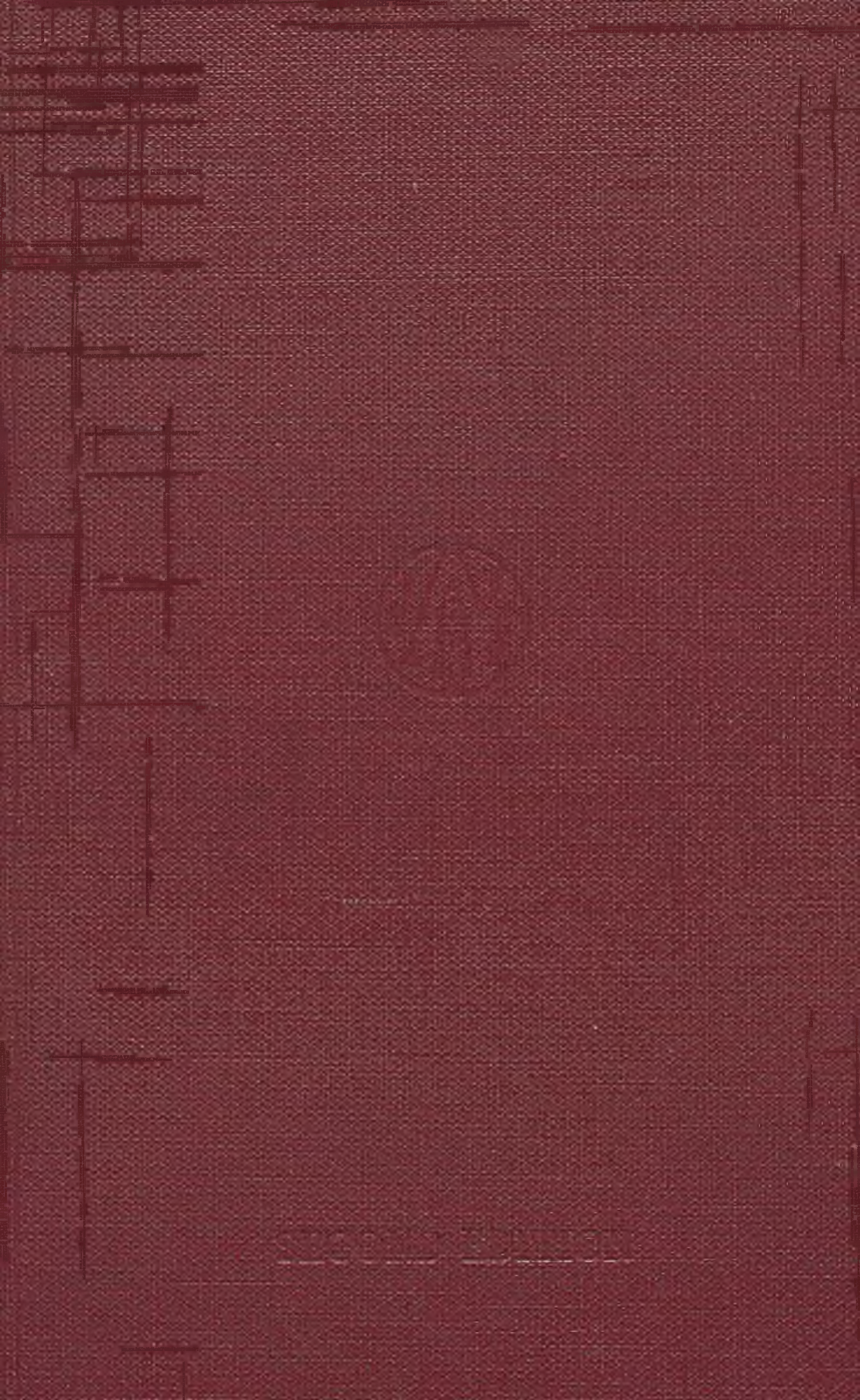

MATERIALS TESTING

THEORY AND PRACTICE

BY

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SECOND EDITION
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IN THE REPRINTING OF THIS BOOK, THE RECOMMENDATIONS OF THE WAR PRODUCTION BOARD HAVE BEEN OBSERVED FOR THE CONSERVATION OF PAPER AND OTHER IMPORTANT WAR MATERIALS. THE CONTENT REMAINS COMPLETE AND UNABRIDGED.

PRINTED IN THE UNITED STATES OF AMERICA

NOTE TO REVISED PRINTING, SECOND EDITION

A new printing of this book has given the authors the opportunity to include additional text material and a few new illustrations and tables.

An entirely new chapter (with illustrations) on photoelastic analysis has been added with special reference to the field of application and the use of the polariscope.

Changes are to be noted in the sections devoted to absorbing recoil, study of elastic range, stress distribution, Charpy test, endurance limit, fineness test, soundness, standard sand, fineness modulus, and concrete beams. Other changes of a minor nature have been made to bring the text in line with A.S.T.M. specifications.

I. H. C.
R. G. A.

CAMBRIDGE, MASS.,
January, 1944.

PREFACE TO SECOND EDITION

In the rapidly changing field of applied science new ideas and developments are ever present. This is particularly true of testing technique where often the proposed requirement or technique of today becomes a discarded method of tomorrow. In this second edition of Materials Testing, after a lapse of ten years since the first publication, the writers have attempted to include only those improvements and developments which have been tried and proven worthy of acceptance as standard. There are many other important developments which are worthy of inclusion but the original purpose of the text has been kept in mind in selecting the ones best adapted for the scope of this book.

In the realm of high precision instruments the Huggenberger tensometer has been selected as the type which the student is most likely to meet in research work. In hardness testing the Vickers and Monotron hardness testers appear and new material in the use of the Rockwell has been added. The subject matter in cement and sand testing has been brought up to date to conform to the changed standards. The Morehouse proving ring has been cited as a new method of machine verification and other changes in that section have been made to conform with present standard procedure. A new chapter has been included on concrete testing and all the specifications cited in the first edition have been revised to meet the changes in the standards of the American Society for Testing Materials. Some changes have been made and new material added in the text to meet difficulties which have been encountered in the presentation of the subject matter to students during the past ten years.

The authors hope that their experience of the past years, as reflected in this new edition, will result in making it more helpful to all who may find cause to make use of it.

I. H. C.
R. G. A.

Cambridge, Mass.,
August, 1935.

PREFACE TO FIRST EDITION

The reader who makes himself familiar with the contents of this volume, either through choice or under compulsion, will note that the writers have attempted in most instances to be general rather than highly specific. The experience of many years in college and technical evening school work has led to the conclusion that general principles are basic, fundamental, and lend themselves to the widest application; while specific items of information are often very superficial and commonly narrow in their application.

This conviction has resulted in the preparation of a small book which is to be treated as a text to accompany a laboratory course in the study of materials under stress, rather than a laboratory manual in the commonly accepted significance of the term. No attempt has been made to outline in detail any particular set of tests or experiments. Rather has it been the aim to indicate basic methods of attack and interpretation. This, it is believed, will put within the reach of the reader those all-important principles upon which the great mass of specifications are based. Certain types of testing which, while important, are somewhat narrow in their application have been carefully eliminated. They constitute the realm of the advanced student and the specialist.

Whether a course in the Testing of Materials be short or long, its investigations must be based on the study of the fundamental stresses and strains and methods for their determination. Each student should become thoroughly familiar with the methods commonly employed in the study of tension, compression, torsion (shear), bending, hardness determination, and shock and repeated stress when possible. He should have in mind the characteristic phenomena evidenced by iron (wrought and cast), steels (carbon and alloy, annealed, heat-treated and overstrained), the simpler non-ferrous alloys, wood, brick, cement and concrete. While special conditions or particular preferences may lead into other fields of investigation, the lines indicated above will furnish the foundation on which to build.

When time permits, manipulative experience and intimate study of the peculiarities of various testing machines are undoubtedly of value. Under intensive training, and in courses, too often abridged, it is felt that the action of the material under observation is most important.

The subject matter between these covers is largely that which the writers have endeavored, year by year, to place within the grasp of those students who have worked with them in the Testing Materials Laboratory of the Massachusetts Institute of Technology.

I. H. C.
R. G. A.

Cambridge, Mass.,
August, 1925.

ACKNOWLEDGMENTS

In the preparation of this book the thesis files of the Mechanical Engineering Department of the Massachusetts Institute of Technology have proved to be a prolific source of certain very valuable data. The publications of the American Society for Testing Materials have been freely drawn upon as the most authentic source of accepted practice in this country. The various symposiums on hardness which have been conducted by the American Society for Metals have been highly suggestive in the preparation of the section devoted to that subject.

Above all, the writers feel a deep debt of gratitude to the entire staff of the Testing Materials Laboratory and particularly to its late head, Professor Harrison W. Hayward, for their most helpful criticisms and whole hearted encouragement.

CONTENTS

MATERIALS TESTING

PROVINCE OF THE TESTING ENGINEER

The work of the testing engineer naturally divides itself into three broad lines of endeavor.

First, he is called upon to determine the various physical properties of materials which are, or may become, of use to the designer and constructing engineer. Such types of investigation may deal with newly developed substances, such as various metallic alloys, clay and cement products, adhesives, abrasives, and so forth; or the material to be studied may be some natural substance made available by changes in economic conditions at home or abroad, such as tropical timber, stone from newly developed quarries, fibers not before recognized by the cordage or textile manufacturers; or further, new exigencies of service may necessitate the study of properties well understood under normal conditions but concerning which nothing is known under the circumstances imposed by later developments, such as the properties of metals at high and low temperatures or when subjected to repeated stresses, or the behavior of iron and steel under the action of superheated steam.

Second, after the various properties of his available materials have been definitely ascertained and proper specifications formulated, he will frequently be required to conduct certain tests of a more or less routine nature, to determine whether or not particular products fulfill these specifications and may be safely accepted and used by the purchaser.

Third, it often becomes necessary to study the behavior of fabricated parts, mechanisms, and structures to determine if possible the strength, points of weakness, and distribution of stress under working conditions.

In all these instances, when feasible, the engineer will naturally attempt to reproduce the conditions of stress which may be expected in practice. This, however, is not always possible. In the determination of the quality of a material it is not always even desirable to make the attempt. Such qualitative tests may in some cases be more truly significant when made by purely arbitrary and artificial methods. For example, cement mortars are always expected to withstand compression or shear only. However, any attempt to determine the quality of the cement under such stress introduces so many troublesome variables that the results of the tests become little more than a mass of inconsistencies. Hence the *quality* of a cement is almost invariably determined by tensile tests on specially and artificially prepared mortars.

Tests, other than those made on fabricated parts, are most commonly performed upon some more or less standardized type of test specimen. The factors vitally affecting the choice of this test piece will be discussed in a later section. Such tests are commonly arranged so that the primary stresses introduced will be as nearly as possible simple tension, simple compression, or pure shear. In certain specific cases, notably in the testing of timber, complex stresses may be imposed combining all of those just mentioned.

THE REPORT

General. The importance of the report of a test cannot be overemphasized. The student is peculiarly prone to feel that the value of a laboratory exercise is chiefly to be found in the accumulation of various data, and that the report is an unmixed evil imposed by irksome authority. This premise cannot be defended. A careful analysis of the results will, in general, afford great value and is most efficacious in the development of a clear understanding of the principles which the investigation is expected to illustrate.

The ability to render a clear, accurate, complete yet concise report often differentiates the man of ability from an inferior competitor and is an invaluable asset to the engineer. If the report be written, the general form and method of presentation are of considerable importance. Let the report be dignified in every respect. There is a vast difference between a concise presentation and a report which is abbreviated. To distinguish between the essential and the non-essential in the matter of detail should ever be the aim of the careful engineer.

It is well to assume that the reader of the report is likely to be wholly unfamiliar with the method of attack. Methods of measurement should be outlined and any unusual measuring devices explained, preferably illustrated by means of a sketch. Methods of load application should be treated in the same manner in order that the reader may have an understanding of the care exercised in the performance of the test.

It is inconceivable that any engineer could consider submitting a penciled report.

Graphs. Plots are a most effective means of presenting facts, peculiarities, and relations. They should be carefully prepared and be easily comprehended without recourse to the accompanying text. Every plot should bear a descriptive title. The scales should be clearly indicated, and the legend should set forth the major items or observations necessary for a correct interpretation of the graph. The salient features of the graph should be carefully indicated.

In general, a graph will be used for one of two purposes: either to avoid interpolation in the use of tabular values, or to represent the general trend of some varying condition or the peculiarities evidenced by the material under investigation.

If the graph is used to replace a table as a reference or correction curve, the scales should be as large as the accuracy of the data will warrant. The estimated digit from the graph should, in general, correspond to the doubtful figure in the observation. Unduly large scales often result in overconfidence in the use of values obtained from the graph and tempt the user to assume a precision in dependent work which is not warrantable.

When the graph is primarily to present some general law of variation or to indicate the general properties of a material the scales should be so chosen that the property under observation will be as clearly defined as possible. In such instances it will be noted that the size of the complete graph should not be too large.

Form. Tabulated data lend themselves more readily to analysis and comparison than the same data scattered through a written paragraph. It is particularly confusing to the reader to be forced to search through a maze of calculations in order to discover the computed results. In general, it is best to eliminate all calculation from the body of the report. Methods and details of computations are more logically placed in an appendix to the report proper.

Discussion and Conclusions. Careful comparisons are of the highest educational value. The results of a single test are unattached and barren facts which may be remembered but are more likely soon to be forgotten. If these results be scanned in the light of standard specifications and requirements or intelligently compared with values commonly quoted by competent authority, then they cease to be mere information and become a part of the general engineering knowledge of the investigator. Discussion and comparison, with the conclusions drawn therefrom, constitute the chief value of a report which pretends to be something beyond the mere tabulation of a few isolated facts and figures.

The practicing engineer frequently finds his reports appearing in unexpected places. Under many circumstances the date and place of test become almost as important as the signature of the writer.

TESTING MACHINES

Essential Features. It is not in any sense the purpose of this book to catalog all the testing machines which the reader is likely to meet, nor does it seem desirable to present a detailed description of any particular type. A few general principles, however, may be in order.

A testing machine is primarily a device for producing distortion in the specimen or part to be investigated. Certain machines go no further than this. Most machines, however, are also arranged to indicate and measure the resistance which the specimen offers to such distortion. The design of the machine then must properly provide:

First, an adequate means of holding the specimen;

Second, a means of producing, at a proper speed, a distortion of the kind desired;

Third, in most instances, a reliable device for measuring the resistance offered by the specimen.

A common type of universal testing machine of 100,000-lb. capacity is shown in Fig. 1*A*. The wing extensions are frequently omitted in cases where it is not desired to test full-sized beam specimens.

Methods of Gripping. The solution of the problem of holding the specimen will vary with the type of distortion desired. For tensile tests, machines are commonly furnished with wedge-shaped jaws fitting into a pocket of similar shape in the heads of the machine. (See Fig. 27.) When the capacity of the machine is not too great, the wedging action of these grips is sufficient to hold the test bar. With very high-capacity machines (1,000,000 lb. or more), the gripping is usually accomplished by means of hydraulic pressure. Many machines are furnished with special types of holders (see Figs. 8 and 28) requiring test pieces with ends threaded or shouldered as the case may be. Special conditions require individual solution. The problem of holding the specimen, fabricated part, device, or structure is one which often imposes a severe tax on the ingenuity of the investigator. It is

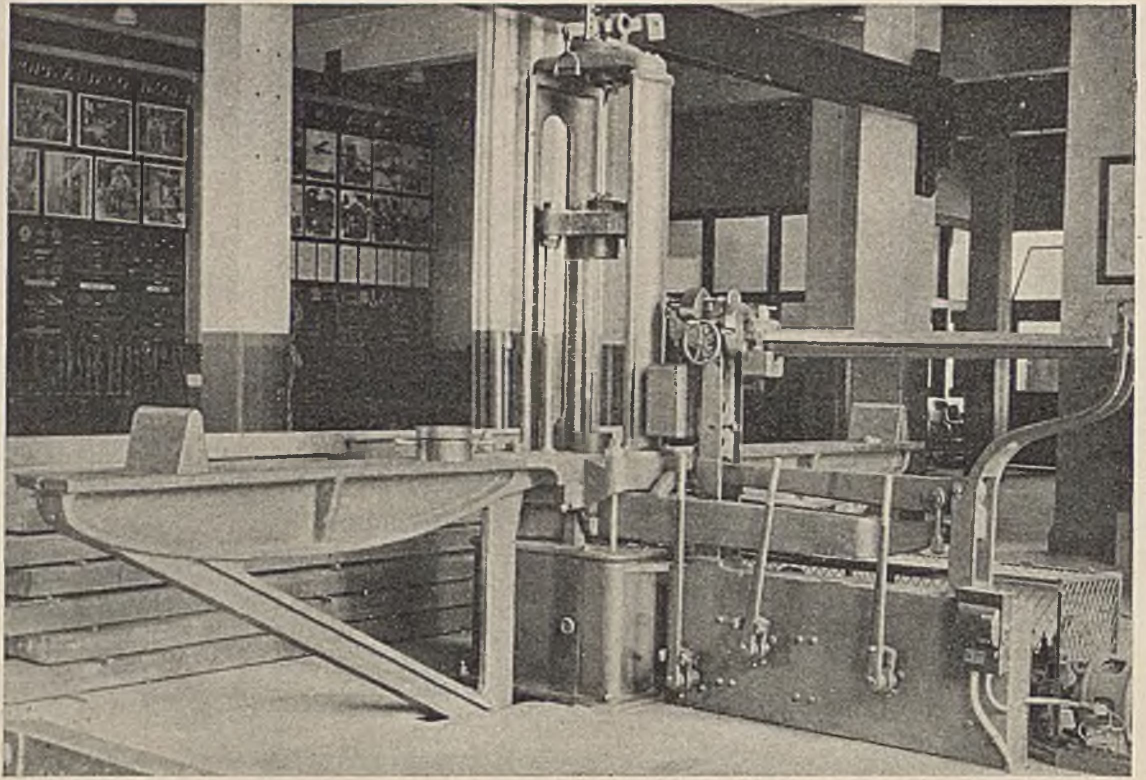
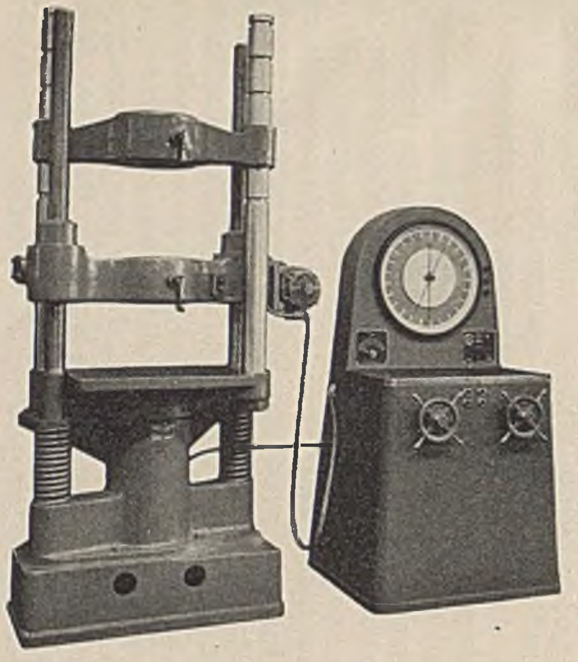
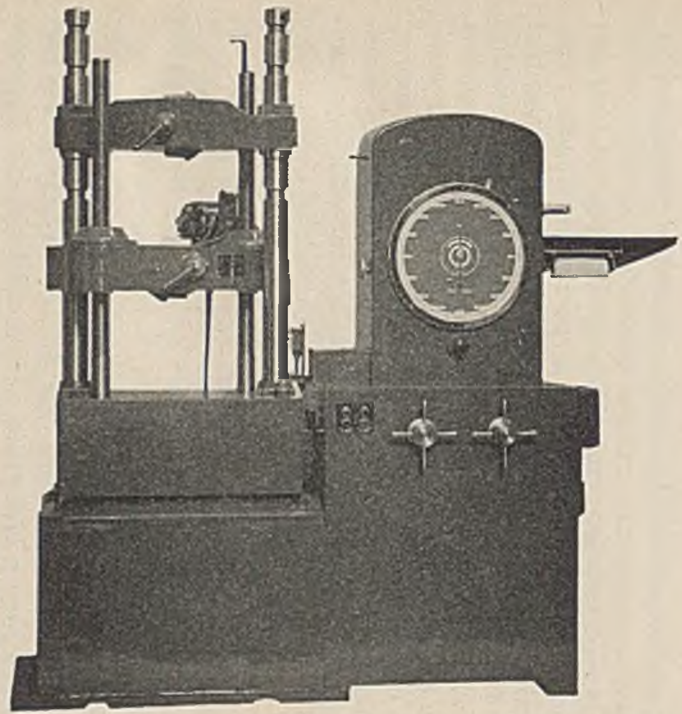


FIG. 1*A*. — Universal testing machine, 100,000 pounds capacity (Riehlé).



Courtesy of Baldwin Southwark

FIG. 1*B*. — Hydraulic testing machine. Hydraulic capsule type.



Courtesy of Tinius Olsen

FIG. 1*C*. — Hydraulic testing machine. Pendulum dynamometer type.

not unusual to perform the actual test in a few minutes when hours have been required in preparation.

Compression tests are commonly made between flat plates, at least one of which is designed with a spherical back mating with a similarly surfaced plate resting against the head or platen of the testing machine. (See Fig. 2*a*.) It is obvious that such a device will automatically adjust itself to slight lack of parallelism between the faces of the test piece. In order to be most effective, the top plane should contain the center of the spherical surface. When light loads are to be used and perfect freedom of the spherical head is desired, a hardened steel hemisphere resting on a hardened steel plate is admirable (Fig. 2*b*). Such hemispheres may be prepared from a high-grade commercial bearing ball without any great difficulty. Occasionally compression heads or plates are arranged to be used with a pin or roller bearing (Fig. 2*c*). This is particularly valuable in studying the action of columns where freedom is desired in but one plane, or in cases where load is to be imposed with definite eccentricity.

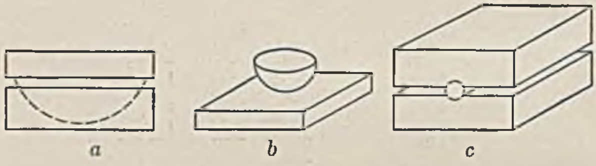


Fig. 2. — Compression blocks.

The holders for torsional tests are ordinarily some type of self-centering chuck, with roughened jaws arranged so that the frictional action of the torsion test piece will tend to increase their grip.

Bending tests made to simulate beam action necessitate some kind of knife-edge support capable of an arrangement for varying span. For the best results these knife edges should be capable of slight lateral motion, although this provision is not always made. This may be accomplished by mounting on rollers as in Fig. 3. If these supports are small they may be made from tool or alloy steel and heat-treated. Larger ones are usually cast and contain hardened steel plates as shown in the figure. In tests on wood or other soft material it is wise to insert small bearing plates between the test piece and the knife edges.

Occasionally machines are devised to produce composite distortions, such as combinations of tension and torsion, compression and torsion, bending combined with tension, compression or torsion, and so forth. Methods of holding under such conditions belong more properly among research problems and will not be discussed in the present volume.

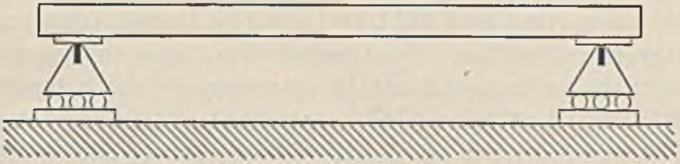


Fig. 3. — Knife-edge supports.

Methods of Deformation. During the distortion of the test piece, one head of the machine remains practically stationary. For tensile and compressive tests, the straining head is commonly moved by one of two methods.

In small or medium-capacity machines, the motion is often imparted by gearing with nut and screw mechanism. Machines are built with two, three, or four screws, and in some special low-capacity testers a single screw suffices to produce the travel of the moving head. Certain types of testing machines make use of rotating screws upon which the straining head rides. Such machines may be set on a solid floor or foundation block. Other machines are designed with rotating nuts in the frame, through which pass translating screws carrying the loading head integral with them. Obviously, this type of machine necessitates provision for the passage of the screws through the foundation if the total motion of the head is of any great magnitude. The motive power may be supplied to the machine by hand, by belting from line shafting, or by direct-connected motor. For general purpose work, where research is likely to be undertaken, it is very desirable to be able to operate the machine by hand even when other power is also available. Direct-connected motors should drive through an intermediate set of gears so arranged that the machine may be reversed without reversing the motor.

Higher-capacity machines, say 500,000 lb. or more, in general employ a nut and screw device for moving the straining head, solely for preliminary adjustment to accommodate the length of the test piece. The actual distortion of the test piece is produced by hydraulic pressure.

As ordinarily installed, gear-driven testing machines provide various speeds of the straining head, ranging within the limits 0.05 in. to 10.0 in. per minute. From four to eight different speeds will generally be available. The most common types of testing machine, such as shown in Fig. 1, are designed to operate so that the moving head will travel down for tension, compression, and transverse loading. For tension, then, the specimen will be between the moving head and the upper head, which is supported on the vertical columns. When operating to produce compression, the specimen will be placed between the straining head and the platen.

The number of separate speeds available with hydraulically motivated testing machines is practically without limit, since the feed of liquid to the pressure cylinder may be controlled by infinitesimal gradations. The maximum speed of the moving head in these machines is usually somewhat lower than for screw operation. With most machines of this type the platen and the upper head are connected and move upward under operation. The location of the test piece is the same as in the screw type.

Weighing the Resistance. As is evident from the previous statement, the resistance to distortion offered by the specimen will always produce a downward reaction on the platen of the machine, either by direct action for compression tests, or indirectly from the upper head through the columns when testing in tension. With machines of this general construction, the measurement of these resistances is a very simple matter. The platen rests on the knife edges of a lever system arranged in a manner very similar to that of the common commercial platform scale.

Before a test is begun, the counterpoise on the graduated scale beam should be set to register zero. With the specimen in place without strain, and all supplementary apparatus, which will produce dead weight on the machine, arranged as it will be during the test, the supplementary counterpoise (usually above and at the extreme left of the scale beam) should be adjusted to bring the beam to an accurate balance. A very small accumulation of oil or grease on the tip of the scale beam may cause it to stick slightly in its extreme positions. This may be troublesome in initial balancing and during the test. The remedy is obvious.

The application of a force to the platen is manifested by an uptilting of the graduated scale beam upon which rides the movable counterpoise. Some machines are arranged so that this counterpoise is moved automatically and in such a manner that the scale beam is held in floating balance. Considerable complication is introduced into the design in such cases. By far the greater number of testing machines rely upon manual operation of the balancing counterpoise.

The force involved, in hydraulic testing machines, is frequently weighed by means of some type of pressure gage. In the cheaper types, which are often designed for field use and are consequently of a portable character, the pressure is received in the gage directly from the pressure in the loading cylinder. In the higher-grade types the reaction from the stationary head is received by a supplementary " hydraulic capsule " from which a proportional part is transmitted to the recording gage. Commonly these gages are calibrated after installation in the machine with which they are actually to be used. By the attachment of differently scaled gages to one machine its flexibility is greatly increased. In this manner it is possible to operate a single machine under loads of a few thousand pounds or over a range of several hundred thousand pounds with errors of less than 1 per cent for either range. Certain types of hydraulic testing machines utilize the displacement of a pendulum as a means of registering the load reaction.

It should be noted and clearly understood that it is only when the scale beam is in floating balance that the position of the poise on the graduated scale has any significance whatsoever. The resistance offered by the test bar, or load on the specimen, is neither reduced nor increased by movement of the counterpoise. If increased distortion produce increased resistance, then the poise must be advanced to produce a balance. If, under certain conditions, an increase in distortion be accompanied by a diminution in resistance, then it becomes necessary to draw back the poise to maintain a balance of the scale beam. The operator does not " take off the load," as is often incorrectly stated; he merely so manipulates the poise that the beam will be held in balance, thus giving a record of the behavior of the material under investigation. In the use of machines furnished with hydrostatic pressure gages this confusion of ideas is much less likely to arise. When such diminution of resistance occurs it is due to some inherent peculiarity of the test piece and is wholly outside the sphere of control of the observer.

Absorbing Recoil. Testing machines are built ruggedly and are expected to perform severe service at times. They should, however, be treated with respect, and proper precautions are necessary to assure satisfactory results. Most of them have some special device for taking up the shock of recoil. The operator should make sure that he understands the action of this device and satisfy himself that it is in proper working condition before attempting to operate the machine. When rubber reaction buffers bear against the platen (as in many vertical testing machines made in this country) the first attention of the operator should be given to their adjustment. They should be ready to act but produce no appreciable pressure on the platen. If the test necessitates a load range running to more than one-quarter or one-third the total capacity of the machine, it is very desirable to follow down slightly on the buffers during the test. In such cases they must never actually be forced against the platen since this will produce some error in the scale reading. After the buffers have been so adjusted during a test, they should be released before performing any subsequent work.

In most of the modern types of hydraulically operated testing machines the recoil is automatically absorbed. Some designs provide for such absorption by means of springs; others employ some sort of hydraulic recoil cylinder. If the load is recorded by means of a Bourdon gage it is well to adjust the shutoff valve for this gage with the smallest opening which will provide satisfactory response to load changes. This protects the gage to some degree from the sudden change of pressure when the test specimen fractures.

Side Clearance. The clearance between the moving head of the machine and the supports of the fixed head should be such that motion of the head either up or down will produce no response on the part of the balanced scale beam. Should the scale beam show serious disturbance when moving the straining head, the accuracy of the observations may be in question. The elimination of such a condition will, in general, necessitate an overhaul of the entire machine by a competent mechanic, and sometimes the trouble is obviated only with the greatest difficulty. Machines in which this maladjustment persists should not be used for very important investigations.

TENSILE TESTS

Physical Properties. By far the great majority of commercial specifications, in so far as they are concerned with the physical properties of the material at hand, are based on tensile tests. Commonly, the properties considered in such tests are yield point, tensile strength (ultimate strength), per cent elongation, and sometimes per cent reduction in area at fracture. For complete understanding of the physical characteristics, there should be added to those already noted, elastic limit, modulus of elasticity, elastic and yield-point ratios, often cold bend tests, and possibly hardness in some cases. Hardness testing will be treated later, as a separate item.

Much confusion has existed, and to some extent persists, as to the exact meaning of the terms used above. The following definitions, published by the A.S.T.M., should tend to clear up this confusion.[1]

Elastic Limit. The greatest stress which a material is capable of developing without a permanent deformation remaining upon complete release of the stress.

NOTE: The true scientific conception of the term stress, at any point in a body, is the intensity of the mutual reaction between adjacent particles. Stress will then be expressed in terms of pounds per square inch or similar units of force intensity. Engineering practice often extends this conception to include the total reaction between the material lying on the opposite sides of a given plane, or, in some cases, even to forces acting externally to the body under consideration. In such instances, stress will be expressed as pounds or other units of force. In general the expressed units or the context will clearly indicate the sense in which the term is being used.

The determination of the elastic limit as thus defined would logically involve the application and release of a succession of increasing loads on a test specimen until there was observed deformation after release of a load. This procedure is very slow,

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[1] A.S.T.M. Designation E6–36.

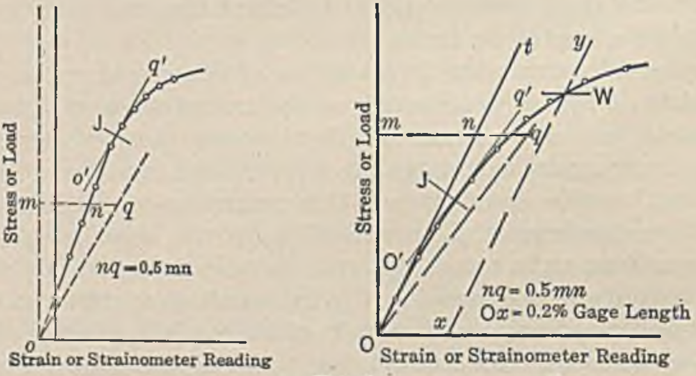
and, since experience does not indicate any appreciable difference between the elastic limit and the limit of proportionality of stress to strain (sometimes called the proportional limit), the determination of the stress at the limit of proportionality of stress to strain is regarded as a sufficiently accurate determination of the elastic limit.

It is obvious that the values obtained in tests for determining the elastic limit will depend on the delicacy of methods and instruments used. It becomes necessary, therefore, that in any test **the method used in obtaining the elastic limit be clearly stated.** The following methods are in common use for approximating a value designated as the elastic limit.

Proportional Limit. The greatest stress which a material is capable of developing without a deviation from the law of proportionality of stress to strain (Hooke's Law).

NOTE: When the elastic limit is approximated by the above method it is frequently designated as the " proportional elastic limit." Some engineers for the sake of brevity call this the " P-limit."

Apparent Elastic Limit. Defined by the late Professor J. B. Johnson as that stress at which the rate of deformation is 50 per cent greater than the initial rate of deformation. A stress-strain or load-deformation diagram is necessary for determining the elastic limit by this method. It is illustrated in Fig. 4*a*. The initial rate of deformation is given by the ratio $mn : Om$. $nq = 0.5\,mn$, $mq = 1.5\,mn$, and the slope of Oq represents a rate of deforma-



a FIG. 4. *b*

tion 50 per cent greater than the initial rate. *O′q′* is drawn parallel to *Oq* and tangent to the stress-strain diagram. The point of tangency, *J*, locates the apparent elastic limit.

It is obvious that this method for approximating the elastic limit will result in a value slightly higher than that indicated by the proportionality method. The difference between the two will be entirely dependent upon the rapidity with which the graph deviates from the initial straight line. The annealed low-carbon steels will show very slight variation between the results from the two methods: in general, higher-carbon, alloy, or steels which have been cold-worked will yield values markedly different.

A great many materials fail to produce a straight line when the load-deformation graph is plotted. Among these will be found most of the non-ferrous metals, some of the heat-treated steels, and castings, particularly those which have not been properly annealed. In such instances the attack just outlined is the only feasible means of approximating a stress which may be used in design in the same manner that the proportional limit is commonly employed.

The graph in Fig. 4*b* represents such a case. The initial tangent *Ot* is used to indicate the initial rate of deformation, and the construction is carried on as previously described. The same nomenclature is used in both graphs of Fig. 4.

Methods of High Precision. When it is desired to determine the elastic limit with a high degree of precision, it is suggested that the experimenter devise his own procedure, and in reporting his results describe the procedure in detail, including a statement of the limits of sensitiveness of the apparatus used and of the procedure followed in plotting the stress-strain diagram from which the determination of the elastic limit is made. It is to be remembered that the accurate determination of the elastic limit requires the use of accurate and sensitive instruments and of accurate methods of plotting test data.

Yield Point. The stress in a material at which there occurs a marked increase in strain without an increase in stress.

Two methods are in use for determining the yield point: (I) the " drop of the beam " method, and (II) the method in which dividers are used.

Method I. In Method I, load is applied to the specimen at a steady rate of increase, and the operator keeps the beam in balance by running out the poise at a steady rate. At the yield point the increase of load stops (and for some metals there is an actual falling off of load), but the operator, running out the poise at a steady rate, is more than likely to overbalance a trifle, and the beam of the machine drops for a brief but appreciable interval of time. In a machine fitted with a self-indicating load-measuring device, there is a sudden halt of the load-indicating pointer, corresponding to the drop of the beam. The load at the " halt " or the " drop " is recorded, and the corresponding stress is taken as the yield point. This method of determining the yield point requires only one man to conduct a test.

Method II. In Method II for determining the yield point, one observer keeps the beam of the testing machine balanced, and another observer, with a pair of dividers, watches for visible elongation between two gage marks on the specimen. When visible stretch is observed, the fact is at once reported to the man operating the beam of the testing machine, the load at that instant is noted, and the stress corresponding to the load is recorded as the yield point.

Yield Strength. The stress at which a material exhibits a specified limiting permanent set.[2]

Several methods are employed for approximating the yield point for materials which do not give definite results by either of the methods described above. This leads to confusion, and different observers may consequently report widely different values for the " yield " of the same material. In order to eliminate this unsatisfactory condition the term yield strength, as defined above, has come into use. The Westinghouse Research Laboratories have used the specified permanent set as 0.20 per cent of the gage length, and many other observers have followed their lead. When the yield strength is so determined the writers have been accustomed to designate it as the " Westinghouse yield point."

A convenient graphical construction for this determination is as follows. It should be noted that within the limits of ordinary laboratory accuracy the amount by which the load-deformation graph deviates from the original straight line (Fig. 4*a*), or from the initial tangent (Fig. 4*b*), is the permanent set or plastic deformation. Hence the line xy drawn parallel with Ot, Fig. 4*b*,

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[2] A.S.T.M. Designations E6–36 and E8–40T.

and so located that

$$Ox = 0.2 \text{ per cent of the gage length}$$

will mark the load W at which the specified permanent set has appeared. A similar construction may be applied to cases represented by the graph, Fig. 4*a*.

Tensile Strength. The maximum tensile stress which a material is capable of withstanding.

NOTE: The engineer commonly considers this stress as the maximum load recorded by the testing machine divided by the original cross-sectional area of the test piece.

Stress-Strain Diagram. A diagram plotted with values of stress as ordinates and values of strain as abscissas.

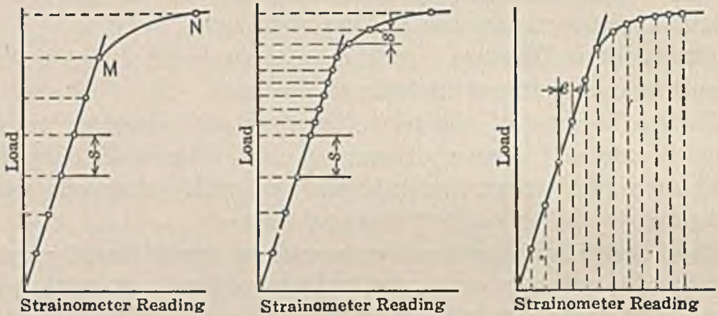
NOTE: The use of the term "stress-strain diagram" is frequently extended to cover diagrams plotted with values of applied load, or applied torque, as ordinates and with values of stretch, compression, deflection, or twist as abscissas.

Load-elongation diagrams are sometimes drawn directly by an autographic attachment to the testing machine. A more usual method of procedure consists in taking a series of load readings (from the balanced scale beam of the testing machine) with corresponding readings of the strain-indicating apparatus. The term "strainometer reading" will be used to denote the reading of the strain-measuring instrument. From these readings, or from values computed from them, there is plotted a diagram with stress-indicating values (load or stress) as ordinates, and strain-indicating values (elongation or strain) as abscissas. In planning such a test it is necessary to decide on the increment of load or the increment of reading of strainometer to be used between successive readings.

In Fig. 5 are shown three typical load-elongation diagrams. The material for all three tests is the same, and the test specimens are all of the same size, so that the diagrams should be the same.

The custom of choosing increments of load rather than increments of strainometer reading is quite common in tests of materials and is followed because, in general, it is easier to compute increments of load than it is to compute increments of strainometer reading. An estimate of the load necessary to stress the specimen up to the knee of the curve is made, and some fraction (frequently one-tenth) of this value is taken as an increment. The computation of the corresponding increment of strainometer reading is more complicated.

The diagram shown in Fig. 5*a* is plotted from points determined by taking uniform increments of load (s). In this diagram it is seen that, owing to the shape of the curve, data for locating points between M and N are lacking. That particular portion of the curve (the " knee " of the curve) is the part for which it is especially desirable to locate several points on the diagram.



(*a*) With Equal Increments of Stress (*b*) With Two Values of Increments of Stress (*c*) With Equal Increments of Strain

Fig. 5.

Sometimes the practice is followed of applying a few increments of load as determined above, and then applying load in much smaller increments (s') until the knee of the curve is passed. Fig. 5*b* shows a diagram obtained in this manner. This method involves a marked increase in the number of readings necessary for a test and, with unknown material, there is always some danger that the knee of the curve will be reached before the use of small increments of load is begun.

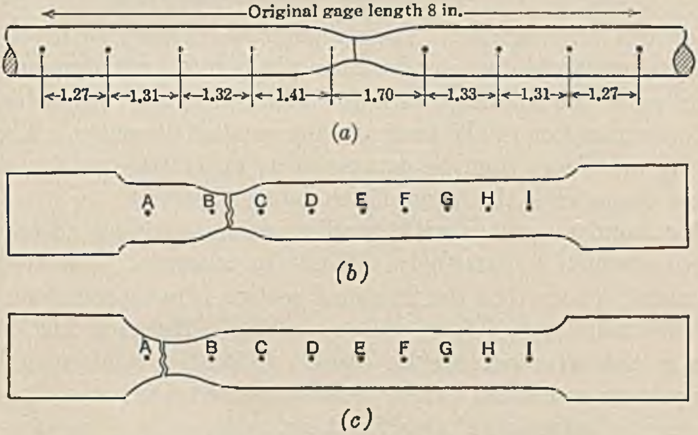
In Fig. 5*c* is shown a diagram plotted from points determined by taking increments of strainometer reading (e). It will be noted that for this diagram there are located several points near the knee of the curve, and the shape of the diagram in this important region is much more definitely determined than for the curve shown in Fig. 5*a*.

Elongation. In most instances, the elongation after fracture may be obtained with sufficient accuracy by matching together the parts of the broken specimen. These must be pressed firmly together, and for this purpose a vise is most convenient. The distance between gage marks may then be measured with dividers to the nearest 0.01 in.

$$\frac{\text{Final length} - \text{Original length}}{\text{Original length}} \times 100 = \text{Per cent elongation}$$

In reporting this value, the original gage length must always be noted in order that the results may receive the proper interpretation.

Some materials, such as a few brasses and bronzes in the cast condition, show appreciably the same degree of elongation in each inch of gage length. Those metals which suffer considerable local reduction before fracture behave very differently. The variation in the deformation along the test bar is clearly shown in Fig. 6*a*. It will be noted that the deformation per inch near the point of rupture is far greater than in other portions of the specimen. In the case cited, the per cent elongation is 36.5 if taken over the entire 8-in. gage length and 55.5 if considered in the original 2 in. containing the point of fracture.



(*a*)

(*b*)

(*c*)

Fig. 6. — Irregular elongation in ductile metal.

In general, the per cent elongation should not be reported if the fracture occurs outside the middle third of the gage length. If for some particular reason it becomes necessary to report on specimens whose fractures are located outside this section, as shown in Fig. 6*b* and Fig. 6*c*, the following procedure may be followed.[3]

I. If the fracture is between A and C, but nearer B than A, the " final length " is considered to be AC plus twice CF.

II. If the fracture is nearer A than B the " final length " is reported as twice AE.

With brittle materials or under other conditions where there is very little local reduction in area at fracture, this consideration may have less significance.

Reduction of Area. If the original specimen is of circular cross-section, it is generally possible to obtain a fair estimate of the area of the narrowest section after fracture. This is commonly determined with thin pointed calipers and read from a steel scale to the nearest 0.01 in. If the material be tested as rolled or cast, without machining, this precision is as great as the conditions will warrant. The diameter at fracture for machined specimens may be measured with a pin-pointed micrometer. In some cases the necking down is slightly irregular, necessitating the determination of the least and the greatest diameter. The resulting area may then be computed as an ellipse or as a circle whose diameter is the mean of the values observed.

Rectangular sections with ductile material produce an area at fracture which is extremely difficult to measure. The flow of the metal is such that the fractured section is not a rectangle but a figure made up of four concave curves. Hence reduction of area is not reported in such cases. Deformed reinforcing bars also present somewhat similar difficulties, and it is not customary to report contraction of area for them.

$$\frac{\text{Original area} - \text{Area at fracture}}{\text{Original area}} \times 100 = \text{Per cent reduction in area}$$

Modulus of Elasticity. Modulus of elasticity is defined as ratio of stress to strain or

$$E = \frac{P \times L}{A \times a}$$

where P = distorting force
L = gage length
A = original area
a = deformation in the gage length.

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[3] A.S.T.M. Designations E8–36 and E8–40T.

If the results of the test be recorded in the form of a stress-strain diagram, then E is the slope of the graph within the elastic range (that is, $E = \tan \alpha$), Fig. 7*a*.

In the strictest conception, this relation should be considered only within the range where it is appreciably constant for materials which may be considered truly elastic. It is customary, however, to extend the application of this idea to materials whose elastic range is extremely limited if it exists at all. Under such circumstances, the ratio of stress to strain must be considered as somewhat of an instantaneous property, whose value changes with the stress in an inverse sense. For example, in the graph (Fig. 7*b*) showing a stress-strain curve for hard-drawn copper, at a very low load, $E = \frac{\Delta f}{\Delta e}$. This value is commonly called the "initial tangent modulus." Other tangent moduli may be determined from the slope of the curve at any designated load such as that where $E = \frac{\Delta f'}{\Delta e'}$. Johnson's method might be used to determine an apparent elastic limit. Under such circumstances, a fair average for E in this range may then be taken as the slope of the line joining the origin with the point on the curve located by the method just mentioned. The value of E thus obtained is designated as the "secant modulus." A value of E known as the

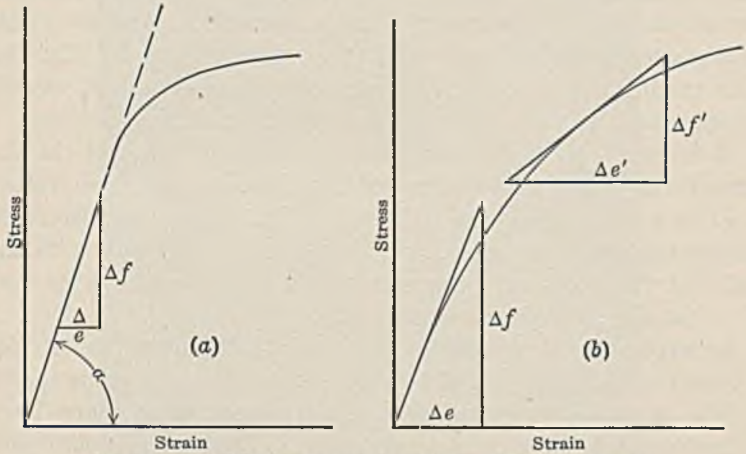

FIG. 7. — (*a*) Machinery steel. (*b*) Hard-drawn copper.

" chord modulus " may be obtained from the slope of a chord drawn between any two desired points on the graph where neither point is at the origin.

It will be noted that the initial tangent modulus is the largest of all these various results. Since the deviation of this type of graph from the initial tangent is, for most metals, due to the plastic action superposed upon the elastic deformation, it is reasonable to consider the initial tangent modulus as the indicator of the true elastic stress-strain relation. Although the curve, Fig. 7*b*, represents the behavior of copper, it is also typical of a large number of the non-ferrous metals. These are all more or less affected by cold-working. Under repeated loading the whole graph approaches closer to the type curve shown by Fig. 7*a*. This modification of form causes all the above-described moduli to approach the value of the initial tangent modulus as a limit.

It is commonly easier and just as satisfactory to plot the observed data directly in the form of a load-elongation graph, rather than as a true stress-strain diagram. The previously described attack may still be carried out if due attention is given to the units of the plot and proper transformations made to express $E = \tan \alpha$ in pounds per square inch.

Arrangement of Apparatus. A very satisfactory set-up for a tensile test making use of two 8-in. Berry strain gages is shown in Fig. 8. The gages are constrained to the same plane by a yoke which is bent to clear the specimen. During the preliminary adjustment it may be found advisable to clamp the instruments firmly to the yoke. The clamping screws must, however, be slightly loose during the test. A pair of heavy rubber bands, one at each end, in line with or slightly inside the gage points, serves to hold the gages firmly against the test piece. As shown, the gage points rest in light center punch marks, affording sufficient accuracy for ordinary work. The use of holes drilled with a No. 53 drill is to be preferred when feasible. For the best conditions, steel clamps such as appear in the apparatus shown in Fig. 51 may be interposed between the gage points and the test piece. The application of two gages as here suggested, making use of the mean values recorded, tends to eliminate many irregularities, such as slight local imperfections in the specimen, slight curvature due to heat-treating strains, small discrepancies in the alignment of heads, and so forth. When conditions are ideal, or somewhat less refinement is needed, a single gage may be clamped to the specimen instead of the pair as has been described. The makers of the instruments furnish a special clamp for this purpose. When drilled holes are used, perfectly satisfactory readings may be made with instruments held by hand against the test piece.

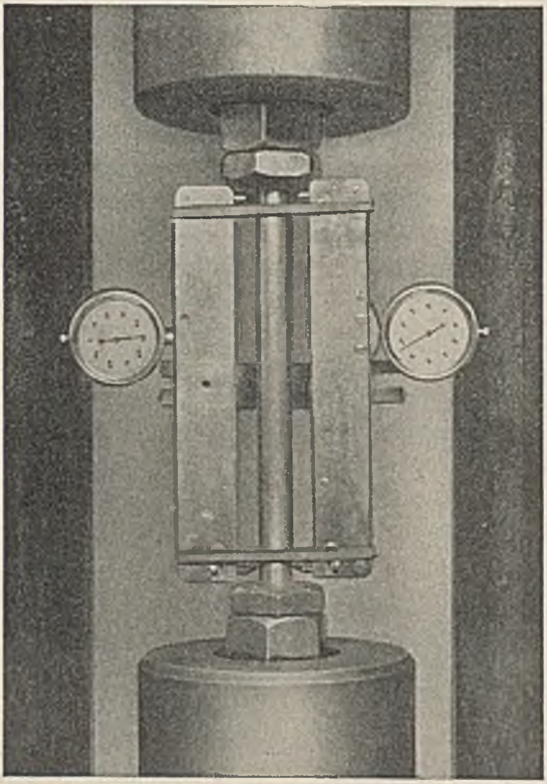

FIG. 8. — Application of Berry strain gages to tensile test specimen.

The gages are reasonably rugged but should nevertheless be safeguarded as much as possible. Ductile materials give sufficient warning, so that the gages may be removed before rupture of the test piece. With brittle or unknown material, every precaution should be taken to prevent injury to the instruments due to unexpected failure.

With proper clamping collars, the rod and micrometer arrangement, as shown in the compression bar (Fig. 52), may be adapted for tensile testing. Such adaptation is very likely to be somewhat cumbersome, however, unless great care is exercised in the design. For wire testing, the writers have found the arrangement indicated by Fig. 47 to work very satisfactorily.

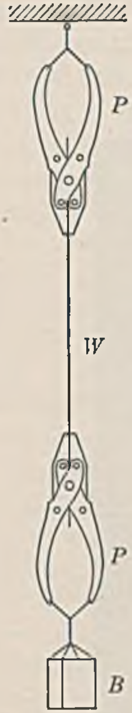

Fig. 9. — Device for testing small wire.

Special Methods. From time to time, the writers have been called upon to make tensile tests involving loads absurdly small in comparison with the capacity of any available testing machine. As a specific instance may be mentioned the testing of copper wire of the size used in winding telephone magnets, where the breaking strength was a matter of ounces rather than pounds. The solution of such a problem is suggested diagrammatically in Fig. 9. *PP* are very light parallel jaw pliers. The handles are drilled and furnished with a loop of flexible wire or strong cord, such as fish line. The upper pair may be supported in any convenient manner. The lower pair supports a paper bucket, *B*. The wire to be tested is shown at *W*. Fine bird shot may be slowly poured into the bucket until the test piece is ruptured. The total weight of bucket, shot, and lower pliers may then be determined and registered as the maximum load on the specimen. Paper markers may be gummed to the test piece to afford a means of noting elongation if it is desired.

GRAPHS

Their Interpretations and Limitations

Salient Features. Many of the inherent peculiarities of the metallic alloys are strikingly presented by their stress-strain or load-elongation diagrams. The student is strongly urged to make careful study of these at every opportunity and learn to sense from them the physical characteristics of the metal that has yielded data for their construction. A somewhat idealized though strictly typical set of such curves is shown by the full lines in Fig. 10, which clearly illustrate the behavior of **simple carbon steels in the annealed condition.** In the analysis of such graphs, the items to be noted are:

1. Maximum ordinate (indicating ultimate strength).
2. Ordinate at yield (indicating yield-point stress).
3. Definition or obscurity of the yield point.
4. Yield-point ratio ($A \div B$).
5. Maximum abscissa (indicating ultimate extension).
6. Droop of the curve after passing maximum (indicating reduction in area).

Even a casual glance at the curves of Fig. 10 will be sufficient to impress the reader with the fact that the metals yielding them are quite different in character.

Influence of Carbon Content. As the carbon content increases, the ultimate strength is greatly enhanced.[1] From a most definite yield point on Curve 1, there is a gradual transi-

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[1] For simple carbon steels in the annealed condition, the tensile strength may be estimated by the following formula:

$$\text{T.S.} = 40{,}000 + 1000\,C + 1000\,P + xMn$$

where C is the carbon point of the steel (a point of carbon equals 0.01 of 1 per cent)

P is the phosphorus content

Mn the manganese content

x is a variable depending upon the manganese and carbon contents.

For a conservative estimate, the formula may be used

$$\text{T.S.} = 40{,}000 + 1000\,C$$

tion to a yield point so obscure, in Curve 4, that it may be anywhere within the range indicated. The yield-point ratio varies from about 0.6 for the low-carbon steels to perhaps 0.9 or more for those of high carbon content. The elongation obviously diminishes with the increase of carbon content. Graph 1 shows a very marked droop after the maximum, indicating great toughness as evidenced by a large contraction of area. The steel for Graph 4 shows practically no such droop, indicating that this metal gives no reduction in cross-sectional area and is hence somewhat brittle.

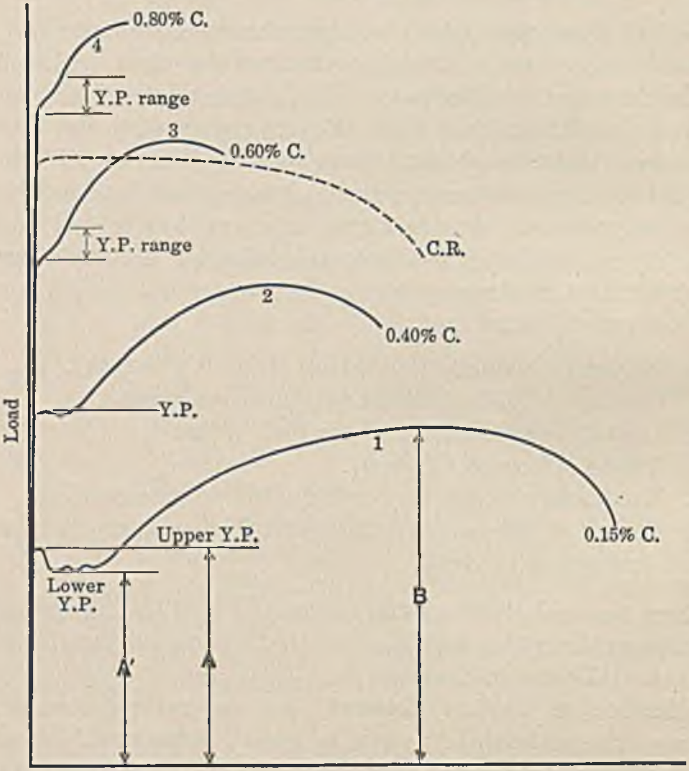

FIG. 10. — Typical graphs for annealed carbon steels.[2]

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[2] The curves of Fig. 10 are typical of the behavior of steels when purchased as "annealed." Careful and thorough annealing in small sections, such as test pieces, will result in more marked yield for the higher-carbon steels and perhaps more difference between the upper and lower yield point for the lower-carbon grades.

It is well to note that the graphs indicated are constructed to a scale which clearly shows plastic behavior only. **The use of such a scale absolutely prevents accurate presentation of any of the elastic phenomena.** Hence, that portion of the curve below the yield point in each case must be interpreted only in a broad sense. Considered in this manner, then, it appears that the earlier portions in each instance are coincident, suggesting that any slight variations in modulus of elasticity that may possibly exist are of a magnitude entirely too small to be indicated in graphs of this type.

After becoming familiar with the general trend of these graphs, the observer often is able to draw very pertinent conclusions from graphs which may differ from these types in certain particulars.

Influence of Overstrain. As a single example, it is not unusual for steel containing about 0.15 to 0.20 per cent of carbon to produce a graph such as that shown by the dotted line (C.R., Fig. 10). The observer who has become familiar with the type curves immediately recognizes the fact that the graph is in a sense abnormal. The chemical composition leads him to expect a graph of the general character of Curve 1. Instead, there is presented a curve whose yield point is very obscure and practically coincides with the maximum load. The highest point in the curve appears when very little extension has been produced; that is, the elongation up to the maximum load is very slight, most of the deformation occurring after the local reduction becomes quite apparent. These various considerations lead immediately to the conclusion that the material is either cold-rolled or cold-forged, or else that it has been taken from a member which has been overstrained in service.

Limitations of Autographic Curves. Graphs of the type just discussed, that is, those presenting the characteristics of the material in the plastic range, may be readily drawn with automatic devices. A ten-fold magnification of the deformation in a 2-in. gage length is ample for such purposes. When it is desired to study the behavior of the metal within the elastic range, such a magnification of the deformation is inadequate. The elastic deformation of the high-grade alloy steels with careful heat-treatment will seldom exceed 0.5 per cent. If a 2-in. gage length is used, this is equivalent to a total distortion of only 0.01 in. in the entire elastic range. Those steels in the annealed condition and the simple carbon steels will show smaller deformations in the elastic range, not because of difference in modulus of elasticity but because of the lower elastic limit. In order that a plot may be drawn to show the inherent characteristics over a range of this magnitude, it is evident that the deformation must be magnified several hundred-fold to present satisfactory graphical evidence. There are a small number of devices which produce, autographically, curves with such magnification and with accuracy sufficient to permit the study of the elastic properties of metals. These devices are extremely valuable in the study of the effect of repeated stress. Investigations of such a character are, however, somewhat beyond the scope of the work intended to be covered by this volume.

Study of Elastic Range. For the ordinary study of elastic behavior, it is most common to observe the deformation with some convenient type of extensometer which will record length variations to about 0.0001 in. Occasionally an accuracy somewhat greater than this may be employed without undue difficulty. The observed data are then plotted, and to them is fitted the best representative line. Many abuses are committed in the construction of these plots. The thoughtless often feel that the accuracy of the work is increased in direct ratio with the scale of the plot. A little consideration will show this to be utterly false. Nothing is gained by unduly exaggerating the possible instrumental, experimental, and personal errors of observation. With high-grade measuring instruments, the instrumental error will, in general, be a fraction of a ten-thousandth part of an inch. It is generally possible to plot the load-elongation graph so that the deformation may be magnified one-thousand-fold. That is, 1 in. = 0.001 in. will not unduly magnify the errors of observation. The selection of the graph paper and the accuracy of the plotting should receive as much attention as the choice of measuring instrument and the precision of its observation.

After the data have been transferred to the graph paper, the utmost skill and the best judgment of the investigator must be brought into play in drawing the line that will most truly represent the facts. Experimental errors generally displace the plotted points so that it is seldom possible to pass a perfectly smooth curve exactly through them all. The question often arises whether to use a straight line or a long-radius curve in the earlier stages of the loading. In many instances, the deviation of the points from a straight line seems to be no more than might be expected from experimental error, as is indicated in the two plots, *A* and *B*, Fig. 11. A careful scrutiny of these two plots, however, will show that in Graph *A* the deviation is more or less alternating in character up to point x, whereas in Graph *B* the deviation is all in one direction up to point y and all in the other sense beyond that point. The data for Graph *A* should then be represented as a straight line, and those for Graph *B* must be represented by a long-radius curve. In lining up data as in *A*, it is generally preferable to draw first that portion which is undoubtedly curved as shown. The straight-line portion may then be drawn. Sometimes a perfect tangency results; sometimes the straight line intersects the curve first drawn. The line produced by this method will generally more truly represent the data than when the straight line is first drawn and the curve grafted on to it.

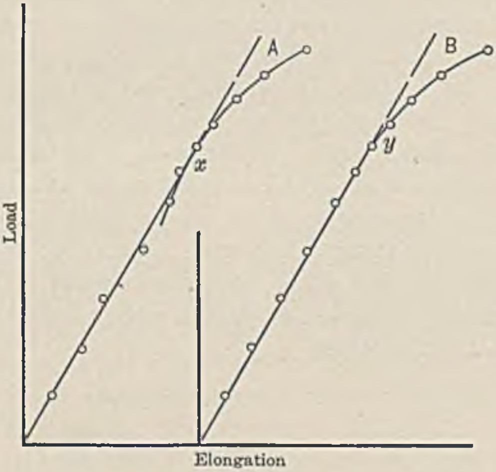

FIG. 11.

From the above discussion it should be apparent that the use of the graph to determine proportional limit is very liable to personal inaccuracy. The elastic limit so located can be no better than the plotting paper and the accuracy of plotting. At best, then, the elastic limit can be only a close approximation.

Graphs are often produced which seem to indicate the existence of an elastic range and a fairly definite elastic limit. The interpretation of all graphs should, however, be influenced by the investigator's knowledge of the material under observation.

Hooke's Law states that elastic bodies under stress react in such a manner that their stress-strain graphs are straight lines and experimental evidence justifies this statement. It is not permissible, however, to assume that a straight-line graph will, of necessity, be a guarantee that the material under consideration is perfectly elastic. It is conceivable that a material might undergo a permanent set which is directly proportional to the stress. As a matter of fact there are materials which closely approximate this behavior. In such instances the summation of elastic deformation and the permanent set will result in a straight-line graph. If it is definitely known that the material takes a set under continued load, or if the deformation has been observed to increase slowly under load, the material is evidently not perfectly elastic. If the material is not elastic, it is consequently improper to report for it a true elastic limit. Under such conditions, obviously, the deviation from a straight line must mean some phenomenon other than the appearance of an elastic limit. This deviation may mean various things; but most commonly, as in the case of wood, concrete, and other non-homogeneous materials, it is probable that the diminished slope is in reality due to local failures and redistribution of stress.

COMPRESSIVE TESTS

General Considerations. Compressive tests naturally divide themselves into two general classes: tests made primarily to determine the properties of the material itself; and tests made for the purpose of studying not only the material but also the effect of the process of manufacture and of the proportions used in the design, or the manner of loading.

Tests made to determine elastic limit, yield point, modulus of elasticity, and ultimate strength (when obtainable) fall into the first class. The definitions of these properties are similar to those noted under tensile methods of test. The difficulties attending compressive tests are generally more troublesome than for tensile tests of the same material. The cross-sectional dimensions of a specimen to be tested in tension may be, and usually are, comparatively small. It is seldom, in fact, that routine testing calls for more than one square inch, or at the most double that amount, as will be noted from the standardized test pieces described elsewhere. Evidently, then, comparatively small testing machines may be used for tensile tests. Moreover, the slenderness of the specimen is not a very serious matter, since the method of testing tends to maintain or even correct the alignment of the axis of the test piece.

Contrasted with this condition, compressive pieces of 1 sq. in. cross-section are, to say the least, a bit diminutive. The common test piece for stone (the 2-in. cube) presents 4 sq. in. to the bearing plate. Many timber tests have been made on specimens of the same size. While it is true that on special occasions specimens may be tested with cross-sections smaller than those suggested, such instances are comparatively few. Compression tests are more frequently conducted on specimens of such size that the common types of testing machines, of 100,000-lb. capacity or less, are wholly inadequate.

Another difficulty that presents itself is the question of slenderness. Instead of tending to rectify any lack of alignment as in tension testing, the compressive action tends to exaggerate it. Slight eccentricity in the line of application of the resultant force fosters incipient lateral deformation, which becomes accentuated as the test progresses. If the length of the specimen is much more than one and one-half times the least thickness (for round or rectangular sections) the failure will, in general, be accompanied by considerable bending if the material is malleable. Specimens from brittle material may be fabricated with somewhat greater ratio of length to thickness.

Preparation of Bearing Faces. Some materials, such as brick or concrete, generally present rough surfaces to the compression heads of the testing machine. These must be cushioned with some slightly yielding material. If the irregularities are not too great, blotting paper, inserted between the heads of the machine and the ends of the specimen, will suffice to prevent undue local pressure and premature failure. Greater irregularities require the interposition of sheet lead, soft pine boards free from knots, or other yielding material. For all-round work, a plaster of Paris facing is probably the most convenient and most effective.

Some authorities recommend that the specimen be grouted in the machine. When a vertical testing machine is used, a trowelful of thick plaster paste may be put on the lower head. On this the test cylinder, brick, or other similar specimen may be bedded. The top surface should be approximately leveled, in two directions at right angles to each other. The top should then be covered with a medium-thick layer of paste and the head of the machine brought down to make contact over the entire surface. A medium quick-setting plaster will generally permit the completion of the test in about half an hour for brick or concrete. This operation is somewhat more troublesome when the equipment available necessitates the use of a horizontal testing machine. It may, however, be accomplished by using a very thick paste. The quick-setting plaster under these conditions necessitates rapid work, and extreme neatness is not possible, to say the least.

A more rapid method consists in facing the specimens outside the machine. Thin oiled paper (the common waxed sandwich paper is highly satisfactory) may be spread on any convenient smooth surface. A grout, sufficient to receive the specimens, may be poured on the paper. Unless the surfaces are very irregular, a thin grout is better than a thick paste. The top surfaces should be set parallel with the facing slab; this may be easily done by leveling if the slab is level. After the first facing is set, the operation must be repeated for the opposite face. This method may result in a slight lack of parallelism between the faces. With reasonable care, this irregularity should not be in excess of that for which compensation may be readily made by the ball-seated compression head. If the machine is not so equipped, the specimen must be grouted in place.

Elastic Limit. The determination of elastic limit and modulus of elasticity is a somewhat difficult task in a compressive test. Accuracy requires a reasonably great gage length and comparatively small cross-section in order that the deformation measurements be made with even fair precision. The methods described under the discussion of tensile testing are equally applicable for determination of elastic limit under compressive test. A gage length of at least eight times the diameter is desirable, although tests are frequently made with a ratio of less than that value. With the proportions indicated, enlarged ends carefully squared with the axis are a great aid in maintaining the alignment of the test bar when testing metals in compression.

Yield Point. Yield point may be determined on very short specimens by noting the load at which the central diameter of the specimen shows appreciable increase. For this determination, ordinary spring calipers are sufficiently accurate if properly set and used. After a careful setting of the calipers for an extremely light touch, they should be slowly passed back and forth across the center diameter of the piece under test. The yielding of the metal is due to displacement of the constituent grains along the mutual grain boundaries, together with slippage of the component parts of the grains along newly developed cleavage (or slip) planes. This action will produce an appreciable change in diameter. When screw-driven machines are used, there may appear a drop of the beam as in tensile testing. Hydraulic machines do not give such sharp indication of the yield of the metal. In any case, the flow of the metal may be quickly and readily discovered by a competent observer using the spring calipers. The slightest appreciable tightening of the points in their passage across the specimen should be taken as the indication of the yield point.

The items corresponding to per cent elongation (per cent contraction) and per cent reduction of area (per cent enlargement) are never considered in compression tests.

Modulus of Elasticity. Modulus of elasticity determinations on short columns may be conveniently made with a type of apparatus using dial indicators, as shown diagrammatically in Fig. 12. This is particularly applicable to the study of wooden members. As will be noted, the apparatus is arranged in duplicate on opposite faces of the column. The upper bracket carries the indicator, *A*. The lower bracket supports the side rod, *R*. As shown, this rod is of light tubing. For long gage distances the central portion may be made of wood about $\frac{3}{4}$ in. by $\frac{3}{4}$ in. The ends of the rod are small metallic pins: the lower one is furnished with a ball gripped by a cup-pointed screw, *S*; the upper one is flat and touches the end of the indicator pin. The upper pin must pass freely through the guide, *G*. Variations in length are read directly from the dials, and the mean of each pair of readings is used.

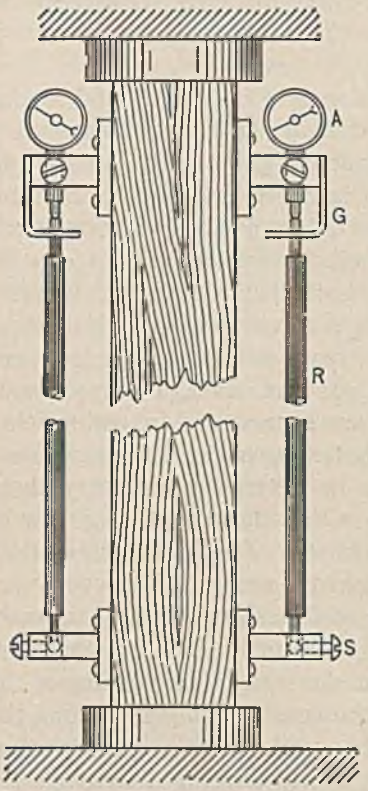

Fig. 12. — Modulus of elasticity apparatus applied to a wooden column.

When used with wooden members, the brackets may be easily fastened with screws. Concrete or masonry columns necessitate the use of special clamping devices. Variations in gage length are met by simple changes in the side rods. If the end pins are made to enter the tubes with an easy force fit, such changes may be quickly and easily made.

Stress Distribution. Under eccentric loading or with built-up or irregular sections, stress distribution study may be desirable. In such instances it will be necessary to attach short-gage strainometers at the critical sections. The data so obtained are easily converted into stress. Such apparatus will be discussed in the section dealing with measuring devices.

TORSIONAL TESTS

Pure Shear. A study of the shearing resistance is sometimes made by what might be termed direct methods. Special devices may be designed to hold the specimen and to produce distortion that will be a fair approximation of pure shear on some given plane. Severe local compressive strains coupled with a certain amount of bending are, however, always present. The results of such tests, then, can never be more than fair approximations.

Shear in Torsion. More commonly, the shearing properties, especially for metals, are studied by means of torsional tests. The calculations are based on assumptions and implied limitations quite similar to those which form the foundation for the common theory of beams. If the material under observation be not elastic or if the stresses induced pass beyond the elastic range of a material considered to be elastic, then the values deduced become approximate. The degree in which these values depart from the truth will be dependent upon the extent to which the conditions of the test depart from those laid down by the basic assumptions of the fundamental theory.

A torsion bar is commonly tested to determine shearing stress at elastic limit, apparent ultimate shearing strength, modulus of elasticity in shear (or modulus of rigidity), and the average number of twists per foot (or per inch) at fracture.

Elastic Limit. The principles laid down for elastic limit in tension are applicable in this case with certain obvious changes in the units. Permanent set determination is practically never used, as would be necessary if the true definition of elastic limit were adhered to strictly. A typical torque-distortion graph is shown in Fig. 13. The ordinate at the point of tangency approximates the torque that produced an elastic limit stress in the surface elements of the torsion bar. This stress may be calculated in accordance with the common torsion theory. As noted in Fig. 14, the stress is not uniform over the cross-section, and the variation is held to be uniform as long as no element is stressed beyond its elastic range. Suppose the solid lines of this figure to represent the stress distribution at the torque that produces the elastic limit stress (fs) in the outermost element. An increase in this torque will cause a variation in the stress distribution, the outer elements entering the range of plastic deformation, while the elastic limit stress appears progressively nearer the center. The stress distribution under such circumstances may then be represented by the dotted line of the figure, where the elastic limit is being imposed on the elements whose distance from the center is r_1. Such a gradual progress of the elastic limit stress tends to obscure the point of tangency in the torque-deformation curve, Fig. 13. Instead of a sharp knee, such as appears in the stress-strain diagram for tension, there is a much more gradual departure from the straight line. The same general reasoning will apply at the yield point. Here, however, the obscuring effect is so marked that there is ordinarily no evidence of yield point in torsion tests.

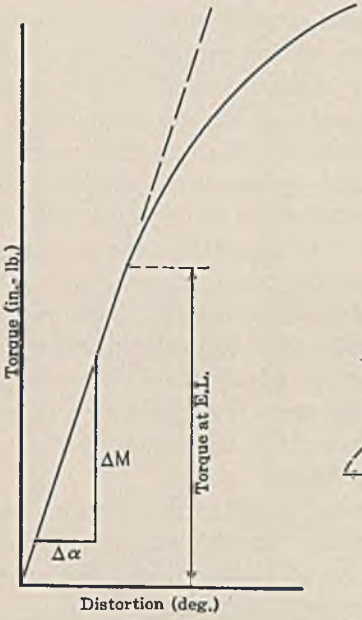

FIG. 13.

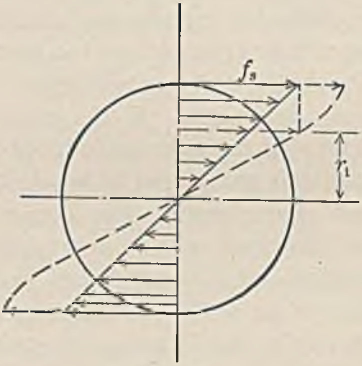

FIG. 14.

Apparent Maximum Fiber Stress. The maximum torque recorded by the testing machine is used as a basis for the calculation of the apparent outside fiber stress at fracture. This value is only an approximation, since the theory assumes that the stress distribution varies uniformly, which is untrue as soon as any element is stressed beyond the elastic range. The apparent value thus calculated is sometimes called the shearing modulus of rupture.

Modulus of Rigidity. The shearing modulus of elasticity is defined as the ratio of shearing stress to shearing strain. This quantity is commonly called the "modulus of rigidity" and results in the relation

$$G = \frac{ML}{Ii}$$

where G = shearing modulus of elasticity (modulus of rigidity)
L = gage length
I = polar moment of inertia of cross-section
i = angular distortion in radians.

This may be determined from the graph by using ΔM in place of M and reducing $\Delta\alpha$ to radians. Obviously, the greater the value used for ΔM the better the chances for accuracy. The values used, however, must be well within the elastic range of the test bar.

Toughness and Homogeneity. The number of complete twists of the specimen per foot of length may well serve as an estimate of the toughness of the material. The distribution of these twists gives some indication of the homogeneity of the material. Variations in hardness will tend to cause localization of the twists, there being less distortion at the points of greater hardness. Torsional tests on wire are usually made to determine only the number and the degree of regularity of the twists. Much may at times be learned from a careful observation of the surface of the torsion member. The presence of slag or incompletely welded gas holes may be clearly indicated by the opening of seams or the lifting of scales from the surface of the test piece while it is being twisted.

Arrangement of Apparatus. A proper arrangement for the study of material under torsion is shown diagrammatically by Fig. 15. The torsion bar is set up in a proper machine, which grips it at the ends so that a torque may be applied as suggested by the couple Mp in a plane perpendicular to the axis of the test piece. This torque is measured at the opposite end through a scale device which registers the balancing couple Ms. At sections, some convenient gage distance apart, such as L, are mounted two graduated sectors, S_1 and S_2. In practice the clamps for these sectors are designed in such a manner that they may be attached and removed while the torsion bar is gripped in the machine. Under the action of the opposed couples, both sectors will be displaced. The angle to be measured is the displacement of one sector relative to the other. A reference line, AB, is carried across the graduated edges of the sectors. This line must be sensibly parallel to the axis of the torsion bar. It must clear the sectors, but the distance between line and sectors must be as small as possible. To avoid parallax error, the observer should read when the line appears to bisect the diameter of the shaft. The thread or wire used as a reference line should be as fine as possible. The writers have found that raw, unwashed silk is highly satisfactory. It is sufficiently strong to support a small weight to hold it taut. When new, it is very smooth and free from projecting fibers and is about as fine as the line on the runner of a good slide rule. The supports for this thread should be carried in such a manner that slight movements of the sectors, which may appear during the test, will not affect the relative position of thread and sectors. The end nearest the power head may be supported from the fixed frame of the testing machine. The holder near the weighing head, M_s, should be supported by that part of the weighing mechanism which carries the jaws. With sectors 10 to 12 in. in radius, this method of observation permits readings whose errors will be not more than 0.02 degree in any case and are commonly less. The error will not be cumulative. Several types of torsion meters are

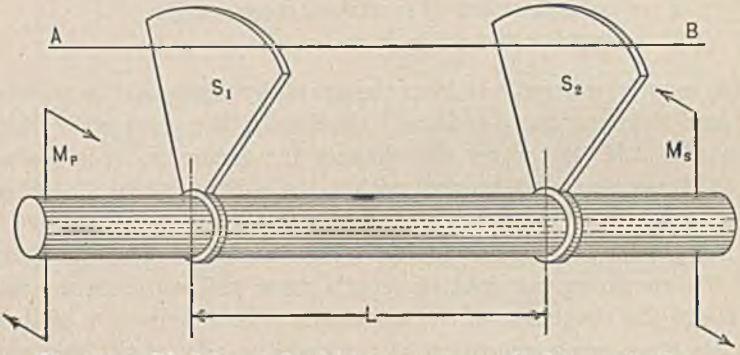

Fig. 15. — Modulus of elasticity apparatus applied to torsion bar.

on the market. Most of them are too complicated and some are too cumbersome for easy operation. A very simple modification of the method previously described consists of the two sectors, only one of which need be graduated. A light rigid arm is attached to the plain sector. This arm must be of such length that a fine pointer at its free end will pass over the graduations on the other sector. In this manner the relative displacements of one sector with respect to the other can be read directly. It is possible to mount a slide rule reading magnifier on this pointer to aid in estimation of fractional divisions. Obviously a given pointer will fit only a single gage length on the bar under investigation. It is generally simpler to provide a series of pointers for different gage lengths rather than to attempt to make a single one which shall be adjustable. If greater precision be desired, it is possible to mount transit telescopes on the torsion bar and compute the angular deformation from readings on a vertical scale at any convenient distance. Such refinement is not generally justifiable.

TRANSVERSE TESTS

Scope. The study of the behavior of material under transverse load is largely confined to timber, cast iron, brick, plastics, specially fabricated members, such as slabs, tile, reinforced beams, and so forth. The testing of timber is so decidedly specialized that a separate section will be given to its consideration.

Cast Iron. Cast iron is studied under transverse load largely because it is difficult to differentiate by any other means between very brittle iron and that possessing a certain degree of toughness.[1] Three different diameters of test bar, 0.875, 1.20, and 2.00 in., are employed, each being tested under concentrated center load on a specified span, 12, 18, and 24 in., respectively. The load shall be applied at such a rate that the fracture shall occur in not less than 15 seconds for the small bar, 20 seconds for the intermediate bar, and 40 seconds for the large bar. The present standard specifications do not contain a deflection requirement, but many engineers include it in their own specifications. It is the opinion of the writers that an observation of the maximum deflection before fracture yields certain information which is not furnished by the strength alone.

Brick. Transverse testing of brick is also a very specialized procedure carefully standardized by the A.S.T.M.[2] The span used is specified as 7 in. with a concentrated load applied at the center. The supporting and loading knife edges must be rounded and slightly curved in the direction of their length, instead of straight as is the usual form. The supporting knife edges must be so designed that they may rock slightly in a direction perpendicular to the span of the brick under test. There are various means of fulfilling these conditions.

Special Methods. The transverse testing of fabricated pieces, such as roof tile, asbestos slabs, wall board, and the like, presents a somewhat peculiar problem. Usually it is not a question of discovering a machine of sufficiently large capacity but one of

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[1] A.S.T.M. Designation A48–41.

[2] A.S.T.M. Designations C62–41T, C67–41, C73–39.

sufficiently large dimensions with the desired degree of sensitiveness. The difficulty may often be overcome by a method suggested in Fig. 16 in which *S* represents a platform scale of proper capacity resting on the platen, *P*, of the testing machine. One end of the fragile test piece rests on the knife edge *A*, supported by the scale. The other end is supported by the knife edge *B*, blocked up from the platen sufficiently to make the test piece level. The straining head of the machine presses against the loading knife edge *L*. Here the testing machine proper is used purely and simply as a device for the production of distortion. The load is weighed by means of the end reaction (half the total center load for central loading) as registered by the platform scale. The writers have made use of such a device in connection with a 400,000-lb. capacity machine when the necessary load was as low as a very few hundred pounds. Innumerable modifications and adaptations of this scheme will doubtless be evident to the reader.

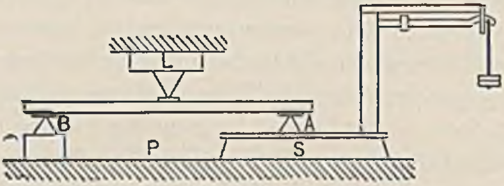

Fig. 16. — Use of auxiliary scale.

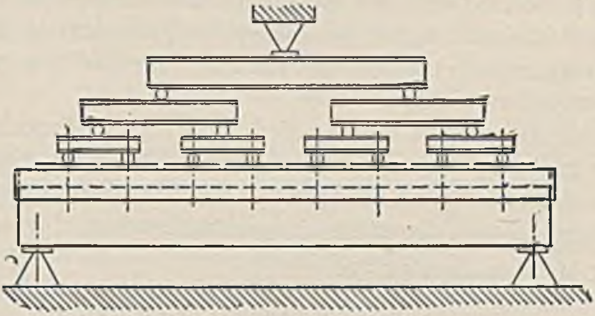

Fig. 17. — Transverse testing distributed load.

Distributed Loading. Sometimes it becomes desirable to arrange for transverse testing under distributed loading. One solution for this problem is suggested in Fig. 17, where a beam is shown bearing a load that closely approximates uniform distribution. Around the beam is loosely fitted a shallow wooden frame filled with sand. If the beam is too irregular, canvas may be necessary to prevent sand leakage between the beam and the frame. Steel plates (8 in the set-up shown) rest on the sand cushion. The system of I-beams resting on rounds and squares, as clearly shown, serves to build up to the single load applied at the top by the testing machine.

Load with varying distribution may be imposed by properly spacing the several bearing blocks.

Cold Bend Tests. The service required of certain materials necessitates qualities which are best studied by bending to a degree not commonly produced in transverse tests as ordinarily understood. Such tests are performed by bending the specimen about a pin of specified diameter. The size of the pin varies with the kind of material and the dimensions of the test piece, which, for round and flat bar stock, is generally used full size as rolled. Test pieces from steel castings, and some forgings, are machined to give a section 1 in. by $\frac{1}{2}$ in. with corners rounded to a radius of not more than $\frac{1}{16}$ in. Rivet stock is required to bend flat upon itself. In most instances bending tests of this character may be performed either by steady pressure or by blows. The steady pressure produced by the special types of bending machines certainly affords more uniform conditions of test, and the results thus obtained should be more reliable. Occasionally these bending tests are performed with hot specimens, as under certain wrought-iron specifications. Again, some specifications, such as those for boiler rivets, require that the test piece be quenched in water from a red heat before bending.

The nicked-bend test is also called for in some instances. Such a test is made by nicking the test piece with a cold-chisel[3] to a prescribed degree, and bending away from the nick. Such tests are discussed more fully under the general heading of fractures.

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[3] A.S.T.M. Designation A41–36.

DYNAMIC TESTS

General Classes. For a long time it has been clearly understood that slowly applied or quiescent loading does not present complete evidence of the true character of many materials. Numerous attempts have been made, and much research carried on, in the attempt to find some basis for prediction of the behavior of materials under the severe conditions of actual service. These have all aimed at the application of controlled dynamic stress. Such tests may readily be divided into general classes, as follows:

First, a test that will produce fracture of a prescribed specimen by means of a single impulse;

Second, the destruction of the specimen by a series of impulses or shocks;

Third, the final failure under the action of repeated and sometimes reversed stresses, which are of a vibratory nature and are not true impulses or impacts.

The determination of the actual stresses produced is almost never attempted in cases one and two. For each type of test and for each individual kind of machine, a special test piece is designed. The greatest care is used in making the test pieces exact duplicates one of another. Then the energy absorbed in producing fracture is directly or indirectly used as a measure of the excellence of the material represented by the specimen.

Fig. 18. — Izod test.

Single-Impact Machines. This group has been fairly completely developed and certain of these machines are well known and in general use. The principal types are as follows: **swinging pendulum** — Charpy, Izod, Amsler; **falling tup** — Amsler, Fremont; **rotating tup** — Guillery. These machines are obtainable in various sizes and having an available striking energy from a few hundred to as many thousand foot-pounds. They are designed so that there is less variation in the striking velocity. In all the standard makes this velocity is between 12 and 30 ft. per second.

Izod Test.[1] The Izod machine clamps a notched bar in heavy jaws so that the center of the notch is level with the top of the clamp faces as suggested by Fig. 18. A swinging pendulum strikes the projecting end and produces rupture under cantilever action. In this type the energy possessed by the pendulum after the fracture is recorded by the machine, and a simple subtraction gives the energy absorbed by the specimen. This type also is so designed that the striking velocity can be varied. In certain research work this is an important item.

Charpy Test.[1] The Charpy machine is designed to break the specimen under either tensile or transverse impact. The exact dimensions of the test piece depend upon the capacity of the machine used. The general form, however, is shown by Fig. 19. The grooved tensile specimen, *A*, is threaded at the ends. One end fits a threaded hole in the swinging pendulum; the other carries a stop block. As the pendulum reaches the bottom of the swing, the stop block is engaged and brought to rest. The energy of the pendulum is sufficient to rupture the specimen. The energy absorbed may readily be calculated by noting the difference between free swing and the swing after rupture of the specimen. In some instances a specimen may be used without notch. In the transverse test the specimen, *B*, rests in a pocket whose edges are represented by *SS*. The blow of the pendulum falls as shown at *P* and in line with the center of the notch. Great care should be exercised in adjusting the specimen so that this alignment may be as nearly perfect as possible. The energy calculation is made as suggested for the tensile specimen. The shape of the notch naturally influences the total energy absorption, because upon it depends the extent of the volume strained by the blow. It is difficult to harmonize the results obtained by different investigators, owing to the lack of true standardization in this matter. With any given notch, however, the results may be considered comparable, which suffices since the machine is commonly used to study the relative excellence of materials or treatments.

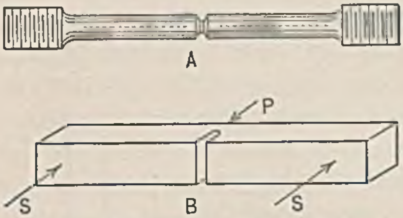

Fig. 19. — Charpy test pieces.

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[1] A.S.T.M. Designation E23–41T.

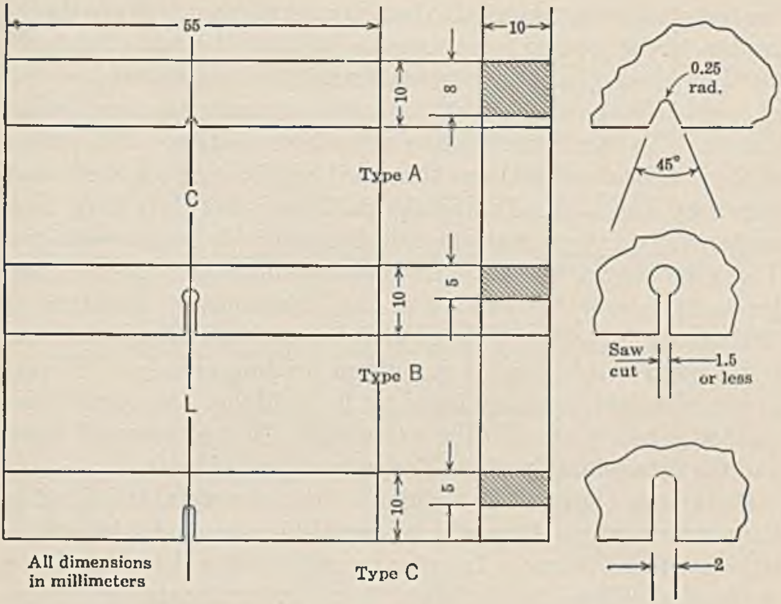

Fig. 20. Charpy specimens.

Repeated Stress. Tests of this kind are somewhat troublesome to make, require considerable time, and are influenced by numerous factors some of which are difficult of control. The shape of the specimen is vital, and surface imperfections are so highly important that the test frequently becomes a test of the skill of the mechanic who has fabricated the specimen rather than a test of the material under investigation. The effect of applications of stress repetition of a cyclic nature without impact have been studied for direct tension and compression; for torsion; for tension and compression by bending; and for a few types of combined stress. The cyclic stress produced by bending has, for the most part, proved the most satisfactory up to the present time. Two such methods of test are shown diagrammatically by Fig. 21. In both of these types

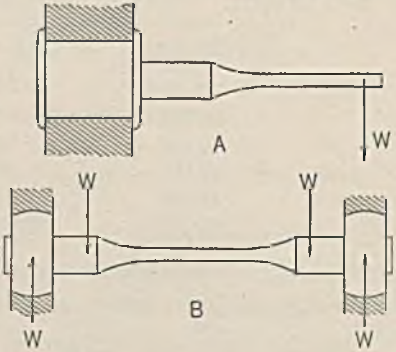

Fig. 21. — Rotating beam method for repeated stress tests.

the test member is subjected to bending as indicated. While the direction of the loading force remains constant the test piece is rotated, producing in every element (except the neutral axis) a cycle of stress passing from maximum tension to maximum compression and back to maximum tension at each revolution. The earlier of these to be developed was that used by Wöhler about 1870 and shown by Fig. 21*A*. During the past few years tests have been made with this type machine utilizing relatively large specimens. The type shown by Fig. 21*B* was first developed by the late Professor Jerome Sondericker at the Massachusetts Institute of Technology in 1892. This method has the advantage that the test section is subjected to a uniform bending moment. Today, in a modernized form developed by R. R. Moore, the Sondericker method is widely used for the study of the effect of repeated stress and the determination of the *Endurance Limit* of metals.

Endurance Limit. The endurance limit of a metal is defined as the stress to which it may be subjected indefinitely by load repetitions without failure. In order to make such a determination a series of specimens is fabricated from identical material. These specimens are tested by subjecting each to some determined stress, as indicated in the preceding paragraph, until failure is produced. It is usual to begin the series by stressing the first specimen to a value somewhat above the elastic limit as determined by the static test and continuing to fracture. A second is then carried through at a lower stress, which is still further reduced for a third, and so on. When a stress is reached which may be repeated 10,000,000 or more times without rupture it is generally held that such stress is near or slightly below the endurance limit.

S-N Graphs. The results of such a series of tests[2] appear below.

STRESS lb. per sq. in.	CYCLES to fracture	REMARKS
50,100	7,100	Broken
45,100	41,500	"
40,100	199,600	"
35,100	1,979,500	"
33,000	10,000,000	Not broken

From such a set of data the endurance limit can be determined and the whole condition best visualized by means of a S-N plot as shown

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[2] Data from tests made by Professor W. M. Murray in the research laboratories of M.I.T., 1940.

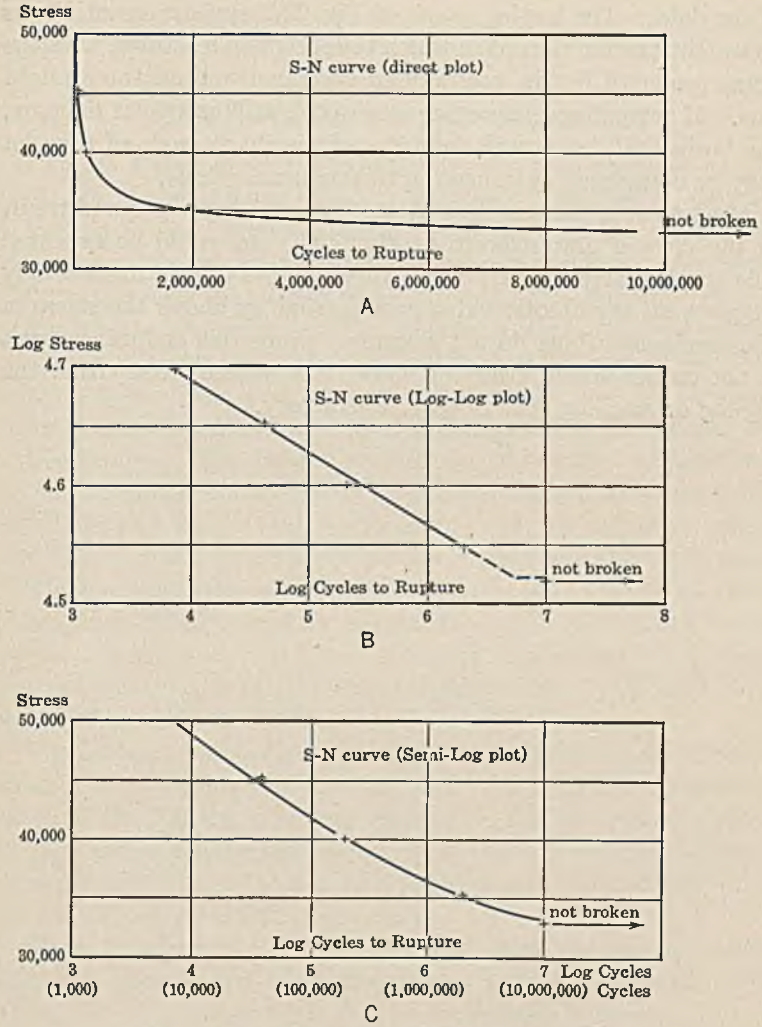

Fig. 22. — S–N graphs (repeated stress test).

by the graphs of Fig. 22. Three methods of plotting may be utilized as shown.

If the data be plotted directly as in Fig. 22*A* certain difficulties are obvious because of the great range of abscissa values (7,000 to 10,000,000 in the case under consideration). The curve thus plotted is strongly suggestive of the rectangular hyperbola. Such resemblance immediately suggests plotting the logarithmic values of the data. The log-log graph of Fig. 22*B* appears essentially as a straight line for all runs in which the specimen fractures, with the point produced by the unfractured specimen well off the straight line. If several specimens are run to ten million cycles or more, the horizontal line is well defined and the sharp angle of the plot may be considered as indicating the endurance limit.

Most tests of this kind are plotted on semi-log paper and result in the type of graph shown in Fig. 22*C*. As would be expected this graph is slightly curved but for the cases of fracture strongly suggests an asymptotic value near or slightly above the stress in the specimens which do not fracture. Since this endurance limit is not an absolutely clear-cut value, it is evident that either the log-log or semi-log plot is very satisfactory.

TEST SPECIMENS AND HOLDERS

Choice of Specimen. Theoretically, the test specimen represents the material from which it is taken. Practically, this assumption is too seldom fulfilled. It is particularly difficult to obtain test pieces that truly represent castings of any kind. Fabricated parts that are to be heat-treated also present very real difficulties to the engineer who wishes to assure himself of the quality and condition of the finished product through a vicarious test on a specimen, even though the specimen may be obtained from a coupon carried with the original forging throughout its entire history. The various precautions to be taken to procure a proper specimen under the conditions just noted are beyond the scope of this book, but the reader should not overlook their reality and importance, in the interpretation of data resulting from tests.

The specimen chosen may be tested in the condition in which it has been rolled, forged, or cast, or it may be machined to some predetermined and, if possible, standard dimensions. The exact type of specimen is often fixed by specifications. The A.S.T.M. makes the following recommendations.[1]

Tension test specimens of wire are of the full-size diameter as drawn, and tension test specimens of rods of ductile metal are often of the full-size diameter as rolled. Tension test specimens of pipe and of tubing are frequently of full size as manufactured, in which case the ends should be plugged with metal plugs which do not extend within the gage marks.

Plate Specimens. The tension test specimen shown in Fig. 23*a* is recommended for plate, shape, and flat material. The thickness of the specimen is that of the material tested.

NOTE: When it is desired to use a specimen with a gage length of less than 8 in., the general proportions of Fig. 23*a* should be followed. Specimens with a gage length of 2 in. are occasionally used. When it is not convenient to machine specimens to the standard shape shown in Fig. 23*a*, specimens may be used with edges machined parallel for the entire length of the specimen. If such specimens are machined with a tool cutting across the edges

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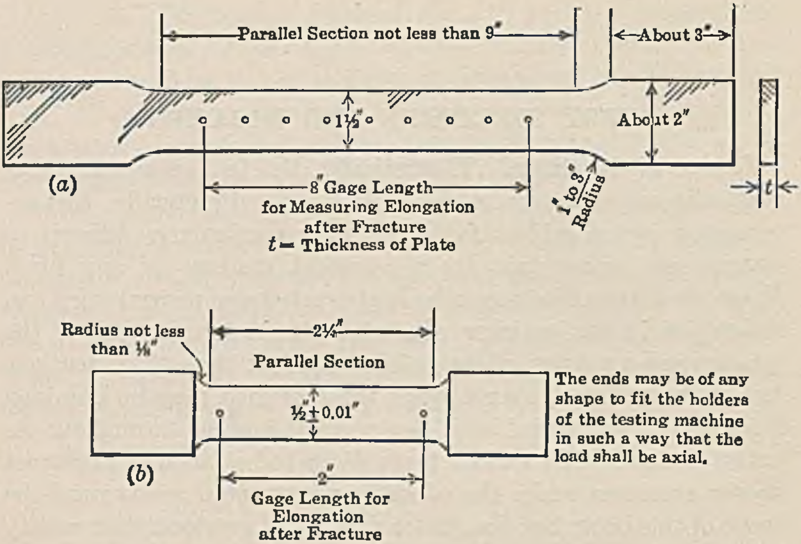
[1] A.S.T.M. Designation E8–40T.



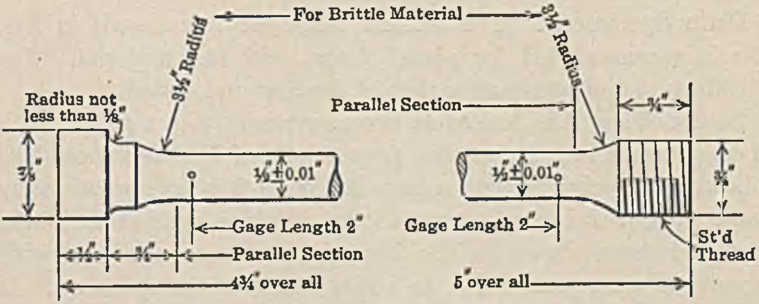
NOTE: It is commonly accepted practice to modify slightly the dimensions of these test pieces as follows.

Fig. 23*a*. " Parallel section " gradually tapered from nominal width at center to 0.004 in. to 0.006 in. over size at tangency of fillet.

For thin material the tendency to tear at the shoulder is minimized by making the width of the enlarged ends equal about 1⅓ times the width of the parallel section.

Fig. 23*b*. " Parallel section " gradually tapered from nominal diameter at center to 0.003 in. over size at the tangency of fillet.

For dimensions of special sub-sized specimens see Appendix, Table III.



(*c*) Specimen with shouldered ends (*d*) Specimen with threaded ends

FIG. 23. — Standard test specimens.

of the specimen, it is important that the transverse tool marks be removed before the specimen is tested.

For thick plate material, it is generally preferable to use a machined specimen rather than a specimen of the full thickness of the plate.

Up to the present time, it has not been possible to fix a definite line between plate material and sheet material.

The Standard 2-Inch Specimen. The tension test specimen shown in Fig. 23*b* is recommended for general use in testing metals. The gage length for measuring elongation after fracture is 2 in.

When it is necessary to cut specimens from material (other than plate, shape, and flat material) which is of such size that the specimen shown in Fig. 23*b* cannot be used, it is recommended that a specimen with dimensions proportional to those shown be used, and that the specimen be made as large as feasible. In any such small-size specimen it is especially important that the gage length for measuring elongation be four times the diameter of the specimen.[2]

In all tension tests of metals, the actual dimensions of cross-section of the test specimen shall be measured with a micrometer reading to $\frac{1}{200}$ of the dimension measured, and the stresses shall be computed on the basis of the measured cross-section; it should never be assumed that the dimensions of the measured cross-section are identical with the nominal dimensions.

NOTE: It will be noted that the tolerance for diameter of specimens shown in Fig. 23*b* permits the use of specimens 0.505 in. in diameter.

For certain materials, more specialized types of test specimens are standardized. Of this class, those most likely to be met in ordinary practice are the standard types for cast-iron and malleable castings.

Cast-Iron Test Piece.[3] The transverse specimen is in the form of a straight cylinder of the dimensions noted under Transverse Tests.

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[2] Tests have shown that geometrically similar test pieces of different sizes deform similarly, giving widely differing load-extension graphs, but the true stress-strain diagrams will be nearly identical in shape if the material be of uniform quality.

[3] A.S.T.M. Designation A48–41.

The proper size and shape of the tensile test piece is shown by Fig. 24 and the accompanying tabulation of dimensions. This specimen shall be machined from the test bars made for the transverse test.

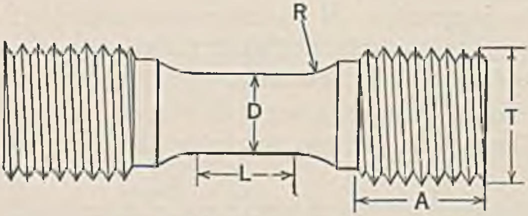

FIG. 24. Tensile specimen for gray iron castings.

DIMENSIONS OF TENSILE SPECIMEN (INCHES)

D	*A*	*T*	*R*
0.505	1	¾	1
0.800	1	1⅛	1
1.25	1¾	1⅞	2

The length of the straight portion *L* shall be equal to or greater than the diameter *D*. The ends may be threaded to fit the available holder; U. S. Standard threads have been found entirely satisfactory.

Malleable Iron Test Piece. The tensile test piece for malleable castings is intended to be used in wedge grips. Castings of this character are not commonly machined. The malleablizing process produces certain changes in composition and structure which give to the casting a skin and a core which are highly characteristic of the material. To machine a specimen under such conditions

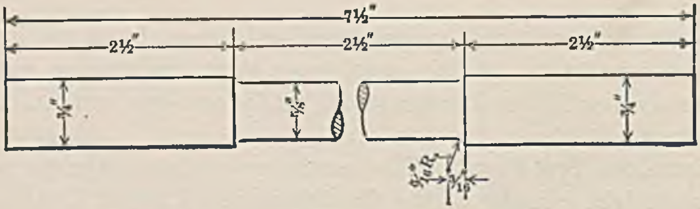

FIG. 25. — Malleable iron test bar.

means the production of a test piece entirely different from the castings which it is supposed to represent — a condition which must be carefully avoided. Hence the specification of the standard test piece (Fig. 25) as shown by the A.S.T.M. Standards.[4] In making the original castings for these test bars, it is common to use raised letters on the patterns to indicate the different melts, and so forth. Great care should be taken in placing them so that they may be avoided in gripping the specimens with the wedge jaws of the machine. Otherwise, severe bending stresses may be induced which will be unfair to the castings.

Machining the Specimen. When the threaded ends are used for gripping in the testing machine, a fairly loose fit is a great aid to the tester. The excess strength in these ends is so marked under most circumstances that there is very slight danger of thread failure. It is the custom of the writers to specify that the outside diameter of the threaded portion be made 0.010 in. to 0.015 in. under size. The thread should then be cut to standard depth. This gives an extremely loose fit but absolutely avoids the necessity of the use of wrenches when fitting the specimen into the holders.

In research work with heat-treated specimens, some difficulty is at times experienced through the tendency for cracks to form at the root of the thread during treatment. This difficulty may be somewhat overcome by using a threading tool with a slightly rounded point instead of the regular type for cutting U. S. Standard thread. The thread diameters recommended above will permit this even though the holders are of the standard thread form. The sharp V thread should never be used in fabricating specimens.

The use of a specimen whose diameter is 0.505 in. greatly simplifies the labor of calculation in connection with the test.

It is very essential that tool marks be carefully removed from the surface of turned specimens. Tests[5] show that in the annealed condition the tensile strength and yield point of carbon steels is not very greatly affected by the condition of the surface of the specimen. The effect on the elongation and the reduction of area is very marked, however, and increases with the carbon

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[4] A.S.T.M. Designation A47–39.

[5] Thesis investigation by W. S. Marder and F. de la Macorra, M.I.T., 1924.

content. For a carbon steel (0.90 per cent C), the elongation (with rough turning — 7.5 per cent in 2 in.) was increased nearly 70 per cent (to 12.4 per cent) when the specimen was polished. Under like conditions, the reduction of area (with a rough turned specimen 4.7 per cent) was increased almost 200 per cent (to 14.0 per cent) by polishing.

When specimens are to be heat-treated after machining, the character of the surface is of paramount importance.

Methods of Holding. Ductile material and particularly long specimens may commonly be held directly by the wedge grips of the testing machine. Standard testing machines are usually furnished with three sets of jaws (Fig. 26, *A*, *B*, *C*) and a series of flat shims (Fig. 26*D*) to provide for specimens of ordinary size and proportions. For flat specimens and small rods or wires, the flat type (*A*) may be used. Intermediate-sized rounds are gripped with type (*B*). For the largest diameters permitted by the capacity of the machine, jaws like (*C*) may be employed.

Fig. 26. — Wedge grips.

Shims, as indicated by (*D*), are used to back up jaws to give proper gripping action. The rounded corner, *R*, must always be placed away from the jaw and toward the head casting of the machine. The head of the shim is generally machined with a sloping surface, *S*. This slope is so made that when in place the entire surface rests flat on the head of the testing machine. One pair will be found to fit properly in each head and they should not be interchanged.

Precautions in Gripping. A proper choice of jaws and shims is very necessary. Under the best conditions, the jaws of the machine will appear as in Fig. 27(*a*). Failure to use shims may result in the condition indicated at (*b*). If the jaws project equally beyond the head and the projection is not too great, it may be possible to complete the test without damage to the apparatus. However, with ductile material there is some diminution of area within the jaws, which will permit an even greater projection before the specimen is broken.

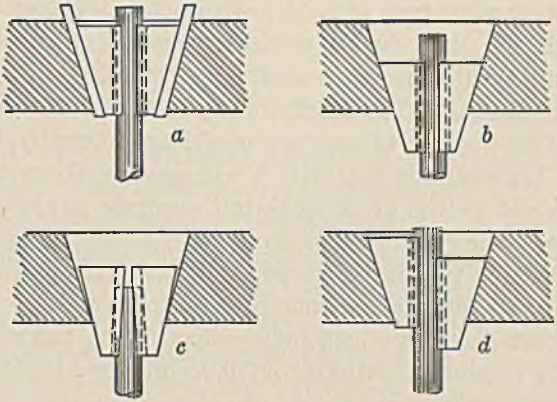

Fig. 27. — Adjustment of wedge grips.

Insufficient length of specimen in the jaws (*c*) is very bad for the apparatus. It will be noted that the jaws bear only at the very edges of the pocket, giving very severe local pressure in the head castings. Also, the reaction of the specimen produces severe bending stresses in the jaws, due to cantilever effect. The probability of the specimen's slipping is very great even if actual breakage of the jaws is escaped.

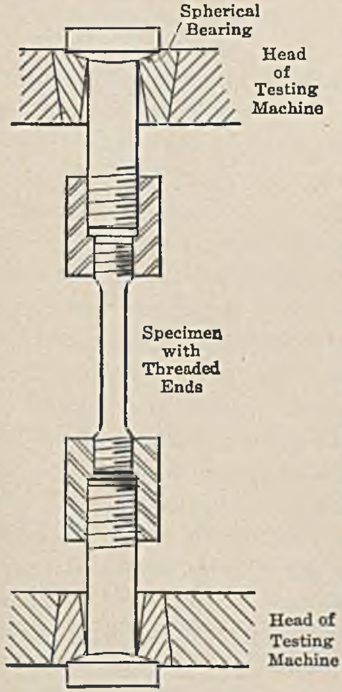

Fig. 28. — Self-aligning tensile holders.

Should one jaw be lower than the other, as in (*d*), it is evident that the end of the specimen will be forced to one side, very seriously affecting the alignment and producing stresses in the specimen due to bending. With short or somewhat brittle specimens, this carelessness may render the results of the test absolutely worthless.

Spherical-Seated Holders. Whenever feasible, the specimen should be held in some device furnished with a flexible bearing resting against a spherical seat.

A very satisfactory type of holder of this class is shown diagrammatically in Fig. 28. Such a device is very effective in assuring that the pull on the specimen shall be truly axial.

Speed of Testing. The results of the test may unquestionably be affected by the rate of application of load. Usually, however, a speed of the straining head which will produce abnormalities in the figures will be too great to permit accurate balancing of the scale beam. For careful elastic-limit determinations, where data are recorded for plotting a graph, it is desirable and generally necessary to operate the machine by hand power.

Yield-point determinations may ordinarily be made with the head of the machine moving about 0.05 in. per minute for each inch of gage length.

FRACTURES AND THEIR SIGNIFICANCE

General. It would indeed be difficult to exaggerate the importance of a careful study of typical fractures. Although it is true that only experience of considerable extent can make the student truly expert in the judging of metals by their fracture, still even a small amount of time devoted to this work is extremely valuable. In the following pages an attempt will be made to point out the salient features to be noted. In the illustrations the writers have been careful to select specimens that overemphasize, if anything, the indicative features. All gradations and variations will appear in practice, and deductions must be thoughtfully made in the light of the type cases which the fracture at hand most nearly represents.

Tensile Fractures. Figure 29 shows five fractured specimens that are fundamental in character.

In *A* is seen the ragged " broken stick " fracture of wrought iron. This appearance is due to the presence, in the metal, of slag which, in the process of manufacture, has been rolled out into threads and streaks. A large slag seam appears widely opened along the entire length of the cylindrical surface of the specimen. It is because of these slag streaks that wrought iron seldom, if ever, gives the true cup-and-cone type of fracture common to the lower-carbon steels which it most nearly resembles in chemical composition and physical properties.

Specimen *B* typifies the perfect cup-and-cone fracture. Seldom is the cup seen in such perfection as is here shown. The usual cup-and-cone fracture, as will be noted in Fig. 31, leaves part of the lip of the cup on each side of the break. The general proportions of the fracture shown here, with the " necking " decidedly local in character and the extremely fine texture, immediately suggest heat-treated material with extreme probability of its being an alloy steel such as chrome-nickel or chrome-vanadium.

The " rosette," or " star," fracture of specimen *C* can never be mistaken. It is always indicative of steel in the sorbitic condition, a result of proper and careful heat-treatment, largely associated with alloy steels. With this type of fracture may be expected high strength and great toughness. Such a steel should admirably withstand shock, vibrations, repeated stress, and general abuse.

A fracture such as that shown at *D* may appear with various

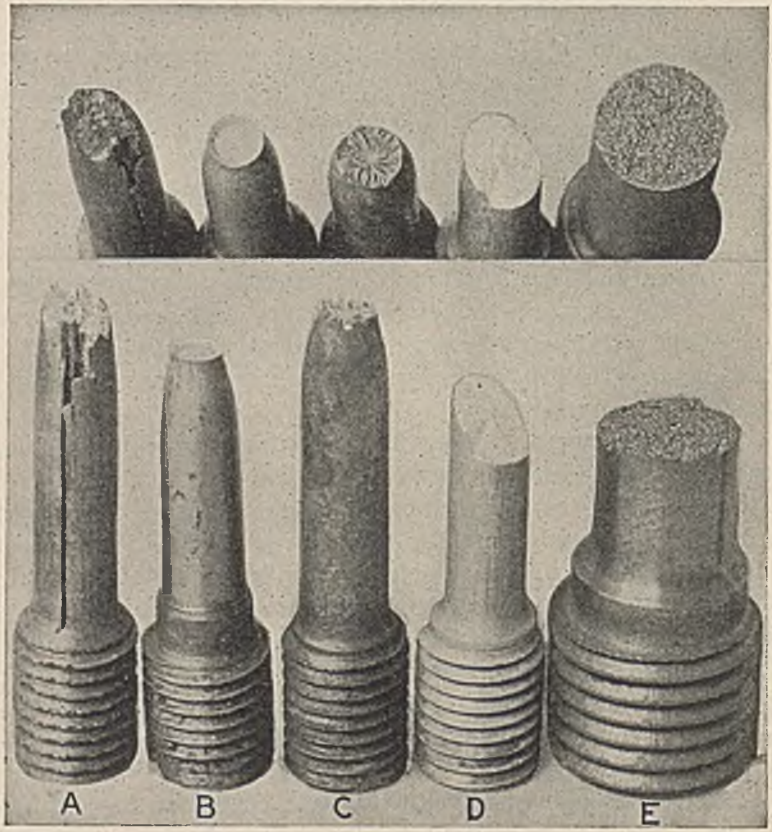

Fig. 29. — Typical tensile fractures:
A — Wrought iron (ragged fracture showing slag):
B — Heat-treated alloy steel (perfect cup-and-cone):
C — Heat-treated alloy steel (rosette fracture).
D — Duralumin, heat-treated (shear fracture).
E — Gray cast iron (granular fracture).

materials possessing a fair degree of tenacity and ductility, particularly those of non-ferrous character. At the very center appears a faint suggestion of a cone, which extends almost to a perfect point instead of being truncated as is common with the ductile steels. The general appearance is that of shear along a plane at 45 degrees with the axis of the specimen. This fracture is especially typical of heat-treated duralumin, which, in fact, furnished the original from which this particular picture was made. A careful study of the cylindrical portion will show faint longitudinal striations in the surface. These commonly appear with this material and also with certain brasses and bronzes in the forged condition. Particularly is this noticeable with tobin bronze after proper working.

The granular fracture of cast iron, as seen at *E*, is quite typical of all the more brittle metals, and in fact appears at times in cast brass even when there is some ductility. In such a fracture, the material is ruptured by a separation confined largely to the grain boundaries and there is commonly little local contraction.

Metallic Flow. If the relative motion of the individual grains is of a shearing nature, confined largely to planes of slippage inclined at approximately 45 degrees with the axis, the fractures will always tend toward some of the characteristics of *A*, *B*, *C*, or *D*. Such action is always present when there is appreciable distortion before fracture. In no other way can there be relative displacement of the individual grains coupled with uninterrupted continuity of the metal. Metallic flow, regardless of the type of stress with which it is coupled, can occur only as shear displacement. In such displacement the individual molecules may be moved without being carried outside the range where mutual attraction maintains the continuity of the solid. Microscopic study of cross-sections of such fractures confirms this hypothesis. Relative displacement that causes separation of the granules in a direction more or less normal to their adjacent faces very

FIG. 30. — Extreme example of cup-and-cone fracture.

quickly moves these faces outside the range of molecular attraction, complete rupture being instantaneous and not, in general, preceded by very appreciable metallic flow. The fracture obtained in testing a piece of brass pump rod, as shown in Fig. 30, illustrates the ultimate extreme of shear displacement of the granules, resulting in a cup-and-cone fracture with the cone coming to an actual point.

In some instances there may be present disturbing factors which influence the fracture. Gray cast iron (Fig. 29*E*), for example, contains myriads of tiny flakes of graphitic carbon. These interrupt the continuity of the metallic matrix in which they are imbedded. They form thousands of points of local weakness at which incipient fracture may begin. Again, their sharp edges act as discontinuities tending to concentrate the internal stress and aid in the propagation of fractures. The rupture, then, starting at these countless centers, spreads along the crystal faces and produces the typical granular break.

Restricted Flow. It may, then, be concluded from this analysis that the type of fracture is influenced by the manner in which the granules are displaced during the straining of the material. It is unquestionably true that the inherent properties of the material, under normal conditions, determine whether the failure will occur through normal displacement at the grain boundaries or initially by shear displacement. That is to say, the fibrous texture of the cup-and-cone or the granular texture of the short break may, under normal circumstances, be connected with the kind of metal and its conditions. Any conditions that tend to restrict the flow of the metal will tend to diminish the amount of shear deformation before fracture and to increase the likelihood of a fracture partaking of a granular nature. Carried to its ultimate conclusion, therefore, this statement leads to the inference that instances may arise in which the fracture may be indicative of the circumstances incident to the load application and shape of the piece rather than of the properties inherent in the metal or its condition.

As an example of this, a piece of rivet steel will, under normal conditions, break with a decided cup-and-cone fracture and show marked fibrous texture. Let a piece of such material be deeply grooved with a sharp threading tool, so that the diameter at the root of the groove is about one-half of the original. This will produce a test piece of an infinitesimal length. Obviously, the flow of metal will be restricted to the highest degree. There will be practically no opportunity for shear displacement at the region of maximum stress. Rupture can take place only by displacement of the grains in a direction practically normal to their surfaces. Hence a fracture will be produced with a texture in part or wholly granular. Not only will the type of fracture be modified by restriction of flow, but the tensile strength, calculated from the area actually bearing the load, will be greatly enhanced. A steel with normal tensile strength of 60,000 lb. per sq. in. may show 90,000 lb. per sq. in. when tested with a sharply grooved specimen of this character.

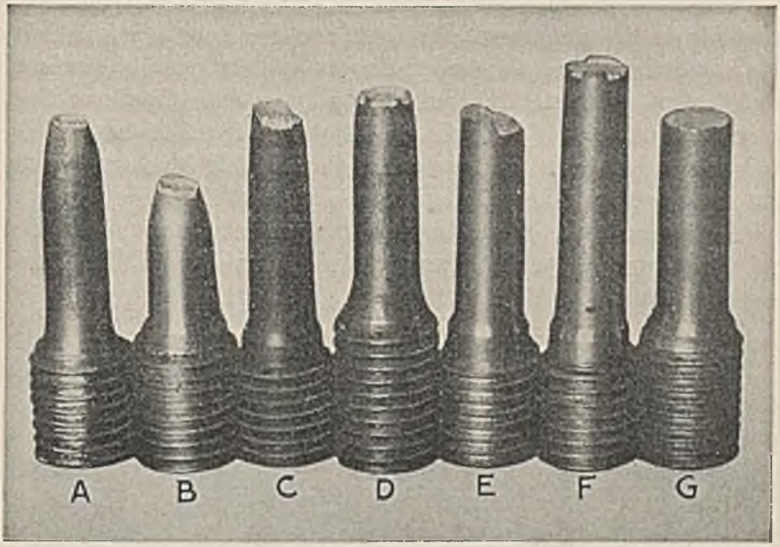

Fig. 31. — Variation of fracture of annealed steel with change in carbon content.

	A	B	C	D	E	F	G
Carbon Per cent	0.05	0.10	0.15–0.20	0.30–0.40	0.50	0.60	0.80
Red. in area Per cent	77.2	71.2	59.5	51.7	36.8	30.5	20.4

Effect of Carbon Content. When simple carbon steels are tested in the annealed condition, the resulting fractures are very characteristic and form a series grading in exact accordance with the carbon content. Such a series of seven test pieces is shown in

Fig. 31, running from a piece of rivet steel, *A*, through the carbon range as indicated to a steel, *G*, which closely borders on the tool steels.

Starting with a deep cup-and-cone fracture with a very small flat at the bottom of the crater, the depth of the cup diminishes until with steel *G* there is but the faintest suggestion of a lip around the edges of the very flat break. It is obvious that the extent of the crater increases as its depth diminishes. In the light of the previous statements, then, the shear displacement for specimen *A* is very great; the shear displacement for *G* is almost negligible, with all the intermediate possibilities illustrated between these extremes.

There is therefore a clear transition, consisting of well-marked steps, from the toughness, ductility, and low tensile strength of the low-carbon steel, to the brittleness and strength of steels of high carbon content. So truly typical are these fractures that very little experience is needed to allow a fair estimation of the carbon content from the fracture **if the steel is known to be in the annealed condition.** Conversely, if the chemical analysis is known, then non-conformity to the series illustrated immediately points to some disturbing element in the previous history of the metal at hand.

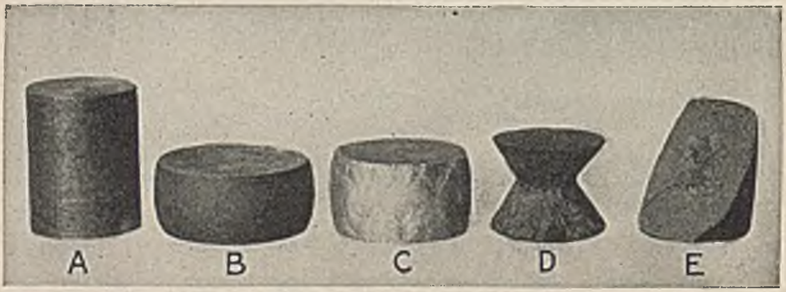

Fig. 32. — Typical compression failures.
A and B–Machinery steel. C–Cast aluminum. D and E–Gray cast iron

Compressive Fractures. Metallic. Figure 32 shows typical fractures which develop in testing metals under compressive load. Common machinery steel of 0.15 to 0.20 per cent carbon appears at *A* (the specimen before test), and at *B*, which shows the result of the application of load of 200,000 lb., the original cross-sectional area being one square inch. Under such action as this, the term ultimate compressive strength has absolutely no significance. The flow of the metal results in an increase of cross-section and there is no true rupture. Any fabricated compression member containing material of this sort will suffer very appreciable distortion when the stress in any element reaches the yield-point stress for that material. This yielding is almost invariably irregular, owing to unavoidable eccentricity of load and frequently to lateral forces. Hence, any appreciable deformation in a compression member, such as is produced at yield-point stress, will destroy alignment and probably result in collapse of the structure. Therefore, it is clear that, for material that acts like specimen *B* under compressive load, the all-important item is the stress at yield point.

Gray cast iron under compression ultimately shatters and produces a fracture such as that shown at *D* and *E*. The symmetrical shear cones of *D* are the ultimate type. Commonly, however, these are but imperfectly formed, as at *E* where the partial formation of such a cone may be detected in the shear surface.

It was stated, in the discussion of the tensile fracture of cast iron, that owing to the graphite crystals the failure occurred by pure tension, without shear displacement of the grains. Under compression the graphitic flakes are more or less harmless. The entire mass here maintains its integrity until shear displacement takes place between and through the metallic granules. There is then some slight flow of cast iron under compression, and a yield point may be detected as described under methods of compression testing. This yield is far above the ultimate strength of the same material when tested in tension. The fracture of cast aluminum (Al 92 per cent, Cu 8 per cent), as shown at *C*, is intermediate between that for the highly malleable steel and the more brittle cast iron. The shear planes, at about 45 degrees, are well defined and may be seen over the entire surface. The testing machine has indicated the passage through a maximum load while the specimen still coheres.

Concrete. In connection with the general discussion of compression fractures (which, for non-cellular material, must of necessity, as we have seen, be in reality shear fractures) it may be in order to devote a little space to the items for consideration in the examination of concrete. Since concrete is inherently a brittle material, it will ultimately crumble or shatter under compressive loads. This disintegration is produced through a combination of shear and lateral tension. If the failure occur at a stress lower than might have been expected, the engineer may gain very valuable information from a careful study of the test piece and its fractured surface. To a certain extent, the wetness of the original mix may be estimated. The presence of air voids at the surface, and more or less throughout the mass, may be indicative of insufficient water. This is a condition but rarely met with when the test piece is made from a batch intended for use in actual construction. It is more likely that there will be an excess of water, which will be manifested by numberless tiny spheroidal holes with very smooth interior surfaces. These represent the globules of excess water which have been unable to escape during the rodding and have become disseminated through the mass. Evaporation and subsequent hydration after setting leave these so-called water voids. They are in themselves conducive to weakness, owing to diminution of the actual cross-section by their presence. Furthermore, some of the excess water which they indicate escapes from the mold or form and carries with it a certain percentage of the cement, making the mix slightly leaner than has been supposed. True air voids, due to insufficient water, must not be confused with voids due to insufficient rodding. One is due to the mixing and affects the entire batch; the other is incidental to the specimen at hand. Voids due to insufficient rodding will, in general, be confined to one end of the test piece — the end that was the bottom when the specimen was made.

Premature failure due to the material itself may be chargeable to the stone, the sand, or the cement. If there be no sheared areas shown by the coarse aggregate, and all the sand particles show their more or less smoothly weathered surfaces, then the failure may be laid to the cement, and may be the result of poor material, improper proportions, or insufficient age of the specimen. On 7-day tests, cement failure is generally the rule since at that age most cements will not have attained a strength sufficiently high to produce rupture in a good aggregate. At 31 days, the cement will, in general, have sufficient adhesive and cohesive strength to produce some fracture in the aggregate. Freshly sheared surfaces in the fine aggregate proclaim it to be relatively the weakest of the constituents. Prevalent shear in the coarse aggregate similarly indicates that the concrete strength registered is close to the maximum attainable with that particular aggregate. Obviously, when failure appears in the cement, increased age or a richer mix may be expected to yield higher values. If the failure appears to any appreciable extent in the aggregate, little can be expected from richer mixes or increased age.

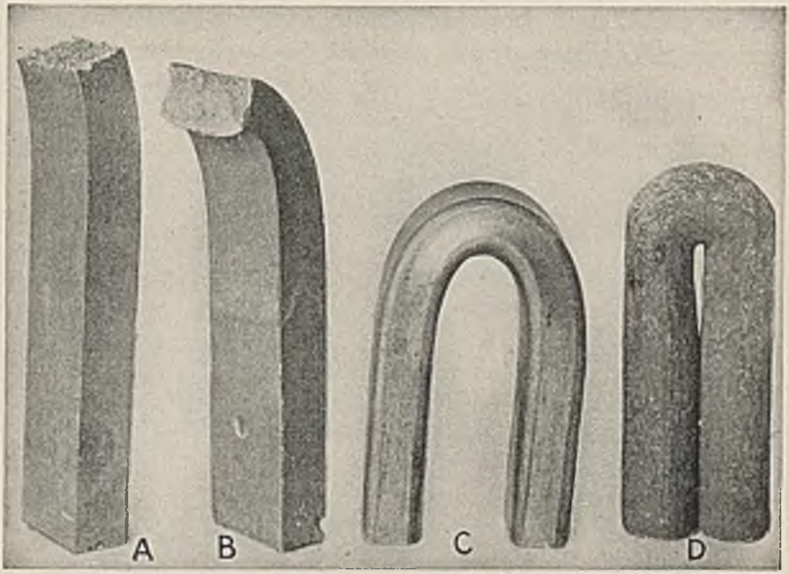

Fig. 33. — Cold bend pieces.
A — Steel casting (before annealing).
B — Steel casting (after proper annealing).
C — Steel forging.
D — Rivet steel.

Cold Bends. The discussion of cold bends under the general caption "fractures" may in some instances involve a misuse of the latter term, as most forged or rolled specimens are expected to withstand such tests without rupture. Such test pieces are illustrated in Fig. 33*C*, which shows the standard cold bend specimen as specified for most types of steel forgings. In the instance illustrated, the specimen has been bent around a pin whose diameter is equal to the thickness of the test piece, namely $\frac{1}{2}$ in. Specimen *D* shows the cold bend test for rivet steel where the specifications require that the specimen be bent flat on itself.

The closure is not absolutely perfect but has been carried as far as is generally practicable. This would be considered to have been bent " flat on itself."

Actual fractures appear in Fig. 33, *A* and *B*, which show bend tests from steel castings. In *A* the casting has not been annealed. Note the very coarse granular break appearing when the specimen has been bent a little more than 45 degrees. After annealing, the same casting *B* shows a much finer texture at the fractured surface and bends nearly 120 degrees before separation occurs.

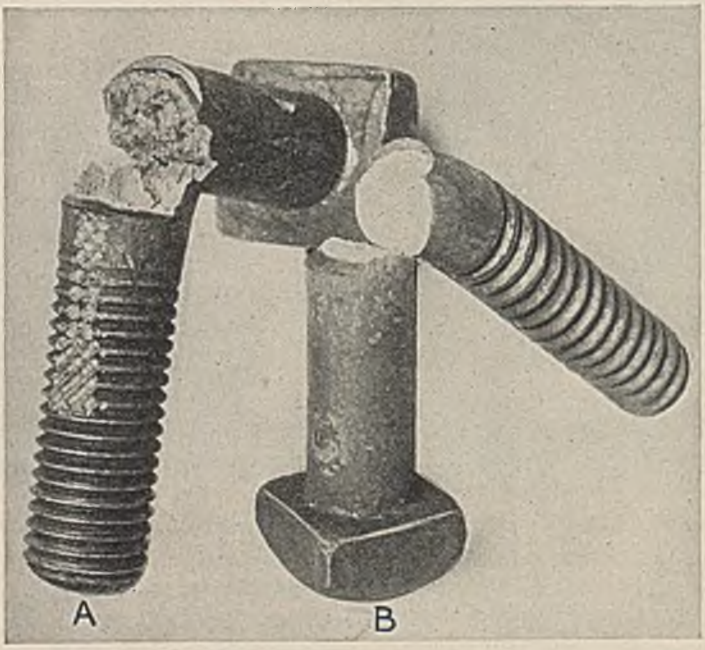

Fig. 34. — Nick-bend tests.
A — Wrought iron bolt. B — Steel lag screw.

Nicked Bends. Wrought-iron specifications, as has been noted elsewhere, commonly call for a " nick-bend test." The fracture from such a cold bend is shown by Fig. 34*A*. The nick has been made with a sharp cold-chisel and opened by bending, as appears. In this particular case, the " woody texture " is absolutely free from crystallin spots. Though not a matter of specification, a similar test is shown for a steel lag screw at *B* of the same figure. Even though the material is undoubtedly a low-carbon steel, the fracture appears finely granular over the entire surface. This is another example of granular fracture produced by restriction of flow at rupture. Such restriction of flow is not possible with wrought iron. The slag seams break the continuity of the metal to such a degree that the separate layers of metal may slide past each other, and pull from a region some distance away from the plane of maximum stress. Hence the "woody texture." A simple test of this sort may serve as a ready means of distinguishing wrought iron from low-carbon steel even where there is scarcely sufficient evidence presented by chemical analysis.

Torsion Fractures. The typical torsion fractures shown in Fig. 35 present some interesting contrasts. Specimen *B* shows the usual characteristics of torsional failure, to be expected with fairly ductile material. The fracture generally starts at some minor surface discontinuity. Thence it progresses inward and around, the fractured surface forming a crescent of continually increasing extent. The point last to rupture is generally more or less off center, as appears in the photograph. All of this, be it understood, takes place in a very short interval of time, but nevertheless is not in any sense instantaneous. During the progress of the fracture, there is appreciable motion between the fracturing surfaces, which are far from plane. The higher portions become engaged under considerable pressure due to the mutual cam action of the surfaces. This condition is such that sufficient heat is commonly generated locally to produce oxidized

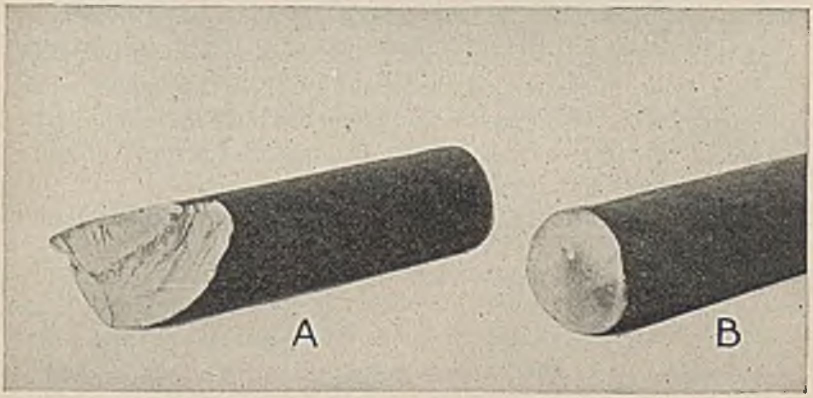

Fig. 35. — Typical fractures in torsion.

areas. One such dark-colored spot appears in the figure. The portion last to fail, it will be observed, is thus subjected to very considerable tensile stress as well as that of shear. The existence of tensile action produces the " pulled out " appearance which sometimes suggests a slight cup-and-cone tendency.

The fracture produced in more brittle materials appears at *A* in sharp contrast with that already discussed. In this instance, the material presents extreme resistance to shear deformation of a plastic nature. Along with the shear stresses induced on the plane perpendicular to the axis of the bar, it is understood from the theory of elasticity that very real tensile stresses appear on the plane at 45 degrees to this direction. Evidently the fracture has taken place on such a plane. The character of the broken surface is decidedly granular, showing further that the rupture has been caused by tensile stresses more or less normal to at least a portion of the grain boundaries. The resistance to shear deformation, then, has exceeded the stress on the shear plane, while the stress on the 45-degree tension plane has built up to a value in excess of the tension resistance of the material across the grain boundaries which happen to coincide approximately with this plane. Such a fracture is typical of all materials that are designated as brittle.

HARDNESS DETERMINATION

Meaning and Application. That certain materials are relatively harder than others is a fact clearly recognized by both the technical and the non-technical. The true meaning of the term, however, does not lend itself to ready definition. It is evident that to the lapidary, the blacksmith, the machinist, and the carpenter the idea of hardness will appear in very different aspects. The best single definition that the writers can propose is that **the hardness of a material is its resistance to penetration under a localized pressure.** It is fully realized that this definition is open to criticism and objection, but it seems to meet the question fairly under most situations. Up to the present time it has not been found practicable, in the testing of hardness, to separate the inherent initial hardness of a material from the hardening which usually results from cold work. All the numerous devices available at this writing produce more or less displacement of the material during the test and automatically introduce this troublesome factor. It has been suggested that some form of magnetic test might be devised to overcome this defect, but it is admitted that its interpretation would be difficult. Hardness is a comparative value, and the test is generally made for one of two reasons: either to test the material against some specified value; or to check the uniformity of the manufactured product. Tests made for the latter purpose play an important part in the control of the various manufacturing methods.

As an example of the former type of test may be mentioned certain Government specifications, such as those for forgings, which designate within limits a definite hardness number for acceptance. These specifications, of course, include other physical properties, and the determination of the hardness number is only a part of the acceptance test.

It is, however, in the second type of test that the hardness machine finds its greatest use. The determination and control of heat-treating processes are rendered more certain by testing the material treated by means of a hardness machine. The raw materials or the finished products may be checked up on a hardness machine and thus the uniformity of all materials can be closely watched. In modern shop practice, some type of hardness measurement is recognized as a valuable aid in the successful operation of many manufacturing processes.

The situation outlined above has led to the development of a numerous family of hardness testers, certain of which will be described. An attempt will be made to indicate the points of excellence of each one mentioned together with its inherent limitations.

Brinell Method.[1] In 1900, Dr. J. A. Brinell first published his method of testing, which consists in pressing a hardened steel ball into the specimen to be tested. The standard ball used is 10 mm. in diameter and the load is either 3000 kg. or 500 kg., depending upon the material of which the specimen is made. In this system the hardness number is defined as the total pressure (kg.) divided by the area of the resulting indentation (sq. mm.). From this it is obvious that the Brinell hardness number is actually a pressure intensity and is actually expressed in stress units. Practically these units never appear when the number is written. From the above definition is developed the following equation:

$$\text{B.H.N.} = \frac{P}{A} = \frac{P}{\frac{\pi D}{2}\left(D - \sqrt{D^2 - d^2}\right)}$$

P = applied load (kg.)
D = diameter of ball (mm.)
d = diameter of impression (mm.)

The actual manipulation of a test consists in putting the specimen on the anvil of the machine (Fig. 36), which is then raised so that the specimen makes contact with the steel ball. The load is applied by means of hydraulic pressure produced by the hand pump. The yoke with the weights attached should be floated instead of determining the load by reference to the gage. This load should be maintained until the metallic flow has been completed, at which time the pressure is released and the specimen taken from the machine. The diameter of the impression is now measured by means of a microscope furnished with an eye-piece micrometer scale.

The hardness number then may be either calculated by the formula or read from a chart prepared from calculated values. (Such charts will be found in the Appendix.)

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[1] A.S.T.M. Designation E10–27.

The rate of application of load and time of sustained pressure both have a bearing on the results obtained. A slow, steady rate should be used in pumping up the pressure. The results of tests show that the full indentation is generally obtained in 45 seconds. In ordinary commercial work a 10- to 20-second interval is generally recommended. For comparative tests the same time interval should always be used.

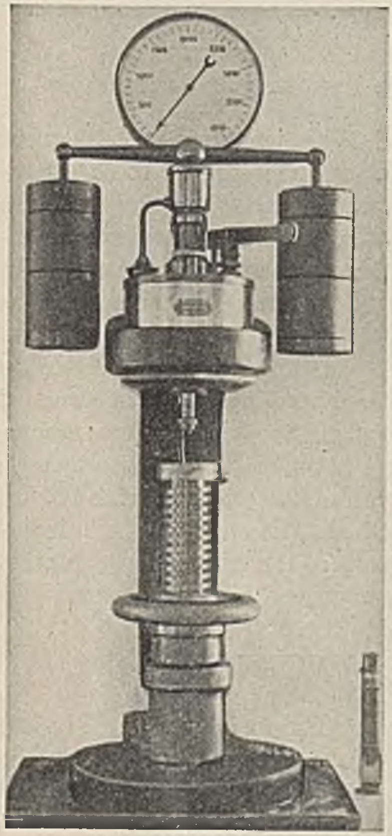

FIG. 36. — Brinell hardness tester.

Precautions. The condition of the ball must be constantly checked up, especially if very hard specimens are being tested. Distortion of the ball may be detected by the shape of the impression. A test giving a distinct oval dent should be thrown out and a new ball inserted in the machine. If materials giving a number below 400 are being tested, permanent distortion of the ball is not likely. Special cold-worked steel balls may be obtained which may be used for hardnesses up to 700, and balls of tungsten carbide are available which may be used on materials with Brinell hardness running up to 1000.

The specimen should be smooth, and its surface flat and at right angles to the direction of load. The smoother the specimen the more easily is the diameter read with the microscope.

The impression should not be made too near an edge or a previous impression in a check test. A straight edge may be held in contact with the side of the specimen to determine whether or not there is a bulge.

The specimen must not be too thin, because in that case there is a restricted flow caused by the anvil, and a false reading is obtained. The minimum thickness should not be less than ten times the depth of the indentation.

The values obtained in the Brinell test are a measure of the resistance to penetration, and, as the indentation is fairly large, they are average values. For many steels, there is a fairly constant relationship between the Brinell number and the tensile strength. The following is an equation showing this:

$$\text{Tensile strength (lb. per sq. in.)} = 515 \times \text{Brinell number}$$

Vickers Method. This method of hardness is one of the most recent to appear, but it is fundamentally so similar to the above that it should be considered at the same time. In this system the hardness number is again defined as the ratio between an impressed load and the area of the resultant indentation. The units are the same as in the Brinell system. The standard machine for this test is shown by Fig. 37. For this test the surface of the specimen must be plane and well polished. The harder the material, the more careful must be the polishing. The standard indentor is a diamond carefully ground to the form of a square-based pyramid in which the angle between the opposite faces is 136 degrees. Pressures may be used ranging from 5 kg. to 120 kg. with the weights commonly furnished. The area of the indentation is computed from the diagonal of the impression. Mathematically the hardness number is expressed by the equation

$$\text{V.H.N.} = \frac{P}{A} = \frac{P}{0.5393\, d^2}$$

The test is conducted as follows. The foot lever (see Fig. 37) is depressed in order to set the mechanism for testing. On the supporting block, carried by the adjustable knee, is placed the material under observation. The knee is raised until the surface of the test piece is within a few thousandths of an inch from the point of the indentor. The mechanism is tripped by the starting lever at the right of the machine head. This unlocks a loading beam which, through the influence of a weight, just visible at the back of the machine, presses the pyramid indentor into the test piece. The loading mechanism is so arranged that the loading is always without shock or jar and the quiescent load is always maintained for the same length of time. The usual pressure is 50 kg. After indentation the knee is lowered and the microscope is swung into place. If the test piece has not been displaced the indentation will be found within the field of the microscope. Careful focusing is essential. By adjustment of the field and manipulation of the eyepiece micrometer it is possible to obtain a reading from which the length of the diagonal of this indentation may be computed. It is not necessary to reduce the ocular reading to actual millimeters since the machine is furnished with a series of charts which translate this reading into hardness number. The machine is also equipped with special holders which permit

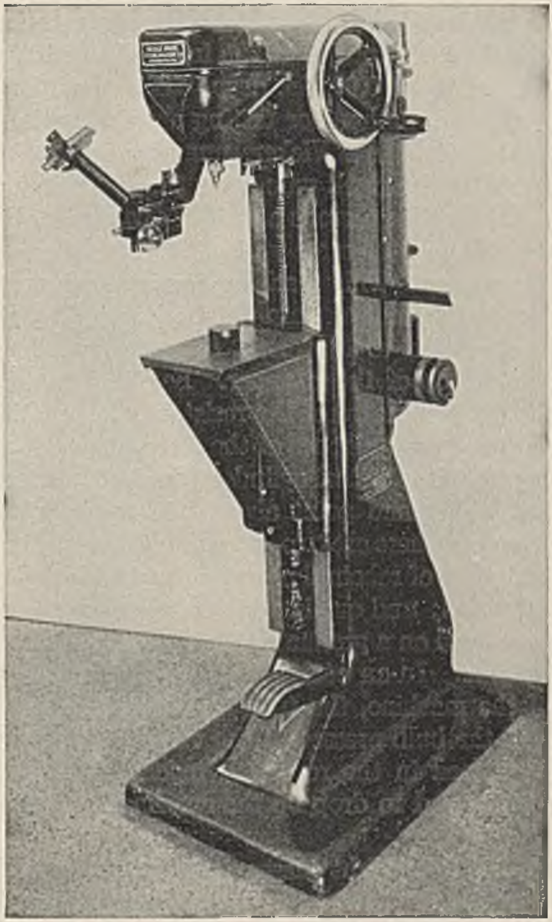

Fig. 37. — Vickers hardness tester.

the use of a 1-mm. or a 2-mm. ball so that Brinell numbers may be obtained directly.

Note: It is seldom necessary and, in the opinion of the writers not desirable, to use pressures in excess of the usual 50 kg. Higher magnifying power, produced with a shorter-focal-length objective, will permit readings when the material is hard and the impressions small. With the lower pressures the indentations in fairly hard materials will be about 0.001 in. deep. This condition makes it possible to use this method for testing sheet material less than 0.01 in. in thickness. The Vickers numbers are about 5 to 10 per cent higher than Brinell values for the same material up to about 400. Above this there is a greater divergence, the Vickers numbers increasing at the more rapid rate.

Shore Scleroscope. This machine consists of a small weight which is dropped from a certain height, through a glass tube, striking the specimen to be tested. The height of rebound is measured at the top of the hammer. For hard materials especially, this is not a measure of the resistance to penetration, but more a measure of the resilience of the piece.

The falling weight is a steel cylinder $\frac{1}{4}$ in. in diameter and $\frac{3}{4}$ in. long. It has a diamond point about 0.02 in. in diameter and blunt on the end. There are two types of machines (Fig. 38): one in which the height of rebound must be caught by the eye, called the visual type (*B*); and one in which a record of the amount of rebound is obtained on a graduated dial (*A*).

Method of Use. In an actual test, the specimen is placed on the anvil of the machine, the tube lowered in contact with the specimen, and the bulb pressed, if the visual type is used, or the knurled nut turned in the recording machine. In either case, the weight is allowed to drop on the specimen and the rebound is noted.

Because the falling weight passes down through the glass tube, it is very essential that the instrument be made plumb before a test is run, so that the weight will not rub on the sides of the tube.

The condition of the striking diamond point is very important and should be checked up frequently, on a hardened test block furnished with the machine, to detect any cracking or chipping of the diamond.

The surface of the specimen should be flat, smooth, and free from oil. Any oil film will cause a low rebound.

The specimen should be moved after each test so that the same spot in the piece is not tested twice. As the spot where the specimen falls is a very small portion of the surface, the average of several readings should be taken as the average scleroscope number.

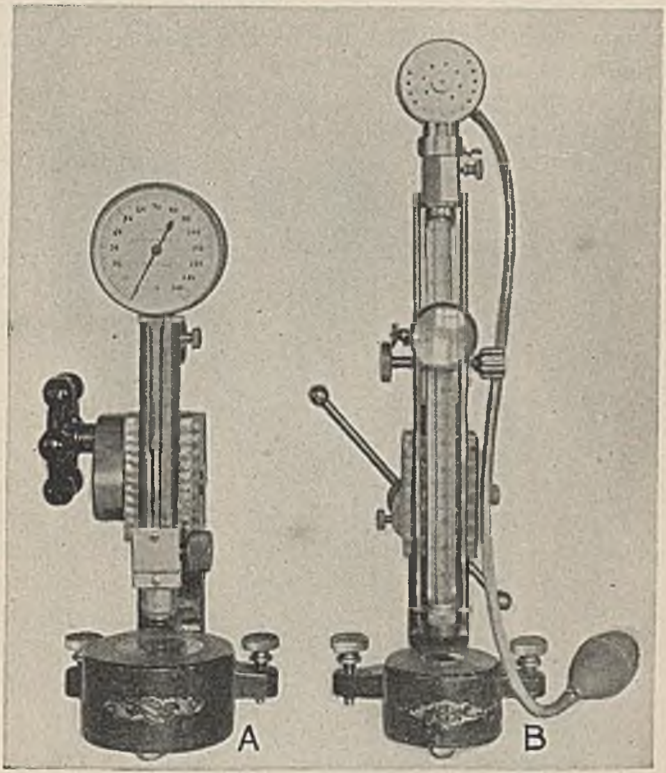

Fig. 38. — Shore scleroscopes.
A — Recording type. B — Visual type.

Very thin specimens will give higher values than thicker ones, because of the influence of the mass effect of the anvil. About $\frac{3}{8}$ in. is the minimum thickness that should be used.

Although the Brinell and scleroscope testers do not determine the hardness number in the same manner, still there is an approximate ratio of 6 to 1 between values obtained on the two machines. The Brinell number equals approximately six times the scleroscope number for the common engineering materials.

The scleroscope gives only comparative values, and therefore dissimilar materials should not be tested and compared by this machine.

It is a very handy and quick device, but care should be exercised in the interpretation of the results obtained, especially if different machines have been used. It has been found that scleroscope testers vary slightly and that the results obtained on different machines do not always check.

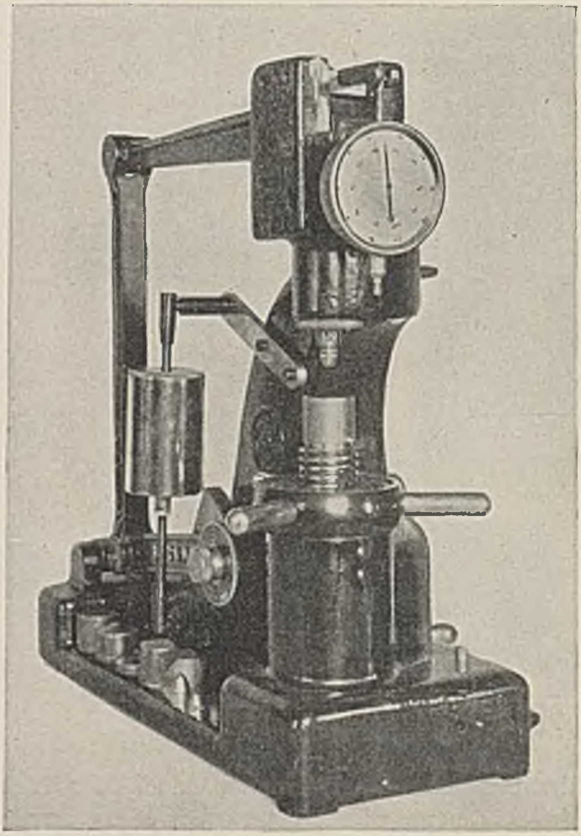

Fig. 39. — Rockwell hardness tester.

Rockwell Method. The Rockwell hardness tester (Fig. 39) operates on the indentation principle. Originally it was intended that the machine should provide two scales of hardness, called respectively the " B " and the " C " scales. The flexibility of the apparatus has resulted in the appearance of a large group each intended for use with specific materials. The standard type of machine is equipped to operate with " major loads " of 60, 100, or 150 kg.

For the softer steels and many of the non-ferrous alloys the B scale is employed. The indentor in this case is a $\frac{1}{16}$-in. steel ball and the major load is 100 kg. The harder steels are tested by using the C scale. In this instance the indentor is a diamond cone with an apical angle of 120 degrees which has its tip rounded to a spherical form. This is technically known as a " brale." When using this scale the major load is 150 kg.

Method. To test a specimen, it is placed on the anvil and brought up into contact with the steel ball in such a way as to apply the " minor load " (see following page). The dial of the machine is adjusted to the " set " position. Release of a trip allows the lever system and weights to increase the pressure to the desired " major load." The rate of application of this load may be controlled by an adjustable dash pot mechanism. After the loading levers have ceased moving the load is reduced to the minor value. The recovery of the test piece and the parts of the machine cause the dial hand to return slightly toward the set position. In this recovered position the indicated number on the proper scale is the Rockwell Hardness Number.

This procedure is shown diagrammatically in Fig. 40.

For the B and C scales the Rockwell number may be defined as follows:

$$R_b = 130 - 500\Delta h \qquad R_c = 100 - 500\Delta h$$

R_b and R_c = Rockwell numbers in the respective scales.

$h = h_1 - h_0$ expressed in millimeters.

In the design of the machines the initial numbers on the respective scales are the first numbers at the right of the equality signs. The $500\Delta h$ is taken care of by the gear train and lever system in the dial mechanism. Since the motion of the indicating pointer is left-handed, the value is subtractive and the actual position of the pointer on the proper scale is the hardness number.

In this manner the machine is made direct reading and the necessity for charts is obviated. From the above it is obvious that any change in the various factors results in a complete change of scale: consequently **the scale must always be indicated when reporting Rockwell hardness numbers.**

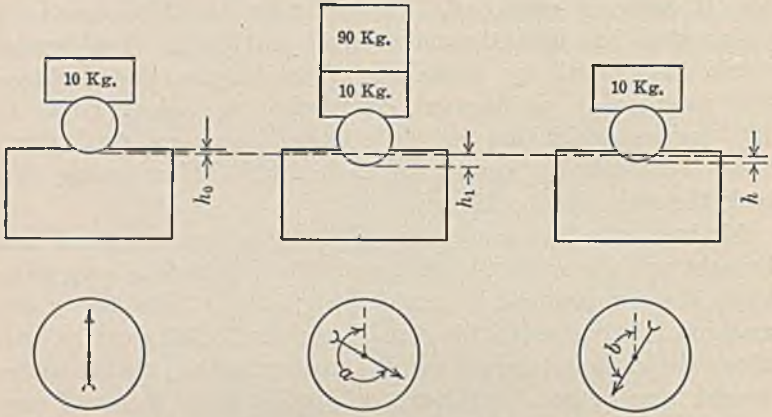

FIG. 40. — Stages in determining Rockwell hardness (B scale).

Rockwell-Brinell Relation. As a result of investigations[2] carried on at the Massachusetts Institute of Technology, the following relationship was found to exist between the Brinell and Rockwell numbers for the same specimens. The investigation of more than 300 separate specimens included all conditions of hardness from very soft to very hard for both ferrous and non-ferrous metals. The curves which were the result of this research are reproduced in Fig. 41 together with the conversion formulas from Brinell to Rockwell numbers, and *vice versa.*

$$B = \frac{R_b + 273}{6.49 - 0.048\,R_b} \qquad B = \left\{\frac{R_c + 192}{88.3}\right\}^{6.21}$$

$$R_b = \frac{B - 42}{0.154 + 0.0074\,B} \qquad R_c = 88.3\,B^{0.161} - 192$$

Other Rockwell Scales. In order to meet the necessity of testing the hardness of thin stock and carburized surfaces, where the thickness of the hard layer is not great, there has been developed a device known as the "Rockwell superficial hardness tester." The dial of this machine is equipped with a single scale.

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[2] Theses at Massachusetts Institute of Technology by F. de la Macorra, 1923, and R. S. Hamilton and W. J. Bagby, 1924.

Recognized Rockwell Scales[3]

Scale Designation			Indentor	Load in Kg.		Read on Dial Scale
				Minor	Major	
Standard Type	Group 1	B	$\frac{1}{16}$-in. ball	10	100	B
		C	Brale	10	150	C
	Group 2	A	Brale	10	60	C
		D	Brale	10	100	C
		E	$\frac{1}{8}$-in. ball	10	100	B
		F	$\frac{1}{16}$-in. ball	10	60	B
		G	$\frac{1}{16}$-in. ball	10	150	B
		H	$\frac{1}{8}$-in. ball	10	60	B
		K	$\frac{1}{8}$-in. ball	10	150	B
	Group 3	L	$\frac{1}{4}$-in. ball	10	60	B
		M	$\frac{1}{4}$-in. ball	10	100	B
		P	$\frac{1}{4}$-in. ball	10	150	B
		R	$\frac{1}{2}$-in. ball	10	60	B
		S	$\frac{1}{2}$ in. ball	10	100	B
		V	$\frac{1}{2}$ in. ball	10	150	B
Superficial Type		15N	Brale	3	15	. . .
		30N	Brale	3	30	. . .
		45N	Brale	3	45	. . .
		15T	$\frac{1}{16}$-in. ball	3	15	. . .
		30T	$\frac{1}{16}$-in. ball	3	30	. . .
		45T	$\frac{1}{16}$-in. ball	3	45	. . .

Other proposed scale groups for superficial type are as follows: W — using $\frac{1}{8}$-in. ball; X — using $\frac{1}{4}$-in. ball; Y — using $\frac{1}{2}$-in. ball.

Monotron Method. This system is based on principles somewhat similar to those in the Brinell method. The chief differences lie in the size of the resulting indentation and the means of expressing the results. The monotron is so arranged that the impression (usually produced by a diamond point ground to conform to the surface of a sphere of diameter 0.75 mm.) is always of a standard depth of 0.0018 in. The pressure in kilograms necessary to produce this indentation is reported as the " monotron hardness number." This machine is flexible in its operation, and at the desire of the investigator or in accordance with the exigencies of the case at hand different indentors may be used or different depths of impression may be produced.

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[3] A.S.T.M. Designations E18–36 and E18–39T.

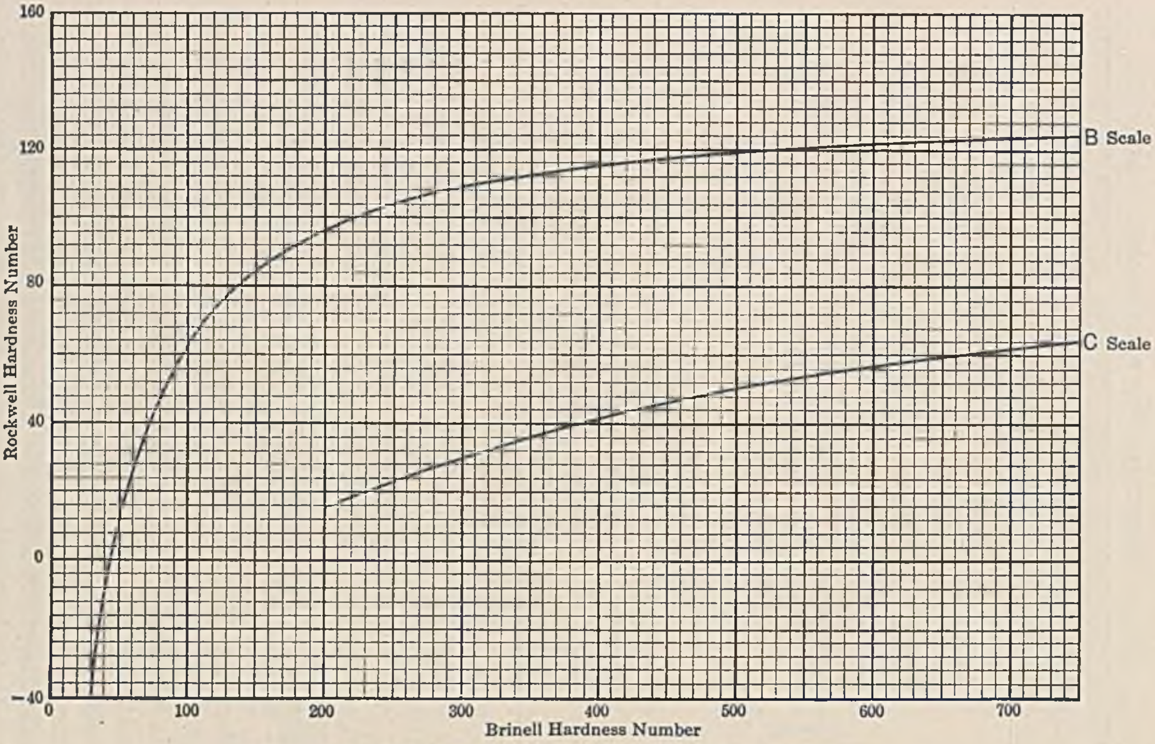

FIG. 41. — Relation between Rockwell and Brinell hardness.

Curve B using Rockwell $\frac{1}{16}$-in ball. Curve C using Rockwell diamond cone.

CEMENT TESTING

General. The determination of the fitness for use of Portland cement as well as other cementing materials is very specialized in the testing field. Unlike most materials, such as the metals and wood which come to the laboratory in finished form with only the shape of the test specimen to be determined, the test pieces for the cementing materials must be fabricated in the laboratory before the test values can be found. The manipulation and fashioning of the material into proper form for test are very important.

After years of research the A.S.T.M. in collaboration with several engineering societies has adopted a test procedure which is universally acknowledged as standard. In these pages the writers will not enumerate in minute detail all the various steps in this procedure. An attempt will be made, however, to discuss the various tests showing the reasons and emphasizing particular precautions that should be employed in making such tests.

A.S.T.M. Specifications. The specifications cover five types of Portland cement, as follows:

Type I. For use in general concrete construction when the special properties specified for types II, III, IV, and V are not required.

Type II. For use in general concrete construction exposed to moderate sulfate action, or where moderate heat of hydration is required.

Type III. For use when high early strength is required.

Types IV and V are not usually carried in stock and are for use when low heat or high sulfate resistance, respectively, are required.

These specifications governing the testing of Portland cement, as set forth by the A.S.T.M., cover four items:[1]

1. Fineness.
2. Strength.
3. Set.
4. Soundness.

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[1] A.S.T.M. Designation C150–42.

The physical requirements of the three common types of Portland cement are as follows:

	Type I	Type II	Type III
Fineness, specific surface, sq. cm. per gr.			
Average value, min.	1500	1600	....
Minimum value, any one sample			
Soundness			
Autoclave expansion, max., per cent	0.50	0.50	0.50
Time of setting (alternate methods)			
Gillmore test:			
Initial set, min., not less than	60	60	60
Final set, hr., not more than	10	10	10
Vicat test:			
Initial set, min., not less than	45	45	45
Final set, hr., not more than	10	10	10
Tensile strength, lb. per sq. in.			
The average of not less than three standard mortar briquets, shall be equal to or higher than the values specified for the ages indicated below:			
1 day in moist air	....	....	275
1 day in moist air, 2 days in water	150	125	375
1 day in moist air, 6 days in water	275	250	....
1 day in moist air, 27 days in water	350	325	....
Compressive strength, lb. per sq. in.			
The average of not less than three mortar cubes shall be equal to or higher than the values specified for the ages indicated below:			
1 day in moist air	....	....	1300
1 day in moist air, 2 days in water	1000	750	3000
1 day in moist air, 6 days in water	2000	1500	....
1 day in moist air, 27 days in water	3000	3000	....

The strength at any age shall be higher than the strength at the next preceding age.
The 28-day test, if required in type III, shall be higher than at 3 days.

Fineness Test.[2] The fineness of Portland cement is determined by the Wagner turbidimeter apparatus and is represented by the specific surface expressed as total surface area in square centimeters per gram of cement.

The Wagner turbidimeter consists essentially of a source of light of constant intensity adjusted so that approximately parallel rays of light pass through a suspension of the cement to be tested

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[2] A.S.T.M. Designation C115–42.

and impinge upon the sensitive plate of a photoelectric cell. The current generated by the cell is measured with a microammeter and the indicated reading is a measure of the turbidity of the suspension. General considerations indicate that turbidity in turn is a measure of the surface area of the suspended sample of cement.

The reader is referred to the A.S.T.M. Standards for a full and detailed description of the apparatus and method of making the test.

Usual Tests. The conditions under which the cement is stored after it has left the manufacturer have a very great and marked effect on items 2, 3, and 4, and the testing laboratory is frequently called upon to check these properties.

In making either a neat mix, which is a mixture of cement and water, or a mortar mix, which is one of cement, sand, and water, the following method from the A.S.T.M. specifications should be followed.[3]

The quantities of dry materials to be mixed at one time shall be 500 grams for neat cement mixtures and not less than 1000 grams nor more than 1200 grams for mortar mixtures. The proportions of cement, or cement and sand, shall be stated by weight in grams of the dry materials; the quantity of water shall be expressed in milliliters. The dry materials shall be weighed, placed upon a non-absorbent surface, thoroughly mixed dry if sand is used, and a crater formed in the center, into which the proper percentage of clean water shall be poured; the material on the outer edge shall be turned into the crater within 30 seconds by the aid of a trowel. After an interval of ½ minute for the absorption of the water, the operation shall be completed by continuous, vigorous mixing, squeezing, and kneading with the hands for 1½ minutes.[4] During the operation of mixing, the hands shall be protected by rubber gloves.

The temperature of the room and the mixing water shall be maintained as nearly as practicable at 21° C. (70° F.).

Normal Consistency. As the setting of a cement is the process of hydration of the cement particles, it is necessary to determine the amount of water that is required to wet the cement properly.

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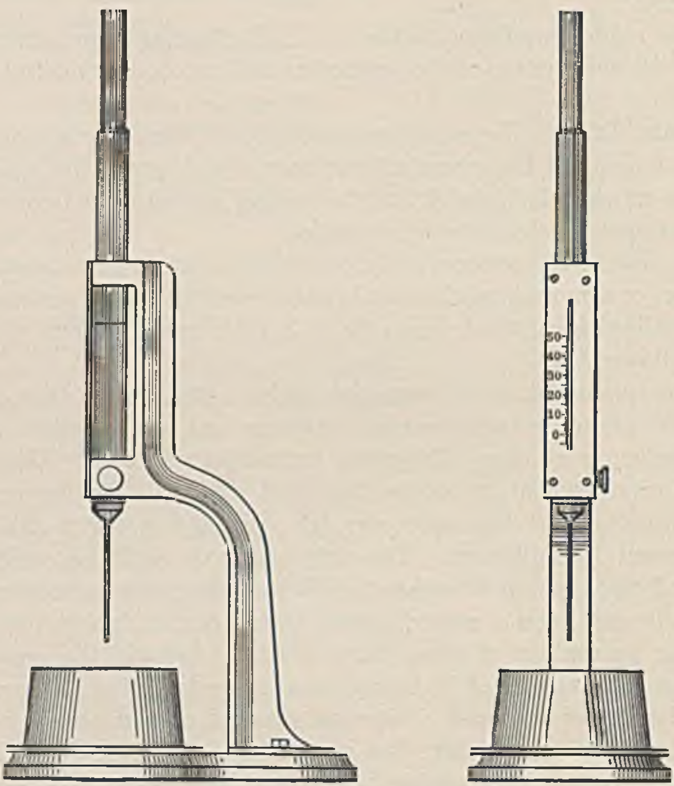
[3] A.S.T.M. Designation C77–40.

[4] In order to secure uniformity in the results of tests for the time of setting and tensile strength, the manner of mixing above described should be carefully followed.

This amount of water produces a paste of normal consistency and should always be determined in testing any cement sample, whether that sample represents a known or an unknown brand of cement. The following is the method recommended by the A.S.T.M. for this determination, making use of the Vicat apparatus (Fig. 42).



VICAT APPARATUS

Fig. 42.

Neat Paste. In making the determination, 500 grams of cement, with a measured quantity of water, shall be kneaded into a paste, and quickly formed into a ball with the hands, completing the operation by tossing it six times from one hand to the other, maintained about 6 in. apart; the ball, resting in the palm of one hand, shall be pressed into the larger end of the rubber ring held in the other hand, completely filling the ring with paste; the excess at the larger end shall then be removed by a single movement of the palm of the hand; the ring shall then be placed on its larger end on a glass plate and the excess paste at the smaller end sliced off at the top of the ring by a single oblique stroke of a trowel held at a slight angle with the top of the ring. During these operations, care shall be taken not to compress the paste. The paste confined in the ring, resting on the plate, shall be placed under the rod, the larger end of which shall be brought in contact with the surface of the paste; the scale shall then be read, and the rod quickly released. The paste shall be of normal consistency when the rod settles to a point 10 mm. below the original surface in ½ minute after being released. The apparatus shall be free from all vibrations during the test. Trial pastes shall be made with varying percentages of water until the normal consistency is obtained. The amount of water required shall be expressed in percentage by weight of the dry cement.

Standard Mortar. The consistency of standard mortar shall depend on the amount of water required to produce a paste of normal consistency from the same sample of cement. The normal consistency of the sample having been determined, the consistency of standard mortar made from the same sample shall be as indicated in the table below, the values being in percentage of the combined dry weights of the cement and standard sand.

PERCENTAGE OF WATER FOR STANDARD MORTARS

Percentage of Water for Neat Cement Paste of Normal Consistency	Percentage of Water for One Cement, Three Standard Ottawa Sand	Percentage of Water for Neat Cement Paste of Normal Consistency	Percentage of Water for One Cement, Three Standard Ottawa Sand
15	9.0	23	10.3
16	9.2	24	10.5
17	9.3	25	10.7
18	9.5	26	10.8
19	9.7	27	11.0
20	9.8	28	11.2
21	10.0	29	11.3
22	10.2	30	11.5

Standard Mix. The standard mix for the strength determination is a mortar composed of 3 parts of standard Ottawa sand and

1 part of the cement, the proportions being by weight. To this mixture is added the water, the amount of which is taken from the table. Immediately after mixing, the briquet molds are filled heaping full without compacting. The mortar is then pressed in firmly with the thumbs, applying pressure 12 times to each briquet, at points to include the entire surface. The pressure shall be such that the simultaneous application of both thumbs will register a pressure of between 15 and 20 lb. The mortar is heaped above the mold and smoothed off with a trowel, care should be taken so that the pressure applied by the trowel is not more than 4 lb. The mold is next turned over upon an oiled plate and the operations of heaping, thumbing, heaping, and smoothing off repeated. The test specimens are kept in the molds in a moist room for 24 hours, after which time they are removed from the molds and immersed in clean water kept at 70° F.

Testing. The briquets should be tested as soon as they are removed from the water. They are tested in a standard briquet-testing machine after being carefully centered. The load should be applied continuously and at the rate of 600 lb. per minute. The tensile test on a cement mortar is, of course, a qualitative one in view of the fact that neither mortar nor concrete is designed to carry any tension. But the test does show the ability of the cement to glue together the particles of standard sand, and thus the binding properties of different cements may be compared with each other and also with standard values. The average tensile strength of three standard Ottawa sand-mortar briquets for Type I shall be equal to or higher than the following:

Age at Test, days	Storage	Tensile Strength lb. per sq. in.
3	1 day in moist air 2 days in water	150
7	1 day in moist air 6 days in water	275
28	1 day in moist air 27 days in water	350

The average tensile strength of standard mortar at 28 days shall be higher than the strength at 7 days.

The 7-day test is desirable in that it shows the probable results before the end of the 28-day interval. These results are only apparent, however, because the cement can be accepted or rejected only on the result of the 28-day test. Some engineers insist that a cement must show an increase of 100 lb. per sq. in. over the 7-day results before they will accept it, although this requirement is not included in the A.S.T.M. specifications.

Time of Set. The set of cement is determined by means of either the Vicat needle or the Gillmore needle.

The cement shall not develop initial set in less than 45 minutes when the Vicat needle is used, or 60 minutes when the Gillmore needle is used. Final set shall be attained within 10 hours.

The following are alternate methods, either of which may be employed.

Using the Vicat Method. A paste of normal consistency shall be molded into the hard rubber ring as described previously, and placed under the rod of the apparatus, the smaller end of which shall then be carefully brought into contact with the surface of the paste, and the rod quickly released. The initial set shall be said to have occurred when the needle ceases to pass a point 5 mm. above the glass plate in ½ minute after being released; and the final set, when the needle does not sink visibly into the paste. The test pieces shall be kept in moist air during the test. This may be accomplished by placing them on a rack over water contained in a pan and covered by a damp cloth, kept from contact with them by means of a wire screen; or they may be stored in a moist closet. Care shall be taken to keep the needle clean, as the collection of cement on the sides of the needle retards the penetration, while cement on the point may increase the penetration. The time of setting is affected not only by the percentage and temperature of the water used and the amount of kneading the paste receives, but also by the temperature and humidity of the air, and its determination is therefore only approximate.

Using the Gillmore Needles. The time of setting shall be determined as follows: A pat of neat cement paste about 3 in. in diameter and ½ in. in thickness, with a flat top, mixed to a normal consistency, shall be kept in moist air at a temperature maintained as nearly as practicable at 21° C. (70° F.), relative humidity 90 per cent. The cement shall be considered to have acquired its initial set when the pat will bear, without appreciable indentation, the Gillmore needle $\frac{1}{12}$ in. in diameter, loaded to weigh $\frac{1}{4}$ lb. The final set has been acquired when the pat will bear, without appreciable indentation, the Gillmore needle $\frac{1}{24}$ in. in diameter, loaded to weigh 1 lb. In making the test, the needles shall be held in a vertical position and applied lightly to the surface of the pat.

A cement must not have a flash set, neither must it set too quickly, because in this case the concrete made with it could not be placed in its permanent position quickly enough, without disturbing that initial crystallization which should not be broken down after it has once started. On the other hand, the cement should set in a reasonable time; otherwise, the whole building operation would be unduly delayed.

Soundness.[5] The soundness of Portland cement is determined by means of an autoclave test on a 1-in. by 1-in. neat cement specimen of 10 in. effective gage length.

The molds for the specimen must be water tight, made of steel for stiffness, and have end plates equipped to hold stainless steel reference points during the setting period. These points are to be $\frac{1}{4}$ in. in diameter and extend into the specimen $\frac{5}{8}$ in.

The molds are filled with a 500-gram sample of neat paste of normal consistency. The filling should be done in two layers, each layer pressed in firmly around the reference points and along the surfaces of the mold in order to obtain a homogeneous specimen. The excess paste is cut off with a trowel flush with the top of the mold and the surface smoothed with a few strokes of a trowel. The completed specimen is stored in the moist room.

Twenty-four hours after molding, the specimens are removed from the moist atmosphere, measured for length, and placed in the autoclave at room temperature on a rack so that the four sides of each specimen will be exposed to saturated steam. The temperature of the autoclave is then raised at such a rate so as to bring the gage pressure of the steam to 295 lb. per sq. in. in 1 to $1\frac{1}{4}$ hours from the time the heat is turned on. This pressure is maintained for 3 hours, at the end of which period the heat supply is shut off and the autoclave cooled at a rate such that the pressure will be released at the end of 1 hour. The specimens are immediately placed in water whose temperature is above 90° C. (194° F.). This water surrounding the bars is now cooled at a uniform rate by

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[5] A.S.T.M. Designation C151–40T.

adding cold water so that the temperature of the water will be lowered to 70° F. in 15 minutes. The specimens are held in this water bath for another 15 minutes at the end of which time they are surface dried and their lengths again measured.

The difference in length of the test specimen before and after the steam bath is determined to the nearest 0.01 per cent of the effective gage length. This value is reported as the autoclave expansion of the cement. A contraction is indicated by a negative sign.

TESTING OF SAND

Comparison with Standard Sand. In testing a fine aggregate (sand) in order to determine whether or not it is fit for use in concrete construction, the A.S.T.M. standards[1] require that plastic mortar cubes (2 in.) be made up with a water-cement ratio of 0.60 and compared by means of a compression test with similar mortar cubes made with the same cement and graded standard sand having a fineness modulus of 2.40.

The strength of the fine aggregate mortar is expressed as a per cent of the standard sand mortar. The per cent specified varies with different localities.

Another method of strength test is to use the briquet testing method. In this test six tensile-test briquets are made with the sand in question and some good brand of cement, and compared with six similar briquets made with standard Ottawa sand and the same cement. The procedure of mixing employed should be the same as that described under cement testing, except that care must be used in mixing the commercial sand so that the proper amount of water is added. This may be done by noting the appearance of the Ottawa sand mix when the trowel is drawn across the mortar and adding water to the commercial sand mortar until it takes on the same trowel test.

Three of each of these sets of briquets are tested after 7 days and the remaining three after 28 days. The storage conditions of the briquets should be the same as in the cement test. The average values from these tests are compared, and the strength of the commercial sand mortar is then expressed as a percentage of the strength of the standard sand mortar. For good commercial sands, this percentage usually varies from 100 to 120. In some localities such sands are so difficult to obtain that the requirements are lowered.

Supplementary Tests. The result of such a comparative test is the only criterion that the engineer or contractor should use in the selection of sand for construction work. There are, however,

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[1] A.S.T.M. Designation C87–42.

other quick tests which partially indicate the fitness of the sand for use, and these tests serve as guides in the selection of the material. These tests are the wash test, the sodium hydroxide or colorimetric test, and the mechanical analysis or sieve test.

The first two tests, the wash and sodium hydroxide tests, are applied in order to find out the amount of harmful material, such as loam, clay, or organic compounds, contained in the sand. All these materials tend to render the sand useless for construction work. If they are present in any large amounts, the gluing action of the cement is very much decreased and a very friable and weak concrete will result. These tests are useful in very quickly determining the presence of this harmful material, thereby making it unnecessary to continue with the longer tensile tests if such preliminary tests show a poor material.

Wash Test. The wash test is made by pouring the sand into a glass graduate or bottle until it is one-third full, and adding water until the total mixture occupies about three-quarters of the volume of the receptacle. The mixture is shaken vigorously, and the observer notes the resulting color and turbidity of the wash water, also the rapidity with which this water clears, the amount of silt which settles on top of the sand, and whether or not this silt has a greasy appearance. Any large amount of loam will show up in the color of the wash water, and the presence of harmful clay will be detected after the suspended material has settled. A very rough determination to show the same thing is made by rubbing some of the sand between moist hands. Any large amount of loam can be detected by the discoloration and greasy feeling on the hands.

Hydroxide Test. The method of testing for organic impurities, in sands intended for use in concrete, as standardized by the A.S.T.M., is given below:[2]

> The test herein specified is an approximate test for the presence of injurious organic compounds in natural sands for cement mortar or concrete. The principal value of the test is in furnishing a warning that further tests of the sand are necessary before they be used in concrete. Sands which produce a color in the sodium hydroxide solution darker than the standard color should be subjected to strength tests in mortar or concrete before use.

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[2] A.S.T.M. Designation C40–33.

A representative test sample of sand of about 1 lb. shall be obtained by quartering or by the use of a sampler.

A 12-oz. graduated glass prescription bottle shall be filled to the 4½-oz. mark with the sand to be tested.

A 3 per cent solution of sodium hydroxide (NaOH) in water shall be added until the volume of sand and liquid after shaking gives a total value of 7 liquid ounces.

The bottle shall be stoppered and shaken thoroughly and then allowed to stand for 24 hours.

A standard color solution shall be prepared by adding 2.5 cc. of a 2 per cent solution of tannic acid in 10 per cent alcohol to 22.5 cc. of a 3 per cent sodium hydroxide solution. This shall be placed in a 12-oz. prescription bottle, stoppered, and allowed to stand for 24 hours, then 25 cc. of water added.

The color of the clear liquid above the sand shall be compared with the standard color solution prepared as in preceding paragraph or with a glass of color similar to the standard solution.

Solutions darker in color than the standard color have a " color value " higher than 250 parts per million in terms of tannic acid.

Mechanical Analysis.[3] The mechanical analysis or sieve test is made for the purpose of determining the grading of the material. The term sand is applied to fine aggregate of such size that all particles will pass a ¼-in. sieve. A sand that contains grains all of one size is not so desirable as a sand that is well graded. The well-graded sand will pack better because the percentage of voids is less. Hence, a sand for construction use should be well graded

U. S. STANDARD SERIES

Designation micron	No.	Sieve Opening	
		in.	mm.
4760	4	0.187	4.76
2380	8	0.094	2.38
1190	16	0.047	1.19
590	30	0.0232	0.59
297	50	0.0117	0.297
149	100	0.0059	0.149

TYLER SERIES

No.	Sieve Opening	
	in.	mm.
4	0.185	4.699
8	0.093	2.362
14	0.046	1.168
28	0.0232	0.589
48	0.0116	0.295
100	0.0058	0.147

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[3] A.S.T.M. Designation C136-39.

and also should be relatively coarse. In performing this test, a 500-gram sample of sand is passed through a nest of six sieves. Sieves in the United States Standard Sieve Series are designated in the A.S.T.M. specifications. These sieves have allowable tolerances in the size of opening which permits the use of sieves in the Tyler Sieve Series. The sieves in the two series are given above; the numbers refer to the wires per inch used in making the sieves. Either hand sieving or some mechanical sieving method may be used, the sieving being continued until not more than 1 per cent by weight of the residue passes any sieve during 1 minute. If the Ro-Tap machine or some similar device is used, between 3 and 4 minutes will suffice for the ordinary sample. The amount of sand held on each of the different sieves is then weighed and expressed as a percentage of the total weight used.

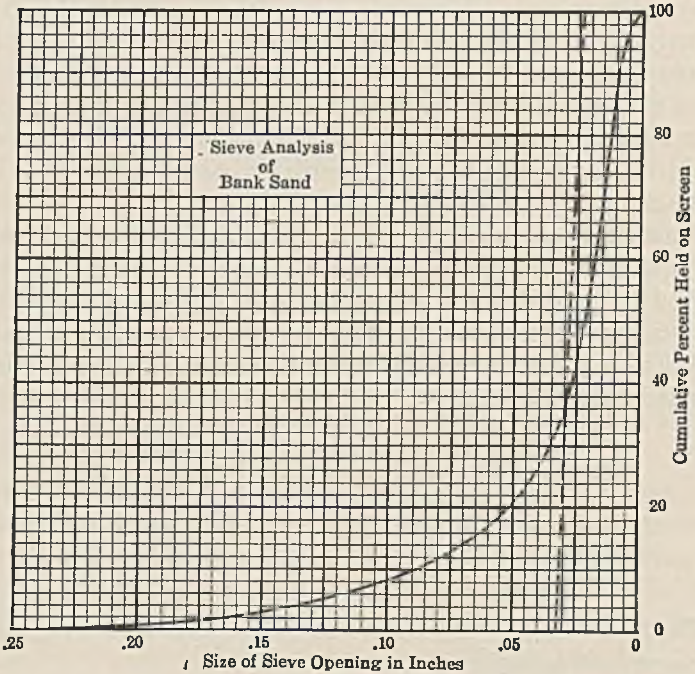

Fig. 43. — Graph for mechanical analysis.

The results may be used comparatively in a table, or a plot may be made, in which case different samples of sand may be very easily and quickly compared. A sample plot is reproduced

(Fig. 43), in which the horizontal values are screen openings measured in inches and the vertical values are cumulative percentages held on the screens. By cumulative percentage is meant the total amount of the sand which would remain on the sieve if only one sieve were used for testing the whole sample. To get the cumulative percentage, therefore, it is necessary to add to the amount held on a given sieve all the percentages that represent material held on sieves coarser than the one in question.

The dotted line represents the screen analysis for standard Ottawa sand. Thus, a comparison of other sands with the standard sand may be roughly made, since the areas under the curves roughly indicate the strength of the mortars. This method should be used advisedly and only by those skilled in reading these charts. Harmful constituents introduce disturbing factors. This sieve analysis is valuable, particularly in checking the sand used from day to day, to see how much variation there is, especially if the run of the bank is being used.

Some engineers prefer to compare the results of the sieve analysis with definite limiting values which, from experience, have proved to be desirable. Many job specifications are drawn up conforming to this idea. The table below is a general specification with limiting percentages which may be altered within the limits to suit local conditions.

	Per Cent
Passing a ⅜-in. sieve	100
Passing a No. 4 sieve	85 to 100
Passing a No. 16 sieve	45 to 80
Passing a No. 50 sieve	2 to 30
Passing a No. 100 sieve	0 to 5

The percentage passing a sieve may be obtained from the cumulative percentage by simple subtraction.

Fineness Modulus. Another method of comparison in the size analysis of sand is by means of the fineness modulus. This term is defined as the sum of the percentages in the sieve analysis divided by 100 when the sieve analysis is expressed as cumulative percentages coarser than each of the sieves Nos. 100, 50, 30, 16, 8, 4. For good sand the value for the fineness modulus should lie between 2½ and 3½, the coarser sands having the larger modulus. This comparison indicates nothing concerning the gradation of the sand in the different sizes. Two sands may have the same fineness modulus and yet, owing to intermediate size gradation, be very different in their usefulness for concrete construction.

Data for the sieve test of a sand and a gravel follow.

FINE AGGREGATE

Tyler Sieve No.	Weight Retained	Per Cent of Sample	Cumulative Per Cent
4	41.6 g.	4.16	4.16
8	135.5	13.57	17.73
14	135.9	13.60	31.33
28	214.4	21.50	52.83
48	257.6	25.80	78.63
100	146.2	14.65	93.28
pan	67.2	6.73	277.96
	998.4 g.	Fineness Modulus = 2.78	

COARSE AGGREGATE

Screen Size	Weight Retained	Per Cent of Sample	Cumulative Per Cent
$\frac{3}{4}$	372 g.	11.6	11.6
$\frac{3}{8}$	1632	50.7	62.3
$\frac{3}{16}$ No. 4	1215	37.7	100.0
	3219 g.		173.9

The sum 173.9 is increased by 500, because each of the sieves smaller than the No. 4 would have 100 as its cumulative per cent. The total sum is therefore 673.9 for this aggregate. The fineness modulus is 6.74.

The fineness moduli of the two samples listed are typical of good concrete material. For large and well-controlled concrete projects the fineness modulus offers a good method of controlling the variable day-to-day run of size of both sand and gravel. An ideal grading curve for several different aggregates is sometimes established for a particular job. By using the fineness moduli of the several aggregates a combination is obtained which is not only economical but is one which produces an easily workable mix.

TESTING OF CONCRETE

General. Concrete is the term applied to the mass of material resulting from the plastic mixture of coarse and fine inert aggregate particles with cement and water, which mass hardens with time and under the proper curing conditions. Research has shown that the compressive strength of concrete is dependent upon the proportions of the mix, the amount of water per volume of cement, and the general technique of mixing. In the determination of the compressive strength of concrete, the laboratory may be called upon to perform either of two functions.

First, cylinders or cores of hardened concrete from some outside source may be submitted for test. The province of the laboratory is then merely that of conducting a proper compression test without regard to the previous fabrication of the test pieces. This is a routine test, and the procedure is covered in the subsequent discussion.

Second, the separate aggregates together with the cement are often submitted and the laboratory must carry out the complete fabrication of the test cylinders, giving due regard to the proper control of mixing, molding, and curing. In the following pages this important aspect of the testing laboratory will be discussed. As the subject is very extensive, only the main and important points which have an educational value in a general testing materials course will be considered. A detailed and complete procedure with numerous references to the literature on the subject may be found in the A.S.T.M. Standards, Designation C39–42.

Proportioning. After the fine and coarse aggregates in room dry condition and the cement have been assembled, the proportions of the mix for a predetermined strength may be found. The quantities of materials may be expressed as 1 volume of cement, ____ volumes of fine aggregate, and ____ volumes of coarse aggregate, or by similar proportions expressed in weight units instead of volume. The exact proportions are often found by a trial-and-error method in which experience plays an important part in the determination. As a starting point, the proportion of fine to coarse aggregate may be taken in the ratio of 1 to 2 and the cement content varied to suit the desired strength.

Size of Specimen. Compression tests of concrete are made on cylinders of diameter equal to one-half the length. The standard size is 6 by 12 in. where the coarse aggregate does not exceed 2 in. in size. For larger aggregates, 8- by 16-in. cylinders are used. Cylinders 3 by 6 in. in size are very convenient if the aggregate does not exceed $\frac{3}{4}$ in.

Mixing. The size of the batch should be such that a small quantity of concrete is left over after a single cylinder has been molded. This may be conveniently determined, for most proportions, by taking the amount of coarse aggregate equal to the volume of the test cylinder. The concrete is mixed by hand in a shallow metal pan using a 10-in. bricklayer's trowel which has been blunted by cutting off about 2 in. of the point. The procedure of mixing is as follows:

1. The cement and fine aggregate are mixed together dry until the mixture is of uniform color.
2. The coarse aggregate is added and mixed dry.
3. Sufficient water is added to produce concrete of the required consistency.
4. The mass of material is mixed thoroughly until the resulting concrete is homogeneous in appearance.

Consistency. The consistency of plasticity of the batch of concrete should be measured immediately after mixing either by the slump cone method or by the flow table.

The slump cone is a metal mold in the form of the frustum of a cone with a base 8 in. in diameter, the upper surface 4 in. in diameter, and the altitude 12 in. It has suitable handles so that it may be held securely in place while being filled.

The mold is filled in three layers, each approximately one-third the volume of the mold. In placing each scoopful of concrete the scoop should be moved around the top edge of the mold, in order to insure an even distribution of concrete within the mold. Each layer of concrete is rodded with 25 strokes of a $\frac{5}{8}$-in. rod, 24 in. in length, bullet pointed at the lower end. The strokes should be distributed in a uniform manner over the cross-section of the mold and should penetrate the underlying layer. The bottom layer should be rodded its full depth. After the top layer has been rodded, the surface of the concrete is struck off with a trowel so that the mold is exactly filled. The mold should be immediately removed by raising it carefully in a vertical direction. The slump is determined by noting the difference between the height of the mold and the vertical height of the mass of concrete. The slump is recorded in terms of inches of subsidence of the specimen.

The flow table test is an alternate method of determining the consistency of the concrete. This method requires a more elaborate equipment than the slump test and will not be discussed.

Molds. The molds in which the concrete cylinders are cast are usually made of metal. Paraffined cardboard molds may be used if care is exercised in manipulation. The molds should be placed on a metal base plate and should be oiled with a heavy mineral oil before using. The molds ought to be tight so that mixing water will not escape when the mold is filled with concrete.

Molding the Specimens. The molds are filled in the same manner as in the slump test, the concrete being placed in three separate layers and each layer rodded 25 times with a bullet-nosed rammer. After the top layer has been rodded, the surface of the concrete is struck off with a trowel and covered with a glass plate which later may be used in capping the test specimens.

Capping the Specimens. Two to four hours after molding, the test specimens may be capped with a thin layer of stiff neat cement paste. A glass or metal plate is worked on the cement paste until the plate rests on the top of the mold. Another method often followed is to allow the cylinder to harden as cast and at some later time to cap the rough end of the cylinder with a face, using plaster of Paris of thick consistency.

Curing the Specimens. Concrete test specimens are removed from the molds 24 to 48 hours after molding and stored in a moist room which is kept at 70° F. and 100 per cent humidity. Damp sand storage may be used if a moist room is not available.

Testing. The usual age of the cylinder at the time of compression test is 28 days. The tests should be made upon the cylinders immediately upon their removal from the curing room. Two diameters should be measured at right angles near the midlength of the cylinder and the area computed from the average.

The load should be transmitted to the cylinder by means of an adjustable bearing block on top of the specimen. The load should be applied uniformly without shock at the rate of 0.05 in. per minute.

The unit compressive strength is calculated in pounds per square inch. The type of failure and the appearance of the concrete should be noted. (See page 63.)

Comparisons. There are no A.S.T.M. specifications for the strength of concrete and, therefore, comparisons of the tested material can be made only in the light of experience and with accepted commercial practice. This is usually accomplished by comparing the compressive strength obtained for a certain water-cement ratio, obtained from the mixing data, with accepted standard values.

A graph showing the trend of the 28-day compressive strength of concrete with varying water-cement ratios is shown in the Appendix and may prove helpful in making comparisons of strengths.

TIMBER TESTING

General Considerations. The peculiarities of timber are so thoroughly outlined in various standard texts on materials that it would seem almost unnecessary to elaborate to any extent on methods employed in timber testing. Experience has shown, however, that timber tests, as frequently conducted, are inadequate in their scope. Hence, a special section devoted to the items to be noted in such tests seems justifiable. Timber may be tested under tensile, compressive, or transverse loading.

Tensile Tests. Tensile tests in a direction across the grain present few difficulties, but the results are of little value. On the other hand, tensile tests lengthwise of the grain are extremely difficult to perform satisfactorily. The problem of holding the specimen presents difficulties not too easily overcome. The strength of the wood elements in a longitudinal direction is so great in comparison with their resistance to shear past each other in the same direction that tensile tests commonly result in the fibers pulling out of the specimen from end to end, rather than in a true tensile rupture. Fortunately timber design in the past has not required exact knowledge of the tensile strength of wood.

Compressive Tests. Timber may be tested in direct compression, either perpendicular or parallel to the grain. Very little difficulty attends either method of test. In tests across the grain, the instant of actual failure is difficult to determine. Many woods, when subjected to a stress perpendicular to their grain, merely compress, without evidence of actual rupture. A total compression of 2 to 5 per cent is sometimes used as the criterion of failure under such conditions. The application of load over a portion of the total area greatly influences the results of tests with lateral pressure on wood. This is due to the fibrous structure of the material. The fibers under the loaded area transfer some of the load to the surrounding area which is not subjected to direct stress.

The computation of stress, based upon the area apparently under pressure, will always result in a value higher than the real lateral resistance of the wood as determined by tests where the entire surface of the test block is loaded.

Transverse Loading. Timber tested in the form of beams may be loaded at a single central point, as in Fig. 44*A*, or by load application at two points, as in Fig. 44*B*. The single-point loading is the more common method. When it is very desirable to study longitudinal shear, the two-point loading is more effective.

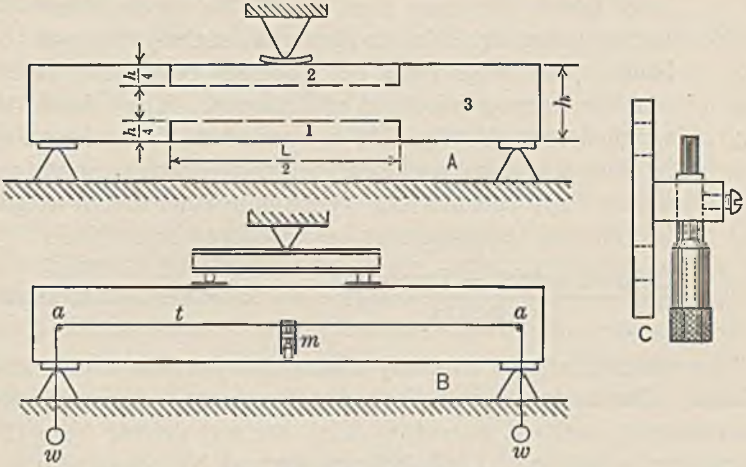

FIG. 44. — Transverse loading.

Preliminary Observations. Certain preliminary observations should always be made if the results of the test are to have any real significance. Among these are:

1. " Density " of the timber as indicated by the rate of growth and the percentage of summer wood.[1] This estimate is made along a radial line in the third, fourth, and fifth inches from the center of the tree. If the center cannot be located, the ring count and summer wood estimate are made over 3 in. that seem fairly to represent the timber.
2. The weight per cubic foot of the sample.
3. The presence and magnitude of irregularities which may affect the strength of the piece under observation, such as knots, pitch pockets, shakes, wane, decay, diagonal grain, mechanical injury, and so forth.
4. The location of these defects. For this purpose it is common

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[1] Dense timber must meet one or the other of the following requirements: (*a*) show 50 per cent or more summer growth; (*b*) show at least ⅓ summer growth and 6 or more rings per inch.

to divide the beam into three volumes, laid out and numbered as in Fig. 44*A*. Defects in volume 3 are not in general recorded unless very serious.

5. The moisture content should always be determined near the point of fracture at the termination of the test. In large beams this may most readily be accomplished by boring holes, say 1 in. in diameter, entirely through the beam. The chips from such borings reasonably represent the average condition of the wood. They should be weighed immediately. At a convenient time, they may be placed in a hot-air oven maintained at a temperature between 210 and 215° F. When no further loss of weight is observed, the chips may be considered dry. Then

$$\frac{\text{Original weight} - \text{Dry weight}}{\text{Dry weight}} \times 100 = \text{Per cent moisture}$$

The observer should carefully distinguish between *checks* and *shakes*. Checks are due to drying. If not continuous for any great length, and not over-deep, they are not defects from the standpoint of strength. Shakes are formed by the separation of the wood along the annual layers. They are always serious and constitute a defect in almost any location.

Time Effect. The time factor is extremely important in the testing of timber. Wood shows continuously increasing deformation under an extended period of loading. Under impulse or load extending over a short period, the behavior of wood, especially if carefully seasoned, is more or less like that of an elastic material. As a structural material, however, it does not seem proper to consider wood to be elastic. During recent years the best authorities have ceased to quote an elastic limit for timber.

The apparent modulus of elasticity for timber will obviously be greatly affected by the time factor. Rapidly conducted tests will, in general, yield a value for modulus of elasticity very appreciably higher than that obtained from " long-time tests."

Full-Size Specimens. Whenever possible, timber tests should be made on full-size specimens. It is only under such circumstances that it is possible to obtain values really representative of conditions which are met in engineering practice. A small specimen may approximately represent the metal of a fair-sized heat if proper precautions be observed in its selection. A small piece of wood, in general, will not fairly represent even the timber from which it is cut. It is doubtless true that the results of tests on small specimens may be interpreted by the experienced so that they may become applicable in the broader sense; nevertheless, they can never completely replace the results of tests on the full-size beam or column.

Transverse tests on timber beams often introduce nice problems of deflection measurement. A simple deflectometer, such as that shown in Fig. 50, may be used in some cases when the distortion of the supporting device may be considered negligible. For full-size beam tests with spans from 12 to 20 ft., the writers have found the method suggested by Fig. 44*B* to work very satisfactorily. Nails (*aa*) in the timber, over the knife edges, on the center line of the face of the beam, serve to support a wire or strong, smooth thread (*t*). This is held taut by small weights (*ww*) and serves as a datum line representing the original center line of the beam. Theoretically, this line should coincide with the neutral plane of the beam, but slight lack of agreement is insufficient to introduce appreciable error. A bracket carrying the micrometer head (*m*) is attached to the face of the beam on the vertical center line of the span or at any other position at which it may be desired to observe the deflection under load. The details of this support are shown in Fig. 44*C*. Under the initial conditions, this micrometer may be adjusted so that it just touches the thread, thus establishing a zero reading for the instrument. The difference between this initial setting and any subsequent reading indicates the deflection at the point under observation. If care be taken to insure approximate parallelism between the end of the micrometer screw and the reference thread, there is no difficulty in obtaining very satisfactory results with this device. Experience has shown that, with an observer of average eyesight and skill, individual settings will give readings varying not more than 0.001 in. and the agreement is generally closer than that value. For the best results, it is desirable to arrange duplicate apparatus on the two vertical faces of the beam. The mean of the results of the two micrometers will thus give a very good average for the deflection. If extreme precision be needed, the use of a wire makes it possible to employ electric contact indication in setting the micrometer. Under ordinary conditions, this is not considered necessary.

MEASURING DEVICES

Selection of Instrument. Much care should be used in the selection of the measuring device for any test. The choice of the instrument depends upon two things: simplicity of operation and accuracy of reading. Complicated devices that require much initial adjustment and careful attention should be avoided unless a high degree of precision is demanded in the test. The properties desired in the test, therefore, should be clearly outlined and the probable deformations expected roughly estimated, so that the selection of the measuring device may be more intelligently made.

Measurement of Diameter. In testing a specimen of circular cross-section the measurement of the diameter is of great importance because all values of stress are expressed in terms of the original area. If the specimen be a rough rolled piece to which no subsequent finishing process has been applied, a micrometer caliper should not be used. In this case, ordinary spring calipers will suffice, but measurements of diameter should be taken at several places on the bar and the average diameter determined. If the specimen has been finished by being turned in a lathe, a micrometer may be used. As this instrument is employed in several types of measuring devices, the method of reading will be explained at this time.

Micrometer Reading. The pitch of the micrometer screw is such that the distance traversed along the stationary frame by the moving barrel, in making one turn, is $\frac{1}{40}$ in. or 0.025 in. This corresponds to one division on the stationary frame, and therefore four of these divisions represent 0.100 in. The bevel edge of the moving barrel is graduated into twenty-five parts, and as one complete revolution of this barrel is equal to 0.025 in., one division of the barrel is equal to 0.001 in. In order to read the setting as shown in Fig. 45, first note the last division that shows on the stationary frame, noting that 0, 1, 2, etc., represent tenths of inches; the reading would be 0.200 in. plus one

Fig. 45. — Standard micrometer head.

division, which means 0.225 in. To this must be added the number of thousandths showing on the barrel read at the fixed reference line. This reading is 16, making the total reading 0.225 + 0.016 or 0.241 in. If a division line does not fall exactly at the fixed reference line, tenths of a space on the barrel may be estimated. This will give an additional decimal place.

Use of Dividers. The simplest device for the measurement of a distance consists of dividers and a steel scale graduated in hundredths of an inch. In using this for a large number of measurements, a handy method is to clamp a block to the scale so that one point of the dividers coincides with an even inch division. By this means measurements may be taken quickly and accurately, as the operator does not have to check up the coincidence of both points of the dividers. The measurement should be taken from some intermediate division, never from the end of the scale.

Yield-Point Indicator. If a distance measurement is desired slightly better than the nearest 0.01 in., a simple lever multiplying device, like the one pictured in Fig. 46, may be used. The relative movement of the two points may be read from the scale. In the actual instrument the smallest division represents 0.001 in. This device is often employed in finding the deformation of a material at the yield point, and an adaptation of this method may be used in a deflectometer which will be described later.

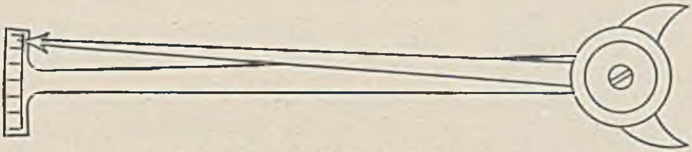

FIG. 46. — Yield-point indicator.

Micrometer Adaptation. A measuring device which is applicable to different kinds of testing is shown in Fig. 52. This consists of two standards, fastened to the specimen near the bottom, and containing sockets for holding the balls on the end of the rods. The two rods extend up through the micrometer frames, guided by insulating bushings. In this particular case, the micrometers are of a special type reading directly to 0.0001 in. In obtaining a reading, the micrometer is turned until contact is made with the upper end of the rod. The operator can tell exactly when this occurs, as the contact closes an electrical circuit in which there is a buzzer. For this purpose the upper half of the rod is insulated from the lower half and also from the upper holder, through which it passes. This device gives very good results, especially on a compression specimen. An ordinary micrometer may be used in place of this special one, in which case the precision of the apparatus is reduced somewhat.

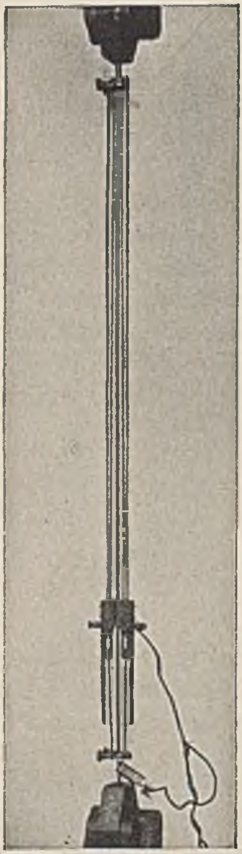

Fig. 47. — Wire extensometer.

A somewhat similar device is used in the wire extensometer shown in Fig. 47. This may be made for any desired gage length by varying the length of rod, the one in the cut being designed for a 30-in. gage length. The clamps are rigidly fastened to the wire by means of thumb screws, and the change of length between the clamps is measured by the micrometers. Contact between the micrometer and the rod is indicated by the closing of an electrical circuit, as in the instrument previously described. This device is a double extensometer measuring the amount of distortion on each side of the specimen. This is desirable for careful work in wire testing, although fairly satisfactory results may be obtained by the use of a single extensometer, which would eliminate one of the micrometers and rods in the picture.

Use of Dial Indicators. As will be seen in Fig. 12, dials may be substituted for the micrometers, in which case no electrical circuit is needed. The dials may be read more quickly than the micrometers, and the readings obtained are as accurate as when the ordinary micrometer is used. This principle is applicable for any gage length, and small changes in length may be measured in an original gage length of several feet. For these large gage lengths, the rods in the instrument may be made of wood with suitable metal studs at the ends for the ball connection.

Special Requirements. For the determination of the elastic limit of a material, especially with 2-in. or 8-in. gage length, a special type of measuring device is commonly employed. The A.S.T.M. recommends that, when elastic limit is to be reported, measurements of deformation be made to at least 0.0001 in. for every inch of gage length. This means that, when the standard 2-in. gage length specimen is being tested, elongation measurements should be taken to at least 0.0002 in. Many different types of instruments may be used for this work. All of them have two outstanding features: first, that they are attached to and held by the specimen and are not supported externally; second, that they may be removed from the specimen when the elastic limit has been reached.

Some of these are the products of various testing laboratories; others are commercial instruments and may be purchased under trade names.

Berry Strain Gage. The Berry strain gage (Fig. 48), invented by Professor H. C. Berry of the University of Pennsylvania, is one of the best known of the latter type and will be described in detail. It consists of a frame made of two pieces of Invar steel, into one end of which is securely fastened a conical point, *A*. Invar steel is used to minimize the effect of the heat of the operator's hand. At *B* there is a V-shaped bearing, which is the fulcrum point for the lever, shown dotted. On one end of the lever *C* is a conical point similar to *A*, and the other end actuates the plunger of an Ames dial. The dials are so constructed that one scale division of the dial represents a 0.001-in. movement of

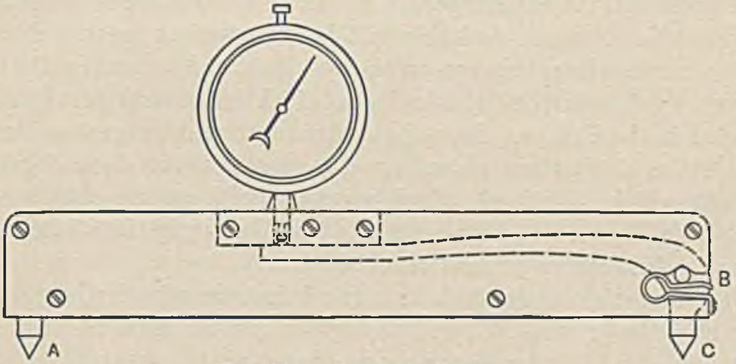

FIG. 48. — Berry strain gage.

the plunger. Since the lever ratio is 5 to 1, one scale division of the dial represents one-fifth of 0.001, or 0.0002-in. relative movement of the conical points which are fitted into center punch holes, or holes specially drilled in the specimen. One-half of a scale division may be readily estimated. This represents 0.0001 in. in the gage length used, which is generally either 2 in. or 8 in. Closer estimation than this should not be used, unless care is taken in the interpretation of the results, because the makers of the dials guarantee them only to the nearest scale division. However, calibration has shown that they are usually more accurate than this guarantee.

For the ordinary determination of elastic limit, where the shape of the load-deformation curve only is desired, the conical points of the instrument may be placed in shallow center punch holes and the instrument fastened to the specimen by means of a suitable clamp provided for that purpose. If a more precise determination is required, holes may be drilled into the specimen, with a No. 55 drill. In this case there is a ring of contact between the edges of the holes and the conical points, so that less variation in readings will ensue. A more desirable but less convenient method is to place hardened steel clamps on the specimen and insert two Berry gages, one on each side, into holes which have been previously drilled in the clamps. Some jig or fixture should be used, so that when the clamps are placed on the specimen the desired gage length will be obtained. Such a set-up, without the clamps, is shown in Fig. 8. In this figure the two Berry gages are inserted directly into center punch holes.

The investigator should bear in mind that the effective length of the short lever arm, *BC*, will be slightly greater when the instrument is used in center punch marks than it will be when seated in drilled holes. If the lever ratio is the correct 5 to 1 for the first case it will be incorrect in the other. It is the practice of the writers to maintain separate instruments specially calibrated for use in the two manners outlined.

When it is not possible or desirable to clamp the Berry gage to the specimen, as in testing a large structure, the points of the instrument may be inserted into properly drilled holes in the structure and a reading taken, the instrument being held in the operator's hand. By this means deformation measurements may be taken and repeated for any number of different pairs of holes in the structure. With a little practice in adjusting the pressure applied in seating the conical points in the gage holes, check readings may be obtained within 0.0002 in. Besides the 2-in. or 8-in. type of Berry strain gage, there is also available an adjustable 20-in. type, which has longer points, so that reinforcing steel, when imbedded in concrete, may be investigated.

Compensating Extensometer. An instrument intended for the determination of elastic deformations is shown in Fig. 53. It was devised and constructed in the Testing Materials Laboratory of the Massachusetts Institute of Technology. It consists of two aluminum yokes, which are of open construction so that they may be easily removed from the specimen. Through these yokes are inserted set screws with hardened points, for attaching the device. The attachment is not direct, however, the set screws being inserted in holes in clamps which are fastened securely to the specimen.

These clamps are in two parts and are fitted with split, removable bushings so that different-sized specimens may be accommodated. The bearing of the bushing on the specimen is at three areas, spaced equally around the circumference. Instead of being designed to make point contact, each bearing is about $\frac{1}{4}$ in. in circumferential length, being slightly rounded in the other direction.

The thumb nuts holding the two halves of the clamps together are fastened down against spring washers, so that, if any slight change of shape of the specimen should occur, that change will be positively taken care of by the take-up of the washers. At equal distances on each side of the holding set screws in the yokes are seats for the attachment of the ball ends of the rods which hold the two yokes apart. These seats are formed by the ends of two cup-point set screws, which are hardened and which fit snugly around the ball. The two steel rods have a ball at each end and are adjusted in the instrument by bringing the cup-point set screws in contact so that there is no play, but still a free turning motion is possible. The distance from center to center of the balls is the same as the gage length, generally either 2 in. or 8 in., although rods of different length may be provided for special work. The upper end of the right-hand rod in the cut bears against the plunger of an Ames dial. The left-hand rod is essentially a link of constant length, and the upper and lower balls act as fulcrums about which the two yokes swing. It can be readily seen that any relative movement between the upper and lower yokes in a direction along the bar will cause the dial plunger to be moved. This movement is twice the actual relative displacement of the yokes. Differences in the extension of the two sides of the specimen are compensated for by the ball action of the rods in their sockets, and by the manner in which the end of the rod and the plunger of the dial bear upon each other, the latter action being that of a sphere on a flat surface.

This instrument forms a four-bar linkage, and slight rocking movements can occur around the mid-points of the yokes without affecting seriously the accuracy of the instrument. By using a special Ames dial, in which one scale division represents a 0.0001-in. movement of the plunger, very satisfactory results can be obtained.

Wire-Wound and Optical Types. There are also other types of instruments which may be used for this class of work. Among them are the wire-wound type of apparatus, the mirror type, and the type that employs a telescope by which the deformations are read from a graduated scale, which is caused to move by the extension of the specimen. Most of these instruments employ two yokes, which are fastened directly to the specimen by three clamping screws inserted in punch marks in the specimen. In the wire-wound type, a wire causes movement of a hand on a graduated dial. This might be shown if the Ames dial in Fig. 53 were removed and a fixed dial substituted. Instead of the rod bearing against the plunger of the dial, a wire would be fastened to the lower yoke, passing up and around the spindle of the pointer of the dial, and the wire kept taut by means of a weight. If this were the case, it would be better to invert the instrument so that the dial would be attached to the bottom yoke, and then the weight could hang freely. The mirror type shows practically the same construction, in that the mirror is caused to tilt by the relative movement of the two yokes and a beam of light is projected on a suitable scale.

All these instruments have their advocates, and it is not the province of this discussion to attempt to suggest the best type. Each particular job may require its own peculiar measuring device, the only limitations being those of reasonable accuracy.

High-Precision Types. One of the most satisfactory high-precision devices available at the present time is the **Huggenberger**

tensometer illustrated by Fig. 49. This is a compound lever mechanism with an ultimate ratio of about 1000 to 1. Since the position of the pointer on the scale can be read accurately to 0.01 in. this device is satisfactory in recording deformations to well within 0.00001 in. It may be clamped directly to the test piece without introducing any of the difficulties noted in the following paragraph. The type shown weighs but $2\frac{1}{4}$ oz. A slightly heavier type is built with a little greater refinement of design and still a third type weighing only $1\frac{3}{4}$ oz. which has a combined lever ratio of about 300 to 1. This last type is very useful where somewhat greater ranges of deformation are to be studied. Obviously these instruments are practicable for study of small strains only. They are obtainable commercially for use with gage lengths from 1 cm. up. The most common type in use in this country is designed for a 1-in. gage length. When so used it becomes a true strain gage. For special research work where ultra-refinement is desired, a device which employs interferometer methods has been used successfully. A precision of one-millionth of an inch is easily obtainable by this method. This precision is beyond that of ordinary laboratory methods, and requires special precautions, because heat and cold will cause changes in deformation much larger than this value.

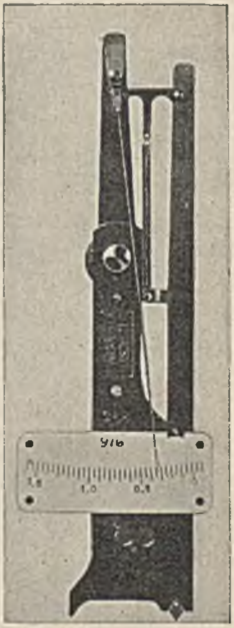

Fig. 49. — Huggenberger tensometer.

Special Precautions. Under some circumstances the method of attachment of an extensometer may have a very appreciable effect on the results of a test. This disturbance is so great in some cases that have come to the attention of the writers that a displacement of the proportional limit as great as 20 per cent has resulted. Heavy instruments require tight clamping. If these clamping pressures are exerted over a small area, often approaching a point in dimensions, the intensity of lateral stress may produce an area with resultant stresses above the yield of the material when the stress in the remainder of the gage length is well within the elastic range. This condition will produce a load elongation graph in which the form is greatly distorted and the proportional limit decidedly lowered. If the instrument be attached directly to the test piece by means of set screws, surface discontinuities will result. Such a condition will produce high local stress concentration which will be additive to the disturbance noted above. If it is necessary to use heavy measuring devices the pressure should be distributed over an appreciable area and point contact avoided whenever possible.

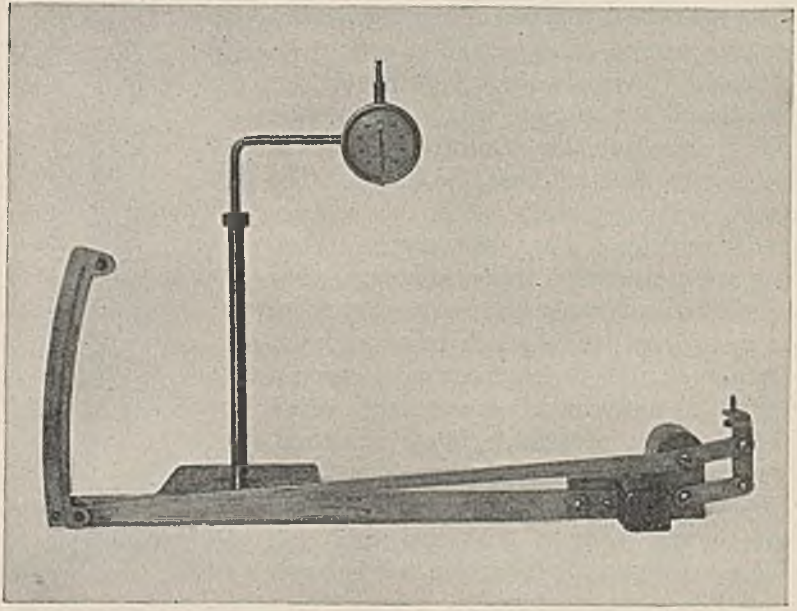

FIG. 50. — Simple deflectometers.

Deflectometers. For the measurement of center deflection in a beam under transverse load, wires may be stretched taut between nails driven into the beam at the neutral axis over the supports. This device is shown in Fig. 44, where it is described in detail.

Another type of deflectometer which may also be used is shown in Fig. 50. A description of this is hardly necessary as the device is so simple in form. In this instrument, by means of the lever, the deflection is read on the scale, which is graduated in hundredths of an inch. Each division is so large that one-tenth of a space may be estimated.

The other instrument in the figure is an adaptation of a dial indicator on which is placed a special back and the whole attached to a rigid frame. In this instrument, deflection readings may be read directly to thousandths of an inch, and estimation of tenths of a space may be made if desired. The adjustable standard permits resetting, making possible precision readings over a wide range.

Torsion Meters. For the measurement of angular distortion in a torsion test, two sectors (Fig. 15) are securely fastened to the bar, a gage length of an integral number of inches usually being chosen. If the radius of the sector is made 12 in., the edge of the sector may be graduated in degrees and each degree divided into five parts, without making the divisions too small. A reference line of fine silk is stretched between two fixed points on the machine, and readings of the angular displacement of the sectors are taken as the bar is twisted. Care should be used in placing the reference line so that it is parallel to the axis of the shaft and just clears the faces of the sectors. In this way, parallax in reading may be avoided, and check readings may be made to one-tenth of a division, corresponding to 0.02 degree.

For very special work, telescopes may be mounted on the sectors, and the angular swing of the latter read on a scale which is erected some distance away from the specimen. In this case, the angle of distortion may be read to very fine limits, but in general this refinement is not necessary.

Calibration of Measuring Instruments. Moving parts are always subject to wear. In some designs special provisions are made either to compensate for this or readily to correct for it by adjustment. When the accuracy of a measuring instrument depends upon the ratio of lever arms it is not always possible to adjust for wear compensation. Use in such cases may necessitate the modification of the instrument constant. The points of the Berry gage become dulled in use and it is frequently necessary to grind them. This operation on point A, Fig. 48, has no effect on the operation of the system. A shortening of point C, on the other hand, results in an increase of the lever ratio. The points are easily removable, and it is possible to correct the ratio by inserting a washer of the proper thickness between this point and the main part of the lever. Since the readings with this instrument are correct to 0.0001 in. only, it is sufficiently accurate to calibrate the instrument by means of high-grade micrometer screws. As previously noted, the Berry gage should be calibrated under the condition for which it is used, that is, either for use with drilled holes or for use with center punch marks. The same gage constant will not apply under both conditions. Reference to the Huggenberger tensometer, Fig. 49, will show that as the contact points wear the short arm of the first lever will be changed in length. The construction of the instrument is such that adjustment cannot be made to compensate for this. Consequently it is necessary to calibrate this instrument at very frequent intervals and determine the true gage constant. This constant will continually increase. When calibrating this device it is necessary to use an accuracy which can best be attained by some sort of interferometer method.[1] Beside the changes in the constant of the instrument due to wear, it is affected by other factors, varying slightly by the pressure of clamping and even by the hardness of the material on which the instrument is being used.

[1] Characteristics of the Huggenberger Tensometer, by R. W. Vose, *Proceedings* A.S.T.M., Vol. 34.

VERIFICATION OF TESTING MACHINES

General Accuracy. Most of the standard types of testing machines are accurate to within ½ per cent when sold by the manufacturers. With proper care and use, they may be expected to maintain this degree of accuracy for many years. From time to time, however, it is desirable to check machines, particularly when the acceptance of material is dependent upon the results of the tests made by means of them. Research should naturally be carried out only on machines whose accuracy is beyond challenge. Court evidence might be questioned unless the expert could certify to the accuracy of his testing device.

When it is a question of checking or calibrating machines of small capacity, the problem is reasonably simple; the difficulty builds up rapidly as the capacity of the machine increases.

A.S.T.M. Specifications.[1] For any loading range a testing machine shall be verified by at least five test loads. The difference between any two successive loads shall not exceed one-third the difference between the maximum and minimum test load. The error at any load shall not exceed 1 per cent except in the case of the Brinell hardness tester where 3 per cent is allowed.

It is recommended that testing machines in constant use be verified at intervals of six months; machines used intermittently should be verified every two or three years. Whenever it is necessary to overhaul a machine or make special adjustments of the weighing mechanism the machine should be verified before being put into service. In reporting a verification the method should be clearly stated, together with the serial numbers of the machine and all apparatus used as well as the names of the manufacturers of the same. The loading range of a testing machine should not be considered to include loads less than 100 times the smallest load which can be read from the indicator of the machine.

Dead-Weight Method. Several lines of attack are in common use. The simplest and most direct is obviously that which employs dead weight and an accurate platform scale of a few hundred pounds' capacity.

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[1] A.S.T.M. Designation E4–36.

In order to investigate the entire range, it is generally necessary to lay short planks of known weight on the platen of the machine. Upon these it is possible to pile material which has been carefully weighed upon the standard scale. For this purpose, pig iron, if it is procurable, makes a very convenient load. The pigs may be readily handled and are easily piled. The load should be piled on the planks symmetrically. During this operation it is wise to protect the screws of the machine with wooden guards. The load must not touch the screws or rub against the temporary screw guards.

The difference between the scale reading for the testing machine and the total weight on the platen, as determined by the standard scale, represents the error. This error is commonly expressed as per cent, thus:

$$\frac{\text{Scale reading} - \text{True load}}{\text{True load}} \times 100 = \text{Per cent error}$$

Several runs should be made both during loading and unloading. If the per cent error is constant, the machine may be used by applying a proper correction factor, although this procedure is not countenanced by the A.S.T.M. Standards.

When the machine is to be used at low loads and a quick check is desired, it is often possible to make use of any individuals who may be conveniently at hand. It is not difficult to stand 15 to 20 persons on the planks previously mentioned, thus giving a load of 3000 to 4000 lb.

The response of the machine to the weight of a single operative may sometimes be used as an indicator of the general condition of the weighing system.

Lever Calibration. The verification of machines for loads ranging above a few thousand pounds is not practicable by the direct dead-weight method. The use of proving levers is then commonly practiced, as shown in Fig. 51. The two levers rest on supports[2] on the weighing platform of the testing machine. These supports shall move easily in a horizontal direction, which insures that the forces at each of the knife edges shall be very nearly vertical. The inner knife edges in each lever bear against a suitable block in the head of the testing machine. Weight trays or hangers are suspended from each of the outer knife edges, and these trays or

[2] A.S.T.M. Designation E4–36.

hangers are loaded with standard weights. The increment of load put on the testing machine by the standard weights is the amount of standard weights multiplied by the lever ratio m/n (Fig. 51).

The knife edges, as well as their supports, shall be of hardened tool steel. The knife edges shall be ground sharp with an angle of 90 degrees. The load on any knife edge shall not exceed 7000 lb. per linear inch. The three knife edges in each lever shall be parallel, and their edges shall lie in a plane. Each lever shall have machined surfaces in this or some parallel plane, upon which a spirit level can be placed.

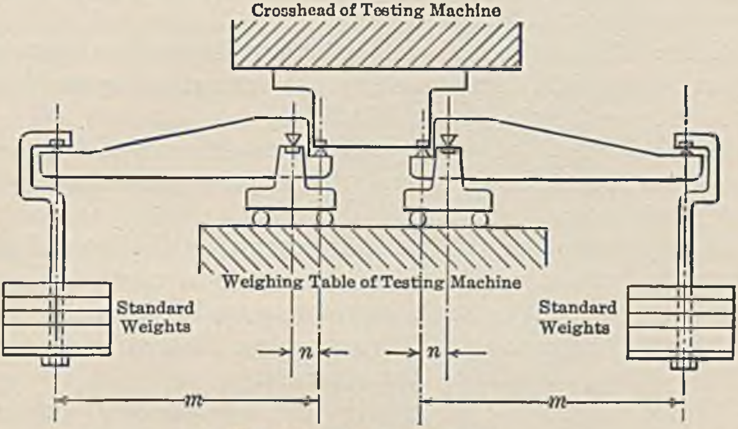

Fig. 51. — Proving levers.

The lever ratio of a proving lever shall be determined by the use of at least three test loads; the amount of weights used shall not be less than the maximum load applied upon one of the arms of a lever in using the levers to verify testing machines. The proving lever shall be balanced over its center knife edge with suitable weight trays suspended from the end knife edges. Standard weights shall then be applied to the trays in three steps, corresponding approximately to 50, 75, and 100 per cent of the weights available, and the proving lever shall then be brought to a balance by the use of small weights and by observations of the freely swinging proving lever. From the weights in the two weight trays, the lever ratio shall be computed.

The proving levers shall be placed symmetrically in the testing machine to be verified, and both levers brought as near to a horizontal position as is feasible, after applying each increment of load, by means of the movable head of the testing machine. The testing machine shall be balanced with the levers in place and the weight trays empty. Standard weights shall be applied in increments, half an increment in each tray, and they shall be removed in a similar manner. The weights shall be placed symmetrically on the weight trays, with the center of gravity of the weights over the center of the tray. The applied load and the indicated load shall be recorded for each test load applied, and the error computed from these data.

Note: The method of verification by standardized proving levers is used, at the present time, only on vertical testing machines. It may be used up to loads of 100,000 lb.

Elastic-Bar Method. Comparison of machines by means of an elastic bar is quite common, and with proper precautions may be fairly satisfactory.

The application of this method presupposes that one of the machines, between which comparisons are to be made, has been previously verified by some accurate method. A special steel test bar is then prepared. This comparison bar may be designed for use either in tension or in compression.

When a compression bar is to be used, it is carefully machined to give an approximately uniform cross-section with squared ends. The proportions must be such that no appreciable lateral deformation will be produced under the greatest load to be used in the test. If the length be 5 to 8 times the diameter, this requirement will be met satisfactorily.

For a tension bar, a straight cylindrical section with enlarged threaded ends is best. The ratio of length to diameter in this instance may be as large as desired.

Compression Comparometer. Such a bar or comparometer arranged for compression is shown in Fig. 52. When in use, at least one of the compression platforms of the machine should be furnished with a spherical seat. The brackets, *A* and *B*, are securely fastened to the bar. The bracket, *B*, carries a precision micrometer, *M*, which, in the device shown, reads directly to 0.0001 in. By estimation, it is possible to read to about one-fifth of that value, permitting a fair estimate to the nearest 0.00002 in. Each rod, *R*, terminates at the bottom in a hardened steel ball.

This ball rests securely in a cup socket in the bracket, *A*. The upper end of each rod passes through an insulating bushing, which replaces the usual micrometer anvil. The rod is made in two sections, each of which is made fast to the insulating bushing, *D*. Thus the upper portion of each rod, with its free end finished to a convex surface, is electrically insulated from the rest of the device. It is thus possible to make use of a battery and buzzer (or head set) circuit, to give accurate indication of contact between the micrometer screw and this insulated portion of the rod. When such a circuit is used, it is desirable to make observations at the closing, rather than at the break, of the circuit. If the micrometer be furnished with a ratchet, the buzzer circuit may be eliminated.

In order to conduct a verification test, the comparometer is carefully centered on the compression platform of the machine that is to be considered as standard. Each micrometer should be carefully set and read. The average of these two readings will then represent the zero point for the device. At each load desired in the verification schedule, the micrometers will again be read and averaged. From these readings it will be possible to establish the change in gage length per thousand pounds of load, which may be considered as the " scale of the comparometer." A repetition of this procedure in the machine to be verified will indicate the

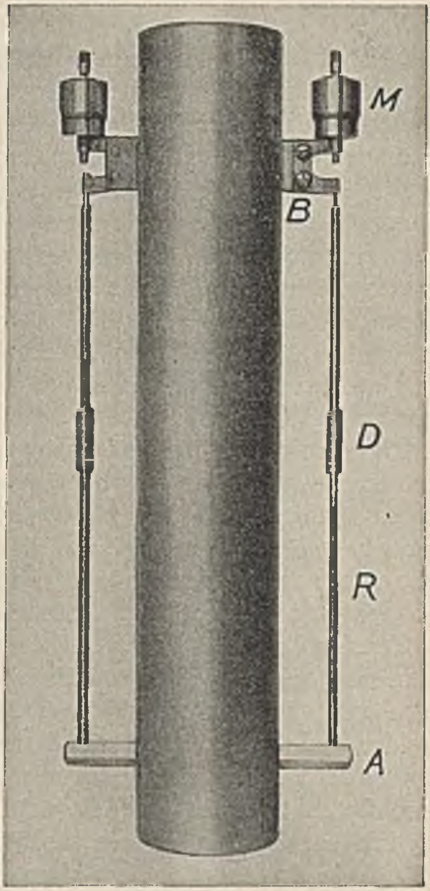

FIG. 52. — Compression comparometer.

closeness of agreement between the two. If the agreement is not perfect, it will be possible to compute the error of the machine under observation from the predetermined scale of the comparometer. The precision of this method of verification will depend entirely upon the design of the device. In the apparatus shown in Fig. 52, the cross-sectional area is made 10 sq. in. and the gage length is 15 in. Assuming $E = 30{,}000{,}000$ lb. per sq. in., this gives a change in micrometer reading of 0.00005 in. per thousand pounds. It is undoubtedly true that the actual value of E may not agree with the value just assumed. Such lack of agreement, however, is of no significance, since the factor used in the calibration is in reality the actual change in micrometer reading determined by actual test as previously outlined. With the best precautions, then, the device may detect a variation of 500 to 1000 lb. throughout its range. At 100,000-lb. load, this means a precision of 0.5 to 1.0 per cent. At lower loads the precision is obviously less, and for very small verification ranges a comparometer of these proportions is useless.

The precision of the device may be increased by diminution of the cross-sectional area or by increase in the gage length. Both these changes, however, have certain practical limitations as already indicated; namely, the stress produced must not exceed the elastic limit of the material, and the slenderness must not be so great as to induce lateral deflection under load.

Tension Comparometer. A comparometer operating under tension may be designed to function in a similar manner (Fig. 53). The ends of the bar should be threaded to fit into a ball-jointed holder, and the entire bar must be machined with extreme nicety. As before, the cross-sectional area is limited by the verification loads and the elastic range of the material. The gage length is limited by the free distance between the tension holders of the machine.

The slenderness of the bar plays no part in the limitation of its proportions, because the tensile stress will maintain the alignment of the axis regardless of its slenderness. For light load verification, the tension comparometer is likely to permit a higher precision.

Companion-Bar Method. Another method for comparison is described by the A.S.T.M. as follows:[3]

When the direct method of verification of a testing machine cannot be carried out, a comparison method of verification may

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[3] A.S.T.M. Designation E4–36.

be used. In this method the machine to be verified is tested by comparing its indications with the corresponding readings obtained under the same conditions by the use of another testing machine, specially tested and verified, as previously specified. The method of verification by comparison shall be carried out by the use of a series of companion specimens, half of which are to be tested in tension in the machine to be verified, and half of which are to be tested in tension in the specially verified testing machine which serves as a standard machine. The general provisions respecting the application of the test loads and the loading range which are outlined in the direct method of verifying testing machines shall apply to the verification of testing machines by the comparison method, so far as is practicable.

NOTE: The method of verification of a testing machine by standard weights and the method of verification by standardized proving levers are both regarded as superior to the method of verification by the use of companion specimens. If the results of a verification test of a testing machine by the comparison method fail to agree with the results of a verification by either the standard-weight method or the proving-lever method, the results of the verification by the comparison method should be discarded.

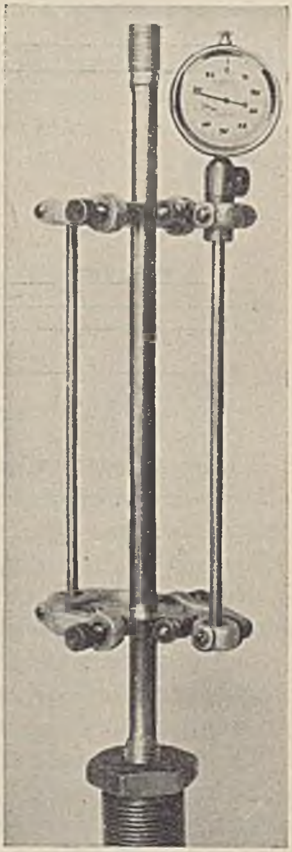
FIG. 53. — Tension comparometer.

For each test load, eight or more tension test specimens shall be cut from soft-rolled or drawn steel and numbered consecutively as in Fig. 54*a*.

The tensile strength of the steel shall be determined by a preliminary test, and the sets of specimens for the comparison test shall have such nominal cross-sectional areas as will give, approximately, the loads required. The form of the specimen shall be as shown in Fig. 54*b*. The ends may be threaded, or otherwise machined, to fit holders, but it is recommended that those specimens shipped to another laboratory be left with cylindrical ends. The actual value of *d* (Fig. 54*b*) for each specimen shall be determined by means of a micrometer.

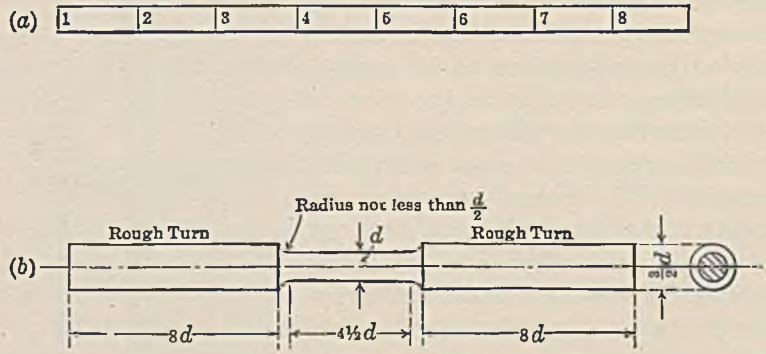

FIG. 54. — Companion bars.

The specimens having odd numbers shall be tested in the machine to be verified, and those having even numbers in the standard testing machine. The tensile strength only shall be determined.

The speed of the testing machine, by which is meant the speed of the pulling head when the machine is running idle with no specimen in the machine, when testing verification specimens shall be approximately the same for both the standard testing machine and the machine being verified. The speed shall be the slowest that can be obtained on both machines.

The average tensile strength (in pounds per square inch) of the odd-numbered specimens, multiplied by the nominal area of cross-section, shall be considered a measure of the indicated load; and the average tensile strength of the even-numbered specimens, multiplied by the nominal area of cross-section, shall be considered a measure of the applied load. The error shall be computed from these data.

If the tensile strength (in pounds per square inch) of any verification specimen varies more than 1 per cent from the mean of the group with which it is tested, its tensile strength shall not be used in computing the error of the testing machine. If more than one specimen in the odd-numbered group or one in the even-numbered group exceeds the allowable variation in tensile strength, all the specimens shall be discarded and another set prepared.

Mutual Comparison. When several different machines are available, particularly when such machines are of varying type, manufacture, and age, it is possible to obtain a very fair verification by means of mutual comparison. If the comparometer bar shows practically identical results in all the machines, the probabilities point to the likelihood of all machines being correct. Obviously, the greater the number and the more varied the type, and so forth, the greater will be this probability. Such a method is not advised if direct calibration is possible, or if a certified machine is available for comparison.

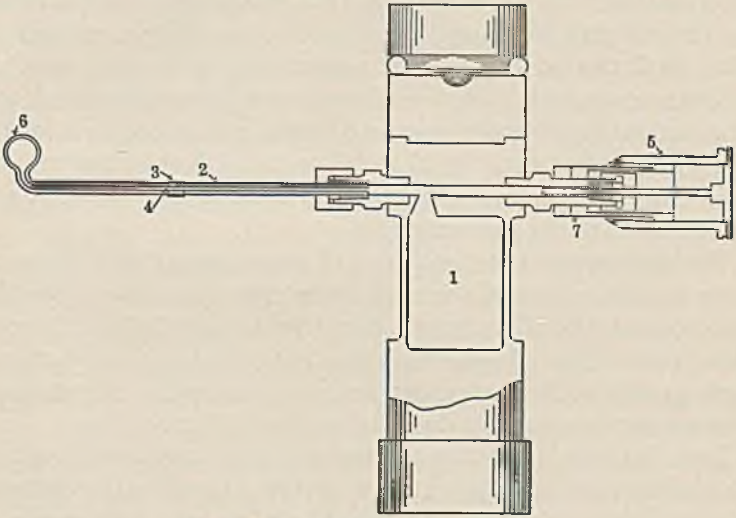

Fig. 55. — Amsler calibration box.

Amsler Calibration Box. The general construction of this device is shown by Fig. 55. It is a hollow cylinder (1) filled with mercury, and the over- or back-flow of the mercury is measured in a capillary tube (2) mounted in the side of the instrument. On this tube is a marker (3) to which the end of the thread of mercury (4) is always brought by turning the micrometer screw (5). The tip of this screw dips into the space filled with mercury, and by entering into this space it forces mercury into the capillary tube.

If this hollow cylinder is subjected to a purely axial compression, its volume decreases. Thereupon, an amount of mercury equal to the diminution in volume is forced out into the capillary tube. The expelled mercury which cannot be kept in the tube (2) collects in the bulb (6) at the end of the tube. By turning the micrometer screw, the thread of mercury is brought back to the line of the marker. The amount of turning given to the micrometer screw is thus a measure of the decrease in volume of the hollow cylinder.

The alloy-steel cylinder shortens proportionally with the loading which acts on its ends. The decrease in volume, and consequently the amount by which the micrometer screw must be turned, are therefore proportional to the load.

In order to obtain large volume displacements of mercury, which are easily observed, the walls of the hollow cylinder are made comparatively thin, and they are thus subjected to high stresses. To prevent any permanent deformation, the cylinder is made of alloy steel, treated and aged by a specially developed process.

The amount which the micrometer screw has to be turned, and thus the readings on the graduated scale, are independent of the size of the capillary tube. If, therefore, this tube becomes broken, it is only necessary to replace it by another one without any recalibration of the instrument.

The displacement of the thread of mercury may be sufficiently large to require several turns of the micrometer screw. For this reason, graduations are provided on the stem (7) to indicate complete turns. The edge of this screw is divided into one hundred parts so as to allow hundredths of a turn to be read. The distance between two consecutive divisions is about 1 mm.

Each box is calibrated by the makers with dead-weight loading. The verification of a machine with this apparatus necessitates the following procedure. If possible, allow the instrument to remain in place on the compression platform of the machine for several hours, in order that a condition of temperature equilibrium may be attained. The device should then be carried through several loading and unloading cycles covering at least the range over which it is to be used during the verification which is being undertaken. After this preliminary "working," one of the chosen loads is applied. While under this load the micrometer head (5) is so adjusted that the end of the mercury column in the capillary tube is at one edge of the marker. The reading of the micrometer is recorded. This adjustment should be repeated and a new (or check) reading recorded. The average of these several readings will be used in the final computations. The load on the box is then reduced to zero and the above schedule of operations repeated. The difference between the micrometer reading under load and at no load is a measure of the displacement of the mercury in the chamber as previously explained. This difference compared with the value obtained from the maker's calibration determines the accuracy of the testing machine. Each box is furnished with the results of the original calibration. The method just outlined minimizes the errors which may be introduced by temperature changes since the time between load and no load readings need be no more than two or three minutes, and a new zero is noted after each load setting.

Morehouse Proving Ring. One of the most satisfactory of the devices for verification of testing machines is the Morehouse[4] proving ring. The principle of this ring is clearly shown by Fig. 56. It is essentially an elastic ring furnished with a very sensitive device for recording elastic changes in diameter under load. These rings are made to operate under both tension or compression, although the one illustrated is built for compression loading only. They are also usable in either vertical or horizontal positions. Since the practical operation is similar under all conditions the following procedure is confined to compressive loading with the ring in the vertical position as shown. In common with all elastic proving apparatus the ring should be allowed to remain on the platen of the machine until it has attained the temperature of the machine and room. Changes of temperature are to be avoided as much as possible although the accepted method of operation, as in the Amsler box, minimizes this factor. Several cycles of loading and releasing should be applied. Under load the reading of the micrometer head is recorded. In order to obtain this reading the central reed is set vibrating. This is best accomplished by deflecting it sidewise about ½ in. with the rubber tip of a lead pencil and releasing. While the reed is vibrating, the micrometer head is rotated slowly until a very faint buzzing is produced as the micrometer tip just touches the weight on the end of the reed. This adjustment must be carefully made. The reed should not be suddenly stopped by the contact; rather it

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[4] Original design by H. L. Whittemore and S. N. Petrenko of the U. S. Bureau of Standards. U. S. Bureau of Standards *Journal of Research*, Vol. 4.

should continue to vibrate for two or three seconds after the buzzing starts. Several settings should be made and if necessary an average obtained. With careful manipulation even different observers are usually able to check the setting, under a given load, within one-tenth of a graduation on the divided head. Load is immediately released to zero and a new reading obtained as described above. The difference between load reading and zero reading is translated into true load on the ring by means of an instrument factor supplied by the Bureau of Standards where all these rings are calibrated before being put into service. Under best conditions of operation the zero readings following successive load readings will check. It should be noted that in every case,

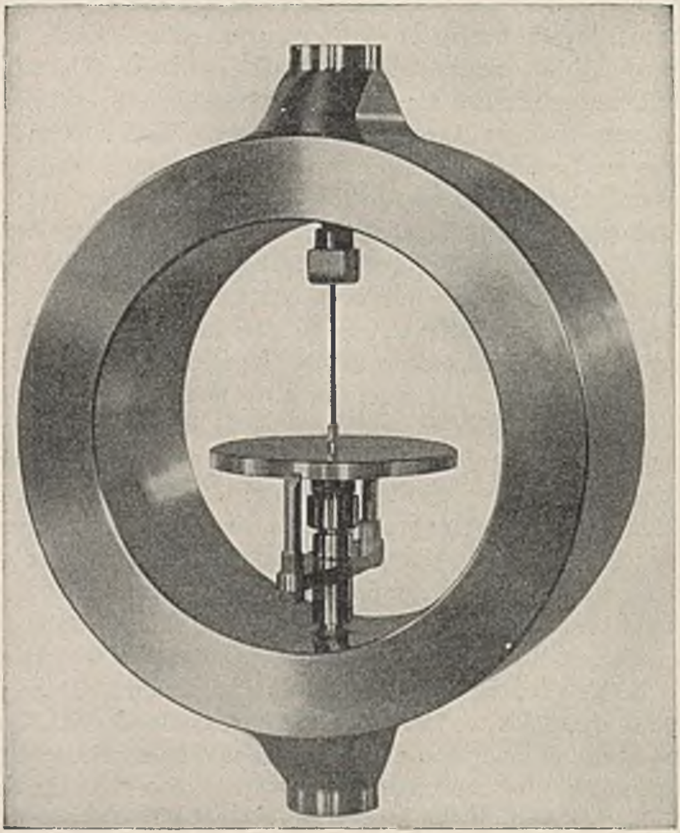

Fig. 56. — Morehouse proving ring, 300,000 lb. capacity.

however, the difference between reading at load and the immediately following reading at zero is used to determine the true load on the ring. From the true load and the load as registered by the machine the error is determined as previously explained.

PHOTOELASTIC ANALYSIS

The Field of Application. Perhaps one of the best services which a brief discussion of this method can perform is to emphasize the thought that the photoelastic method at present is definitely limited in its scope. In the earlier days of its rise attempts were made to apply it to the solution of problems for which it was not at that time fitted. The power of the method and its field are being continually enlarged. The discussion here developed will be confined to cases of " plane stress " although considerable extension into three-dimensional stress has been made. For the field of study for which this text is adapted the discussion will be limited to consideration of stress concentration due to character of design in fabricated parts; the magnitude of such stress at free boundaries; the method of determination of the planes of principal stress; and brief mention of some of the methods for determining the magnitude of the principal stresses.

The Polariscope. The apparatus used for this type of stress analysis consists essentially of the following elements:

1. Source of light.
2. Polarizer.
3. Analyzer.
4. Various lenses to control direction of light propagation.
5. Filters when monochromatic light is desired.
6. Quarter wave plates if circular polarization is necessary.

When the solution of the problem at hand requires determination of the orientation of planes of principal stress, it is sometimes desirable to make use of " white light." The source of such light will be largely dependent upon the desired area of the field to be illuminated. A large proportion of the problems which yield to the photoelastic approach can best be solved by the use of monochromatic light. For this purpose the mercury vapor lamp is most satisfactory. Light from such a source passed through a #62 Wratten Filter becomes almost perfectly monochromatic with a wave length of 5461 Å.

Plane polarization may be produced by the Nichol prism or Polaroid plates.[1] A Nichol polarizer is commonly of small cross-sectional area, whereas the field of illumination for anything but the smallest models will be of considerable area. This disparity of areas necessitates the use of several lenses in the light path. The light must be " condensed " to pass through the Nichol for polarization; the polarized beam must be " diverged " and rendered into a large field of parallel rays, in which field will be placed the stressed specimen; again " condensation " is needed to pass through the analyzer; a final system of lenses provides the projection of an image of size convenient for direct visual observation or for photography. Such a set-up requires lenses of considerable size and of high degree of refractive perfection. The supporting and adjustment of this lens system requires careful design and manipulation.

Obviously since Polaroid plates can be obtained in almost any desired size, the lens system may be greatly modified and for certain cases of direct observation may be completely eliminated when such plates are used.

A complete analysis of the " quarter wave " ($\lambda/4$) plate would be out of place in this text. It is possible, however, to visualize its action to some extent as follows. This plate is composed of some substance, generally mica, which allows light to pass in two mutually perpendicular planes. Not only is the incident ray so broken down, but these resultant rays are each plane polarized and emerge from the plate with the phase of one retarded relative to the other. Figure 57 shows such a condition. (NOTE: In this figure the effect is produced by a stressed body instead of a $\lambda/4$ plate.) If the thickness of this mica plate is such that the relative retardation is $n(\lambda/4)$, where n is any odd integer, the

---

[1] Polaroid is a cellulose film containing a complex organic salt made from quinine, hydriodic acid, and sulphuric acid. This compound is dispersed in colloidal suspension in the cellulose matrix. A unidirectional flow produced by forcing the plastic cellulose through a narrow slit causes the organic salt to crystallize into sub-microscopic crystals of needle form arranged with their long axes all in one direction. This orientation of the crystal axes determines the plane of polarization and light passing through the film becomes plane polarized in the direction of the long axes of the crystals.

resultant of these two waves is said to be "circularly polarized."[2]

Temporary Double Refraction. Some materials in a normal unstressed condition are known as "double refractive." Most transparent materials assume this property under a state of strain. In Fig. 57, the body *M* represents such a strained medium. The line *RR* represents the line of propagation of a ray of monochromatic light approaching *M* with a plane of polarization *ZZ*, and passing through the medium *M* at the point *O*. It is assumed that the state of strain is such that at the point *O* the principal planes of stress are *P* and *Q*.

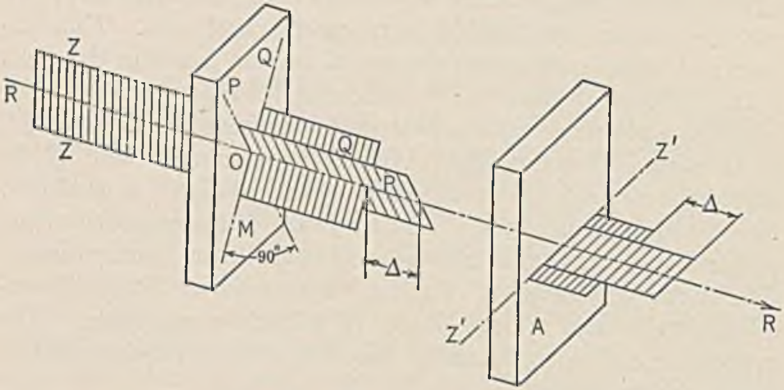

Fig. 57. — Photoelastic diagram.

Under the assumed conditions the light will emerge from *M* at the point *O*, in two components. Each component will be plane polarized and the planes of polarization will be *P* and *Q* respectively. Moreover, the speed of transmission of this light is different on each plane[3] so that there will be a relative retardation of phase of one component as compared with the other. This difference in phase, Δ, is proportional to the difference in the principal strains and the thickness in the direction *RR*. If the material

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[2] Any treatise on optics will show that the resultant of the light vectors representing two such waves is a vector of constant magnitude but of constantly changing direction. The terminus of this vector may be considered to trace a spiral whose axis is the path of propagation of the light ray. Expressed differently, the light at any instant is plane polarized but the plane of polarization is changing at an astronomical speed.

[3] The component on the principal compression plane is usually retarded relative to that on the tension plane.

is elastic and has the same modulus of elasticity in tension and compression, this difference in phase is also proportional to the difference in principal stress. The analyzer, A, is set with its plane of polarization $Z'Z'$ at 90° to the plane of the polarizer ZZ. Hence, the two light rays meet the polarizer at an angle with $Z'Z'$. Each wave, P and Q, is split by the analyzer and one component of each is rotated into the plane $Z'Z'$. Upon emergence along this plane there are actually two plane polarized light waves coincident as to plane but out of phase by the amount of relative retardation, Δ, produced in the planes of principal stress in the medium M. This condition results in some degree of interference.

When Δ is equal to $N\lambda/2$ and N is an even integer the rays emerging from the analyzer will be in phase and maximum brilliancy along R is produced. If N is an odd integer the interference is complete and the resultant light along R is zero if the optical system is ideal; in any case such a condition results in minimum brilliancy along R.[4]

If the medium M be subjected to a stress condition which is uniform over all sections perpendicular to RR and the stress magnitudes be increased or decreased through a sufficient range, then the entire medium will pass through a series of illuminations and dimmings as viewed through the analyzer. Such a condition may readily be produced in a model subjected to pure tension or compression.

Isochromatic Lines. Nearly all the problems in stress analysis which lend themselves to this method of study result in models in which the condition of stress is complex and varies from point to point in the model. At all points in which the stress difference gives retardation such that complete interference is produced the illumination will be at a minimum. In general there will exist many points with this particular stress difference and the locus of such a series of points will appear as a dark band when the model is properly viewed. Such loci are known as isochromatic lines and are shown in Fig. 58 which is the model of a beam supported at SS and subjected to the load, P, at the center.

Since this model was set up with **dark background conditions** it would appear uniformly dark under zero stress conditions. As the load, P, is increased the isochromatic lines begin to form at the

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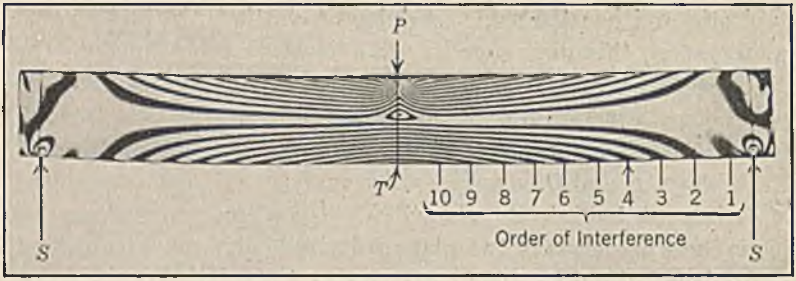
[4] In this discussion it is assumed that the polariscope is arranged to give what is known as "dark background."



Photograph by W. M. Murray

FIG. 58. — Simple beam under center load showing isochromatic lines.

points of high stress. Consider one such point only, such as point T. Under the effect of increasing load the isochromatic, forming at T, will expand into an arch which works inward and extends to wider and wider points of intersection with the bottom edge of the model. Alternations of maximum and minimum brilliancy appear at T, and repeat this behavior to give the pattern shown in Fig. 58. A similar phenomenon appears at the point of loading. At this point there is, however, greater complication because the load contact produces compressive stresses in a vertical direction which, combined with the stresses due to the bending action, result in the series of sharply curved isochromatics in this area. These successive isochromatics represent different "orders" of stress difference.

The small dot at the center of the model in line with the load is the vestige of the initial zero stress condition. Counting out from that point appear the various orders of interference. The small closed triangle is No. 1, as are also the isochromatics near the supports and in the upper corners. It should be noted that, for all orders other than zero, these isochromatics will be either closed figures or will terminate at a free boundary. Along the edge of the beam one of the principal stresses is zero: hence by means of the fringe constant the order of interference may be used to compute the actual stress at the point of its intersection with the edge.

Fringe Constant. By use of a properly loaded tensile specimen data may be obtained which lead to an interpretation of the significance of the orders of interference. When such a specimen is centrally loaded the entire central portion of the model will pass through the successive orders of complete interference. The appearance of the first complete interference means that the stress intensity and the thickness are such that the resultant phase difference is one-half a wave length. That is, the **number of orders is proportional to the product of the stress and the thickness of the model in the direction of the wave propagation.** From this consideration it is customary to express a quantity as the fringe constant which is defined by the equation

$$\text{F.C.} = \frac{\text{Stress} \times \text{Thickness}}{\text{Number of orders}}$$

Solving this equation for stress, the relation becomes

$$\text{Stress} = \frac{\text{F.C.} \times \text{Order number}}{\text{Thickness}}$$

This equation is correct as stated for cases such as the tensile test, which is commonly used to determine this fringe constant for the particular material used in the problem under consideration, because **one of the principal stresses is zero.** It should be kept in mind, however, that actually the term stress should be interpreted as meaning the difference in principal stresses; the equation then for the general case should be written

$$P - Q = \frac{\text{F.C.} \times \text{Order number}}{\text{Thickness}}$$

In this form the equation may be used to determine the **difference of principal stress** at any point along an isochromatic line if the order of interference for that line is known. If the sum of the principal stresses can be determined this value with the above-noted equation permits the evaluation of both the principal stresses. Methods for determining this sum are available but in general are too complex for this brief discussion.

Isoclinic lines. At various locations in a stressed model there exist conditions of stress such that the plane of one of the principal stresses coincides with the plane of polarization of the light entering the model. At all points where this condition prevails the light ray will pass directly through without the separation into components and approach the analyzer in the plane of original polarization. Since the planes of polarization of the polarizer and the analyzer are at right angles, no light will pass the analyzer and minimum illumination will result. The locus of these points will also be a dark line known as an isoclinic. From this consideration develops the definition: **an isoclinic line is the locus of all points at which one of the planes of the principal stresses coincides with the plane of initial polarization.**

When monochromatic light is used the isoclinics are not directly distinguishable from isochromatics. The two types of lines may, however, be distinguished by a slight rotation of the plane of polarization. If the lines remain stationary as the plane is rotated slightly they are isochromatics; isoclinics will shift position with slight rotation of the plane of polarization. A change from monochromatic to white light is most effective in that this modification causes the isochromatics to become colored while isoclinics remain "black." Because of this phenomenon many photoelastic assemblies are so arranged that the shift from white to monochromatic light is easily accomplished.

APPENDIX

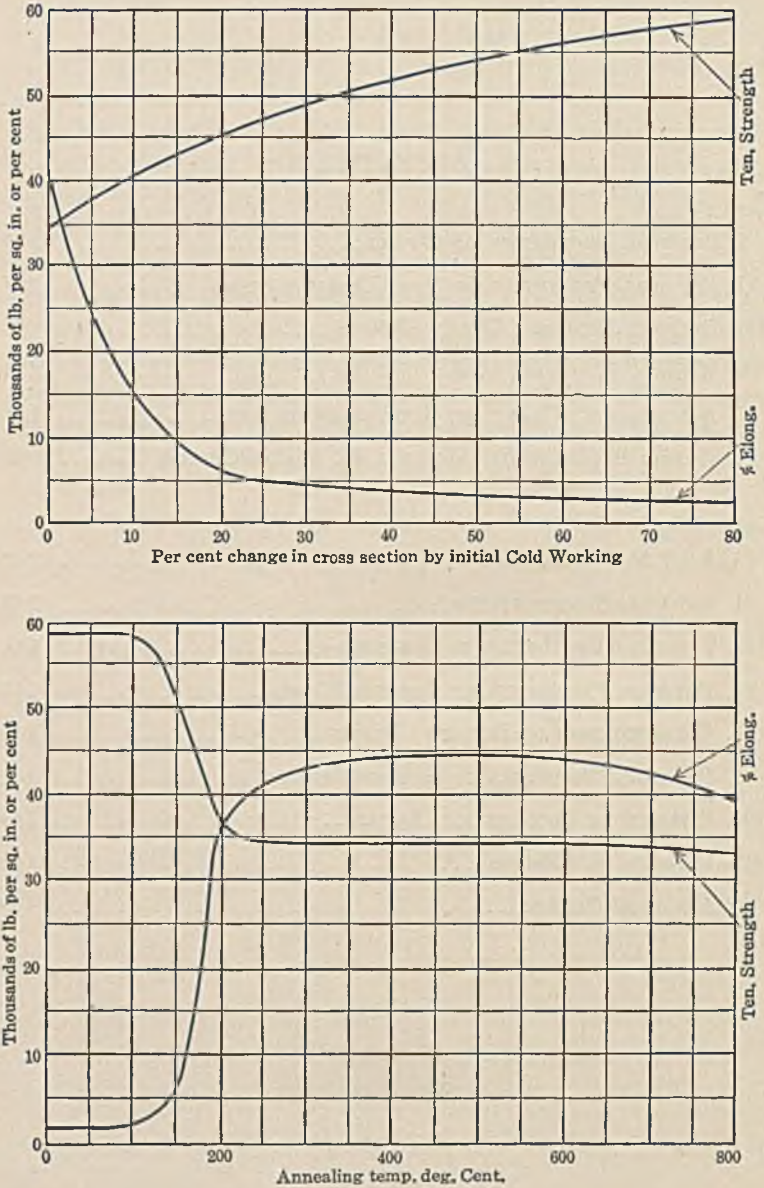


Plate I. Grard's curves showing the variations in the physical properties of electrolytic copper.

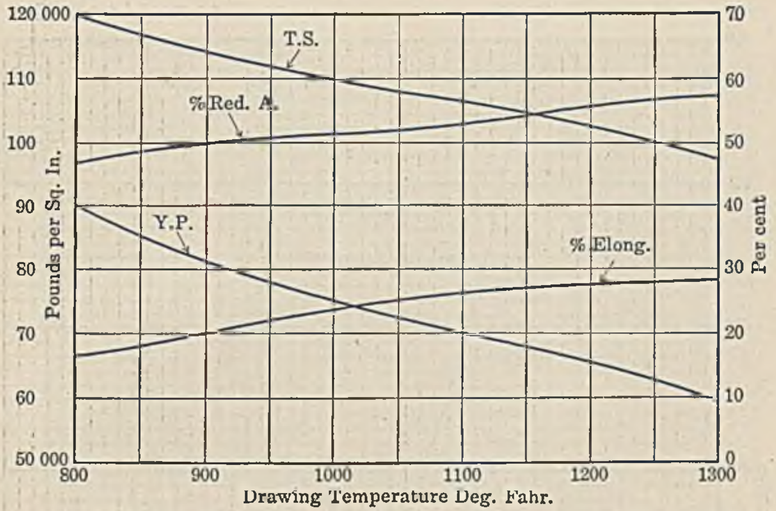


Plate II (*a*). Physical properties of S.A.E. 1045 steel, water-quenched from 1500° F. and drawn at varying temperatures as indicated.

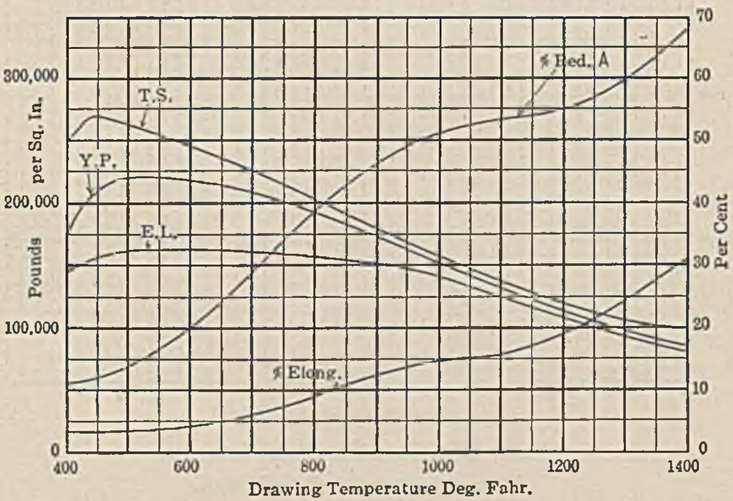


Plate II (*b*). Physical properties of chrome-vanadium steel, oil-quenched from 1575° F. and drawn at varying temperatures as indicated. S.A.E. 6150.

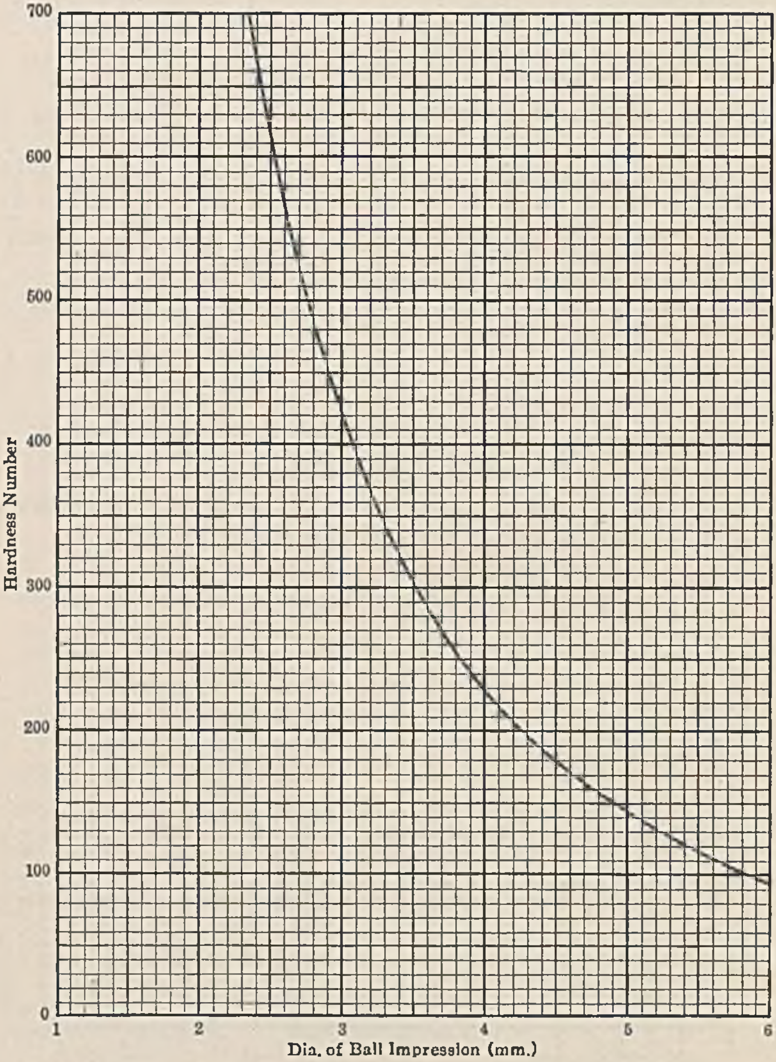


PLATE III. Brinell hardness numbers.
Diameter of steel ball = 10 mm.
Pressure used = 3000 kg.

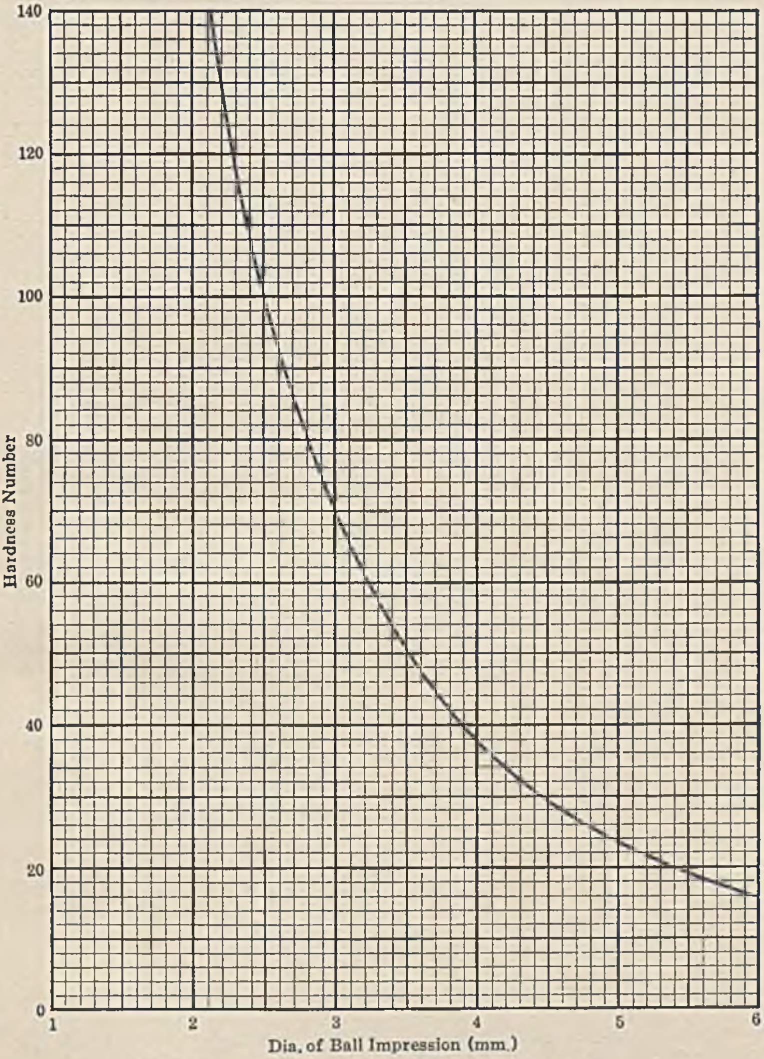
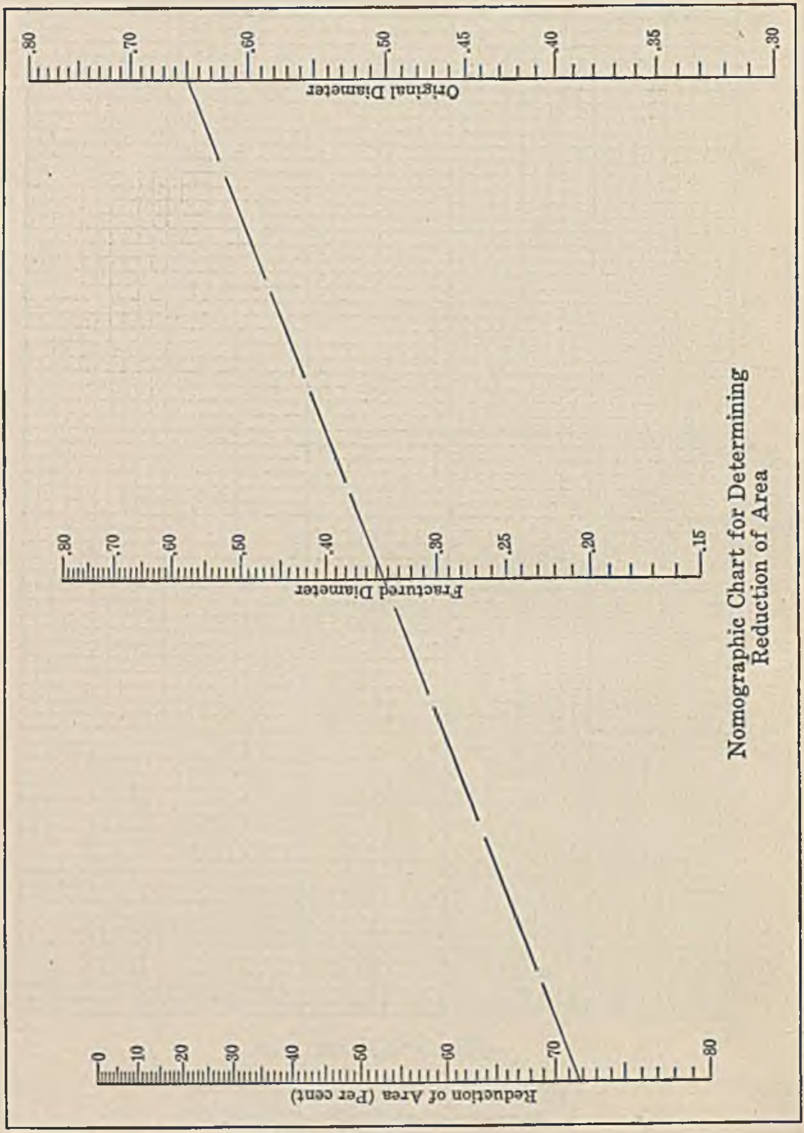


PLATE IV. Brinell hardness numbers.
Diameter of steel ball = 10 mm.
Pressure used = 500 kg.



Nomographic Chart for Determining
Reduction of Area

PLATE V.

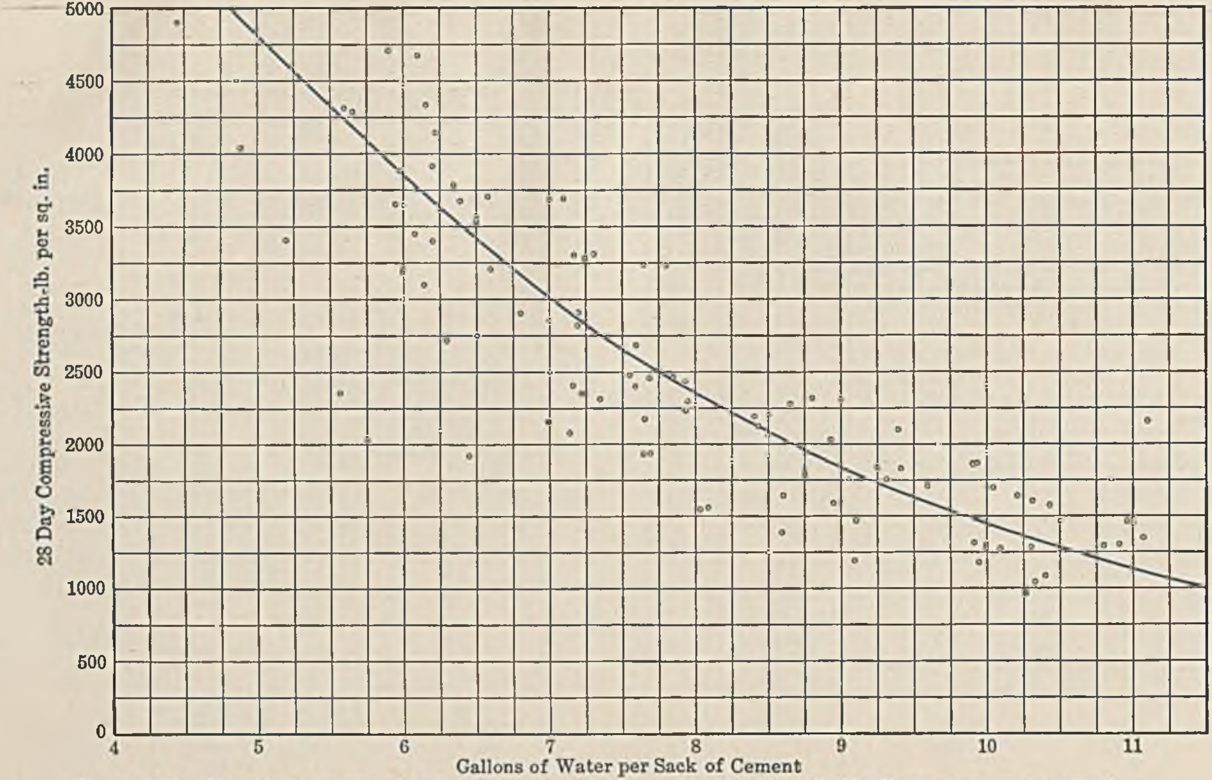


Plate VI. Trend of compressive strength *vs.* water-cement ratio for individually-cast concrete cylinders.

TABLE I — A.S.T.M. SPECIFICATIONS FOR COMMON METALS

Material	A.S.T.M. Serial Designation	Tensile Strength Lb./sq. in.	Yield Point Lb./sq. in. (Min.)	Per cent Elongation in. 8″ (Min.)	Cold Bend Test	Remarks
Refined Wrought-Iron Bars.	A41–36	48,000 (min.)*	25,000*	22*	180°* pin = 2d.	Nick-bend. Crystalline area not more than 10% of fractured area.
Boiler Rivet Steel.	A31–39	45,000–55,000	0.5 T.S.	$\frac{1{,}500{,}000}{\text{T.S.}}$	180° Flat	Elongation need not exceed 30%.
Structural Rivet Steel	A141–39	52,000–62,000	0.5 T.S.	$\frac{1{,}500{,}000}{\text{T.S.}}$	180° Flat	Yield point never less than 28,000 lb./sq. in.
Ship Rivet Steel.	A131–39	55,000–65,000	0.5 T.S.	$\frac{1{,}500{,}000^*}{\text{T.S.}}$	180° Flat	Yield point never less than 30,000 lb./sq. in.
Steel for Bridges and Buildings.	A7–39	60,000–72,000	0.5 T.S.	$\frac{1{,}500{,}000^*}{\text{T.S.}}$	180° (pin = ½d.) for ¾″ and under*	Yield point never less than 33,000 lb./sq. in. Elongation in 2″ = 22% (min.).
Reinforcing Steel (Billet)* Structural Grade . . .	A15–39	55,000–75,000	33,000	(Pl.) $\frac{1{,}400{,}000}{\text{T.S.}}$ (Def.) $\frac{1{,}250{,}000}{\text{T.S.}}$	(Pl.) 180° pin = d. (Def.) 180° pin = d.	Tensile Strength and Yield-point specifications same for both Plain and Deformed bars. Elongation — structural grade. Plain — 20% min. Deformed — 18% min. Elongation — intermediate grade. Plain — 16% min. Deformed — 14% min. Cold bend tests for ¾″ and under.
Intermediate Grade. . .	A15–39	70,000–90,000	40,000	(Pl.) $\frac{1{,}300{,}000}{\text{T.S.}}$ (Def.) $\frac{1{,}125{,}000}{\text{T.S.}}$	(Pl.) 180° pin = 2d. (Def.) 180° pin = 3d.	
Hard Grade.	A15–39	80,000 (min.)	50,000	(Pl.) $\frac{1{,}200{,}000}{\text{T.S.}}$ (Def.) $\frac{1{,}000{,}000}{\text{T.S.}}$	(Pl.) 180° pin = 3d. (Def.) 180° pin = 4d.	

* For modifications applicable to special conditions consult complete A.S.T.M. Specifications.

TABLE II — A.S.T.M. SPECIFICATIONS FOR COMMON METALS

<table>
<tr><th>Material</th><th>A.S.T.M Serial Designation</th><th>Tensile Strength Lb./sq. in. (Min.)</th><th>Yield Point Lb./sq. in. (Min.)</th><th>Per cent Elongation in 2" (Min.)</th><th>Reduction of Area Per cent (Min.)</th><th colspan="2">Remarks</th></tr>
<tr><td>Mach. Forgings*
Untreated (Class D)</td><td>A235–40T</td><td>75,000</td><td>0.5 T.S.</td><td>Not less than 18</td><td>Not less than 24</td><td colspan="2">For forgings where all sections are less than 8" in thickness or diameter.</td></tr>
<tr><td>Annealed (Class E)</td><td></td><td>75,000</td><td>0.5 T.S.</td><td>$\frac{1,800,000}{\text{T.S.}}$
Not less than 20</td><td>$\frac{2,800,000}{\text{T.S.}}$
Not less than 33</td><td colspan="2"></td></tr>
<tr><td>Steel Castings (Annealed)*
Grade H1</td><td>A27–39</td><td>80,000</td><td>40,000</td><td>17</td><td>25</td><td colspan="2"></td></tr>
<tr><td>Grade B2</td><td></td><td>70,000</td><td>35,000</td><td>20</td><td>30</td><td colspan="2"></td></tr>
<tr><td>Grade A1</td><td></td><td>60,000</td><td>30,000</td><td>24</td><td>35</td><td colspan="2"></td></tr>
<tr><td>Malleable Iron Castings
Grade 32,510</td><td>A47–33</td><td>50,000</td><td>32,500</td><td>10</td><td></td><td colspan="2"></td></tr>
<tr><td>Grade 35,018</td><td></td><td>53,000</td><td>35,000</td><td>18</td><td></td><td colspan="2"></td></tr>
<tr><td>Gray Iron Castings</td><td>A48–41</td><td></td><td></td><td></td><td colspan="3">Transverse Test Bar. Center Load Lb. (Min.)</td></tr>
<tr><td>Class No.</td><td></td><td></td><td></td><td></td><td>Span 12" D = 0.875"</td><td>Span 18" D = 1.20"</td><td>Span 24" D = 2.0"</td></tr>
<tr><td>20</td><td></td><td>20,000</td><td></td><td></td><td>900</td><td>1,800</td><td>6,000</td></tr>
<tr><td>25</td><td></td><td>25,000</td><td></td><td></td><td>1,025</td><td>2,000</td><td>6,800</td></tr>
<tr><td>30</td><td></td><td>30,000</td><td></td><td></td><td>1,150</td><td>2,200</td><td>7,600</td></tr>
<tr><td>35</td><td></td><td>35,000</td><td></td><td></td><td>1,275</td><td>2,400</td><td>8,300</td></tr>
<tr><td>40</td><td></td><td>40,000</td><td></td><td></td><td>1,400</td><td>2,600</td><td>9,100</td></tr>
<tr><td>50</td><td></td><td>50,000</td><td></td><td></td><td>1,675</td><td>3,000</td><td>10,300</td></tr>
<tr><td>60</td><td></td><td>60,000</td><td></td><td></td><td>1,925</td><td>3,400</td><td>12,500</td></tr>
<tr><td>Bronze Casting</td><td>B60–41</td><td>38,000</td><td>16,000</td><td>22</td><td colspan="3">Copper, 86–89%. Tin, 7.5–11%. Zinc, 1.5–4.5%.</td></tr>
<tr><td>Free Cutting Brass Rod*</td><td>B16–41</td><td>55,000</td><td>25,000</td><td>15</td><td colspan="3">Copper, 60–63%. Lead, 2.5–3.75%. Zinc, remainder.
Cold bend. 120° Pin = 2d.</td></tr>
</table>

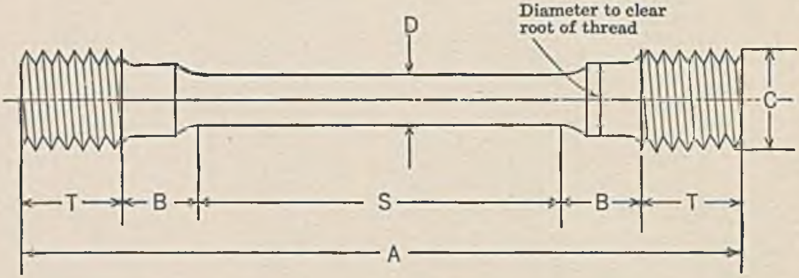
* For grades and classes not listed consult Complete A.S.T.M. Specifications.

TABLE III

Tensile Test Specimens (Sub-Sized)

Recognized standard proportions.

All dimensions in inches.



D	C	Threads per Inch	A	B	T	S
0.500	$\frac{3}{4}$	10	$5\frac{1}{2}$	$\frac{5}{8}$	1	$2\frac{1}{4}$
0.438	$\frac{5}{8}$	11	5	$\frac{5}{8}$	$\frac{7}{8}$	2
0.375	$\frac{9}{16}$	12	$4\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	$1\frac{3}{4}$
0.313	$\frac{1}{2}$	13	$3\frac{3}{4}$	$\frac{1}{2}$	$\frac{5}{8}$	$1\frac{1}{2}$
0.250	$\frac{7}{16}$	14	3	$\frac{3}{8}$	$\frac{7}{16}$	$1\frac{1}{4}$
0.188	$\frac{3}{8}$	16	$2\frac{3}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	1
0.125	$\frac{1}{4}$	20	$2\frac{1}{8}$	$\frac{5}{16}$	$\frac{3}{8}$	$\frac{3}{4}$

Note: It is recognized as good practice to make the largest of the specimens here listed with a central diameter of 0.505 in. In order to force the fracture into the central third it is permitted to make the central straight section the nominal diameter (0.505 in.) and to taper gradually to 0.003 in. over size at the beginning of the fillets.

In all cases the gage length should be made equal to 4D.

TABLE IV

PHYSICAL PROPERTIES OF SEVERAL COMMON WOODS

	Weight, Lb. per cu. ft.		Modulus of Rupture, Lb. per sq. in.		Modulus of Elasticity, 1000 lb. per sq. in.		Max. Crushing Strength Parallel to Grain, Lb. per sq. in.		Shear Str. Parallel to Grain, Lb. per sq. in.
	Green	Air Dry	Green	Air Dry	Green	Air Dry	Green	Air Dry	Green
Ash, white...	*51*	44	*10,800*	18,600	*1,640*	1,980	*4,610*	9,420	*1,600*
Hickory......	*64*	50	*11,100*	21,600	*1,570*	2,380	*4,480*	10,610	*1,200*
Maple, red...	*51*	37	*7,800*	14,200	*1,420*	1,740	*3,350*	7,330	*1,000*
Oak, white...	*62*	48	*8,300*	15,200	*1,250*	1,780	*3,560*	7,610	*1,200,*
Cedar, western....	*27*	22	*5,200*	8,800	*950*	1,250	*2,840*	6,320	*700*
Cypress......	*48*	30	*6,800*	11,300	*1,190*	1,540	*3,490*	7,690	*800*
Douglas Fir..	*38*	30	*7,800*	10,300	*1,580*	1,460	*3,940*	7,090	*850*
Hemlock, western....	*45*	31	*6,000*	11,400	*940*	1,180	*2,890*	7,510	....
Pine, long leaf...	*50*	42	*8,700*	16,700	*1,630*	2,200	*4,390*	10,880	*1,000*
Pine, short leaf...	*50*	38	*8,000*	13,900	*1,450*	1,970	*3,810*	8,660	*900*
Pine, white...	*39*	29	*5,700*	11,500	*1,330*	1,690	*3,070*	7,840	*600*
Spruce, Sitka	*33*	26	*5,500*	11,200	*1,180*	1,610	*2,600*	5,770	*750*
Spruce, white......	*33*	28	*5,400*	9,200	*980*	1,390	*2,380*	6,020	*650*

NOTE: The above values are the results of tests made upon small, straight-grain selected samples.

TABLE V

Building Bricks — Classifications and Specifications

*Sand-Lime Building Brick**

Grade	Compressive Strength (bricks flatwise), Lb. per sq. in. Minimum		Modulus of Rupture (bricks flatwise), Lb. per sq. in. Minimum	
	Mean of 5 Tests	Individual	Mean of 5 Tests	Individual
Grade SW.	4500	3500	600	400
Grade MW.	2500	2000	450	300
Grade NW.	1500	1500	300	200

* A.S.T.M. Designation C73–39.

Brick shall conform to the following dimensions:

Depth 2¼ in. plus or minus ⅛ in.
Width 3¾ in. “ “ “ ⅛ in.
Length 8 in. “ “ “ ¼ in.

*Clay Building Brick**

Designation	Compressive Strength (brick flatwise) Lb. per sq. in. Minimum		Maximum Water Absorption 5-hour Boiling Per Cent		Maximum Saturation Coefficient	
	Average of 5 Brick	Individual	Average of 5 Brick	Individual	Average of 5 Brick	Individual
Grade SW	3000	2500	17	20	0.78	0.80
Grade MW	2500	2200	22	25	0.88	0.90
Grade NW	1500	1250	. .	. .	. . . .	. . . .

* A.S.T.M. Designation C62–41T.

The saturation coefficient is the ratio of absorption by 24-hour submersion in cold water to that after 5-hour submersion in boiling water.

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[1] A.S.T.M. Designation C73–39.

[2] A.S.T.M. Designation C62–41T.

TABLE VI — PHYSICAL PROPERTIES OF COMMON METALS

	Material	Weight, Lb. per cu. in.	Ultimate Strength, Lb. per sq. in.			Modulus of Elasticity, Lb. per sq. in.	
			Tension	Compression	Shear	Tension or Compression (E)	Shear (G)
	Wrought Iron	.278	41–54,000		33–42,000	28,000,000 30,000,000	11,000,000 12,500,000
	Rivet Steel	.283	46–60,000		37–50,000		
	Steel, 0.10% C	.283	55–65,000		45–50,000		
	0.25% C	.283	70–80,000		60–65,000		
	0.50% C	.283	90–100,000		75–80,000		
	Piano Wire	.266	250–300,000			26–27,000,000	
Cast Alloys	Foundry Brass	.29(±)	25–35,000	12–16,000		9–10,000,000	4–5,000,000
	Manganese Bronze	.32(±)	85–95,000	60–70,000			
	Phosphor Bronze	.32(±)	30–35,000	24–30,000	14–16,000	12–14,000,000	
	Aluminum Bronze	.278	65–75,000	18–20,000	40–50,000	16–18,000,000	
	Everdur (Silicon Bronze)	.32(±)	55–60,000			12–14,000,000	
Wrought Alloys	Cartridge Brass	.308	Hard 86,000				
			Soft 47,000			14–18,000,000	
	Muntz Metal	.319	Hard 95,000		Hard 57–60,000	14–18,000,000	4–5,000,000*
			Soft 50,000		Soft 47,000*		4–5,000,000*
	Tobin Bronze	.32(±)	Hard 70–90,000		55–60,000	13–14,000,000*	5–6,000,000*
			Soft 54,000			6,000,000*	
	Phosphor Bronze	.32(±)	Hard 95,000		Hard 70–75,000*	15,000,000*	6–7,000,000*
			Soft 45,000				
	Monel Metal (Rolled)	.323	90–100,000		65–80,000	22–25,000,000	9–10,000,000
	Everdur (Rolled)	.32(±)	50–110,000			13–16,000,000	

* Thesis, Eskin and Fish, M.I.T., 1926.

TABLE VII

Weights of Square and Round Steel Bars Based on the Value 0.283 Lb. per Cu. In.

Size, Inches	Weight, Lb. per Foot		Area, Square Inches		Size, Inches	Weight, Lb. per Foot		Area, Square Inches	
	□	○	□	○		□	○	□	○
0					1	**3.400**	**2.670**	**1.0000**	**.7854**
$\frac{1}{16}$	.013	.010	.0039	.0031	$\frac{1}{16}$	3.838	3.015	1.1289	.8866
$\frac{1}{8}$	.053	.042	.0156	.0123	$\frac{1}{8}$	**4.303**	3.380	**1.2656**	.9940
$\frac{3}{16}$	.120	.094	.0352	.0276	$\frac{3}{16}$	4.795	3.766	1.4102	1.1075
$\frac{1}{4}$	.213	**.167**	.0625	**.0491**	$\frac{1}{4}$	**5.313**	4.172	**1.5625**	1.2272
$\frac{5}{16}$	.332	.261	.0977	.0767	$\frac{5}{16}$	5.857	4.600	1.7227	1.3530
$\frac{3}{8}$	.478	**.376**	.1406	**.1105**	$\frac{3}{8}$	6.428	5.049	1.8906	1.4849
$\frac{7}{16}$	.651	.511	.1914	.1503	$\frac{7}{16}$	7.026	5.518	2.0664	1.6230
$\frac{1}{2}$	**.850**	**.668**	**.2500**	**.1963**	$\frac{1}{2}$	7.650	6.008	2.2500	1.7671
$\frac{9}{16}$	1.076	.845	.3164	.2485	$\frac{9}{16}$	8.301	6.519	2.4414	1.9175
$\frac{5}{8}$	1.328	**1.043**	.3906	**.3068**	$\frac{5}{8}$	8.978	7.051	2.6406	2.0739
$\frac{11}{16}$	1.607	1.262	.4727	.3712	$\frac{11}{16}$	9.682	7.604	2.8477	2.2305
$\frac{3}{4}$	1.913	**1.502**	.5625	**.4418**	$\frac{3}{4}$	10.413	8.178	3.0625	2.4053
$\frac{13}{16}$	2.245	1.763	.6602	.5185	$\frac{13}{16}$	11.170	8.773	3.2852	2.5802
$\frac{7}{8}$	2.603	**2.044**	.7656	**.6013**	$\frac{7}{8}$	11.953	9.388	3.5156	2.7612
$\frac{15}{16}$	2.988	2.347	.8789	.6903	$\frac{15}{16}$	12.763	10.024	3.7539	2.9483
					2	13.600	10.681	4.0000	3.1416

The cross-sectional areas and the weights of the standard sizes of deformed reinforcing bars agree very closely with the values in the above table.

The nominal values quoted for such bars by the manufacturers in general differ from those here quoted by less than one per cent.

This furnishes a convenient means of checking the cross-sectional area when testing reinforcing steel, the standard sizes of which are indicated in bold-face type.

TABLE VIII

Conversion of Degrees to Radians

	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	Interpolation values	
0	.0000	.0017	.0035	.0052	.0070	.0087	.0105	.0122	.0140	.0157	Deg.	Rad.
1	.0175	.0192	.0210	.0227	.0245	.0262	.0280	.0297	.0315	.0332	0.01	.0002
2	.0349	.0366	.0384	.0401	.0419	.0436	.0454	.0471	.0489	.0506	0.02	.0003
3	.0524	.0541	.0559	.0576	.0594	.0611	.0629	.0646	.0664	.0681	0.03	.0005
4	.0698	.0715	.0733	.0750	.0768	.0785	.0803	.0820	.0838	.0855	0.04	.0007
5	.0873	.0890	.0908	.0925	.0943	.0960	.0978	.0995	.1013	.1030	0.05	.0009
6	.1047	.1064	.1082	.1099	.1117	.1134	.1152	.1169	.1187	.1204	0.06	.0010
7	.1222	.1239	.1257	.1274	.1292	.1309	.1327	.1344	.1362	.1379	0.07	.0012
8	.1396	.1413	.1431	.1448	.1466	.1483	.1501	.1518	.1536	.1553	0.08	.0014
9	.1571	.1588	.1606	.1623	.1641	.1658	.1676	.1693	.1711	.1728	0.09	.0016
10	.1745	.1762	.1780	.1797	.1815	.1832	.1850	.1867	.1885	.1902		

TABLE IX

Areas of Circles

Diam.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009
.10	.00785	.00801	.00817	.00833	.00849	.00866	.00882	.00899	.00916	.00933
.11	.00950	.00968	.00985	.01003	.01021	.01039	.01057	.01075	.01094	.01112
.12	.01131	.01150	.01169	.01188	.01208	.01227	.01247	.01267	.01287	.01307
.13	.01327	.01348	.01368	.01389	.01410	.01431	.01453	.01474	.01496	.01517
.14	.01539	.01561	.01584	.01606	.01629	.01651	.01674	.01697	.01720	.01744
.15	.01767	.01791	.01815	.01839	.01863	.01887	.01911	.01936	.01961	.01986
.16	.02011	.02036	.02061	.02087	.02112	.02138	.02164	.02190	.02217	.02243
.17	.02270	.02297	.02324	.02351	.02378	.02405	.02433	.02461	.02488	.02516
.18	.02545	.02573	.02602	.02630	.02659	.02688	.02717	.02745	.02776	.02806
.19	.02835	.02865	.02895	.02926	.02956	.02986	.03017	.03048	.03079	.03110
.20	.03142	.03173	.03205	.03237	.03269	.03301	.03333	.03365	.03398	.03431
.21	.03464	.03497	.03530	.03563	.03597	.03631	.03664	.03698	.03733	.03767
.22	.03801	.03836	.03871	.03906	.03941	.03976	.04012	.04047	.04083	.04119
.23	.04155	.04191	.04227	.04264	.04301	.04337	.04374	.04412	.04449	.04486
.24	.04524	.04562	.04600	.04638	.04676	.04714	.04753	.04792	.04831	.04870
.25	.04909	.04948	.04988	.05027	.05067	.05107	.05147	.05187	.05228	.05269
.26	.05309	.05350	.05391	.05433	.05474	.05515	.05557	.05599	.05641	.05683
.27	.05726	.05768	.05811	.05853	.05896	.05940	.05983	.06026	.06070	.06114
.28	.06158	.06202	.06246	.06290	.06335	.06379	.06424	.06469	.06514	.06560
.29	.06605	.06651	.06697	.06743	.06789	.06835	.06881	.06928	.06975	.07022
.30	.07069	.07116	.07163	.07211	.07258	.07306	.07354	.07402	.07451	.07499
.31	.07548	.07596	.07645	.07694	.07744	.07793	.07843	.07892	.07942	.07992
.32	.08042	.08093	.08143	.08194	.08245	.08296	.08347	.08398	.08450	.08501
.33	.08553	.08605	.08657	.08709	.08762	.08814	.08867	.08920	.08973	.09026
.34	.09079	.09133	.09186	.09240	.09294	.09348	.09402	.09457	.09511	.09566
.35	.09621	.09676	.09731	.09787	.09842	.09898	.09954	.1001	.1007	.1012
.36	.1018	.1024	.1029	.1035	.1041	.1046	.1052	.1058	.1064	.1069
.37	.1075	.1081	.1087	.1093	.1099	.1104	.1110	.1116	.1122	.1128
.38	.1134	.1140	.1146	.1152	.1158	.1164	.1170	.1176	.1182	.1188
.39	.1195	.1201	.1207	.1213	.1219	.1225	.1232	.1238	.1244	.1250
.40	.1257	.1263	.1269	.1276	.1282	.1288	.1295	.1301	.1307	.1314
.41	.1320	.1327	.1333	.1340	.1346	.1353	.1359	.1366	.1372	.1379
.42	.1385	.1392	.1399	.1405	.1412	.1419	.1425	.1432	.1439	.1445
.43	.1452	.1459	.1466	.1473	.1479	.1486	.1493	.1500	.1507	.1514
.44	.1521	.1527	.1534	.1541	.1548	.1555	.1562	.1569	.1576	.1583
.45	.1590	.1598	.1605	.1612	.1619	.1626	.1633	.1640	.1647	.1655
.46	.1662	.1669	.1676	.1684	.1691	.1698	.1706	.1713	.1720	.1728
.47	.1735	.1742	.1750	.1757	.1765	.1772	.1780	.1787	.1795	.1802
.48	.1810	.1817	.1825	.1832	.1840	.1847	.1855	.1863	.1870	.1878
.49	.1886	.1893	.1901	.1909	.1917	.1924	.1932	.1940	.1948	.1956
.50	.1963	.1971	.1979	.1987	.1995	.2003	.2011	.2019	.2027	.2035
.51	.2043	.2051	.2059	.2067	.2075	.2083	.2091	.2099	.2107	.2116
.52	.2124	.2132	.2140	.2148	.2157	.2165	.2173	.2181	.2190	.2198
.53	.2206	.2215	.2223	.2231	.2240	.2248	.2256	.2265	.2273	.2282
.54	.2290	.2299	.2307	.2316	.2324	.2333	.2341	.2350	.2359	.2367

TABLE IX (*Continued*)

AREAS OF CIRCLES

Diam.	.000	.001	.002	.003	.004	.005	.006	.007	.008	.009
.55	.2376	.2384	.2393	.2402	.2411	.2419	.2428	.2437	.2445	.2454
.56	.2463	.2472	.2481	.2489	.2498	.2507	.2516	.2525	.2534	.2543
.57	.2552	.2561	.2570	.2579	.2588	.2597	.2606	.2615	.2624	.2633
.58	.2642	.2651	.2660	.2669	.2679	.2688	.2697	.2706	.2715	.2725
.59	.2734	.2743	.2753	.2762	.2771	.2781	.2790	.2799	.2808	.2818
.60	.2827	.2837	.2846	.2856	.2865	.2875	.2884	.2894	.2903	.2913
.61	.2922	.2932	.2942	.2951	.2961	.2971	.2980	.2990	.3000	.3009
.62	.3019	.3029	.3039	.3048	.3058	.3068	.3078	.3088	.3097	.3107
.63	.3117	.3127	.3137	.3147	.3157	.3167	.3177	.3187	.3197	.3207
.64	.3217	.3227	.3237	.3247	.3257	.3267	.3278	.3288	.3298	.3308
.65	.3318	.3329	.3339	.3349	.3359	.3370	.3380	.3390	.3400	.3411
.66	.3421	.3432	.3442	.3452	.3463	.3473	.3484	.3494	.3505	.3515
.67	.3526	.3536	.3547	.3557	.3568	.3578	.3589	.3600	.3610	.3621
.68	.3632	.3642	.3653	.3664	.3675	.3685	.3696	.3707	.3718	.3728
.69	.3739	.3750	.3761	.3772	.3783	.3794	.3805	.3816	.3826	.3837
.70	.3848	.3859	.3870	.3882	.3893	.3904	.3915	.3926	.3937	.3948
.71	.3959	.3970	.3982	.3993	.4004	.4015	.4026	.4038	.4049	.4060
.72	.4072	.4083	.4094	.4106	.4117	.4128	.4140	.4151	.4162	.4174
.73	.4185	.4197	.4208	.4220	.4231	.4243	.4254	.4266	.4278	.4289
.74	.4301	.4312	.4324	.4336	.4347	.4359	.4371	.4383	.4394	.4406
.75	.4418	.4430	.4441	.4453	.4465	.4477	.4489	.4501	.4513	.4525
.76	.4536	.4548	.4560	.4572	.4584	.4596	.4608	.4620	.4632	.4645
.77	.4657	.4669	.4681	.4693	.4705	.4717	.4729	.4742	.4754	.4766
.78	.4778	.4791	.4803	.4815	.4827	.4840	.4852	.4865	.4877	.4889
.79	.4902	.4914	.4927	.4939	.4951	.4964	.4976	.4989	.5001	.5014
.80	.5027	.5039	.5052	.5064	.5077	.5090	.5102	.5115	.5128	.5140
.81	.5153	.5166	.5178	.5191	.5204	.5217	.5230	.5242	.5255	.5268
.82	.5281	.5294	.5307	.5320	.5333	.5346	.5359	.5372	.5385	.5398
.83	.5411	.5424	.5437	.5450	.5463	.5476	.5489	.5502	.5515	.5529
.84	.5542	.5555	.5568	.5581	.5595	.5608	.5621	.5635	.5648	.5661
.85	.5675	.5688	.5701	.5715	.5728	.5741	.5755	.5768	.5781	.5795
.86	.5809	.5822	.5836	.5850	.5863	.5877	.5890	.5904	.5918	.5931
.87	.5945	.5958	.5972	.5986	.6000	.6013	.6027	.6041	.6055	.6068
.88	.6082	.6096	.6110	.6124	.6138	.6151	.6165	.6179	.6193	.6207
.89	.6221	.6235	.6249	.6263	.6277	.6291	.6305	.6319	.6333	.6348
.90	.6362	.6376	.6390	.6404	.6418	.6433	.6447	.6461	.6475	.6490
.91	.6504	.6518	.6533	.6547	.6561	.6576	.6590	.6604	.6619	.6633
.92	.6648	.6662	.6677	.6691	.6706	.6720	.6735	.6749	.6764	.6778
.93	.6793	.6808	.6822	.6837	.6851	.6866	.6881	.6896	.6910	.6925
.94	.6940	.6955	.6969	.6984	.6999	.7014	.7029	.7044	.7058	.7073
.95	.7088	.7103	.7118	.7133	.7148	.7163	.7178	.7193	.7208	.7223
.96	.7238	.7253	.7268	.7284	.7299	.7314	.7329	.7344	.7359	.7375
.97	.7390	.7405	.7420	.7436	.7451	.7466	.7482	.7497	.7512	.7528
.98	.7543	.7558	.7574	.7589	.7605	.7620	.7636	.7651	.7667	.7682
.99	.7698	.7713	.7729	.7744	.7760	.7776	.7791	.7807	.7823	.7838

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