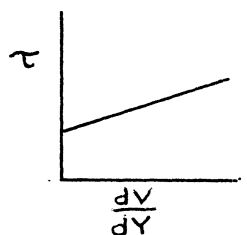


Dilatant Fluid

Figure III

A fluid which exhibits a plastic behavior has a definite yield stress which must be exceeded before flow will begin. Once the fluid flows

the shear stress is proportional to the velocity gradient(1) (8). Figure IV represents a typical plastic fluid.



Plastic Fluid

Figure IV

V. C. Behn(9) in 1962 used a rheological approach in the examination of digested sludge. His study investigated the procedures and techniques for obtaining parameters for non-Newtonian systems. The techniques involved the use of capillary and rotational viscometers. Both viscometers were found feasible for the construction of shear stress-velocity gradient curves. However, the capillary viscometer was found to be the most generally useful of the two instruments because of the wider range of velocity gradients. In an independent study with the rotational viscometer he found that, for a limited range of velocity gradients, the data for digested sludge showed it to be pseudoplastic in behavior.

In 1939, Babbit and Caldwell(11), in an investigation involving the laminar flow of sludges in pipes found that sewage sludge exhibited a plastic behavior. They also found in their investigation that for sludge flowing in a circular pipe, a critical velocity is encountered as the velocity of flow is increased. Below the critical velocity the flow is laminar and above this velocity the flow is turbulent. The critical velocity does not always occur at the same velocity in a given pipe with a given sludge. They found there is a lower critical velocity, below which the flow is laminar, and an upper critical velocity above which the flow is turbulent. Between the lower and upper critical velocities the flow was found to be either laminar or turbulent or a combination of the two.

### III METHODS AND MATERIALS

The Blacksburg Sewage Treatment Plant and the Roanoke Sewage Treatment Plant were the sources for the sludges in the investigation. A preliminary investigation was performed using samples of raw sludge and digested sludge from the Blacksburg Plant to become familiar with behavior of the sludge and obtain practice in the use of the apparatus employed in the experiment.

Activated sludge from the Roanoke Plant was taken directly from the aeration tank at three points along its length. The sludge was black in color, homogeneous, and non-viscous.

Digested sludge from the Blacksburg Plant was drawn directly from the anaerobic digester. The digested sludge was black in color, homogeneous, relatively thick and sticky.

Raw sludge samples were taken from the Blacksburg Plant and the Roanoke Plant. The samples from both locations were drawn directly from the primary sedimentation hoppers. The raw sludge from the Blacksburg Plant was brown in color, heterogeneous, lumpy, and contained pieces of paper and undigested waste material. The raw sludge from the Roanoke Plant was black in color, homogeneous, and less viscous than that from the Blacksburg Plant.

The rheological examination of the sewage sludges was performed within six hours after the collection of each sample and was carried out at room temperature. A four speed Brookfield Syncro-lectric Viscosimeter Model RVF manufactured by Brookfield Engineering Laboratories, Inc., Stoughton, Massachusetts with its spindle guard removed was used in the examination. A specially constructed spindle, 1.27 cm in diameter and 7.70 cm long, was used to obtain the data because the available spindles were too small for these relatively non-viscous samples. The sludge sample was placed in a 1500 ml beaker which was large enough for the spindle to rotate in an effectively infinite medium, unaffected by wall proximity.

The sample of well mixed sludge was poured in the beaker to a depth of five inches. The spindle was lowered into the sample to a depth as indicated in Figure V. The spindle was allowed to rotate until the deflection needle settled down to a constant reading. Subsequent readings were made every minute for ten minutes and then deflection readings were recorded at fifteen and twenty minutes. The above procedure was repeated three more times giving a total of four runs for each of the four spindle speeds. After each run the sample was poured back into its original container and thoroughly mixed before the next run.

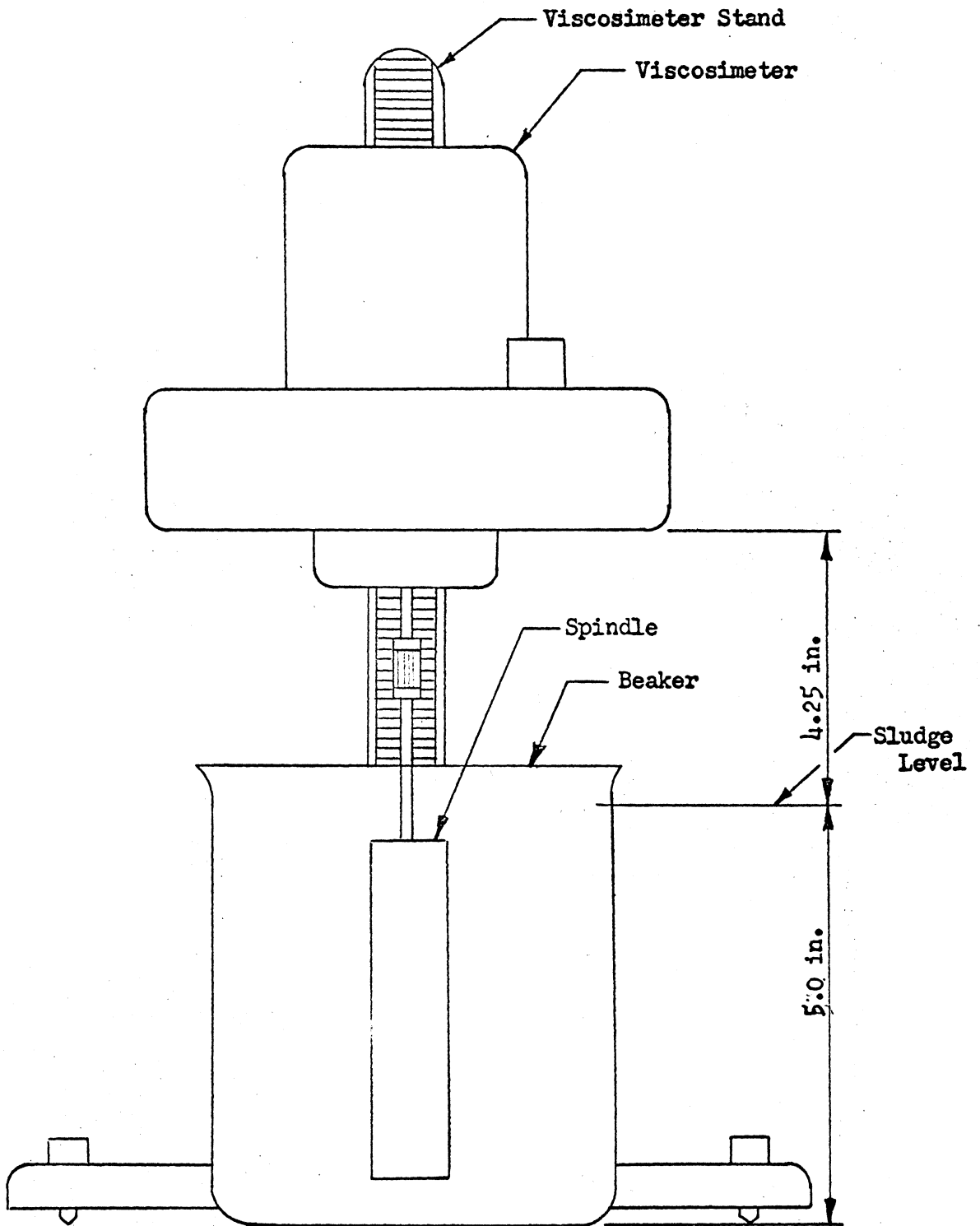


FIGURE V

BROOKFIELD VISCOSIMETER

The reason four sets of readings were obtained at each of the four spindle speeds was to determine if the experiments showed any inconsistency, which they did not. The deflection readings were then averaged to obtain the final reading.

The following equations were adapted from equations developed by Krieger and Maron (3), and are the same equations used by Deindoerfer and West (1) in their rheological examination of fermentation broths. They permit the calculation of shear stress and velocity gradients from direct measurements made using the Brookfield viscosimeter.

$$\begin{aligned}\tau &= C\theta/2\pi hr_b^2 \\ \frac{dv}{dy} &= 4\theta(dN/d\theta) \\ \tau &= \text{shear stress, g cm}^{-1} \text{ sec}^{-2} \\ C &= \text{viscosimeter spring constant, g cm}^2 \text{ sec}^2 (\text{deflect unit})^{-1} \\ h &= \text{spindle height, cm} \\ r_b &= \text{spindle radius, cm} \\ \frac{dv}{dy} &= \text{shear rate, sec}^{-1} \\ \theta &= \text{spindle deflection, deflection units} \\ N &= \text{spindle rotational speed, rpm}\end{aligned}$$

#### IV. EXPERIMENTAL RESULTS

##### Experiment A. The Rheological Examination of Domestic Digested Sludge

The objective of the experiment was to determine the shear stress and velocity gradient of digested sludge after various settling times. By plotting shear stress versus velocity gradient the behavior of the sludge as Newtonian or non-Newtonian can be determined.

The results obtained by recording the deflection reading from the 100 scale of the Brookfield viscosimeter while the sludge settled for twenty minutes are in Table I.

Table I

Deflection Readings of the Brookfield Viscosimeter  
Using Domestic Digested Sludge

Time, Min	Deflection* at Spindle Speeds			
	2 rpm	4 rpm	10 rpm	20 rpm
0.0	12.6	14.6	18.8	25.1
1.0	11.7	13.8	17.3	22.6
2.0	11.4	12.8	16.4	21.0
3.0	11.1	12.5	15.9	20.7
4.0	10.9	12.3	15.4	20.1
5.0	10.7	12.0	15.0	19.4
6.0	10.5	11.9	14.8	19.2
7.0	10.3	11.7	14.6	19.0
8.0	10.2	11.7	14.5	18.4
9.0	10.1	11.5	14.5	18.3
10.0	10.0	11.1	14.5	17.9
15.0	9.7	11.1	14.4	17.4
20.0	9.2	10.6	13.9	16.8

\*Deflection Units

These results are typical in that they were close to data obtained in preliminary tests with other sludge samples.

Using the data from Table I, a series of graphs were plotted from which values of  $dN/d\theta$  were determined by taking slopes. A typical working graph is shown in Figure VI and values of  $dN/d\theta$  are shown in Table II.

Table II

Values of  $dN/d\theta$  at Various Settling Times

Spindle Speed, rpm	Slope $dN/d\theta$ at Settling Time, Min				
	0.0 min	5.0 min	10.0 min	15.0 min	20.0 min
2	0.91*	1.46*	1.26*	1.07*	1.16*
4	1.10	1.69	1.50	1.46	1.50
10	1.56	2.21	2.50	2.72	2.71
20	1.91	2.92	3.22	3.75	4.25

\* Units =  $\frac{\text{rpm}}{\text{deflection units}}$

Table I showed that as the settling time increased the deflection readings decreased, thus the slope  $dN/d\theta$  should increase as the spindle speed increased or with increased settling time. Table II shows the former to be true, however the slope  $dN/d\theta$  did not necessarily show a steady increase with increased settling time.

The values of shear stress and velocity gradient are tabulated in Table III and Table IV and a graphical relationship is shown in Figures VII-XI.

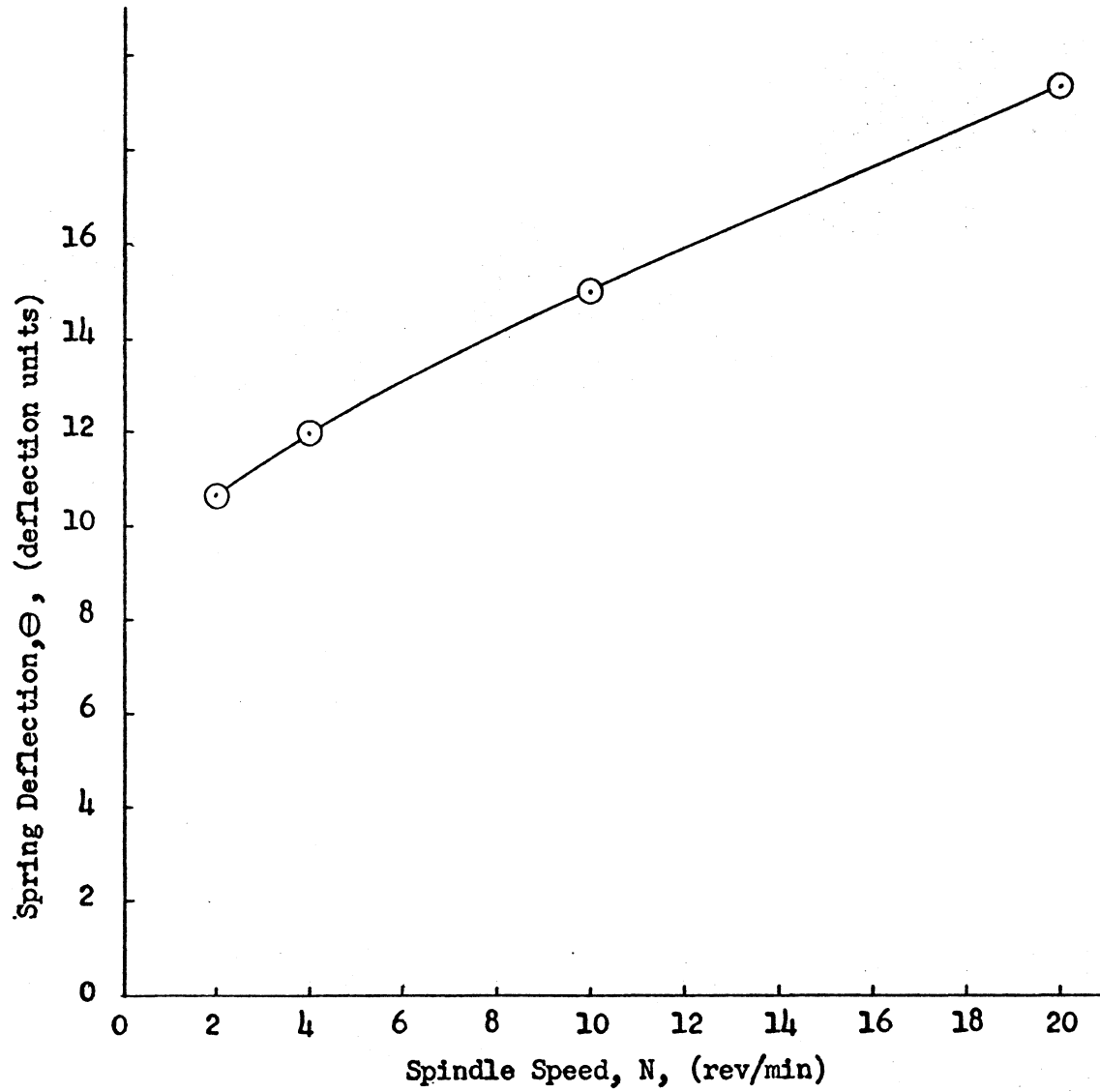


FIGURE VI: DOMESTIC DIGESTED SLUDGE AT T=5.0 MINUTES

Table III

Shear Stress for Domestic Digested Sludge

Spindle Speed, rpm	Shear Stress ( $\text{gm}^{-1} \text{sec}^{-2}$ ) at Settling Time				
	0.0 min	5.0 min	10.0 min	15.0 min	20.0 min
2	46.4	39.4	36.8	35.7	33.8
4	53.7	44.2	40.9	40.9	39.0
10	69.1	55.2	53.4	53.0	51.2
20	92.4	70.6	66.0	64.0	61.9

Table IV

Velocity Gradients for Domestic Digested Sludge

Spindle Speed, rpm	Velocity Gradient at Settling Time				
	0.0 min	5.0 min	10.0 min	15.0 min	20.0 min
2	144 $\text{sec}^{-1}$	196 $\text{sec}^{-1}$	158 $\text{sec}^{-1}$	130 $\text{sec}^{-1}$	134 $\text{sec}^{-1}$
4	201	254	209	204	198
10	368	416	455	492	473
20	603	712	724	820	897

When the sludge was thoroughly mixed at  $t = 0$  minutes, the shear stress was expected to be at maximum. This was substantiated by the results in Table III. As the heavier sludge particles settled to the bottom the shear stress decreased, as shown in Table III, for each individual spindle speed. Also it was expected that the shear stress should increase with the spindle speed at a given time as shown in Table III.

Figures VII-XI show that as settling time increased the slope of the graph of shear stress versus velocity gradient gradually decreased.

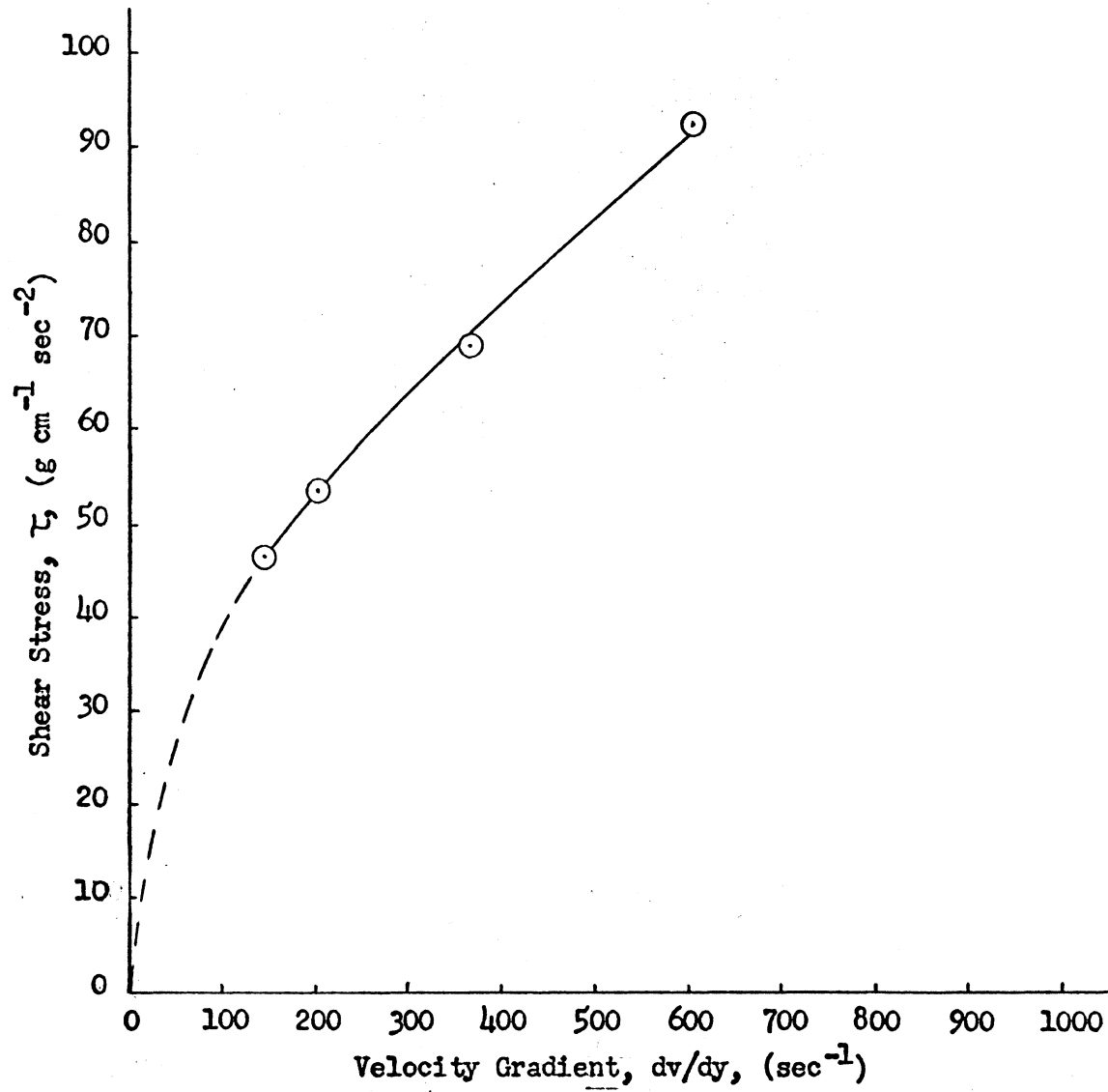


FIGURE VII: DOMESTIC DIGESTED SLUDGE AT T=0.0 MINUTES

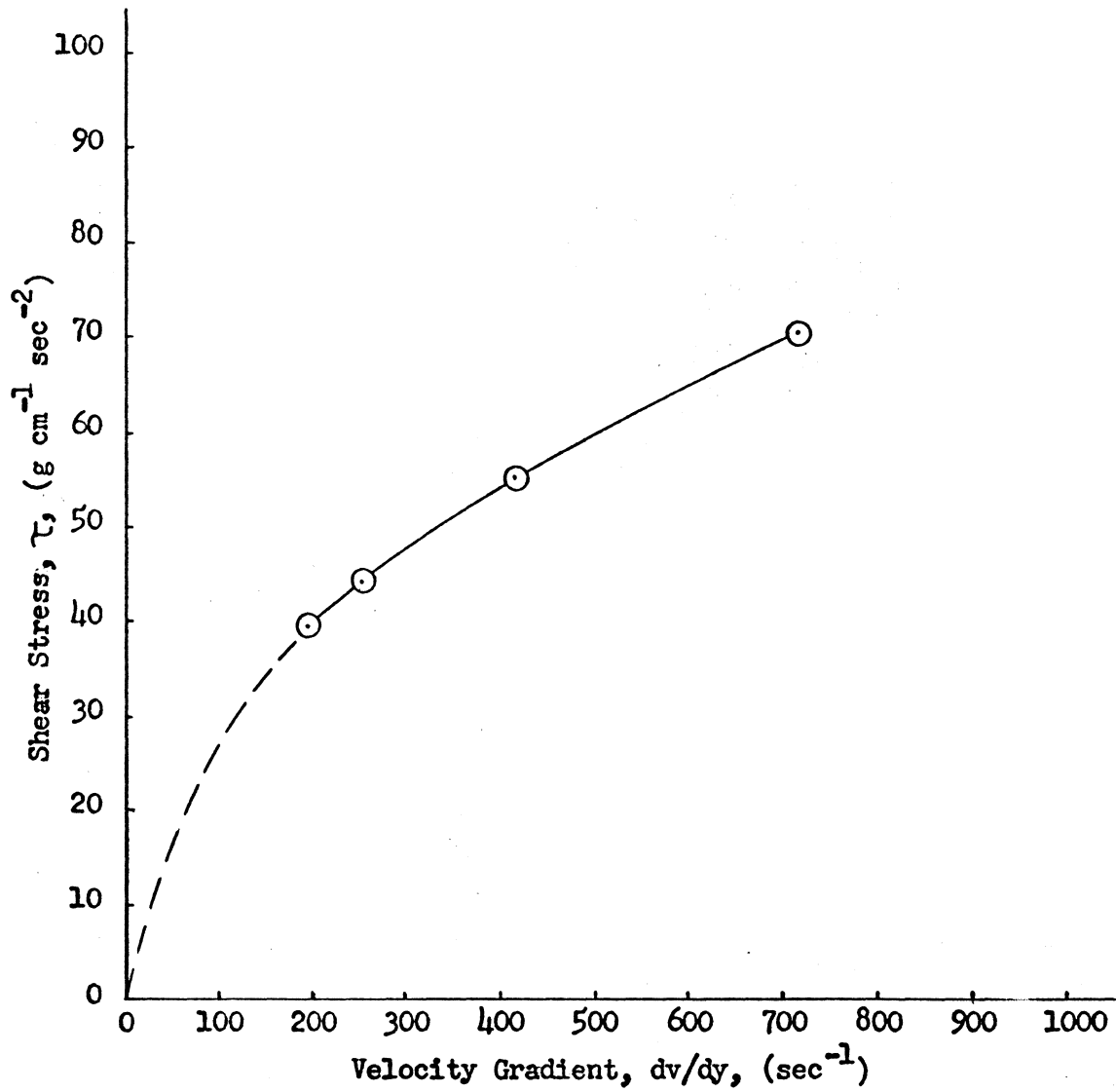


FIGURE VIII: DOMESTIC DIGESTED SLUDGE AT T=5.0 MINUTES

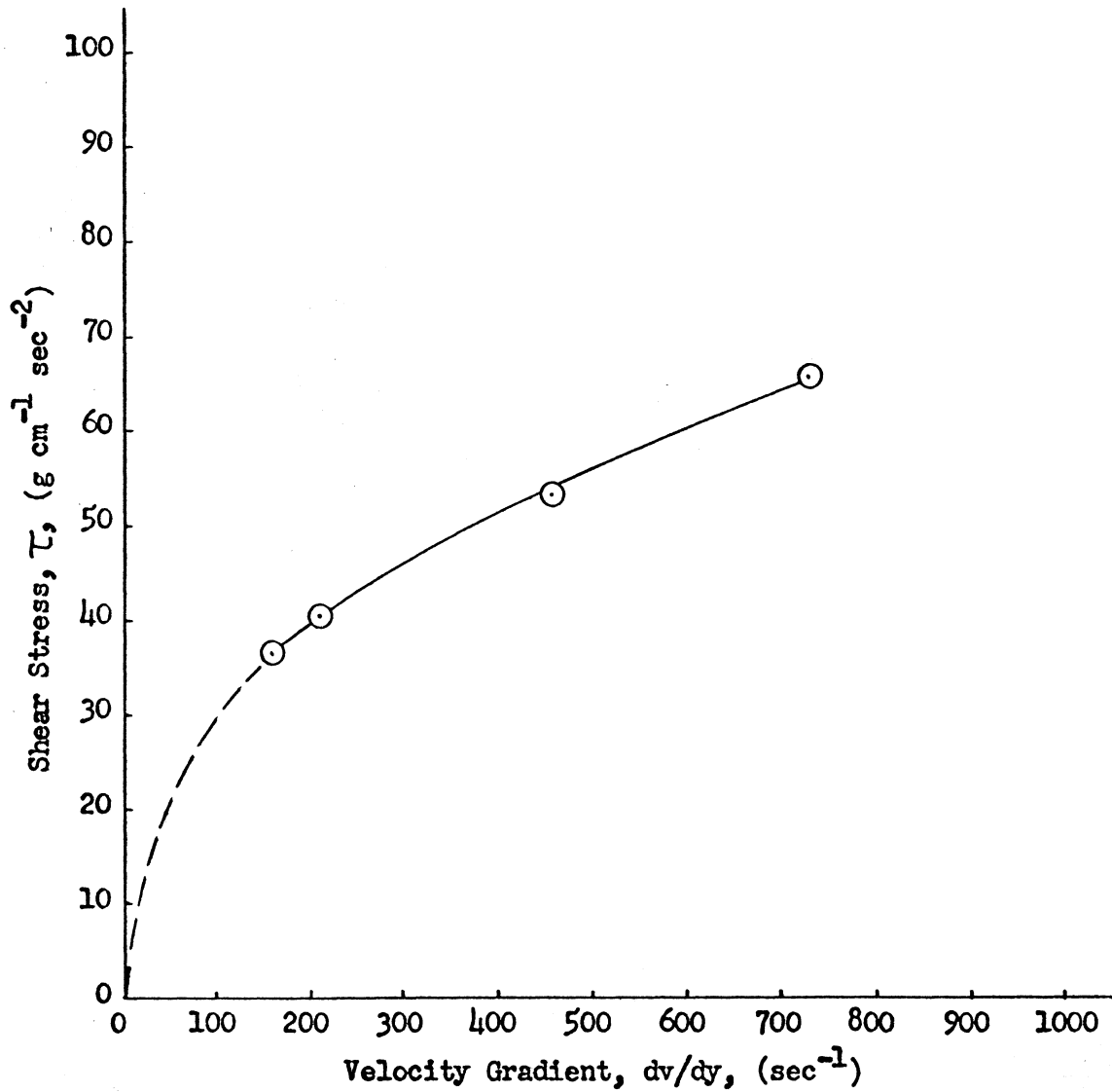


FIGURE IX: DOMESTIC DIGESTED SLUDGE AT T=10.0 MINUTES

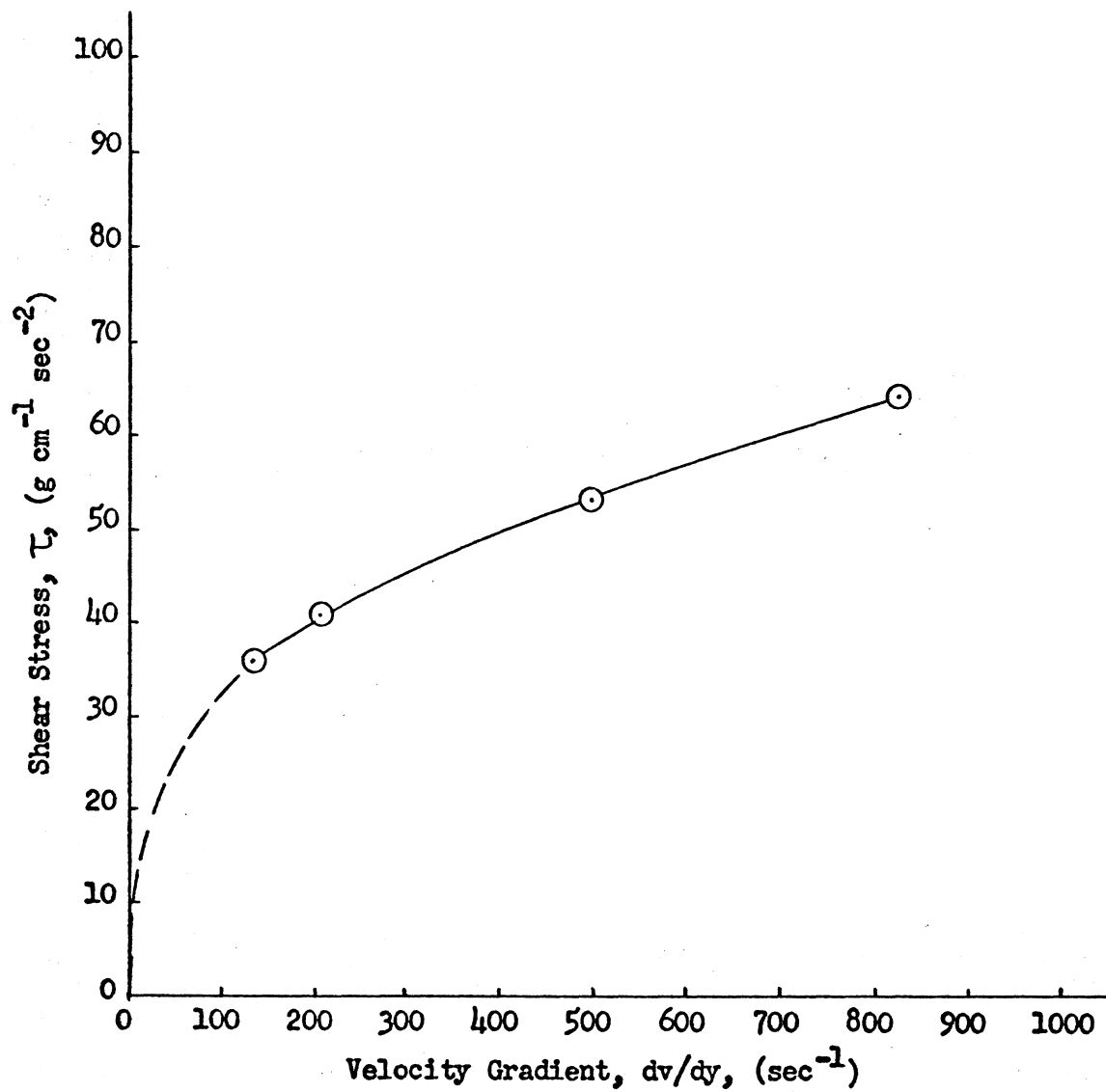


FIGURE X: DOMESTIC DIGESTED SLUDGE AT T=15.0 MINUTES

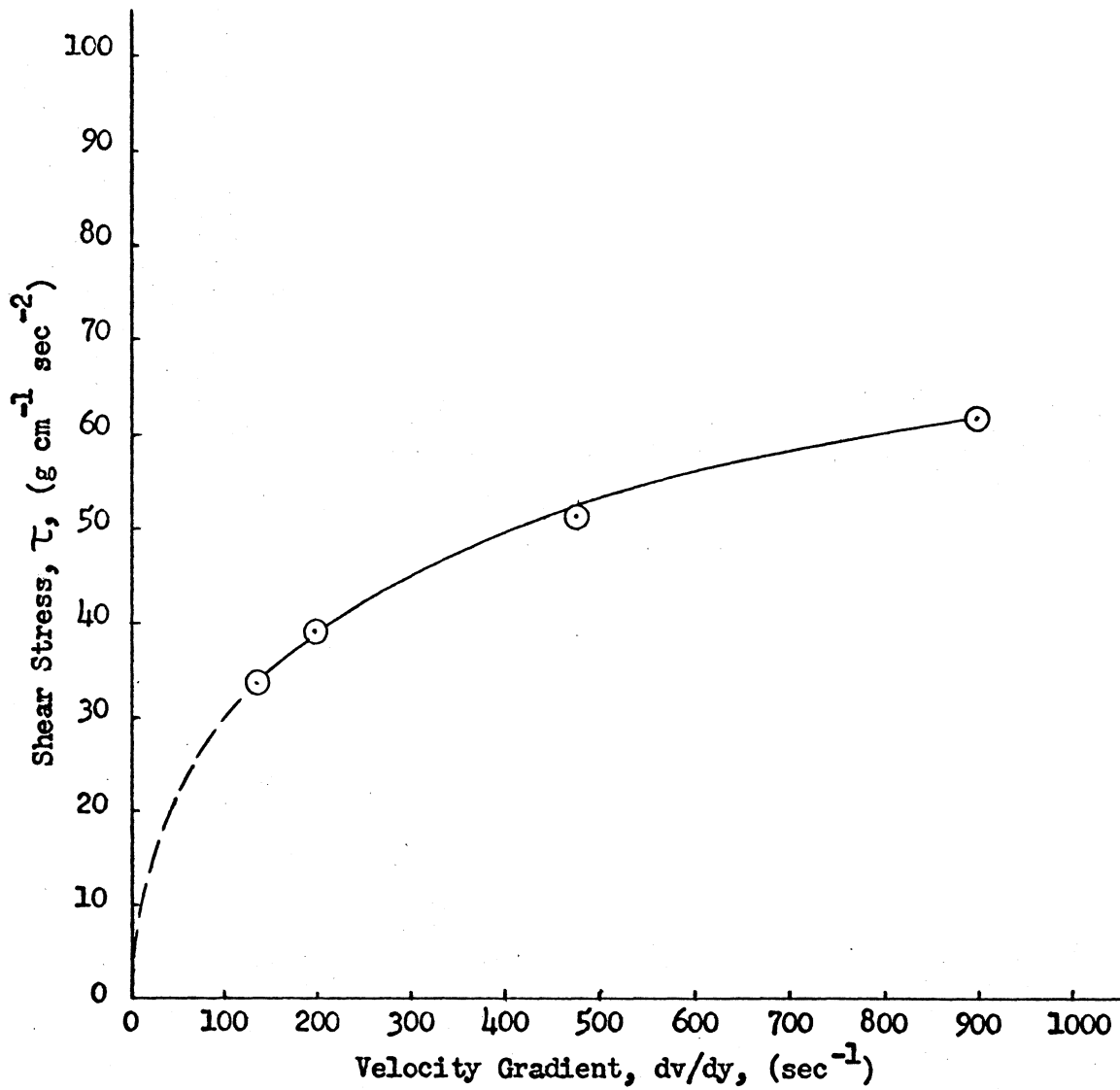


FIGURE XI: DOMESTIC DIGESTED SLUDGE AT T=20.0 MINUTES

**Experiment B - The Rheological Examination of Domestic Raw Sludge**

The object of the experiment was to determine the shear stress and velocity gradient of raw sludge at various settling times. By plotting shear stress versus velocity gradient the rheological behavior of the sludge can be determined.

The results obtained by recording the deflection reading from the 100 scale of the Brookfield viscosimeter while the sludge settled through a range of twenty minutes are in Table V.

**Table V**  
**Deflection Readings of the Brookfield Viscosimeter**  
**Using Domestic Raw Sludge**

Time, Min	Deflection* at Spindle Speed, rpm			
	2 rpm	4 rpm	10 rpm	20 rpm
0.0	4.2	4.6	6.6	8.3
1.0	3.1	3.5	4.9	7.1
2.0	2.9	3.2	4.4	5.6
3.0	2.6	3.0	4.2	5.5
4.0	2.4	2.9	4.1	5.0
5.0	2.4	2.8	4.0	4.8
6.0	2.3	2.7	3.9	4.6
7.0	2.2	2.6	3.7	4.5
8.0	2.1	2.5	3.6	4.5
9.0	2.0	2.5	3.5	4.4
10.0	2.0	2.5	3.4	4.3
15.0	1.9	2.4	3.3	4.1
20.0	1.8	2.3	3.1	3.9

\* Deflection Units

These results are typical in that they are close to data obtained in preliminary tests with other sludge samples.

Using the data from Table V, a series of graphs were plotted from which values of  $dN/d\theta$  were determined by taking slopes. A typical working graph is shown in Figure XII and values of  $dN/d\theta$  are shown in Table VI.

Table VI

Values of  $dN/d\theta$  at Various Settling Times

Spindle Speed, rpm	Slope $dN/d\theta$ at Settling Time, Min				
	0.0 min	5.0 min	10.0 min	15.0 min	20.0 min
2	2.14*	2.75*	3.75*	3.60*	3.60*
4	2.66	3.50	4.84	4.66	5.00
10	4.90	9.00	8.00	8.00	7.50
20	6.50	14.00	15.00	16.00	15.00

\* Units =  $\frac{\text{rpm}}{\text{deflection units}}$

Table V showed that as the settling time increased the deflection readings decreased, thus the slope  $dN/d\theta$  should increase as the spindle speed increased or with increased settling time. Table VI shows the former to be true, however, the slope  $dN/d\theta$  did not necessarily show a steady increase with increased settling time.

The values of calculated shear stress and velocity gradient are tabulated in Table VII and Table VIII and are shown graphically in Figures XIII-XVII.

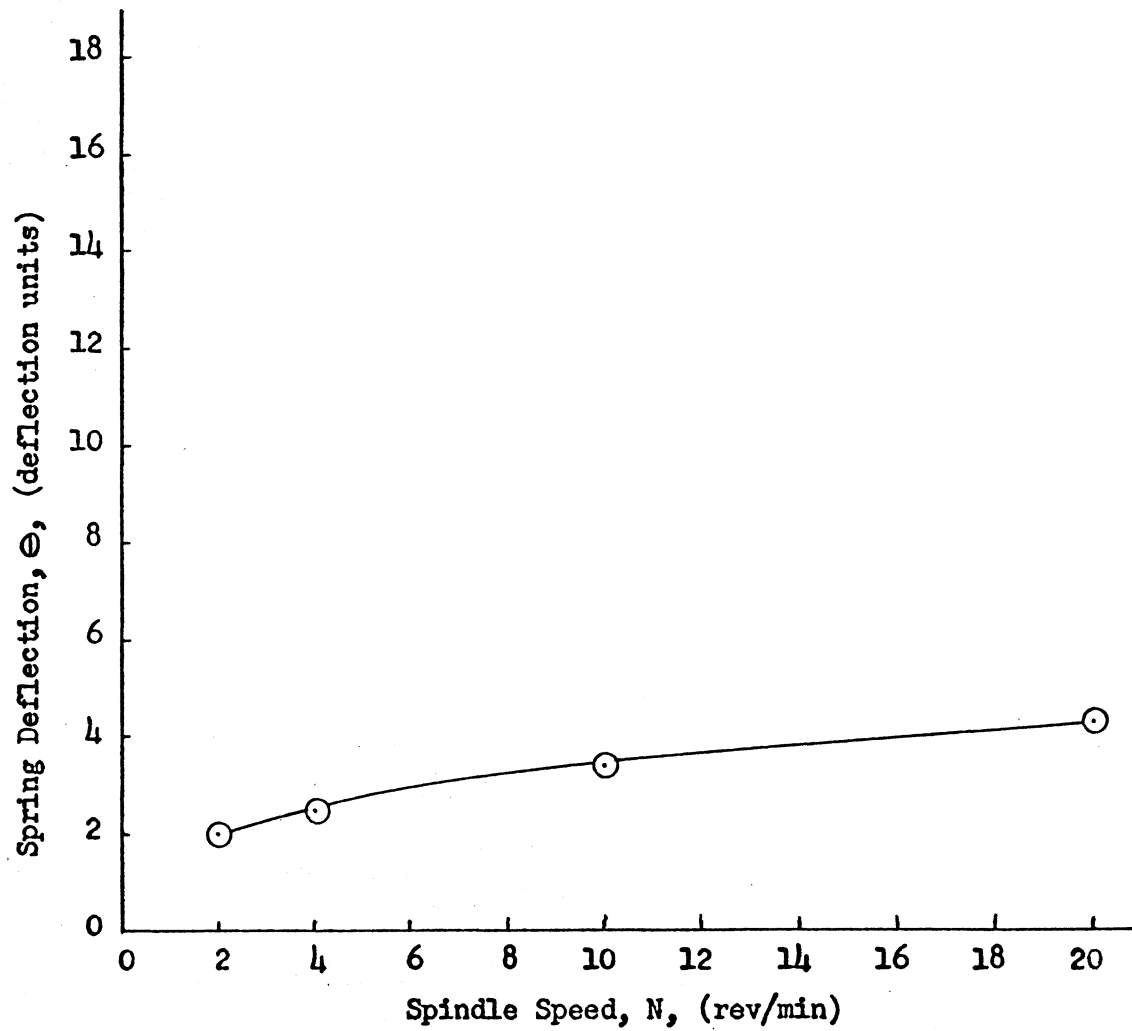


FIGURE XII: DOMESTIC RAW SLUDGE AT T=10.0 MINUTES

Table VII

Shear Stress for Domestic Raw Sludge

Spindle Speed, rpm	Shear Stress ( $\text{gm}^{-1} \text{sec}^{-2}$ ) at Settling Time				
	0.0 min	5.0 min	10.0 min	15.0 min	20.0 min
2	15.4	8.8	7.4	7.0	6.6
4	16.9	10.3	9.2	8.8	8.5
10	24.3	14.7	12.5	12.1	11.4
20	30.0	17.7	15.8	15.1	14.4

Table VIII

Velocity Gradients for Domestic Raw Sludge

Spindle Speed, rpm	Velocity Gradients at Settling Time				
	0.0 min	5.0 min	10.0 min	15.0 min	20.0 min
2	113 $\text{sec}^{-1}$	83 $\text{sec}^{-1}$	94 $\text{sec}^{-1}$	86 $\text{sec}^{-1}$	81 $\text{sec}^{-1}$
4	153	123	152	141	144
10	406	452	302	332	292
20	680	845	810	825	735

At  $t = 0$  minutes the shear stress of the mixed sludge was at a maximum. As time increased it was expected that the shear stress would decrease because the heavier sludge particles settled to the bottom. Table VII shows that for each individual spindle speed the shear stress did decrease as the settling time increased from  $t = 0$  minutes to  $t = 20$  minutes.

At a given time the shear stress should increase as the spindle speed increases and in Table VII this is confirmed.

Figures XIII-XVII show that as the settling time increased the slope of the graph of shear stress versus velocity gradient gradually decreased.

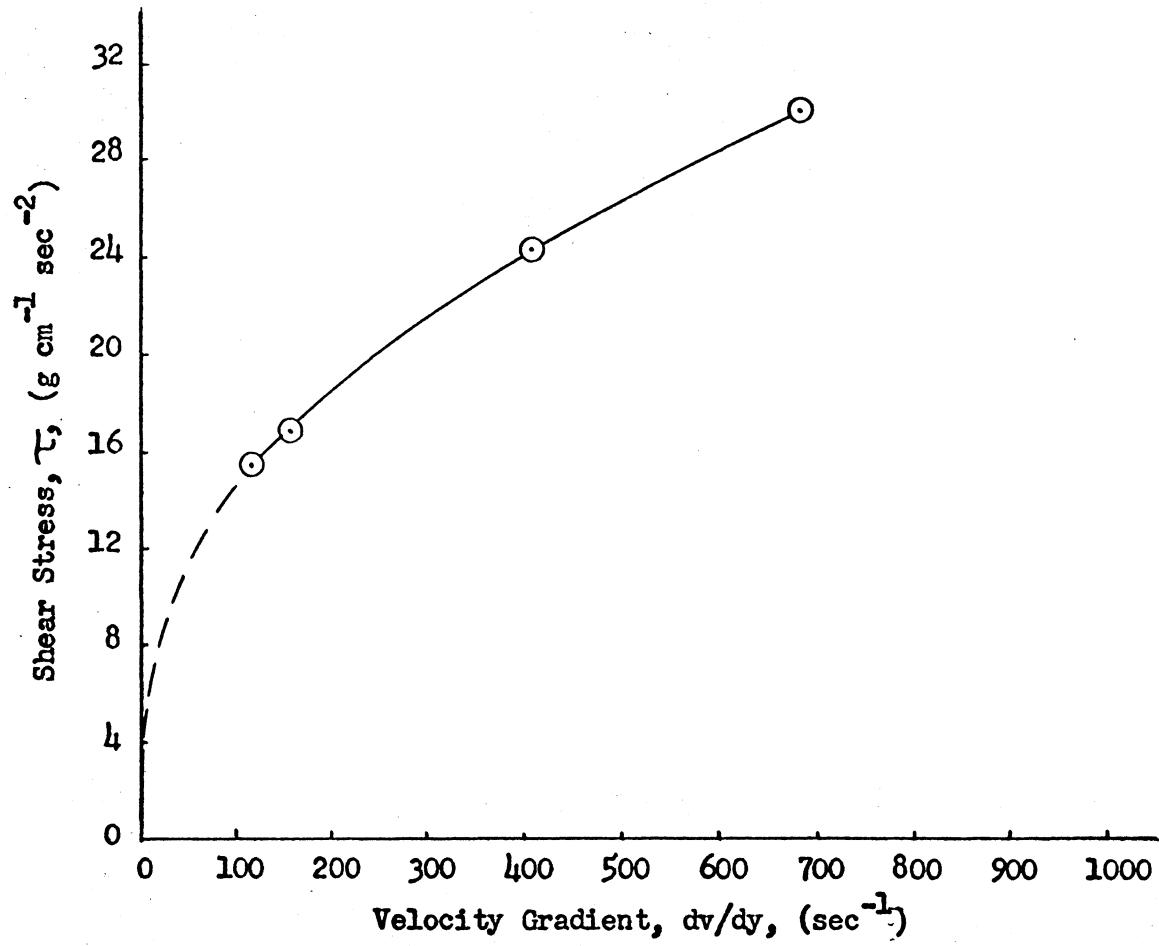


FIGURE XIII: DOMESTIC RAW SLUDGE AT T=0.0 MINUTES

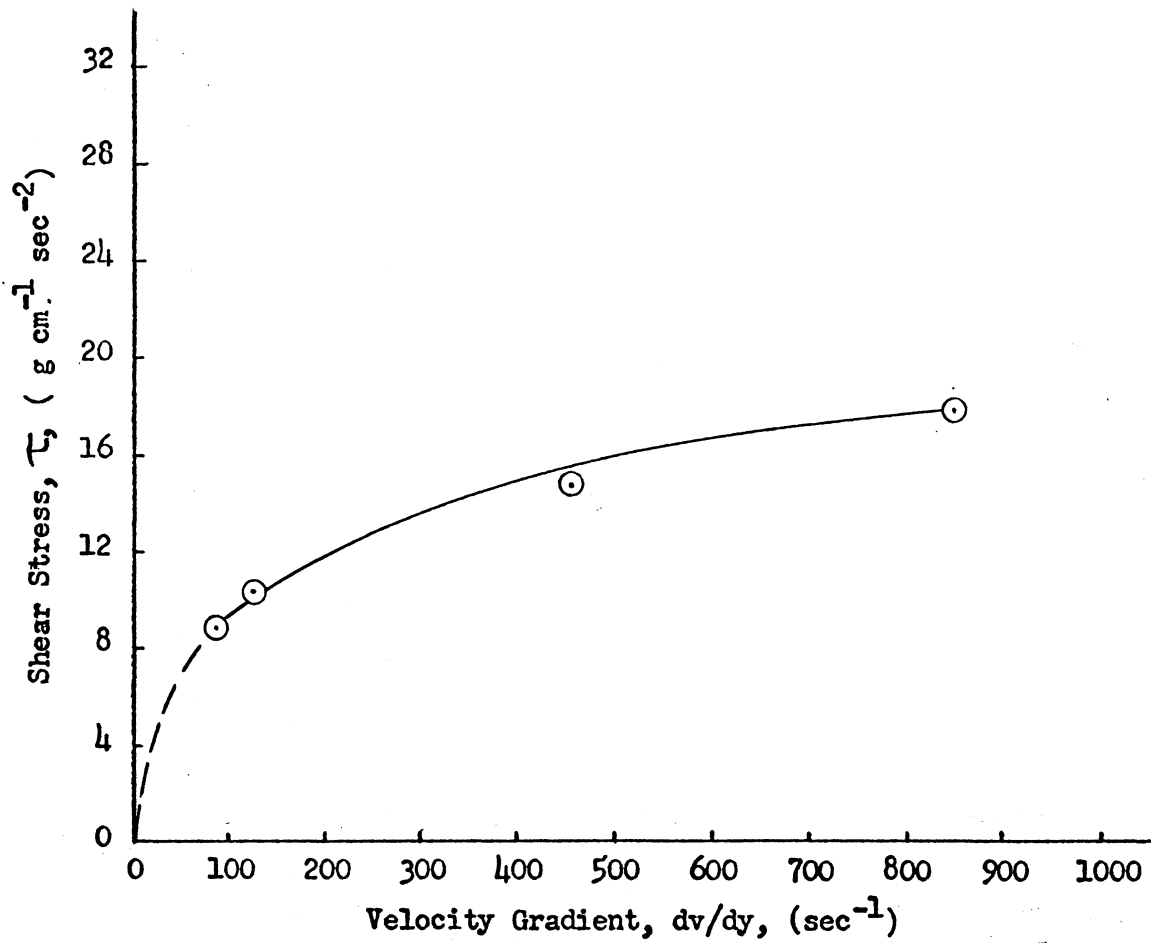


FIGURE XIV: DOMESTIC RAW SLUDGE AT T=5.0 MINUTES

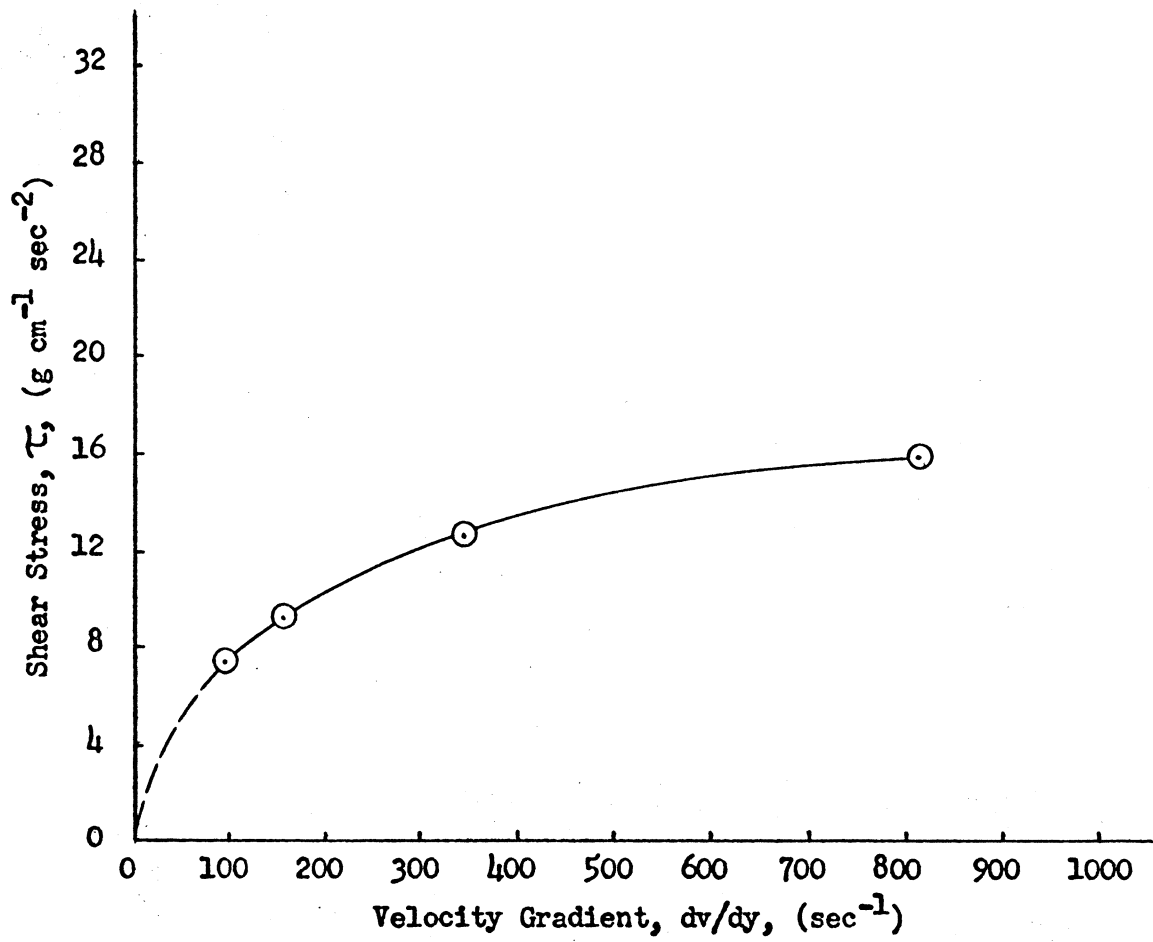


FIGURE XV: DOMESTIC RAW SLUDGE AT T=10.0 MINUTES

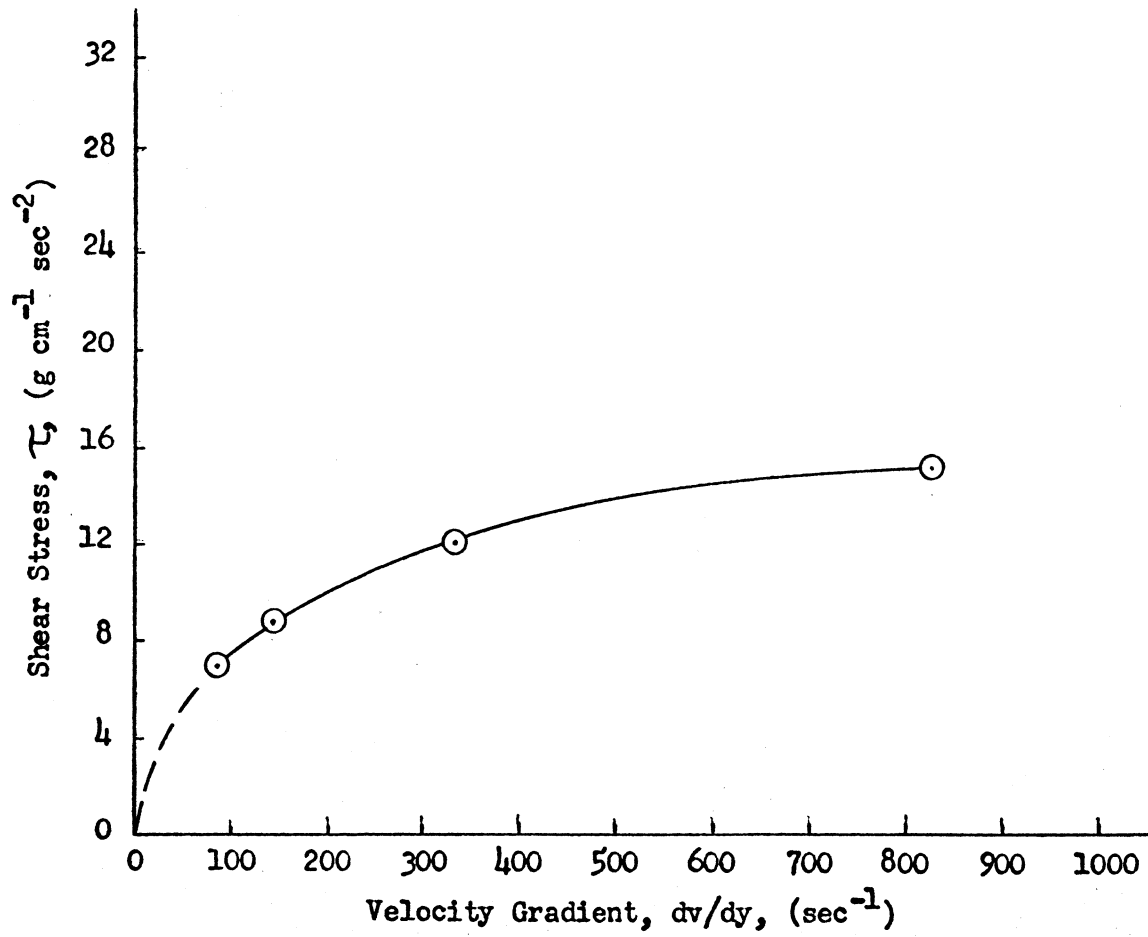


FIGURE XVI: DOMESTIC RAW SLUDGE AT T=15.0 MINUTES

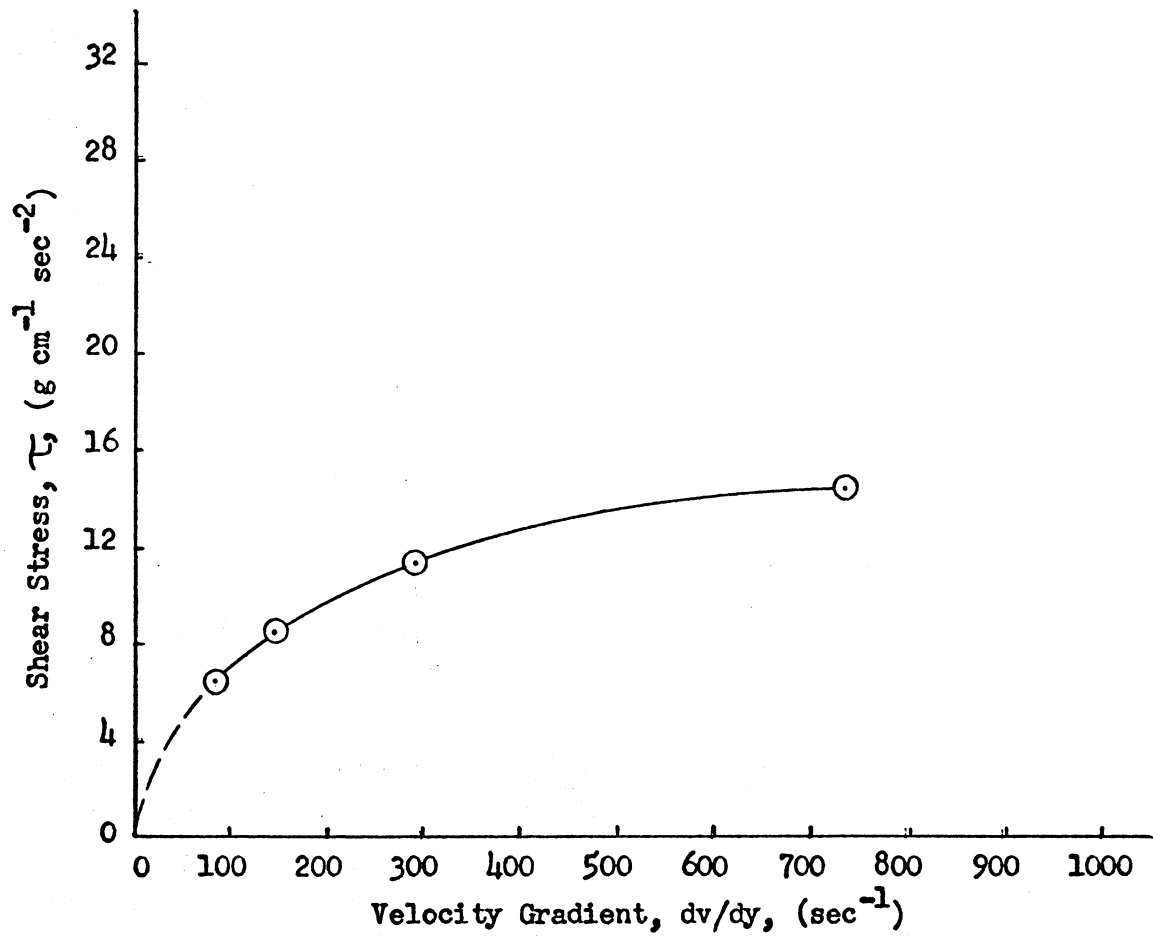


FIGURE XVII: DOMESTIC RAW SLUDGE AT T=20.0 MINUTES

## VI. DISCUSSION OF RESULTS

The results of the rheological examination of the digested and raw sludge from the Blacksburg Plant showed that the methods were adequate for determining flow parameters. The data were similar in both experiments in that a definite trend existed and both could be characterized as pseudoplastic. The heavier sludge particles settled leaving the smaller particles in suspension, thus causing the sludge concentration to decrease. The deflection readings decreased as a result and a plot of deflection readings versus spindle speeds showed the values of  $dn/d\theta$  to increase with respect to spindle speed.

In both experiments the values of shear stress decreased with respect to settling time because shear stress was dependent on sludge concentration and the concentration was becoming less. Also, Tables III and VII show that the digested sludge had higher shear stress values than raw sludge; this was expected from the appearance of the sludges.

Plots of shear stress versus velocity gradient indicated no change in the rheological characteristics of the sludges as settling time increased. The shape of the curves in both experiments showed the sludges to be pseudoplastic in behavior. However, a further investigation would better establish the behavior, especially at the lower spindle speeds, because the lower spindle speeds give corresponding low values of shear stress and velocity gradient.

The results of the rheological examination of the activated sludge and raw sludge from the Roanoke Sewage Treatment Plant were inconclusive. The sludges were not viscous enough to give a deflection reading using the Brookfield viscosimeter. To obtain readings using the activated and raw sludge the spindle speed needed to be increased beyond 20 rpm or the spindle needed to be increased in diameter. The spindle speed could not be increased beyond 20 rpm with the variable viscosimeter. Time did not permit aquisition of a new spindle from the manufacturer and therefore further examination was not attempted.

## VI. CONCLUSIONS

Sewage sludges show a definite non-Newtonian behavior. A non-Newtonian fluid is classified as plastic, pseudoplastic or dilatant. A plastic fluid exhibits a definite yield stress which must be exceeded before flow will begin. Once the fluid flows the shear stress is proportional to the velocity gradient. A pseudoplastic or dilatant fluid does not exhibit a linear relationship between shear stress and velocity gradient.

The digested sludge and raw sludge examined both exhibited pseudoplastic behavior. The plot of shear stress versus velocity gradient in both instances showed that no linearity existed between the two. The rheological behavior of the sludges did not change with respect to settling time and the higher values of shear stress for the digested sludge indicated it to be more viscous than the raw sludge.

## VII. SUMMARY

Rheology has been successfully used in many fields for years as a means of classifying fluids and studying their flow characteristics. Only recently has the importance of rheology in sanitary engineering, primarily in the study of sludges, become a reality.

Samples of digested and raw sludges were drawn from the Blacksburg Treatment Plant to be used in a rheological experiment. A Brookfield viscosimeter was used in the study of the sludges and deflection readings were recorded as the sludge settled.

Using equations adapted from those developed by Krieger and Maron(1) the shear stress and velocity gradients of the sludges were calculated. A study of shear stress plotted against velocity gradient clearly showed the digested sludge and the raw sludge were pseudoplastic and the digested sludge was more viscous than the raw sludge.

VIII. ACKNOWLEDGEMENTS

The author would like to express his appreciation to his thesis advisor, Dr. Henry R. Bungay, III, for his constant encouragement and constructive criticism.

He wishes also to express his appreciation to Dr. W. A. Parsons for his helpful criticism and guidance throughout the entire Masters program.

IX. BIBLIOGRAPHY

1. Deindoerfer, F. H. and West, J. M., "Rheological Examination of Some Fermentation Broths," J. Biochem. Microbiol. Technol. Eng. 2: 165-175 (1960)
2. Deindoerfer, F. H. and West, J. M., "Rheological Properties of Fermentation Broths," Adv. Appl. Microbiol, 2: 265-273 (1960)
3. Krieger, I. M. and Maron, S. H. "Direct Determination of the Flow Curves of Non-Newtonian Fluid. Part III Standardized Treatment of Viscometric Data," J. Appl. Phys. 25: 72 (1954)
4. Van Wazer, J. R., Lyons, J. W., Kim, K. Y., and Colwell, R. E., "A Laboratory Handbook of Rheology," John Wiley and Sons, New York, (1963)
5. Deindoerfer, F. H. and West, J. M., "Engineering Advances in Fermentation Practice," Industrial and Engineering Chemistry, 52: Pg. 59 (1960).
6. Merrington, A. C., "Viscometry," Longmans, Green and Co., New York, (1949)
7. Ames, W. F. and Behn, V. C., "Application of the Method of Composition and Linear Regression Analysis to a Problem

- Involving a Pseudoplastic Suspension," Transactions of the Society of Rheology, Vol. 5, Pg. 53-56, (1961)
8. Behn, V. C., Carver, C. E., Krokosky, E. M., Ripken, J. F., Schiffman, R. L. and Bugliarello, G.  
"Non-Newtonian Flows," Civil Engineering, 68-70, (August, 1960)
  9. Behn, V. C., "Experimental Determination of Sludge Flow Parameters," ASCE Journal of the Sanitary Engineering Division, Vol. 88, SA 3 pg. 39-53, May, 1962.
  10. Behn, V. C., "Flow Equations for Sewage Sludges," ASCE Journal of the Water Pollution Control Federation, Vol. 32, pg. 728-740, July, 1960
  11. Babbitt, H. E. and Caldwell, D. H., "Laminar Flow of Sludges in Pipes with Special Reference to Sewage Sludge," University of Illinois Bulletin, Vol. 37, No. 12, November, 1939

**The vita has been removed from  
the scanned document**

XI. APPENDICES

Sample calculation of shear stress and velocity gradient used in Experiment A and Experiment B.

Shear Stress

$$\tau = \frac{C\theta}{2\pi hr_b^2}$$

$\tau$  - Shear Stress,  $g\text{ cm}^{-1}\text{ sec}^{-2}$

C - Viscosimeter Spring Constant-  $g\text{ cm}^2\text{ sec}^2\text{ (deflec. unit)}^{-1}$

h - Spindle Height, cm

$r_b$  - Spindle Radius, cm

$$\tau = \frac{(71.87\text{ ycm}^2\text{ Sec}^{-2}\text{ (deflection units)}^{-1}) (12.6\text{ deflection units})}{(2) (3.14) (7.7\text{ cm}) (0.635\text{ cm})^2}$$

$$\tau = 46.4\text{ cm}^{-1}\text{ sec}^{-2}$$

Velocity Gradient

$$\frac{dv}{dy} = 4\pi\theta \left( \frac{dN}{d\theta} \right)$$

$\frac{dv}{dy}$  = Velocity Gradient,  $\text{Sec}^{-1}$

$\theta$  - Spindle Deflection, Deflection Units

N - Spindle Rotational Speed, rpm

$$\frac{dv}{dy} = (4) (3.14) (12.6\text{ deflection units}) \left( 0.91 \frac{\text{rpm}}{\text{deflection units}} \right)$$

$$\frac{dv}{dy} = 144\text{ sec}^{-1}$$

## Abstract

### Rheological Examination of Domestic Digested Sludge

The flow parameters involved in the transportation of sludge from the place of origin to the place of disposal has long been a problem to the sanitary engineer. To obtain the greatest efficiency in the design of pumps and pipelines the properties of sludge need to be thoroughly understood.

This investigation examined the flow characteristic of raw and digested sludge from the Blacksburg Treatment Plant using a rheological approach. A Brookfield viscosimeter was used in the investigation and formulas developed by Krieger and Maron (1) were used to determine the shear stress and velocity gradient. A series of graphs involving shear stress vs velocity gradient were plotted. These graphs were compared to the Standard Newtonian and Non-Newtonian curves, in order to determine the flow behaviour of the sludges.

The results showed the method of analysis was satisfactory for determining the flow behaviour of sewage sludges. The curves obtained showed that the raw and digested sludge examined was pseudoplastic in behaviour and shear stress values for the domestic sludge showed it to be more viscous than the raw sludge.

---

<sup>1</sup>Krieger, I. M. and Maron, S. M. "Direct Determination of the Flow Curves of Non-Newtonian Fluid. Part III Standardized Treatment of Viscometric Data." J. Appl. Phys. 25: 72 (1954)