STUDIES OF MACHINES FOR EXTRUDING CLAY COLUMNS

AUGERS, SPACERS, AND DIES FOR BRICK MACHINES

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ABSTRACT

In this investigation special mechanical apparatus was designed and built to measure and record the work done on a known weight of extruded material by any practical combination of auger, spacer, and die. Electric metering devices were modified to compensate for current difficulties in the electric-power service and to measure accurately the power input to the auger machine. Means were devised to make comparisons between the workable characteristics of various clays and shales and for selecting the extruding equipment to mold them efficiently into suitable commercial forms.

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I. INTRODUCTION

Practically no fundamental data are available as a basis for the intelligent design and operation of continuous extrusion machines used for molding plastic materials. This is especially true of auger machines used for molding clays in the process of making stiff-mud bricks, hollow blocks, and similar products.

The inventor (58)[1] of the first successful auger brick machine used in America was granted letters patent in 1863. This machine produced a continuous bar or column of clay by extrusion from a die opening, the propelling force being supplied by a rotating auger; hence the name "auger machine."

This machine was the forerunner of the present auger machines in which the same original principles of barrel, die, and rotating auger are present as were incorporated in its predecessor. The improvements which have been made, in the absence of fundamental data, have resulted mostly from "cut-and-try" methods through cooperation between machine builder and machine user. The principal improvements made to date have been toward increasing the size and capacity of the machine to meet present-day demands for greater production.

The urgent need for reliable data to improve the design and operation of auger machines was emphasized at a conference of Government and industrial representatives in the fall of 1923. As a result of this conference, the Bureau of Standards undertook a study of the design factors pertaining to augers, spacers, and dies for extrusion machines.

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[1] The figures in parentheses here and throughout the text relate to the numbered references in the bibliography at the end of this paper.

Considerable experimental work of general interest has been done by various clay-equipment firms and private individuals in the production field, but no fundamental laws of design or operation have been developed. This made it necessary to do considerable pioneer work in practically all phases of this investigation. Individual features in the development of the extrusion machine have been worked out to meet particular requirements of certain manufacturers of clay wares, and are therefore of limited value to others whose problems or clays are different. Nevertheless, the combination of the best features resulting from such experience has been the guiding influence enabling the equipment builder to develop the auger machines in use at the present time.

Certain inherent difficulties have always attended the use of extrusion machines for the manufacture of heavy-clay products, such as the development of uneven stresses and column defects in the molding operation. Many attempts have been made to overcome the defects which are present to a greater or less degree in brick and hollow ware made by the auger machine. These defects, however, depend to some extent upon the nature of the clay used. It appears that certain types of clay work better with certain forms of augers than with others when combined with a die of a certain length and taper. A proper die for very plastic clay may not work as satisfactorily with the same auger for a lean clay. So far the method of "cut-and-try" has been the principal means of finding out what combinations of auger, spacer, and die will work a particular type of clay most satisfactorily. Very little experimental work has been done on the extrusion machine as a whole, but considerable work has been done on the flow of plastic materials through dies, principally by Artz (11), Morris (26), Brand (30), Stull (36), and others.

The physical properties of the clays and shales found in different parts of the country or even in the same locality are so vastly different that many combinations of types of augers and dies are necessary in order to successfully mold the different shales and clays into desired shapes by the extrusion process. It is also known that column speed is materially affected by the length and taper of the cone-shaped nozzle or approach to the die and that excessive taper causes excessive differential flow and greater resulting friction. This increased friction has its advantages, however, in knitting spirals and cleavages in the clay caused by the rotation of the auger. The principal determining factors regarding the proper distance between the die and the auger tip are: (1) Uneven flow of material, (2) torn corners, (3) cracked column, and (4) equalization of pressure back of the die. The temper of the clay must be regulated to the proper degree and sufficient "flow resistance" must be provided; otherwise the clay will not have sufficient pressure to fill the die and form a perfect column. Any plastic clay in the stiff-mud state may be made to flow through a die if sufficient pressure is applied, but the important problem is to determine what the design factors are that contribute to the perfection of the clay column and at the same time to determine what effect these have on power consumption.

In the following work methods have been devised for isolating and studying the causes of these difficulties, with a view to determining what the design factors are that control or govern them and to obtain data upon which to base fundamental design specifications. Several preliminary runs were made using brick and hollow-tile dies, preparatory to arranging a schedule of tests on types of augers, different lengths and tapers of dies, and various lengths of collective spacers, comprising approximately 300 extrusion tests, 1,400 flow tests, and 4,000 moisture determinations. The study of the performance of augers, dies, and collective spacers has been accomplished by eliminating as many of the above-mentioned variables as possible and then correlating the remaining variables in such a manner as to single out the performance of each auger, die, and collective spacer.

Other laboratory tests were made simultaneously with the extrusion tests to determine the water content for best workability of the material by the use of a separate piece of apparatus called a flow cylinder and a special constant-speed testing machine. The workability of the material is indicated by the pressure in pounds per square inch required to produce flow through a ½-inch-diameter orifice and is hereinafter referred to as "flow pressure."

To facilitate in maintaining the moisture in the material within suitable limits a moisture-proof chamber was constructed of about 2 tons capacity, in which the tempered material was stored ready for use.

In addition to the laboratory work, the available literature and Patent Office records dealing with the development of auger machines and dies during the past 60 years have been reviewed.

II. SCOPE OF THE INVESTIGATION

This investigation embodies a study of the fundamental principles employed by the trade in the formation of a clay column by means of mechanically forcing plastic clay through a die with a rotating auger. The major considerations of this part of the investigation comprise a study of the design factors of augers, spacers, and dies and the types best suited to the physical characteristics of the clay or shale with which the tests were made.

Although the problem of laminations has not been seriously considered in this part of the investigation, the tendency of the various designs of augers and dies to increase or eliminate auger and die laminations has been noted. The principal studies entering into this section of the investigation are:

1. A study of the tempering and molding properties of several clays and the selection of one suitable for repeated use in making extrusion tests.

2. Determination of the proper amount of water to be added in tempering the clays and shales used in the tests in order to obtain the most stable working conditions.

3. Effect of moisture change and effect of repeated extrusion on the workability of the tempered material.

4. Power consumption, production, and quality of the product, depending upon the following:

A. Performance and relative efficiency of augers.

B. Effect of the distance of the ingress of the die from the auger tip (hereinafter referred to as the collective space).

C. Effect of die length.

D. Effect of die lubrication.

In addition to the usual ceramic-laboratory apparatus, the equipment used consists of a 2,000-pound capacity testing machine; a stiff-mud auger machine of a typical design; single, double, and triple wing augers; 6, 8, and 10 inch lengths of 1° taper standard brick dies; an 8-inch length of 4° taper, metal-lined, wooden die; electric indicating and recording instruments for measuring the electric-power input to the auger machine; specially designed apparatus for measuring the pressure required to produce flow in the tempered materials and the actual power consumed by various types of augers, dies, and spacers; also attachments for measuring the speed, volume, and weight of the extruded materials.

III. DESIGN AND OPERATION OF PLANT

1. DESIGN CONDITIONS

(*a*) Method of Attack.—The extrusion machine used requires a maximum of approximately 45 horsepower at full capacity when working a stiff-mud mixture. It was evident from the start that it would be necessary to deal with a considerable amount of power in the matter of designing a dynamometer to absorb and measure the load. Several methods of attack were carefully considered. In one of these it was proposed to obtain data for an efficiency curve by extending a small shaft through a specially constructed thrust bearing at the end of the auger shaft so as to install a Prony brake and dynamometer. By this means a known load could be imposed in addition to the gross power required to operate the machine when extruding the clay and overcoming the friction losses of the machine. By varying the imposed load a known amount and noting the changes in the gross power input it would be possible to obtain data for plotting efficiency curves with kilowatt-hours input as abscissae and per cent efficiency as ordinates. This was abandoned because of the difficulty in maintaining a constant load on the auger machine long enough to apply a brake load and obtain accurate readings and also on account of the expense and design difficulties involved in attaching a Prony brake of sufficient capacity to absorb loads varying from 15 to 20 horsepower.

Another method considered was to key an arm and a sleeve to the auger shaft so that the main-shaft gear would be free to rotate and compress a torsion spring which would show by a graduated segment the torque exerted on the auger shaft. This was also abandoned due to design difficulties, such as slow auger-shaft speed and vibrations.

The dynamometer method finally adopted was developed and designed by the investigator. The device which measures the useful work done by the auger and die directly in foot-pounds has proved very satisfactory as to accuracy and reliability. The measuring and registering elements are inclosed in dust-proof housings mounted on solid foundations independent of those for the auger machine and located several feet away. This type of design makes it possible to eliminate most of the vibrations of the auger machine that could not be overcome by the torsion spring or differential-type dynamometer.

The original design of the auger machine used employed a plain thrust bearing for the auger shaft. (Fig. 1.) To eliminate variable friction losses from the measurement of the useful work done by the auger, it was necessary to replace the plain bearing with a tapered-roller thrust bearing. In calculating the maximum thrust of the auger shaft for design purposes and for reference, the following auger-machine dimensions are given:

Diameter of single-thread impeller screw (see fig. 2 at *J*)	inches	13. 50
Pitch of single-thread impeller screw	do	8. 00
Angle of single-thread impeller screw		10° 35′
The last 8 inches of impeller screw adjacent to the triple-threaded auger tip is tapered down to a diameter of	inches	13. 00
Diameter of the tip section adjacent to the impeller screw (see fig. 2 at *M*)	inches	12. 50
Diameter of the tip section at the delivering blades	do	11. 25
Pitch of each thread on the tip section of the auger	do	13. 125

(*b*) CALCULATING THE AUGER THRUST.—The following values were obtained by measurements during preliminary experiments:

Speed of motor, 1,200 r. p. m.; maximum h. p., 45.

Speed of auger, 35 r. p. m.

Power loss through machine to auger by actual test, 13½ h. p.

45 − 13½ = 31½ effective horsepower causing the auger to rotate.

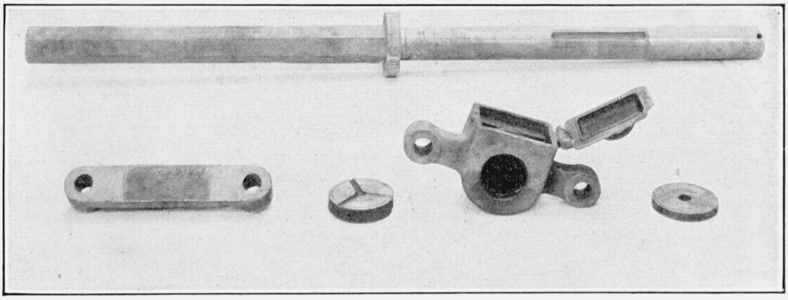


FIG. 1.—*Auger shaft and plain thrust bearing*

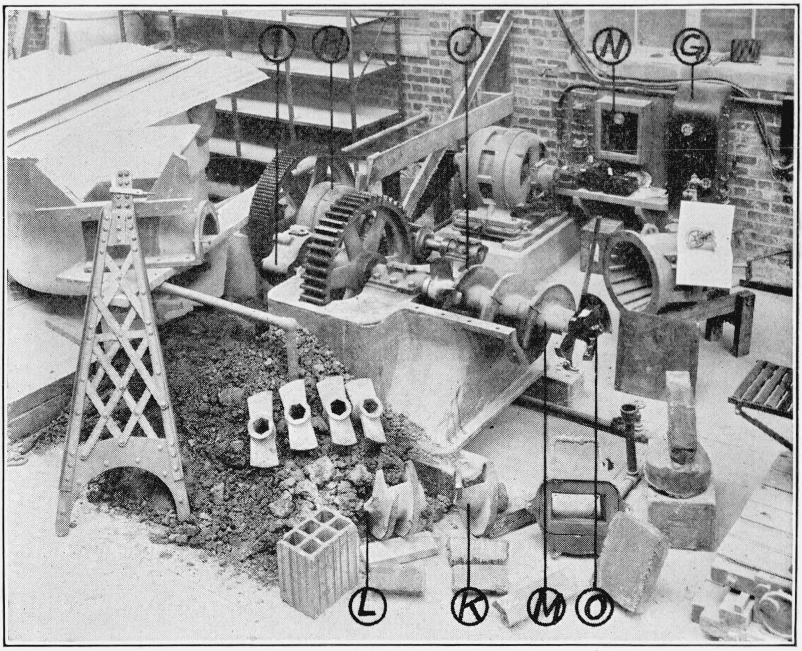
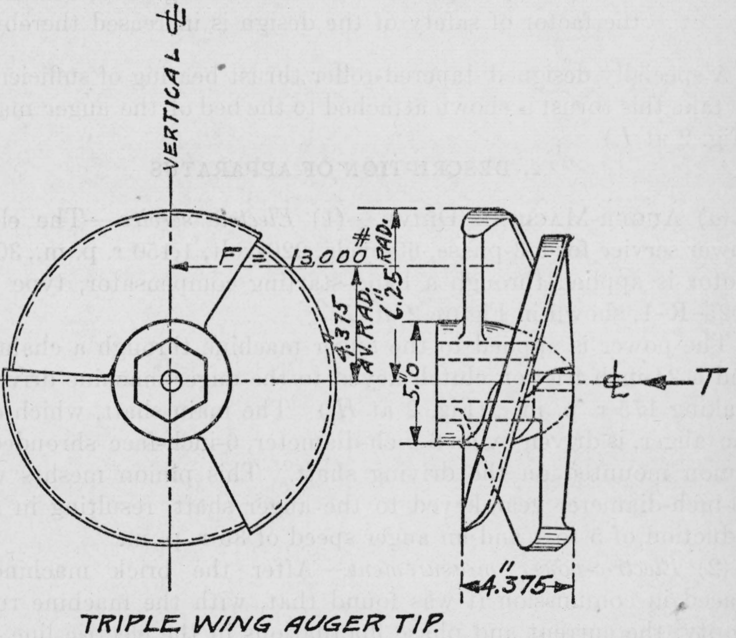


FIG. 2.—*Auger machine (partly dismantled) and motor drive*

Let F = a force such that, when applied perpendicularly to a plane passing through the central axis of the auger at a distance from this central axis equal to the radius of the pitch line of the auger thread, it would produce a resistance to turning equal to that produced by the clay when being extruded. The radius of the pitch line of the screw is shown in Figure 3 as 4.375 inches.

Let W = work performed per minute in foot-pounds, then $\frac{W}{33,000}$ = h. p. consumed.



TRIPLE WING AUGER TIP.

FIG. 3

Let V = velocity of the point of application of F, in feet per minute.
$= 2\pi \times$ rad. in feet, $\times$ r. p. m.

Then $W = FV = 2\pi \times 0.364 \text{ feet} \times 35 \times F$

$$HP = \frac{W}{33,000} = \frac{2\pi \times 0.364 \text{ feet} \times 35 \times F}{33,000} = 31.5 \text{ h. p. (as previously stated).}$$

$$\text{Hence } F = \frac{31.5 \times 33,000}{6.28 \times 0.364 \times 35} = 13,000 \text{ pounds.}$$

Let T = the calculated thrust from the auger.

Let p = the pitch of the thread on the auger.
= 13.125 inches.

r = the radius of the pitch line of the screw, 4.375 inches, as before.

Since the mechanics of the action of a screw is the same as for an inclined plane whose base is $=2\pi r$ and whose altitude is equal to the pitch, "p," we have the proportion

$$F:T=p:2\pi r$$

$$T=\frac{2\pi r\times F}{p}=\frac{6.28\times 4.375\text{ inches}\times 13{,}000}{13.125\text{ inches}}$$

$T=27{,}250$ pounds, approximate thrust on the plain bearing shown in Figure 1. The power lost due to the propeller blades cutting through the clay and the friction of the clay sliding through the auger and barrel is disregarded, inasmuch as the factor of safety of the design is increased thereby.

A specially designed tapered-roller thrust bearing of sufficient size to take this thrust is shown attached to the bed of the auger machine. (Fig. 2 at *I*.)

2. DESCRIPTION OF APPARATUS

(*a*) Auger-Machine Drive.—(1) *Electric service.*—The electric-power service for a 3-phase, 60-cycle, 220-volt, 1,150 r. p. m., 30 h. p. motor is applied through a hand-starting compensator, type C. R. 5025–R–1, shown in Figure 2 at *G*.

The power is applied to the auger machine through a chain drive and a 24-inch friction clutch keyed to the auger-machine drive shaft making 175 r. p. m. (Fig. 2 at *H*.) The main shaft, which carries the auger, is driven by an 8-inch-diameter, 6-inch-face shrouded steel pinion mounted on the driving shaft. This pinion meshes with a 40-inch-diameter gear keyed to the auger shaft, resulting in a gear reduction of 5 to 1 and an auger speed of 35 r. p. m.

(2) *Electric-power measurement.*—After the brick machine was placed in commission it was found that, with the machine running empty, the current and phase fluctuations in the electric line varied the power consumption as much as 5½ h. p. in a period of 20 minutes or less. To overcome the fluctuating conditions of current and phase in the line supplying power to the laboratory, a modified integrating switchboard-type kw.-hour meter was installed (see fig. 2 at *N*) which would integrate the power delivered to the motor, irrespective of the current and phase fluctuations of the line. The recording mechanism of the meter was replaced by a graduated dial mounted on a shaft geared direct to the armature spindle, so that the total revolutions of the armature could be counted and the actual power consumed over any given period of time calculated. After calibration it was possible to measure the actual power consumed by the auger machine to within 1 per cent with this instrument.

(*b*) Auger-Machine Equipment.—(1) *Augers.*—The term "auger" as herein used refers to all of the revolving element of the auger

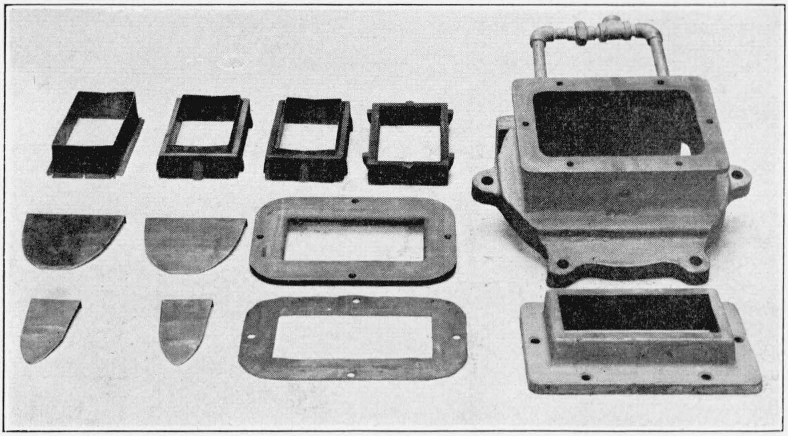


FIG. 4.—*One degree taper brick die dismantled*

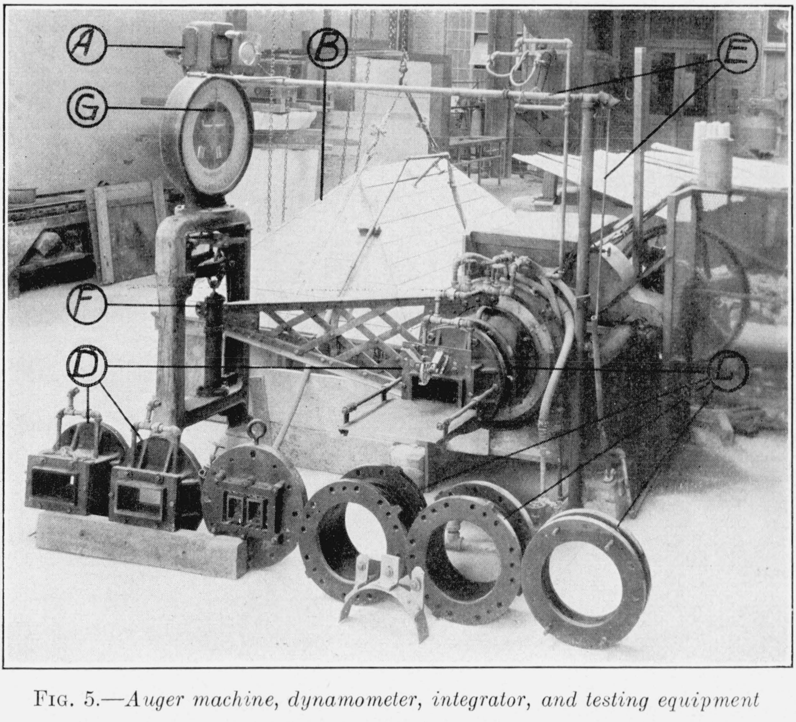


FIG. 5.—*Auger machine, dynamometer, integrator, and testing equipment*

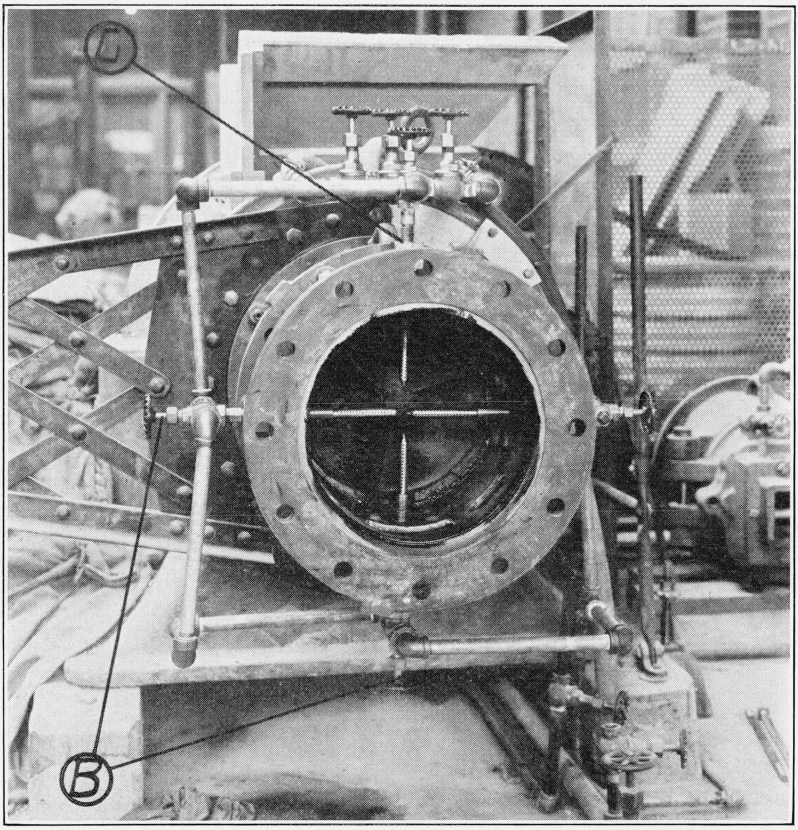


Fig. 6.—*Collective spacer containing perforated needles*

machine contained in the auger barrel (fig. 2 at *J*), and consists of three impeller blades 13½ inches in diameter, with four beaded-edge half wings 13½ inches in diameter, and one of the three designs of auger tips, as follows:

One single-wing 6-inch pitch, beaded-edge, tapered auger tip, 11 inches long; large diameter 13 inches, small diameter 11 inches. (Fig. 2 at *K*.)

One double-wing beaded-edge auger tip, 11 inches long; large diameter 13 inches, small diameter 10¾ inches. The first turn, or 360°, of thread on the large diameter has a 5-inch pitch; the pitch of the remaining one-fourth turn of the two threads on the small diameter increases from 5 inches at the back to 7 inches at the front or tip of the auger. (Fig. 2 at *L*.)

One triple-wing 13⅛-inch pitch (or 4⅜ inches between centers of successive wings), beaded-edge auger tip, 5¼ inches long; large diameter 12½ inches, small diameter 11¼ inches. (Fig. 2 at *O*.)

These three auger tips are interchangeable; the impellers and half wings are not.

(2) *Dies.*—Tests were made with seven different brick dies, described as follows:

One zero degree taper nonlubricated brick die 8¾ by 4⅛ by 8 inches long.

Three 1° taper brick dies, each 8¾ by 4⅛ inches, in three lengths (6, 8, and 10 inches, respectively), all arranged for lubrication. (See figs. 4 and 5 at *D*.)

Two 2° taper brick dies, one 8¾ by 4⅛ by 8 inches long and one 9¾ by 4¼ by 9 inches long, arranged for lubrication.

One 4° taper brick die 8¾ by 4⅛ by 8 inches long, constructed of wood, lined with molybdenum, and arranged for lubrication.

(3) *Collective spacers.*—Four collective spacers the same diameter as the auger barrel were made of 12-inch-diameter standard W. I. flanged pipe, in lengths varying from 4 to 10 inches in increments of 2 inches. (Fig. 5 at *C*.) These spacers can be combined so as to make additional spacers varying in length from 12 to 24 inches in 2-inch increments. A tapered approach to the rectangular ingress of the die was provided by 45° fillets fitting inside of the spacer and held in position by a thin metal diaphragm.

(4) *Device used in studying the flow of plastic material through dies.*—A 12-inch-diameter collective spacer 11 inches long (fig. 6) is equipped with externally adjustable perforated needles extending into the center of the auger barrel at the tip of the auger. These needles are provided with flexible pipe connections, so that steam, water, or other liquids can be injected into the moving clay at any depth desired in order to determine their effect on column flow. They may also be used to inject colored liquids to stain the material as it leaves

the auger, so that the flow of the material through the spacer and die may be studied. The depth of the needles can be regulated from the outside by turning the depth plug *c*. (Fig. 6.) The pressure of the liquid to be injected is controlled by a pressure-reducing valve in the air line to the reservoir and by individual valves for each needle. (Fig. 6 at *B*.) The needles themselves assist in shredding the clay and breaking up auger laminations. Preliminary attempts to remove the entrapped air by applying a vacuum to these needles were not successful. The effect of an excess of air in the clay, however, was very marked. When compressed air at 50 pounds per square inch was forced into the material as it left the auger, large blisters were produced on the surface of the clay column.

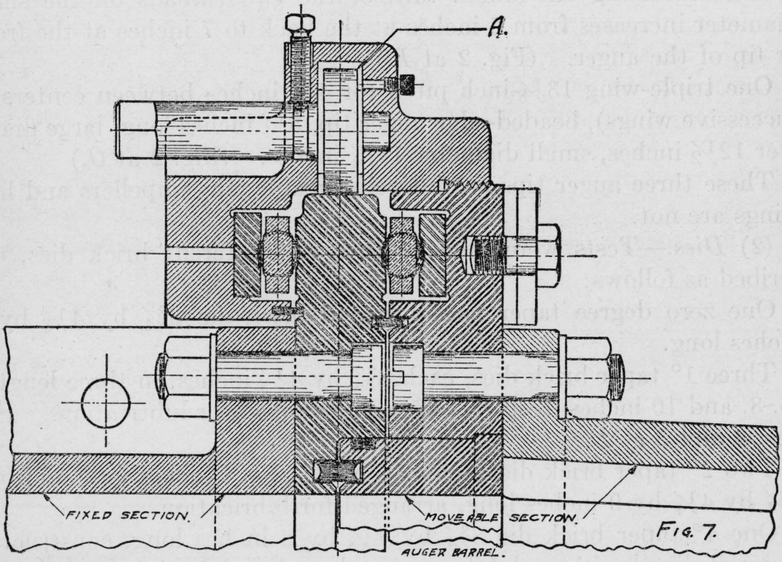


Fig. 7.—*Cross-section view of part of ball-bearing joint*

(*c*) Dynamometer Assembly.—(1) *Ball-bearing joint.*—The torsion-measuring apparatus shown in cross section of assembly (fig. 7) consists of two large hardened-steel disks or flanges (shown in fig. 8 at *A* and *B*). These disks are bolted to the flanges of the auger barrel and carry ball races to accommodate a series of $\frac{11}{16}$-inch-diameter hardened chrome nickel-steel balls. (Fig. 8 at *C*.) The outer edge of one of these disks (fig. 8 at *A*), called the "centering disk," is ground to provide a path for six hardened-steel rollers mounted on eccentric trunion pins (fig. 9; also fig. 7 at *A*). The other large-diameter disk (fig. 8 at *B*), called the "retaining flange," carries the die, the tapered nozzle or approach to the die, and a sealing sleeve that protects the ball-bearing joint (shown assembled in fig. 7). The circumference of the retaining flange is accurately machined to

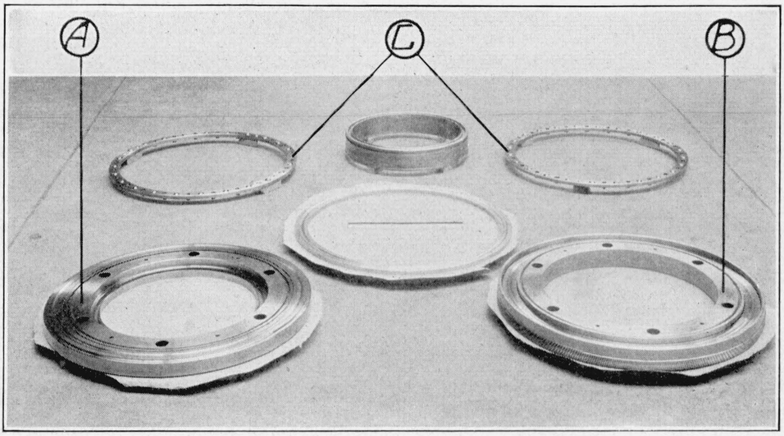


FIG. 8.—*Major parts of ball-bearing joint*

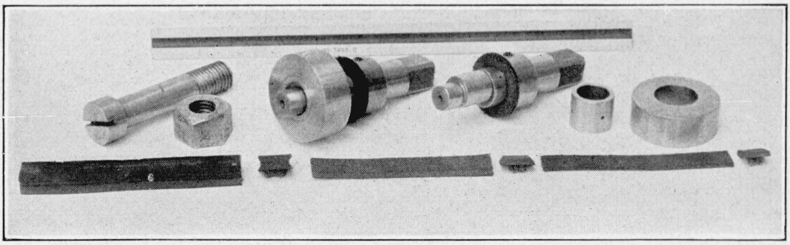


FIG. 9.—*Miscellaneous parts of ball-bearing joint*

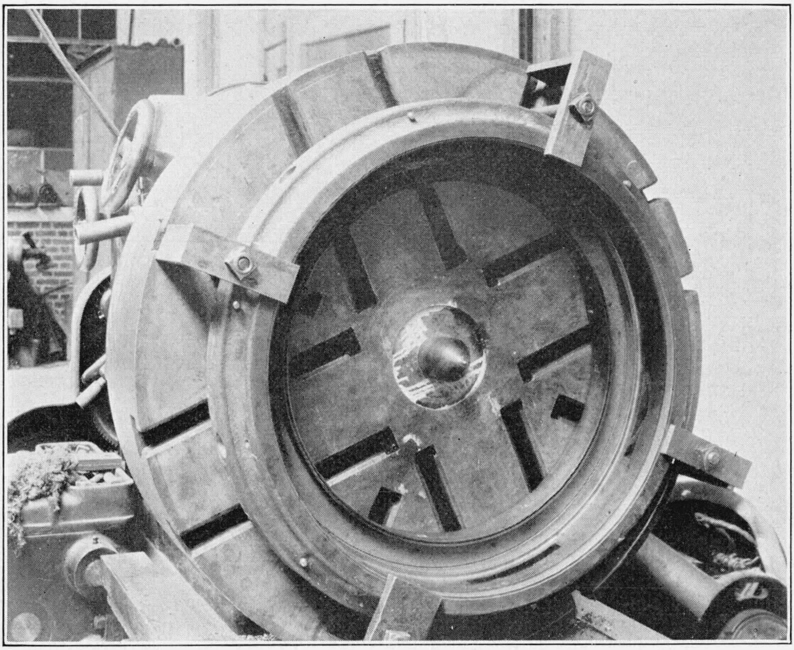


FIG. 10.—*Housing for ball-bearing joint* (*in process of machining*)

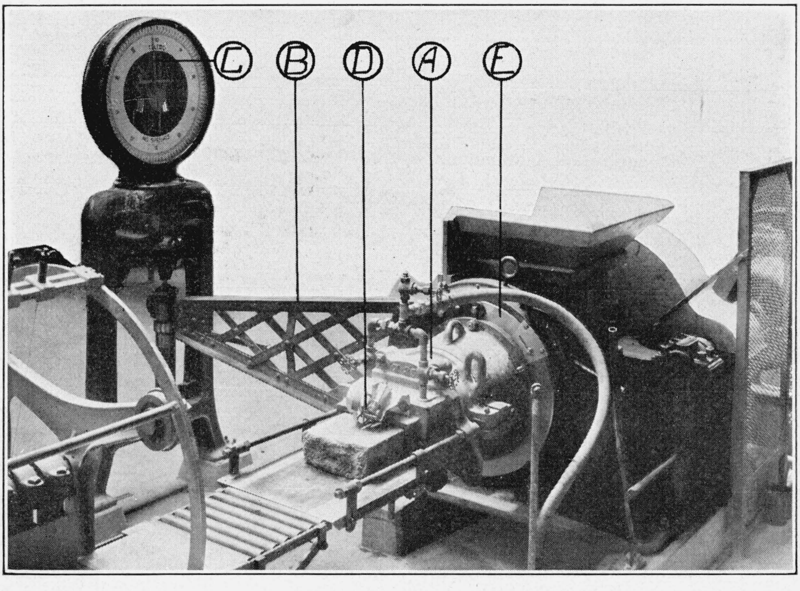


FIG. 11.—*Ball-bearing joint installation* (E)

provide a centering surface and a threaded portion which engages with an outer shell, shown in the process of manufacture, clamped to the faceplate of a lathe. (Fig. 10.) This cast-iron shell provides a housing for the ball-bearing joint, as well as providing adjustments for the annular rollers, and the two sets of ball bearings, all of which constitute a large inclosed dust-proof, water-tight drum having a storage space for lubrication, so that the rollers and ball bearings operate in a bath of oil (shown assembled in fig. 11 at *E*).

(2) *Dynamometer integrator.*—In the operation of the apparatus the useful work done by different designs of augers in forcing plastic materials through various combinations of spacers and dies is manifested in the form of a torsional moment of a constantly varying magnitude.

To determine the total amount of torque developed during a test, it is necessary to totalize these increments of torque. Consequently, an integrator which operates on the planimeter principle was installed on top of the dynamometer-scale drum. (Fig. 5 at *A*.) The registering mechanism of the integrator and the weighing mechanism of the scale are connected by a steelyard rod. (Fig. 5 at *G*.) A 5-inch-diameter revolving steel disk in the integrator is driven by a jointed shaft directly connected to the drive shaft of the auger machine. (Fig. 5 at *E*.) As the torsional moment varies in magnitude, a small hardened-steel friction wheel is moved across the face of the revolving disk a distance from the center proportional to the magnitude of the instantaneous torque. The friction wheel operates a revolution counter through a worm-and-gear reduction which registers the total integrated horsepower minutes developed by the auger.

(3) *Calibrating the scale and integrator.*—A 1,000-pound-capacity no-spring scale, modified by the installation of a new 1,500-pound-capacity scale head, was tested and calibrated to weigh within a possible error of 1 pound in 1,000 by suspending dead weights in increments of 50 pounds from the end of a cantilever beam. The error at 250, 500, 750, and 1,000 pounds was halved, as the load was repeatedly increased and decreased through the cycle from 0 to 1,000 pounds and back to zero.

The integrator is calibrated by—

(*a*) Adjusting the poise on the tare beam of the scale so that the dial hand registers zero with the auger machine running empty.

(*b*) The small planimeter wheel is brought to the center of the disk while the scale registers zero. This is done by adjusting the turnbuckle in the steelyard rod.

(*c*) With the auger machine running empty, dead weights in 250-pound increments are applied at the end of the dynamometer arm by means of an extension which can be attached at *F*. (Fig. 5.) The integrator, if in adjustment, will record 0 at no load, 8¾ h. p. m. at

250 pounds, 17½ h. p. m. at 500 pounds, 26¼ h. p. m. at 750 pounds, and 35 h. p. m. at 1,000 pounds, either during the calibration or an actual test, where the load is constantly changing.

The horsepower minutes (h. p. m.) consumed by the auger in extruding a certain weight of material is:

$$H.\,P.\,M.=\frac{PLN}{33{,}000}=\frac{PN}{1{,}000}$$

where P = the pull of the dynamometer arm on the scale in pounds.

L = the length of the dynamometer arm in feet × $2\pi = 5.25 \times 6.283$.

N = the number of auger revolutions per minute.

When P is 1,000 pounds, the auger develops 1 horsepower minute per revolution.

3. OPERATION OF PLANT

(*a*) Measuring the Flow Pressure.—A piece of apparatus was also developed for determining the pressure required to force samples of the tempered materials through an orifice. This consists of a cylinder, 2¼ inches inside diameter and 8 inches long, closed at the top by a ½-inch hardened-steel plate and provided with a ½-inch-diameter orifice at the center. Through this orifice plastic material is expelled by a close-fitting piston 4 square inches in area, moving at the rate of three-fourths inch per minute. A small briquet left in the apparatus after the flow test is made is used for making a moisture determination.

The loaded cylinder is placed in a vertical position between the upper and lower plates of the 2,000-pound testing machine. This machine is sensitive to one-half pound and is accurate within ±1 per cent up to 750 pounds.

(*b*) Making the Moisture Determinations.—Before tempering the screened clay its natural moisture is determined by drying three weighed samples to constant weight at 110° C. The moisture found in the material is expressed in per cent of the weight of the dry material and is the average of the three samples.

The moisture content of the tempered material is determined by taking the average of three moisture determinations made from samples of the plastic material taken just before each extrusion test.

(*c*) Column Speed and Capacity of the Extrusion Machine.—The column speed and capacity of the machine at 35 r. p. m. is approximately 8 feet per minute when using a die with a rectangular opening of 8¾ by 4⅛ inches. This is equivalent to about 10 tons of material, or 3,000 standard-size cut face brick per hour. A small lineal measuring device (fig. 11 at *D*) is attached to the egress of the die to measure the amount of material extruded in each test. From these data the total length and weight of the material extruded are obtained.

(*d*) Measuring the Power Absorbed by the Auger.—By inserting the ball-bearing joint in the auger barrel as shown in Figure 11 at *E* and replacing the original plain thrust bearing at the rear end of the auger shaft by a tapered-roller thrust bearing (fig. 2 at *I*), it is possible to measure the actual power absorbed by the auger in forcing the material through the die, and incidentally establish a comparison between different designs of augers, collective spacers, and dies.

The ball-bearing joint previously described is made a part of the auger machine proper (fig. 2) and constitutes a swiveled auger barrel mounted on ball bearings and steel rollers in such a way as to carry the die, the approach to the die, the collective spacer, and the sleeve surrounding the auger. The swiveled auger barrel (fig. 11 at *E*) transmits the torque developed by the auger to the dynamometer scale by means of the 63-inch arm (fig. 11 at *B*). The magnitude of the torque developed is indicated by a hand which oscillates back and forth over a graduated dial. (Fig. 11 at *C*.) The total power absorbed by the auger on a measured quantity of material is recorded by an integrator attached to the weighing mechanism of the dynamometer scale, described under III 2 (*c*), (2).

(*e*) Making the Extrusion Test.—In operating the testing plant the clay or shale, which has been previously tempered to the proper consistency as determined by a preliminary flow test, is fed into the hopper of the auger machine by hand at a uniform rate.

After making necessary adjustments and changes to insure a smooth operation of the plant and the formation of a characteristic column of clay, which usually takes about two minutes, readings are taken simultaneously on all instruments, which include the electric-power meter and ammeter, the footage measurer, the integrator, and the timer. At the conclusion of the test the same instruments are again read. The difference between readings gives (1) current demand and total electric energy consumed, (2) useful power developed by the auger, and (3) weight of the material extruded during the test. The total work done by the auger in forcing the material through the machine is recorded by the integrator, and the length of the column of formed material is measured and recorded by the lineal counter. Defects of any kind appearing in the clay bar are noted. Immediately after completing the test the formed material is cut into small pieces and stored in the moisture-tight chamber (fig. 5 at *B*) preparatory to the next test.

The average flow pressure and average moisture content are determined from the three samples of the material taken just before each extrusion test. The instantaneous torsional reactions produced by the auger as it forces the material through the machine are noted from time to time during the test. From these data performance curves are plotted, showing the weight of material extruded per h. p. m., the weight of material extruded per unit of time, the pressure per square inch required to produce flow, and the moisture content of the material at the time the test was made.[2]

IV. STUDIES OF CLAY AND SHALE IN THE DEVELOPMENT OF TEST PROCEDURE

1. PLASTICITY RANGE OF THE CLAYS AND SHALES STUDIED

It was considered that three clays or shales, such as are used in the industry, covering in a very general way the range from low through medium to high plasticity, would be sufficient to establish the data required for the design of the most important types of augers and dies.

2. PRELIMINARY STUDIES TO DEVELOP TEST PROCEDURE

Extrusion tests were made on a Virginia surface clay to ascertain the approximate maximum load demand for dynamometer-design purposes. (Table 1.) Also preliminary tests were made on a plastic shale from Illinois, a hard shale and a No. 2 plastic fire clay from western Maryland, and a medium plastic clay from eastern Maryland. These tests were made to ascertain the effects of slight changes in moisture content on the flow pressure and to develop methods of maintaining the moisture content of the tempered material within permissible limits.

TABLE 1.—*Preliminary test to ascertain the maximum efficient capacity of the auger machine used, and the corresponding value of current taken by the driving motor*

[Auger-machine equipment: Triple-wing auger, 8-inch—1° taper die, and 6-inch spacer]

VIRGINIA SURFACE CLAY—FUSION POINT 2,600° F.

Trial No.	Amperes at motor terminals	Average electric h. p. input	Remarks
1	49– 56.5	3.26	Motor operating chain drive only.
2[a]	90– 95	41.00	Motor operating auger machine full of clay.
3[b]	96–105	45.25	Clay churning back around impellers badly.
4	92–101	42.00	Do.
5	90– 98	39.00	Clay churning back around impellers reduced.
6	75– 90	34.50	Clay churning back around impellers eliminated.
7	62– 75	27.00	No churning at three-fourths capacity, die lubricated.
8	72– 85	33.00	No churning at seven-eighths capacity, die not lubricated.

[a] Circuit breaker tripped at 95 amperes.
[b] Circuit breaker adjusted to trip at 110 amperes.

NOTE.—The capacity of the auger machine at which the set-up operates the best corresponds to a measured value of current through the motor of between 75 and 85 amperes (obtained by taking the lowest limit of current in trial No. 6 and the highest limit in trial No. 8). Forcing the auger machine beyond this capacity results in the material churning back around the impellers. Also, when the current at the motor terminals exceeds 95 amperes, objectionable current and voltage fluctuations occur in the electric-power service.

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[2] Four families of curves are plotted on each sheet; average values of moisture content, total flow pressure, pounds of material extruded per minute, and pounds of material extruded per horsepower minute (h. p. m.) comprise the ordinates. Four lengths of collective spacers comprise the abscissas.

3. PREPARATION OF THE CLAY

Proper preparation of the clay is important, inasmuch as improperly tempered clays are often responsible for badly formed clay columns. The effect on the working behavior of a clay by changing its water content during tempering is different in clays of different physical properties. Nevertheless, an increase in water content increases the ease of flow and the sticking properties, so that lamination planes when formed will knit more easily. On the other hand, the increase of water content may also decrease the viscosity and internal friction of the clay, so that differential flow of the center portion of the column is increased.

When the clay is put through the extrusion machine, it is affected the same as by an extra pugging, and, in general, the more a clay is pugged the more easily it is extruded. As an illustration, the medium plastic clay from eastern Maryland was tempered with 25.8 per cent water and pugged two and one-half minutes in a wet pan. This material, when put through the extrusion machine the first time, required 26.68 h. p. m. per ton of clay extruded, but when put through the second time required only 25.9 h. p. m. per ton of extruded material, a decrease in power of 2.9 per cent. To reduce this variable where the same material is to be used several times in making a series of tests, it is given an initial extrusion before an actual test is made.

4. EFFECT OF MOISTURE LOSS VERSUS REPEATED USE ON FLOW PRESSURE

Before reliable data could be obtained regarding the performance of various designs of augers and dies it was necessary to determine what changes take place in the flow pressure of the clays and shales due to changes in the moisture content and what changes take place due to repeated pugging and storage during a series of tests. Therefore, studies were made of the effects of variations in moisture as well as repeated extrusions on the flow pressure of a plastic shale from Danville, Ill., and a No. 2 plastic fire clay from Mount Savage, Md. The flow pressure of the plastic shale increased 11.3 per cent for a decrease of approximately 2.7 per cent of the total amount of water used in tempering the dry shale. The flow pressure of the No. 2 plastic fire clay increased 51.3 per cent for a decrease of approximately 2.3 per cent of the total amount of water used in tempering the dry clay. The decrease in moisture in both cases is due primarily to the material drying out during storage. The increase in flow pressure in each case is the result of the combined effect of moisture decrease and repeated pugging as the material passed through the auger machine. (See Tables 2 and 3.)

From the foregoing it is evident (1) that the flow pressure of the Illinois plastic shale is less affected by variations in moisture content, repeated pugging, and storage than the No. 2 plastic fire clay; and (2) the enormous increase in flow pressure compared with the small decrease in water content in the region of the point of optimum plasticity illustrates the wide fluctuations in power required to operate an auger machine, due to variations in the water content of the tempered clay.

TABLE 2.—*Workable characteristics of a No. 2 fire clay from western Maryland*

[Auger-machine equipment used in all tests: Triple-wing auger, 11-inch spacer, two-cell hollow-tile die with cores removed]

Extrusion No.	Total moisture in the clay	Flow pressure	Clay extruded per h. p. m.	Remarks
	Per cent	*Lbs./in.²*	*Pounds*	
	26.70	62.0		Moisture and flow at time clay was tempered, 24 hours before extrusion No. 1.
1	25.62	66.0	12.15	Moisture and flow before extrusion No. 1.
	25.60	78.5		Moisture and flow after extrusion No. 1.
2	25.37	79.9	12.67	Moisture and flow before extrusion No. 2.
	25.38	85.5		Moisture and flow after extrusion No. 2.
3	25.28	85.8	12.6	Moisture and flow before extrusion No. 3.
	25.27	90.8		Moisture and flow after extrusion No. 3.
4	25.10	91.1	12.92	Moisture and flow before extrusion No. 4.
	25.04	99.9		Moisture and flow after extrusion No. 4.

NOTE.—Clay stored under damp sacks 24 hours between extrusions.

Decrease in moisture from 25.62 to 25.04 is 2.27 per cent. The increase in flow pressure due to this moisture change is 51.3 per cent.

TABLE 3.—*Workable characteristics of a plastic shale from central Illinois*

[Auger-machine equipment used in all tests: Triple-wing auger, 11-inch spacer, two-cell hollow-tile die with cores removed]

Extrusion No.	Total moisture in the shale	Flow pressure	Shale extruded per h. p. m.	Remarks
	Per cent	*Lbs./in.²*	*Pounds*	
	23.05	64.9		Moisture and flow at time shale was tempered, 24 hours before extrusion No. 1.
1	23.09	64.3	11.9	Moisture and flow before extrusion No. 1.
	23.30	54.6		Moisture and flow after extrusion No. 1.
2	23.00	67.3	12.5	Moisture and flow before extrusion No. 2.
	22.84	61.5		Moisture and flow after extrusion No. 2.
3[1]	22.76	69.7	10.03	Moisture and flow before extrusion No. 3.
	22.80	72.0		Moisture and flow after extrusion No. 3.
4	22.60	68.0	11.42	Moisture and flow before extrusion No. 4.
	22.47	71.5		Moisture and flow after extrusion No. 4.

[1] Shale stored under wet sacks 48 hours between extrusions Nos. 2 and 3.

NOTE.—Shale stored under wet sacks 24 hours between extrusions except as noted.

Decrease in moisture from 23.09 to 22.47 is 2.68 per cent. The increase in flow pressure due to this moisture change is 11.3 per cent.

Tests similar to those referred to above were made on a brick shale from central Maryland and a brick clay from eastern Maryland with a view of obtaining a plastic material that would stand repeated pugging without materially affecting the properties governing its workable characteristics.

It was found that the flow pressure of the brick shale increased 184.0 per cent for a decrease of 8.6 per cent of the moisture content. (See Table 4.) The shale swedged poorly and could only be extruded twice; it would not flow under pressure when tempered with 14 per cent water, and with 18 per cent water it was very soft and would not hold its shape. With 16 per cent water it worked best but not satisfactorily, as some of the water squeezed out at pressures below 50 pounds per square inch. The flow pressure of the brick clay was found to remain practically constant during the first four extrusions, provided the variation in total moisture content was kept within about 5 per cent of the dry material by weight. When the number of extrusions were continued to six, the flow pressure changed 48 per cent for a moisture change of 9.27 per cent of the maximum moisture of the clay (see Table 5), which is small compared to the change in flow pressure of the No. 2 plastic fire clay (see Table 2).

These tests indicated that the eastern Maryland brick clay is a tough, medium plastic material, the flow pressure of which remains almost constant during repeated extrusions. (See Table 6.) Because of its practically constant working properties the eastern Maryland brick clay was used exclusively throughout the remainder of the tests herein reported. After tempering with 25½ per cent total water and pugging two and one-half minutes in a wet pan the clay could be used satisfactorily for 10 or 12 successive extrusion tests; however, the flow pressure gradually increased coincident with the decrease in moisture during each successive extrusion test.

TABLE 4.—*Workable characteristics of a hard, slaty brick shale from western Maryland*

[Auger-machine equipment used in all tests: Triple-wing auger, 11-inch spacer, two-cell hollow-tile die with cores removed]

Extrusion No.	Total moisture in the shale	Flow pressure	Shale extruded per h. p. m.	Remarks
	Per cent	*Lbs./in.*^{2}	*Pounds*	
	16.91	98.0		Moisture and flow at time shale was tempered, 24 hours before extrusion No. 1.
1	17.52	109.0	16.6	Moisture and flow before extrusion No. 1.
	16.86	124.0		Moisture and flow after extrusion No. 1.
2	16.61	168.0	13.0	Moisture and flow before extrusion No. 2.
	16.52	187.6		Moisture and flow after extrusion No. 2.
3	16.27	201.9	7.22	Moisture and flow before extrusion No. 3.
	16.02	309.5		Moisture and flow after extrusion No. 3.
4	16.14	313.5	(1)	Moisture and flow before extrusion No. 4.
	15.35	350.0		Moisture and flow after extrusion No. 4.

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[1] Extrusion No. 4 could not be continued to completion on account of material becoming too dry to be extruded when operating the equipment at 50 per cent overload.

NOTE.—Shale stored under wet sacks 24 hours between extrusions.

Decrease in moisture from 17.52 to 16.02 is 8.61 per cent. The increase in flow pressure due to this moisture change is 184.0 per cent. Both of these values would be larger if the data for the uncompleted extrusion No. 4 were used.

TABLE 5.—*Workable characteristics of a medium-plastic brick clay from eastern Maryland*

[Auger-machine equipment used in all tests: Triple-wing auger, 11-inch spacer, two-cell hollow-tile die with cores removed]

Extrusion No.	Total moisture in the clay	Flow pressure	Clay extruded per h. p. m.	Remarks
	Per cent	*Lbs./in.^{2}*	*Pounds*	
	24.67	67.2	----------	Moisture and flow at time clay was tempered, 24 hours before extrusion No. 1.
1	25.35	63.2	24.81	Moisture and flow before extrusion No. 1.
	25.20	60.7	----------	Moisture and flow after extrusion No. 1.
2	24.45	66.0	23.85	Moisture and flow before extrusion No. 2.
	24.40	64.0	----------	Moisture and flow after extrusion No. 2.
3	25.13	66.5	24.25	Moisture and flow before extrusion No. 3.
	25.10	73.2	----------	Moisture and flow after extrusion No. 3.
4	24.15	69.0	23.12	Moisture and flow before extrusion No. 4.
	24.10	69.2	----------	Moisture and flow after extrusion No. 4.
5[1]	23.76	72.0	20.82	Moisture and flow before extrusion No. 5.
	23.63	78.0	----------	Moisture and flow after extrusion No. 5.
6[2]	23.40	83.5	20.56	Moisture and flow before extrusion No. 6.
	23.00	93.5	----------	Moisture and flow after extrusion No. 6.

[1] Clay stored under wet sacks 72 hours between extrusions Nos. 4 and 5.
[2] Clay stored under wet sacks 48 hours between extrusions Nos. 5 and 6.

NOTE.—Clay stored under wet sacks 24 hours between extrusions except as noted.
Decrease in moisture from 25.35 to 24.10 is 4.91 per cent. The increase in flow pressure due to this moisture change is 9.5 per cent.
The decrease in moisture from 25.35 to 23.00 is 9.27 per cent. The increase in flow pressure due to this moisture change is 48 per cent.

TABLE 6.—*Workable characteristics of a medium-plastic brick clay from eastern Maryland; reground and retempered after being extruded six times* [1]

[Auger-machine equipment used in all tests: Triple-wing auger, 11-inch spacer, two-cell hollow-tile die with cores removed]

Extrusion No.	Total moisture in the clay	Flow pressure	Clay extruded per h. p. m.	Remarks
	Per cent	*Lbs./in.^{2}*	*Pounds*	
	23.77	67.5	----------	Moisture and flow at time clay was tempered, 6 hours before extrusion No. 1.
1	23.77	67.5	20.58	Moisture and flow before extrusion No. 1.
	23.75	79.0	----------	Moisture and flow after extrusion No. 1.
2	23.90	63.0	20.03	Moisture and flow before extrusion No. 2.
	23.75	77.5	----------	Moisture and flow after extrusion No. 2.
3	23.75	76.0	20.07	Moisture and flow before extrusion No. 3.
	23.29	82.0	----------	Moisture and flow after extrusion No. 3.
4	23.10	81.0	20.29	Moisture and flow before extrusion No. 4.
	23.00	80.0	----------	Moisture and flow after extrusion No. 4.

[1] See Table 5.

NOTE.—Clay stored under wet sacks 24 hours between extrusions.
Decrease in moisture from 23.77 to 23.00 is 3.24 per cent. The increase in flow pressure due to this moisture change is 18.5 per cent.

A parallel series of 12 tests were made using "new material" with 25.4 per cent water in series (c) and "old or used retempered material" with 25.3 per cent water in series (b). The same combinations of equipment were used as in previous tests, consisting of a single-wing auger with a change of three 1° taper dry dies of 6, 8, and 10 inch lengths, respectively, and four different spacers with each change of die. These spacers were 4, 6, 8, and 10 inches in length. From the results of these 24 tests shown in Table 7 it is evident that the gradual moisture drop is responsible for practically all the increase in the flow pressure. In general, the least change in the flow pressure is coincident with the least change in the moisture content. The total decrease in moisture content throughout the 12 tests was 2 per cent in the old and 1.8 per cent in the new. The corresponding increase in flow pressure required for the two materials due to drop in moisture amounted to 85 per cent for the old and 69 per cent for the new.

TABLE 7.—*Results of a parallel series of 12 tests on used and unused medium plastic Maryland brick clay*

Extrusion No.	Equipment combinations	Clay extruded per h. p. m.	Flow pressure on piston area 4 square inches	Total moisture in the clay	Values used in plotting moisture curves= $\frac{b+c}{2}$	Remarks
		Pounds	*Pounds*	*Per cent*		
2–b	1- 6- 4[1]	62.2	245	25.30	25.35	"b" denotes used (retempered) material.
2–c		77.2	222	25.40		"c" denotes new material.
3–b	1- 6- 6	61.0	275	25.07	25.13	
3–c		67.0	239	25.19		
4–b	1- 6- 8	54.0	282	24.96	25.07	
4–c		63.0	235	25.18		
5–b	1- 6-10	51.8	287	24.74	24.83	
5–c		54.0	250	24.93		46 hours after material was tempered.
6–b	1- 8-10	45.5	307	24.58	24.73	6-inch die replaced by 8-inch die.
6–c		46.8	258	24.89		
7–b	1- 8- 8	50.8	325	24.43	24.50	
7–c		55.0	270	24.57		
8–b	1- 8- 6	55.0	326	24.26	24.36	
8–c		65.4	295	24.46		
9–b	1- 8- 4	63.7	373	23.98	24.13	
9–c		70.2	302	24.29		95 hours after material was tempered.
10–b	1-10- 4	57.6	374	23.67	23.80	8-inch die replaced by 10-inch die.
10–c		58.0	317	23.94		
11–b	1-10- 6	55.8	394	23.59	23.72	
11–c		50.2	342	23.86		
12–b	1-10- 8	39.6	420	23.51	23.61	
12–c		40.0	350	23.72		
13–b	1-10-10	32.2	452	23.30	23.45	144 hours after material was tempered.
13–c		36.7	373	23.60		

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[1] The first figure denotes the number of wings on the auger tip, the second the length of the die in inches, and the third the length of the collective spacer in inches.

The greatest variation in output per unit of power for any two corresponding extrusion tests of old and new material occurred when using a 6-inch die and a 4-inch spacer and amounted to 19¾ per cent, being less for the old material, when expressed in terms of the output of the new material. The least variation in output of old material, compared to that of the new material occurred when a 10-inch die and an 8-inch spacer were used, and amounted to 1¼ per cent of the output of the new material. (See Table 7, fig. 12.)

In the case of this particular clay the reuse of the tempered material has a comparatively small effect on its working properties from an extrusion-test standpoint so long as the moisture content is controlled within a variation of 1 or 2 pounds of water per 100 pounds of clay. (See Tables 5, 6, and 7.)

V. PRESENTATION OF DATA AND DISCUSSION OF RESULTS

1. CONDITIONS UNDER WHICH TESTS WERE MADE

The procedure in making these tests is essentially that outlined under III, 3, (*e*). The method of tempering the eastern Maryland clay used in these tests is described under IV, 3 and 4.

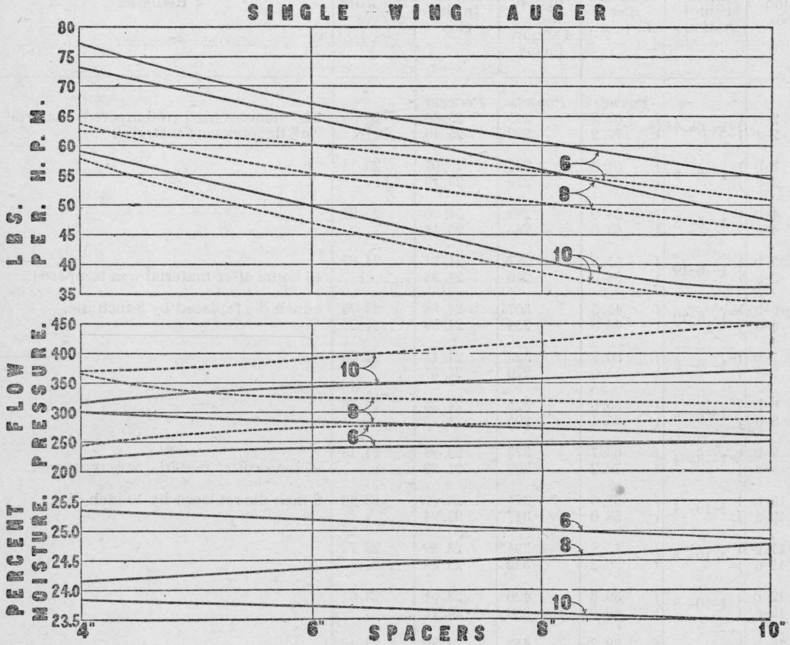

FIG. 12.—*Effects of moisture loss versus repeated use on flow pressure (workable characteristics)*

Solid-line graphs are for new (unused) material. Dotted-line graphs are for old (retempered) material

2. PERFORMANCE AND RELATIVE EFFICIENCY OF AUGERS

(*a*) SINGLE-WING AUGER.—The performance of a single-wing auger in extruding the clay is shown in Table 8 and Figure 13. The results are average values obtained experimentally in duplicate tests on each combination of equipment shown in the table.

TABLE 8.—*Average values of single-wing auger tests*

	Equipment combinations—Single-wing auger constant, taper 1° and egress 4⅛ by 8¾ inches for all dies											
	6-inch die constant, variable spacer length				8-inch die constant, variable spacer length				10-inch die constant, variable spacer length			
	1-6-4[1]	1-6-6	1-6-8	1-6-10	1-8-10	1-8-8	1-8-6	1-8-4	1-10-4	1-10-6	1-10-8	1-10-10
Pounds of clay extruded per h. p. m.[2]	80.4	68.6	61.5	54.0	46.8	53.2	65.8	71.2	66.2	54.8	36.7	34.6
Flow pressure in pounds per square inch	50.0	53.0	54.0	57.0	64.0	65.0	67.0	70.0	79.0	82.0	87.5	97.5
Per cent total moisture in the clay	25.9	25.6	25.5	25.3	25.2	24.9	24.8	24.7	24.3	24.2	23.9	23.4
Output in pounds of clay per minute	165	179	187	195	208	220	227	227	236	241	258	278

[1] The first figure denotes the number of wings on the auger, the second the length of the die in inches, and the third the length in inches of the collective spacer used in each test.

[2] H. p. m. denotes horsepower minutes.

It is apparent that the 4-inch-length spacer and 6-inch-length die combination gives the greatest output per unit of power, while the 10-inch-length die and 10-inch-length spacer combination gives the smallest output; however, the objectionable column defects coincident with the use of the 4-inch spacer—namely, cracking, tearing, and flaking—are almost entirely eliminated when a 6-inch-length spacer is used and are entirely overcome when an 8-inch-length spacer is used indicating that the most efficient single-wing auger equipment is narrowed down to an 8-inch-length spacer and a 6-inch-length die.

(*b*) DOUBLE-WING AUGER.—The performance of a double-wing auger, under comparable conditions of operation prevailing for single and triple wing augers regarding equipment and material, is shown graphically in Figure 14 and by Table 9 for average values resulting from a series of 40 tests.

TABLE 9.—*Average values of double-wing auger tests*

	Equipment combinations—Double-wing auger constant, taper 1° and egress 4⅛ by 8¾ inches for all dies											
	10-inch die constant, variable spacer length				8-inch die constant, variable spacer length				6-inch die constant, variable spacer length			
	2-10-10[1]	2-10-8	2-10-6	2-10-4	2-8-4	2-8-6	2-8-8	2-8-10	2-6-10	2-6-8	2-6-6	2-6-4
Pounds of clay extruded per h. p. m.[2]	26.8	22.80	25.00	40.20	42.70	39.40	34.10	31.70	34.40	37.50	41.60	44.20
Flow pressure in pounds per square inch	65.0	84.50	93.50	62.00	57.00	54.00	56.50	55.50	66.00	70.00	73.00	78.00
Per cent total moisture in the clay	24.7	23.84	23.52	24.74	25.28	25.23	24.96	24.85	24.56	24.53	24.32	24.10
Output in pounds of clay per minute	314	316	365	348	328	320	323	340	337	362	386	398

[1] In the various combinations the first figure denotes the number of wings on the auger, the second the length of the die in inches, and the third the length of the collective spacer in inches.

[2] H. p. m. denotes horsepower minutes.

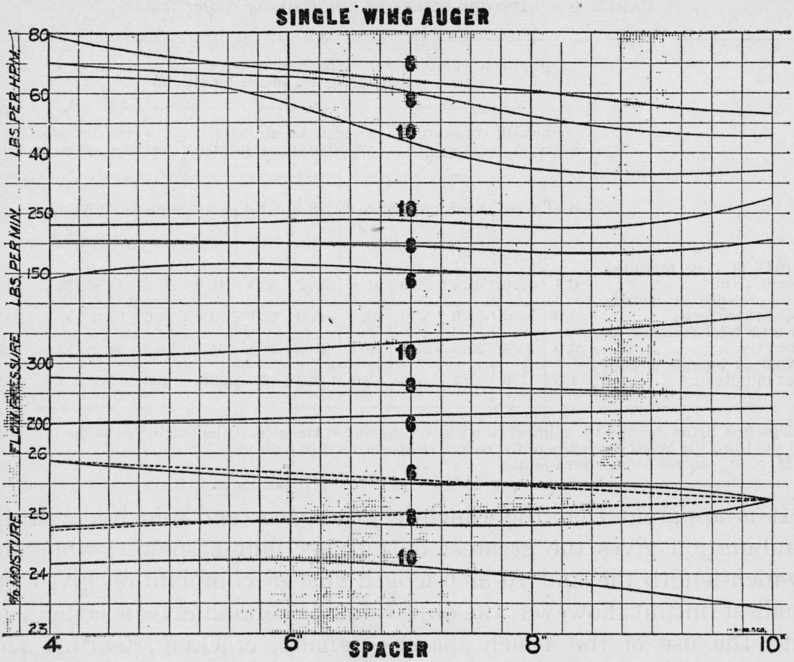

FIG. 13.—*Performance of a single-wing auger*

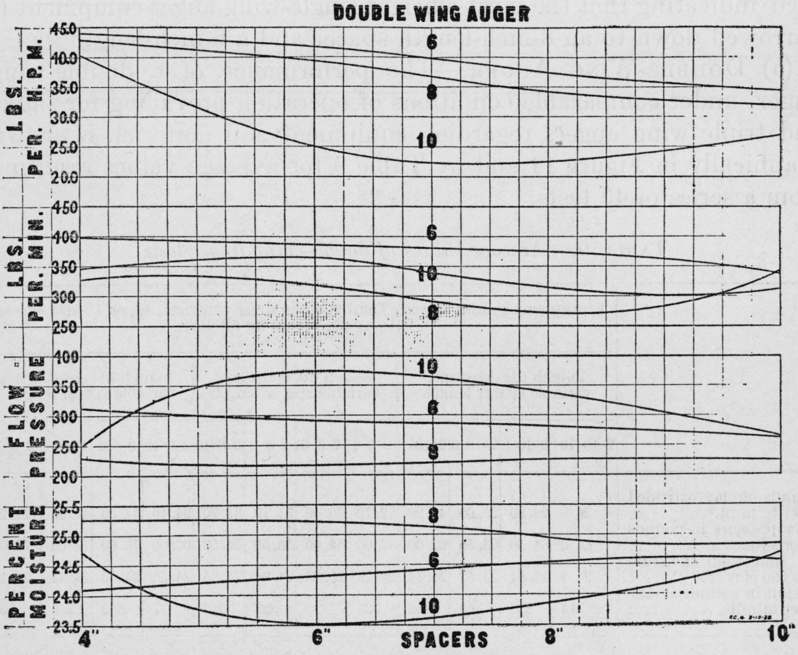

FIG. 14.—*Performance of a double-wing auger*

The 6-inch-length die and 6-inch-length collective spacer rate the highest output in pounds of clay per unit of power, without producing a defective column. The 4-inch-length collective spacer and 6-inch-length die have a slightly higher output per unit of power but produce transverse cracks and, therefore, a defective column.

(*c*) TRIPLE-WING-AUGER.—The performance of a triple-wing auger under operating conditions comparable with those prevailing during tests on single and double wing augers is shown graphically in Figure 15 and by Table 10 for average values resulting from a series of 30 tests.

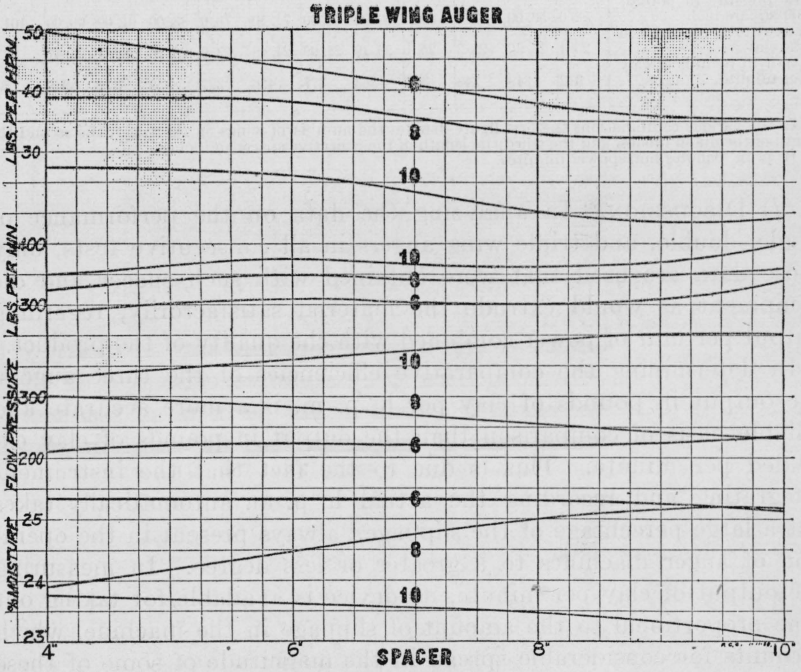

FIG. 15.—*Performance of a triple-wing auger*

As in the studies of single and double wing augers, the 4-inch-length collective spacer produced a defective column because of the proximity of the die to the auger. The results also show that collective spacers longer than 8 inches are wasteful of power.

As in the case of the single-wing auger, the most efficient combination of equipment based on output of clay per unit of power combined with quality of the clay column is an 8-inch-length spacer and a 6-inch-length die.

TABLE 10.—*Average values of triple-wing auger tests*

	Equipment combinations—Triple-wing auger constant, taper 1° and egress 4⅛ by 8¾ inches for all dies											
	6-inch die constant, variable spacer length				8-inch die constant, variable spacer length				10-inch die constant, variable spacer length			
	3-6-4[1]	3-6-6	3-6-8	3-6-10	3-8-10	3-8-8	3-8-6	3-8-4	3-10-4	3-10-6	3-10-8	3-10-10
Pounds of clay extruded per h. p. m.[2]	50. 5	44. 40	35. 3	36. 1	34. 76	33. 50	38. 90	39. 4	26. 80	26. 60	20. 90	19. 8
Flow pressure in pounds per square inch	53. 0	56. 00	57. 5	60. 0	60. 00	65. 00	71. 50	76. 0	83. 00	91. 00	99. 00	101. 0
Per cent total moisture in the clay	25. 4	25. 32	25. 3	25. 1	25. 19	24. 99	24. 48	23. 9	23. 76	23. 63	23. 47	23. 0
Output in pounds of clay per minute	312	349	343	363	363	377	456	327	352	376	348	397

[1] In the various combinations the first figure denotes the number of wings on the auger, the second the length of the die in inches, and the third the length of the collective spacer in inches.

[2] H. p. m. denotes horsepower minutes.

(*d*) DISCUSSION.—In analyzing the data on the performance of single, double, and triple wing augers in all consecutive tests, only those data are used that were obtained with such spacer and die equipment as would extrude the material satisfactorily, regarding output per unit of power combined with the quality of the product.

In determining the comparative efficiencies of the three augers, the output in pounds of clay per h. p. m. is a more accurate and reliable basis of comparison than the output in pounds of clay extruded per minute. This is due to the fact that the instrument integrating and recording the actual h. p. m. automatically takes out a large percentage of the slippage,[3] always present in the operation of auger machines to a greater or less degree. In measuring the output of clay per minute, no device is available for taking out time proportional to the amount of slippage in the machine, which accounts for considerable spread in the magnitude of some of these values. However, corrections have been made by extrapolation where slippage is known to exist, for the sake of studying the actual trend of the results.

From the foregoing it appears that the greatest output per minute occurs where the flow pressure is greatest, also the slippage is the least where the moisture content is the least, indicating that a slight excess of water above that required to produce optimum plasticity decreases viscosity of the clay, and consequently increases slippage.

The average relative efficiencies of the single, double, and triple wing augers based on the output per unit of power (see Table 11, column 7) are in the order and magnitude of 100, 60.57, and 60.53,

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[3] Slippage is a term used here to designate a condition existing in auger-extrusion machines where the speed of travel of the extruded material slows down or stops entirely and is usually due either to irregularity in the quantity of material carried forward by the impeller blades or to very wet or very dry material becoming wedged in the auger spirals and revolving with the auger.

respectively. The average relative efficiencies of the same three augers based on the output of material per unit of time (Table 11, column 8) are in the order and magnitude of 49.3, 90.1, and 95.1, respectively, which is the reverse of the order of magnitude of efficiencies of the same three augers based on the output per unit of power. These data indicate that the pressure in the extruded material is increased more by augers having multiple wings than by augers having a single wing and that the friction loss due to the material sliding through the auger wings increased as the number of wings on the auger increased.

It is obvious that the most important design factors are primarily those having to do with the development of an auger capable of delivering the greatest volume of material with the greatest axial thrust per unit of power consumed. Of the three types of augers used in these tests, the single-wing auger is the most efficient in point of power consumption and is the type the most capable of such development.

Table 11.—*Average relative efficiencies of single, double, and triple wing augers when operating in combinations using 6 and 8 inch dies and 6 and 8 inch spacers*

6-INCH-LENGTH 1° TAPER DRY DIE AND A 6-INCH-LENGTH COLLECTIVE SPACER

Equipment combinations	Flow pressure	Moisture in the clay	Output in pounds per h. p. m.[2]	Output in pounds per minute, measured	Output in pounds per minute, corrected for slippage	Efficient in pounds per h. p. m.	Efficient in pounds per minute
	Lbs./in.²	*Per cent*				*Per cent*	*Per cent*
1-6-6[1]	53.0	25.57	68.60	167.5	179	100.0	46.4
2-6-6	73.0	24.32	41.60	386.0	386	60.7	100.0
3-6-6	56.6	25.32	44.40	312.0	349	64.8	90.5
6-INCH-LENGTH 1° TAPER DRY DIE AND AN 8-INCH-LENGTH COLLECTIVE SPACER							
1-6-8	54.0	25.50	61.50	155.3	187	100.0	51.7
2-6-8	70.0	24.53	37.50	362.0	362	61.0	100.0
3-6-8	57.5	25.31	35.37	300.0	343	57.6	95.0
8-INCH-LENGTH 1° TAPER DRY DIE AND A 6-INCH-LENGTH COLLECTIVE SPACER							
1-8-6	67.0	24.88	65.83	201.2	227	100.0	49.8
2-8-6	54.0	25.23	39.40	320.0	320	60.0	70.2
3-8-6	71.5	24.48	38.90	440.0	456	59.2	100.0

[1] In the various combinations the first figure denotes the number of wings on the auger, the second the length of the die in inches, and the third the length of the collective spacer in inches.

[2] H. p. m. denotes horsepower minutes.

It is apparent from the performance curves (figs. 13, 14, and 15) that the output per unit of power for all designs of augers and all designs of brick dies and spacers decreases as the length of the die or the length of the collective spacer increases.

3. COLLECTIVE SPACERS

(*a*) Effect of Length on Power Consumption and Quality of the Product.—The length of the intermediate collective chamber or spacer between the tip of the auger and the ingress of the die is a very important factor in the quality of the clay column and in the power consumption. In auger machines equipped with brick dies the greater the length of the collective spacer the greater the power consumption per thousand brick extruded.

Four-inch-length collective spacers produce transverse column cracks as the result of a variable and uneven pressure behind the die ingress, resulting in a zigzag motion of the clay column as it emerges from the die. This is because the die is so close to the tip of the auger that the individual thrusts from the wings on the auger as these wings pass the horizontal plane of the die are transmitted through the die to the extruded clay column.

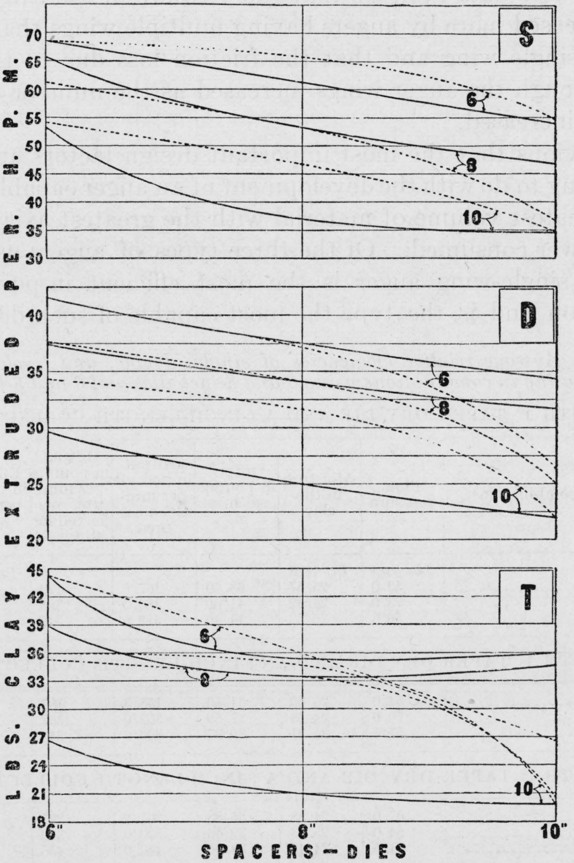

FIG. 16.—*Comparative effects of die and spacer lengths on output*

NOTE.—Pounds of clay extruded per horsepower minute plotted on the ordinate, with dies and spacers varying in length plotted on the abscissa, for different augers as indicated.

S, single-wing auger.
D, double-wing auger.
T, triple-wing auger.
Dotted lines denote spacer constant with 6, 8, and 10 inch dies.
Solid lines denote dies constant with 6, 8, and 10 inch spacers.
Different spacers and dies are plotted on the abscissa in the same units, viz, 6, 8, and 10 inch for the three different charts, S, D, and T. (See Table 12.)

In all tests where spacers 4 inches or less in length were used with single, double, and triple wing augers, transverse column cracks were produced. While 6-inch spacers gave satisfactory results with double and triple wing augers, it was evident that 8-inch spacers are preferable where single-wing augers are used, since the greater volume of elastic material under pressure in the 8-inch spacer more completely dissipates the excessive alternate thrusts characteristic of the single-wing auger. The 8-inch spacer also has the effect of producing better equalization of pressure across the ingress opening of the die.

(*b*) DISCUSSION.—Collective spacers more than 8 inches in length are of no special advantage in molding common brick columns. In special cases, however, where a very straight flowing clay column of extra good structure is desired, it may be advantageous to use collective spacers longer than 8 inches. Nevertheless, any length of collective spacer greater than that required to overcome uneven flow through the die due to the thrust of the auger wings is unnecessary and wasteful of power.

The effect of collective spacer length on output per unit of power and quality of the ware does not follow the same law that applies to the effect of the length of the brick die on output per unit of power and quality of the ware.

By referring to Table 12 and Figure 16 the relative effect on output per unit of power caused by increasing the length of the die in increments of 2 inches from 6 to 10 inches is shown by the length of the intercepted ordinates between the solid curves as they cross the page from left to right.

TABLE 12.—*Average values (used in plotting graphs, fig. 16), showing the comparative effect of die length and spacer length on output per h. p. m.*

SINGLE-WING AUGER

Dies constant; spacers varying				Spacers constant; dies varying			
Length of dies			Length of spacer	Length of die	Length of spacers		
6 inches	8 inches	10 inches			6 inches	8 inches	10 inches
Clay extruded per h. p. m.					Clay extruded per h. p. m.		
Pounds	*Pounds*	*Pounds*	*Inches*	*Inches*	*Pounds*	*Pounds*	*Pounds*
68.60	65.83	53.20	6	6	68.60	61.50	54.00
61.50	53.20	37.00	8	8	65.83	53.20	46.80
54.00	46.80	34.60	10	10	54.80	36.75	34.60

DOUBLE-WING AUGER

41.60	37.40	29.70	6	6	41.60	37.50	34.40
37.50	34.10	25.10	8	8	37.30	34.10	31.70
34.40	31.70	21.90	10	10	26.50	25.00	21.90

TRIPLE-WING AUGER

44.40	38.90	26.60	6	6	44.40	35.37	36.10
35.37	33.50	20.90	8	8	36.00	33.50	34.76
36.10	34.76	19.80	10	10	26.60	20.90	19.80

NOTE.—A medium plastic clay from eastern Maryland used in all tests. The total moisture content varied from 25.57 per cent maximum to 23 per cent minimum, The corresponding effect on output per unit of power caused by increasing the length of the spacer by 2-inch increments from 6 to 10 inches is likewise shown as the dotted curves cross the page from left to right.

By comparing the slope of each solid curve with the slope of each corresponding dotted curve as they cross the 6, 8, and 10 inch ordinates of the graph, it is seen that an increase in the length of the die causes nearly twice the decrease in output per unit of power as does a corresponding increase in the length of the spacer.

Although insufficient data have been obtained from which definite conclusions can be drawn, those which have been obtained indicate that any length of die greater than that necessary to form a clay column of satisfactory structure is unnecessary and rapidly decreases the output efficiency of the machine. A corresponding increase in the length of the spacer, however, is apparently independent of the dimensions of the clay column molded and, as compared with the effect of increasing the length of the brick die, only slightly reduces the output efficiency of the machine.

4. BRICK DIES

(*a*) EFFECT OF LENGTH ON POWER CONSUMPTION AND QUALITY OF THE PRODUCT.—(See 3 (*a*), Collective spacers.)

(*b*) EFFECT OF LUBRICATION OF DIE ON POWER CONSUMPTION AND QUALITY OF THE PRODUCT.—Although the study of the lubrication of dies is to be undertaken in a future investigation, preliminary tests have been made which furnish interesting tentative information subject to verification by more complete experimental data.

The theory of lubrication of brick and hollow-tile dies is similar to that of oil lubrication of the moving metal surfaces in contact with each other in machinery. In the case of plastic materials we are not limited to oils, but can use water, steam, or even air. In lubricating dies for molding plastic materials it is necessary to provide a constant film or cushion of lubricant between the plastic material and the metal, so that the two materials do not come in contact. To accomplish this it is necessary to force the lubricant into the die at pressures sufficient to offset the internal pressure of the plastic material against the metal surfaces of the die.

Serious difficulties are encountered in attempting to equalize this varying pressure of the material against the inner walls of the die when using oil, water, steam, or other liquids as a lubricant, it being necessary to constantly regulate the pressure of the lubricant in order to balance the variable internal pressure of the material and maintain the film or cushion between the plastic material and the die; otherwise the lubricant will spurt out in streams, cutting grooves in the column and producing a "slimy," defective surface.

With air as a lubricant the pressure does not require close regulation. Much smaller supply pipes and orifice openings can be used to supply the required volume and pressure. The finish of the molded column is not impaired by air lubrication. The use of air as a lubricant for brick dies is shown, by experimental data, to decrease the power consumption from 8 to 10 per cent, depending to some extent on the physical characteristics of the materials extruded.

The only cost of compressed air as a lubricant is the equipment and power required for its application. Oils and such liquids for lubrication are not available without more or less expense and trouble. Where steam is used to lubricate the die in plants electrically operated, special provisions must be made for producing and maintaining the steam by operating a boiler at the required pressure. The equipment for air lubrication consists of a small power-driven compressor and necessary piping to supply air to the die. Usual temperature changes do not affect the flow; it is safe, easily applied, and free from detrimental effects on the product.

Each lubrication test was made in two steps. In the first step the die was operated dry prior to lubrication. In the second step the die was lubricated either by steam, water, or air. The effects of steam, water, and air lubrication on 1°, 2°, and 3° taper, 8-inch length standard-size cut brick dies of the four-liner Niedergesaess type are shown in Table 13, and graphically in Figure 17.

The results of lubrication on the 3° taper die show that steam lubrication increased the dry-die output per unit of power 25 per cent. Water increased it 20.6 per cent, and compressed air increased it 8.3 per cent indicating that steam as a lubricant is three times as effective as compressed air and one-fifth more effective than cold water, all other conditions being considered constant.

TABLE 13.—*Effect of air, steam, and water lubrication on the performance of 1°, 2°, and 3° taper brick dies*

	Equipment combinations—Single-wing auger and 6-inch collective spacer constant											
	8-inch length, 1° taper die constant, variable conditions of lubrication				8-inch length, 2° taper die constant, variable conditions of lubrication				8-inch length, 3° taper die constant, variable conditions of lubrication			
	Dry die	Air at 8 pounds per square inch	Steam at 10 pounds per square inch	Water at 8 pounds per square inch	Dry die	Air at 10 pounds per square inch	Steam at 15 pounds per square inch	Water at 12 pounds per square inch	Dry die	Air at 25 pounds per square inch	Steam at 30 pounds per square inch	Water at 25 pounds per square inch
Pounds of clay extruded per h. p. m.	88.00	93.00	--------	--------	86.00	90.00	--------	--------	74.00	80.10	--------	--------
	91.00	--------	113.10	--------	86.60	--------	105.50	--------	78.80	--------	98.40	--------
	80.00	--------	--------	100.00	77.70	--------	--------	92.80	68.00	--------	--------	82.00
Flow pressure in pounds per square inch	67.00	67.00	--------	--------	70.00	70.00	--------	--------	73.00	73.00	--------	--------
	68.50	--------	68.50	--------	72.00	--------	72.00	--------	81.00	--------	81.00	--------
	73.00	--------	--------	73.00	76.00	--------	--------	76.00	85.00	--------	--------	85.00
Per cent total moisture in the clay	24.73	24.73	--------	--------	24.60	24.60	--------	--------	24.12	24.12	--------	--------
	24.72	--------	24.72	--------	24.38	--------	24.38	--------	23.86	--------	23.86	--------
	24.43	--------	--------	24.43	24.21	--------	--------	24.21	23.84	--------	--------	23.84
Output in pounds of clay per minute	323.00	268.00	--------	--------	346.00	309.00	--------	--------	385.00	321.00	--------	--------
	313.00	--------	308.00	--------	331.00	--------	325.00	--------	333.00	--------	328.00	--------
	328.00	--------	--------	315.00	342.00	--------	--------	327.00	391.00	--------	--------	368.00

The comparative efficiencies of steam, water, and air as lubricants are questionable because of insufficient data. The dies were obtained on the open market and were designed especially for steam lubrication, and therefore may not be suitable for the most efficient application of water or air. Nevertheless, the results are valuable, indicating that air has certain advantages and possiblities as a lubricant sufficient in value to warrant further investigation.

(*c*) DISCUSSION.—Long dies produce greater retardation of flow at the corners, due to increased friction, while short dies do not overcome the zigzagging motion to the clay column, thus producing column cracks, especially where the die is set within 6 inches or less of the auger tip. Excessive taper causes increased friction and differential flow. Greater auger thrust is required to overcome the resulting increased friction, and the differential flow tends to destroy the helical structure.

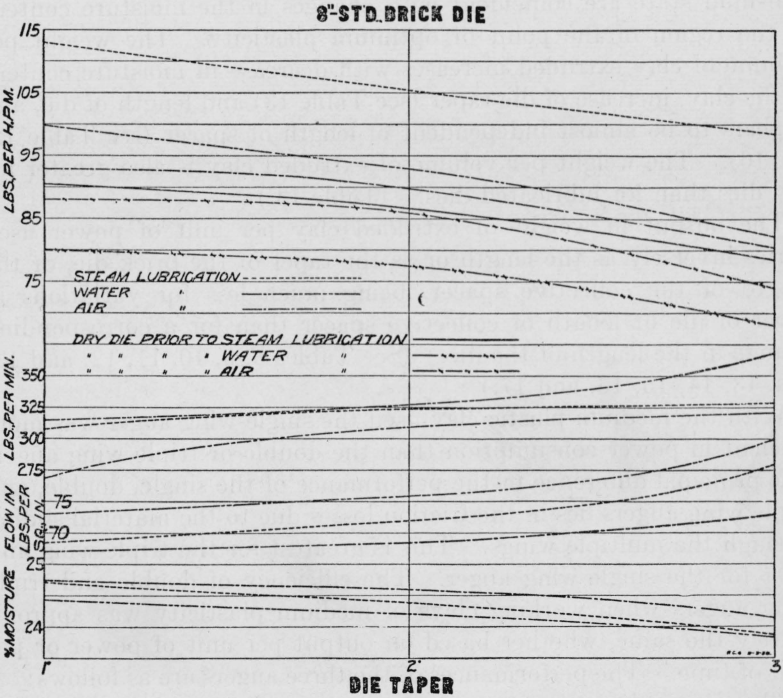

FIG. 17.—*Effects of air, steam, and water lubrication on 1°, 2°, and 3° taper dies*

The outlet dimensions of a high-tapered die must be smaller than those of a low-tapered die to produce the same-sized clay column, due to greater elastic compression in the die and the resultant expansion of the clay as the column emerges from the die (33). Any die taper greater than that required for maximum discharge and to eliminate excessive auger laminations is wasteful of power and produces a poor structure, because the expansion of the clay column is accompanied by a weakening of the clay bar. More complete experimental data, however, are necessary before the principles governing the proper relation of the taper of a die to its length can be definitely determined.

VI. CONCLUSIONS

Results of the foregoing studies are summarized in the following conclusions:

Marked changes in the flow pressure for plastic clay or shale in the stiff-mud state are coincident with changes in the moisture content in the region of the point of optimum plasticity. The weight per volume of clay extruded increases with decrease in moisture content of the clay, increase of die taper (see Table 13) and length of die, and appears to be almost independent of length of spacer (see Table 12, fig. 16). The weight per volume of extruded clay is also greater for dry dies than for lubricated dies. (Table 13.)

The output in weight of extruded clay per unit of power used varies inversely as the length or as the taper of the brick die, or the length of the collective spacer, being much less for variations in taper of die or length of collective spacer than for a corresponding change in the length of the die. (See Tables 8, 9, 10, 11, 12, and 13; figs. 13, 14, 15, 16, and 17.)

With the medium plastic clay used the single-wing auger was more efficient in power consumption than the double or triple wing auger. The principal difference in the performance of the single, double, and triple wing augers lies in the friction losses due to the material sliding through the multiple wings. This is greatest for the triple-wing and least for the single-wing auger. The efficiency of double and triple wing augers when working clays of medium plasticity was approximately the same, whether based on output per unit of power or per unit of time. The performances of the three augers are as follows:

The single-wing auger extrudes a greater weight of clay per unit of power than the double or triple wing auger, but must be farther from the die to overcome uneven flow.

The double-wing auger reduces uneven flow by giving a more even pressure to the clay column than the single-wing auger.

The triple-wing auger gives a more even pressure through the die than either the single or double wing auger, but occupies slightly more space in the auger barrel, develops more friction, and is not as efficient for short, lean clays as a single or double wing auger.

For producing a clay column free from objectionable defects, the combination giving the maximum quantity of material extruded per unit of power was a single-wing auger, with an 8-inch spacer and a 6-inch die, whereas the maximum quantity of material extruded per minute was obtained with a triple-wing auger, an 8-inch spacer, and a 6-inch die.

The following observations as to the probable advantages and possibilities of the apparatus developed and used for this work seem justified:

1. It will measure small differences in the torque required to extrude clay and shale of different plastic consistencies under varied conditions of operation as regards auger, spacer, and die equipment.
2. It affords a practical means of studying the workable characteristics of clays and shales and provides a reliable method of determining the auger and die equipment best suited to their physical properties and the class of product to be manufactured.
3. It can be used to study the effects of various lubricants on power consumption, quantity output, and quality of product.

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