STATISTICAL ANALYSIS AND PRESENTATION OF BALL CLAY TESTS

FOR LOW-TENSION ELECTRICAL PORCELAIN

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I. INTRODUCTION

For the past two years, considerable interest has been shown in the testing and classification of ball clays by the members of the Whitewares and Materials and Equipment Divisions of the American Ceramic Society. Three symposiums have been held and many valuable facts have been presented. Preliminary tests of various sorts have been made, but due to the scope and complexity of the problem, the actual testing program has not been started.

The importance of ball clays in the ceramic industry cannot be overestimated. They find extensive use in the whitewares, stoneware, terra cotta, refractories, and porcelain enamel industries. The chief use of the raw material is to provide plasticity and act as a binder for the body. At high temperatures, the ball clay acts as a mineralizer and aids the action of the fluxing materials in the body. Much of the ball clay is incorporated into the glassy phase and serves as a bond for the more refractory body components.

Although ball clays are generally given the chemical formula for kaolinite, it must be remembered that they are much more complex materials and contain a greater amount of impurities than the kaolins. Due to these impurities, the ball clays are less refractory than the kaolins. Because of the complex make-up of the material, which may be also attributed in part to the geological history, the grain size distribution, and the method of preparing it for utilization, the testing of ball clays has presented many difficulties. It is practically impossible to make satisfactory tests on pure ball clays due to their inherent properties of high

plasticity and their tendency to warp in drying and firing. Furthermore, tests made on the ball clays alone are often inconsistent with the results obtained when the clays are incorporated into the body. For these reasons, many experimenters have used the 50-50 ball clay-flint mixture as a means of testing the properties of the ball clays. The Standard Test Methods (14) require standard 20-30-mesh Ottawa sand for dry transverse strength tests. Certain authorities recommend the incorporation of the ball clays into a commercial or standard body as a means of directly studying the effects of the ball clays. Blume (12) has suggested the use of a standard body of the low-tension electrical porcelain type. The present investigation was in line with this suggestion.

The objects of the investigation were:

(1.) to study the effects of various ball clays on the properties of a standard body, and

(2.) to study this method for the testing of ball clays.

Statistical methods have been used throughout and it is believed that worthwhile results for a study of this type can be obtained only by these methods. The experiment was set up so that a factorial design was in effect. A study was made of the effects of the different ball clays used, per cent water of plasticity or water contents of the wet-dust, and the temperature or cone of firing on the standard body.

The dry-mix method for preparing the various bodies was used. The batch composition was:

25% China Clay
25% Feldspar } Held constant
25% Flint
25% Ball Clay (Being tested)

Six ball clays were used, and these were prepared or purified before compounding the body. An attempt was made to standardize the other materials in the body as to grain size, source, etc. Three levels of water contents for the wet-dust were used and controlled by Student's t-distribution at 10, 12, and 14% of the weight of the dry materials. Samples were formed in two shapes in hydraulic dry-presses and fired in an electric Globar kiln at cones 9, 10, and 11. Tests were made on the green, dry, and fired specimens. The grain size distributions of all materials used were determined, and calculations were made to determine the chemical analyses and empirical formulas of the fired bodies. Analyses of variance were made on five of the properties and the factorial design, difference between two means, t-test, and the test for linear or regression trends have been used in analysing the data.

II. THE REVIEW OF THE LITERATURE

Ries (1) states that the term ball clay is applied to those clays
possessing good plasticity, usually strong bonding power, high refrac-
toriness, and which burn white or creamy white. Ball clays are of the
sedimentary type. Wilson (2) states that the material represents the
finest of pure clay substances which will float the longest time in quiet
lakes. On firing, the deformation (3) range varies from cone 18 to cone
24. The vitrification range is from cone 8 to cone 10.

In this country these clays are found chiefly in Kentucky and Tennessee,
with other deposits in Mississippi and New Jersey. Very good deposits
are located in England, and English ball clays were preferred by con-
sumers for many years. Domestic deposits occur in massive, indistinctly
stratified beds of remarkable purity and uniformity, sometimes overlain
by lignite and with considerable lignite scattered through the clay itself.
Their name is derived from the original method of clay working in England,
where the clay was mined by the open-pit method and taken from the pit in
the form of balls weighing about 33 pounds each.

Blue ball clays are very fine in texture, and extremely plastic.
The chief characteristics of this type are extreme freedom from color when
burned, extreme fineness of particles, absence of refractoriness, and high
fired strength.

The term black ball clay is applied to certain white-burning plastic
clays of Tertiary origin, very closely allied to blue ball clays, but so
deeply stained with carbonaceous matter as to be black in the raw condition.
This color disappears on heating, so that some of these very dark clays

burn as light as the other types. The carbonaceous matter reduces the ferric oxide or hematite (Fe_2O_3) to the ferrous oxide (FeO) which does not produce as dark a stain.

The chief use of ball clay in the ceramic industry is as a bond. It is used in whitewares as a binder and as a source of plasticity for the body mass. In this field, ball clays find extensive use in the production of hotel china, semi-vitreous whiteware, vitreous sanitary ware, electrical porcelain, and spark plugs. They also find wide usage in the tile, refractories, and porcelain enamel industries.

The present trend is towards the use of higher percentages of ball clay and the replacement of the very plastic English ball clays by the less plastic, domestic ones. This is practical because certain American types have low drying shrinkages and give very little warpage.

English ball clays are more siliceous than most domestic types, and the better ones are black, with a bright, glossy appearance. Loomis (11) has found that certain English ball clays have finer grain sizes than many domestic ones.

Grim and Bray (4) state that a representative Kentucky ball clay consists principally of kaolinite, from 10 to 15% each of illite and quartz, and a small amount of montmorillonite. McVay (5) states that other minerals are frequently present including zircon, rutile, mica, and tourmaline. Theiss (6) says that ball clays do not differ greatly from the kaolins or china clays, except that they contain such impurities as iron, titanium, magnesia, and alkalies.

Watts (7) explains that ball clays are employed in various ceramic

batches because of (a) their plasticity, (b) dry strength, (c) drying

shrinkage, (d) impurities, and (e) response to electrolytes.

In the fired state, the important properties are (a) temperatures

of vitrification, (b) rate of vitrification, (c) fired density, (d) fired

strength, (e) firing shrinkage, and (f) fired color over the vitrification

range.

The importance and effect of the organic matter which is present

in the clay has been the subject of much discussion. In the process of

manufacture for whitewares, much of the lignite, and other forms of

carbonaceous matter are removed by lawning or screening the clay slip.

Schramm (8), however, has concluded from an extended trial, that the

significant organic matter is that present in soluble or colloidal form,

and that the clays owe their properties to these colloids in conjunction

with their fine particle size.

Searle (9) in his extensive work on ceramic materials, states that

the carbonaceous matter does not affect the fired color unless reducing

atmosphere is maintained in the kiln. It may, however, increase the poros-

ity and, consequently, the absorption. If considerable lignite is in

the unfired ware, the shrinkage will be higher than might otherwise be

expected.

It is extremely difficult to produce perfectly white goods as even

minute amounts of iron oxide have a strong power of discoloration. The

latter may be minimized when it only occurs to a very small extent by

(a) the use of a reducing fire during part of the burning period, or

(b) by adding a suitable coloring agent to neutralize the color and so

produce a pure white color. The iron oxide should be as low as possible to prevent this defect.

Sortwell (10), in a general way, notes that the ball clay has an important effect on the mechanical strength of fired bodies, which should be taken into consideration in developing compositions of high strength. It is easily recognized by authorities that the ball clay acts as a flux and as a mineralizer to speed the formation of glass due to accessory fluxing raw materials.

The various practical and theoretical properties of ball clays have been tested by many investigators in numerous ways for the past forty years. Blume (12) concludes that the tests made on pure ball clays are often inconsistent with the results obtained when the clays are incorporated in the body. He suggests that it might be well to make tests of the ball clays in combination with the other commonly used materials. He suggests the use of a standard body containing 25% of the ball clay being tested, 25% of feldspar, 25% of flint, and 25% of china clay. Except for the ball clays, the other materials should be standardized as to grain size, source, etc. If all of the ball clays were to be tested in this standard body and the data were listed, a fair idea of the properties imparted by each clay when incorporated in commercial bodies would be obtained. From this standpoint, with various modifications, the present work was performed. Blume recommends that the following properties be studied: (a) Unfired properties: (1) drying shrinkage, (2) water of plasticity, (3) mobility, (4) stickiness, (5) dry strength, and (6) percentage of carbon; (b) fired properties: (1) firing shrinkage, (2) fired strength, (3) color, and (4) firing range.

This agrees with the ideas of Wilson and Hixon (13) who state that in the past fifteen years, the practical tests have been neglected. These authorities believe that the best method of evaluating ball clays, which among themselves show many individual traits, is to study their behavior under working conditions. The extremely important and fundamental research in the fields of base-exchange, hydrogen-ion, particle-sizing, and clay-mineral studies adds to our accessory knowledge and helps to answer the question of why clays behave as they do. Nevertheless, the best and final test of an unknown clay is to study it in full-sized batches in regular operation. The next best test is one which uses full-sized specimens in regular operation; the third uses smaller or sample specimens in regular operation; and the fourth is a series of simulative service tests with laboratory equipment and test kilns. The worst tests are those which are indirect, such as judging the fired color, plastic working properties, and P.C.E. from chemical analysis.

Further, they state that clays have inherent variables which result from their geologic history and subsequent treatment which affect their working properties, including (1) particle size, (2) degree of dispersion, (3) accessory constituents and their magnitude, including quartz, carbon, gibbsite, mica, etc., (4) type of predominating mineral, such as kaolinite or montmorillonite, and (5) character of the particle surface and the ion adsorbed thereon.

These inherent properties affect (a) the water content required, (b) shrinkage, (c) pore space, (d) strength and (e) resistance to cracking.

Correlations can be made between the preceding causes and effects in

a general way; but for tests covering all of the whiteware clays, it has been impossible to obtain mathematical comparisons with such a large number of coacting variables for all of the different methods of molding different sizes and shapes of products.

The Standard Test Methods require standard Ottawa sand of 20 to 30 mesh for the dry transverse strength of ball clays. These test specimens cannot be used for firing because of the weakness produced by the expansion of the coarse quartz particles. Ball clay operators have adopted generally the use of 50% potter's flint, but no specifications have been made for the flint.

These authors have tested various ball clays by mixing the required amount of the clay with zero, 20, 40, 60, 80% of a North Carolina flint, together with a check specimen of 100% flint. Rather thorough studies have been made and they conclude that the group testing of variable clay-flint mixtures, controlled water content, and separate batch mixing is an excellent check method for test correlation and produces characteristic, individualistic patterns for each clay. They suggest the method outlined above for the improvement of standard clay tests and offer additional suggestions for greater accuracy in the testing procedure and increasing the value of the results obtained.

Since the publications of the Standard Test Methods (14) in 1928, considerable work has been done using the 50 - 50 ball clay-flint mixture to determine the properties of the various ball clays. It is likely that the current Symposium on the Testing and Classification of Ball Clays will adopt this method for their test work. This method is used in testing plastic, extruded samples and as yet nothing has been

said about testing dry press were in this manner. The advantages of the 50-50 mixture are numerous. Russell (17) states that the ratio of the non-plastic to the clay by this mixture is about the same as the ratio in an average porcelain body. Also, it is readily recognized that the flint is a rather inert ingredient and only one minor variable is introduced to lessen the accuracy of the test. Further, it is almost impossible to handle 100% ball clay for many tests. When the ball clay is mixed with the silica and fired, its effect as a flux may be studied. Of course, there will always be numerous tests that must be made on the pure clay.

Parmalee and McVay (15) have tested the dry transverse strength of the 50-50 mixture and made other tests on the ball clays alone.

Wills (16), in a study of warpage on firing, used a standard body for determining the effects of the feldspar. The body which was prepared in the slip form consisted of:

Standard ball clay	22.5%
Standard china clay	22.5%
Standard flint	22.5%
Feldspar to be tested	32.5%

Westman (18), in a study of permeable pressing of various body compositions, used an electrical procelain body consisting of:

English china clay	30%
Dorset ball clay	20%
Flint	20%
Feldspar	30%

Permeable pressing is a rather theoretical approach and the work of this author tends to compare the effects of removing the water from a ceramic body by means of permeable pressing with the removing of water by ordinary drying means. It was found that when a pressure of 8280 p.s.i. was applied that drying shrinkage was eliminated and the firing shrinkage greatly reduced.

With regard to the use of a standard body, Campbell (19) says that in any particular plant, a ball clay should be substituted in the normal body for the direct interpretation of results. If the ball clay is the only variable from the usual procedure, the influence of a clay under test can be noted readily.

It is generally agreed that tests made on 100% ball clay are not reliable. It is extremely difficult to make bars free from air bubbles and laminations, and such bars are difficult to oxidize.

A combination of clay and coarse standard-mesh (20 to 30) sand produces specimens more free of air bubbles and laminations and an open structure more conducive to oxidation. Mechanically, however, these bars are weak. Erratic results are achieved, therefore, in strength tests.

Ball clay incorporated into a standard body appears to be the ideal set-up for testing these clays. In the fired tests, the results parallel the behavior of a fired body and thus aid in a more direct interpretation of the results.

Balinkin (20) tested nineteen samples of fired ball clay samples by measuring the amount of light reflected by the sample throughout the visible spectrum. A Hardy recording spectrophotometer was used to draw reflectance

curves in which per cent reflectance was plotted against the wave length. This procedure could well be followed with the fired samples of standard bodies as suggested by Campbell, Blume, Wilson and Hixon, and others.

The body as outlined by Blume above when formed by dry-press methods is similar to a low-tension electrical porcelain body. The similarity is only approximate, however, as electrical porcelain of this type usually contains a greater percentage of feldspar and less ball clay. Often, auxiliary fluxes are used and the percentages of flint and kaolin vary within limits. Snyder (21) states that electrical porcelains are produced in an extremely wide range of shapes and sizes, but the entire production falls into two well-defined classes; namely, wet process and dry process. The former type, as the name implies, is formed either by casting or working in the plastic state, and such procelain is so compounded and fired as to be completely vitrified. It is absolutely non-absorptive and is well suited for insulating against high voltages. The second type, usually referred to as dry-press porcelain, while dense and strong, is inherently slightly absorptive and is suited only for low-voltage applications, say up to 440 volts.

Further, he says that the dry mixing method of body preparation has been adopted and is replacing the previously used wet methods. This permits much better control of moisture content and greatly assists in dimensional control.

Along this line, Fix (22) lists several advantages of the dry-mixing process, both from the standpoint of economy and from the standpoint of a better resulting product. In a second paper (23), he points out examples of types of ceramic plants where savings have been effected by the use of the dry-mix process.

Concerning the process, Rapp (24) has studied the effect of mixing time, order of addition of ingredients in compounding the mixture, and the use of deflocculating agents on the physical properties of an electrical porcelain body. He states, however, that his conclusions are probably only applicable to the particular body used.

Snyder and Harnish (25) find from a series of laboratory and design tests that the quality of dry-process porcelain prepared by dry mixing, both mechanically and electrically, is equal to that prepared by the wet methods. Further, they state that the advantages of lower labor costs, better control of moisture content, lower operating and maintenance costs, while partially offset by higher raw materials cost, have fully justified adoption of the dry-mixing process for dry-process porcelain manufacture.

Rigterink (26) describes the properties of ceramic materials used for electrical insulators in detail. In general, the materials possess high mechanical strength, resistance to cold flow, ability to withstand high temperatures, high dielectric strength, resistance to all chemicals except hydrofluoric acid, and low porosities. He lists the following properties of electrical porcelain:

Specific weight	$2.3 - 2.5$ gm./cm.^{3}
Per cent absorption	$0 - 2.0$
Compressive strength	$40,000 - 60,000$ p.s.i.
Tensile strength	$2,000 - 7,000$ p.s.i.

With reference to physical properties, Riddle and Laird (27) found that electrical porcelain was about 5.9 times as strong in compression as

in tension. This cannot be adopted as a standard by any means, as the ratio would vary with the two types of electrical porcelain, the composition of the body itself, the method used in the production of the piece, and for several other reasons.

With regard to the raw materials, Thiess (6) states that ball clay is the least controllable ingredient of any whiteware body. Its function is to supply plasticity, dry strength, and it should fire light in color. Acting as a flux at high temperatures, it gives great toughness to the ware. In electrical porcelain, particularly, the drying and firing shrinkages must be considered. In dry process bodies, from 10 to 20% of ball clay is used.

Twells and Lin (28) say that it is necessary that there be some kind of a very refractory substance, not easily attacked by fluxes, present in any vitrified body to act as a skeleton structure and thus prevent warpage. This function is generally fulfilled by the flint.

Watts (29) concludes that dry-pressing produces more exact shapes than any other method. Spurnier (30) says that water content is the chief factor in controlling shrinkage in ware made by this method. Birch, in a report on some refractory tests (31), found that the transverse strength of dry and green dry-pressed refractory brick increases with increase of forming pressure, the greater increments of increase being at the lower pressures. It is likely, that the same is true of other products formed by dry-pressing within certain limits of pressure.

On firing, if the ware (29) is not perfectly vitrified, it does not possess any great insulating properties, even when perfectly dry. In

this connection, Fritz and Harrison (32) believe that electrical porcelain

has several physical requirements which may be affected by the thermal

history of the ware; viz., (1) it must be completely impervious; (2) it

must have high strength and toughness; and (3) it is manufactured by the

one-fire process in rather complicated shapes that involve abrupt changes

in cross section and in ware weighing hundreds of pounds per piece.

They conclude, however, that ball clays have the least important

effect of any of the body materials on the susceptibility of the body to

changes in its thermal history. This is because the ball clays seem to be

assimilated so rapidly into the glass phase.

Monack and Smith (33) add that although decided overfiring does not de-

crease the dielectric strength, it must be remembered that the development of

brittleness with higher firing is a serious defect in porcelain, and that

proper firing involves a compromise between electrical properties and

mechanical properties in the finished product.

Recent improvements in the product (34) lie in the field of greater

accuracy and closer dimensions formerly believed impossible in ceramics.

Use of Statistics in Ceramics. Westman (35) has written several

papers on the use and application of statistics to ceramic research, test

and control. Monack (36) has also done work involving practical methods.

He states that most measurements of the modulus of elasticity of ceramic

materials are based upon an insufficient number of samples. Likely, this

is true of other measurements where the range is great and the homogeneity

of the material is a variable. Ferguson (37) concludes that plant and

laboratory test data may often yield more information if modern statistical

methods are applied to them. His paper deals with the simple concepts including averages, distribution curves, the average and standard deviations, probable error, and the method of comparing two means.

Moran (38), in a paper on analytical control methods, states that a primary concept of nature is that no one measurement is exact. When the conditions that obtain in commercial control laboratories are considered, this concept becomes more important. Since these variations are known to exist, they are a constant threat to good commercial operation until they are quantitatively determined. In addition, there also exists a tendency on the part of many engineers, sales personnel, and others to treat a single analytical result as an exact quantity and to make decisions therefrom that would be unjustifiable if the significance of the result were known. The author then sets up an outline for the establishment of quality control.

No reference in the literature could be found where statistical methods were applied to the testing of ball clays. Although factorial design has found wide application in agriculture, biology, and medicine, its use in engineering and in the testing of various materials has, unfortunately, been neglected. It is believed that the advantages of using statistical methods and particularly factorial design will pay big dividends in the testing of ball clays and other ceramic materials. This design is one in which the effects of several factors, for instance, water content, method of manufacture, and variations in the batch may be studied simultaneously, thereby, giving the experimenter an idea of what occurs when the different variables are combined.

III. THE INVESTIGATION

Object of Investigation. The primary purpose of the investigation
was to study the action of six ball clays incorporated into a standard body,
similar to that of a low-tension electrical porcelain body. As suggested
by Watts (39), three different water contents or water of plasticity levels,
were used in forming the test specimens. The eighteen bodies (six clays
employed x three water contents) were fired at three different cones. In
the analysis of results, the factorial design and the use of statistical
methods permitted the formation of conclusions which otherwise would be
impossible. It was possible (1) to study the effects of three variables
on the properties of the body composition; (2) the joint effects of clays
and water content on the green and dry properties; (3) the joint effects of
clays and water contents, clays and firing temperature, water contents and
firing temperature; and (4) the triple effect, on the fired properties.

A secondary object of the investigation was a study of this method
for the testing of ball clays.

It was not an object of the investigation to say that one ball clay
is superior to another. This is impossible for several reasons:

    (1.) The ball clays have been tested in only one type of body.

    (2.) Only one procedure has been followed. A somewhat different
        procedure might feasibly change the results.

    (3.) Many tests must be made to prove the superiority of any one
        ball clay.

Certain tests were made as a means of standardization and to discover

for the purpose of controlling, or eliminating, undesirable sources of variation. Such tests include particle size determinations, mechanical moisture in the various materials, and the determination of water of plasticity of the bodies. (Actually, the bodies were not in the plastic state, but rather in the form of "wet-dust" before pressing, but the term "water of plasticity" will be used for the sake of simplicity.)

The properties which were investigated include:

(1.) Particle size investigations of all materials.

(2.) Mechanical moisture in all materials.

(3.) Water of plasticity of the bodies (controlled at 10, 12, and 14% on the dry basis).

(4.) Green compressive strength of the bodies.

(5.) Drying shrinkages of the bodies.

(6.) Dry compressive strength of the bodies.

(7.) Fired compressive strength of the bodies at cones 9, 10, and 11.

(8.) Firing shrinkage of the bodies at cones 9, 10, and 11.

(9.) Per cent absorption of the bodies at cones 9, 10, and 11.

(10.) Visual observations, particularly color of the bodies, fired at cones 9, 10, and 11.

It was originally planned to study the fired color by means of spectrophotometry (20) where the amount of light reflected by the various samples throughout the visible spectrum is measured. However, it proved impossible to secure the necessary equipment during the war emergency. Perhaps this could be continued in the future.

Materials Used. Four Tennessee and two Kentucky ball clays were used
in the investigation. The chemical analyses of these clays and of the flint,
feldspar, and china clay used in the preparation of the standard body are
tabulated in TABLE I. Most of the ball clays used are of primary importance
in the ceramic industry. The Wade #5 ball clay was included because of
special interest attached to its physical properties, rather than because
of its industrial importance. (See Appendix.) Representative samples of
all materials were supplied by their producers. Some were stored in wooden
bins, while others were left in their original containers, that is, in paper
or burlap sacks until ready for use. (There was insufficient bin space for
storage of all materials, which would have been more desirable.) The china
clay used had been air-floated, and the flint and feldspar used were of
pottery fineness. Before preparation, most of the ball clays were in the
form of lumps, two or three inches in diameter. None of the ball clays had
been air-floated.

Apparatus Used. Sufficient description of the apparatus will be given
as it appears in its relative order of use under Procedure.

Method of Procedure: Preparation of the Ball Clays. Both the pro-
cedure for the preparation of the ball clays and that for the mixing of the
test or standard bodies were modified from that of Campbell (19). It is
believed that the method of preparing the ball clays tended to put all of
the clays on an equal basis, and eliminate certain of the variables which
might have been introduced such as moisture content, method and time of
storage, per cent of impurities in the clays, and others. Also, the method

followed eliminated many impurities and prepared the clays for the dry mixing. Approximately fifteen pounds of the ball clays were drawn or sampled from all parts of the bin or sack. The material was reduced by a jaw crusher and ground between adjustable, smooth, steel rolls. It was screened using a 4-mesh sieve mounted in a gyratory riddle. The rejects were reground until all would pass the 4-mesh sieve.

An electric blunger of the paddle wheel type was used in the blunging operation. On the basis of the weight of the -4-mesh clay, 150% of water was introduced into the blunger, and the clay was added very slowly, in order that the blunging be as thorough as possible and practically all of the clay be suspended in the water. No deflocculants were used. After all of the clay had been introduced, the operation was continued for twenty minutes and the position of the paddle wheel was changed at intervals. A very fluid slip was produced, the degree of fluidity depending on the clay being prepared.

The slip was screened or lawned using a 100-mesh sieve in the gyratory riddle. A portion of the slip was introduced before the motor was started. This prevented splashing. This was continued until all of the slip had been poured onto the sieve and about two pounds of excess water added and the vibration continued to carry through other fine material which had not gone through the sieve openings on previous vibrations. No attempt was made, however, to wash all of the material through the sieve. The -100- mesh slip drained from the riddle into enameled buckets and was poured into cloth lined plaster molds. It was left in the molds for about two days until the resulting mass was no longer plastic and contained less than 20%

of water. The cakes were broken up into small chunks, placed in shallow
wooden boxes, and dried in a laboratory-size, tunnel-type drier. Drying
was continued until the clay contained less than 2.0%, but more than 0.5%
of moisture (wet basis.) This was determined by the usual method on
samples ground to pass 20-mesh. The material was reduced to pass 20-mesh,
check determinations made for moisture, and, if satisfactory, stored in
glass jars. (See Figure 1.)

The impurities removed from the clays included mainly lignite, free
silica, and some iron oxide. Some clay was also left on the sieve. The
Wade #5 ball clay contained the greatest amount of impurities, practically
all of which was lignite, while the Old Mine #4 contained the least.

Preparation of the Standard Bodies. The standard body used consisted
of:

Hillman Clay	25%
Madoc (S) Spar	25%
Pennsylvania Flint	25%
Ball clay being tested	25%

The feldspar used is the high potash, body-type. The purity of the flint
is apparent from its chemical analysis. In the compounding of TABLE I,
corrections were made for the mechanical moisture in the various materials.
These chemical analyses are for the ball clays before preparation. It is
likely that the process of preparation changed the analysis to some extent.
The values for per cent loss on ignition would probably be lower, as well
as the per cent silica, and the per cent iron oxide. One figure after the
decimal place was used except when the amount of an oxide was less than
one-tenth of one per cent, in which case two figures were used to indicate
the order of magnitude of the particular oxide. It is obvious that only
the first figure is significant in most cases.

Raw Material	Usage	SiO$_2$	Al$_2$O$_3$	Fe$_2$O$_3$	TiO$_2$	CaO	MgO	Na$_2$O	K$_2$O	P$_2$O$_5$	Ign.L	%Moist
Hillman Clay (United Clay Mines, Trenton,N.J.)	Standard Body Ingredient	46.0	35.9	0.3	1.4	0.1	0.04	0.2	0.1	---	14.5	1.6
Madoc (S) Spar (Cons. Feld. Co. Erwin, Tenn.)	Standard Body Ingredient	65.6	19.8	0.05	---	1.1	Tr.	4.8	8.5	---	0.2	0.2
Pennsylvania Flint (Penn. Pulv. Co., Lewisburg, Pa.)	Standard Body Ingredient	99.8	0.2	0.01	---	---	---	---	---	---	---	0.1
Champ.-Chall. Ball Clay* (H.C.Spinks Clay Co., Weakely Co)	Body # 2	53.8	29.0	1.4	1.4	0.1	0.01	0.2 (combined)		---	13.3	1.1
Old Mine # 4 B.C. (Ky.- Tenn. Clay Co. Mayfield, Ky.)	Body # 4	51.4	31.1	1.2	1.7	0.2	0.5	0.6	0.4	---	12.1	1.1
Bell's Dark B.C. (Bell Clay Co., Gleason, Tenn.)	Body # 5	52.1	30.0	0.9	1.4	0.4	0.4	1.0 (combined)		---	12.4	1.8
Jernigan B. C. (H.C.Spinks Clay Co. Weakely Co., Tenn.)	Body # 6	53.6	29.2	1.1	1.2	0.2	0.6	0.2	1.8	0.2	11.6	0.8
Ky # 5 B.C. (Ky. Clay Min. Co., Mayfield, Ky.)	Body # 7	56.4	26.1	0.6	2.5	Tr.	0.5	Tr.	Tr.	---	13.6	1.5
Wade # 5 B.C. (Ky.- Tenn. Clay Co. Whitlock, Tenn.)	Body # 8	43.2	35.4	1.0	0.7	0.1	Tr.	0.4	2.0	---	15.7	1.9

TABLE I - CHEMICAL ANALYSES OF ALL RAW MATERIALS

* Tenn. Ball Clay

Five hundred grams of each material were weighed out. (No correction was made for moisture contents as all of the materials contained less than 2.0% moisture, and the range for the ball clays, the variable ingredient, was only slightly greater than 1.0%. The materials
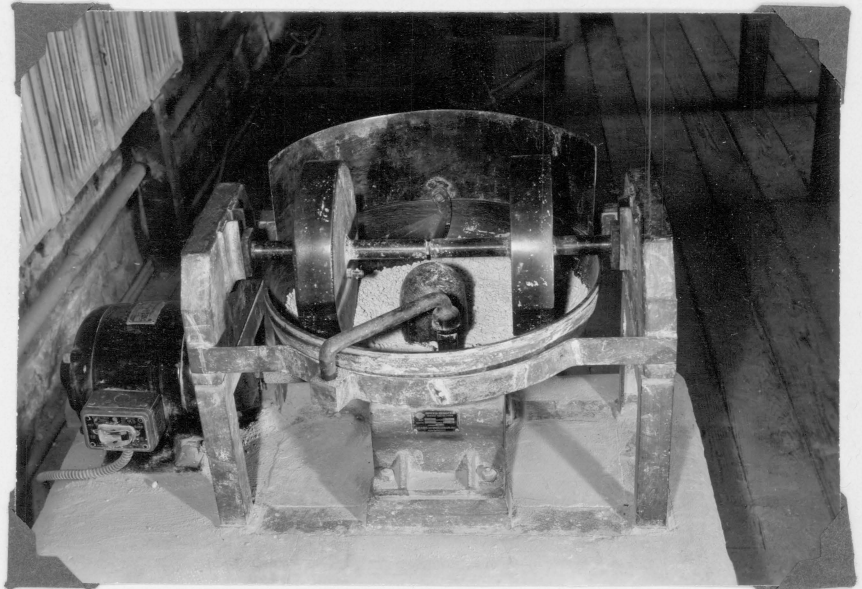
Figure 1. Dry pan used in the preparation of the ball clays and in mixing the standard bodies.

were transferred to a small dry pan (Figure 1) and dry-mixed for twenty minutes, using the star-shaped paddle wheel, side scraper, and manual stirring to mix the body as thoroughly as possible. Water was added and the muller wheels mounted in place. In each case, about one per cent of water in excess of the desired amount was added to allow for evaporation and other loss. The dry pan was revolved for five additional minutes to allow the water to become well mixed with the materials and then cut off. A scoop-full of the "wet-dust" was transferred to a nest of vibrating sieves consisting of 10 and 20 mesh sieves and a bottom pan. The 10-mesh sieve was covered by a clean, moistened cloth which helped to prevent evaporation during screening. This sieve served as a buffer on which large lumps could be reduced by gentle tapping with a spatula. Rejects from the 20-mesh sieve were placed in a large, porcelain mortar which was also covered by a

clean, moistened cloth. These were reduced and mixed manually, using a porcelain pestle, and reintroduced through the nest of sieves. Material passing the 20-mesh sieve was placed in a covered, one gallon, glass jar. This procedure was continued until all of the material had been removed from the dry pan. To completely fill the glass jars, and to insure a sufficient amount of the wet dust for all test specimens, it was necessary to repeat the process a second time. The chief difficulty encountered in the preparation of the various bodies was controlling the water contents. Batches were prepared for each of the six bodies, until their water contents were not significantly different from 10, 12, and 14% (using Student's distribution) and were significantly different from each other.

Distilled water was not used in the blunging operation or in the preparation of the bodies. This was for two reasons:

(1.) Difficulty of obtaining sufficient distilled water.

(2.) Distilled water is not used in industrial practice.

The water used had a total alkalinity of 196 parts per million of $Ca(HCO_3)_2$ expressed as $CaCO_3$. Its soap hardness as $CaCO_3$ is generally 240, but ranges up to 360. About 0.2 grams of $CaCO_3$ would be introduced with each liter of water.

Forming of the Test Specimens. The "wet-dust" was constantly stirred and mixed in the jars during the sample forming operation to give uniform water distribution within the mass. The jars were covered at all times except when weighing or mixing the material.

Samples were formed by dry-pressing in two sizes. A batch of sixty

Ball Clay Storage

Crushing

Grinding

Screening 4-mesh

Weighing

Blunging ← 150 % Water

Screening → Impurities & Oversize Particles

Water Absorption → Water

Drying @ 60 - 65° C.

Grinding (Dry Pan)

Screening 20-mesh

Prepared Ball Clay   China Clay   Feldspar   Flint

Weighing   Weighing   Weighing   Weighing

Dry Mixing (20 Min.)

Water Added → Wet Mixing (5 Min.)

Screening 20-mesh   Reducing and Mixing in Porcelain Mortar

Rejects

Storage (24 Hours)

Sample Batch Weighing

Forming of Cylinders   Forming of Discs

Drying   Drying

Testing   Testing

Figure 2.

FLOW SHEET FOR THE BALL CLAY PREPARATION, MIXING OF THE BODY, AND FORMING OF THE TEST SPECIMENS.

grams and a maximum pressure of 1500 p.s.i. were used in both operations.

Samples to be used for compressive strength tests were pressed in the

shape of a cylinder with a diameter of 1.25" and a height of about 1.5"

depending on the amount of water in the dust. The variation in heights

was seldom more than 0.15" from the general average and this difference

would not affect the
results. Samples from
the same batch showed
very little differences
in height. Navias (40)
recommends the 1:1 ratio
of height to diameter
for test samples of the
electrical porcelain
type and the samples
used did not differ
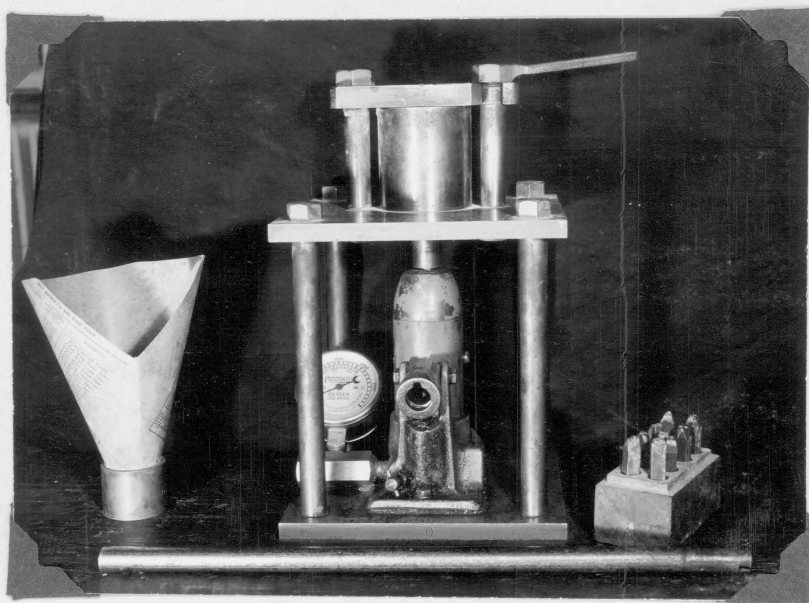
Figure 3. Dry press used in forming the
cylinders.

greatly from this ratio. The press used in forming these samples, which

will henceforth be referred to as cylinders, was made from a 3000 lb. jack

and had a guage attached. (See Figure 3.)

Cylindrical samples which were used in determining linear shrinkage,

per cent absorption, and fired color, were formed in a larger press (Figure

4) having a rated capacity of 40,000 lb. on the ram. These samples, which

will be referred to as discs, had a diameter of 2.28" and a height of 0.45"

(approximately). A flow sheet for the preparation of the ball clays, mixing

of the bodies, and forming of the test samples is shown in Figure 2.

Sample Testing. Immediately
after forming and before ejection
from the mold box, samples were
numbered to indicate the body com-
position and the approximate value
of the water of plasticity. Thus
body 2 with 10% of water was num-
bered —20. Twenty-four cylinders
and sixteen discs were formed. For
every three or four cylinders
pressed, one was given a sub-number
and weighed to an accuracy of one-
hundredth of a gram. All discs
were given a sub-number. Four
cylinders for each body and each
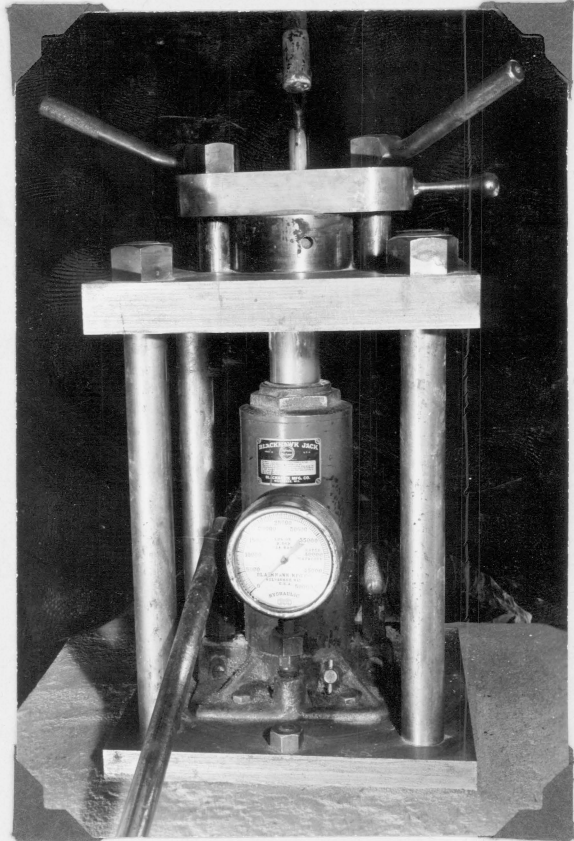
Figure 4. Dry press used in forming
the discs.

water content were broken in compression immediately after forming. A 1000-
10,000 lb., screw-type, Olsen testing machine was used and the load applied
mechanically at a rate of 0.024 inches per minute. (See Figure 5) For the
testing, a spherical seat was used.

The remainder of the samples were air-dried for twenty-four hours and
placed in a thermostatically controlled dryer. Artificial drying proceeded
according to the following schedule:

$$2 \text{ hr. @ } 75 - 80^{\circ}C.$$

$$2 \text{ hr. @ } 110^{\circ}C.$$

$$8 \text{ hr. @ } 120^{\circ}C.$$

Those cylinders which had been weighed after forming were reweighed, and the per cent water of plasticity for each sample determined. Using Student's distribution, the data was tested to see if the values were significantly different from the desired amount. At the start of the investigation, much data and many batches were discarded because of difficulty in obtaining the desired water contents. After the method had been perfected, the range

for all samples of a particular batch was generally less than $\angle$ or $-$ 0.5% and most of the averages were very close to the desired figure. Only those batches which were not significantly different from what they were intended to be were used.
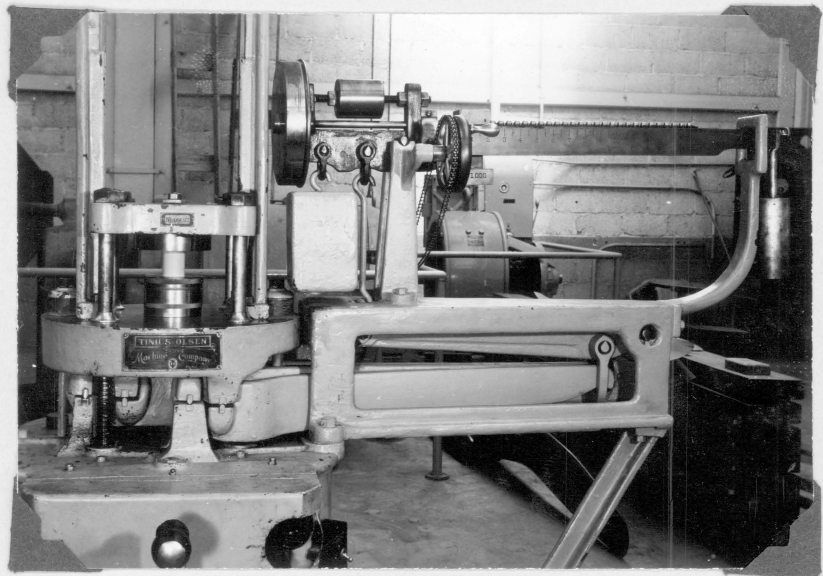
Figure 5. Olsen testing machine used to determine the green and dry compressive strength of the cylinders. A sample is shown resting on the spherical seat.

The cylinders were then tested for dry strength in the same manner as for green compressive strength. The discs were measured, using a rigidly mounted Ames dial above a flat surface, to the thousandth of an inch. It was seen that no determinable drying shrinkage had occurred on any samples.

The samples were fired in an electric Globar kiln using natural draft. The program for the firing was regulated by the Wheelco Capicitrol apparatus,

using the standard program disc. New heating elements were used and the actual kiln temperature, as determined by the thermocouple, followed the schedule for the disc very closely. Three firings were made. To accommodate all of the samples, it was necessary to put three slabs in the furnace. The first firing was intended to be cone 9. It was determined by placing six cone placques in the furnace that there was one-half of a cone difference between all parts of the furnace. The first firing, then, was actually cone 9^3 to cone 9. On this basis, a test firing was made to determine if the properties of the same body with the same water content were affected by relative placement within the kiln. There was no difference in the shrinkage between samples on the three slabs, and no significant difference in the values for fired compressive strength. An analysis of variance showed that there was significant difference at the 5% level (F distribution) for the values for the per cent absorption between the samples which were placed on the three slabs. The averages were:

Top slab	3.2%
Middle slab	2.9%
Bottom slab	3.0%

From a practical standpoint, this variation has little significance; however, for the other two firings all samples were placed within the furnace and on the slabs by means of random numbers. The second firing was to cone 10^3 to cone 10, but will be referred to as the cone 10 firing. The same is true of the third firing which was to cone 11^3 to cone 11. The furnace was allowed to cool naturally to room temperature. The samples were removed, cleaned and inspected. One disc for each body, water content, and firing

was reserved for visual observations. (See Appendix III for firing

schedule.)

The diameters of the cylinders were measured to the thousandth of an

inch with the Ames dial as above, and their areas calculated. These were

tested for fired compressive strength using a 10,000 - 50,000 - 100,000 lb.,

screw-type, Olsen testing machine. (Figure 6) The ultimate load was re-

corded for four samples
under each set of con-
ditions, that is, for
each body, water content
and firing. In this
connection, four repli-
cations were used in
all physical tests on
the samples. Fired di-
ameters of the discs
were measured and
shrinkages calculated.
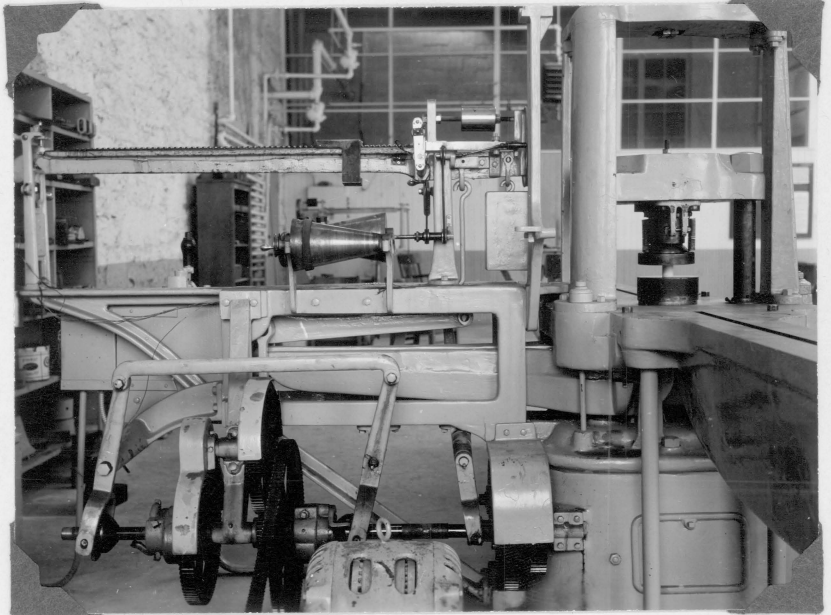
Figure 6. Olsen testing machine used to determine
fired compressive strengths. A sample is shown
in place between the spherical head and stationary
seat.

Per cent absorption was determined by the two hour boil method of Andrews

(41). The samples were dried for twenty-four hours at 110°C. and dessicated

over sulfuric acid before determining their dried weights.

Andreasen Pipette Determinations. The method of Loomis (11) was fol-

lowed exactly except that a constant temperature bath was not available

and room temperature (25°C.) was used in the calculations. For the feldspar,

a 0.01 molar solution of oxalic acid was used as the dispersing agent as
recommended by Russell and Weisz (42). The distribution chart for each
material was calculated and from these, the distribution charts of the
six bodies were drawn. All materials were plotted as the width of equiva-
lent cubes, although this is not the actual case with flint, and possibly
feldspar.

Results. From the chemical analyses of the various raw materials
in the batch of the six standard bodies, the chemical analyses of the
bodies were calculated. From the chemical analyses of the bodies, their
empirical formulas were calculated and were carried to three places after
the decimal, only in an attempt to show the small differences in the body
compositions. It is not likely, that the empirical formula is ever accu-
rate to more than two places. The grain size distributions of the bodies
were calculated from the grain size distributions of the raw materials in
the batch. Grain size is expressed as the width of equivalent cubes. The
above data are shown in Figures 7 to 12.

The results of the tests for green, dry, and fired compressive
strengths, per cent fired shrinkage, and per cent fired absorption are
shown in Tables 2 to 6. The analysis of variance tables for these proper-
ties are shown in Tables 7 to 11.

Concerning the phraseology used in the analysis of variance tables
and in other parts of this report, it is well to mention that certain
terms have been used interchangeably. In the analysis of variance, the
term clays means the variation in the values which may be attributed by
statistical methods to the use of the different ball clays in the standard

body. The term <u>water contents</u> which is synonomous with the term per cent water of plasticity means the variation which may be attributed to the use of the 10, 12, and 14% water of plasticity levels in the preparation of the bodies. <u>Firings</u>, the <u>temperature of firing</u> the samples, and the <u>cone</u> at which the samples were fired, all have the same meaning. Actually, of course, the cone 10 firing was completed at a higher temperature than the cone 9 firing, and so forth. The term <u>firings</u> means the variation in the values which may be attributed to the use of three firings instead of one.

The <u>interaction term</u> for <u>clays</u> and <u>water contents</u> means the variation in the values for a particular property being tested which may be attributed to <u>combining</u> the <u>different clays</u> with the <u>different water contents</u>. That is, increasing the water contents may affect a body A differently than another body B. This holds true for the interaction terms for <u>clays</u> and <u>firings</u>, and for <u>water contents</u> and <u>firings</u>.

The <u>second order interaction</u> term shows the effects of combining the <u>three variables</u> in <u>different ways</u> and when it is significant, it means that the variables interact differently.

Finally, it must be pointed out that the terms <u>bodies</u> and <u>clays</u> (meaning ball clays) have been used somewhat interchangeably. When one body is compared with a second body, it is inferred that the differences between the two are due to the fact that the bodies contain different ball clays.

Table 12 shows the effect of the ball clays on the properties of the standard body. These are the properties that have been treated in the

various analysis of variance tables. This table combines the effects of water contents and firing temperatures and considers the effects of the ball clays for the ranges used in the investigation.

Visual observations for fired color represents the opinion of several observers. All of the discs were essentially white, although some were considerably speckled or mottled. It was noted that the water contents have no visible effect on the color of the fired samples. It was not difficult, however, to distinguish between the different bodies and the different firings. Body 2 had a slight yellow tinge and was lightest in color at cone 9 and darkest at cone 10. Body 4 was very similar to body 2. Body 5 had the most uniform color throughout the range of firings. Body 6 had a more pronounced yellow tinge and was lightest at cone 9. At cones 10 and 11, this body was darker and had a grayish tinge. Body 7 was similar to body 6 except that at cones 10 and 11, there was a grayish-yellow tinge. Body 8 was the lightest of all bodies for all firings, but was very slightly darker at cones 10 and 11.

BODY # 2

(Figure 7.)

CALCULATED CHEMICAL ANALYSIS, EMPIRICAL FORMULA, AND GRAIN SIZE DISTRIBUTION.

CHEMICAL ANALYSIS

SiO_2 --- 71.4

Al_2O_3 -- 22.8

Fe_2O_3 -- 0.5

TiO_2 --- 0.8

CaO --- 0.3

MgO --- 0.01

$KNaO$ --- 4.2

EMPIRICAL FORMULA

$$\left. \begin{array}{l} .241\ KNaO \\ .027\ CaO \\ .001\ MgO \end{array} \right\} \quad \begin{array}{l} 1.000\ Al_2O_3 \\ .013\ Fe_2O_3 \end{array} \left. \right\} \quad \begin{array}{l} 5.304\ SiO_2 \\ .040\ TiO_2 \end{array}$$

Note. The empirical formula for this body(and
the others that follow) was calculated from
the calculated chemical analysis before the
second figure after the decimal was rounded
off. However, the chemical analysis is only
approximately accurate to the first figure
after the decimal, and the second figure was
dropped except when the amount was very small.
The empirical formula was carried to three
decimal places in order that small differences
in body composition might be shown.
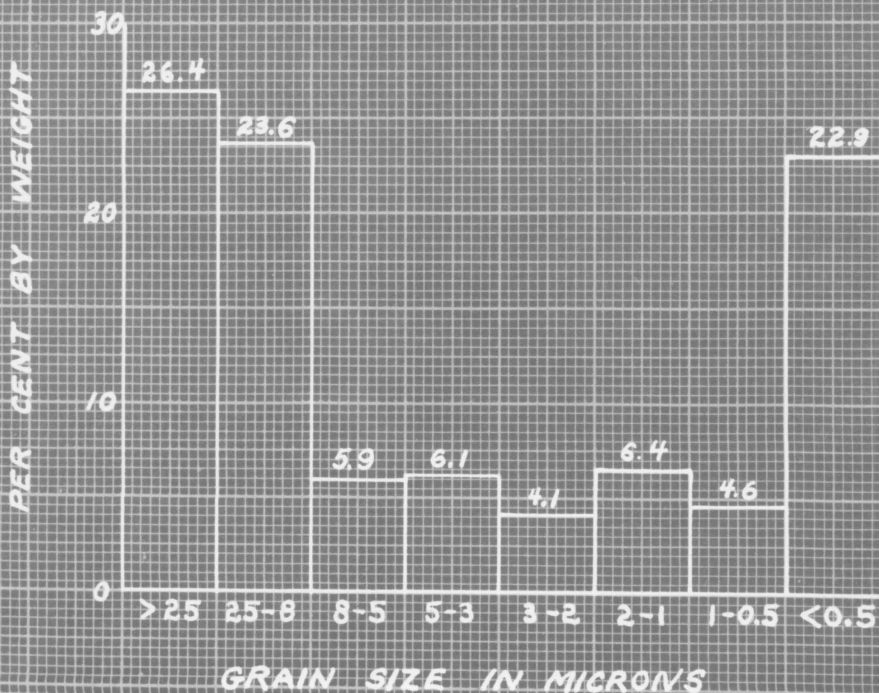
BODY # 4

(Figure 8.)

CALCULATED CHEMICAL ANALYSIS, EMPIRICAL FORMULA, AND GRAIN SIZE DISTRIBUTION.

CHEMICAL ANALYSIS

SiO_2 --- 70.8

Al_2O_3 -- 23.5 .

Fe_2O_3 -- 0.4

TiO_2 --- 0.8

CaO --- 0.4

MgO --- 0.1

Na_2O --- 1.5

K_2O --- 2.4

EMPIRICAL FORMULA

$$\left.\begin{array}{l} .113\ K_2O \\ .104\ Na_2O \\ .030\ CaO \\ .017\ MgO \end{array}\right\} \left.\begin{array}{l} 1.000\ Al_2O_3 \\ .013\ Fe_2O_3 \end{array}\right\} \begin{array}{l} 5.126\ SiO_2 \\ .043\ TiO2 \end{array}$$
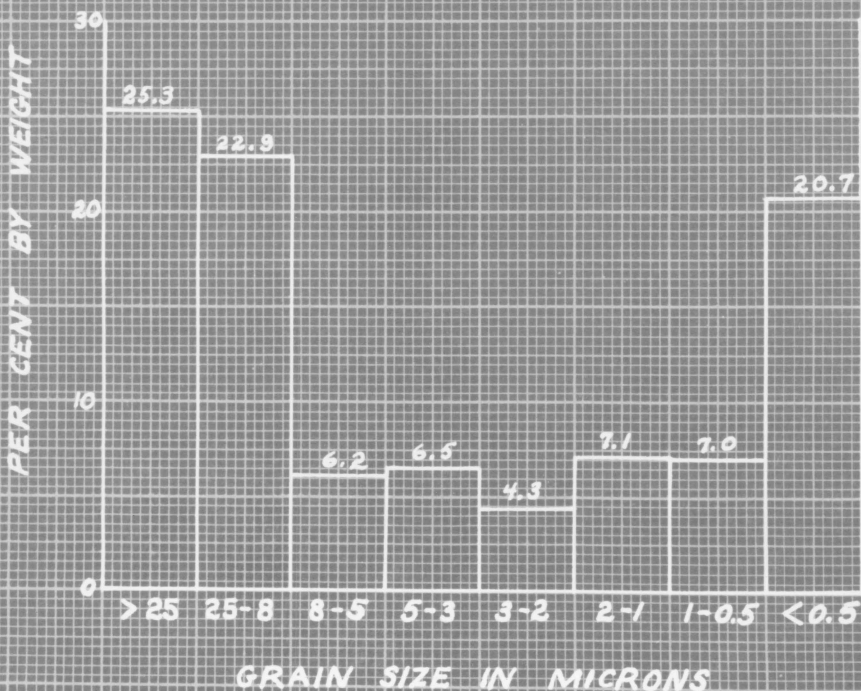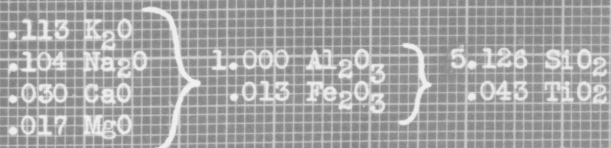
BODY # 5

(Figure 9.)

CALCULATED CHEMICAL ANALYSIS, EMPIRICAL FORMULA, AND GRAIN SIZE DISTRIBUTION.

CHEMICAL ANALYSIS

SiO_2 --- 71.2

Al_2O_3 -- 23.2

Fe_2O_3 -- 0.3

TiO_2 --- 0.8

CaO ---- 0.4

MgO ---- 0.1

$KNaO$ --- 3.9

EMPIRICAL FORMULA

$$\left.\begin{array}{l} .219\ KNaO \\ .035\ CaO \\ .013\ MgO \end{array}\right\} \begin{array}{l} 1.000\ Al_2O_3 \\ .009\ Fe_2O_3 \end{array} \left.\right\} \begin{array}{l} 5.197\ SiO_2 \\ .039\ TiO_2 \end{array}$$

PER CENT BY WEIGHT

30

25.4 23.1

20

23.5

10

5.8 5.5

3.7

6.3 6.7

0

>25- 25-8 8-5 5-3 3-2 2-1 1-0.5 <0.5

GRAIN SIZE IN MICRONS
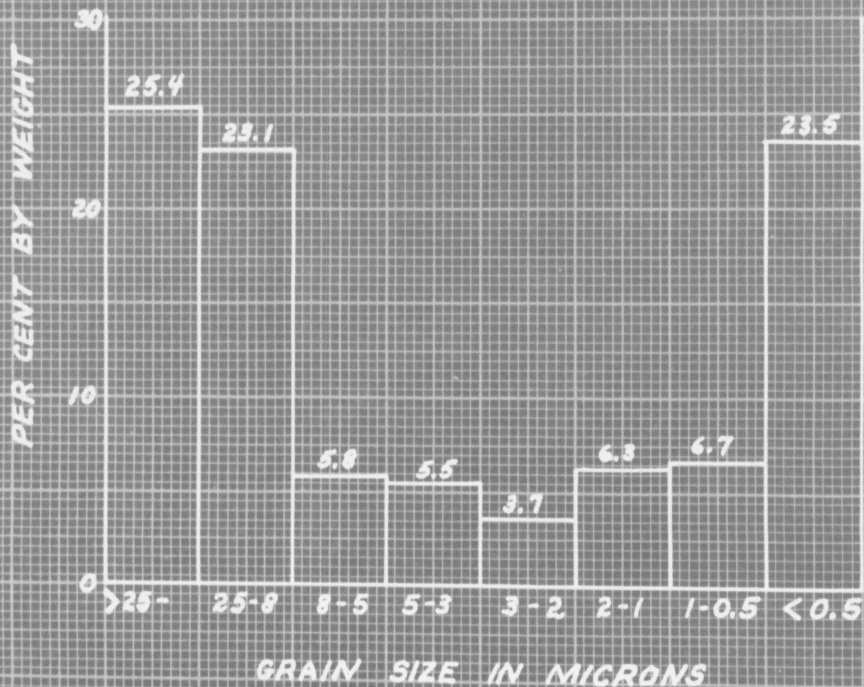
BODY # 6

(Figure 10.)

CALCULATED CHEMICAL ANALYSIS, EMPIRICAL FORMULA, AND GRAIN SIZE DISTRIBUTION.

CHEMICAL ANALYSIS

SiO_2 --- 71.2

Al_2O_3 -- 22.9

Fe_2O_3 --- 0.4

TiO_2 --- 0.7

CaO --- 0.4

MgO --- 0.2

Na_2O --- 1.4

K_2O --- 2.8

P_2O_5 --- 0.05

EMPIRICAL FORMULA

$\left.\begin{array}{l}.133\ K_2O \\ .102\ Na_2O \\ .031\ CaO \\ .018\ MgO\end{array}\right\}$ $\left.\begin{array}{l}1.000\ Al_2O_3 \\ .009\ Fe_2O_3\end{array}\right\}$ $\begin{array}{l}5.267\ SiO_2 \\ .040\ TiO_2 \\ .002\ P_2O_5\end{array}$

PER CENT BY WEIGHT vs GRAIN SIZE IN MICRONS

> 25: 25.6; 25-8: 24.1; 8-5: 6.1; 5-3: 8.0; 3-2: 5.6; 2-1: 8.9; 1-0.5: 5.9; <0.5: 15.8
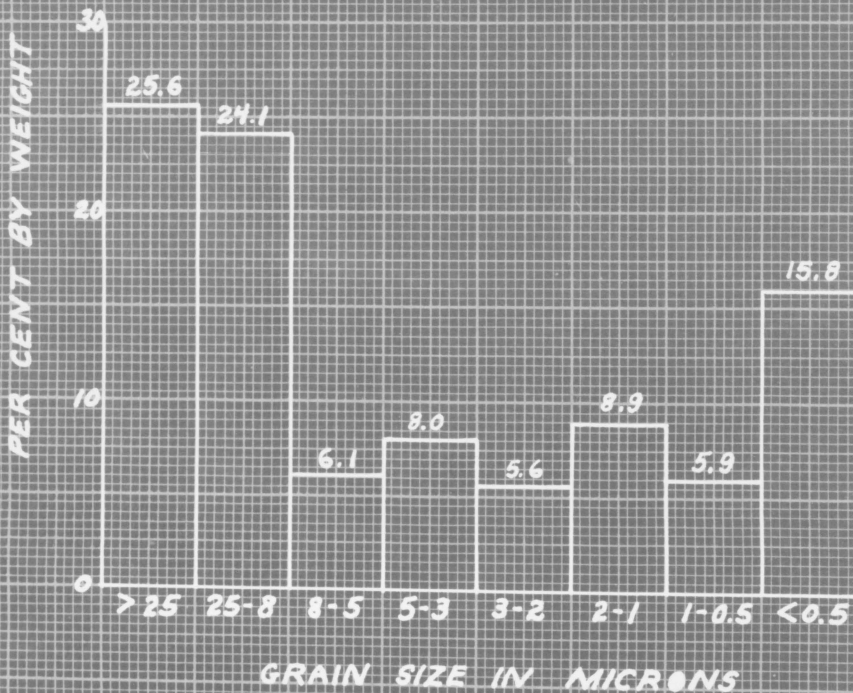
BODY # 7

(Figure 11.)

CALCULATED CHEMICAL ANALYSIS, EMPIRICAL FORMULA, AND GRAIN SIZE DISTRIBUTION.

CHEMICAL ANALYSIS

SiO_2 --- 72.4

Al_2O_3 -- 22.2

Fe_2O_3 -- 0.3

TiO_2 --- 1.1

CaO --- 0.3

MgO --- 0.1

Na_2O --- 1.4

K_2O --- 2.3

EMPIRICAL FORMULA

.115 K_2O
.101 Na_2O
.028 CaO
.018 MgO
} 1.000 Al_2O_3
.009 Fe_2O_3
} 5.548 SiO_2
.060 TiO_2

Grain size distribution histogram. PER CENT BY WEIGHT (y-axis) vs GRAIN SIZE IN MICRONS (x-axis).

Grain size	>25	25-8	8-5	5-3	3-2	2-1	1-0.5	<0.5
Per cent	27.3	25.5	7.4	7.6	5.1	7.7	5.7	13.7
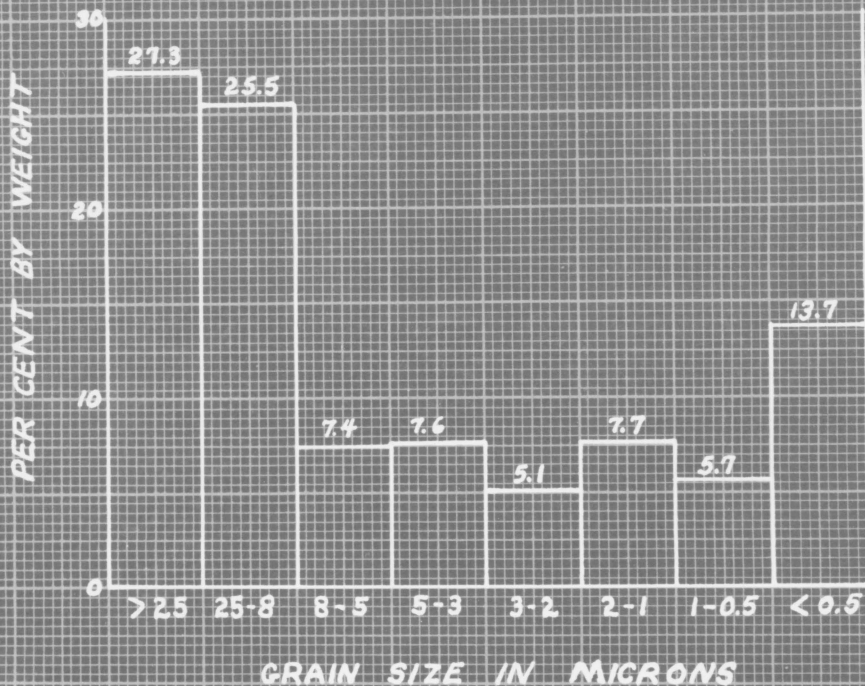
BODY # 8

(Figure 12.)

CALCULATED CHEMICAL ANALYSIS, EMPIRICAL FORMULA, AND GRAIN SIZE DISTRIBUTION.

CHEMICAL ANALYSIS

SiO_2 --- 69.4

Al_2O_3 -- 24.9

Fe_2O_3 --- 0.4

TiO_2 --- 0.6

CaO --- 0.4

MgO --- 0.01

Na_2O --- 1.5

K_2O --- 2.9

EMPIRICAL FORMULA

$$\left.\begin{array}{l} .127 \ K_2O \\ .098 \ Na_2O \\ .025 \ CaO \\ .001 \ MgO \end{array}\right\} \begin{array}{l} 1.000 \ Al_2O_3 \\ .008 \ Fe_2O_3 \end{array} \left.\begin{array}{l} \\ \end{array}\right\} \begin{array}{l} 4.754 \ SiO_2 \\ .029 \ TiO_2 \end{array}$$

Grain size distribution bar chart. PER CENT BY WEIGHT (vertical axis) vs GRAIN SIZE IN MICRONS (horizontal axis):

>25: 25.8
25-8: 23.3
8-5: 5.7
5-3: 5.6
3-2: 4.0
2-1: 7.7
1-0.5: 6.4
<0.5: 21.5
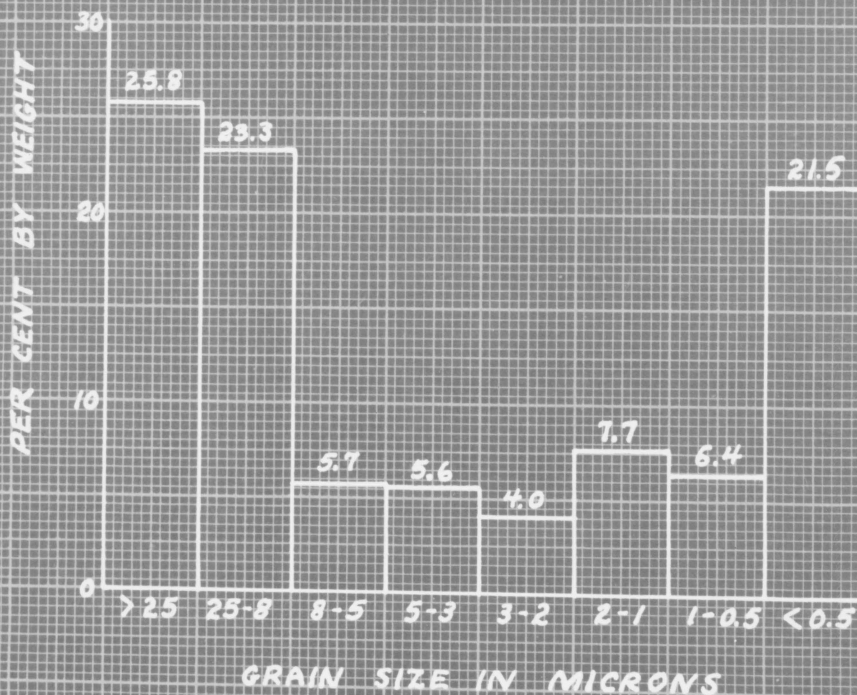
Table 2

RESULTS OF GREEN COMPRESSIVE STRENGTH TESTS

(P.S.I.)

Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
169	173	176	128	141	140	130	148	137	123	141	141	139	151	144	132	135	147	2,595
167	173	167	122	135	141	124	152	135	120	144	136	128	147	150	125	140	135	2,541
162	173	178	129	143	145	123	155	148	125	145	148	131	150	146	127	143	144	2,615
166	185	177	127	143	145	120	156	153	128	138	148	136	154	158	126	148	139	2,647
664	704	698	506	562	571	497	611	573	496	568	573	534	602	598	510	566	565	10,398

Table 3

RESULTS OF DRY COMPRESSIVE STRENGTH TESTS

(P.S.I.)

Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
348	288	368	165	223	258	190	288	339	219	298	373	241	539	481	283	267	353	5,521
306	260	427	152	282	264	169	292	348	210	307	334	231	544	502	261	244	365	5,498
326	296	348	188	248	275	187	288	351	194	285	355	226	455	563	281	291	340	5,497
303	300	408	166	214	296	209	279	349	203	263	372	261	477	500	274	277	372	5,523
1283	1144	1551	671	967	1093	755	1147	1387	826	1153	1434	959	2015	2046	1099	1079	1430	22,039

Table 4

RESULTS OF FIRED COMPRESSIVE STRENGTH TESTS

(X 1000 P.S.I.)

Cone 9 Firing

Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
12.8	11.7	15.0	13.4	16.8	14.6	10.4	10.0	14.0	20.0	22.4	16.8	13.3	16.3	33.0	18.3	20.1	19.6	298.5
13.8	12.6	11.1	15.6	16.5	14.2	11.2	10.8	15.8	22.9	23.4	18.7	19.8	19.0	29.5	19.7	19.5	14.9	309.0
15.1	13.0	12.4	16.2	16.4	16.8	10.9	11.3	11.6	22.7	21.6	22.3	13.7	27.2	26.1	20.1	20.3	19.5	317.2
16.0	14.7	14.2	13.4	19.7	16.2	10.8	12.3	11.1	25.6	29.3	16.5	16.8	27.1	27.1	19.0	17.1	17.5	324.4
57.7	52.0	52.7	58.6	69.4	61.8	43.3	44.4	52.5	91.2	96.7	74.3	63.6	89.6	115.7	77.1	77.0	71.5	1249.1

Cone 10 Firing

Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
24.8	21.4	20.2	18.3	24.5	21.8	19.6	18.9	15.2	23.7	29.4	30.3	30.6	30.0	27.5	19.3	30.4	30.1	436.0
27.0	20.3	23.8	23.7	23.5	24.8	22.0	16.0	16.9	28.8	28.7	30.4	24.8	26.9	29.7	25.8	26.1	24.1	443.3
24.6	19.9	21.3	21.7	20.9	26.3	23.3	18.9	14.8	29.3	26.5	32.6	26.9	24.2	27.8	25.4	27.1	23.9	435.4
25.9	22.5	19.5	23.4	22.7	23.0	20.4	16.0	19.9	29.7	30.5	29.2	26.1	23.5	27.3	23.1	25.4	25.6	433.7
102.3	84.1	84.8	87.1	91.6	95.9	85.3	69.8	66.8	111.5	115.1	122.5	108.4	104.6	112.3	93.6	109.0	103.7	1748.4

Cone 11 Firing

Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
24.1	20.4	15.1	17.3	21.0	19.8	16.4	20.2	19.6	23.9	27.6	25.9	19.3	32.9	28.8	27.5	30.2	24.8	414.8
25.9	17.9	19.1	16.5	21.2	18.1	19.7	17.0	16.9	20.1	23.1	26.0	30.3	36.5	29.6	28.8	27.4	25.2	419.3
29.5	23.5	16.9	19.2	21.1	19.0	17.1	17.0	20.7	22.7	26.7	25.4	18.9	28.0	30.1	26.5	24.2	27.8	414.3
25.6	22.1	16.1	20.9	20.3	23.1	19.0	20.1	20.4	26.0	28.7	28.2	28.6	28.9	31.7	24.6	21.0	26.8	432.1
105.1	83.9	67.2	73.9	83.6	80.0	72.2	74.3	77.6	92.7	106.1	105.5	97.1	126.3	120.2	107.4	102.8	104.6	1680.5

Table 5

RESULTS OF % FIRED SHRINKAGE TESTS

Cone 9 Firing

	Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
	8.1	8.7	8.6	10.0	9.7	9.7	9.1	9.0	9.0	10.4	9.9	9.3	8.9	9.2	9.0	10.8	10.8	10.4	170.6
	8.1	8.9	8.9	10.0	9.7	9.4	8.8	8.4	9.0	10.8	10.1	9.3	9.4	9.1	9.0	11.0	10.4	10.1	170.4
	8.2	8.7	8.8	10.0	9.6	9.3	8.8	8.4	8.9	10.4	9.7	9.5	9.4	9.2	9.0	11.0	10.4	10.6	169.9
	8.1	8.7	8.7	10.0	9.7	9.5	9.3	8.4	8.8	10.6	9.9	9.7	8.7	9.3	9.3	10.8	10.7	10.3	170.5
	32.5	35.0	35.0	40.0	38.7	37.9	36.0	34.2	35.7	42.2	39.6	37.8	36.4	36.8	36.3	43.6	42.3	41.4	681.4

Cone 10 Firing

	Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
	8.9	9.8	9.2	10.8	10.5	10.4	10.6	9.8	9.4	11.4	11.2	10.8	10.7	10.3	9.7	12.1	11.8	11.8	189.2
	9.0	9.6	9.4	10.6	10.7	10.0	10.5	10.0	9.8	11.3	10.9	10.7	10.7	10.3	10.0	11.8	11.9	11.5	188.7
	8.6	9.6	9.4	10.7	10.7	10.2	10.5	9.8	9.7	11.5	10.9	10.8	10.6	10.2	10.1	12.0	11.9	11.6	188.8
	9.3	9.7	9.5	10.3	10.8	10.2	10.5	10.0	9.4	11.3	11.0	10.6	10.6	10.4	10.0	11.9	12.2	11.3	189.0
	35.8	38.7	37.5	42.4	42.7	40.8	42.1	39.6	38.3	45.5	44.0	42.9	42.6	41.2	39.8	47.8	47.8	46.2	755.7

Cone 11 Firing

	Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
	9.2	10.0	9.9	10.8	10.9	10.5	10.7	10.1	9.9	11.5	11.2	10.7	10.6	10.4	10.1	12.2	12.0	11.5	192.2
	9.5	9.6	9.8	11.0	10.8	10.5	10.7	10.2	9.9	11.7	11.2	10.8	10.7	10.4	9.9	12.3	12.2	11.9	193.1
	9.1	9.7	9.7	11.2	10.8	10.0	10.8	10.2	9.9	11.5	11.1	11.0	10.7	10.4	10.2	11.9	12.1	11.6	191.9
	9.3	10.0	9.7	11.0	10.9	10.4	10.8	10.2	9.7	11.4	11.2	11.1	10.7	10.4	10.1	12.4	12.0	11.9	193.2
	37.1	39.3	39.1	44.0	43.4	41.4	43.0	40.7	39.4	46.1	44.7	43.6	42.7	41.6	40.3	48.8	48.3	46.9	770.4

Table 6

RESULTS OF % FIRED ABSORPTION TESTS

Cone 9 Firing

	Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
	4.2	5.6	4.1	4.3	4.1	3.7	6.0	5.2	5.2	3.2	4.2	4.2	4.6	3.6	3.1	4.0	3.9	3.7	76.9
	4.2	5.3	4.5	4.3	3.9	4.1	6.5	5.8	4.6	3.4	2.8	4.1	4.2	3.5	3.0	4.0	4.5	4.1	76.8
	3.9	5.6	4.5	4.1	4.2	4.1	6.6	6.0	4.7	3.3	4.0	3.4	5.3	3.5	3.3	3.8	4.1	3.5	77.9
	4.1	5.3	4.5	4.1	3.7	3.5	5.9	6.0	4.7	3.3	3.9	3.4	4.5	3.5	3.0	4.3	4.2	4.3	76.2
	16.4	21.8	17.6	16.8	15.9	15.4	25.0	23.0	19.2	13.2	14.9	15.1	18.6	14.1	12.4	16.1	16.7	15.6	307.8

Cone 10 Firing

	Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
	2.2	3.1	2.9	1.9	2.4	2.0	3.1	3.2	3.1	1.2	1.0	1.1	2.2	2.0	2.2	2.7	2.7	2.0	41.0
	2.3	3.2	2.4	2.3	2.2	2.3	3.4	2.9	2.6	1.0	.9	1.1	2.2	1.9	1.7	2.8	2.5	2.7	40.4
	2.7	3.6	2.5	2.2	2.1	1.9	3.2	3.1	2.9	1.1	1.0	1.0	2.2	2.0	1.8	2.4	2.5	2.4	40.6
	2.3	3.5	2.2	2.3	2.1	2.1	3.2	3.3	3.2	1.3	1.1	1.1	2.5	2.1	1.6	2.7	2.2	2.8	41.6
	9.5	13.4	10.0	8.7	8.8	8.3	12.9	12.5	11.8	4.6	4.0	4.3	9.1	8.0	7.3	10.6	9.9	9.9	163.6

Cone 11 Firing

	Body #2			Body #4			Body #5			Body #6			Body #7			Body #8			Total
	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	0	2	4	
	2.0	2.6	2.4	1.8	1.4	2.0	2.7	2.4	2.3	1.0	1.1	1.0	1.7	1.5	2.2	1.8	1.9	2.1	33.9
	1.9	3.0	2.2	1.7	1.7	1.6	2.8	2.8	2.3	1.0	.8	.8	1.6	1.6	1.7	1.6	1.7	2.0	32.8
	2.1	3.3	2.3	1.8	1.9	2.0	2.7	2.6	3.1	1.2	1.0	.9	1.5	1.4	1.3	2.3	1.9	1.9	35.2
	1.9	3.4	2.2	1.6	1.9	1.8	2.9	2.4	2.9	1.0	1.1	.8	1.6	1.5	1.5	1.8	1.8	1.7	33.8
	7.9	12.3	9.1	6.9	6.9	7.4	11.1	10.2	10.6	4.2	4.0	3.5	6.4	6.0	6.7	7.5	7.3	7.7	135.7

Table 7.

ANALYSIS OF VARIANCE TABLE FOR GREEN COMPRESSIVE STRENGTH

Source of Variation	D/F	Sum of Squares	Mean Square	F
Replications	3	329.9	109.97	6.427 64.27 ✔
Clays	5	11,675.8	2335.16	136.48 ✔
Water Contents	2	4218.0	2109.00	123.26 ✔
Clays x W.C.	10	489.2	48.92	2.86 ✔
Error	51	872.6	17.11	————
Total	71	17,585.5		

Table 8.

ANALYSIS OF VARIANCE TABLE FOR DRY COMPRESSIVE STRENGTH

Source of Variation	D/F	Sum of Squares	Mean Square	F
Replications	3	33.5	11.16	———— ✘
Clays	5	251,173.3	50,234.65	96.99 ✔
Water Contents	2	235,096.5	117,548.25	226.96 ✔
Clays x W.C.	10	117,856.8	11,785.68	22.76 ✔
Error	51	26,414.3	517.93	————
Total	71	630,574.4		

✘ - Not significant

✔ - Indicates significance at the 1% level.

Table 9.

ANALYSIS OF VARIANCE TABLE FOR FIRED COMPRESSIVE STRENGTH

(Values Should Be Multiplied By 1000 P.S.I.)

Source of Variation	D/F	Sum of Squares	Mean Square	F
Replications	3	15.70	5.23	0.94 ✗
Clays	5	2764.73	552.94	99.27 ✓
Water Contents	2	21.12	10.56	1.90 ✗
Firings	2	2037.11	1018.55	182.86 ✓
Clays x W.C.	10	473.75	47.37	8.50 ✓
Clays x Firings	10	195.98	19.59	3.52 ✓
Firings x W.C.	4	40.91	10.22	1.83 ✗
Clays x Firings x Water Contents	20	421.59	21.08	3.78 ✓
Error	159	885.82	5.57	———
Total	215	6856.71		

✗ - Not significant

✓ - Indicates significance at 1% level.

Table 10.

ANALYSIS OF VARIANCE FOR PER CENT FIRED SHRINKAGE

Source of Variation	D/F	Sum of Squares	Mean Square	F
Replications	3	0.045	0.0150	0.60 ✗
Clays	5	119.292	23.8584	954.32 ✓
Water Contents	2	5.721	2.8605	113.49 ✓
Firings	2	63.230	31.6150	1254.56 ✓
Clays x W.C.	10	8.077	0.8077	32.05 ✓
Clays x Firings	10	1.442	0.1442	5.72 ✓
Firings x W.C.	4	0.476	0.1190	4.72 ✓
Clays x Firings x Water Contents	20	1.914	0.0957	3.80 ✓
Error	159	4.008	0.0252	————
Total	215	204.205		

Table 11.

ANALYSIS OF VARIANCE FOR PER CENT FIRED ABSORPTION

Source of Variation	D/F	Sum of Squares	Mean Square	F
Replications	3	0.1276	0.0425	1.01 ˣ
Clays	5	78.4942	15.6988	372.01 ᵛ
Water Contents	2	2.4049	1.2024	28.49 ᵛ
Firings	2	236.9929	118.4964	2807.97 ᵛ
Clays x W.C.	10	11.4606	1.1461	27.16 ᵛ
Clays x Firings	10	6.2693	0.6269	14.85 ᵛ
Firings x W.C.	4	1.6507	0.4127	9.78 ᵛ
Clays x Firings x Water Contents	20	4.7805	0.2390	5.66 ᵛ
Error	159	6.7149	0.0422	————
Total	215	348.8956		

Table 12. Effect of Ball Clays on All Properties

Property	Body No.	Final Average	Diff. for Significance
Green Compressive Strength (p.s.i.)	2	172.2	4.6
	7	144.5	
	5	140.1	
	8	136.7	
	4	136.8	
	6	136.4	
Dry Compressive Strength (p.s.i.)	7	418.3	17.6
	2	331.5	
	8	300.7	
	6	284.4	
	5	274.1	
	4	227.6	
Fired Compressive Strength (x 1000 p.s.i)	7	26.1	1.45
	6	25.4	
	8	23.5	
	4	19.5	
	2	19.2	
	5	16.3	
Per Cent Fired Shrinkage	8	11.5	0.10
	6	10.7	
	4	10.3	
	7	9.9	
	5	9.7	
	2	9.2	
Per Cent Fired Absorption	5	3.8	0.13
	2	3.3	
	8	2.8	
	4	2.6	
	7	2.5	
	6	1.9	

Explanatory Note. The bodies are listed in the order of decreasing numerical value for the final average, which represents the average of all tests for the particular property of the body. This average includes all values for the different water contents and, for the fired properties, the different temperatures or cones of firing. For any property, to test the significance of one body against a second, compare the difference between the two with the difference for significance.

Conclusions from the Statistical Analysis. Green Compressive Strength.

(1.) The effects of clays, water contents, clays x water contents, and replications are significant. The variation due to clays and to water contents are the same except for random fluctuations.

(2.) The test for significance was made using the error term; however, it is well to note that both clays and water contents would have been significant if tested against the second-order interaction term which means that recommendations can be made for clays and water contents in general.

(3.) Bodies 4 and 6 tend to become stronger with additions of water while the other bodies differ from these two significantly in this respect. All bodies appear weaker with only 10% water of plasticity. The variation due to water contents was so irregular that no significant linear relation between it and green compressive strength can be claimed.

(4.) For the effect of the clays on the bodies, body 2 is significantly stronger than the others. See Table 12.

Dry Compressive Strength.

(1.) The effect of replications is not significant. The effects of clays, water contents, and the interaction for clays x water contents are significant.

(2.) It is interesting to note that when water contents are tested against the interaction term, their effect is still significant. This means that general recommendations can be made for water

contents regardless of the clay used. The fact that the inter-
action term is significant shows that the clays are affected dif-
ferently by changes in water contents.

(3.) However, the dry compressive strength is increased directly with
the water content of the body and the amount of variation not
accounted for by this relationship is not significant.

(4.) For the effect of the clays on the bodies, see Table 12.

Fired Compressive Strength.

(1.) The effects of replications, water contents, and the interaction
term for firings and water contests are not significant. All other
effects are significant. The error was rather large as would be
expected. The greatest amount of variation is due to the firings
and to the clays.

(2.) The variation of fired compressive strength is so irregular that
no significant linear relationship between it and the temperature
or cone of firing can be claimed. Bodies 7 and 8 appear to become
stronger as the temperature of firing is increased, but the other
bodies behave differently, and many are weaker at the cone 11 firing
than at the cone 10 firing.

(3.) Water contents do not affect fired compressive strength.

(4.) The interaction for clays and water contents is significant showing
that the fired compressive strength of certain clays is affected
differently by water contents than others. The fact that the triple
order interaction is significant shows that the effects of firing and

water contents vary with the different clays. Here again is shown the differences in the clays.

(5.) Bodies 7 and 6 are the best with regard to fired compressive strength. See Table 12 for the effect of the other clays on the standard bodies.

Fired Shrinkage.

(1.) All effects are significant except replications. The variation due to error is very small.

(2.) The variability due to clays is not significantly different from that due to firings.

(3.) It is seen that water contents affect the fired shrinkage property of the various bodies differently. However, if body 2 is omitted (which does not follow the general trend for the other bodies), it can be shown that the shrinkage is inversely proportional to the water contents.

(4.) No significant linear relationship was found between fired shrinkage and the cone of firing as most of the increase in shrinkage occurred between the cone 9 firing and the cone 10 firing.

(5.) For the effect of clays on the fired shrinkage of the bodies see Table 12. Since the error mean square or the variation due to error is so small, all of the differences for the effects of the clays are significant; however, from a practical standpoint this difference may be too small to have value. The greatest shrinkage was 11.5% on the average and the lowest was 9.2% on the average, a range of only 2.3%.

Fired Absorption.

(1.) All effects are significant except the replications. As would be expected, the greatest variation is contributed by the firings. Considerable variation is due to the clays. The error mean square or the variation due to error is small.

(2.) Recommendations for clays in general can be made as shown by the fact that the mean square or variance for clays is significant even when compared with the mean square for the interactions of clays and firings, and clays and water contents.

(3.) No significant linear relationship can be claimed for the effect of firings on absorption as, again, most of the difference in absorption occurs between the cone 9 and cone 10.

(4.) It is seen that the effects of water contents are widely different for the various bodies. No significant relationship can be claimed for water contents and absorption due to the high variability between the various bodies.

(5.) For the effects of clays on the absorption properties of the various bodies see Table 12.

IV. DISCUSSION OF RESULTS

In the plots of the grain size distributions for the six bodies, the arbitrary particle size groups used by Loomis (11) have been employed. This grouping of the fractions is particularly suitable for the distribution charts for pure ball clays. However, as applied to the grain size distributions for the bodies, it is satisfactory since the essential differences contributed by the ball clays can be readily noted. Body 7 containing Kentucky No. 5 ball clay appears to be composed of the relatively coarsest particles which, of course, are due to the ball clay. On the other hand, body 5 is composed of the relatively finest particles which are contributed by the Bell's dark ball clay. Although the grain size distributions of the different ball clays agree in their relative order with the determinations as made by Loomis, all values were at least 5% of the weight percentages lower than the corresponding value as determined by this authority. The reason for these proportional differences is not readily apparent. If the differences did not apply to all of the ball clays investigated in each case, they could perhaps be blamed on the differences in the samples. Therefore, there must be some reason for these constant differences in results. It is possible that the use of a constant temperature bath controlled at 30°C. would increase the agreement of the results since the only difference between the two tests is the temperature of the suspending medium. Duplicate determinations were made on some of the materials, and the results usually checked with 1% of the weight percentages. It was noted that the characteristic curves for the ball clays

and the china clay were better than the curves for the non-plastic materials. It was also found that better results could be obtained for the finer particle sizes of the feldspar when a 0.01 molar solution of oxalic acid was used as the dispersing agent rather than distilled water.

All of the bodies contained very closely the same weight percentage of RO oxides. When their compositions are plotted on an RO-Al_2O_3-SiO_2 diagram, the points lie almost on a straight line which is parallel to the Al_2O_3-SiO_2 join. It is difficult to make correlations or comparisons between the chemical analyses or empirical formulas of the bodies and their physical properties, due to the fact that many different accessory oxides are present in varying small amounts, and that these oxides are often contributed by different minerals. The particles sizes of the various components vary and consequently influence the formation of the glassy phase in the body. Furthermore, the compositions of the glassy phases in the different bodies may vary. There are other variables which might affect the properties, such as the method of preparing the materials, method of mixing the bodies, etc.; although these have been standardized in the present work.

However, it is possible in a general way to compare the effects of iron oxide and titanium oxide on the fired colors of the discs. Body 8, which contained the least amount of TiO_2 and probably less Fe_2O_3 on the basis of the empirical formula was the best body with regard to fired color. This comparison tends to hold to a lesser extent for the other bodies; although, again there are certain variables which might influence the results.

Green compressive strength is affected by the clays used in the standard body, the water contents of the body, and by the interaction of the clays and the water contents. That is, an increase in water contents may increase the green compressive strength of a body containing ball clay A somewhat, and may not affect the strength of the body containing ball clay B, or may decrease the property. There is no significant linear trend for the effects of water contents used on the green compressive strength. Table 12 shows that body 2 had the highest green compressive strength and that there was little practical difference in the average values for the other bodies.

Likewise, the dry compressive strengths of the bodies are affected by the ball clays used, by the water contents of the wet-dust, and by the interaction of the clays and the water contents. The effects of water contents are very pronounced, or significant, on this property. For the six ball clays and the three water contents used, it has been shown that the overall effect is linear. That is, as the water content is increased from 10% to 12% to 14%, the dry compressive strengths of the bodies in general are proportionally increased. However, since only four replications were used, and since the bodies containing different ball clays are differently affected by water contents (as shown by the significance of the interaction term), and since there is considerable variation due to error; it is difficult to show the effects of increasing the water content on the individual bodies. Therefore, it was difficult to plot significant curves or straight lines for the relationship of water content to dry compressive strength for individual bodies. Many of the points for a particular body

are not significant from each other when only three degrees of freedom
may be used. A straight line relationship was plotted (See Figure 13)
for body 6 which was significant at the 5% level for F, or in other words,
the three points thusly determined would be a straight line 95% of the
time. The points for body 5 were significantly different from each other
but can be represented by a straight line only at about the 10% level
which is too low from a statistical viewpoint. These points were also
plotted (Figure 13) and a straight line relationship indicated. This was
done because of the difficulty in plotting only three points, and the
relationship is expressed about as well by a straight line as by a curve.
Furthermore, it is possible that the effect would have been linear had
the number of replications been increased. For the above-mentioned
reasons, it was not feasible to plot the average values for other bodies.
Table 12 shows that for the range of water contents, there is considerable
variation in the average values for dry compressive strength. Body 7 ap-
pears to be the best in this property.

Fired compressive strength of the body is affected by the ball clays
used, the temperature of firing, and certain interactions. Water contents,
in general, seem to have no effect on this property for the range covered.
It has been shown, however, that the different bodies are variously af-
fected by the water contents, even though the overall effect is neglible.
All bodies are weaker at cone 9. Certain of the bodies are weaker at cone
11 than at cone 10, due to the formation of excessive glassy phase which
weakens the bodies. Other effects have been considered under <u>Conclusions</u>
<u>from the Statistical Analysis. Fired Compressive Strength.</u> There ia a

Figure 13.

RELATION OF % WATER OF PLASTICITY

TO DRY COMPRESSIVE STRENGTH FOR

BODIES 5 AND 6.
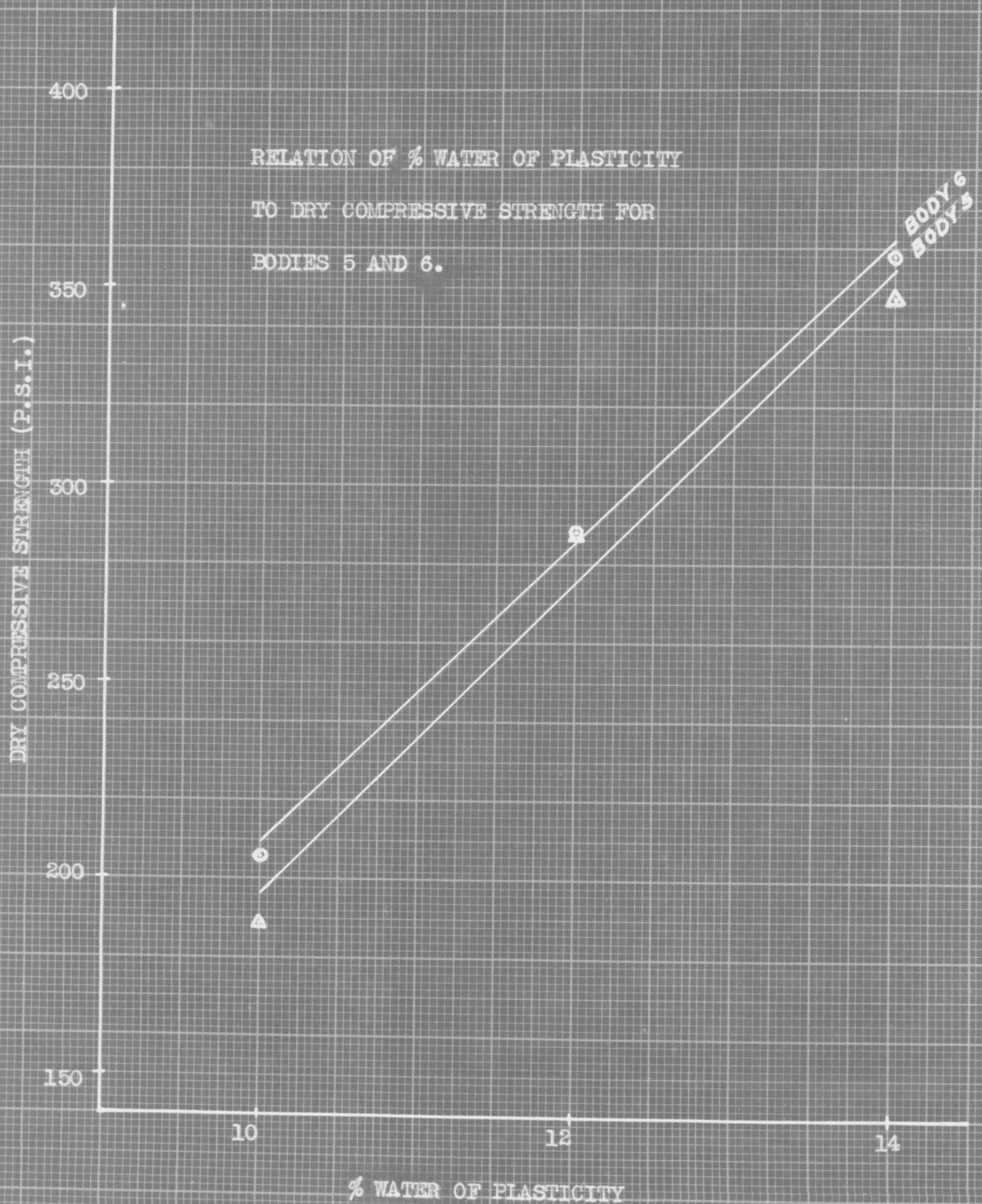
wide range for the final average (Table 12) for the different bodies.

Fired shrinkage is a property which can be measured rather accurately. To measure the shrinkage of a disc, several values of the diameter of the disc should be taken as accurately as possible both before and after firing. The averages of these values should be used in calculating the result. From the analysis of variance for this property it is noted that all effects are significant. The fact that the error mean square is so small shows that there is very little difference between the individual samples for any one set of conditions. Although it was shown that the overall effect of water contents on fired shrinkage is linear for bodies 4, 5, 6, 7, and 8, the actual differences in the shrinkages between bodies of different water contents are so small, that they have little or no practical value. The average difference is only 0.2%. Furthermore, this is an overall effect and because the water contents affect the various bodies differently, this linear effect cannot be shown on individual bodies. In other words, water contents do not inversely affect the fired shrinkage of each body, but if such were the case, the effect would, in most cases, be too small to consider. It is noted from a study of the data that the differential shrinkage between cones 9 and 10 is relatively large, whereas the differential shrinkage between cones 9 and 10 is small in comparison. Then it is obvious that no significant linear trend can be claimed. The greatest average shrinkage occurred on body 8, and the least on body 2. As previously pointed out, the range is small.

From a study of the results on the per cent absorption tests, it is apparent that no linear trends can be claimed. This is confirmed by the

analysis of variance. As was the case with fired shrinkage, most of the decrease in absorption takes place between cones 9 and 10. A desirable property for electrical porcelain is zero absorption. At cone 11, body 6 had an average absorption of 1.0%. At this cone, the absorption for all bodies was reasonably low. For zero absorption more fluxing oxides would have to be introduced into the batch. This is generally accomplished by adding greater amounts of the feldspar than the 25% used in this standard body, and/or accessory fluxes such as whiting.

It was found that increasing the 2-hour boil to 4-hours did not increase the per cent absorption more than 0.1%, if at all.

In this study, drying shrinkage was zero because of the small amount of the water in the wet-dust (for all water contents) and because the samples were formed by the dry-press method.

V. CONCLUSIONS

(1.) The effects of using different ball clays on the physical properties of the standard body have been shown. Although variations in all of the physical properties can be attributed to the use of different ball clays, these variations are more pronounced on the compressive strength properties. Since feldspar mainly controls fired shrinkage and fired absorption, and since the same amount of feldspar was used in each body, the effects of using different ball clays on these physical properties were not so pronounced.

(2.) The use of different water contents affects all of the physical properties except fired compressive strength, where the variation due to water contents was not significant.

(3.) In general, an increase in water content proportionally increases the dry compressive strength for the bodies studied. This is an overall effect for all bodies and can be applied only for the water contents used in the investigation.

(4.) Drying shrinkage was zero in all cases.

(5.) It has been shown by statistical methods that water contents affect the properties of the bodies containing different ball clays in different ways.

(6.) The fired compressive strength of bodies 7 and 8 increased as the temperature of firing was raised. This did not apply for the other bodies, and many were weaker at cone 11 than at cone 10.

(7.) An overall linear effect was noted for the inverse action of water contents on fired shrinkage for bodies 4,5,6,7, and 8. This effect did not apply to individual bodies for several reasons and has little significance since the average difference was only 0.2% between the different water contents.

(8.) None of the bodies investigated had zero absorption, even at cone 11. At this cone, the per cent absorption was relatively low for all bodies and body 6 had only 1.0%.

(9.) Because of the general similarity of the chemical analyses of the fired bodies the particular differences in all small amounts of the various RO oxides, and a number of physical and chemical variables introduced by the use of different ball clays, it is practically impossible to correlate the physical properties of the fired bodies with their chemical analyses.

(10.) It is possible, in a general way, to show the effect of TiO_2 and Fe_2O_3 on the fired color of the bodies. Body 8 containing the least amount of these coloring oxides had the **best white color** at all cones.

(11.) From the **results of** this investigation, body 7 appears **to be the best body.**

(12.) The method used in this investigation has proved satisfactory for the testing of ball clays, and for studying the effects of all variables on the properties of the standard body. The use of statistical methods has increased the amount of worthwhile information which could be obtained from the tests. More information may be obtained for the individual bodies if the number of replications is increased.

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APPENDIX I

Columbus, Ohio
January 11, 1944

Dear Mr. Venable:

Yours January 7. My data on relative industrial importance of ball clays is two years old but was obtained by a survey of a considerable number of the recognized ceramists using such clays. The list compiled at that time is as follows:

Kentucky Ball Clays *

(a) Old Mine No. 4

(a) Kentucky Dark Special

(b) Kentucky No. 12

(b) Kentucky No. 6

(b) Kentucky No. 1

(a) Kentucky No. 5

(a) KCM

(b) Kentucky No. 2

(b) Kentucky "B"

Tennessee Ball Clays*

(a) Jernigan

(b) C & C

(a) Bell's Dark

(b) Bell's Medium

(a) Bell's Dresden

(a) Tennessee No. 5

(a) Tennessee No. 7

(b) No. 1 SGP

*(Listed a, b and c in order of decreasing consumption)

Several other clays were mentioned by one reference only, but the above are evidently the most widely used, both in the east, north and middle west.

Your proposed thesis sounds very promising, but if you dry press your trials, you must control the water content and pressures very accurately. Based on my experience, you should use 3 water contents for each clay so that the data provides a curve and permits comparison of the different clays. With one constant water content some bodies will be too wet and some too dry for good pressing, and in the absence of any standard method of determining the required water content of the test bodies you could not hope to develop comparable data. My suggestion would be to limit the clays tested to six or eight and cover sufficient water variation and perhaps molding pressures so that the merits of the testing system would be disclosed.

I am glad you are undertaking this study and hope you may be able to attend the coming American Ceramic Society convention where the data developed and the problems encountered should have much interest for the Whiteware Division.

Sincerely yours,

Arthur S. Watts
Professor of Ceramic Engr.
The Ohio State University

<u>APPENDIX II</u>

East Pittsburgh, Pa.
January 13, 1944

Dear Mr. Venable:

It is pleasing to note your interest in the testing of ball clays. Thus far in our "Testing and Classification of Ball Clays" in the White Wares Division of the American Ceramic Society, we have not progressed to the point of selecting specific clays for test. I, therefore, have some hesitancy about making recommendations of representative ball clays for test lest someone misconstrue my intentions.

However, since you must select ball clays for your testing program, I will list sixteen representative clays. Please bear in mind that this is no final listing of the sixteen most representative clays. The mine locations are indicated in parentheses.

1. Champion & Challenger (Tennessee)

2. Jernigan (Tennessee)

3. Victoria (Tennessee)

4. Rex (Tennessee)

5. Old Mine No. 4 (Kentucky)

6. Special (Kentucky)

7. No. 5 (Tennessee)

8. Martin No. 5 (Tennessee)

9. Bell's Dark (Tennessee)

10. Cooley No. 2 (Kentucky)

11. Kentucky #1

12. Kentucky #5

13. "B" (Kentucky)

14. Mississippi M. & D.

15. Black (England)

16. Light (England)

Only one Mississippi clay has been listed, since it is the only one with which I am familiar.

There are a few points in your method of attack which merit some discussion. In your flow sheet No. 1 on "Ball Clay Preparation" you indicate a drying treatment at 100°C. While all ball clays would be affected in their plastic and bonding properties by such severe drying, I rather doubt that a uniform effect would result. I would suggest that any artificial drying be done below 60°C. and that normal temperatures be used if possible. Drying should be accomplished through the use of accelerated air movement (such as would result through the use of fans) rather than through the application of heat. You could, of course, use absorption slabs for preliminary drying, and combine this as drying progresses with rapid air circulation over the moist clay. If you cannot dry the clay in a reasonable period, some artificial heat will be required in the latter stages, but it should not be excessive.

In your flow sheet No. 2 for "Standard Method of Mixing" I note that you propose to prepare bodies containing 20 mesh ball clay in a dry-mixing unit. You should attempt to pulverize your clays much finer, or you will need to adopt a substitute method of blunging and drying your bodies prior to dry mixing of the mass for specimen preparation.

If you have no suitable pulverizing equipment, I suggest that you start with 4 mesh or finer ball clay, prepare your body by blunging, and carry it through flow sheet No. 1. There would then be no need to carry the clay alone through this blunging treatment and the amount of work you would do would be no greater than originally planned. So far as I can see there would be no major disadvantages to this procedure.

I trust that you will have success in your endeavor. Please advise if I can be of further service.

Yours very truly,

Ralston Russell, Jr.
Research Laboratories
Westinghouse Elec. & Mfg. Co.

Appendix III.

FIRING SCHEDULE USED.

The firings all followed the schedule very closely. This schedule
is for the the disc control on the Globar electric laboratory kiln used.

Start		------	215°F.
1st hour		------	300
2nd	"	------	520
3rd	"	------	900
4th	"	------	1200
5th	"	------	1420
6th	"	------	1610
7th	"	------	1720
8th	"	------	1820
9th	"	------	1920
10th	"	------	2010
11th	"	------	2110
12th	"	------	2220
13th	"	------	2300
14th	"	------	2410

The cone 9 firing ceased at approximately 2315°.

The cone 10 firing ceased at approximately 2355°.

The cone 11 firing ceased at approximately 2380°.

Method for Calculating the Analysis of Variance from Table 2.

Correction Term $= C = \dfrac{(10,398)^2}{72} = 1,501,644.5$

Total Sum of Squares $= \sum \left[(169)^2 + (173)^2 + \ldots\ldots + (139)^2 \right] - C = 17,585.5$

Sum of Squares for Replications $= \dfrac{\sum (2595)^2 + (2541)^2 + (2615)^2 + (2647)^2}{18} - C$
$= 329.9$

Table for Clays and Water Contents

Clays / W.C.	2	4	5	6	7	8	Total
10%	664	506	497	496	534	510	3207
12%	704	562	611	568	602	566	3613
14%	698	571	573	573	598	565	3578
Total	2066	1639	1681	1637	1734	1641	10,398

S.S. for Clays $= \dfrac{\sum (2066)^2 + \ldots\ldots + (1641)^2}{12} - C = 11,675.8$

S.S. for W.C. $= \dfrac{\sum (3207)^2 + (3613)^2 + (3578)^2}{24} - C = 4218.0$

Total S.S. for Clays & W.C. $= \dfrac{\sum (664)^2 + \ldots\ldots + (565)^2}{4} - C = 16,383.0$

Analysis of Var. for Clays & W.C.

Source of Variation	D/F	Sum of Squares
Clays	5	11,675.8
Water Contents	2	4218.0
Clays x W.C.	10	489.2
Total	17	16,383.0

Explanatory Note. The table for clays and water contents is formed by taking the sum of the replications. In the table for the analysis of variance for clays and water contents. the interaction term is determined by subtraction. It is now possible to make the complete analysis of variance table by placing in the table the variation due to replications, and determining the error S.S. by subtraction. See Table 7.