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THE RHEOLOGY LEAFLET



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No. 7 November, 1938

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TENTH ANNUAL MEETING

This issue of the Leaflet is intended to serve primarily as a program for the annual meeting of the Society, which is to be held at the Mellon Institute of Industrial Research, University of Pittsburgh, on December 28 to 29. Our technical sessions will be held at the Mellon Institute Auditorium, 4400 Fifth Avenue, Pittsburgh, which has been made available to us through the courtesy of the University of Pittsburgh.

The thanks of the Society are also due to the Committee on Arrangements, constituted as follows:

Dr. E. Ward Tillotson, Chairman, Dr. A. Nadai, Dr. E. Hutchisson, Dr. G. R. Sturm.

The program appears on the pages following. This is the fruit of the labors of the Program Committee, consisting of:

Mr. H. R. Lillie, Chairman, Prof. E. C. Bingham, Dr. J. H. Dillon, Dr. E. Hutchisson, Dr. E. W. Tillotson, Mr. R. N. Traxler and Dr. H. F. Wakefield.

Along with our own program is given that for a session of the Chemical Engineering Symposium, which will be held in the Little Theatre of the Carnegie Institute of Technology on the afternoon of December 28. This session is part of a meeting of the Division of Industrial and Engineering Chemistry of the American Chemical Society. The Society of Rheology has collaborated with the Committee of the Chemical Engineering Symposium in preparing the program for this session, and two of the four papers scheduled are by our members. The afternoon of December 28 is therefore being left free to permit attendance at the Symposium.

In addition to the program, this issue of the Leaflet contains abstracts of the papers to be presented at the meeting, and also the revised report of the Committee on Definitions and Nomenclature. The original report was published in Leaflet No. 1, May 1937, and discussed at the last annual meeting. As a result of this discussion, the Society adopted a resolution referring the report to the Committee for revision. The report as given here has been revised in the light of the discussion on which this action was based, and is now offered to the Society for adoption. Discussion of the report is scheduled as part of the program for the session to be held the morning of December 29.

PROGRAM

TENTH ANNUAL MEETING

MELLON INSTITUTE, PITTSBURGH, PA.

December 28-29, 1938

December 28.

- 9:00- 9:45 A. M.** Registration at Bellefield Avenue Entrance, Mellon Institute of Industrial Research.
- 10:00 A. M.** Technical Session — Mellon Institute. Greeting by E. W. Tillotson, Assistant Director, Mellon Institute.
- 10:15** M. L. Huggins, Eastman Kodak Co., "The Staudinger Viscosity Law."
- 10:40** E. C. Bingham and Harold C. Adams, Lafayette College, "Fluidity of Electrolytic Solutions."
- 11:05** P. W. Kinney, Armstrong Cork Co., "The Relation of Fluidity to Volume in Organic Liquids."
- 11:30** P. S. Roller, U. S. Bureau of Mines, "Plastic Flow of Dispersions, and a New Approach to the Study of Plasticity."
- 12:00 M.** A. Gemant, University of Wisconsin, "Mobility of Ions in Plastic Dielectrics."
- 12:30 P. M.** Luncheon
- 2:00 P. M.** Chemical Engineering Symposium of the American Chemical Society. To be held at the "Little Theater", Carnegie Institute of Technology, located about one-half mile from Mellon Institute. The following papers will be presented:
- M. D. Hersey (Soc. Rheol.), Kingsbury Machine Works, "Dimensional Analysis Applied to Fluid Motion."
- M. P. O'Brien, R. G. Folsom and F. Jonassen (A.C.S.), Univ. of Cal., "Fluid Resistance in Pipes."

R. H. Ewell (Soc. Rheol.), Purdue Univ., "The Viscosity of Liquid Mixtures: Ideal and non-Ideal Behavior."

R. H. Wilhelm, D. M. Wroughton, and W. E. Loeffel (A.C.S.), Princeton Univ., "Flow of Suspensions: I. A Concentric Motor Driven Viscometer; II. Flow of Suspensions through Pipes."

6:30 P. M. Rheology Dinner — Webster Hall Hotel.

December 29.

8:45 A. M. Technical Session, Mellon Institute.

8:45 E. P. Irany, Shawinigan Chemicals, Ltd., Canada, "Viscosity and Constitution."

9:30 A. Kirkpatrick, Monsanto Chemical Co., "Some Relations between Chemical Structure and Plasticizing Effect.

9:50 F. E. Dart and E. Guth, University of Notre Dame, "The Thermoelastic Properties and the Equation of State of Rubber."

10:10 R. H. Ewell, Purdue Univ., "Theoretical Consideration Concerning the Viscosity of Binary Silicate Glasses."

10:30 R. B. Dow, Pennsylvania State College, "Recent Developments in the Study of Viscosity of Lubricating Oils at High Pressure."

10:50 H. Eyring, J. F. Kinkaid and D. Frisch, Princeton Univ., "Pressure and Temperature Effects on Viscosity."

11:15 R. B. Dow, Pennsylvania State College, "Viscosity of CCl_4 - CS_2 Mixtures of Liquids at High Pressure."

11:45 Report of Committee on Definitions and Nomenclature.

12:30 P. M. Luncheon — Business Meeting.

2:00 P. M. Plant Trips to be announced at the meeting.

ABSTRACTS OF PAPERS

The Staudinger Viscosity Law

Maurice L. Huggins, Eastman Kodak Co.

An equation has recently (*J. Phys. Chem.*, **42**, 911 (1938)) been derived for the specific viscosity of a dilute solution of "randomly-kinked" chain molecules, which, for long chains and small concentrations, is of the same form as Staudinger's empirical "law": $\eta_{sp} = k_s n c$

The validity of this equation for actual solutions, and the nature and magnitude of the derivations to be expected will be discussed, also methods for the theoretical and experimental determination of the constant, k_s .

Effects due to the nature of the solvent, of the repeating units in the chain, and of the end groups will be considered and illustrated with experimental data.

The Relation of Fluidity to Volume in Organic Liquids

P. W. Kinney, Armstrong Cork Company

Viscosity data have been studied for a large number of compounds, including several members of the homologous series of normal aliphatic hydrocarbons, ethers, thiols, mercaptans, bromides, acids, alcohols and esters. The results are utilized in a critical examination of the validity of two expressions relating viscosity to molecular volume. One is the hyperbolic equation:

$$V = A \phi - B/\phi + C$$

in which V and ϕ are molecular volume and fluidity. The other is the Batschinski expression:

$$\eta = C/(v - \omega)$$

where η and $(v - \omega)$ are viscosity and "free volume." The two expressions differ only in the correction term $(-B/\phi)$. Results show: (1) the hyperbolic expression holds for all compounds studied, while the Batschinski equation fails in the case of those either associated or of high molecular weight; (2) A varies parabolically, and B exponentially, with the number of carbon atoms; (3) C is additive and closely related to Batschinski's limiting volume ω ; (4) the "corrected free volume" varies exponentially with the number of carbon atoms in an homologous series; and (5) the constants A , B , and C can be utilized in calculating association in associated series, or in predicting viscosities in undetermined members of the various homologous series.

Plastic Flow of Dispersions, and a New Approach to the Study of Plasticity.

Paul S. Roller, U. S. Bureau of Mines.

It is argued that since plasticity is the property defining ease of deformation, the variables in which it is expressed should be stress and permanent strain, rather than shearing stress and rate of shear. This contention is based on experiments measuring permanent deformation under compressive stress, using plastic dispersions containing particles ranging from microscopic to granular in size. A general law was found to hold:

$$K = \frac{dp/p}{dv/v} = \frac{\log(p/p_0)}{\log(h/h_0)}$$

where dp and dv are increments of pressure p and volume v and h is sample height. K is called the coefficient of renitence as a measure of resistance to continued plastic flow, while p is identified with yield value. The constants K and p uniquely determine the plastic behavior. The former is dependent upon the sort of phase present but independent of the relative amount, while p depends on the liquid-solid ratio. Highly plastic materials are characterized by a K less than about unity, K being as high as 35 for some only slightly plastic dispersions. If K is too large, desired workability cannot be secured by any practicable increase in solid-liquid ratio. Cohesion is found to be measured by the amount of liquid retained at a specified yield value in dispersions of about the same value of K . This liquid retention (at constant p) appears to be related to fineness of solid subdivision. Rate of stress affects the plastic flow constants but little. A theoretical treatment of plastic flow in dispersions, from the standpoint of factors determining attractive forces between particles (electrokinetic potential, solvation and dispersity) leads to the deduction that the greater the force of attraction at unit distance of separation of particles, the greater the plasticity. Experiments confirm the theoretically expected results.

Mobility of Ions in Plastic Dielectrics

A. Gemant, University of Wisconsin

The paper is concerned with ionic mobility in vitreous dielectrics, which generally exhibit a finite plasticity. The fundamental idea is to deal with the deformation as caused by the motion of an ion in the same way as macroscopic deformations of the plastic are dealt with. This latter can be described by means of three constants of the material, namely plasticity, elasticity and solid friction, and the same should hold for the molecular deformation around a moving ion.

In applying this idea to the ionic motion in a d. c. field, it appears that, although the largest part of the work done by the field is converted into heat, a small fraction is retained by the ion in the form of kinetic energy. This fraction increases with increasing field strength. If the amount of energy collected in this way reaches the ionization energy, ionization will set in, leading to an increase of the electrical conductivity. This phenomenon has been observed with a great number of dielectric materials. The theory requires the effect to become appreciable between 10^4 and 10^5 Volts/cm, in agreement with observations.

In extending the theory to ionic mobility in an a. c. field, it appears that plasticity loses its significance and the losses are controlled only by the solid friction. The dielectric loss factor, or the equivalent a. c. conductivity can be computed by means of the solid friction coefficients, as known from mechanical vibrations, and the a. c. conductivity turns out to be two or three orders larger than the d. c. conductivity. This is a fact well known from experimental data. Thus the theory accounts for the dielectric losses even in the absence of any special mechanism, dipolar rotation, for instance.

Dimensional Analysis Applied to Fluid Motion

Mayo D. Hersey, Kingsbury Machine Works

This paper offers a brief review of a well-established method not yet as widely used as it deserves to be. The dimensional method is helpful as a step in the development and checking of theoretical equations, but finds its greatest value in the planning and interpretation of experimental work.

The contributions of Fourier, the late Lord Rayleigh, Edgar Buckingham, and others are outlined. The practical use of the theorem of "dimensionless variables" in reducing the number of factors requiring experimental variation is explained, closely following Buckingham's treatment. Its analogy with the phase-rule in certain particulars is indicated, also its use in extrapolating and generalizing empirical equations. Model experiments and dynamical similarity are discussed.

The foregoing principles will be illustrated by such examples as (1) critical velocity for turbulent motion in pipes, with extension to non-Newtonian materials; (2) the viscosity effect in Venturi tubes; (3) resistance to the movement of bodies through a fluid, including the motion of a rolling ball in a tube of liquid; (4) windage resistance of rotating bodies; (5) propellers and stirrers; and (6) fluid film lubrication.

The Viscosity of Liquid Mixtures: Ideal and Non-Ideal Behavior

R. H. Ewell, Purdue University

Since it has been shown that flow can be successfully treated as

a unimolecular rate process, flow in a mixture of liquids can be considered as analogous to several unimolecular reactions, which yield the same product, proceeding simultaneously in the same vessel. This concept leads directly to the ideal law $\phi = \sum N_1 \phi_1^0$ where N = mole fraction. This relation is analogous in form and in "raison d'être" to the thermodynamic ideal laws:

$$p = \sum N_1 p_1^0$$

$$V = \sum N_1 V_1^0$$

$$H = \sum N_1 H_1^0$$

where p = vapor pressure, V = molar volume, H = molar heat content.

While these relations give the "ideal" behavior, they do not give the "normal" behavior. The "normal" behavior is that of small positive deviations from the laws, since the van der Waals energy between two unlike molecules, E_{ab} , is equal to $E_{aa} E_{bb}$, which is always less than the average of the energies between the like molecules, i. e., $(E_{aa} + E_{bb})/2$. Since the normal behavior is an expansion on mixing, the viscosity of a mixture will be given by:

$$\phi = \sum N_1 \phi_1^0 + \left(\frac{\partial \phi}{\partial V}\right)_T \Delta V$$

$\left(\frac{\partial \phi}{\partial V}\right)_T$ has a value of 10 to 20 for most liquids. The surprisingly large value of this coefficient is just the reason why the ideal law of mixtures for viscosity has not been recognized in the past by experimental workers.

Structure changes on mixing lead to more pronounced deviations from ideal. If hydrogen bonds are broken, e. g., in mixtures of benzene and alcohol, large positive deviations occur. If hydrogen bonds are formed, e. g., in mixtures of acetone and chloroform, large negative deviations occur. If hydrogen bonds are both broken and formed, both positive and negative deviations occur in different concentration ranges, e. g., in mixtures of chloroform and alcohol.

A systematic classification of the viscosity (and other properties) of liquid mixtures is developed on this basis, and practically complete agreement with experiment is observed.

Viscosity and Constitution

E. P. Irany, Shawinigan Chemicals, Ltd. Canada

The inter-molecular forces are still neglected in our current concepts of liquid viscosity. The normal paraffins usually provide the testing ground for new empirical rules of constitutionally additive viscosity, but among the members of this series, the inter-molecular forces are negligible, and agreement is deceptively easy. The result is mostly

an invalid generalization including substances of pronounced polarity, supplemented by arbitrary "association factors".

According to graphical evidence, the general viscosity function contains at least two independent constitutive parameters. In truly polymer-homologous series one parameter is constant, the other additive; in these cases, constitutional analysis of viscosity is possible by graphical methods, using functional viscosity scales.

Some Relations Between Chemical Structure and Plasticizing Effect

A. Kirkpatrick, Monsanto Chemical Co., St. Louis, Mo.

The inter-relation between the chemical constitution and structure of plasticizers and plastics is discussed. The results obtained with Sulfonamide, Phthalate and Phosphate plasticizers in cellulose acetate compositions are used as examples and the author speculates on the possibility of formulating general rules from such data.

The Thermoelastic Properties and The Equation of State of Rubber

F. E. Dart and E. Guth, University of Notre Dame

The high reversible elasticity and the anomalous thermoelastic behavior of rubber are explained in terms of the molecular structure of rubber without making any arbitrary assumptions. Rubber consists of large chain molecules which can have a more or less curved form, due to the possibility of free rotations around single C - C bonds. This curved form is the most probable one according to the statistical interpretation of the second law of thermodynamics. If a stress is applied these curved molecules will be straightened, thus giving a transition to a less probable state. When the stress is released, the thermal agitation causes a retraction. Rubber elasticity is then analogous to the elasticity of a gas or liquid.

Curves giving the thermal state equation for some pure gum rubber samples will be shown together with curves showing the reproducibility of the results and the dependence of the stress-strain hysteresis loops upon the number of extensions and the temperature. The thermal state equation and the so-called caloric state equation together determine completely the thermodynamics of stretched rubber.

Theoretical Consideration Concerning the Viscosity of Binary Silicate Glasses

R. H. Ewell, Purdue University

Energy considerations dictate that the unit of flow in any silicate glass shall include only one silicon atom. The work of Warren shows that in soda-silica glasses each silicon is surrounded by four bonds which may be Si-O-Si covalent bonds or Si-O $\begin{matrix} \text{Na} \\ \text{Na} \end{matrix}$ O-Si electrostatic

bridges. The energy required to break the former bond is 100,000 cal. and the latter about 74,000 cal., including electrostatic, van der Waals and repulsive energies. Five possible units of flow are therefore distinguished according to whether a given silicon has 0, 1, 2, 3 or 4 of the 100,000 cal. bonds replaced by 74,000 cal. bonds. Assuming that the entropy of activation of flow is the same for all five units of flow and that flow in a mixture is given by $\phi = \sum N_1 \phi_1^0$, a quantitative expression for the viscosity of a soda-silica glass as a function of the composition is derived. The relation agrees well with experimental data and appears to be based on an essentially correct mechanism. This view is entirely at odds with the views of Preston and Seddon on compound formation in glasses and their interpretation of the irregular waves sometimes observed in the viscosity-composition curves of binary glasses. It seems probable that these waves are not real, but are due to poor data.

Recent Developments in the Study of Viscosity of Lubricating Oils at High Pressure.

R. B. Dow, Pennsylvania State College

Previous investigations reported from this laboratory have shown that the pressure coefficient of viscosity of lubricating oils depends to a high degree upon the nature of the crude. Measurements were made with the rolling-ball type of high pressure viscometer. Recent studies have been made with a Margule's concentric cylinder viscometer adapted to high pressure measurements. This instrument checked a rolling-ball viscometer over the same pressure and temperature range, using the same sample of oil. An Extract and Raffinate were produced by an acetone solvent extraction process from a Pennsylvania oil; their pressure coefficients of viscosity were similar to those of a coastal oil of low V. I. and a Pennsylvania oil of high V. I., respectively, thus substantiating previous measurements of the author. Six Pennsylvania oils, refined in various ways, and of various molecular weights and boiling point ranges have been studied to obtain correlation of chemical and physical properties with pressure coefficient of viscosity.

Pressure and Temperature Effects on Viscosity

Henry Eyring, John F. Kincaid and David Frisch, Princeton University

The general statistical theory of reaction rates as applied to viscosity will be given in outline. The free energy of activation for viscous flow is related to an entropy and energy of activation by the same equations as for any equilibrium. This, for the theory of viscosity, is perfectly general and independent of the mechanism. The rolling over

each other of pairs of molecules lying in adjoining layers seems to be the most probable mechanism. However, molecules can only roll past each other if there is a hole in the liquid about a third the size of the molecules in the proper place. If there is no external pressure such a hole involves an activation energy of about one third the energy of vaporization. At higher pressures the work done in forming the hole against the external pressure must be added. The relationship between viscosity and diffusion will also be discussed as well as the changes in these properties which accompany freezing.

Viscosity of CCl_4 - CS_2 Mixtures of Liquids at High Pressure

R. B. Dow, Pennsylvania State College

The viscosity-temperature characteristics of CCl_4 - CS_2 mixtures have been studied over a pressure range of $10,000 \text{ Kg/cm}^2$. The concentrations were 15, 30, 50, 65, and 75% by volume of CS_2 . Bridgman's falling weight viscometer was used for the measurements. The results obtained and their significance to theories of viscosity is discussed at length, particularly from the point of view of association, molecular interlocking, and activation energy (Andrade; Eyring and Ewell). Schottky's theorem is applied to show that a characteristic equation of state is not known that is applicable to the internal energy changes of viscous flow at high pressure at constant temperature.

A Thermodynamic Theory of the Strength of Materials*

M. Reiner, Jerusalem, Palestine, and K. Weisenberg,
Southampton, England

It is well known that in the ordinary tensile test of steel the strength of the testpiece, as indicated by the testing machine is considerably increased with increased speed of deformation. A dynamical theory of strength of materials, which takes account of the velocity of deformation, has been worked out by Reiner and Freudenthal (Congress for Applied Mechanics 1938, Cambridge, Mass., U.S.A.). This is now founded upon Thermodynamics. "Failure" of a structural element, either through excessive (plastic) deformation or through rupture, is accordingly governed by a maximum value of the intrinsic free energy, which can be "stored up" in the element. It is shown that this carries with it as a consequence that the failure-stress of an elastic material, which shows damping of its free oscillations increases with increasing velocity of strain. This explains the phenomenon mentioned in the first sentence above.

* This paper arrived too late for inclusion in the program, and will be read by title only.

A REPORT ON RHEOLOGICAL DEFINITIONS AND NOMENCLATURE

Foreword

In the following report by the Committee on Definitions and Nomenclature, an attempt is made to develop a complete, logical and self-consistent system of classification of materials according to their rheological properties. It is intended that the system shall provide a classification for all conceivable types of behavior of materials in deformation. The system has been developed on the basis of current usage to the extent permitted by logic and self-consistency.

The classification and the accompanying definitions have been developed in terms of idealized materials to which actual materials can be compared. In other words, ideal types of behavior and deformation are postulated which are susceptible of exact definition and classification. Actual materials can then be described in terms of the ideal types to which their behavior approximates. It should be borne in mind that an actual material with rheological properties coinciding exactly with those of a single idealized material is the exception rather than the rule. In applying to actual materials the quantitative definitions for idealized materials, great caution must be used.

It is recognized that the classification of a particular material may sometimes depend upon the method of measurement. This is particularly true as applied to the precision attained. The recognition of a measureable "yield stress," for example, may depend upon the precision of the measurement and upon the duration of the test. These uncertainties in the classification of materials result from the fact that it is sometimes either impossible or unimportant to determine for actual materials some of the characteristics which can be theoretically distinguished.

In this system of classification and definitions, only shearing strains and stresses are of interest, and the relations involved are expressed with reference to simple shear. Many of the concepts defined here in terms of simple shear are closely related to those usually defined by engineers in terms of more complex types of deformation, such as those arising in tension and compression tests. These deformations, while involving simultaneous shears in three dimensions and hence analytically complex, are often easier to produce experimentally than a simple shear. They therefore serve as a basis for many useful and practical concepts and definitions in the field of engineering. Where an analysis of the fundamental behavior of the material in deformation is required, these engineering tests may be reduced to a combination of shears, and described in terms of the concepts used in this report.

A general relation between strain and stress applies to any point within a material, and except in extraordinary circumstances, these values will vary at different points. The quantities involved in these relations applying to individual points within the material cannot be observed directly. Observable quantities such as efflux-rate, pressure, etc., can be obtained by integrating the basic point relations and can then be compared with the values obtained experimentally. It is, however, always possible, at least formally, to devise experiments and methods of analysis by which the fundamental relationship can be completely determined from experimental data.

Although all materials exhibit the inertia effects associated with acceleration of the mass elements within the material, these effects are ignored as being irrelevant in the classification and definitions given below. It should be noted that turbulence and related hydrodynamical properties belong in this category.

Descriptive Definitions

Consistency is the resistance to flow of a material (See Quantitative Definitions).

Plasticity is that property of a body by virtue of which it retains a fraction of its deformation after reduction of the deforming stress to zero.

Elasticity is that property of a body by virtue of which it recovers its original size and shape after deformation.

Thixotropy is that property of a body by virtue of which its consistency is reduced by previous deformation.

Strain hardening is that property of a body by virtue of which the stress required for permanent deformation increases with the extent of previous permanent deformation.

Hysteresis is that property of a body by virtue of which the relation between stress and strain for decreasing stress differs from that for increasing stress. Materials exhibiting hysteresis are known as **hysteretics**.

A **fluid** is a substance which undergoes continuous deformation when subjected to shear stress.

A **solid** is a substance which undergoes permanent deformation or rupture only when subjected to shear stress in excess of a certain minimum value.

Quantitative Definitions

A **simple shear** is a deformation in which the material at any point has moved parallel to a fixed line in a reference plane by an

amount which is proportional to the distance of the point from the plane. Such a deformation is shown in Figure 1, the full lines showing the initial shape and the dotted lines the final shape. OO is the fixed line in the reference plane, P is the original position of a point in the body, and P' its position after deformation. The shear strain, ϵ , is given by the ratio of the displacement ds to the distance dx of the point P from OO, or $\epsilon = ds/dx$.

The **angle of shear** is the angle whose tangent is the shear strain. In Figure 1 the angle α is the angle of shear ($\alpha = \tan^{-1} ds/dx$).

The **rate of shear** is the time rate of change of shear strain. In Figure 1 the rate of shear is given by:

$$\frac{dv}{dx} = \frac{d}{dt} \left(\frac{ds}{dx} \right)$$

A **complex shear** is the resultant of two or more simple shears. For simplicity, the definitions given in this report are stated in terms of simple shear, it being understood that the same definitions apply in the case of complex shears resulting from simple shears of the same type.

The **consistency** of a material is the ratio of the shear stress to the rate of shear.

The **viscosity** of a simple liquid is the constant ratio of shear stress to the rate of shear.

Note: The term "viscosity" is applied only to simple liquids. However, the adjective "viscous" does not necessarily imply a linear relation between shear stress and rate of shear and is used in the more general sense in the term "plastico-viscous", defined below.

The **poise** is the unit of viscosity in the C.G.S. system.

The **fluidity** of a simple liquid is the reciprocal of the viscosity.

The **rhe** is the unit of fluidity in the C.G.S. system.

The **mobility** μ is the quantity defined by the equation:

$$\frac{dv}{dx} = \mu (F - F_0)$$

characterizing the deformation of a body for which the rate of shear $\frac{dv}{dx}$ is a linear function of the shear stress F for stresses greater than the yield stress F_0 , and is zero for stresses less than F_0 .

The **yield stress** of a solid is the shear stress which must be equalled or exceeded to produce permanent deformation.

The **elastic limit in shear** of a solid is the maximum deformation

that is elastic and the minimum deformation that results in rupture or in permanent deformation.

The **shear strength** of a solid is the minimum value of shear stress at which macroscopic rupture occurs.

The **shear modulus of elasticity** (modulus of rigidity) of an elastic solid is the constant ratio of shear stress to shear strain for values of the shear strain below the elastic limit.

Classification

The classification of idealized types of materials is in terms of their behavior under load, or the relation between strain and stress. The stress at any point within a material is a function of the strain and its time derivative, or rate of strain. In all materials the second time derivative of strain determines the inertia effect. As noted above, this effect is ignored in these definitions.

The stress may depend to some extent on the prior strain or deformation history of the material. Such dependence upon the prior strain is regarded for convenience as a secondary characteristic, materials being classified primarily by the actual relation between stress and instantaneous strain or rate of strain without regard to differences in this relationship that would result from a different strain history.

Classes of Fluids

(a) A **gas** is a fluid distinguished from a liquid by its behavior under hydrostatic pressure changes. This distinction is irrelevant to this classification, as it does not involve shear stresses. Under shear stress the behavior of a gas is identical with that of a simple liquid.

(b) A **simple liquid** (Newtonian liquid) is one for which the rate of shear is proportional to the shear stress. Symbolically:

$$\frac{dv}{dx} = \frac{1}{\eta} \tau \quad (\text{See Summary})$$

(c) A **complex liquid** (Non-Newtonian liquid) is one for which the rate of shear is a function of shear stress only, this function being other than that of direct proportionality. Symbolically:

$$\frac{dv}{dx} = f(\tau) > 0 \quad (\text{See Summary})$$

Classes of Solids

(a) An **elastic solid** is one for which the shear strain is a single valued monotonic function of the shear stress for all values of the

latter below the shear strength. Symbolically:

$$\epsilon = f(F) > 0, \frac{d\epsilon}{dF} > 0, 0 < F < F_{\alpha} \quad (\text{See Summary})$$

(b) A **Hookian solid** is an elastic solid for which the shear strain is directly proportional to the shear stress for all values of the latter below the shear strength. Symbolically:

$$\epsilon = \frac{F}{G}, 0 < F < F_{\alpha} \quad (\text{See Summary})$$

Reduction of the shearing stress to zero results in the immediate and complete disappearance of the strain.

(c) A **plastic solid** is one which obeys the law of an elastic solid for shear stress below the yield stress, and for shear stress in excess of this value is permanently deformed at a rate controlled only by the inertia reaction. Symbolically:

$$\epsilon = f(F) > 0, \frac{d\epsilon}{dF} > 0, 0 < F < F_0$$

$$\epsilon > 0, \frac{dv}{dx} > 0, F_0 < F < F_{\alpha} \quad (\text{See Summary})$$

Reduction of the shear stress to zero results in an immediate recovery of the elastic portion of the strain. The strain in excess of that experienced up to the yield point remains as permanent deformation.

(d) A **plastico-viscous solid** is one for which the deformation for shear stress below the yield stress is that of an elastic solid, and which for shear stress above that value deforms continuously at a rate of shear which is a function of the shear stress. Symbolically:

$$\epsilon = f(F) > 0, \frac{d\epsilon}{dF} > 0, 0 < F < F_{\alpha}$$

$$\frac{dv}{dx} = f(F) > 0, F_0 < F < F_{\alpha} \quad (\text{See Summary})$$

Reduction of the shear stress to a value below the yield stress results in the immediate reduction of the rate of shear to zero. The strain in excess of that experienced up to the yield point remains as permanent deformation.

(e) A **complex solid** is one for which the shear stress required for deformation is a function of both the shear strain and rate of strain. Symbolically:

$$\epsilon = f(F, \frac{dv}{dx})$$

Prior Strain

The classification given above is without regard to prior strain. When the terms defined above are used without qualification it is implied that the stress-strain relation is independent of the strain previously experienced. Materials for which the stress-strain relation

is dependent on prior strain should be described as **Thixotropic** or **Strain Hardening** in the senses in which these terms are defined above.

Rheological Diagram

It is recommended that wherever possible published data on complex liquids should include not only the observed quantities such as pressure, time of efflux, etc., but in addition the calculated basic quantities. The preferred curve should show consistency, fluidity, or rate of shear plotted against shear stress, rather, than efflux rate against pressure, or rate of rotation against torque.

Rheological Curve or **Rheological Diagram** are suggested as short convenient terms for curves of these preferred types.

SUMMARY OF RHEOLOGICAL NOMENCLATURE

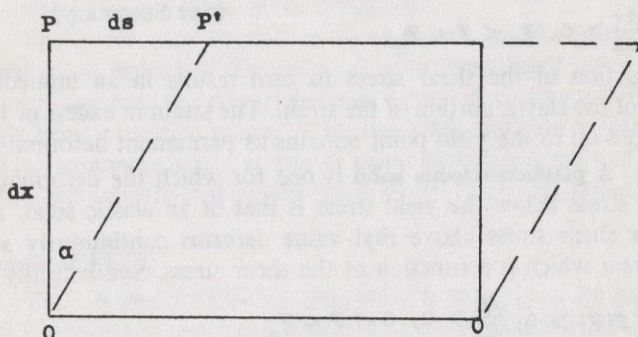


Figure 1 Simple Shear

s: Linear displacement parallel to direction of deformation.

x: Linear coordinate in the plane of the deformation and normal to direction to deformation.

$v=ds/dt$: linear velocity.

dv/dx : Rate of shear.

F: Shearing stress.

$\epsilon=ds/dx$: shear strain.

F₀: Yield stress.

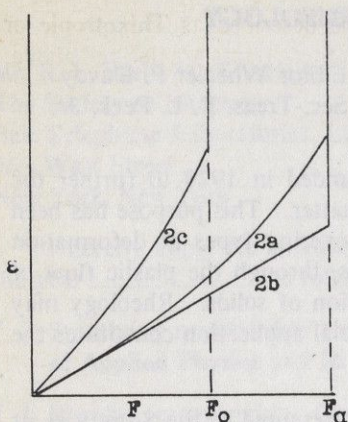
F_{0r}: Shearing stress at rupture (shear strength).

η : Coefficient of viscosity.

G: Shear modulus of elasticity (modulus of rigidity)

p: Coefficient of mobility.

$F/\frac{dv}{dx}$: Consistency.



1. Fluids

(a) Gas

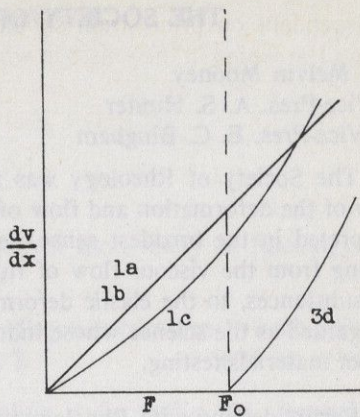
$$\frac{dv}{dx} = \frac{1}{\eta} F$$

(b) Simple Liquid

$$\frac{dv}{dx} = \frac{1}{\eta} F$$

(c) Complex Liquid

$$\frac{dv}{dx} = f(F) > 0$$



2. Solids

(a) Elastic Solid

$$\epsilon = f(F) > 0, 0 < F < F_\alpha$$

(b) Hookian Solid

$$\epsilon = \frac{F}{G}, 0 < F < F_\alpha$$

(c) Plastic Solid

$$\epsilon = f(F) > 0, 0 < F < F_0$$

$$\epsilon > 0, \frac{dv}{dx} > 0, F_0 < F < F_\alpha$$

(d) Plastico-Viscous Solid

$$\epsilon = f(F) > 0, 0 < F < F_0$$

$$\frac{dv}{dx} = f(F) > 0, F_0 < F < F_\alpha$$

(e) Complex Solid

$$F = f(\epsilon, \frac{dv}{dx})$$

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