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Title POZZOLANIC PROPERTIES OF OREGON VOLCANIC ASH

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The use of pozzolanic materials as replacements for some portion of the portland cement in concrete has increased steadily, and currently, much interest is being shown in employing these materials in major concrete dam construction.

Proper usage of suitable pozzolans produces concrete having increased resistance to acid and alkali waters, lower heat of hydration, lower permeability, less water gain, and reduced expansion from chemical reaction between the portland cement alkalies and reactive aggregates. Using pozzolans also tends to reduce the demand for portland cement which has been taxing this nation's cement facilities.

This investigation has attempted to evaluate the pozzolanic properties of selected volcanic ash samples with a view toward possible commercial development of Oregon's deposits. The project was undertaken by the Engineering Experiment Station, Oregon State College, with the cooperation of the Raw Materials Survey, the State Department of Geology and Mineral Industries, and the Department of Mechanical Engineering, Oregon State College.

The criterion used for pozzolanic activity was compressive strength results of 2-inch mortar cubes in which ash replaced some portion of the portland cement. Eleven ash samples from throughout the State of Oregon were tested using each as a 10%, 20%, 30%, and 40% cement replacement, by weight. Specimens were prepared for testing at ages of 7 days, 28 days, 3 months, 6 months, and one year. A limited investigation was also made concerning the effects of cement alkalinity upon pozzolanic properties of certain samples. In all, 900 test specimens were made.

The compressive strength data from the 7-day, 28-day, 3-month, and 6-month tests have been processed and are included here. It was found that the portland cement-volcanic ash mortars exhibited pozzolanic properties in varying degrees, with all samples showing continued compressive strength gains with time at various replacements. To simplify comparisons as much as possible, most of the results are presented by means of strength ratios in which compressive strength data are compared to the strength of control specimens wherein no cement was replaced by volcanic ash.

Considering 6-month results at the 20 per cent replacement level, the two samples of most pozzolanic promise are P-8484, which developed 98 per cent of control strength, and P-8441, which was 97 per cent of control strength. The four next best materials are P-8480, P-8443, P-8479, and P-8442 which attained, respectively, 80 per cent, 79 per cent, 79 per cent, and 75 per cent of control strength. The remaining samples ranged from 50 per cent to 68 per cent, and of these, the two least favorable are P-8519 and P-8483.

A correlation was indicated between particle size and pozzolanic activity. Particle fineness determinations suggested that the two least favorable samples were of the smallest specific surface, while the two samples of most pozzolanic promise possessed the greatest specific surface. Of the most encouraging materials, at least two had been subjected to crushing before submission for test. This emphasizes the necessity for further study of crushing or grinding as a means of obtaining maximum pozzolanic values.

From the results of these tests and others made by the Bureau of Reclamation, it may be stated that deposits of Oregon volcanic ash have value as pozzolanic materials. Further research in this field seems extremely desirable in view of the tremendous quantities of these materials that might be used successfully in massive concrete construction in the Pacific Northwest.

# POZZOLANIC PROPERTIES OF OREGON VOLCANIC ASH

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### FOREWORD

Pozzolans are siliceous materials, natural or artificial, processed or unprocessed, which, though not cementitious in themselves, contain constituents that will, at ordinary temperatures, combine with lime in the presence of water to form compounds which have a low solubility and possess cementing properties (14, p53).

The use of pozzolans as replacements for some part of the portland cement in concrete has increased steadily, and currently, much interest is being shown in employing these materials in major concrete dam construction.

Proper usage of suitable pozzolans produces concrete having increased resistance to acid and alkali waters, lower heat of hydration, lower permeability, less water gain, and reduced expansion from chemical reaction between alkalies in the portland cement and reactive aggregates. Using pozzolans also tends to reduce the demand for portland cement which has been taxing this nation's cement facilities.

According to the Bureau of Reclamation,

> Use of pozzolanic admixtures will (1) permit standardization of portland cement to the extent that wide demand for special cements, such as low-alkali, sulfate-resistant, or low-heat types, will be decreased or eliminated; (2) more positive insurance against deterioration of concrete through cement-aggregate reaction or sulfate attack will be

obtained; and (3) the volume of portland cement required for construction of Bureau projects will be decreased, thus reducing the overwhelming load of demand upon the manufacturing plants. To elucidate the last point, it may be stated that the existing cement plants will not be able to supply cement required to fulfill anticipated construction schedules in Fiscal Year 1950 and Fiscal Year 1951, if the public demand is maintained at expected levels. If pozzolanic materials not requiring processing by facilities of cement plants can be used to replace 20 to 30 per cent of the normally required portland cement, the supply of cement may meet demands.

Because only a few sources of pozzolanic materials capable of fulfilling technical requirements are known in the United States, additional sources must be discovered before widespread use of portland-pozzolan cement is feasible (8, p3).

This investigation has attempted to evaluate the pozzolanic properties of 11 samples of Oregon volcanic ash with a view toward possible commercial development of this State's extensive ash deposits.

The project was undertaken by the Engineering Experiment Station, Oregon State College, with the cooperation of the following:

1. Raw Materials Survey
2. Oregon State Department of Geology and Mineral Industries
3. Department of Mechanical Engineering, Oregon State College
4. Individual submitters of test material.

# INTRODUCTION

## Historical Development of Pozzolan Cements

Although cements have been used in construction for several thousands of years, remarkable results were obtained in earlier structures without the aid of any cementing material. In prehistoric megalithic structures and in the Cyclopean masonry of Greece, use was made of earth walls rammed in successive layers or of stone blocks set one above another. Even though stable because of the heavy masses involved, Cyclopean work gave place to masonry or brickwork erected with the use of some plastic cementing agent.

Our present-day system of uniting blocks and slabs of stone with a sand and cement mortar is found in the massive masonry constructions of the Egyptians. Although generally described as "burnt lime," the Egyptian cementing material has been shown by chemical examination to be calcined gypsum (5, p2).

During the Greek and Roman periods, calcined limestone was widely used as a cementing agent, and it was later learned that certain volcanic deposits, if finely ground and mixed with the lime and sand, yielded a mortar which possessed superior strength, hardened under water, and resisted the agressive action of fresh or salt water.

For this purpose, the Greeks employed a volcanic tuff from the island of Santorin, while the Roman builders extensively used the volcanic ash found near Pozzuoli, Italy. This latter substance has acquired the name "pozzolan," a general term now considered to include many similar materials. These materials differ from cements in that they will not react singly with water to form cementing compounds.

Tributes to the Roman pozzolanic materials and workmanship are the existing Pantheon, Colosseum, Basilica of Constantine, and other structures which have well withstood the exposure of 2000 years.

The development of natural cements and portland cements in the nineteenth century encouraged greater use of concrete in construction. In Germany, France, Italy, and other European countries there is a widespread use of blended cement composed of a pozzolan and portland cement. This portland-pozzolan cement is extensively used in marine and hydraulic structures, rendering them more resistant to action of aggressive waters and less permeable to the passage of moisture.

An early example of the use of portland-pozzolan cement in the United States is the Los Angeles aqueduct completed in 1912, where a pozzolan replaced 50 per cent, by volume, of the required 1,500,000 barrels of cement. In 1935, 600,000 barrels of portland-pozzolan cement were used in the Bonneville Dam spillway. This cement consisted of 75 per cent portland cement interground with 25 per cent calcined pozzolan. Other major uses of portland-pozzolan cement were made in the Golden Gate and San Francisco Bay Bridges. It was especially valuable here because of its resistance to alkali soils and sulfate waters. In the Friant Dam, on the San Joaquin River in California, it was used economically since land acquired for reservoir right-of-way included a deposit of naturally fine pumicite. Twenty per cent pumicite, by weight of cement, was batched separately at the mixer in the 1,750,000 cubic yards of concrete required. Altus Dam, in Oklahoma, used a pozzolan as a 35 per cent replacement, by weight, of the cement content needed. Davis Dam is being built on the Lower Colorado River in a locality where all nearby deposits contain aggregate which appear chemically reactive. A portland-pozzolan cement is therefore being utilized to control reactive expansion. In Hungry Horse Dam, now under construction in western Montana, between 30 and 40 per cent of the portland cement is being replaced by a fly ash pozzolan. In addition to yielding a better concrete, this replacement is expected to result in considerable savings (7, pp17,19,21,26).

## Pozzolanic Materials

Materials used as pozzolans may be divided into several major groups as follows: (1) Those derived from volcanic rocks in which the amorphous constituent is a glass produced by fusion--(volcanic ash, pumicite, pumice, obsidian, scoria, and tuffs); (2) Those derived from rocks or earth in which the silica component contains opal either from precipitation of silica from solution or from the remains of organisms--(diatomaceous earth, chert, shale and certain clays); and (3) Industrial by-products--(fly ash, blast furnace slag, and powdered brick).

In this investigation, the materials tested for pozzolanic activity were samples of Oregon volcanic ash. The origin of this ash and other pumiceous materials would appear pertinent here.

Nearly all geologists agree that a heavy basaltic material exists beneath the ocean floors and under the continents, and it is this basaltic shell, when converted to a pasty liquid called magma, that constitutes the source of all the lavas and ashes erupted by volcanoes.

Once the magma is produced, it tends to rise to the surface and comes to occupy reservoirs at depths of a few miles beneath the earth's surface which then act as feeding chambers for most volcanoes. Crystallization of the magma commences with none of the early forming crystals abstracting gas from the magma. The residual liquid becomes increasingly charged with volatile ingredients until the concentration is such that the gas can no longer be held in solution. Bubbles then form, and the magma starts to effervesce. The pressure becomes excessive against the reservoir roof, and the frothy magma blasts a passage to the surface, exploding violently into showers of volcanic ash and pumice. The heavier material descends around the volcano while the lighter material may be windborne for miles.

The Pacific Northwest enjoys a rich volcanic history. Even in early Eocene time (60 million years ago) a few thick flows of pasty lava were discharged from volcanoes in eastern Washington (15, p15). Since this time, Oregon has been the recipient of colossal amounts of volcanic material either explosively erupted from cones, or discharged quietly through swarms of vertical fissures. An example of the latter quiet lava flow is the Columbia River basalts covering about 250,000 square miles of the Pacific Northwest.

Other remaining evidences of major volcanic activity are the Cascades, with Mounts Shasta, Jefferson, Hood, Adams, St Helens, Rainier, and Mazama. Probably no single volcanic event in Oregon was more dramatic than the decapitation of Mount Mazama approximately 10,000 years ago. The rapid eruptions of many cubic miles of pumice from the reservoir beneath this volcano withdrew support, led to the engulfment of the summit, and resulted in the famed scenic spot of Crater Lake.

Oregon's landscape is changing endlessly. The few instances of volcanic activity cited here, together with the countless thousands of volcanoes that have reared their heads, lived, died, and vanished, have all contributed to the extensive deposits of volcanic ash and pumice found in this State.

## Advantages of Pozzolans

Many beneficial results may be obtained by the use of a suitable pozzolan as a replacement for approximately 10 to 30 per cent, by weight, of the portland cement in a mix. Several examples of economy already have been cited. Other features that will be briefly discussed are heat of hydration, permeability, grindability, workability, bleeding and segregation, alkali-aggregate reaction, resistance to aggressive waters, and strength.

The problem of heat generation and dissipation in large, massive structures is an important one. Cements which generate less heat of hydration are distinctly advantageous in mass concrete construction, because they minimize the temperature rise and subsequent cooling which, in turn, effect thermal volume changes and frequently produce internal cracks. Davis and others (3, p112) found that portland-pozzolan cements generate less heat than the portland cements, with the reduction in heat generation roughly proportional to the amount of pozzolan. They learned also that a larger proportion of the heat is generated at the early ages for portland-pozzolan cements than for portland cements.

Concerning permeability, Davis (1, p12) states that available investigations exhibit similar trends; for lean mixes such as employed in mass construction, a suitably fine pozzolan used as a moderate to high cement replacement will lead to a degree of water-tightness not otherwise obtainable. This is also borne out by investigations at the University of California by Davis and others (3, p98) which show that a portland-pozzolan cement exhibits far greater resistance to the percolation of water than does a medium-lime or low-lime portland cement.

With regard to grindability, there is an apparent agreement among investigators that with few exceptions, the portland-pozzolan cements are more grindable (and finer) than the portland cements with which the pozzolans are blended, when ground under like conditions for equal periods of time (11, p75).

Pozzolans have been generally observed to increase the workability of the concrete in which they are utilized. One of the best pozzolans in this respect is fly ash, probably due to its spherical particles acting as ball-bearings and thus reducing friction.

The tendency toward bleeding and segregation is characteristically decreased in a mortar or concrete when pozzolan is used as a cement replacement. The improvements in these properties are more pronounced in lean mixes than in rich ones, and the degree of improvement is greatly affected by the character and fineness of pozzolan as well as by the percentage of replacement (1, p7).

Considerable research has been done recently upon cement-aggregate reaction and its resulting excessive expansion in concrete structures. Comprehensive results compiled by Stanton (13, p179) appear to justify the conclusion that a permanent correction for expansive reaction may be obtained with a suitable pozzolan. Investigations by Scholer and Peyton (12, p31), and Lerch (6, p153) similarly emphasize that abnormal expansion and pattern cracking may be avoided or minimized with proved pozzolanic materials. In general, the pozzolans high in opal have been found more effective than pumicite or fly ash in this respect.

Regarding reaction to aggressive waters, Davis, Hanna, and Brown (2, p131) have found that certain pozzolans materially improve resistance to sulfate action. This improvement is large for cements high in tricalcium aluminate. Finely divided diatomites appear most effective in this respect followed by the pozzolans high in glass, such as pumicite. Generally speaking, the higher the amount of replacement, the greater the resistance to disintegration by sulfate action (1, p12).

Insofar as strength considerations are concerned, it appears that for lean mixes and active pozzolans, the compressive strength of concrete at later ages is equal to or greater for the portland-pozzolan cements than for the corresponding portland cements. However, for richer mixes the compressive strength of concrete is less for the portland-pozzolan cements than for the corresponding portland cements.

The foregoing statements illustrate, to a limited extent, the potentialities of using portland-pozzolan cements in massive concrete construction, and perhaps helps justify pozzolanic research.

## Pozzolanic Activity

Description. As portland cement hydrates, calcium hydroxide (hydrated lime) is liberated. This compound contributes no strength to the concrete, is soluble in water and may be removed by leaching action (1, p4). A pozzolan will react with the calcium hydroxide and is thought to replace it with a hydrous calcium silicate which is a cementitious compound of relatively low solubility. The result, then, is to add water-tightness and strength to the concrete. The increase of strength, however, is generally not apparent until later ages.

Evaluation. The chemistry of the pozzolanic action is not fully understood. As a result, it is very difficult to establish criteria which definitely evaluate a pozzolan without relying upon extensive long-time tests. The evaluation of pozzolans' quality is further complicated by the fact that, in themselves, they have no cementitious properties and, for strength characteristics, must be tested in combination with lime or portland cement. However, strength tests because of their direct application to the uses of pozzolans are generally considered the most satisfactory (10, p109), and are the evaluating means used in this investigation.

Following is a brief treatment of other methods sometimes employed in the attempt to determine a pozzolan's worth. These are chemical analysis, solubility studies, lime absorption, and optical methods.

A chemical analysis performed upon a pozzolan will yield its percentages of silica and alumina which are generally considered the active portions. However, no correlation has been shown between the analysis and the activity (10, p110).

Solubility studies attempt to relate the activity to the amount of material soluble in various acid or alkali solutions. In discussing Lea's work on this subject, Moran and Gilliland state that the determination of soluble $SiO_2$ and $R_2O_3$ has some value in comparing materials of the same type, but does not indicate the quality of pozzolans as a whole (10, p110).

Since a pozzolan will combine with lime, the measurement of the rate of reduction of the free lime content of a pozzolan mortar would appear to yield an indication of the activity of the pozzolan. The determination of free lime content in mortars is difficult, however, and subject to rather large errors. Another method is to measure the rate of fall of electrical conductivity of a lime solution in which the pozzolan has been immersed. From this rate may be calculated the lime removal rate which is then taken as a measure of the pozzolan's activity.

Information may also be gained by optical methods. A petrographic analysis will identify and estimate amounts of the constituents which are thought to contribute to pozzolanic activity. This analysis also reveals weathering and alteration of natural pozzolans which may affect their chemical activities.

The x-ray diffraction pattern is a new technique useful in evaluating pozzolans. It is adapted particularly to identification and study of crystalline materials. While the pattern of a glassy pozzolan is of little value in identifying the effective constituent, it will predict the behavior of this constituent as a pozzolan and indicate its effectiveness in reducing expansion of mortar or concrete resulting from alkali-aggregate reaction (10, p128).

Influencing Factors. Some of the various factors considered influential in the development of pozzolanic activity are richness of mix, intimacy of mix, curing conditions and times, percentage of replacement, type of pozzolan, type of cement, calcination, and particle size.

With respect to richness of mix, many investigators agree that pozzolanic activity decreases as the richness of mix increases. According to the Bureau of Reclamation, compressive strength of portland-pozzolan concrete usually is lower at early ages than that of portland-cement concrete, but at later ages, the strengths are comparable (within 10 or 15 per cent), or for lean mixes are higher (8, p2).

Intergrinding of pozzolan and portland cement has been shown to materially increase the interaction of the two materials and to improve the properties of the combination. This is attributed to a more intimate mixture of the materials (11, p80).

Davis, Hanna, and Brown (2, pp133-138) investigated volcanic glasses in their studies. They found that under wet storage conditions, control mortar specimens composed of ordinary portland cement exhibited substantial retrogression in strength with time, while pozzolan cement mortars using volcanic glasses continued to increase in strength throughout a five-year test period. The volcanic glasses also showed the highest rate of increase in compressive strength ratio (portland-pozzolan cement to straight portland cement control) between seven days and ten years. The highest compressive strength ratios at the age of ten years were produced by volcanic glasses and opaline shales.

Temperature is thought to affect the rate of pozzolanic reaction more than it does the rate of hydration of normal portland cement. The reaction is accelerated to a greater degree by high temperatures and retarded to a greater degree by low temperatures. Therefore, curing temperatures may affect compressive strength results obtained.

In regard to the effects of varying replacements, it is generally agreed that, regardless of the type of pozzolan, the greater the amount of replacement the less the strength ratio at early ages. The optimum replacement varies with the material but usually ranges from 10 to 30 per cent, based on the weight of portland cement-pozzolan mixture.

The type of pozzolan used greatly affects the resulting pozzolanic activity. A general agreement among various investigators shows that the materials of diatomaceous origin are the most active, followed in order by the volcanic silicas, clays, and siliceous rocks.

Pozzolanic activity arises from the reaction of calcium hydroxide and the active ingredients of the pozzolan, and the quantity of calcium hydroxide available is, in turn, dependent upon the composition of the portland cement used. Cements high in tricalcium silicate liberate more calcium hydroxide during their hydration than do those lower in tricalcium silicate. In general, then, larger replacements may be employed for a type I or type II cement than for a type IV cement (1, p7). A high-lime clinker in portland-pozzolan cements also results in greater benefits.

Heat treatment of natural pozzolans is an important process in the development of satisfactory pozzolanic properties. The reactivity of some materials with the constituents of hydrating portland cement is greatly increased by calcination at certain temperatures, but with some pozzolans, calcination has either no significant beneficial effect or a detrimental effect. However, for pozzolans whose active ingredient is volcanic glass, calcination has proven helpful. For these materials, compressive strength results of portland cement-pozzolan mortars increase with temperature of calcination usually attaining highest values after calcination at 1000 F to 1600 F (9, p63).

Particle size of a pozzolan may be related to the activity evidenced. Davis and Klein (4, p96) in their investigations have shown that, for constant flow, concretes with very fine diatomite exhibit early and later-age compressive strengths greater than for concretes containing the same weight replacement of coarser diatomite. One of the effects of calcining may be the resulting changes in fineness induced by shattering or sintering of the particles. Lea and Desch (5, p261) show that with lime-pozzolana mortars, the mortar using a 43 per cent residue on 170 mesh sieve attains only half the 28-day compressive strength of the mortar using a three per cent residue on the same sieve.

It is generally considered that the reaction between cement and water takes place only at the surface of the solid particles. Therefore, the more finely ground the cement, the greater will be the exposed surface in proportion to mass, and the greater will be the proportion of cement which reacts. The foregoing tends to support the theory that associates particle size and pozzolanic activity.

# SCOPE

This investigation has attempted to evaluate the pozzolanic properties of 11 different samples of Oregon volcanic ash. This was done by obtaining compressive strengths of two-inch mortar cubes in which ash replaced a portion of the portland cement. These strengths were then compared to strengths of control cubes in which no ash replaced portland cement. For each sample of ash tested, cubes were molded with 10, 20, 30, and 40 per cent of the portland cement (by weight) replaced by ash. Specimens were prepared for testing at ages of seven days, 28 days, three months, six months, and one year. Together with control specimens, this resulted in a total of 900 specimens.

Particle size determinations were made for each sample by the hydrometer method to determine whether strength results might be associated with fineness of material used.

A limited investigation was also made of the influence of cement alkalinity upon pozzolanic activity. An encouraging sample and a poor sample (on the basis of 28-day results) were thus tested using cements of high and low alkalinity.

This thesis concerns itself with the seven-day, 28-day, three-month, and six-month test results. At the completion of the one-year tests, a report will be written encompassing the results of the entire investigation.

## MATERIALS AND APPARATUS

The four constituents of the mortar cubes were volcanic ash, portland cement, Ottawa sand, and tap water.

The ash samples were secured and submitted by the Portland Office, Oregon Department of Geology and Mineral Industries. Preliminary petrographic descriptions and locations of the samples may be found in the Appendix.

Three types of portland cement were employed. All ash samples were first used with Type I general purpose cement. In addition, two cements of varying alkali content were obtained from the Portland Cement Association. Cement No. 13 has the following alkali content: 0.04 per cent $Na_2O$, 0.19 per cent $K_2O$, and 0.17 per cent total as $Na_2O$. Cement No. 18168 has the following alkali content: 0.20 per cent $Na_2O$, 0.97 per cent $K_2O$, and 0.84 per cent total as $Na_2O$. The latter two cements were used with only certain samples of ash.

The aggregate was standard graded Ottawa sand.

The mixing of the mortar was accomplished by the use of an aluminum bowl of five-quart capacity, a large stirring spoon, and a rubber glove. Water was measured and added by a 1000 ml graduate. Consistency was determined by using a flow table with a one-half inch drop and a flow mold of four-inch inner-base diameter. Standard two-inch gang molds, in units of three, were utilized in the molding operation. A small section of wax-impregnated wood, ½" x 1" x 4", was used as a tamper, and a trowel served to strike off the molds.

The cement, volcanic ash, and Ottawa sand were weighed by means of a Toledo scale No. 19076Y.

An electrically driven Abbe jar mill, approximately 12 inches in diameter and 12 inches long was employed to inter-mix the ash and cement. The charge was 1480 g of smooth flint pebbles ranging in size from four to 16 cubic centimeters. An automatic timing mechanism permitted runs of constant duration.

After twenty-four hours in a moist cabinet, the specimens were removed from the molds, marked with waterproof yellow crayon, and placed in slowly moving water in a fog curing room. The room temperature was 71 F.

In the particle size determinations the following items were used: A Taylor water hydrometer calibrated in grams of soil colloids per liter; assorted beakers and graduates; a constant temperature water bath; a dispersion cup and shaker; distilled water; thermometer; an analytical balance; an oven operating at 280 F; the following Tyler standard sieves: 14, 20, 40, 65, 150, and 200; and a Rotap sieving machine equipped with automatic timer.

For the testing of specimens, a 60,000 lb Southwark-Emery hydraulic testing machine, No. 68515, was employed until its removal from the Engineering Laboratory. Henceforward, a 30,000 lb Tinius Olsen screw-gear testing machine, No. 9288, was used. Most of the three-month results were obtained on the hydraulic machine, and all of the six-month tests were conducted upon the Olsen machine.

## PROCEDURE

### Mixing

As a guide for the mixing procedure, ASTM C 109-44, Compressive Strength of Hydraulic-Cement Mortars, was followed where possible. In this respect, a constant weight ratio (1:2.75) of cement mixture (portland cement plus volcanic ash) to Ottawa sand was employed while adding enough water in each mix to yield a constant flow (100 to 115 per cent).

Since it was desired to determine the pozzolanic properties of each sample as received, the sample preparation consisted only of screening and using that portion which passed a No. 14 sieve.

It was known that 1200 g of cement mixture (volcanic ash plus portland cement), 3300 g of sand, and the necessary water would yield the mortar required for 15 cubes. For the first replacement of the first sample, then, 10 per cent of the total cement mixture, or 120 g, was ash. The remaining 90 per cent, or 1080 g, was portland cement. These materials were weighed on the Toledo scale and placed in the jar mill together with the charge of flint pebbles. The mill was then set to operate for 21½ minutes, through use of the timing mechanism. This resulted in 1000 revolutions.

During the mill's operation, the gang molds were prepared for use. After a thorough cleaning, the component parts of the molds were lightly oiled, assembled, and sealed at the base with melted paraffin.

At the completion of the mixing operation, the cement mixture was removed and placed in a pan for use. It was noticed at this time that there was apparently some reduction in size of larger ash particles. However, it was felt that this mixing operation would simulate, to some extent, the particle size reduction a similar material would experience in a normal, commercial mixing operation.

A 1000 ml graduate was filled with water, and 3300 g of Ottawa sand was weighed on the Toledo scale and placed in a pan for use. The rubber glove and the interior of the mixing bowl were wiped with a damp cloth.

The mixing then commenced. An amount of water, estimated to be somewhat less than that required, was added to the bowl. The total cement mixture was introduced, and the bowl's contents were stirred with the large spoon for one minute. Approximately half of the sand was then added, and the mixing continued for one minute, accomplished by a kneading action with one hand enclosed in a rubber glove and by the spoon-stirring action. The remaining sand was then placed in the bowl, and the same kneading and stirring action took place for two and one-half minutes.

During this latter operation, water was added if it appeared necessary. The flow mold was then half filled with mortar, tamped twenty times with the prepared tamper, entirely filled, tamped twenty times, and then struck off evenly with a trowel. One minute was devoted to this operation, that is, from the completion of the mixing until the flow mold was raised. After removing the mold, the flow table was dropped twenty-five times in 15 seconds. If the flow was greater than the permitted maximum of 115 per cent, the mix was discarded. In instances where the flow was less than 100 per cent the trial batch was returned to the bowl, water was added, and the bowl's contents were thoroughly mixed after which the flow test was again made. If the required flow was not obtained in two trials, the mix was discarded.

The water requirement was recorded after the proper flow was obtained, and the prepared gang molds were filled as stipulated in ASTM C 109-44. All molds were half filled and tamped thirty-two times in 10 seconds. The molds then were filled, and the tamping procedure repeated. The molds were struck off evenly with a trowel, and after being marked, were placed in a moist closet for twenty-four hours. At the end of this time, the cubes were marked, removed from the molds, and placed under water in the fog curing room to await testing.

This procedure was followed in the mixing, molding, and curing of all 11 samples.

On the basis of 28-day strength results for the 10 per cent replacements, sample P-8441 appeared promising. This sample was therefore re-tested using both a high alkali cement and a low alkali cement to learn the effects of cement alkalinity upon pozzolanic properties. Upon the same basis, sample P-8444 appeared discouraging. This sample was accordingly investigated using a high alkali cement. The mixing procedure in the alkalinity test duplicated that already described.

## Testing

Samples were transported from the curing room to the testing machine in a container of water and were kept submerged until the time of test. With the machine in readiness, the specimens were wiped dry with paper towels, measured, and tested in compression on two plane sides until failure. Using the hydraulic machine, load was applied at an average rate of 12,000 lb per square inch per minute. With the screw-gear machine, the tests were conducted at the slow-back speed of 0.04 inches per minute. The ultimate loads were recorded.

## Determining Particle Size

The evaluation of fineness was complicated by the physical mixing of ash and cement that had taken place in the jar mill. Since some of the ash particles had been reduced in size by this operation, a true picture of the effective particle size could be obtained only following the inter-mixing. The ash-cement mixture obviously could not be used with a hydrometer whose calibration depended upon the use of water as the medium. Ultimately, the decision was made to process 1200 g of ash (the weight of original ash-cement mixture) in the jar mill under the same conditions employed before, and to perform the analysis upon this. While the fineness results obtained in this manner may not reflect the true ash condition as it entered the mix, the results should serve well to yield a relative comparison of fineness between samples.

The procedure followed was that stipulated by ASTM D422-39, Mechanical Analysis of Soils.

In the determination, 1200 g of material that had passed the No. 14 sieve was jar milled and quartered. Sixty-five grams were then weighed out and recorded. Of this, a 10 g quantity was dried in the oven at 280 F to learn the hygroscopic moisture content. The remaining quantity of 55 g was placed in a beaker with 200 ml of distilled water to stand for at least 18 hours. The sample was then washed into a dispersion cup, and distilled water was added. Twenty milliliters of a deflocculating agent (sodium silicate) were added, and the contents were mixed in a shaker for one minute. The mix was transferred to a graduate, and distilled water was added until the total volume was 1000 ml. The graduate was placed in the water bath until temperatures were constant. The graduate was then removed, shaken for one minute and replaced in the bath, with the time being noted. Hydrometer readings and water bath readings were then taken at one minute, two minutes, five minutes, 15 minutes, 30 minutes, 60 minutes, 250 minutes and 1440 minutes.

After the final readings, the graduate's contents were washed on a No. 200 sieve. The material retained on the 200 sieve was dried in the oven. A sieve analysis was performed on this material using sieve Nos 20, 40, 65, 150, and 200 and a Rotap sieving machine adjusted to operate for five minutes. Material remaining on each sieve was weighed on an analytical balance. The required calculations were then performed and particle size distribution curves were plotted.

# RESULTS

In processing the results for this investigation, compressive strengths were obtained by averaging test values for three mortar cubes of each mix. If any of the three values varied by more than 10 per cent from the computed average, it was discarded, and the average of the remaining two results was then used. This is in accordance with ASTM C 109-44. The described variation occurred twenty-two times in 240 cases. To simplify comparisons as much as possible, most of the results are presented and discussed by means of strength ratios in which compressive strengths are compared to the strength of control specimens wherein no cement was replaced by volcanic ash.

In evaluating these findings, it should be realized that they are based upon mortars and do not necessarily apply to concretes. Also, the tests were conducted upon small specimens and may not be representative of the conditions encountered in massive structures. Furthermore, it should be kept in mind that this test's basis has been a strength comparison of mortars with equal flow and not equal water-cement ratios. The value of these results should be in portraying a qualitative rather than quantitative comparison of the 11 samples tested for pozzolanic activity.

Tables A, B, C, and D--located in the Appendix--represent the average compressive strengths and strength ratios for all cement-ash mortars, including the cement alkalinity test. The strength ratios and other data pertinent to this study are presented in Table 1.

Except for the 10 per cent replacements, the strength ratios of Table 1 show a general increase with age as would be expected from the continued combining of calcium hydroxide and the pozzolan. At the 10 per cent replacement level, however, relatively little ash is available for combination, and it is thought that the strength increase due to pozzolanic action is probably insufficient to offset the normal strength retrogression with time that has been found characteristic of portland cement mortars cured under water (2, p131).

The figures shown in the column headed "ratio of water to cement plus ash" are not meant to be descriptive of the water-cement ratio of the mix since the ash materials probably had differing absorptive qualities, and no attempt was made to place the material in a saturated, surface-dry condition. This column is best interpreted as the water requirements for equal flow.

A general evaluation of the 11 ash samples has been made by investigating the strength gain of each at the

TABLE 1

PROPERTIES OF VOLCANIC ASH AS A POZZOLAN

| Volcanic Ash Sample[1] No. | Source | % Replacement[2] (by wt) | Portland cement used | Ratio of water to cement plus ash (by wt) | Estimated glass content (%) | Specific surface[3] ($cm^2/g$) | Compressive Strength Ratios[4] (%) 7-day | 28-day | 3 mo | 6 mo |
|---|---|---|---|---|---|---|---|---|---|---|
| CONTROL | | 0 | Type I | 0.60 | | | 100 | 100 | 100 | 100 |
| P-8441 | Terrill Silica Deposit, Oregon City | 10 | " | 0.61 | 60-70 | 5250 | 86 | 88 | 104 | 98 |
| | | 20 | | 0.63 | | | 61 | 79 | 90 | 97 |
| | | 30 | | 0.65 | | | 54 | 65 | 77 | 78 |
| | | 40 | | 0.66 | | | 36 | 43 | 58 | 66 |
| P-8442 | Salt Creek, Baker County | 10 | " | 0.59 | 75-85 | 2350 | 66 | 76 | 90 | 90 |
| | | 20 | | 0.62 | | | 53 | 61 | 76 | 75 |
| | | 30 | | 0.64 | | | 39 | 47 | 62 | 62 |
| | | 40 | | 0.67 | | | 32 | 39 | 54 | 59 |
| P-8443 | Chemult Area, Klamath County | 10 | " | 0.57 | 80-85 | 2650 | 83 | 86 | 99 | 95 |
| | | 20 | | 0.60 | | | 56 | 66 | 72 | 79 |
| | | 30 | | 0.61 | | | 40 | 46 | 57 | 62 |
| | | 40 | | 0.64 | | | 34 | 40 | 50 | 56 |
| P-8444 | Chemult Area, Klamath County | 10 | " | 0.61 | 85-90 | 2050 | 70 | 68 | 79 | 77 |
| | | 20 | | 0.62 | | | 43 | 50 | 66 | 65 |
| | | 30 | | 0.68 | | | 33 | 38 | 51 | 58 |
| | | 40 | | 0.73 | | | 26 | 31 | 39 | 42 |
| P-8451 | Near Tumalo, Deschutes County | 10 | " | 0.60 | 85-90 | 1650 | 58 | 75 | 85 | 78 |
| | | 20 | | 0.64 | | | 44 | 52 | 66 | 68 |

TABLE 1 (CONTINUED)

PROPERTIES OF VOLCANIC ASH AS A POZZOLAN

| Volcanic Ash Sample[1] No. | Source | % Replacement[2] (by wt) | Portland cement used | Ratio of water to cement plus ash (by wt) | Estimated glass content (%) | Specific surface[3] ($cm^2/g$) | Compressive Strength Ratios[4] (%) 7-day | 28-day | 3 mo | 6 mo |
|---|---|---|---|---|---|---|---|---|---|---|
| P-8451 (Continued) | | 30 | Type I | 0.66 | | | 32 | 37 | 49 | 52 |
| | | 40 | | 0.71 | | | 22 | 27 | 36 | 43 |
| P-8479 | Carlton Pumice Pit, Jackson County | 10 | " | 0.63 | 60-65 | 2400 | 69 | 77 | 88 | 81 |
| | | 20 | | 0.67 | | | 55 | 64 | 70 | 79 |
| | | 30 | | 0.69 | | | 38 | 45 | 53 | 62 |
| | | 40 | | 0.73 | | | 21 | 30 | 39 | 42 |
| P-8480 | Carlton Pumice Pit, Jackson County | 10 | " | 0.60 | 60-65 | 2350 | 67 | 70 | 81 | 86 |
| | | 20 | | 0.64 | | | 57 | 60 | 73 | 80 |
| | | 30 | | 0.68 | | | 38 | 42 | 54 | 57 |
| | | 40 | | 0.75 | | | 26 | 29 | 44 | 43 |
| P-8481 | Carlton Pumice Pit, Jackson County | 10 | " | 0.64 | 70-80 | 2150 | 82 | 80 | 91 | 87 |
| | | 20 | | 0.65 | | | 50 | 53 | 64 | 68 |
| | | 30 | | 0.70 | | | 34 | 46 | 51 | 58 |
| | | 40 | | 0.76 | | | 20 | 30 | 35 | 40 |
| P-8483 | Sleeper Pit, Near Bend | 10 | " | 0.61 | 85 | 1190 | 62 | 73 | 83 | 82 |
| | | 20 | | 0.66 | | | 43 | 47 | 51 | 59 |
| | | 30 | | 0.70 | | | 26 | 36 | 42 | 47 |
| | | 40 | | 0.75 | | | 18 | 25 | 30 | 31 |

TABLE 1 (CONTINUED)

PROPERTIES OF VOLCANIC ASH AS A POZZOLAN

| Volcanic Ash Sample[1] No. | Source | % Replacement[2] (by wt) | Portland cement used | Ratio of water to cement plus ash (by wt) | Estimated glass content (%) | Specific surface[3] (cm²/g) | Compressive Strength Ratios[4] (%) 7-day | 28-day | 3 mo | 6 mo |
|---|---|---|---|---|---|---|---|---|---|---|
| P-8484 | Sleeper Pit, Near Bend | 10 | Type I | 0.58 | 95 | 3160 | 69 | 86 | 97 | 108 |
| | | 20 | | 0.61 | | | 66 | 76 | 92 | 98 |
| | | 30 | | 0.65 | | | 50 | 67 | 88 | 96 |
| | | 40 | | 0.66 | | | 32 | 46 | 67 | 86 |
| P-8519 | Malheur County | 10 | " | 0.62 | 95+ | 1400 | 55 | 66 | 63 | 73 |
| | | 20 | | 0.68 | | | 48 | 57 | 46 | 50 |
| | | 30 | | 0.72 | | | 38 | 41 | 43 | 45 |
| | | 40 | | 0.79 | | | 21 | 25 | 30 | 31 |
| CONTROL | | 0 | High Alkali | 0.58 | | | 100 | 100 | 100 | 100 |
| P-8441 | Terrill, Silica Deposit, Oregon City | 10 | " | 0.59 | 60-70 | 5250 | 108 | 114 | 93 | 102 |
| | | 20 | | 0.60 | | | 88 | 97 | 87 | 91 |
| | | 30 | | 0.64 | | | 65 | 74 | 71 | 82 |
| | | 40 | | 0.69 | | | 37 | 45 | 50 | 61 |
| P-8444 | Chemult Area, Klamath County | 10 | " | 0.60 | 85-90 | 2050 | 99 | 100 | 83 | 84 |
| | | 20 | | 0.64 | | | 66 | 72 | 67 | 75 |
| | | 30 | | 0.68 | | | 46 | 58 | 52 | 54 |
| | | 40 | | 0.72 | | | 29 | 36 | 37 | 41 |

TABLE 1 (CONTINUED)

PROPERTIES OF VOLCANIC ASH AS A POZZOLAN

| Volcanic Ash Sample[1] No. | Source | % Replacement[2] (by wt) | Portland cement used | Ratio of water to cement plus ash (by wt) | Estimated glass content (%) | Specific surface[3] ($cm^2/g$) | Compressive Strength Ratios[4] (%) 7-day | 28-day | 3 mo | 6 mo |
|---|---|---|---|---|---|---|---|---|---|---|
| CONTROL | | 0 | Low Alkali | 0.58 | | | 100 | 100 | 100 | 100 |
| P-8441 | Terrill Silica Deposit, Oregon City | 10 | " | 0.60 | 60-70 | 5250 | 92 | 72 | 79 | 84 |
| | | 20 | " | 0.61 | | | 70 | 57 | 66 | 73 |
| | | 30 | | 0.69 | | | 52 | 46 | 56 | 64 |
| | | 40 | | 0.67 | | | 40 | 37 | 49 | 55 |

[1]More complete locations and petrographic descriptions will be found in the Appendix.

[2]Per cent replacements are by weight of cement-ash mixture.

[3]Determined by hydrometer.

[4]Ratio of compressive strength result to compressive strength of control specimens in which no cement was replaced by volcanic ash.

20 per cent replacement level. This is portrayed by the curves of Figure 1. As shown, two of the samples, P-8484 and P-8441, closely approach control strength at six months. Three others--P-8480, P-8479, and P-8443--exhibit encouraging rates of strength increase. P-8481 and P-8451 also continue to gain in strength although at slower rates. Extrapolation of the plotted curves would indicate that several of the samples may equal or surpass control strength at the end of one year. An inspection of the unprocessed yearly data supports this theory for samples P-8484, P-8441, P-8443, and P-8442.

The curve for sample P-8519 appears out of line when compared to the smooth trends evidenced by the remaining 10 samples. The three-month strength, especially, seems low. It may be significant to note that this material also possesses one of the two lowest specific surface values.

A comparison of selected samples may be seen in Figures 2, 3, and 4 which treat 10 per cent replacements, 20 per cent replacements, and 30 per cent replacements, respectively. The samples chosen for presentation here are the six strongest at the 20 per cent replacement level at the age of six months.

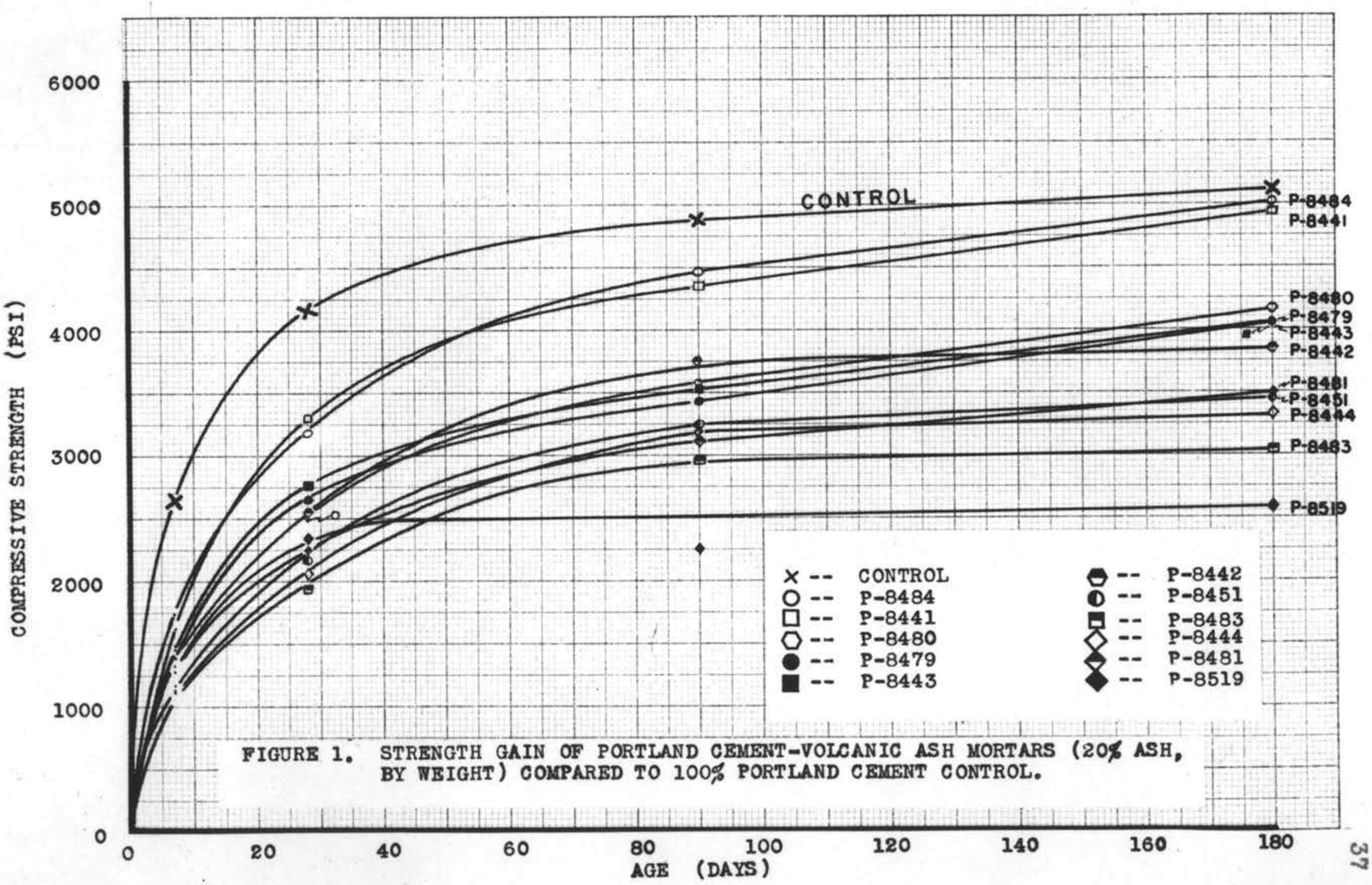


FIGURE 1. STRENGTH GAIN OF PORTLAND CEMENT-VOLCANIC ASH MORTARS (20% ASH, BY WEIGHT) COMPARED TO 100% PORTLAND CEMENT CONTROL.

Figure 2 shows P-8484 achieving 108 per cent of control strength and P-8441, 98 per cent of control strength. Also apparent is the retrogression of strength previously discussed. This phenomenon will be much less apparent at one year if evident at all, judging from the unprocessed yearly data. The control strength at this age appears to decrease while all six mortars have continued to gain in strength. The resultant effect is to increase the yearly strength ratios for the 10 per cent replacements and to swing the curves upward.

Figure 3, dealing with 20 per cent replacements, reveals samples P-8484 and P-8441 both approaching 100 per cent at six months. A steady strength increase is also indicated for the remaining samples with the exception of P-8442. Again, however, this sample increases in yearly strength ratio and all will probably exhibit steady upward trends when plotted with one year results.

There is, perhaps, not as much difference as might be expected between the 20 per cent replacement results of Figure 3 and the 10 per cent replacement results shown in Figure 2. At the 20 per cent level, the strength ratios vary from 75 per cent to 98 per cent while the 10 per cent strength ratios range from 81 per cent to 108 per cent.

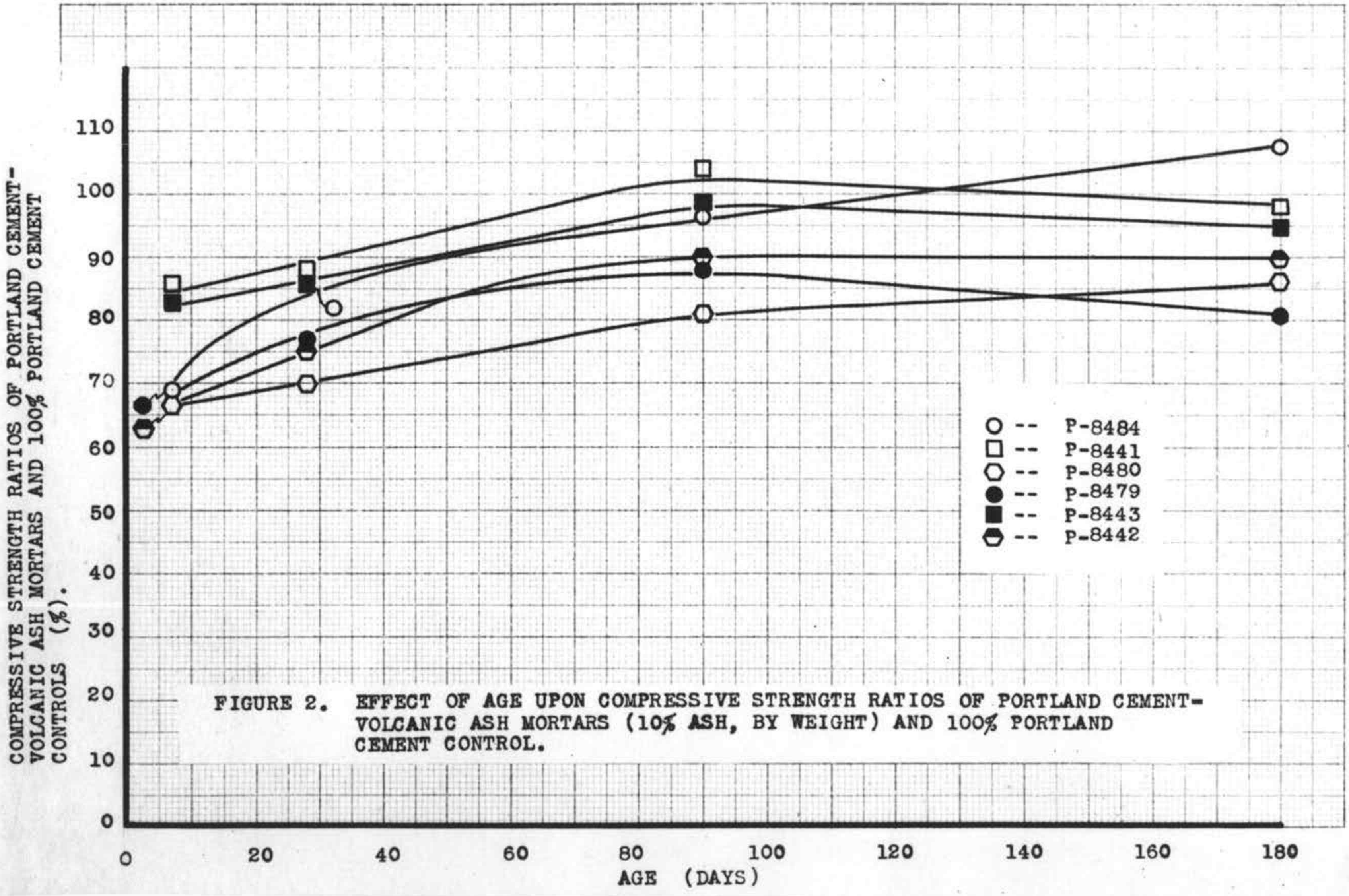


FIGURE 2. EFFECT OF AGE UPON COMPRESSIVE STRENGTH RATIOS OF PORTLAND CEMENT-VOLCANIC ASH MORTARS (10% ASH, BY WEIGHT) AND 100% PORTLAND CEMENT CONTROL.

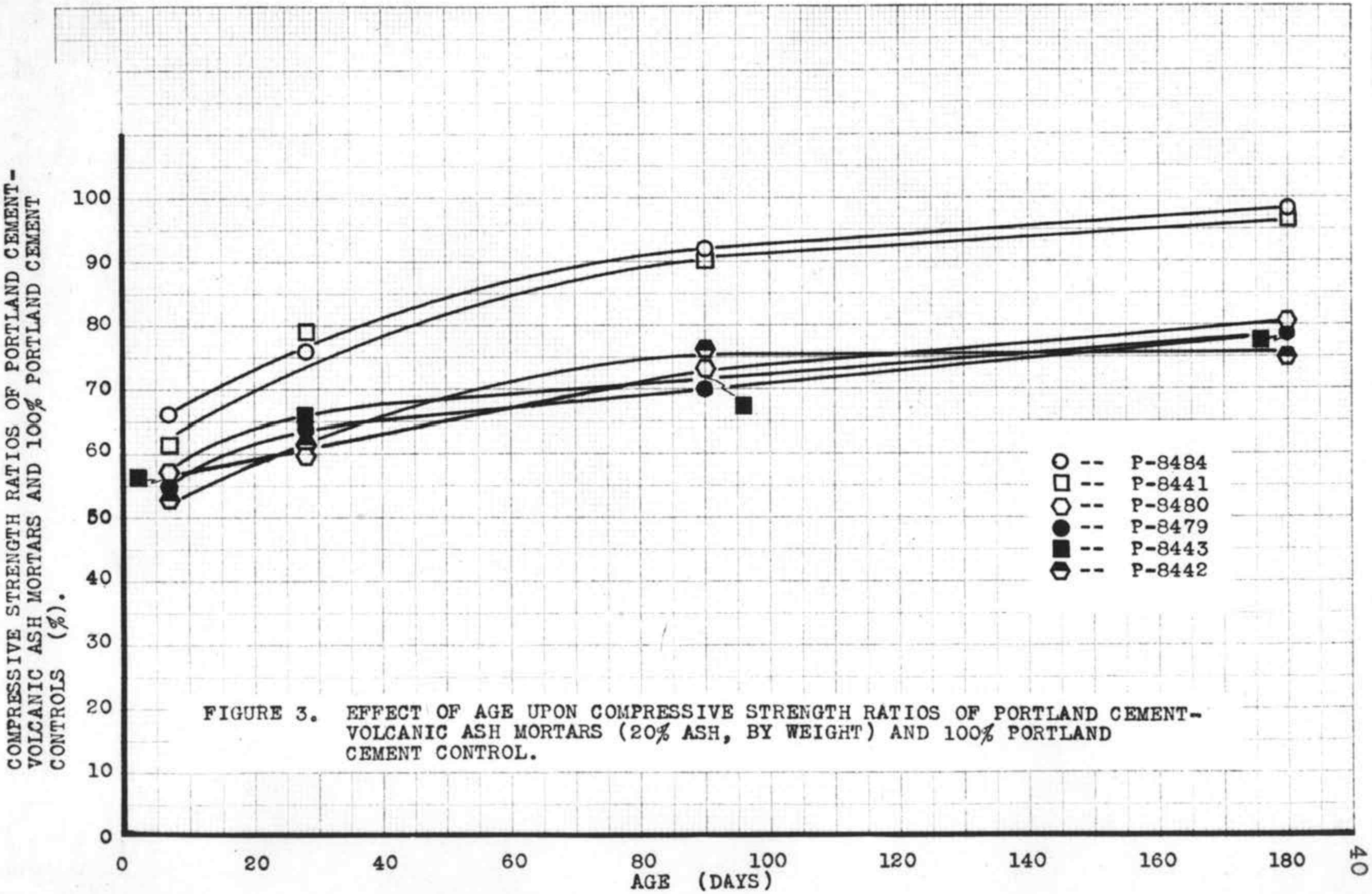


FIGURE 3. EFFECT OF AGE UPON COMPRESSIVE STRENGTH RATIOS OF PORTLAND CEMENT-VOLCANIC ASH MORTARS (20% ASH, BY WEIGHT) AND 100% PORTLAND CEMENT CONTROL.

Figure 4 concerns itself with the results of the 30 per cent replacements. Here, P-8484 and P-8441 continue to yield comparatively high strength ratios. P-8484 seems exceptionally strong, and at 40 per cent replacement, this sample attains 86 per cent of control strength. The remaining four curves appear well clustered--a result that was also apparent at the 20 per cent level but not at the 10 per cent replacement.

Considering Figures 2, 3, and 4 collectively, the curves for the 20 per cent replacements appear most promising as to continued gain in strength with time. It might also be stated generally that a greater strength advantage is seen from 30 to 20 per cent replacement than is apparent from 20 to 10 per cent replacement. P-8484 should be excepted from this observation, however, since it is relatively strong at all replacements used.

Figure 5 describes the effect of various cement replacements upon compressive strength ratios. The same six samples treated previously are included here. P-8484 shows an increase and then a decrease in strength ratio as portland cement is replaced with an equal weight of volcanic ash. P-8441 tends to remain nearly constant up to about 20 per cent replacement and then falls off with greater replacement. The remaining samples slope downward

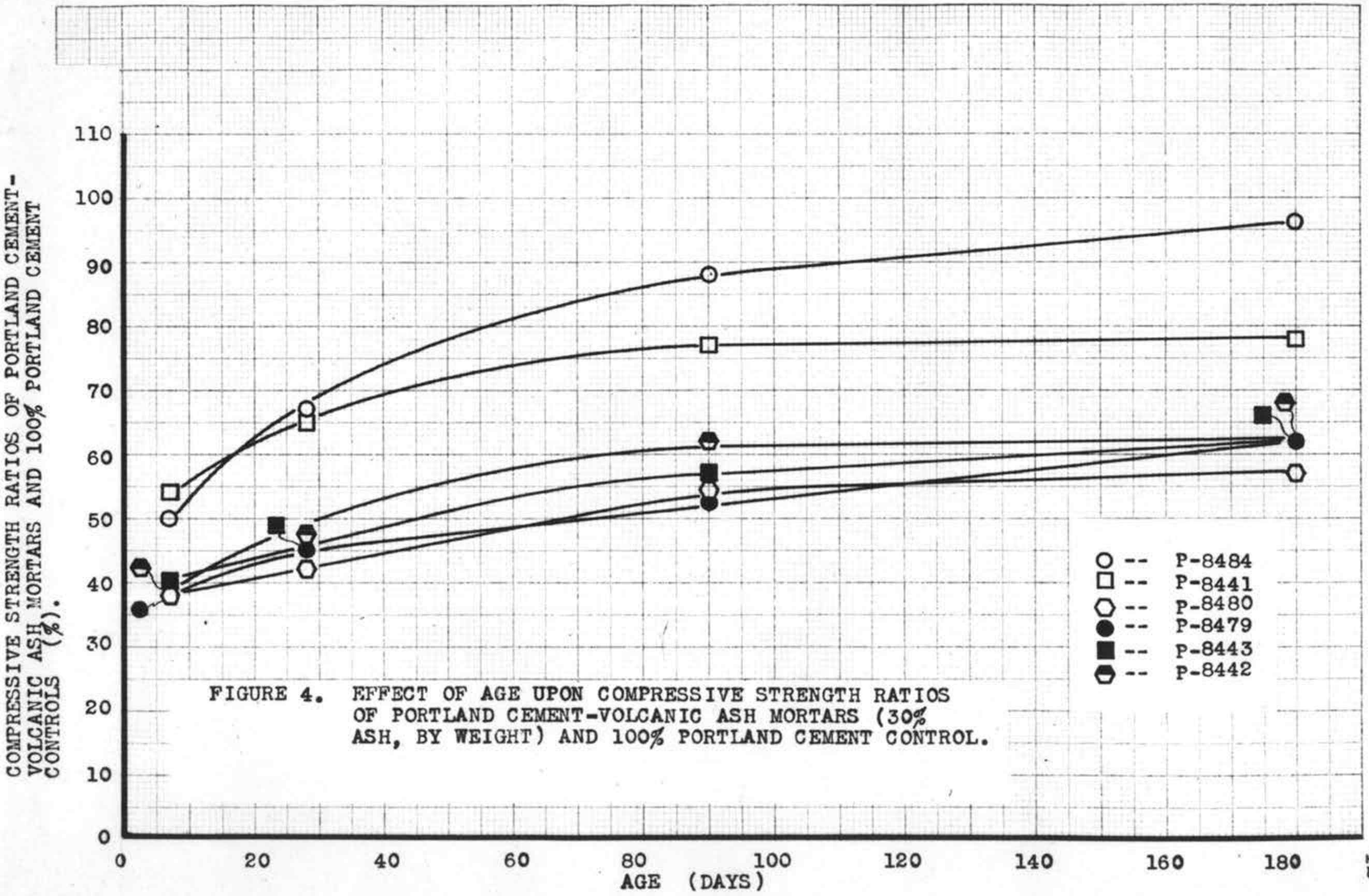


FIGURE 4. EFFECT OF AGE UPON COMPRESSIVE STRENGTH RATIOS OF PORTLAND CEMENT-VOLCANIC ASH MORTARS (30% ASH, BY WEIGHT) AND 100% PORTLAND CEMENT CONTROL.

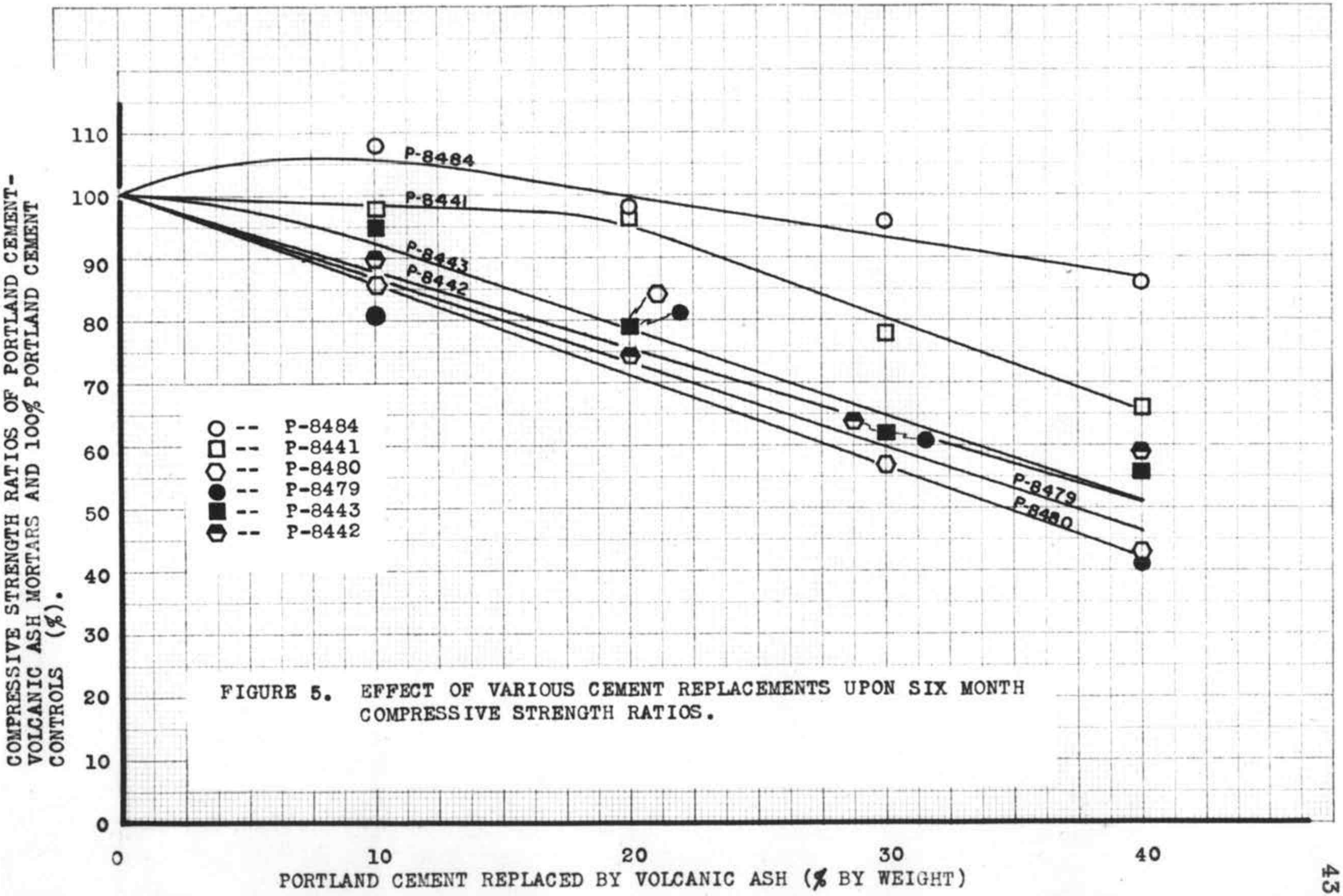


FIGURE 5. EFFECT OF VARIOUS CEMENT REPLACEMENTS UPON SIX MONTH COMPRESSIVE STRENGTH RATIOS.

sharply with increased replacement. At the 20 per cent level, the strength ratios for the four poorest samples shown are rather closely clustered as is the case also at the 30 per cent replacement. As the flatness of its curve testifies, sample P-8484 gives good results at large replacements; it attains 90 per cent of control strength at about 35 per cent replacement. The grouping of the curves for the lower samples pointed out earlier is also apparent here.

Figure 6 deals with the influence of cement alkalinity upon pozzolanic action. It is known that a cause of abnormal expansion and pattern cracking in concrete structures is the chemical interaction of the alkalies in portland cement and certain siliceous mineral constituents of aggregates. It is also known that some protection in this problem may be provided by limiting the alkali content of the cement or by employing certain pozzolanic materials. In this brief test it was desired to learn if the pozzolanic activity was increased by supplying greater quantities of alkali for combination with the reactive silica of the pozzolan. In the strength ratios for any one curve, the compressive strengths are related to the strength of a control made from cement of the corresponding alkalinity.

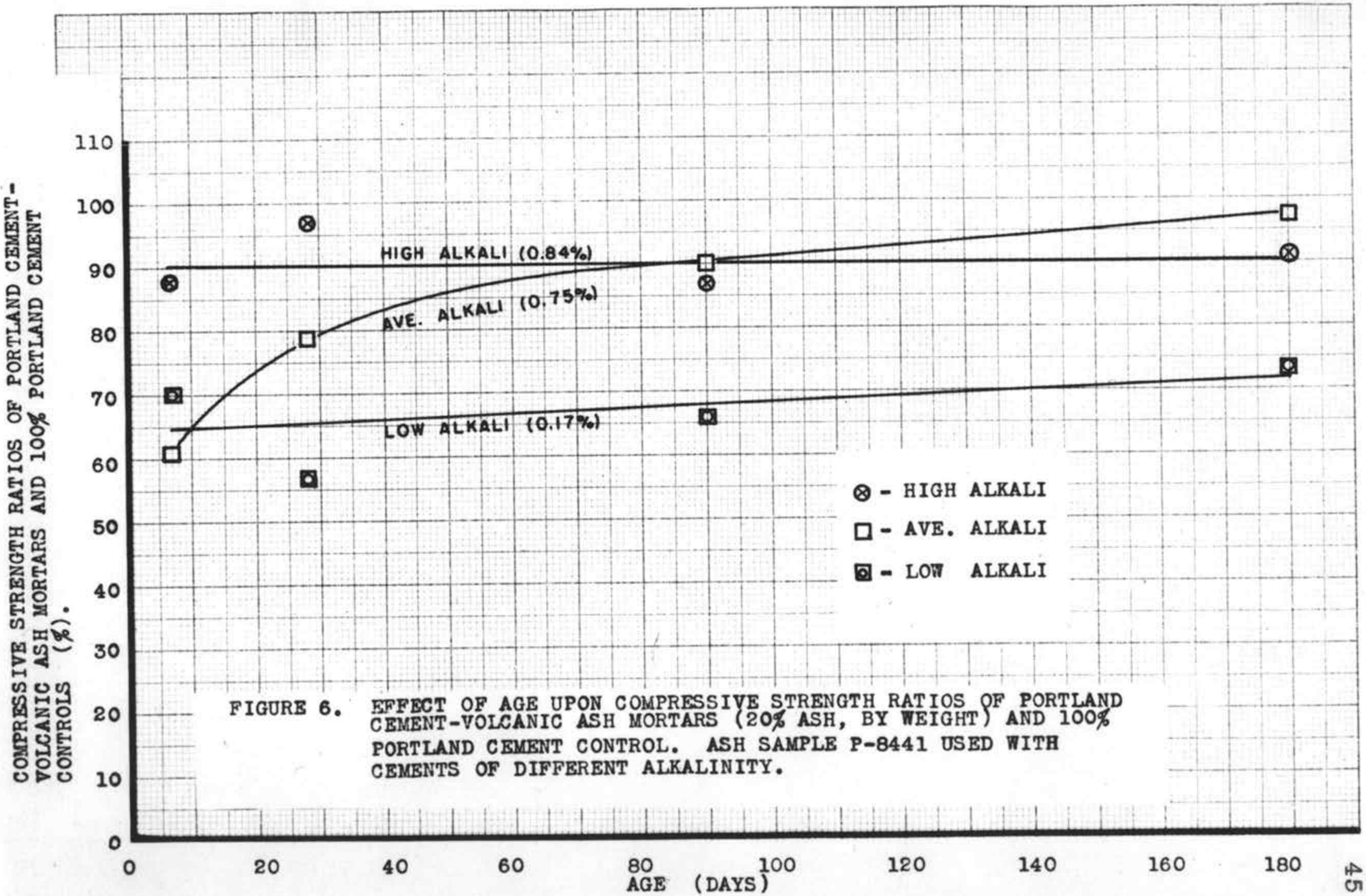


FIGURE 6. EFFECT OF AGE UPON COMPRESSIVE STRENGTH RATIOS OF PORTLAND CEMENT-VOLCANIC ASH MORTARS (20% ASH, BY WEIGHT) AND 100% PORTLAND CEMENT CONTROL. ASH SAMPLE P-8441 USED WITH CEMENTS OF DIFFERENT ALKALINITY.

It will be seen that there is a much less definite trend indicated for the high and low alkali cements than for the normal cement. Other than alkali contents, little is known concerning the quality or fineness of the different cements used, although at the time of mixing, it was observed that both the high and low alkali cements contained several small lumps. Any of these factors might contribute to the observed scattering of points.

A fact considered significant here is that the control specimens for the high and low alkali cements gained strength much more rapidly from one month to six months than did the normal alkali control. This may be seen in Tables A and C, Appendix. Such a gain in control strength might tend to parallel a pozzolanic strength increase, and the result would then be a generally constant strength ratio. This may explain the flat characteristic of the high and low alkali curves. It would be difficult to attempt a comparison between the high alkali and normal alkali cements in view of the small difference in alkali contents. Considered as a whole, however, it appears that a definite difference in pozzolanic activity is shown with high and low alkali cements.

In studying the possible correlation between fineness and pozzolanic activity of a material, particle size distribution was determined as outlined in ASTM D 422-39, Mechanical Analysis of Soils.

The required calculations were performed as directed, and grain size accumulation curves were plotted for the two most promising and the two least promising ash samples (from a strength standpoint) and are shown in Figure 7. There appears to be a definite correlation between particle size of a sample and its pozzolanic activity. As indicated by the curves, the two strongest samples are of smallest particle size, and the two weakest are more coarse. The curves for the remaining seven samples are not shown, but all lie within the area bounded by the plotted curves.

For comparison, the particle size of each sample has been expressed in specific surface which was determined in the following manner:

Assuming each ash particle to be spherical,

$$\text{Surface area of particle} = \pi D^2$$
$$\text{Volume of particle} = \frac{\pi D^3}{6}$$
$$\text{Weight} = V\sigma$$

Where D = diameter of particle, cm
V = volume of particle, cu cm
$\sigma$ = density of particle, g/cu cm

then, specific surface or $\frac{\text{area}}{\text{weight}} = \frac{\pi D^2 (6)}{\pi D^3 \sigma}$

$$= \frac{6}{D\sigma}$$

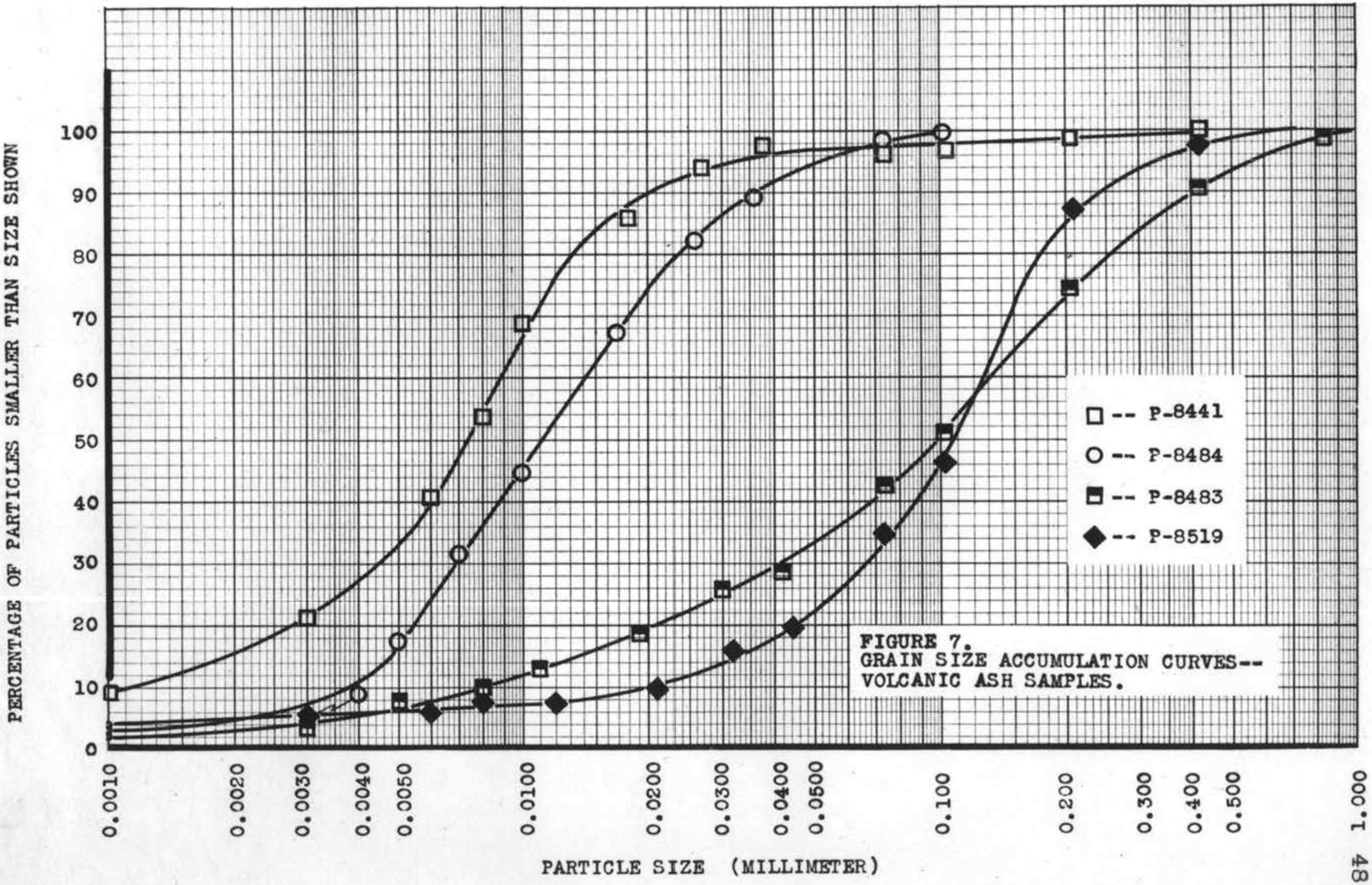


FIGURE 7.
GRAIN SIZE ACCUMULATION CURVES--
VOLCANIC ASH SAMPLES.

In the final expression it is seen that the specific surface depends only upon the diameter, the density of the particles, and a constant. All ash samples are assumed to be of the same density--2.37 grams per cubic centimeter. Further assumptions consider the material between 1.000 mm and 0.100 mm in size to be 0.500 mm, that between 0.100 mm and 0.0100 mm to be 0.0500 mm, that between 0.0100 mm and 0.0010 mm to be 0.0050 mm, and finally, the colloids smaller than 0.0010 mm are considered 0.0010 mm. In this way, the amount of material considered 0.500 mm, for example, is represented by an intercept on the ordinate of Figure 7, and it is this intercept quantity that is assumed to be 0.500 mm in subsequent calculations.

Employing this arbitrary method permitted a specific surface calculation in the manner shown for sample P-8483:

$$\text{Specific Surface} = \frac{6}{D\sigma}$$

$$= \frac{6}{2.37\text{g/cu cm}}\left(\frac{49\%}{0.05\text{ cm}} + \frac{40\%}{0.005\text{ cm}} + \frac{9\%}{0.0005\text{ cm}} + \frac{2\%}{0.0001\text{ cm}}\right)$$

$$= \frac{2.53}{\text{g/cu cm}}\,(10 + 80 + 180 + 200)\,\frac{1}{\text{cm}}$$

$$= \frac{2.53}{\text{g/cu cm}}\,(470)\,\frac{1}{\text{cm}}$$

$$= \underline{\underline{1190\text{ sq cm/g}}}$$

Values were thus computed for each sample and are indicated in the general data sheet, Table 1.

Figure 8 is a plot of strength variation with material fineness at a six-month age and at the 20 per cent level. It should be emphasized that each plotted point for this curve represents a different sample. As such, it cannot be concluded that the strength variation displayed is controlled only by specific surface. However, the interesting feature here is the unmistakable upward trend in strength ratio with increase in specific surface.

In comparing Figures 1 and 8, it will be seen that the two strongest samples, P-8484 and P-8441, are also the two samples with greatest specific surface. The next strongest four samples are also the next four highest in specific surface. The same relationship holds true for the next strongest three samples and, finally, for the two weakest samples.

Judging from these results it appears that particle size plays an important role in pozzolanic activity.

Three of the samples tested were from the same quarry but represented three different ash layers. P-8479 was from a lower layer, P-8480 was from an intermediate layer, and P-8481 was from a top layer. In comparing these three

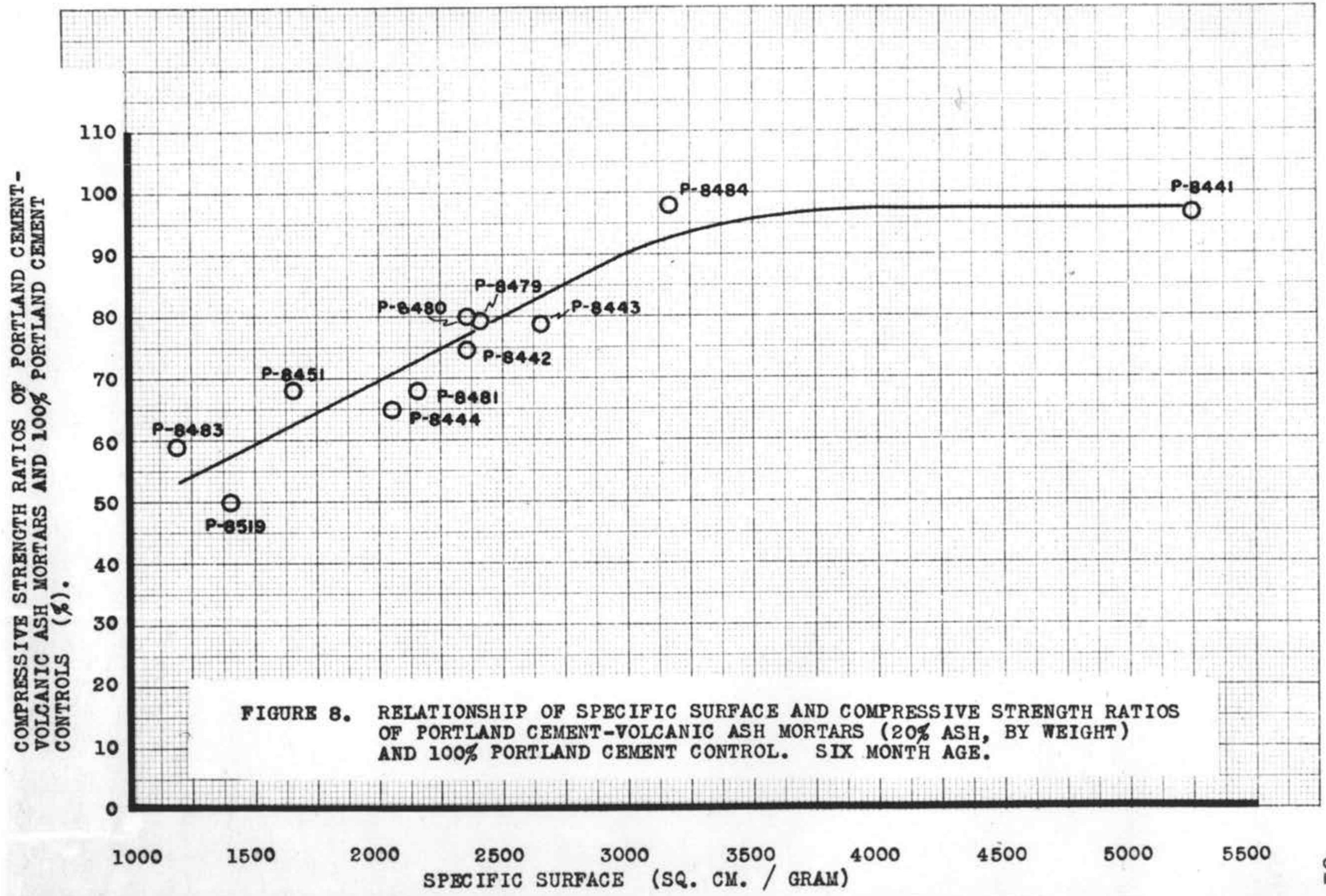


FIGURE 8. RELATIONSHIP OF SPECIFIC SURFACE AND COMPRESSIVE STRENGTH RATIOS OF PORTLAND CEMENT-VOLCANIC ASH MORTARS (20% ASH, BY WEIGHT) AND 100% PORTLAND CEMENT CONTROL. SIX MONTH AGE.

ashes, it will be seen that, petrographically, they are quite similar. As for strength developments, Figure 1 indicates almost identical characteristics for P-8479 and P-8480, and both samples seem superior to P-8481.

Particle size determination for the above three materials revealed nearly equal values as indicated in Figure 8. As was the case with the strength results, P-8479 and P-8480 were essentially the same, while P-8481 seemed inferior. Although little may be concluded from this analysis as to the effects of layer depth upon pozzolanic properties, it is felt that the results help strengthen the correlation between particle size and pozzolanic activity.

As shown in the petrographic descriptions, see Appendix, seven of the ash samples are gray or white, and four are pink or red. Referring to Figure 1, it is interesting to note that six of the seven strongest samples are gray or white in color, while three of the four weakest are pink or red. The one gray ash that falls in the weaker group is P-8519. This particular material is unique in several respects: (1) It was observed to contain many quartz-like particles, (2) From the strength standpoint, it was the least promising material tested, (3) It contains the highest percentage of volcanic glass,

(4) It has a perlitic structure, and (5) It possesses the second lowest specific surface.

Although ash color could serve only as a broad pozzolanic criterion at best, it is entirely possible that the most satisfactory pozzolanic materials, in general, are of gray or white color.

In analyzing the reasons for the apparently superior pozzolanic properties of samples P-8484 and P-8441, it is interesting to note the following factors which distinguish these materials from others:

1. Both have specific surface values far greater than the remaining nine samples.

2. Sample P-8484 is a material that had been crushed and air separated before submission for test.

3. Sample P-8441 is a material that was received in chunks. Although as large as eggs, these chunks could be crushed by hand and when wetted, appeared plastic.

In addition, the material of third highest specific surface, P-8443, is described petrographically as "crushed pumice." From strength and particle size standpoints, this sample may be considered one of the better materials following the above-mentioned two.

From these observations it would appear that the most encouraging materials were those with greatest specific surface, and of those with greatest specific surface, at least two had been subjected to crushing before use in this study. Speaking collectively of the ash samples, then, this would seem to emphasize the necessity for some degree of crushing or grinding before maximum pozzolanic properties may be attained.

## CONCLUSIONS

The results of this investigation permit the following conclusions to be drawn:

1. Under laboratory conditions of wet storage, portland cement-volcanic ash mortars exhibited pozzolanic properties.

2. Excepting three of the 10 per cent replacements and one 20 per cent replacement, all samples showed continuous compressive strength gains with time at the 10, 20, 30, and 40 per cent replacements.

3. Considering six-month results at the 20 per cent replacement level, the two samples of most pozzolanic promise are P-8484, which developed 98 per cent of control strength, and P-8441, which was 97 per cent of control strength. The four next best materials are P-8480, P-8443, P-8479, and P-8442 which attained, respectively, 80 per cent, 79 per cent, 79 per cent, and 75 per cent of control strength. The remaining samples ranged from 50 per cent to 68 per cent, and of these, the two least favorable are P-8519 and P-8483.

4. When subjected to comparable jar mill action, the samples of greatest specific surface were P-8441 and P-8484. Those of next highest specific surface were P-8443, P-8479, P-8442, and P-8480. The materials of

least specific surface were P-8519 and P-8483.

5. Generally, the 20 per cent replacements appear most promising as to continued gain in strength ratio with time.

6. Portland cement of high alkali content seems to induce greater pozzolanic activity than does portland cement of low alkali content.

7. There appears to be a correlation between particle size and pozzolanic activity.

From the results of these tests and others made by the Bureau of Reclamation, it may be stated definitely that deposits of Oregon volcanic ash have value as pozzolanic materials. Further research in this field seems extremely desirable in view of the tremendous quantities of these materials that might successfully be used in massive concrete construction in the Northwest.

## RECOMMENDATIONS FOR FURTHER RESEARCH

The following factors are suggested as desirable components of future pozzolanic studies:

1. Limitation of early age tests and extension of curing times past one year.

2. Employment of leaner mixes.

3. Curing of specimens in moist air as well as under water.

4. Investigation of effect of calcining.

5. Utilization of different particle sizes of one material.

6. More thorough study of the two best-appearing samples of this investigation.

7. Determination of the correlation, if any, between the findings presented here and results obtained from various short-time tests for pozzolanic properties.

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APPENDIXES

APPENDIX TABLE A

COMPRESSIVE STRENGTHS OF VOLCANIC ASH-PORTLAND CEMENT[1] MORTAR CUBES (psi)

(Averages of Three Cubes)

| Sample | 7-Day Replacement[2] 10% | 20% | 30% | 40% | 28-Day Replacement[2] 10% | 20% | 30% | 40% | 3-Month Replacement[2] 10% | 20% | 30% | 40% | 6-Month Replacement[2] 10% | 20% | 30% | 40% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P-8484 | 1825 | 1730 | 1325 | 850 | 3605 | 3185 | 2780 | 1920 | 4735 | 4475 | 4305 | 3265 | 5505 | 5025 | 4920 | 4425 |
| P-8451 | 1520 | 1165 | 835 | 585 | 3115 | 2170 | 1565 | 1140 | 4145 | 3245 | 2400 | 1780 | 4005 | 3460 | 2675 | 2175 |
| P-8483 | 1635 | 1130 | 695 | 470 | 3040 | 1965 | 1505 | 1055 | 4040 | 2960 | 2060 | 1455 | 4185 | 3020 | 2420 | 1565 |
| P-8442 | 1755 | 1390 | 1035 | 835 | 3155 | 2530 | 1940 | 1630 | 4375 | 3715 | 3025 | 2625 | 4640 | 3830 | 3195 | 3005 |
| P-8444 | 1840 | 1145 | 860 | 680 | 2855 | 2080 | 1590 | 1295 | 3870 | 3225 | 2515 | 1920 | 3950 | 3330 | 2960 | 2140 |
| P-8479 | 1820 | 1455 | 1015 | 550 | 3225 | 2655 | 1860 | 1235 | 4285 | 3435 | 2585 | 1905 | 4145 | 4050 | 3185 | 2150 |
| P-8441 | 2265 | 1620 | 1415 | 955 | 3685 | 3300 | 2705 | 1815 | 5105 | 4370 | 3765 | 2830 | 5015 | 4955 | 4005 | 3395 |
| P-8443 | 2195 | 1485 | 1055 | 885 | 3590 | 2775 | 1915 | 1665 | 4845 | 3525 | 2765 | 2445 | 4880 | 4050 | 3190 | 2885 |
| P-8480 | 1770 | 1495 | 990 | 675 | 2910 | 2505 | 1740 | 1225 | 3975 | 3560 | 2645 | 2140 | 4440 | 4130 | 2940 | 2180 |
| P-8481 | 2160 | 1325 | 895 | 530 | 3345 | 2215 | 1920 | 1275 | 4425 | 3120 | 2505 | 1685 | 4485 | 3490 | 2980 | 2065 |
| P-8519 | 1460 | 1270 | 1015 | 565 | 2770 | 2355 | 1705 | 1045 | 3085 | 2235 | 2105 | 1485 | 3765 | 2590 | 2320 | 1580 |
| (Portland cement control) | 2580 | | | | 3905 | | | | 5065 | | | | 4935 | | | |
| (Portland cement control) | 2710 | | | | 4445 | | | | 4715 | | | | 5300 | | | |

[1]Normal alkali cement.

[2]Per cent replacements are by weight.

## APPENDIX TABLE B

### COMPRESSIVE STRENGTH RATIOS[1] OF VOLCANIC ASH-PORTLAND CEMENT[2] MORTAR CUBES (%)

(Averages of Three Cubes)

| Sample | 7-Day Replacement[3] | | | | 28-Day Replacement[3] | | | | 3-Month Replacement[3] | | | | 6-Month Replacement[3] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10% | 20% | 30% | 40% | 10% | 20% | 30% | 40% | 10% | 20% | 30% | 40% | 10% | 20% | 30% | 40% |
| P-8484 | 69 | 66 | 50 | 32 | 86 | 76 | 67 | 46 | 97 | 92 | 88 | 67 | 108 | 98 | 96 | 86 |
| P-8451 | 58 | 44 | 32 | 22 | 75 | 52 | 37 | 27 | 85 | 66 | 49 | 36 | 78 | 68 | 52 | 43 |
| P-8483 | 62 | 43 | 26 | 18 | 73 | 47 | 36 | 25 | 83 | 61 | 42 | 30 | 82 | 59 | 47 | 31 |
| P-8442 | 66 | 53 | 39 | 32 | 76 | 61 | 47 | 39 | 90 | 76 | 62 | 54 | 90 | 75 | 62 | 59 |
| P-8444 | 70 | 43 | 33 | 26 | 68 | 50 | 38 | 31 | 79 | 66 | 51 | 39 | 77 | 65 | 58 | 42 |
| P-8479 | 69 | 55 | 38 | 21 | 77 | 64 | 45 | 30 | 88 | 70 | 53 | 39 | 81 | 79 | 62 | 42 |
| P-8441 | 86 | 61 | 54 | 36 | 88 | 79 | 65 | 43 | 104 | 90 | 77 | 58 | 98 | 97 | 78 | 66 |
| P-8443 | 83 | 56 | 40 | 34 | 86 | 66 | 46 | 40 | 99 | 72 | 57 | 50 | 95 | 79 | 62 | 56 |
| P-8480 | 67 | 57 | 38 | 26 | 70 | 60 | 42 | 29 | 81 | 73 | 54 | 44 | 86 | 80 | 57 | 43 |
| P-8481 | 82 | 50 | 34 | 20 | 80 | 53 | 46 | 30 | 91 | 64 | 51 | 35 | 87 | 68 | 58 | 40 |
| P-8519 | 55 | 48 | 38 | 21 | 66 | 57 | 41 | 25 | 63 | 46 | 43 | 30 | 73 | 50 | 45 | 31 |

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[1]Ratios of Compressive Strengths of Volcanic Ash-Portland Cement Mortars and 100% Portland Cement Controls.

[2]Normal alkali cement.

[3]Per cent replacements are by weight.

# APPENDIX TABLE C

## COMPRESSIVE STRENGTHS OF VOLCANIC ASH-PORTLAND CEMENT MORTAR CUBES (PSI) HIGH ALKALI AND LOW ALKALI PORTLAND CEMENTS

(Averages of 3 Cubes)

| | | 7-Day Replacement[1] | | | | 28-Day Replacement[1] | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample | Cement | 10% | 20% | 30% | 40% | 10% | 20% | 30% | 40% |
| Control | Low Alkali | 2485 | | | | 5020 | | | |
| P-8441 | " | 2295 | 1725 | 1290 | 1005 | 3620 | 2880 | 2320 | 1855 |
| P-8444 | High Alkali | 2500 | 1680 | 1180 | 735 | 4105 | 2945 | 2370 | 1455 |
| P-8441 | " | 2740 | 2240 | 1640 | 935 | 4645 | 3955 | 3025 | 1830 |
| Control | " | 2545 | | | | 4090 | | | |

| | | 3-Month Replacement[1] | | | | 6-Month Replacement[1] | | | |
|---|---|---|---|---|---|---|---|---|---|
| Sample | Cement | 10% | 20% | 30% | 40% | 10% | 20% | 30% | 40% |
| Control | Low Alkali | 6175 | | | | 6890 | | | |
| P-8441 | " | 4890 | 4050 | 3425 | 3005 | 5745 | 5030 | 4385 | 3815 |
| P-8444 | High Alkali | 4275 | 3445 | 2685 | 1910 | 4565 | 4065 | 2945 | 2220 |
| P-8441 | " | 4780 | 4495 | 3675 | 2565 | 5565 | 4980 | 4455 | 3335 |
| Control | " | 5165 | | | | 5475 | | | |

[1]Per cent replacements are by weight.

## APPENDIX TABLE D

## COMPRESSIVE STRENGTH RATIOS[1] (%)--HIGH ALKALI AND LOW ALKALI PORTLAND CEMENTS

(Averages of Three Cubes)

| | | 7-Day Replacement[2] | | | | 28-Day Replacement[2] | | | | 3-Month Replacement[2] | | | | 6-Month Replacement[2] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% | 20% | 30% | 40% | 10% | 20% | 30% | 40% | 10% | 20% | 30% | 40% | 10% | 20% | 30% | 40% |
| P-8441 | Low Alkali | 92 | 70 | 52 | 40 | 72 | 57 | 46 | 37 | 79 | 66 | 56 | 49 | 84 | 73 | 64 | 55 |
| P-8444 | High Alkali | 99 | 66 | 46 | 29 | 100 | 72 | 58 | 36 | 83 | 67 | 52 | 37 | 84 | 75 | 54 | 41 |
| P-8441 | High Alkali | 108 | 88 | 65 | 37 | 114 | 97 | 74 | 45 | 93 | 87 | 71 | 50 | 102 | 91 | 82 | 61 |

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[1]Ratios of compressive strengths of volcanic ash-portland cement mortars and 100% portland cement controls.

[2]Per cent replacements are by weight.

# APPENDIX E

## PRELIMINARY PETROGRAPHIC DESCRIPTIONS

Sample No. P-8441

Location: Terrill silica deposit
In Oregon City proper, just south of Rebecca and west of Georgia Streets.
Sec 32, T 2 S, R 2 E
Clackamas County.

Sample submitted by: Portland Office
Oregon Department of Geology and Mineral Industries

Megascopic description: Gray to white in color. Fine grained. Water laid.

Microscopic description:

Volcanic glass - estimated 60-70%
n = circa 1.52 but , suggesting an andesitic magma.

Mineral grains - estimated 25-35%
dominant = feldspar
sub-dominant = hornblende, quartz (?), other minerals.

Diatoms - estimated 2-3%
dominant = small Melosiras but many species present.

Remarks: This material shows very little alteration. Very little opaline silica present. Extremely fine grained, average particle size circa 0.014 mm.

Sample No. P-8442

Location: Where Baker-Medical Springs Highway crosses
Salt Creek.
Sec 4, T 7 S, R 41 E
Baker County

Sample submitted by: N. S. Wagner, Field Geologist,
Oregon Department of Geology and
Mineral Industries

Megascopic description: Loose, fine-grained ash with
occasional pebbles of pumice.
Color = gray

Microscopic description:

Volcanic glass - estimated 75-85%
n = circa 1.51, suggesting a dacitic magma.

Mineral grains - estimated 15-25%
dominant = feldspar
n = circa 1.55, slightly
basic andesine or labradorite

sub-dominant = hornblende, magnetite, and
other minerals.

Diatoms = none

Remarks: Indicates a typical volcanic ash. Feldspars
rimmed with glass. Mineral grains quite large.

Sample No. P-8443

Location: NE ¼, SE ¼, Sec 9, T 27 S, R 9 E
Klamath County
Chemult area

Sample submitted by: Chrystalite Aggregates,
Chemult, Oregon

Megascopic description: Loose, gray color, fine-grained.

Microscopic description:

Volcanic glass - estimated 80-85%
n = circa 1.51, suggesting a dacitic magma.

Mineral grains - estimated 15-20%
dominant = feldspar
n = 1.55 and 1.56 probably closer to 1.56.
Therefore, labradorite.

sub-dominant = hornblende, magnetite, and other minerals.

Diatoms = none

Remarks: This is crushed pumice. Mineral grains relatively free of glass fringe. Inclusions numerous. Grains fresh.

Sample No. P-8444

Location: NE $\frac{1}{4}$, SE $\frac{1}{4}$, Sec 9, T 27 S, R 9 E
Klamath County
Chemult area

Sample submitted by: Chrystalite Aggregates,
Chemult, Oregon

Megascopic description:

Loose, salmon pink colored volcanic ash with frequent particles of pumice up to $\frac{1}{4}$ inch.

Microscopic description:

Volcanic glass - estimated 85-90%
n = circa 1.51 but ,
suggesting dacitic magma.

Mineral grains - estimated 10-15%
dominant feldspar
n = 1.55, 1.56. Labradorite.

sub-dominant = usual mineral sequence.

Diatoms - none

Remarks: Feldspars show incipient alteration. Color due to coating of iron oxides on grains. Mineral grains ringed with glass. Inclusions numerous.

Sample No. P-8451

Location: One mile west of Tumalo
Sec ?, T 16 S, R 11 E
Deschutes County

Sample submitted by: Mr. L. A. Williamson
Bend, Oregon

Megascopic description:

Light pink to salmon colored volcanic ash with pebbles of pumice up to one inch.

Microscopic description:

Volcanic glass - estimated 85-90%
n = circa 1.51 but , suggesting a dacitic magma.

Mineral grains - estimated 10-15%
dominant = feldspar
n = circa 1.555. Basic andesine or labradorite.

sub-dominant = usual mineral sequence.

Diatoms - none.

Remarks: Feldspars show some alteration, about the same as in P-8444. Color due to coating of iron oxides. Mineral grains large and small, sometimes ringed with glass. Inclusions frequent.

Sample No. P-8479   Carlton #1

Location: Carlton (Tucker) Pumice Pit
On Medford-Crater Lake Highway
Sec 23, T 33 S, R 1 E
Jackson County

Sample submitted by: D. J. White, Geologist
Oregon Department of Geology and
Mineral Industries

Megascopic description:

Reddish colored volcanic ash with numerous angular fragments of pumice up to ¼ inch. Not consolidated.

Microscopic description:

Volcanic glass - estimated 60-65%
n = 1.51 but circa, suggesting a dacitic magma.
Shows some alteration.

Pumice fragments - estimated 5-10%

Mineral grains - estimated 25-30%
dominant = feldspar
n = circa 1.56 (labradorite)
sub-dominant = mafic minerals, including some chlorite.

Remarks: Mafic minerals more abundant than in previous samples or any of this lot. Aside from this, the sample shows typical textures and mineral assemblage of a volcanic ash.

Considerable staining of fragments by iron oxides.

Sample No. P-8480 Carlton #2

Location: Carlton (Tucker) Pumice Pit
On Medford-Crater Lake Highway
Sec 23, T 33 S, R 1 E
Jackson County

Sample submitted by: D. J. White, Geologist
Oregon Department of Geology and
Mineral Industries

Megascopic description:

Tan-gray ash with some angular fragments of pumice up to ¼ inch. Not consolidated.

Microscopic description:

Volcanic glass - estimated 60-65%
n = circa 1.51 but , suggesting a dacitic magma.

Mineral grains - estimated 35-40%
dominant = feldspar
n = circa 1.56 but (labradorite)
some zoned crystalls.
sub-dominant = usual mineral sequence

Remarks: Some iron oxide staining. Typical volcanic ash.

Sample No. P-8481 Carlton #3

Location: Carlton (Tucker) Pumice Pit
On Medford-Crater Lake Highway
Sec 23, T 33 S, R 1 E
Jackson County

Sample submitted by: D. J. White, Geologist
Oregon Department of Geology and
Mineral Industries

Megascopic description:

Gray volcanic ash with pumice granules up to ½ inch in diameter and minor rock grit.

Microscopic description:

Volcanic glass - estimated 70-80%
n = circa 1.51 but , suggesting a dacitic magma.

Mineral grains - estimated 10-15%
dominant = feldspar
n = circa 1.555 (labradorite)
sub-dominant = usual mineral sequence.

Rock grit 5%

Pumice grit 5-10%

Remarks: Minor iron oxide staining.

Typical volcanic ash.

Sample No. P-8483 Sleeper # 1

Location: "Approximately one mile west of Bend, Oregon."
From Sleeper pit.

Sample submitted by: Mr. Merle Sleeper
Bend, Oregon

Megascopic description:

Light pink volcanic ash containing grit to granule size angular pumice fragments. Unconsolidated.

Microscopic description:

Volcanic glass - estimated circa 85%
n = circa 1.507, indicating a magma of intermediate composition.

Mineral grains - estimated circa 10%
dominant = feldspar
n = 1.55 but circa (basic andesine).
very minor mafic

Rock fragments - estimated circa 5%

Remarks: This is a pure volcanic ash. It has a very minor amount of mineral grains. Staining by iron oxide is minor. Both glass shards and mineral grains are fairly large in comparison to other materials submitted.

Sample No. P-8484   Sleeper # 2

Location: "Approximately one mile west of Bend, Oregon."
From Sleeper pit.

Sample submitted by: Mr. Merle Sleeper
Bend, Oregon

Megascopic description:

Dead white, finely powdered pumice.

Microscopic description:

Volcanic glass - estimated circa 95%
n =   and   1.50, suggesting a silicic magma.

Mineral grains - estimated circa 5%
dominant = feldspar
n = circa 1.54. Determination difficult, so index is questionable. Suggests basic oligoclase.
very minor mafic.

Remarks: This is a very fresh appearing material. Particle size is quite small. Mineral grains are very minor and of very small size.

Author's Note: By communication with Mr. Sleeper, it was learned that this material had been crushed and air separated.

Sample No. P-8519

Location: $E\frac{1}{2}$ of $SE\frac{1}{4}$ of sec 33, T 31 S, R 46 E
Malheur County

Sample submitted by: Mrs. Ethel M. Goss
IOOF Building
Adrian, Oregon
via Baker Field Office

Megascopic description:

Loosely indurated gray volcanic ash. In semi-consolidated masses has perlitic structure. Very clean.

Microscopic description:

Volcanic glass - estimated over 95%
$n = 1.50$, suggesting a silicic magma.

Mineral grains - negligible. Mostly feldspar, rimmed with glass.
Some chlorite seen.

Remarks: This contains the highest percentage of volcanic glass of any sample submitted. All fresh. Samples from this locality have previously been submitted to this Department as Nos IB 64 and IB 84.