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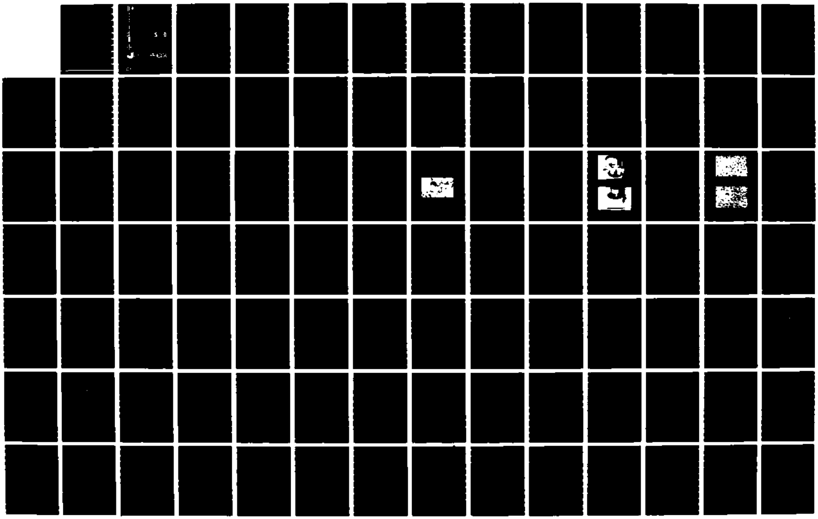

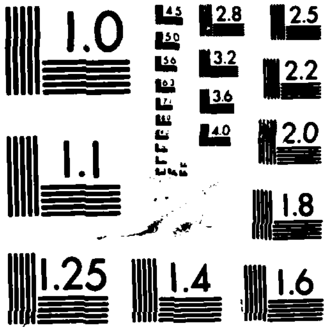

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Properties of Cement Compacts Prepared by High-Pressure Compaction

JEFFREY R. BORMAN
W. B. LEDBETTER
MATTI RELIS

TEXAS A&M UNIVERSITY
CIVIL ENGINEERING DEPARTMENT
COLLEGE STATION, TX 77843

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FINAL REPORT

MAY 1984 - AUGUST 1985

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SECURITY CLASSIFICATION OF THIS PAGE

AD-A172075

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release. Distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ESL-TR-85-54

6a. NAME OF PERFORMING ORGANIZATION Texas A&M University	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION HQ Air Force Engineering and Services Center
6c. ADDRESS (City, State and ZIP Code) Civil Engineering Department College Station, TX 77843		7b. ADDRESS (City, State and ZIP Code) Engineering and Services Laboratory (RDCS) Tyndall AFB, FL 32403
8a. NAME OF FUNDING/SPONSORING ORGANIZATION HQ Air Force Eng & Svcs Center	8b. OFFICE SYMBOL (If applicable) RDCS	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER FO 8635-84-K-0053
8c. ADDRESS (City, State and ZIP Code) Engineering and Services Laboratory Tyndall AFB, FL 32403		10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
62601F	2673	-	0033

11. TITLE (Include Security Classification) Properties of Cement Compacts Prepared by High-Pressure Compaction

12. PERSONAL AUTHOR(S)
Jeffrey R. Borman, W.B. Ledbetter, Matti Relis

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final Report	FROM May 84 TO Aug 85	May 1986	124

16. SUPPLEMENTARY NOTATION
Availability of this report is specified on reverse of front cover.

17. COSATI CODES		
FIELD	GROUP	SUB. GR.
13	13	
13	02	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
high strength cement, cementitious materials, high strength concrete, fly ash

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The purpose of this investigation was to determine the combined effects of fly ash as a partial replacement for portland cement and the use of high-pressure compaction in reducing the porosity and increasing the compressive strength of prepared miniature compacts.

According to current practice and theory, for specialized uses, portland cement concrete materials with strengths approaching 20,000 psi (140 MPa) may be produced by reducing the amount of porosity present in the microstructure of the paste-matrix material. To accomplish this, both high-pressure compaction and increased formation of cementitious products from a pozzolanic reaction have provided excellent results. However, judging from an extensive literature survey, the effect of combining the two has not been examined. (Continued on back of page)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL LCDR Thomas J. Hilferty	22b. TELEPHONE NUMBER (Include Area Code) (904)283-6237	22c. OFFICE SYMBOL RDCS

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

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The three main parameters investigated included the initial compacted porosity level from high-pressure compaction, the percentage fly ash replacement of the cement, and curing duration. Additionally, the effects of accelerated curing by oven-drying was explored.

The study revealed that high-pressure compaction, followed by accelerated curing, is an excellent means of producing a low-porosity condition and, thereby, a greater strength in a cementitious material. Strengths in excess of 72,000 psi (500 MPa) were developed. Confirming earlier findings, it was found that while increased hydration product formation occurs under conditions of greater porosity, the resulting strength is not as high as when lower initial porosities are achieved through greater compaction. Thus, reducing the initial porosity of the cement system is seen as the single most important factor toward achieving ultra-high strengths. It was also found that particle gradation and compatibility are important considerations when producing the compacts. The existence of an optimum percentage of fly ash replacement for cement in the prepared compacts could not be determined. The expected increase in strength from the pozzolanic reaction was not apparent as increasing amounts of fly ash provided for decreasing strength levels. The partial cause is believed to be inadequate curing duration, allowing for incomplete formation of the pozzolanic reaction. Another cause could be the amount of necessary calcium hydroxide available in the low-porosity compacts.

PREFACE

This report was prepared by the Civil Engineering Division, Texas Engineering Experiment Station, Texas A&M University System, College Station, Texas 77843-3136, under Contract Number F08635-84-K-0053 for the Air Force Engineering and Services Center, Engineering and Services Laboratory (HQ AFESC/RD), Tyndall Air Force Base, Florida.

This report summarizes work done between May 1984 and August 1985. The HQ AFESC/RDCS project officer was Thomas Hilferty, LCDR, USN.

The authors wish to acknowledge the valuable assistance of several people and firms. Mr. Phillip Harris , Vice President, Texas Industries, provided advice and council on the design of the experiments, the interpretation of the results, and the wording of the report. Texas Industries and Gifford-Hill & Co., donated the cement and fly ash, respectively. Mr Joe Brusse of the TEES Engineering Shops assisted in the fabrication of the segmented die system. Mrs Melody Meyer typed and helped proofread the report.

To each of these persons and firms, we offer our heartfelt thanks.

This report has been reviewed by the Public Affairs office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public including foreign nationals.

This technical report has been approved for publication.

THOMAS J. HILFERTY, LCDR, USN
Project Officer

Everett L. Mabry
EVERETT L. MABRY, LT COL, USAF
Chief, Engineering Research Division

William S. Strickland
WILLIAM S. STRICKLAND, GM-14
Chief, Facility Systems
and Analysis

Robert E. Boyer
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Director, Engineering and Services
Laboratory

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SECTION I

INTRODUCTION

A. OBJECTIVES

The primary objective of this study was to determine the combined effects of the use of high-pressure compaction and fly ash as a partial replacement for portland cement on the compressive strength development of prepared miniature compacts. Also of interest were the effects of high-pressure compaction on the porosity, the hydration process and the pozzolanic reaction in the prepared compacts. An additional objective was to produce data which could be used to investigate the production of ultra-high-strength mortar and concrete cubes from large-scale high-pressure compaction.

B. BACKGROUND

Current concrete technology has produced concrete with compressive strengths from 10,000 to 12,000 psi (70 to 80 MPa). Generally, this has been created by optimizing the concrete constituents, and using special additives. Current practice and theory say, however, that, for specialized uses, a portland cement concrete material with strength approaching 20,000 psi (140 MPa) may be produced by reducing both porosity and strength-reducing void space in the microstructure of the paste-matrix material. This should be possible by high-pressure compaction and by adding pozzolanic mixtures such as fly ash to bring about increased cementitious binding.

C. SCOPE

The test parameters chosen for study in the laboratory investigation included: (1) percentage of porosity, (2) percentage of replacement of portland cement with fly ash, (3) curing time, and (4) limited accelerated curing of the prepared compacts.

SECTION II

LITERATURE REVIEW

A. PRESENT STATUS

In recent decades, the construction industry has placed increased reliance on concrete which develops compressive strengths of 10,000 to 12,000 psi (70 to 80 MPa) in relatively short times (References 1,2). The consistent production and usage of concrete with strengths significantly greater than this remains, however, more difficult to achieve, because of many variables influencing the development of strength in such a heterogeneous material as portland cement concrete (Reference 3). In practice, production of concrete at the 10,000 to 12,000 psi (70 to 80 MPa) strength level generally depends on optimization of the constituent materials (aggregate, cement, water, and various admixtures in the proper combinations) and quality control in the mixing, batching, and placement techniques (References 4,5,6,7,8).

In addition, to produce a concrete with compressive strength at the ultra-high-strength level of 20,000 psi (140 MPa), it is necessary to significantly increase the strength of the weaker binder or matrix material in a given concrete batch. According to current practice and theory, the amount of porosity present in a matrix material is <u>the most influential factor</u> concerning strength. Thus, to produce an ultra-high-strength material, the microstructure of the matrix must be modified to significantly reduce porosity level (Reference 3,9,10,11,12,13). This can best be done by high-pressure compaction and increased cementitious binding.

B. STRENGTH IN A CONCRETE AND MORTAR

In a concrete batch, the matrix is actually the "glue" which binds the various sizes and types of aggregate together. Because the aggregate often has far superior strength than the matrix material, the strength of the matrix material must be improved for a higher strength material to be achieved (Reference 3).

The microstructure of the matrix material is the controlling factor for matrix strength (Reference 3). The matrix is initially a two-component system consisting of anhydrous cement and water. When the cement particles are exposed to water, the major cement compounds, namely tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF) begin hydration and the formation of cement gel and calcium hydroxide. Most of the cement gel is composed of calcium-silicate-hydrates (C-S-H), which are primarily responsible for strength in a matrix material. The calcium hydroxide is believed to have no major impact on strength other than the occupation of detrimental void space and increased surface area contact between the different particles of the matrix (Reference 13). However, in the presence of a pozzolan, it becomes a vital part of the hydration process.

As the hydration process proceeds, the gel effectively coats the cement particles with various layers of hydration products. Within a few hours after the beginning of the hydration process, the matrix material consists of the cement gel, remaining unhydrated cement material, available free water, and void space or porosity. The majority of the porosity has developed as the hydration of the cement particles has "used" the available water in the vicinity, creating a remnant of water-filled space in the hydrating paste. The amount of cement gel or hydration product will continue to increase while sufficient water is available to encourage the hydration process. Current theory states that the cement gel product can only form in the void provided by the exchange of available free water through the hydration process. During this process, the surface area of the gel solid product increases tremendously (Reference 3,12,13,14).

The strength of the cement paste is developed as the cement gel hydration product continues to form around each cement particle and expands outwardly as hydration proceeds, increasing the amount of surface area contact between the various components in the paste. It is generally believed that two types of cohesive bonds give the matrix material its strength. One is the physical attraction between the surfaces of the hydrated cement particles known as van der Waals forces. The second type of cohesion is made up of the interlocking and interwoven filaments, fibrals, and plate-like formations of the hydration product. This type of bond provides the greatest strength in the paste material (Reference 12).

Both of these bonds, however, are highly dependent upon the amount of surface area of the various hydration products in contact and the distance between these products. This surface area contact is a function of the amount of void space created by the depletion of the surrounding water in the hydration process. The void space caused by the depletion of water has the most significant impact on the strength of the matrix material (References 3,12,13,14). This is the reason for the relationship between a lower water-cement ratio and a higher resulting compressive strength in a normally prepared portland cement mortar or concrete.

Excluding the larger voids which occur due to improper and insufficient consolidation in a mortar or concrete, two types of voids or pores develop in a paste during the hydration process and contribute to the total porosity of the matrix. One type, gel pores, exists <u>within</u> the cement gel product as interconnected spaces or voids between the fibrous, interwoven filaments of the gel product. In normally hydrated cements, gel pores are an integral part of the hydration product and, typically, occupy approximately one-fourth the total volume of cement gel (References 12,13). As the hydration process proceeds and the cement gel increases in volume, the gel pore space will increase by the same degree and continue to occupy approximately one-fourth the total volume of hydration product. Gel pores are considered to have less influence on the engineering properties of a hydrated portland cement paste than other types of voids and pore space (References 3,12,13,14).

The other type of pores, termed capillary pores, is the larger of the void spaces present in the paste and is defined as the space which exists between the various hydrating cement particles. The influence of the initial amount of water used in the formation of the paste on the resulting capillary porosity is extreme, because increasing amounts of water will further separate the individual cement grains, making sufficient particle surface area contact increasingly difficult (Reference 3,12,13,14).

The total amount of capillary porosity present in the paste depends on the amount of water used in its formation and the consolidation effort applied to the freshly mixed paste. The total volume of the capillary porosity in a paste decreases as the volume of the hydration product increases, depleting available water from the surrounding vicinity and replacing that space with cement gel (Reference 3,12,13,14). Because of this, it is highly beneficial to use extremely low water-cement ratios and to reduce potential void space between the individual cement particles before the hydration process begins (Reference 15). In the production of ultra-high-strength portland cement paste, the elimination of substantial amounts of this type of porosity is a primary concern and the high-pressure compaction of anhydrous portland cement is particularly well-suited to this objective.

C. THE STRENGTH - POROSITY RELATIONSHIP

The physical properties of a portland cement paste depend on its internal structure and porosity. Extensive research supports the conclusion that compressive strength increases as porosity decreases and material density increases (References 11,19,20,24,31). The following summary focuses on four relationships developed from previous work. The relationship which established the framework for cement strength - porosity research in this century was probably developed by Abrams in 1919 (Reference 15). Abrams' concept stated that the strength of a portland cement paste is inversely related to the initial water-cement ratio used in its formation.

This concept was later expanded by T.C. Powers who developed the minimum water-cement ratio needed for the complete hydration of all cement pastes. Pastes with ratios in excess of the minimum water form deleterious capillary porosity and reduced strength (Reference 13).

Another strength, porosity, on water-cement ratio relationship significant to concrete strength technology is based on the concept that the strength of a portland cement paste is proportional to the increase in the gel/space ratio. Developed by Powers and Brownyard, this relationship states that the strength of a material is directly proportional to the concentration of the hydration products developed in the space available for the hydration to occur (Reference 13).

This relationship is expressed in the form:

$$S = (S^{o})X^{n} \tag{1}$$

where S is the predicted strength of the paste,

S^{o} is the intrinsic strength of the cement gel (i.e.X=1),

X is the ratio of gel volume to gel volume plus capillary porosity (Gel/Space Ratio),

n is a constant, depending on the cement characteristics, and typically is a value in the range of 2.6 to 3.0.

The rationale of this equation is to relate the compressive strength which could be achieved to the actual hydration product formation and initial water-cement ratio. When water is combined with the anhydrous cement material, the quantity of available space for hydration product formation equals the amount of space occupied by the mixing water. After a certain degree of hydration, the available space becomes the volume of hydration product plus the capillary pores that exist. There is a significant relationship between a lower volume of capillary pores and the corresponding increase in the concentration of the hydration product in the space available for the hydration to occur, indicating an increasing amount of surface area contact among the many components in the hydrating matrix. It can then be deduced that strength in a portland cement paste increases as the surface area contact between the various hydration products increases.

As the porosity of a portland cement paste decreases and the strength increases, the matrix material will behave as a brittle material and its mechanical properties such as strength may be compared with those of ceramic materials (Reference 11). With the high-pressure compaction of anhydrous cement, the porosity is significantly reduced, resulting in ultrahigh strengths. It is then appropriate to use a relationship which defines the porosity-strength relationship for various types of brittle, low-porosity, high-strength materials.

This relationship is:

$$S=S_{o}e^{-kp} \tag{2}$$

where

P is the fractional porosity at a given time, and

K is a constant which depends on the system being studied (References 11,13).

This relationship is well-suited to portland cement materials, because of the wide range of porosity values for which the expression holds true. In addition, as the porosity level approaches very low values, the compressive strength increases tremendously.

While this relationship is an excellent model of the general relationship between porosity, hydration, and strength for normally prepared cement pastes, other factors (such as cement composition, morphology and bonding properties of the hydration products) also affect the strength of cement paste, especially after it has hardened (set) (Reference 31). This is particularly true in the case of highly compressed, low-porosity portland cement pastes.

According to work by Relis and Soroka, other factors have been found to produce excellent strength correlations for the extremely low-porosity range produced by the high-pressure compaction of anhydrous cement powders (Reference 31). This work is based on the rationale that the three components of a set cement, namely porosity, hydration product, and unhydrated cement are interrelated and a change in one will result in a change of the other two. If it is assumed that both porosity and the amount of hydration product in the matrix are influential to strength, then in a low-porosity system the strength of a hydrated cement will increase with an increase in the volume of hydration product and a decrease in the porosity level. It is possible for the unhydrated cement grains to be stronger than the C-S-H gel hydration product formed, which would mean that a large concentration of unhydrated cement material would also contribute to compressive strength (Reference 31).

From this concept, the following relationship was developed:

$$S = (W^{*}_{hp} \times G^{*}_{c})/P_{f} \qquad (3)$$

where W^{*}_{hp} is the weight concentration of hydration product formed,

G^{*}_{c} is the weight concentration of unhydrated cement,

P_{f} is the final porosity in fractional form.

Using this equation, excellent results have been obtained for up to 28 days of curing (Reference 31). For periods greater than 28 days, other age factors appear to apply, and this relationship does not correlate well with actual strengths.

Several conclusions can be drawn concerning the relationship between compressive strength and porosity conditions in portland cement pastes, mortars or concretes. They are:

1. Porosity is inversely related to strength. When porosity of the system is decreased, the compressive strength increases (water - cement ratio law).

2. If more water is used than is needed for hydration, strength is reduced.

3. The formation of hydration products produces higher strengths by decreasing porosity and increasing the amount of surface area contact between the many particles composing the matrix.

4. In most instances, porosity has the greatest influence in strength development for portland cement systems, however, at extremely low-porosity levels, concentration of unhydrated cement material may have considerable influence on the strength.

These conclusions can help in understanding the importance of the high-pressure compaction in the production of a high-strength material. If the compaction is performed on an anhydrous portland cement, the effects of excessive amounts of water are eliminated because the necessary moisture for hydration is imbibed through porosity existing between the cement particles. Thus, high-pressure compaction of anhydrous portland cement is an attractive method of producing a high-strength system.

D. HIGH-PRESSURE COMPACTION

The objective of high-pressure compaction is to increase the surface area contact and consequently reduce the void space between the powder material so that interparticle forces may develop which will produce high strengths (Reference 16). This may be accomplished by particle sliding or rearrangement, plastic and elastic deformation of the material being compacted and particle fragmentation (Reference 17). Figure 1 shows a schematic representation of these three processes (Reference 18).

Two interrelated stages occur in application of high-pressure to a particulate material. These are (1) the process by which the particulate material will attain a state of close packing or low-porosity and (2) the process by which the particulate materials cohere between themselves, resulting in a high-strength material. This second process is commonly accomplished by various methods of adhesion and aids significantly in producing the stable, high-strength, condition (Reference 18).

The first stage in the compaction of particulate material is the general rearrangement of the particles to obtain a condition of closer packing or lower porosity. This occurs as the material chooses a "path of least resistance" and the material

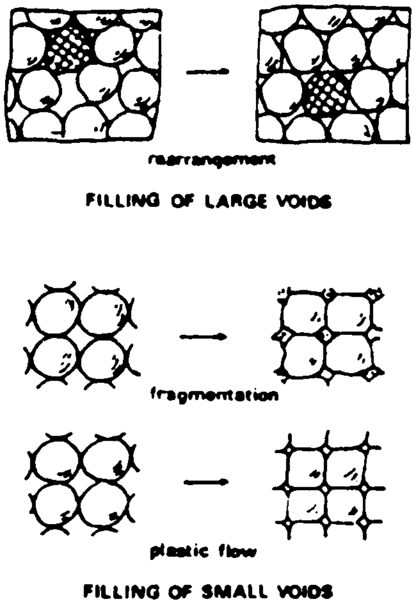


Figure 1. Schematic Diagram of Compaction Process in Particulate Material (Reference 18)

particles slide next to and in between each other. The elimination of the larger voids is the primary occurrence at this stage. At this point, much of the compaction energy input is dissipated in overcoming the interparticle frictional forces which exist at material contact points. For fine ceramic powders, it has been found that under the comparatively low pressures induced in this initial stage, one-half to one-third of the total sample volume reduction will occur (References 16,18).

The second stage in the compaction process occurs as increasing pressures are applied and depends on the elasticity and plasticity of the compressed powder particles in further obtaining a reduction in voids. Plastic deformation and fracture of the material particles are common during this stage. Under the higher pressure associated with this stage, the particles will either fracture or deform plastically and flow into the available voids, reducing the spaces remaining from the first stage. This action results in increased surface area of interparticle contact and, therefore, increases the area available for interparticle bonding. If the particles fracture, large reductions in sample volumes may occur, a common characteristic of brittle materials. Substantial amounts of particle interlocking may occur depending on the geometrical properties of the particles (References 16,18). Rough textured, sharp, angular particles interlock better than smooth-surfaced, spherical particles.

These various stages take place simultaneously throughout all portions of the powder material as the compaction pressure is applied and continues until the porosity and void content of the sample approaches zero and the compact density approaches the true density of the component materials. Throughout both stages of the compaction process, elastic compression of the trapped air and the particulate materials occurs. As the pressure becomes extremely high, the void - porosity system will become fully disconnected, consisting only of very minute isolated pores throughout the system. As this destruction of the void - porosity system occurs, extremely high internal gas pressures develop and the compression of the material results in the storage of elastic energy. When the compaction pressure is released, a great deal of stored energy will also be released. Thus, current technology indicates that release of the compaction pressure on the compact sample should be done gradually to eliminate the risk of total compact disintegration (References 16,18).

During the process of compacting particulate materials, particle shape, texture, strength, plasticity and elasticity influence the results. Studies have shown that, as the reduction in the larger voids occurs, an increase in the number of smaller voids also occurs. Initial gradation of the material has a significant effect on the amount and type of void reduction which occurs. Studies have shown that compaction of single-size particles results in higher amounts of particle fracture. However, with the inclusion of a range of sized particles, researchers have found that the amount of fracturing diminishes significantly (Reference 17).

The type of machinery used also affects the goal of producing the highest density possible. Frictional forces commonly develop along the walls and the top and bottom of the pressing die. These frictional forces produce shear forces at the wall-particle interface resulting in nonuniform pressure distributions. Theoretically, the compacting pressure should be transmitted throughout the material, providing uniform pressure and constant density. This is not the case, however, as the frictional forces lead to various points of weakness in a pressure-produced compact. Various lubricants can reduce this frictional effect; however, they may have a detrimental effect on the strength produced (References 16,18). Figure 2 shows a typical pressure contour pattern which may develop in a high-pressure compact (Reference 18).

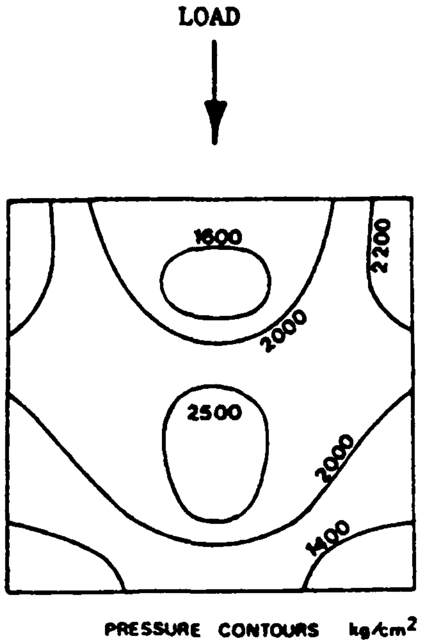


Figure 2. Typical Pressure Contours Which Develop in Prepared Compacts (Reference 18)

E. HIGH-PRESSURE COMPACTION OF PORTLAND CEMENT POWDERS AND PASTES

A thorough search of the literature yielded very little information on the high-pressure compaction of portland cement systems. The search, however, provided substantial amounts of information concerning the high-pressure compaction of portland cement pastes and anhydrous powder (References 19,20,21,22,24,25, 31).

From the literature surveyed, the high-pressure compaction of both cement pastes and anhydrous cement is typically performed with the aid of a specifically designed die or mold (References 20,22,23). High-pressure compaction of a material with a die consists of the placement of the anhydrous powder or cement paste in the die chamber and the insertion of a plunger into this chamber to compact the material. The degree of powder compaction can either be limited by the stroke of the ram or by the level of compaction effort applied (References 20,22).

Because of the extremely high production pressures, dies must be made of high-strength materials. To eliminate as much of the friction as possible between the plunger and the die walls, dies must be made of hardened steel with smoothly tooled surfaces (References 20,22). The tolerance of fit between the plunger and the die chamber is also critical, because powder under pressure will "escape" around the plunger, leading to an increase in the friction between the plunger and the die walls. In many instances this friction is reduced with the use of special lubricants such as stearic acid or mold oils (References 19,20,24).

Generally, high-pressure compaction produces small specimens, whether with anhydrous cement, paste or mortar (References 19,20,21,22,23,24). This is because smaller specimens permit the use of smaller capacity production equipment such as hydraulic presses and because more specimens can be made more quickly and cheaply under stricter quality control conditions (Reference 22). Compacts of 1 cubic centimeter are commonly produced (Reference 22). Samples have been produced as cubes, cylinders, and disks (References 20,21,22,23).

The level of compaction pressure varied and seemed to depend on the general intent of the individual laboratory program and the limits of the available equipment. The lowest compaction pressure in the literature was 1500 psi (10.3 MPa) while the highest appeared to be 116,000 psi (800 MPa) (References 20,21). The rate of loading was seldom mentioned in the literature. Two values reported were 4,380 psi (30.2 MPa) per minute in one instance and 11,220 psi (77.4 MPa) per minute in another (References 20,22).

Researchers seem to think it is advantageous to hold the production pressure for a spefified period once the desired pressure level has been reached (References 19,20,22,23,25). In these studies typical holding times of 1 to 3 minutes were commonly used, with excellent results. However, it appears that holding the production pressure for an excessive amount of time has little effect on the initial porosity of the compact or its ultimate compressive strength (References 19,20,22,23).

For an anhydrous material, the quality control of the prepared compacts was much better than for a paste or mortar material (Reference 22). There were no complications concerning the correct amount of water and the mixing. Calculation of the initial porosity of the unhydrated compact was simple as the specific gravity of the powder, bulk weight and and bulk volume provided this value. The mixing water content in this type of compact will be essentially the volume of the void within the cube which will be filled with water upon immersion, and the initial porosity of an anhydrous compact will be a crude measure of the water-cement ratio for a prepared compact.

A unique phenomenon makes paste material attractive for high-pressure compaction tests, because there is an optimum water content for each production pressure. This is defined as the water content at which water from the paste material was not pressed out as a specific compaction pressure was applied (Reference 21). This optimum level decreases as the compaction pressure increases.

The optimum water content is unusual, because compacts prepared with amounts of water increasing from zero to the optimum level exhibited increasing density, while compacts prepared with water contents above the optimum level, exhibited lower densities. The strengths at early ages followed the same pattern; i.e., increasing with higher density and lower porosity.

However, over time, the effects of this initial finding became less evident due to the formation of hydration products (References 19,21). In summary, it appears that with high-pressure compaction of portland cement, a certain optimum water content acts as a lubricant between the individual particles of cement resulting in denser, lower-porosity materials at a given production pressure.

Studies show that cements with lower specific surface areas (coarser material) compacted at the lower production pressures, produce compacts of lower apparent specific volumes (Reference 20). This means that for the compaction of coarser materials, the resultant porosity is lower than that of the finer materials. This relationship is more evident for the lower production pressures. Concerning the importance of particle size distribution, it appears that a mix combination of two-thirds coarser particles with one-third finer particles will result in the lowest porosity for a given production pressure (Reference 20). A similar coarse-aggregate to fine-aggregate ratio is needed for a well-graded concrete mix.

In the formation of portland cement compacts there is difficulty in controlling the porosity and dimensions of the prepared compact because of expansion upon the removal of the compaction pressure. This is typically overcome by taking the expansion into account and adjusting the quantity of initial material inserted into the die. In this way, fairly constant results can be obtained. This expansion primarily depends upon the characteristics of the powder (References 20,22).

Another problem is termed the "detachment of end caps," referring to the formation of small cracks around the perimeter of the prepared compact at the surface where the plunger applied the compactive pressure. These cracks usually extend into the compact and intersect internally at a certain distance. This results in a "cap-like" failure on that surface of the compact (Reference 20).

Possible explanations for this failure are:

1. Nonuniform powder distribution in the die chamber before the compaction pressure is applied may result in shear concentrations, resulting in nonuniform expansion upon release of the compaction pressure.

2. Insufficient rigidity in the material of the die wall may allow the compacted material to expand radially during compaction causing a shear failure at the point of pressure application.

3. Residual triaxial compression-tension stresses may be created, if the radial pressure that develops between the compact and the die wall does not dissipate as the compaction pressure is released.

4. The outer surface of the compact might develop a crack if, upon the removal of the compaction pressure, a nonuniform expansion is caused by friction between the die wall and the powder.

5. The compact may burst upon removal of the compaction pressure through the release of pockets of compressed air.

It appears that this "cap" failure is minimized by the use of lubricants on the die walls and the ram - powder interface (Reference 20).

Before the hydration process begins, the compact is stable only because of the adhesive forces present between the particles (Reference 20). Curing conditions for compacts prepared in previous work vary as much as the production pressures. Much of the work utilized curing conditions which involved high-temperature curing (References 19,20,22,24,26).

Generally, the most common curing regime for simple compressive strength determinations is the immersion of the compacts in deionized or distilled water for the required time (References 19,21,22,24). The temperature of this water ranged from 68° to 70°F (20° to 25°C). The extreme internal pressure caused the calcium hydroxide produced in the hydration process to leach from the compacts. Some researchers believe that compacts cured in a saturated lime solution will provide zero to minimal leaching (Reference 29). Further studies have proved otherwise (Reference 29).

Testing conditions were numerous and varied. Loading rates varied from 4,350 psi (30 MPa) per minute to 8,000 psi (55 MPa) per minute (References 19,20). In one instance, the surface was ground to obtain a smooth surface for testing (Reference 20). Occasionally, special devices were employed for loading because of the small size of the compacted specimens (Reference 22). There was no record of end-capping.

F. HYDRATION OF PREPARED COMPACTS

The process of hydration in high-pressure compacts is more complex than in normally prepared material. Generally, as the compaction pressure decreases, the resulting compacted material will have a higher degree of hydration (Reference 21,28). The greater the initial porosity level, the greater the degree of structural change within the compact from curing (Reference 28). Compacts prepared at higher compaction pressures, with the resultant increase in structural density, exhibit slower rates of hydration and hydrate at later ages (Reference 28).

However, for the condition of initial porosity where less hydration product is formed, this hydration product has a far greater effect on strength, primarily because of the relatively large increase in surface area contact between the various products in the system. The resulting percentage change in total porosity is also greater (Reference 21). This process is referred to as an increase in the specific binding capacity of the hydration product formed (Reference 28).

It has been generally believed that no new forms of hydration product are produced as a result of high-pressure compaction (References 23,28). Upon visual inspection with sophisticated equipment, products of C-S-H, calcium hydroxide and other common hydration products are clearly visible, however in decreasing amounts as the initial porosity decreases (Reference 28). The characteristic fibrous growths, rosettes of the C-S-H materials, and platlets of calcium hydroxide become less evident as the production pressure increases (Reference 23). In general, the greater the production pressure, the more amorphous the structure of the compact appears. The rate of hydration product formation also influences the microstructure of the compacted material (Reference 23).

The extremely high concentration of cement material present in pressure-prepared compacts may have negative effects on the hydration process. Chief among these are extremely high-temperature evolutions leading to thermal cracking, deleterious expansion of the compact if hydration proceeds at an uncontrolled pace, and the formation of a limiting mechanism which hinders the hydration of material deeper within the compact. Concerning the first two potential problems, subsequent laboratory tests have shown that neither extremely high temperature evolutions nor uncontrolled expansion occurs for smaller-sized compacts, but as the size of the compact increases, these effects may become more influential (Reference 20).

The concept of a limiting mechanism has some merit. In theory, there is a limited amount of water for hydration, which permeates to the inner portions of the compacted material. Permeability is further reduced by the formation of hydration products in the outer portions of the compacted material, which can virtually eliminate the exposure of the unhydrated material within the compact to water (References 20,29,30). This hydration reaction has been described as occurring in two stages (Reference 29). The first stage involves hydration occurring through solution with the hydration product precipitating on the surface of the cement grains. This type of hydration occurs upon the initial exposure of the prepared compact to a curing solution. The second stage is hydration through diffusion which occurs at the cement - gel interface. The necessary moisture must pass through the cement gel which has developed around the individual cement grains (Reference 29). Studies show that the rate of take-up of water decreases with decreasing initial porosity and also with increases in curing duration (Reference 20). However, during this second stage the diffusion rate of water through the hydrate layers can be materially increased by raising the curing temperature, as will be shown later in this report.

The average density of the hydration product in high-pressure prepared material increases with (1) the increase in the degree of hydration and (2) the decrease in the initial porosity (References 29,30). This relationship is a result of pressure build-up due to volume constraints which develop in the compact as the hydration product forms. The hydration products produced by diffusion are denser than formed by solution (References 29,30). The relative amount of hydration product formed by diffusion increases with an increase in degree of hydration and a decrease in porosity (References 29,30).

G. STRENGTH - POROSITY CONSIDERATIONS OF PREPARED COMPACTS

The inverse relation between strength and porosity, when combined with the formation of hydration product relationship, reveals two important general rules. First, compressive strength increases with a decrease in porosity, and second, conditions of greater initial porosity allow for greater formation of hydration products. Therefore, compacts with higher initial porosities will show a greater amount of strength gain with time (although not necessarily greater strength), than compacts with lower initial porosities (References 19,20,25). This relationship between porosity and strength for an initial porosity range from 20 to 35 percent appears to exist as a simple linear relation (References 19,20,25). Elimination of as much initial porosity as possible is the most influential method of producing a high-strength material (References 19,20,25).

The level of initial porosity obtained in compacts of portland cement depends on the amount of compaction pressure used and the cement particle size distribution (Reference 20). An initial porosity level of 20 to 35 percent has been achieved in laboratory studies (References 19,20,25,30).

Assuming the specific volume of evaporable water is unity, the final porosity of a compacted material can be estimated by the quantity of evaporable water at 220°F (105°C) (Reference 29). This estimation accounts for a large portion of the gel porosity as well as the capillary porosity present in a hydrated system. Some observers feel, however, that at the temperature used to determine the "total" free water content, some free water still exists within the paste which contributes to the total porosity content (References 12,13). For this reason, another procedure often used is a loss on ignition test at 1800°F (1000° C) which has produced final porosity levels ranging from 10 to 30 percent (References 19,20,21,26,29). These lower final-porosity values have been achieved with addition of heat to the process of compaction and subsequent curing (References 26,32).

Because of the numerous variables effecting the strength of the compacts, it is very difficult to compare the strengths achieved from the various studies. Compressive strengths as great as 40,000 to 50,000 psi (280 to 340 MPa) have been obtained in 28 days in a simple laboratory situation of high-pressure compaction and moist curing of small compacts, but in many cases the small size of the test specimens had a tremendous influence on the results (References 20,24). Compressive strengths approaching 95,000 psi (650 MPa) in 28 days have been produced by heating the material while compacting (References 23,24,31). This procedure, termed hot-pressing, caused a more rapid hydration which caused a substantial material rearrangement within the microstructure of the material (Reference 24). This method achieved an actual porosity of 1.8 percent, which is considered to be the closest approach to zero porosity or theoretical density for portland cement system attained (Reference 24).

A number of prediction equations have been proposed to predict the strength of prepared compact samples from their porosity levels (References 19,20). Theoretical ultimate strengths of approximately 72,000 psi (500 MPa) at zero porosity have been predicted by the compaction of anhydrous powder (References 19,20). Because of the initial anhydrous condition, this value is believed to be a prediction of the strength of anhydrous clinker material (Reference 20). The bond created in a portland cement system is a hydrate bond, however, and not a ceramic bond as exists in clinker material. Because of this, it appears that the ultimate strength of a hydrated material may be much greater, depending primarily on the amount of initial porosity reduction which can be obtained through high-pressure compaction.

H. POZZOLANIC REACTIONS

A pozzolanic reaction is a chemical reaction in which available siliceous materials react in the presence of water with the free lime or calcium hydroxide ($Ca(OH)_2$) produced by the hydration process to produce calcium-silicate-hydrates (C-S-H). In equation form this reaction can be written as :

$$CH + S + H \Rightarrow C\text{-}S\text{-}H$$

where: CH represents calcium hydroxide,

S represents silica dioxide,

H represents water, and

C-S-H represents calcium-silicate-hydrate formed (Reference 13).

The lime itself is not cementitious in nature, but the addition of a pozzolan to portland cement results in increased strength by transforming the noncementitious lime into cementitious calcium-silicate-hydrates. In this way a pozzolanic material increases the concentration of strength-producing calcium-silicate-hydrates at the expense of free calcium hydroxide.

I. FLY ASH AS A POZZOLAN

ASTM C618 defines a fly ash as a pozzolan normally produced during the burning of coal products in a furnace (Reference 33). A Class "C" fly ash is one which possesses both pozzolanic and cementitious properties and generally contains a considerable amount (>10 percent) of lime (in a combined state). A Class "F" fly ash has pozzolanic properties only and generally contains little or no lime. The Class "F" fly ashes are considered low-lime fly ashes while the Class "C" fly ashes, which contain as much as 40 percent lime in a combined state, are considered high-lime fly ashes (Reference 34).

During the exposure to the extremely high temperatures in the boiler, the noncombustibles in the coal form tiny spherical droplets varying in size from 1 micron to 1 millimeter. Figure 3 shows a example of Class "C" fly ash particles as photographed by a scanning electron microscope and magnified 3000 times.

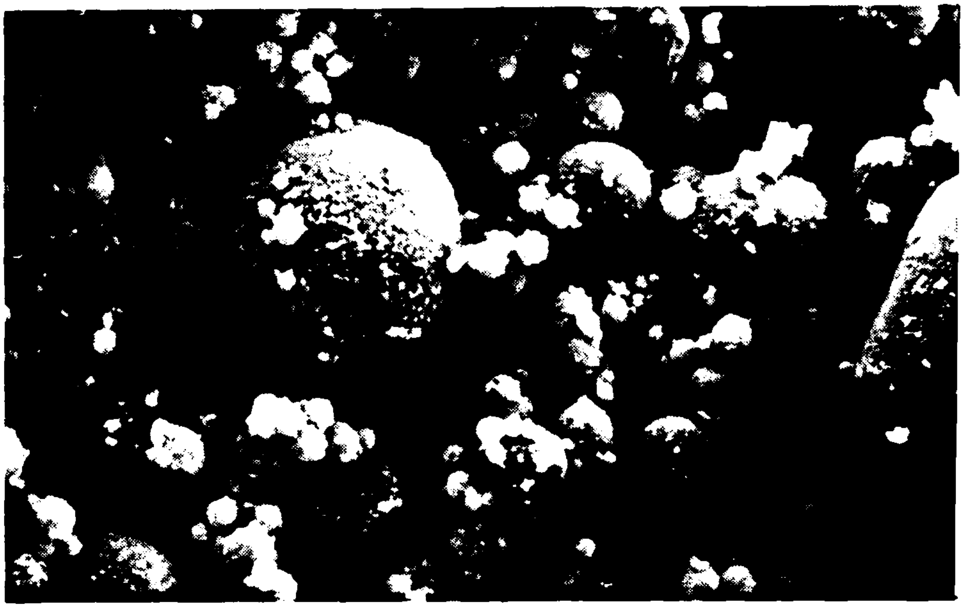


Figure 3. Typical Class "C" Fly Ash Material
Magnified 3000 Times

In general, the finer the fly ash, the greater the amount of pozzolanic activity (Reference 34). Since most fly ash are of the coarser variety, the consequential low surface area results in a slower lime-pozzolan reaction in the presence of water. This is why many portland cement products containing fly ash as a pozzolan often exhibit lower early compressive strengths, but, at later ages, produce substantial strength increases. This development of higher ultimate strengths makes fly ash very attractive as a partial replacement for portland cement (References 1,2,5,8,35).

Better workability, placeability, finishability and pumpability all improve in a mix containing fly ash. Often the water-cement ratio can also be lowered, since much of the water used in a mix is for workability. Fly ash will lower the rate of heat liberation due to a decreased rate of hydration. Impermeability and durability of hardened concrete are also improved (References 8, 35).

Typically, rates of replacement of the fly ash for the portland cement range from 15 to 30 percent and can be done on a pound for pound basis provided a high-lime, good quality fly ash is used (References 1,2,8,34). The optimum amount for replacment depends upon mix characteristics, as well as the reactivity of the fly ash used.

SECTION III

LABORATORY INVESTIGATION

A. Materials and Equipment

The cement selected was Type III cement produced by Texas Industries Inc. at their Midlothian, Texas plant. The fly ash selected was an ASTM C618 Class "C" produced at Caison, Texas and marketed by Gifford-Hill Company of Dallas, Texas. Complete chemical and physical analysis test results for both materials are included in Appendix A.

The die equipment (patent pending) for this study was designed and developed by Dr. Matti Relis (References 22,29,30,31). Figures 4 and 5 show disassembled and assembled views of the die, respectively. This particular die is segmented, with the four interior segments tooled for exact fit and held together by a clamp ring bolted to the baseplate. The compacting ram is then inserted into the chamber formed by the tooled segments. The die is fabricated entirely from A-2 tool steel and heat-treated to a Rockwell C60 hardness.

For a summary of the actual operation of the die, see Appendix B. The die functions on the general principle that, by controlling the depth at which the ram penetrates into the die chamber, all compacts prepared will be nominally of the same size. This is accomplished through the use of the spacer piece which surrounds the ram. As the compactive force is applied, the ram head will come into contact with the spacer disk and at this instant, compaction effort is halted. Porosity of the prepared compacts is controlled by the amount of powder initially placed in the die chamber and the applied compaction pressure.

B. Program Design

The calculated initial porosity, percentage fly ash replacement by weight for cement, and curing duration were selected for investigation. The target values for initial porosity were 20, 23, 26, 29, and 32 percent. This range of values was chosen so that a distinct relationship could be determined concerning the effect of porosity on the other variables. Four fly ash replacement values were selected; 0, 10, 20, and 30 percent by weight of the cement. All compacts were prepared with anhydrous material. Three, 7, 28, and 90-day curing times were utilized.

In addition to the possible combinations of the three main parameters, compacts were prepared for testing in both saturated surface dry (SSD) and oven-dried (OD) condition. The primary purpose of preparing compacts for both of these conditions was to determine an approximation of the final porosity of the compacted material. The process of oven-drying had a significant effect, producing a much higher strength material, probably due in part

Figure 4. Disassembled View of the Die Used for Compaction

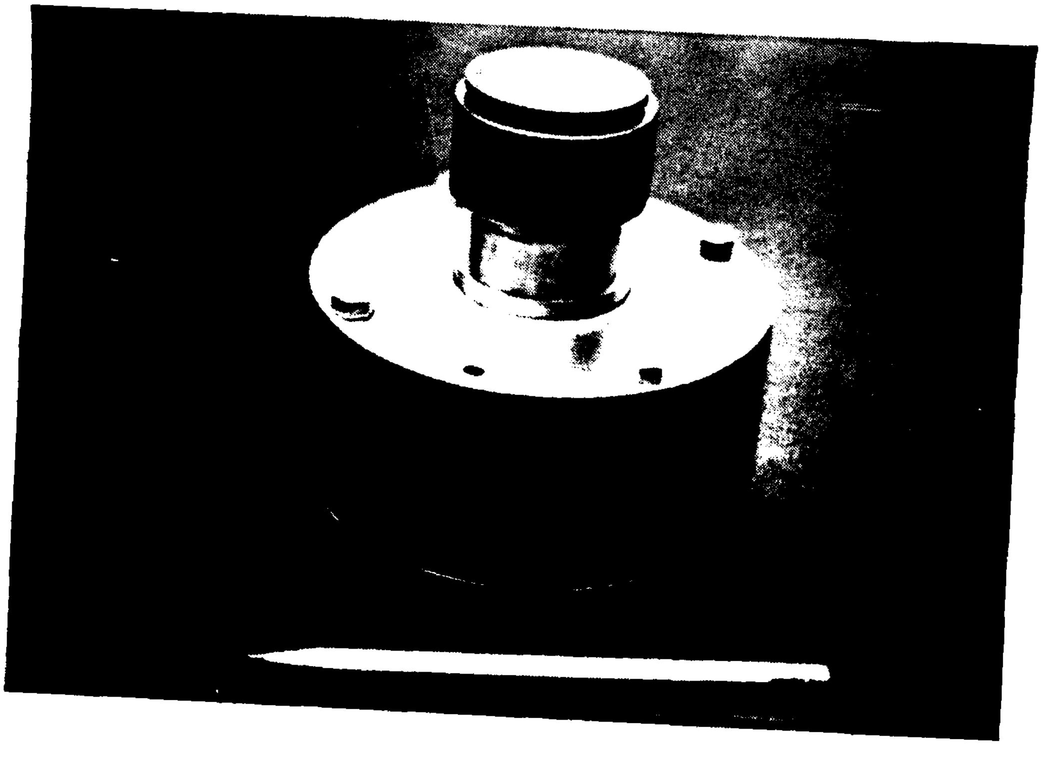


Figure 5. Assembled View of the Die Used for Compaction

to restrained shrinkage stresses which developed in the dried compact, but primarily due to accelerated water diffusion rates.

Unforeseen complications developed associated with the high-pressure compaction of two very different powder materials. Figures 6 and 7 show the variations in size and shape between the rough, angular, irregular shaped particles of the cement and the smoother, more spherical particles of fly ash. Laboratory experimentation demonstrated that the raw fly ash contained some extremely large particles which disrupted the proper high-pressure compaction of the compacts. Larger spherical fly ash particles not compatible with the angular crushed cement particles were eliminated by using only fly ash which passed an ASTM 100 wire mesh sieve (i.e., < 150 microns).

This sieving process also virtually eliminated all visible unburned carbon particles from inclusion in the compacts, producing a more compatible gradation of fly ash and more physically stable prepared compacts.

The laboratory program in Table 1 was developed and used throughout the project.

For control purposes and ease in terminology throughout the project, the term "series" was used to define set of prepared compacts having the same parameter values as defined in Table 1. Each "series" consisted of at least six individual compacts (of eight that were prepared), all having the same percentage of fly ash replacement for cement, the same target initial porosity and the same curing duration. A total of 74 series were prepared for testing in the SSD condition and an additional 74 series for the OD condition.

The numbering system shown in Figure 8 was used throughout the project. An alphabetical symbol (B, C, D, or E) was used to denote curing duration; an upper-case letter denoted a compact tested in the SSD condition and a lower-case letter denoted a compact tested in the OD condition. For the parameters of calculated initial porosity and percentage fly ash replacement of the cement material, numerical symbols as denoted in the figure were utilized. The letter "S" was used to denote when the sieved fly ash material was used. If no "S" appears, only cement was used. The letter "R" was added when it became evident that remakes of some compacts were necessary in an effort to collect usable data. In addition, each compact of a particular series was assigned a unique alphanumeric symbol for identification purposes.

C. PERFORMANCE OF THE LABORATORY PROGRAM

The first major step in the performance of the laboratory investigation was to determine the relationships among the amount of powder used, required production pressure, and the porosity produced by that amount of powder. For this determination, 10 series of three to eight compacts each were prepared from various

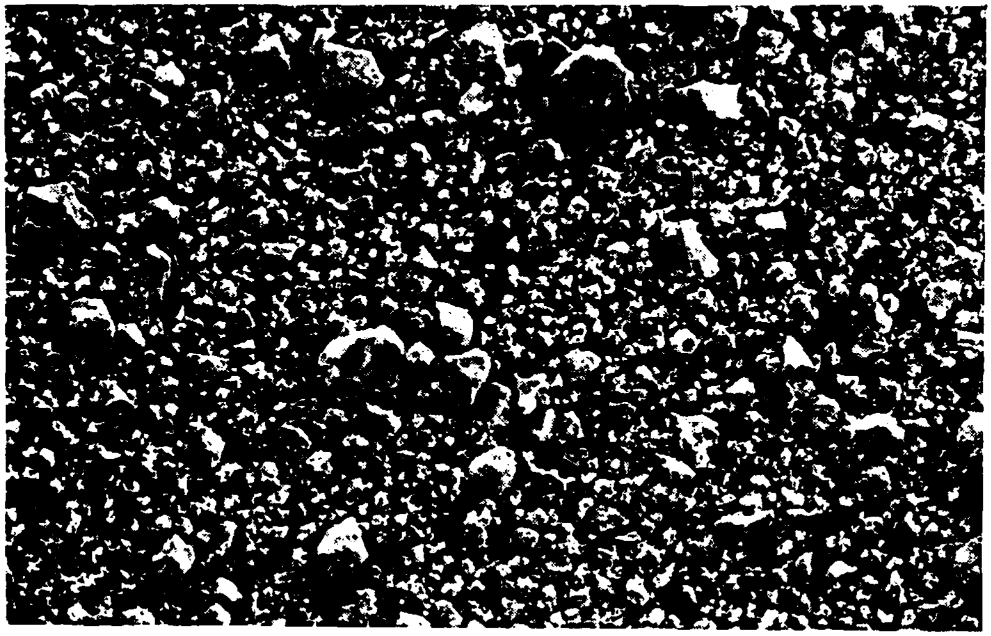


Figure 6. Typical Type III Portland Cement Material Used in the Compacts Magnified 300 Times

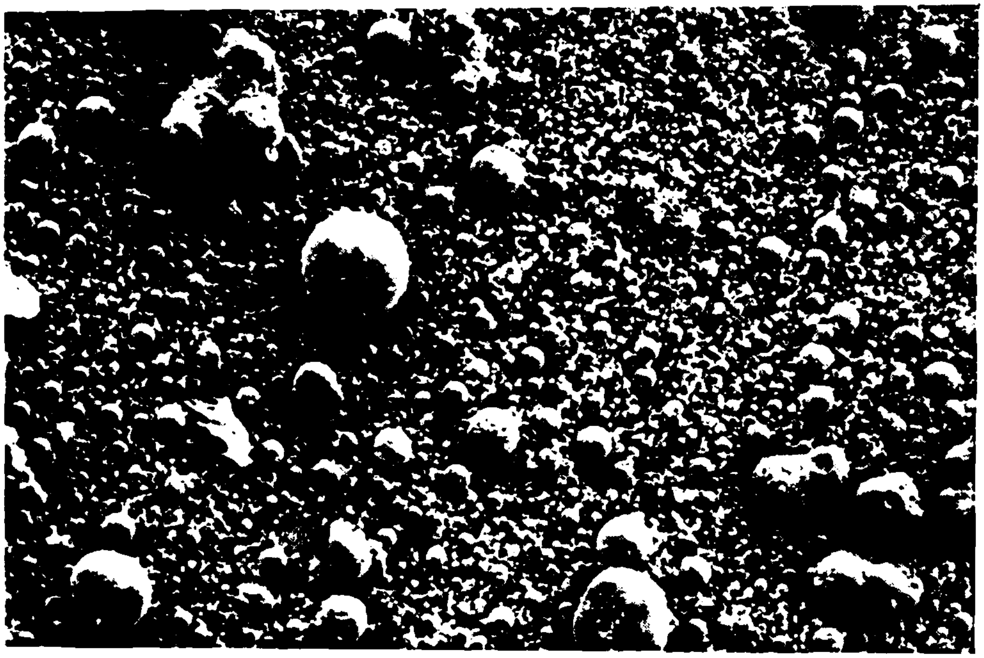


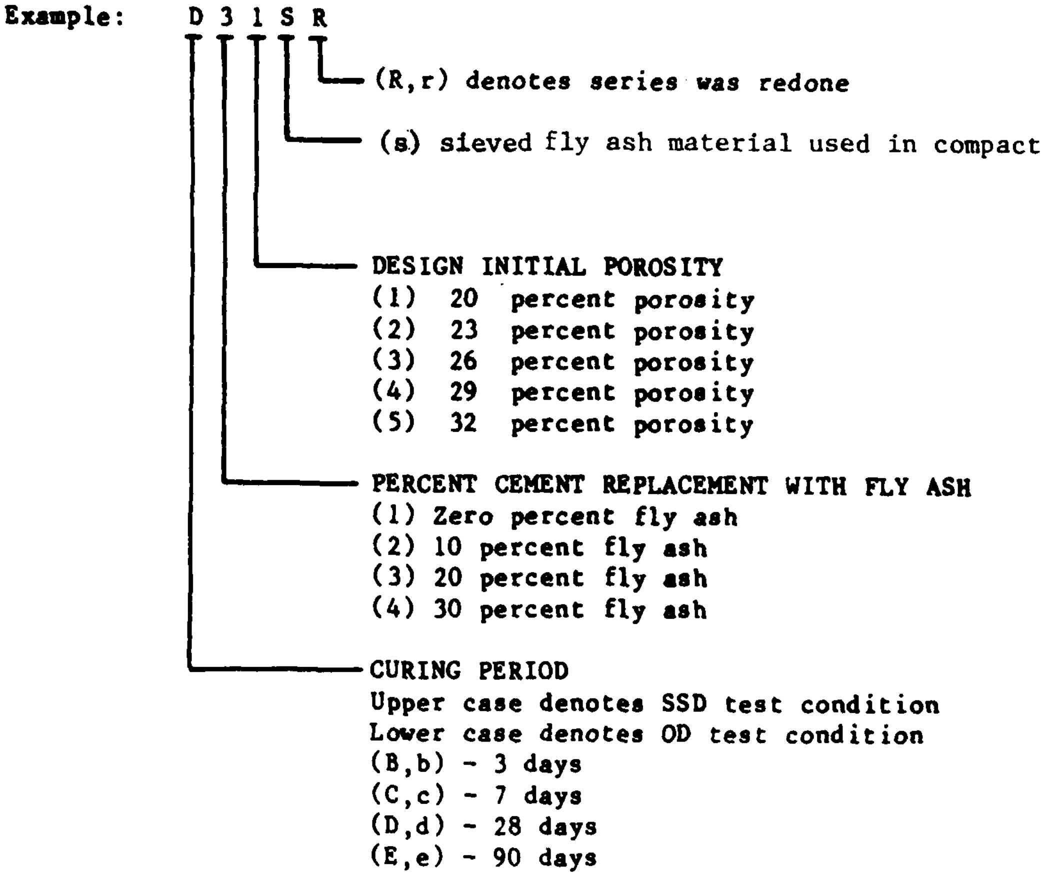
Figure 7. Typical Class "C" fly Ash Material Used in Compacts Magnified 300 Times

TABLE 1. TARGET-CALCULATED INITIAL POROSITY PERCENTAGE FOR THE LABORATORY PROGRAM

Curing Period (days)	Percent Fly Ash Replacement For Cement			
	0	10	20	30
3	20,23,26,29,32			
7	20,23,26,29,32	20,26,32 S	20,26,32 S	20,26,32 S
28	20,23,26,29,32	20,26,32 S	20,26,32 S	20,26,32 S
90	20,23,26,29,32	20,23,26,29,32 S	20,23,26,29,32 S	20,23,26,29,32 S

Legend:
1. S denotes compacts were prepared with sieved fly ash material passing a No. 100 sieve.

Note: All parameter combinations were prepared for testing in the Saturated Surface Dry and Oven Dried conditions.



Example: D 3 1 S R

(R,r) denotes series was redone

(s) sieved fly ash material used in compact

DESIGN INITIAL POROSITY
(1) 20 percent porosity
(2) 23 percent porosity
(3) 26 percent porosity
(4) 29 percent porosity
(5) 32 percent porosity

PERCENT CEMENT REPLACEMENT WITH FLY ASH
(1) Zero percent fly ash
(2) 10 percent fly ash
(3) 20 percent fly ash
(4) 30 percent fly ash

CURING PERIOD
Upper case denotes SSD test condition
Lower case denotes OD test condition
(B,b) - 3 days
(C,c) - 7 days
(D,d) - 28 days
(E,e) - 90 days

Figure 8. Compact Series Numbering System

amounts of anhydrous cement powder. The initial porosities were then calculated using the bulk volume, weight, and specific gravity of the cement. A linear regression analysis was performed to relate the amount of powder added to the die to the porosity obtained upon full compaction. Full compaction is defined as the compaction effort at the time the ram head contacts the spacer piece.

The resulting linear regression equation was:

$$P_i = - 17.8013 W_o + 71.2672 \quad (4)$$

where P_i is the calculated initial porosity, and

W_o is the weight of powder placed in the die for compaction.

The r^2 or coefficient of determination for this equation is 0.994 (Reference 37). Further discussion of the development of this equation is contained in Appendix C.

Because of this excellent relationship, it was simply a matter of solving the equation to determine the amount of powder to be used in producing a desired initial porosity. It is important to note that W_o is the weight of powder placed in the die before the compaction process and not the weight of the compact upon preparation. This method of weighing powder accounts for the minor loss of powder between the ram and the die walls during the compaction process.

The next major step, was to determine the powder weights needed to produce the desired porosity at each level of fly ash replacement for the cement. This was accomplished through the determination of a factor which accounted for the specific gravity of the fly ash and the percent replacement of fly ash in a particular compact. Once this factor was calculated, the needed powder weight necessary to produce a desired porosity was determined by multiplying the appropriate weight of cement by the appropriate factor. A complete discussion of this procedure is contained in Appendix C.

Figure 9 shows the essential steps followed in the production of the compacts. A more in-depth description is given in Appendix B. As shown in Figure 9, after curing, the compacts were weighed and measured in the SSD condition. Depending on the initial intent of the individual series, the compacts were then tested for compressive strength in the SSD condition or placed in a convection oven at 220°F (105°C) for determination of the final porosity. These OD compacts were also tested for compressive strength.

The last phase of the laboratory investigation involved the data preparation and analysis of all the various dimensions and weights obtained during the actual performance.

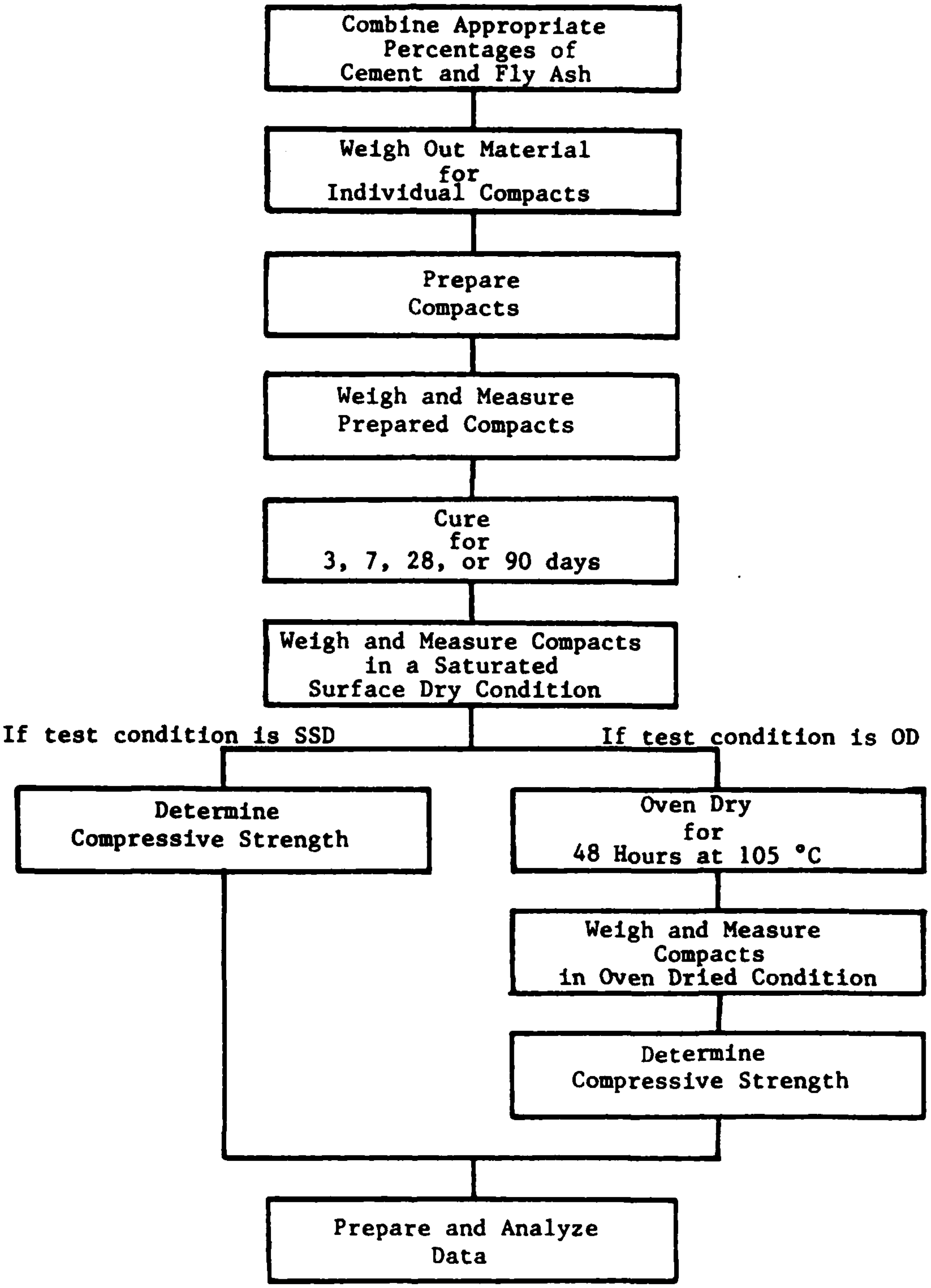


Figure 9. Flowchart of Laboratory Procedures

The initial porosity was determined for each of the individual compacts prepared, from the initial weight and dimensions. The equation used for the calculation of the initial porosity was:

$$P_i = 1 - ((W_1/V_o)((\%C/SG_c) + (\%FA/SG_{fa}))) \qquad (5)$$

where P_i is the calculated initial porosity,

W_1 is the initial weight of the prepared compact,

V_o is the volume of the prepared compact,

$\%C$ is the percentage by weight of cement in the compact,

$\%FA$ is the percentage by weight of fly ash in the compact,

SG_c is the specific gravity of the cement, 3.13 ,

SG_{fa} is the specific gravity of the fly ash, 2.71 for the unsieved fly ash material and 2.75 for the sieved fly ash material.

The derivation of this equation is given in Appendix D. Once the calculated initial porosity was determined for each individual compact of a certain series, an average calculated initial porosity was determined for that series. The standard deviation and coefficient of variation were also determined for each series. The same procedure was also followed for the various data contained in Appendix E. The values for each unique series are an average of the values for the six to eight individual compacts of each series. All further data analyzed in the following sections are based on these average values for each individual series.

SECTION IV

LABORATORY RESULTS

A. INTRODUCTION

Many of the data analyses contained in this section utilized linear regression analysis. Appendix F contains the pertinent data for each analysis performed and is referenced to the figure for which the equation applies. As the equations were generally not determined for predictive purposes, the figures in this section include only the coefficient of determination (r^2) for each relationship.

B. RESULTS OF DIE OPERATION

Figure 10 shows the relationship between the weight of the prepared compacts and the calculated initial porosity achieved for the various percentages of fly ash replacement for cement. Note the distinct delineation between the various percentages of fly ash. For all practical purposes, the weight values listed in this figure may be used for the approximation of the amount of powder material needed to produce a certain initial porosity. Judging from the coefficients of determination listed in the figure, the linear relationships determined between prepared compact weights and calculated initial porosities are excellent.

Furthermore, it appears that the initial prediction equation (Equation (4) in Section III and Equation (C-2) in Appendix C) for cement only (zero percent fly ash) can be used to determine the amount of powder necessary to produce a certain initial porosity. For the various percentages of fly ash (10, 20, 30 percent), the initial powder weights used appear to be less than the amount actually needed to produce a target initial porosity. This can be observed by entering Figure 10 with the weight of powder material needed to produce a desired initial porosity at a certain percentage of fly ash replacement, as taken from Table C-3, and reading the corresponding calculated initial porosity which should be obtained. This signifies that the factors which were used to determine the amount of material containing fly ash were slightly lower than needed. Perhaps the specific gravity of the fly ash material was greater than the 2.75 value determined in the laboratory and used throughout the project. This deviation did not alter the results.

Figure 11 shows the relationship between the weight of the prepared compacts and the production pressure. As the weight of the compact increases, the production pressure also increases. Note that the relationship is linear when plotted semilogarithmically, and the accompanying coefficients of determination signify an excellent relationship between the two. Again, as in Figure 10, a distinct delineation between the various percentages of fly ash can be observed. For a particular production pressure, as the percentage of fly ash

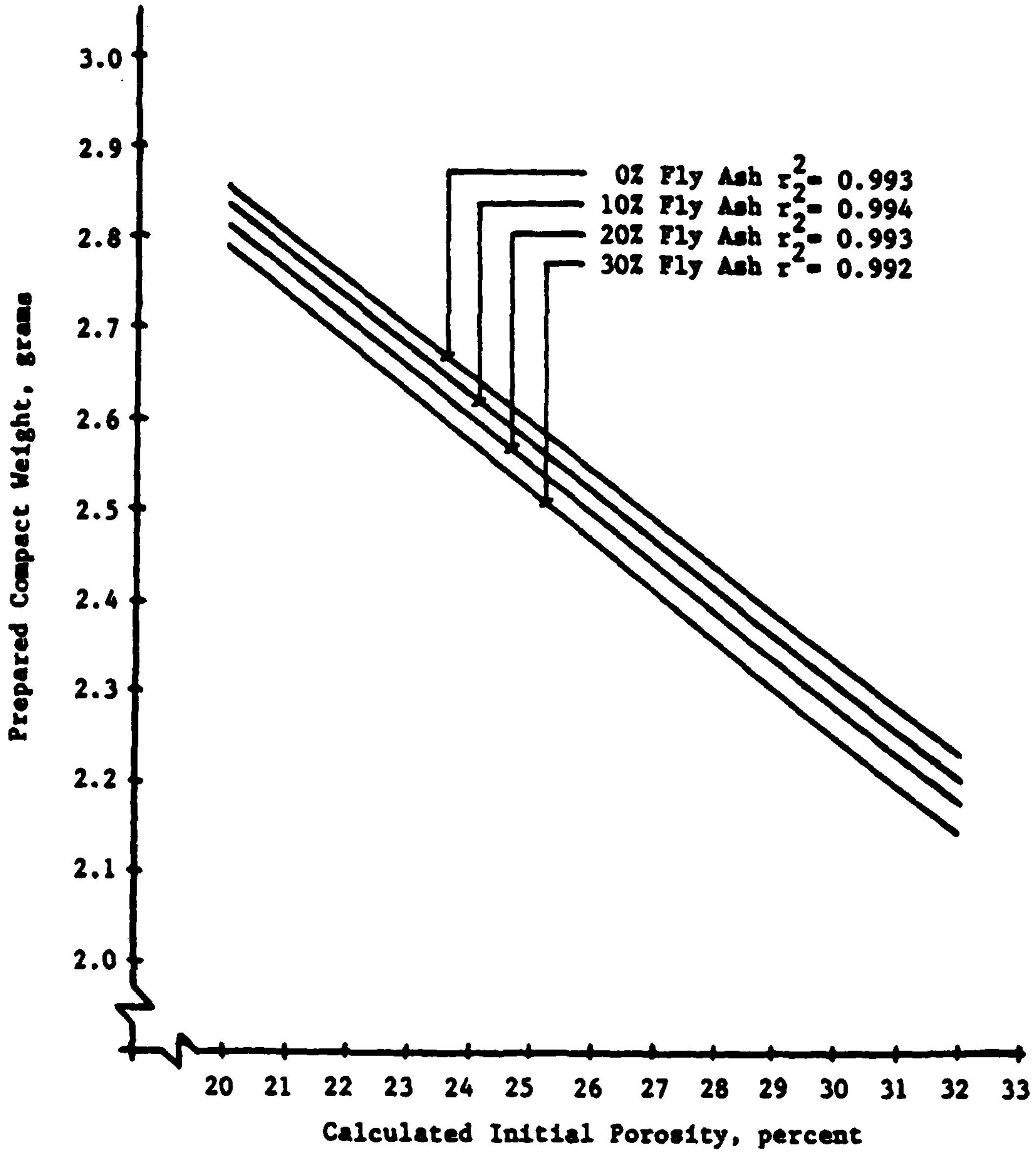


Figure 10. Prepared Compact Weight vs. Calculated Initial Porosity Relationship for 0, 10, 20, and 30 Percent Fly Ash Replacement

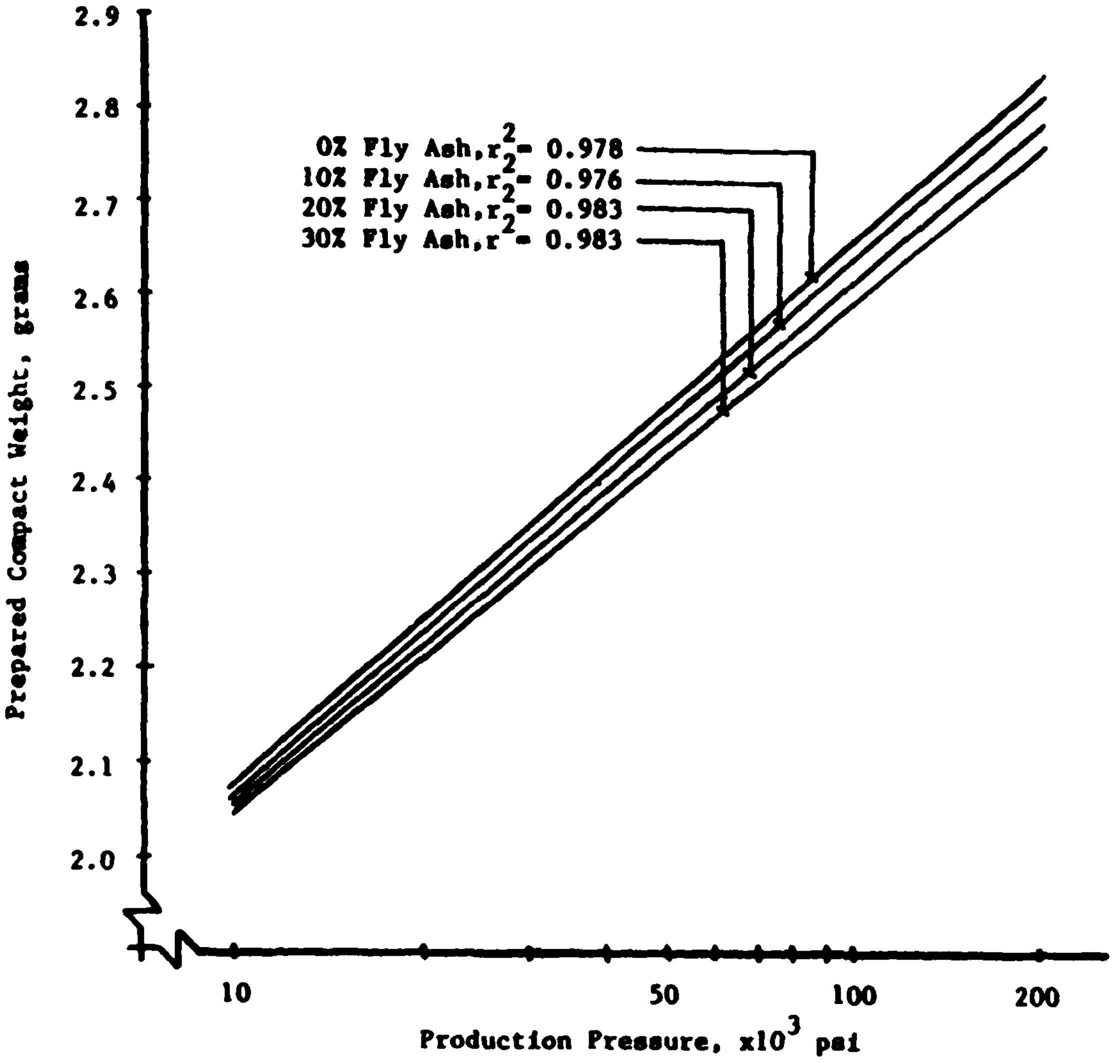


Figure 11. Prepared Compact Weight vs. Production Pressure Relationship for 0, 10, 20, and 30 Percent Fly Ash Replacement (Note: 1 psi = 0.006895 MPa)

decreases in the compacts, the weight of the powder needed and the resulting weight of the prepared compacts increases. This is because of the lower specific gravity of the fly ash.

There also appears to be a much greater difference between the weight of the prepared compacts containing 0 percent fly ash and 30 percent fly ash at the higher production pressures. The reason is unclear. One possible explanation is that, at the higher production pressures, more powder material is needed and the effects of an inaccurate specific gravity value for the fly ash may be compounded. Or possibly the contrast in particle shape and texture of the two materials causes the amount of compaction and porosity reduction to vary. A third possibility is that increased particle surface area in the compact is created by crushing fly ash particles in the compact at extremely high pressures. If this is the case, the formation of a greater number of smaller particles resulted in larger porosities, thus, less powder weight was required to achieve full compaction.

From the excellent relationships of prepared compact weight, calculated initial porosity, and production pressure, the calculated initial porosity and the Base 10 logarithm of production pressure can be considered synonymous in the analyses of data. Figure 12 shows that calculated initial porosity is inversely proportional to the log of the production pressure. Note the excellent correlation ($r^2 = 0.991$) although data for all percentages of fly ash were used. Hereafter, the terms, "production pressure" and "porosity" are considered synonymous.

C. RESULTS PERTAINING TO THE INITIAL PARAMETERS

From the final porosity determination of the OD compacts, a regression analysis was performed to relate the final porosity to the initial porosity. From the equations, the final porosity of the compacts tested in the SSD condtion were estimated and used for data analysis purposes. Since the final porosity depends on the initial porosity (and the synonomous production pressure), the relationship between final porosity and production pressure was analyzed (Figure 13). The best correlations were achieved by considering each percentage of fly ash replacement separately. For a given initial porosity, as the percentage of fly ash was increased, the final porosity also increased. This indicates the formation of less hydration product as the percentage of fly ash increases.

The general relationship of the lines representing the various percentages of fly ash indicate that the effects of fly ash on the final porosity become less as the production pressure is decreased (or the initial porosity is increased). This indicates that, at the higher initial porosity conditions, regardless of the percentage of fly ash, porosity is reduced the same amount by the formation of hydration products. At the lower initial porosity conditions, the formation of hydration product and the resulting final porosities are lowest when <u>no</u> fly ash is used. It should be noted, however, that FINAL strengths

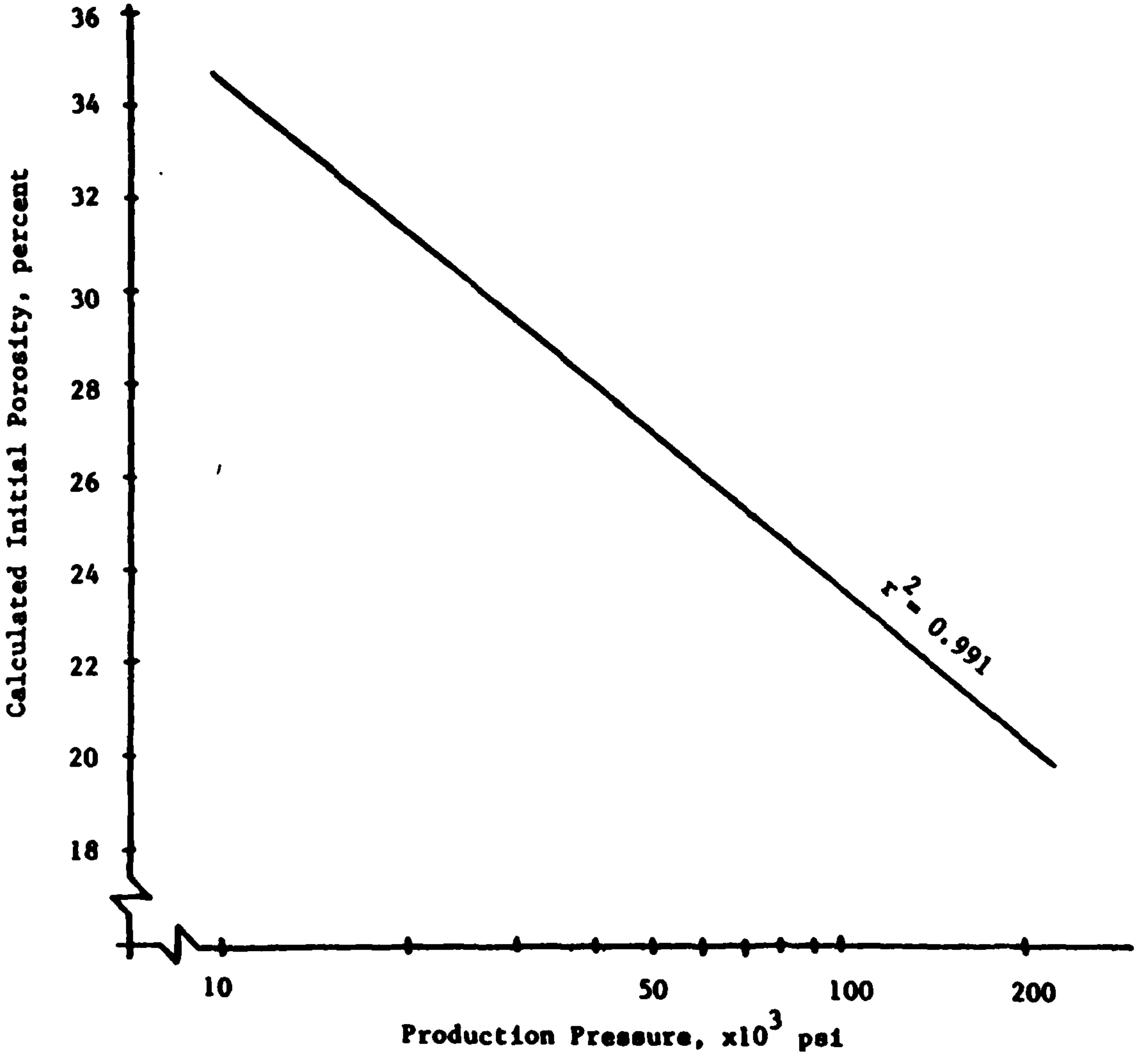


Figure 12. Normalized Calculated Initial Porosity vs. Production Pressure Relationship (Note: 1 psi = 0.006895 MPa)

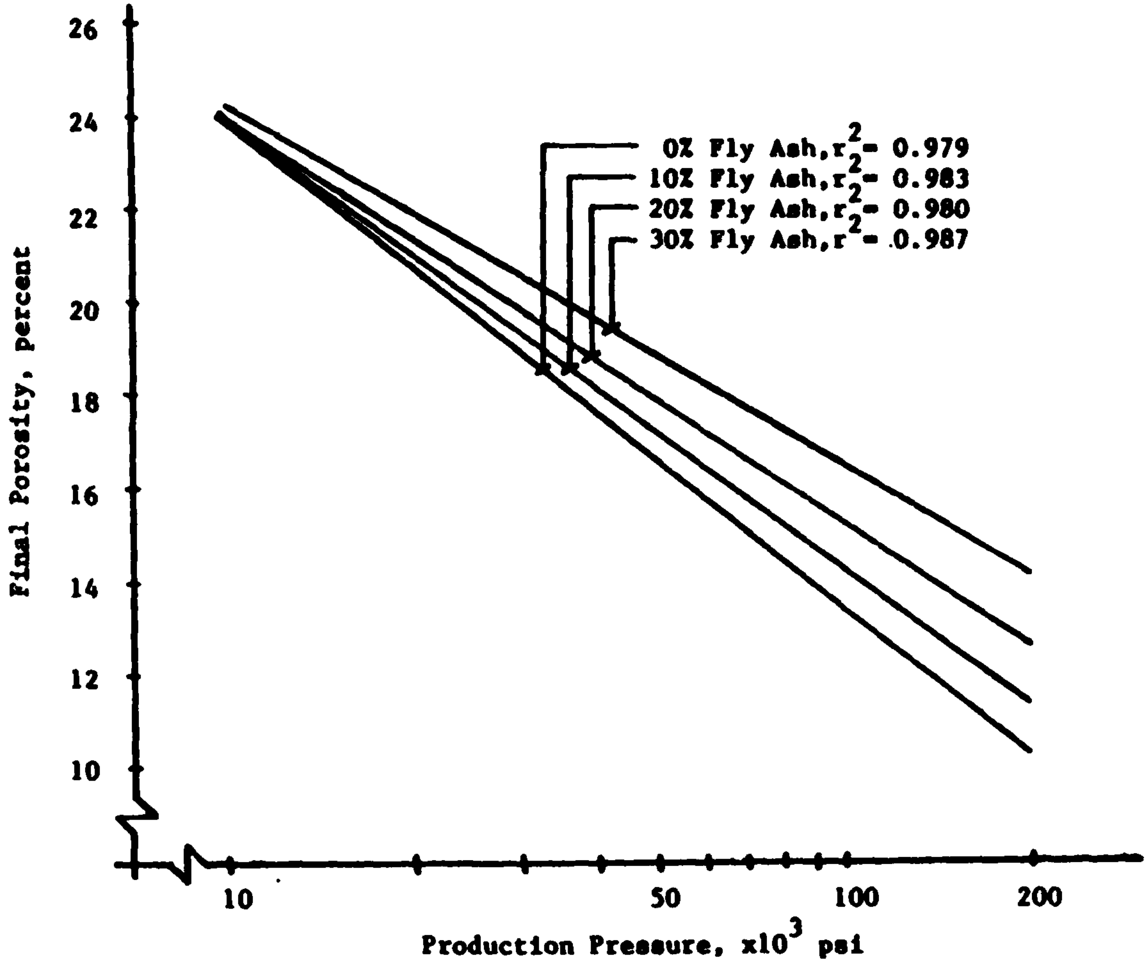


Figure 13. Final Porosity vs. Production Pressure Relationship for 0, 10, 20, and 30 Percent Fly Ash Replacement (Note: 1 psi = 0.006895 MPa)

follow the well-known rules governing strength development, which will be discussed in detail later in this report. One possible explanation may be that the low initial porosity conditions increasingly inhibit the formation of hydration products. Another key point is that, with increasing amounts of fly ash, less cement is present, which reduces the amount of hydration products and calcium hydroxide formed. This may be directly related to the amount of calcium hydroxide available for pozzolanic reaction. Since calcium hydroxide will only form in available free space, the low porosity may reduce both hydration and pozzolanic reactions.

Density determinations were made at the three distinct stages of the testing process as follows, (1) the initial density of the compacts before hydration, (2) an SSD density as the compacts were removed from the curing solution; and (3) an OD density after oven-drying for 48 hours. Figures 14, 15, 16, and 17 demonstrate the relationships between the various densities. As expected, as the production pressure increases, the densities of the compacts increase and porosity decreases. The difference between the OD density and the initial density is a measure of the amount of formed hydration product. Of course, the OD compact will still contain a certain amount of combined water in various stages. If this quantity of combined water is considered to be a constant percentage of the hydration product, then the general trends should be valid.

Figure 14 shows the density - production pressure relationships for the 100 percent portland cement compacts. A close examination of the relationship between the OD density and the initial density reveals that the difference in density (0.17 g/cm^3) at the lowest production pressure is greater than the difference in density (0.11 g/cm^3) at the higher production pressure. This signifies the formation of more hydration products at the lower production pressures, which have higher porosities. Figures 15, 16, and 17 show that similar relationships exist for the various percentages of fly ash replacements. As the percentage of fly ash in the compacts increases, the differences in the density-changes at the lowest and highest production pressures decreases. This is believed to signify the formation of less hydration products as the percentage of fly ash is increased, coupled with the formation of less hydration products as the production pressure is increased.

Since the density of the compacts is a function of the level of porosity they contain, examination of the change in porosity from the initial to the final condition should tend to support the statement that less hydration occurred as the production pressure increased, as Figure 18 shows. This finding focuses attention on the strength properties of the hydrate. Regardless of the quantity of hydrate, the highest strengths were achieved at the lowest porosities, as will be discussed later.

Figure 18 is a normalized representation of the porosity - production pressure data obtained during the investigation. The

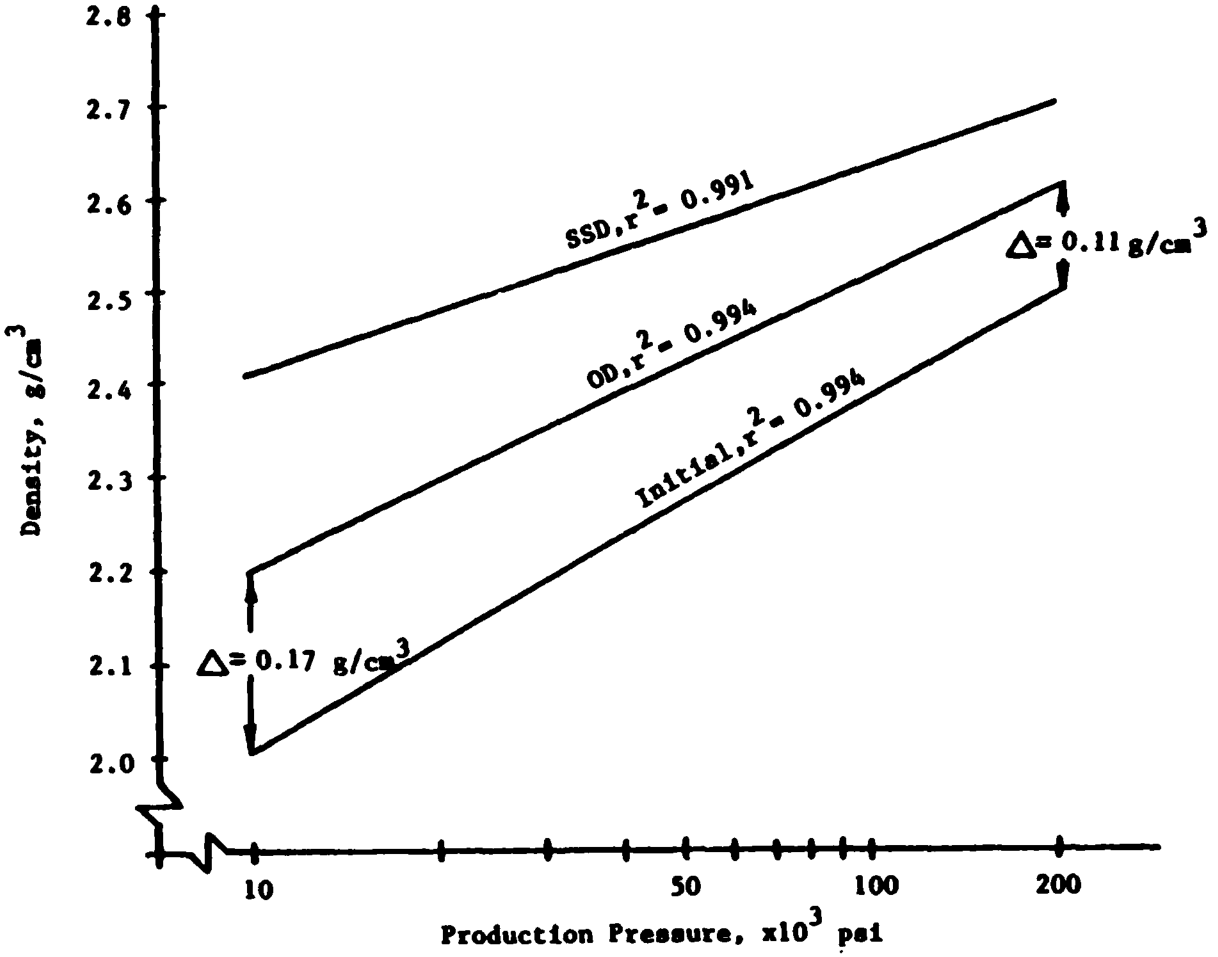


Figure 14. Density vs. Production Pressure Relationship for 100 Percent Portland Cement Compacts (Note: 1 psi = 0.006895 MPa)

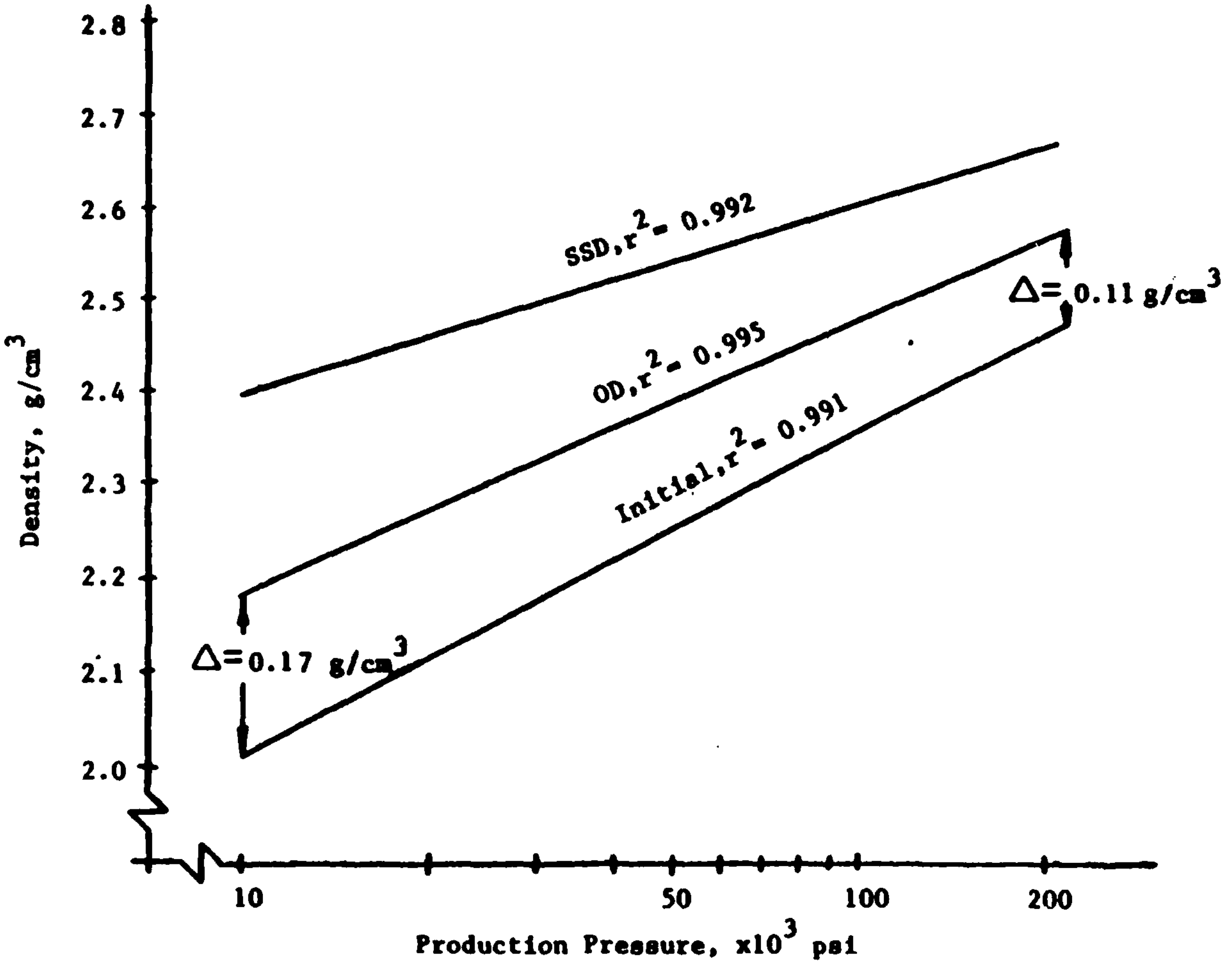


Figure 15. Density vs. Production Pressure Relationship for Compacts Containing 10 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

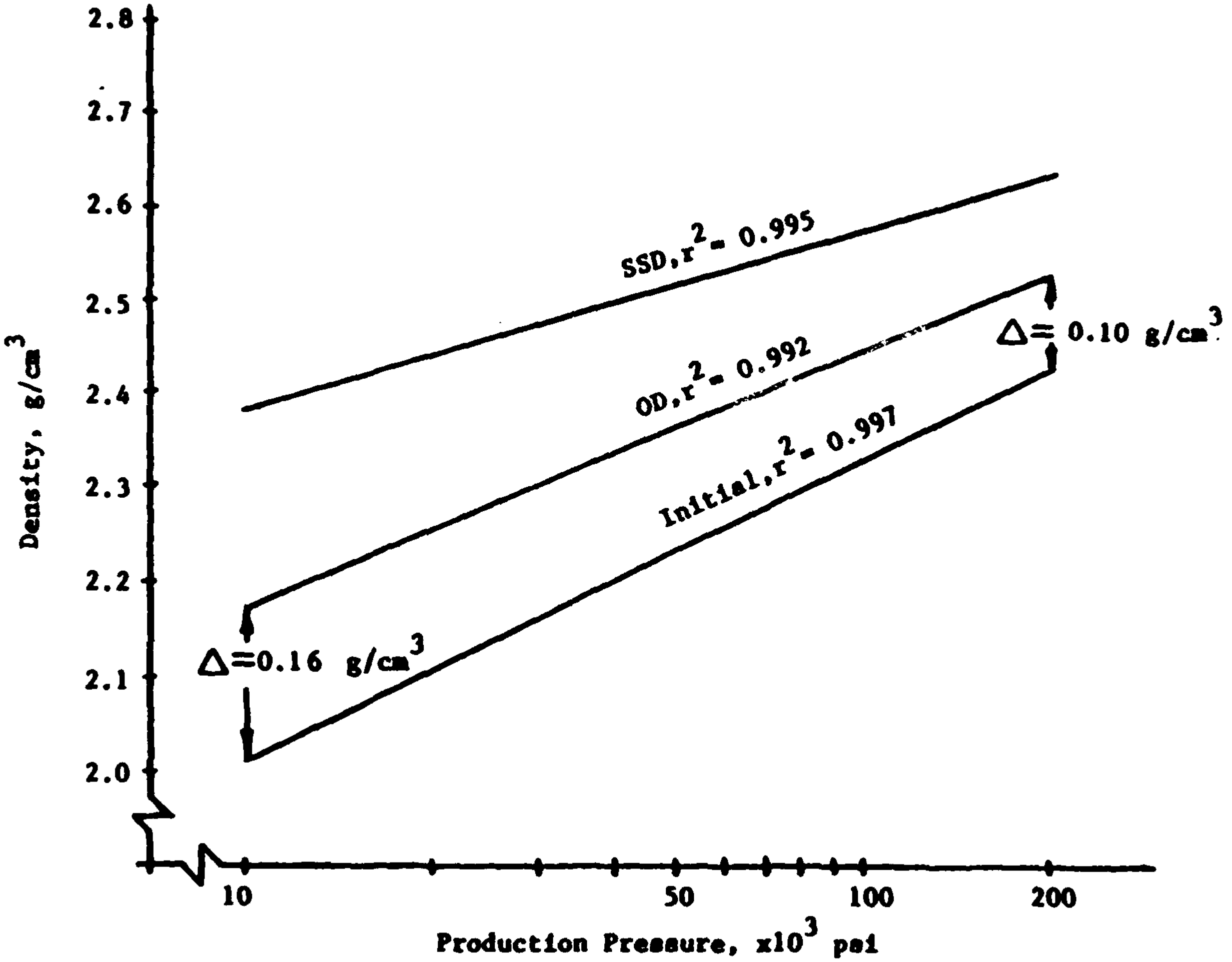


Figure 16. Density vs. Production Pressure Relationship for Compacts Containing 20 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

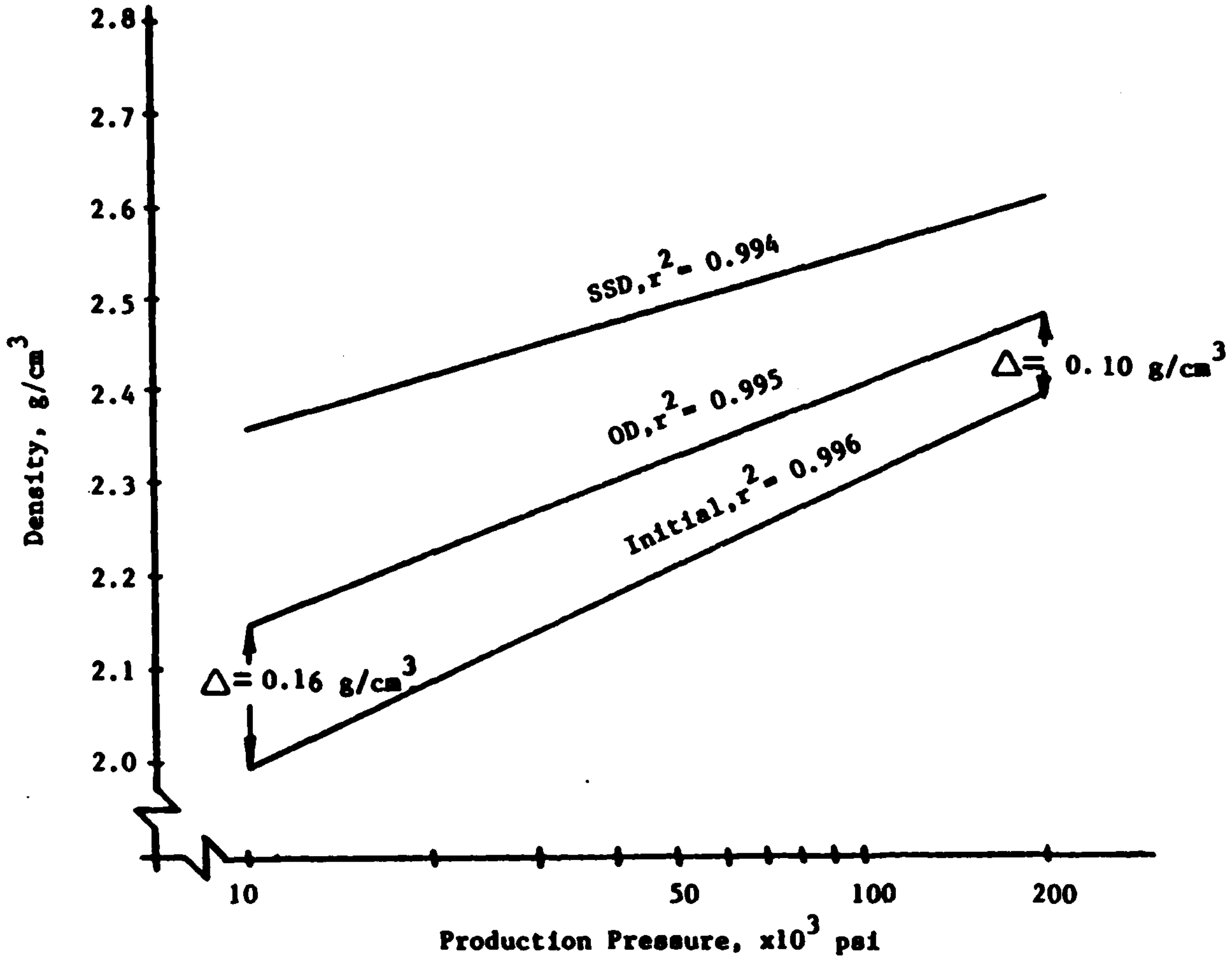


Figure 17. Density vs. Production Pressure Relationship for Compacts Containing 30 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

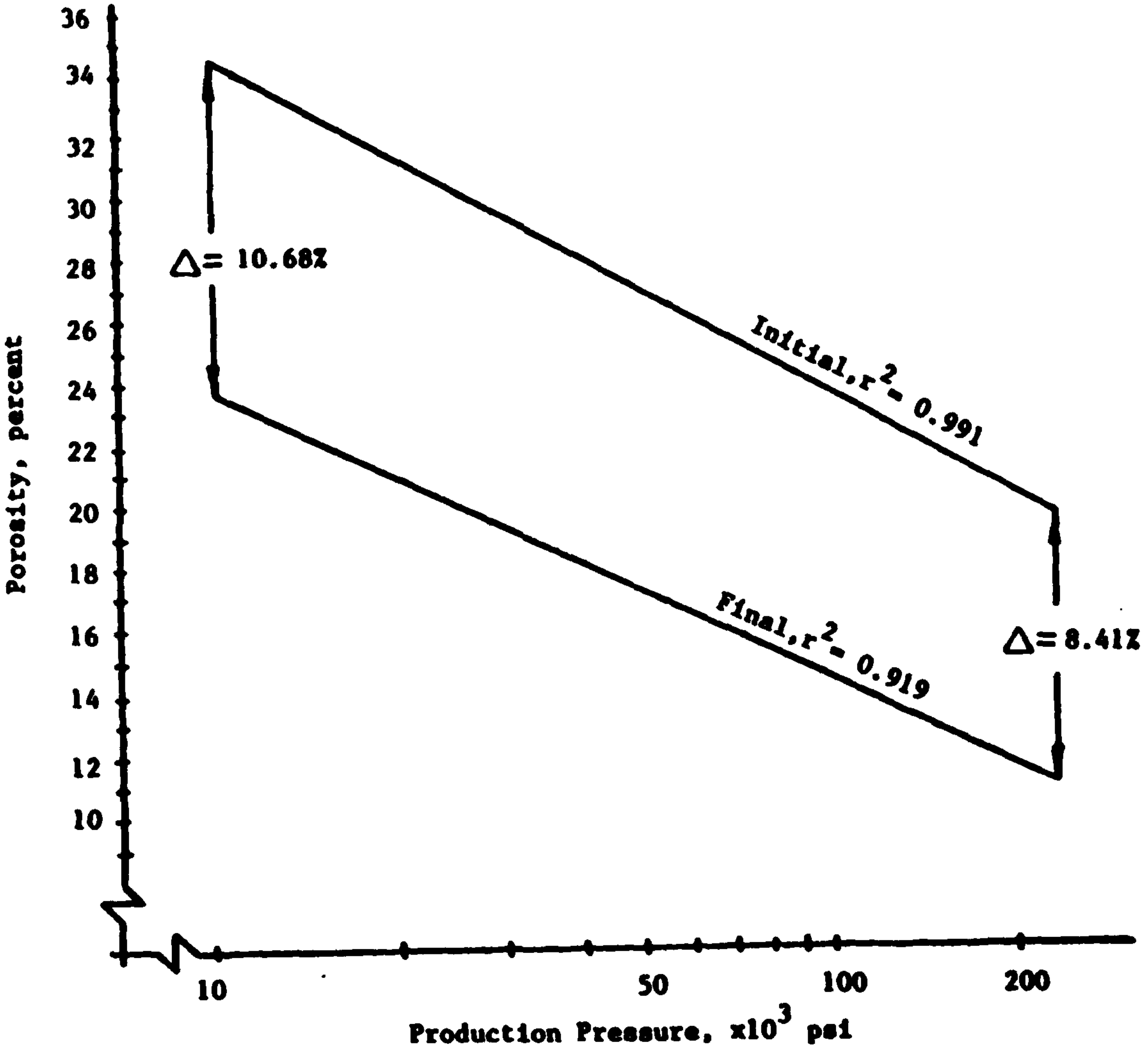


Figure 18. Normalized Final and Initial Porosity vs. Production Pressure Relationships (Note: 1 psi = 0.006895 MPa)

initial porosity line is the same as shown in Figure 12. To determine the change in porosity from the initial to final conditions, the final porosity line was added. For compacts prepared at the highest production pressure, the total average change in porosity was 8.41 percent. The compacts prepared at the lowest production pressure had an average change in porosity of 10.68 percent. This supports the statement that increased hydration occurs at conditions of greater porosity, resulting in a greater percentage reduction in porosity (but not necessarily a correspondingly large increase in final strength). Note further that, at the highest production pressure, the resulting change in porosity (8.41 percent) was a 41 percent reduction in porosity. At the lowest production pressure, the resulting change in porosity (10.68 percent) resulted in only a 31 percent reduction in porosity. The formation of hydration products in compacts prepared at higher production pressures influences porosity reduction much more than hydration products formed in compacts prepared at lower production pressures. This agrees with the principle of increased specific binding capacity as discussed in Section II.

Figure 19 provides some interesting insight into these relationships. In general, the relationship between production pressure, reduction in porosity, and the percentage of fly ash replacement is such that the formation of hydration products increases as the production pressure and percentage of fly ash replacement decreases. On a percentage basis, however, the hydration products formed in compacts produced at higher production pressures have a greater influence on porosity reduction than compacts prepared at lower production pressures.

At the 0 percent fly ash level, a wide variation in porosity reduction occurs, depending on the production pressure and resulting initial porosity. However, at the 30 percent fly ash level, the percent reduction in porosity is changed much less with changes in production pressure. This shows the hydration rate of 100 percent portland cement compacts (measured as a percentage change in porosity over a given time period) is greatly influenced by differing compaction pressures and the associated changes in initial porosity. Cubes containing 30 percent fly ash, however, appear to be relatively insensitive to such changes which may be because less cement is present in these compacts.

D. COMPRESSIVE STRENGTH RESULTS

Figure 20 shows the SSD compressive strength results in relation to production pressure for the 100 percent portland cement compacts. Generally, as the production pressure increased, the compressive strength at all ages also increased. The influence of curing duration on the resulting compressive strength is also clearly evident. There was a significant

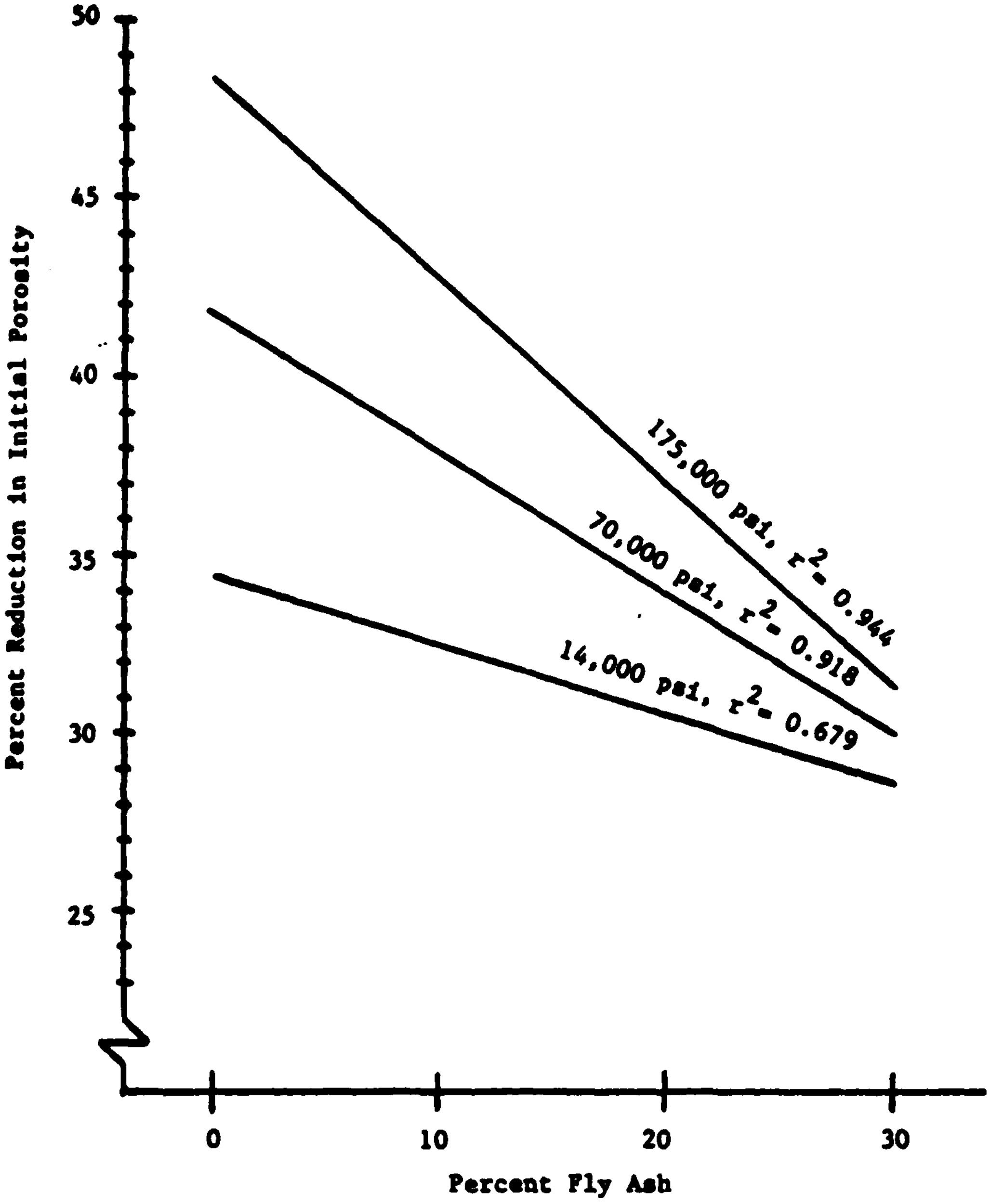


Figure 19. Percent Reduction in Porosity vs. Percentage Fly Ash Replacement Relationship at 14,000, 70,000, and 175,000 psi Production Pressures (Note: 1 psi = 0.006895 MPa)

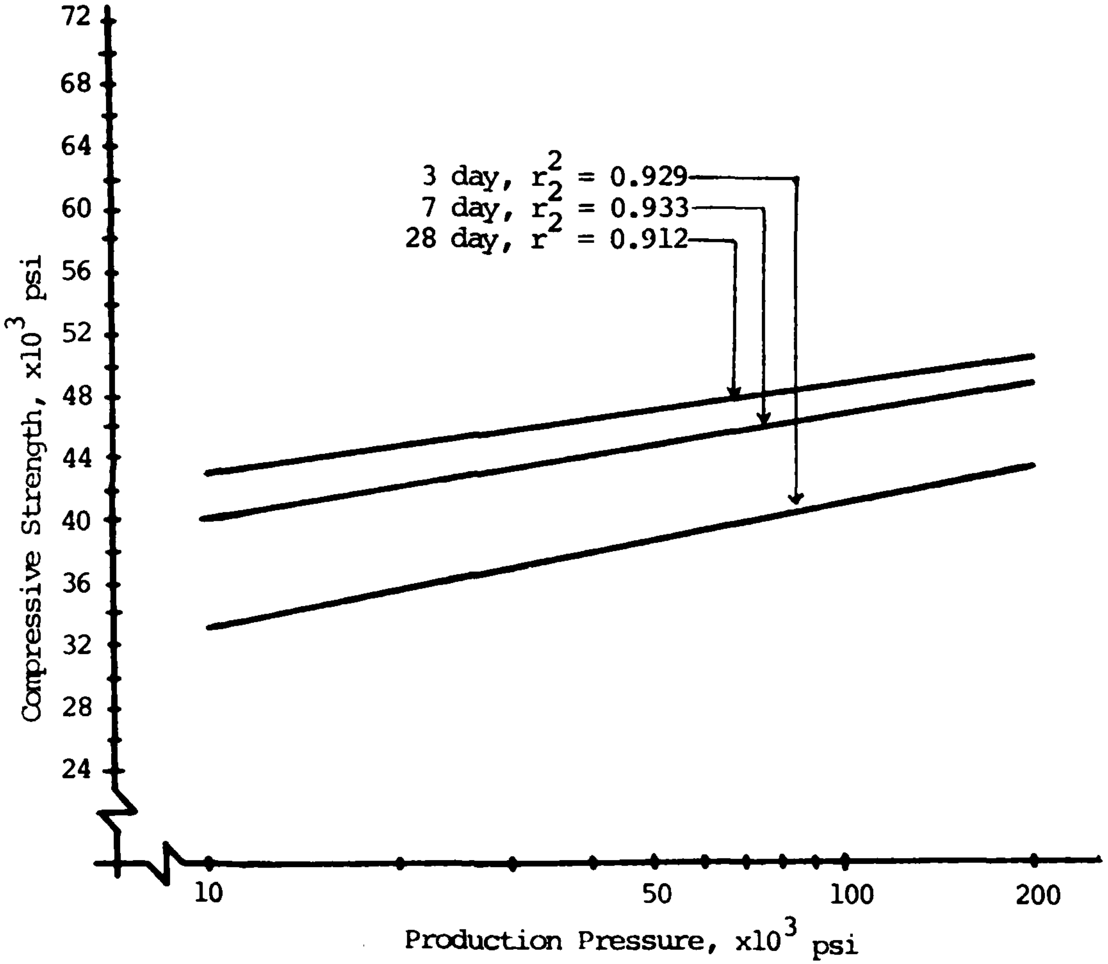


Figure 20. SSD Compressive Strength vs. Production Pressure Relationship for 100 Percent Portland Cement Compacts at 3, 7, and 28 Days of Age (Note: 1 psi = 0.006895 MPa)

increase in strength at all production pressures from the 3 to 7 day curing period and a smaller increase in strength which occurred from 7 to 28 days. Strength data for cement-only compacts cured for 90 days were not available.

Figure 20 also shows the magnitudes of strength increases at various production pressures. Note the decreasing difference in the magnitude of strength gain as the production pressure was increased. For higher production pressures, greater strengths at early ages were developed. However, due to increased hydration with higher porosity, the strengths of the compacts produced at the lowest production pressures approach the strengths of the compacts prepared at the higher production pressure, as curing duration increases. This trend in strength increase at lower production pressures again supports conclusions drawn from the earlier figures that a greater amount of hydration occurs in compacts with higher porosity.

Figures 21, 22, and 23 show the relationships between SSD compressive strength and production-pressure for various fly ash replacements. The same general trends that existed for the 100 percent portland cement compacts are evident. As curing duration was increased, the SSD compressive strength also increased, regardless of the percentage of fly ash. As the percentage of fly ash was increased, the strength at the lower production pressures more closely approached that of the compacts prepared at the higher production pressures. Evidently, as the percentage of fly ash is increased, the relationship of a higher pressure compaction producing a higher strength material diminishes. This is particularly evident for the longer curing durations.

Figures 24, 25, 26, and 27 show that increased hydration, formed with higher initial porosity and lower pressure, had a positive effect on relative increase in the compressive strength. The influence of curing duration on increasing strength is also evident from these figures. Generally, these figures show that from either 7 to 28 days, or 7 to 90 days, the compacts prepared at the lowest production pressures experienced the greatest relative increase in SSD compressive strength. This can be misinterpreted, because the compressive strengths of the compacts prepared at higher production pressures were already extremely high because of the mechanical reduction of porosity. Thus, the resulting percent change in strength was low. On a relative basis however, these figures do show the tremendous influence of the increased formation of hydration products on the compressive strength.

While previous figures presented the influence of curing duration on the compressive strength, the following figures present the influence of the fly ash on compressive strength. Figure 28 shows the influence of final porosity on the 7-day compressive strength of compacts containing various percentages of fly ash. Increasing the percentage of fly ash in the compacts noticeably decreased compressive strengths. This is a

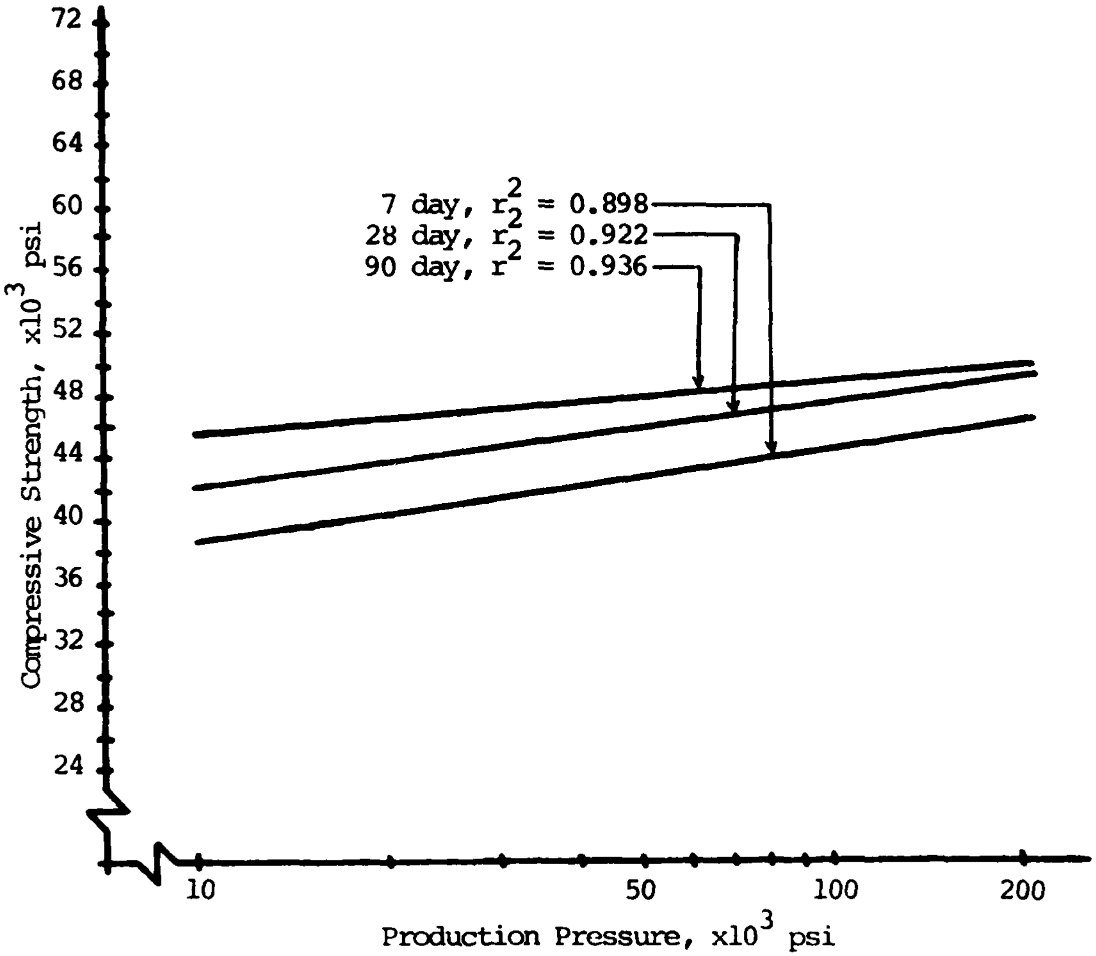


Figure 21. SSD Compressive Strength vs. Production Pressure Relationship at 7, 28, and 90 Days of Age for Compacts Containing 10 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

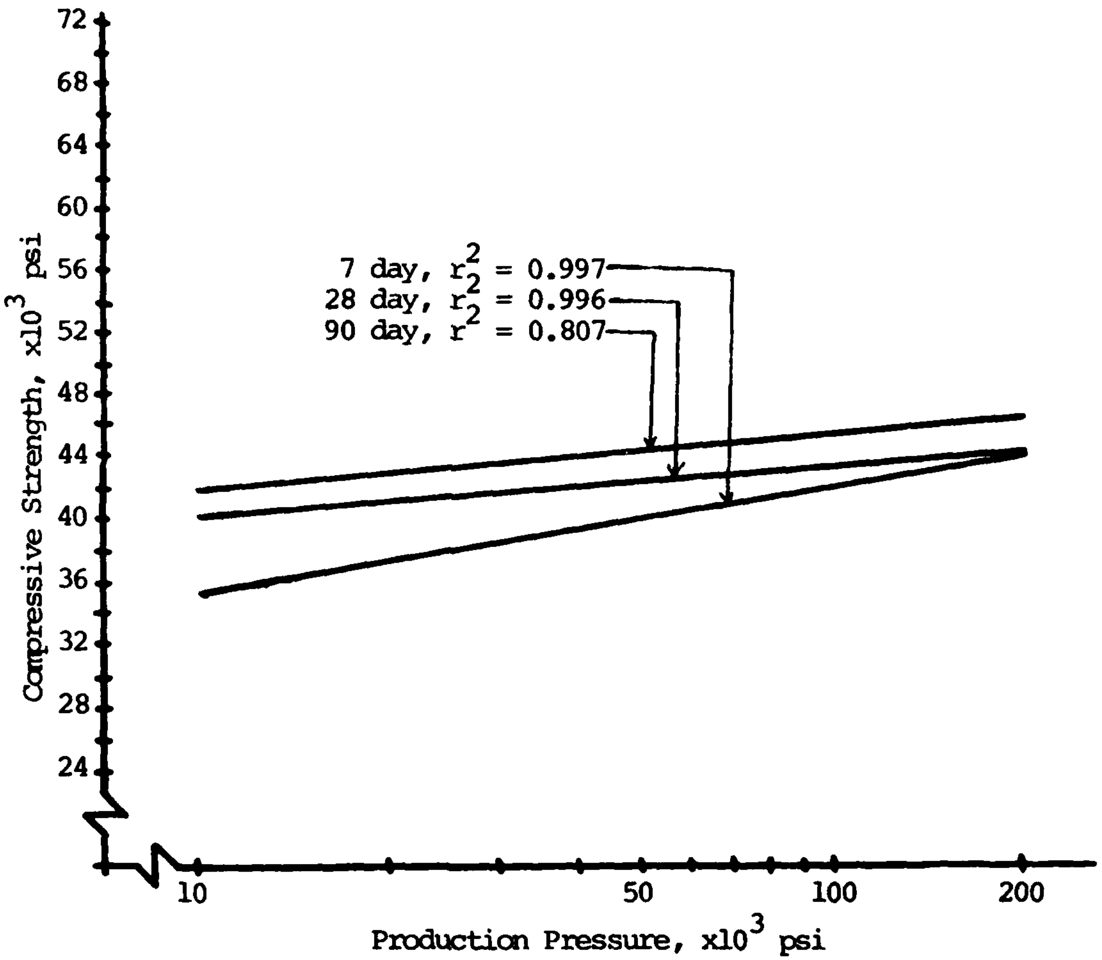


Figure 22. SSD Compressive Strength vs. Production Pressure Relationship at 7, 28, and 90 Days of Age for Compacts Containing 20 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

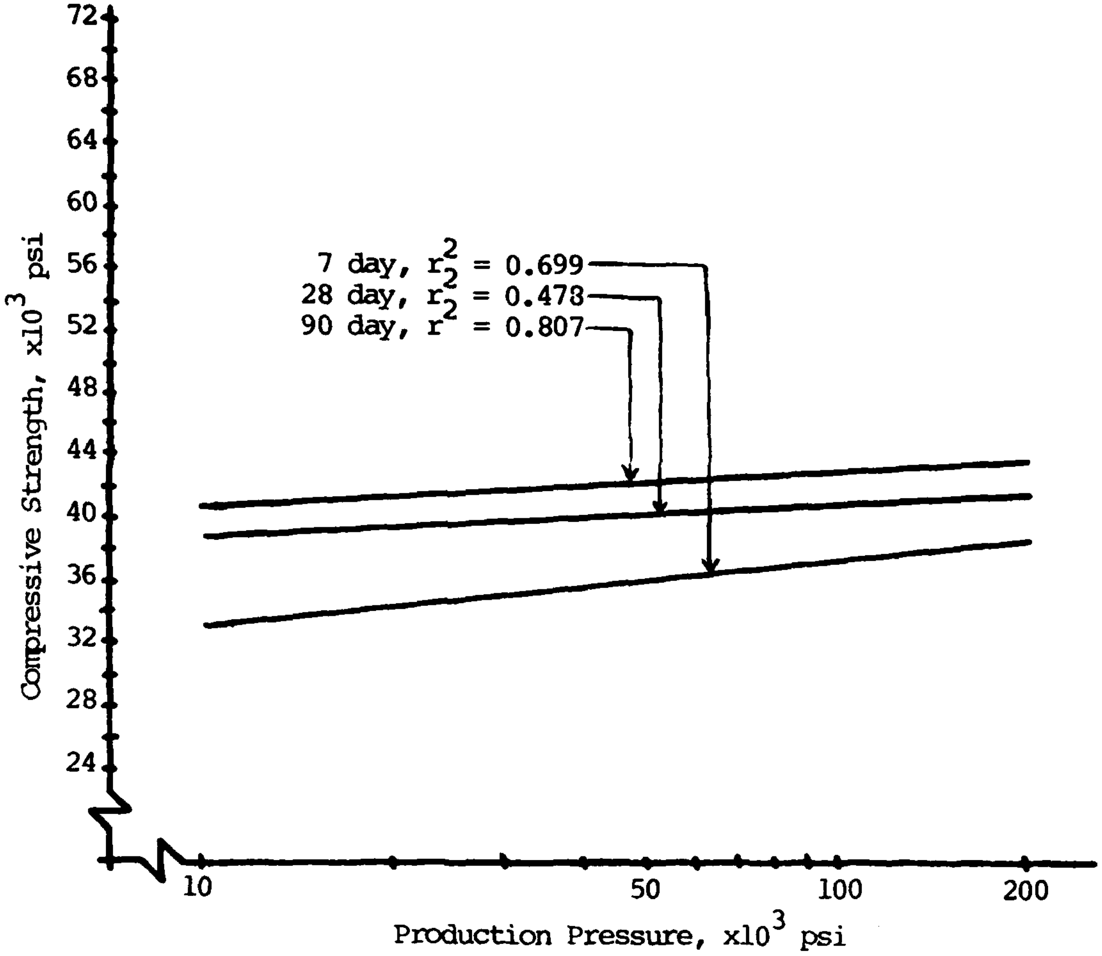


Figure 23. SSD Compressive Strength vs. Production Pressure Relationship at 7, 28, and 90 Days of Age for Compacts Containing 30 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

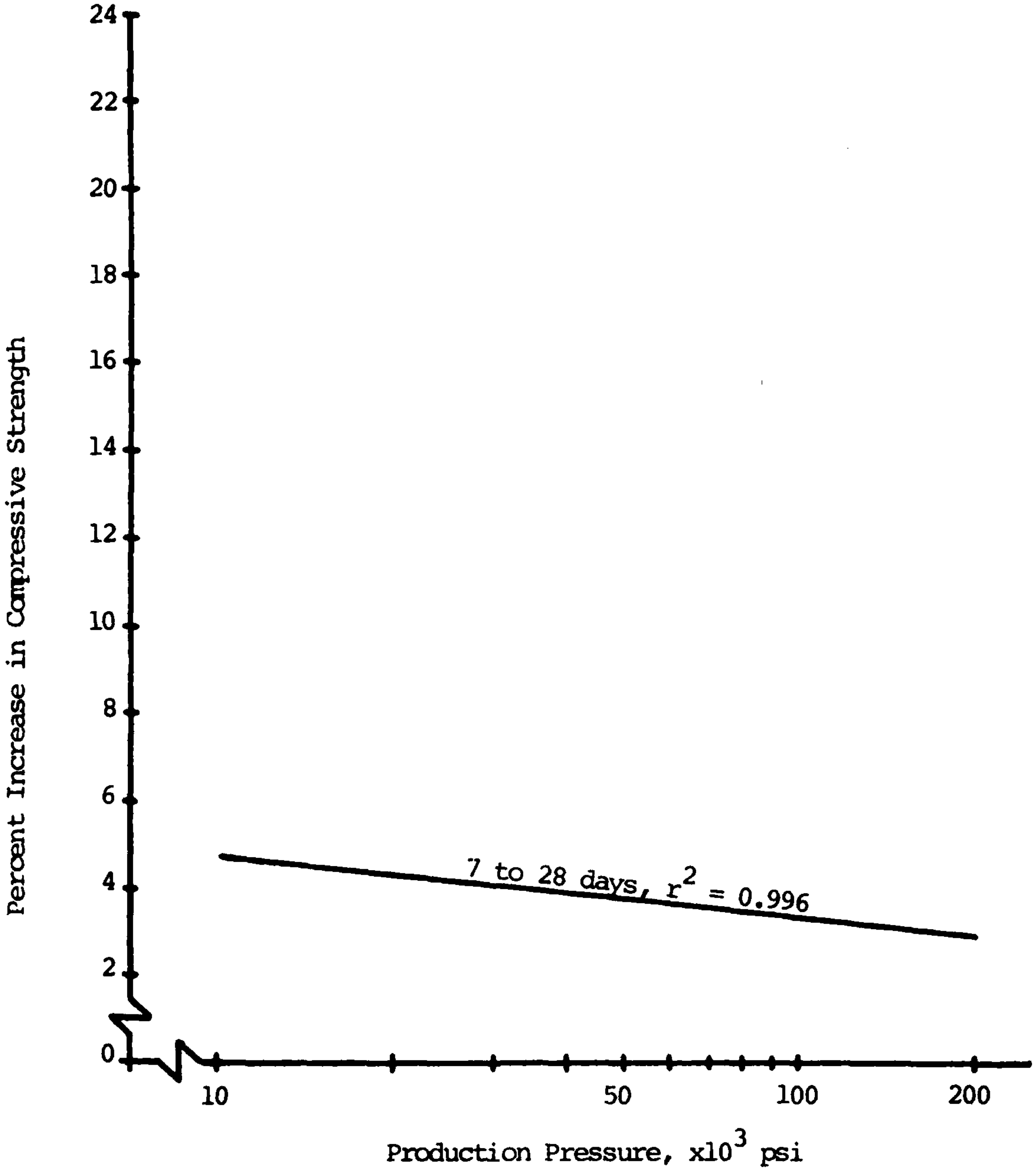


Figure 24. Percent Increase in SSD Compressive Strength From 7 to 28 Days vs. Production Pressure Relationship for 100 Percent Portland Cement Compacts (Note: 1 psi = 0.006895 MPa)

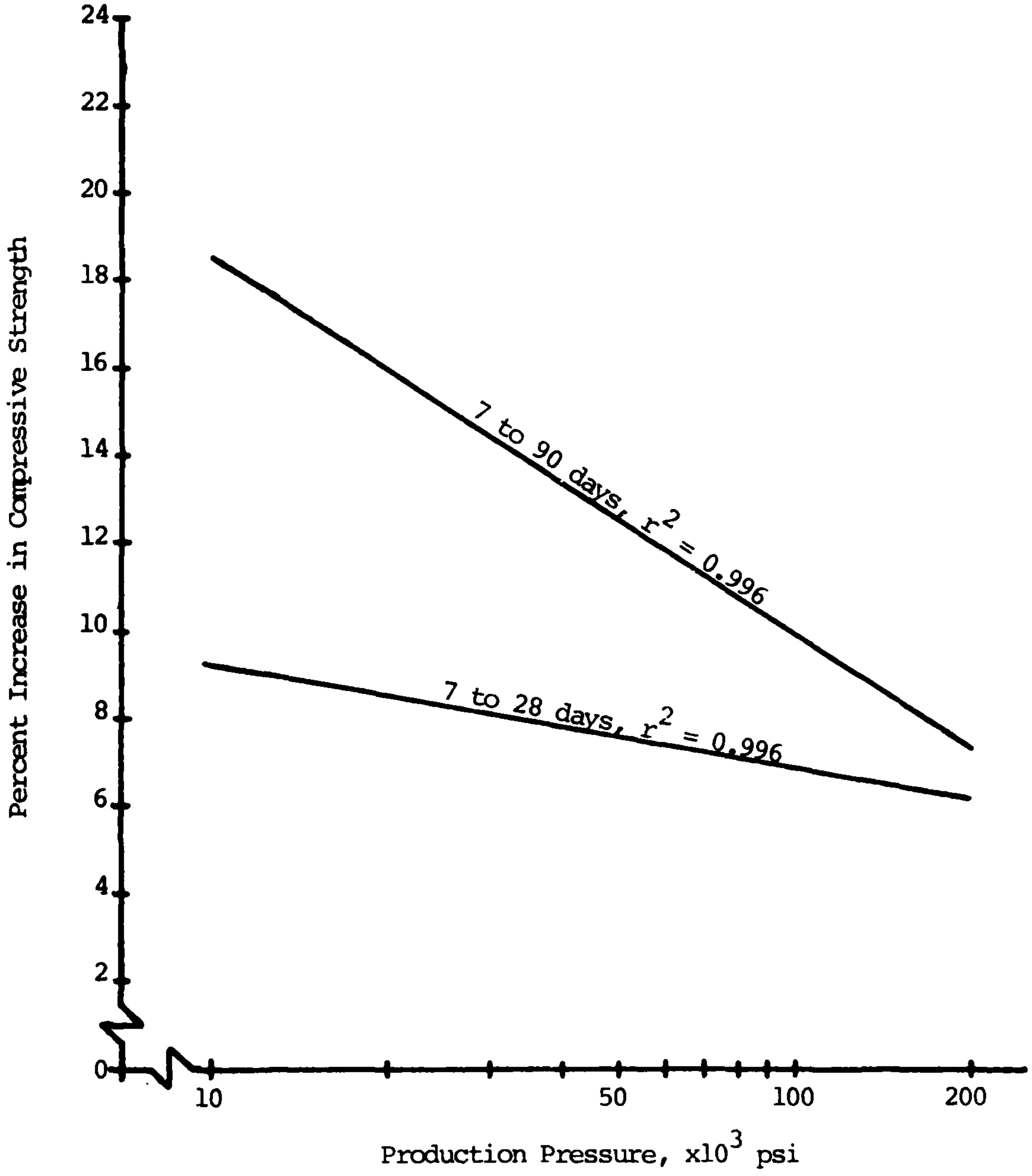


Figure 25. Percent Increase in SSD Compressive Strength From 7 to 28 and 7 to 90 Days vs. Production Pressure Relationships for Compacts Containing 10 Percent Fly Ash
(Note: 1 psi = 0.006895 MPa)

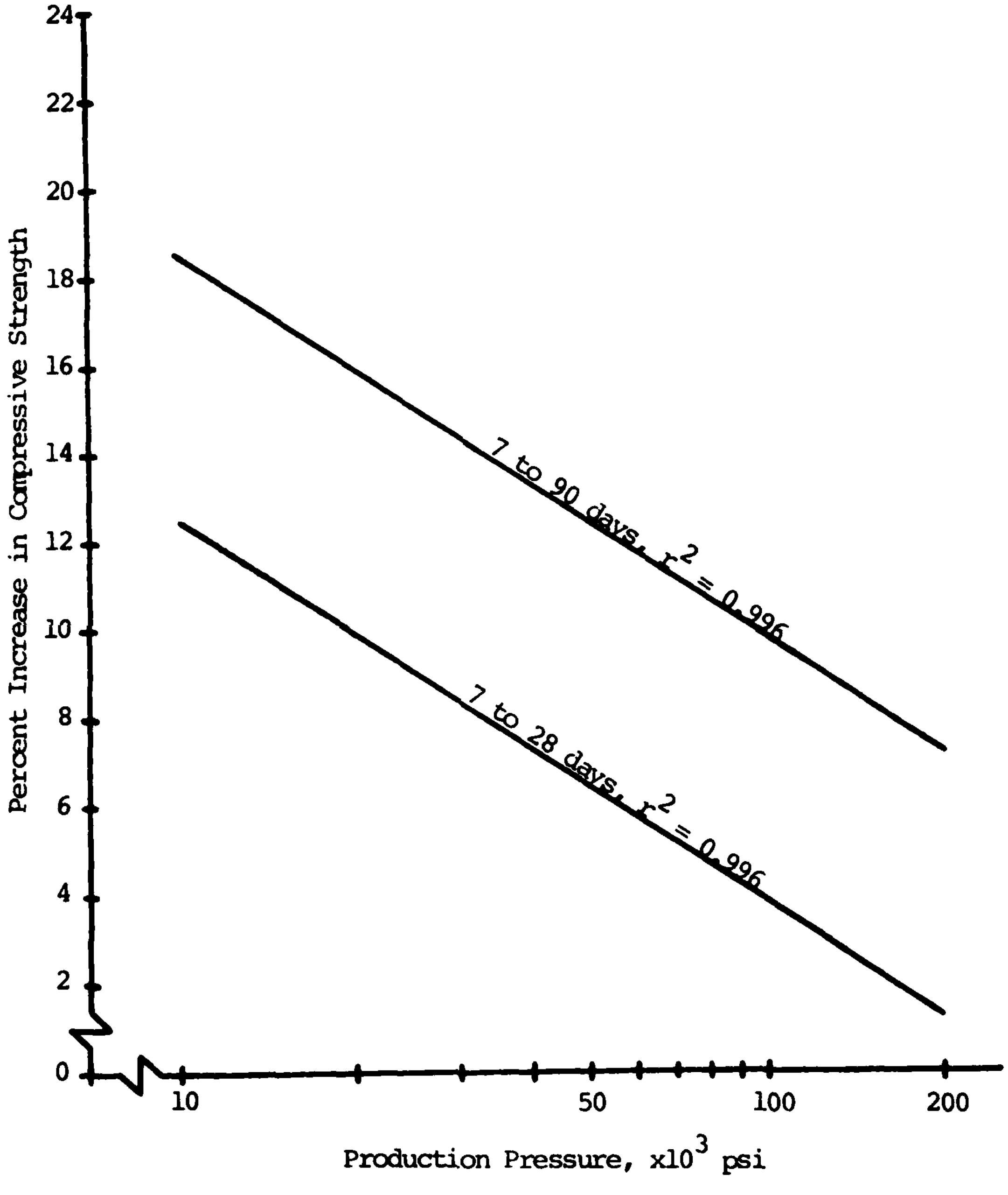


Figure 26. Percent Increase in SSD Compressive Strength From 7 to 28 and 7 to 90 vs. Production Pressure Relationships for Compacts Containing 20 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

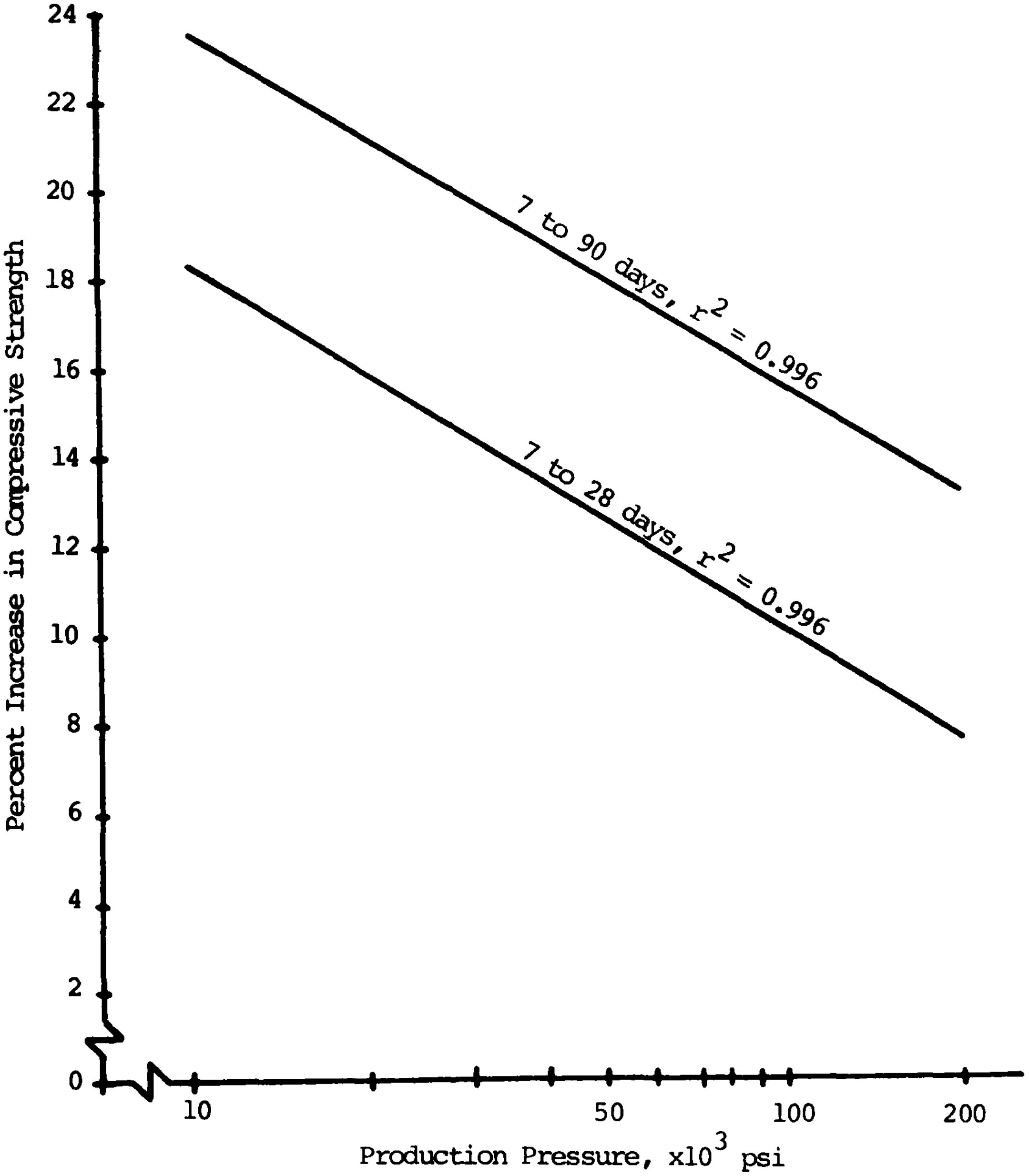


Figure 27. Percent Increase in SSD Compressive Strength From 7 to 28 and 7 to 90 vs. Production Pressure Relationships for Compacts Containing 30 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

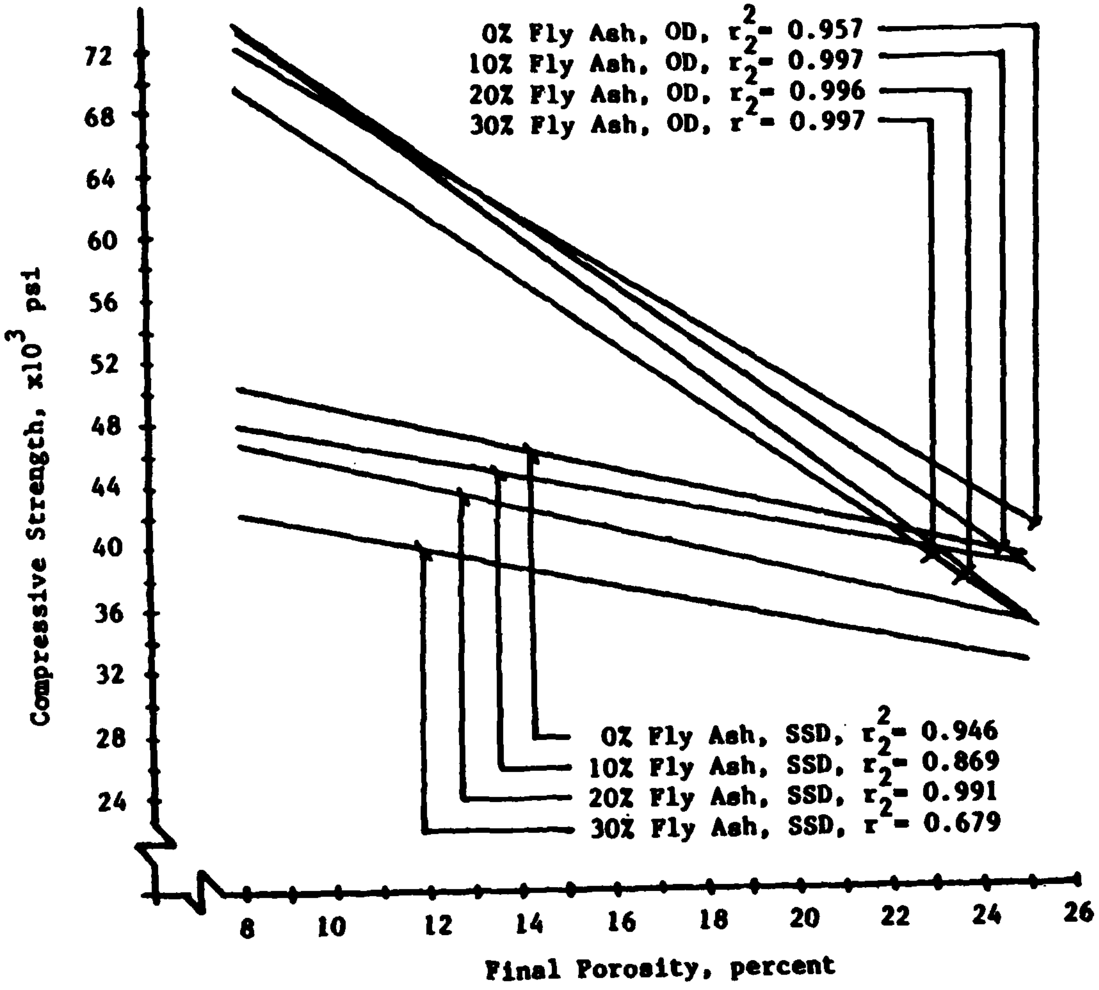


Figure 28. SSD and OD Compressive Strength vs. Final Porosity Relationghips at 7 Days of Age for Compacts Containing 0, 10, 20, and 30 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

reasonable result at this early age, because the pozzolanic reaction is slow in developing and because less cement is present. The parallel relationships of the lines draw attention to the equality of the strength reductions as the percentage of fly ash was increased for all levels of porosity shown.

For comparison purposes, the compressive strengths achieved in the OD compacts are included on this figure. Note the large increase in strength of the compacts due to the oven-drying procedure and the pronounced effects of low levels of porosity on compact strength. The highest strength occurred at the lower porosities at all ages tested, which could mean that the greatest restrained shrinkage stress developed in the low porosity specimens. In typical concretes, current theory indicates that low-porosity conditions provide for less shrinkage of the material and, therefore, formation of less restrained shrinkage stress. Because of this, the high strengths cannot be attributed wholly to the formation of restrained shrinkage stress. To the contrary, the major factor driving this strength - porosity relationship in the OD compacts could be the rapid formation of additional, very influential, strength-producing hydration products caused by accelerating the water diffusion rates during the oven drying process. This would explain the higher strengths at the lower porosity conditions.

Figure 29 shows the influence of final porosity on the compressive strength following 28 days of curing. Again, increasing amounts of fly ash reduced the compressive strength at all porosity levels. Observing the SSD data, there appears to be a more significant increase in strength for the 0 and 10 percent of fly ash replacements than for the 20 and 30 percent. This figure suggests that the replacement of cement with up to about 10 percent in the high-pressure compaction process has very little effect on 28 day strength. With replacements over 20 percent, however, the reduction in strength becomes substantial at 28 days. Observing the OD strength data, this trend is supported as the compacts containing 30 percent fly ash exhibited lower strengths than the compacts containing lesser amounts of fly ash.

Figure 30 shows the relationship which existed at 90 days of curing between the final porosity and compressive strength. Compressive strength data for the 100 percent portland cement compacts were unavailable at 90 days. However the same general trends that existed for the 7 and 28 days of age appear to exist for 90 days of curing. For the higher-porosity conditions, a similar result can be observed for amounts of fly ash greater than 20 percent. At the lower-porosity conditions this point is not as obvious. Again observing the OD strengths, particularly at the lower porosities, the delineation between 10 and 20 percent fly ash producing very different strengths becomes visible.

At the initial outset of the laboratory investigation, the influence of fly ash on the strength of the prepared compacts was

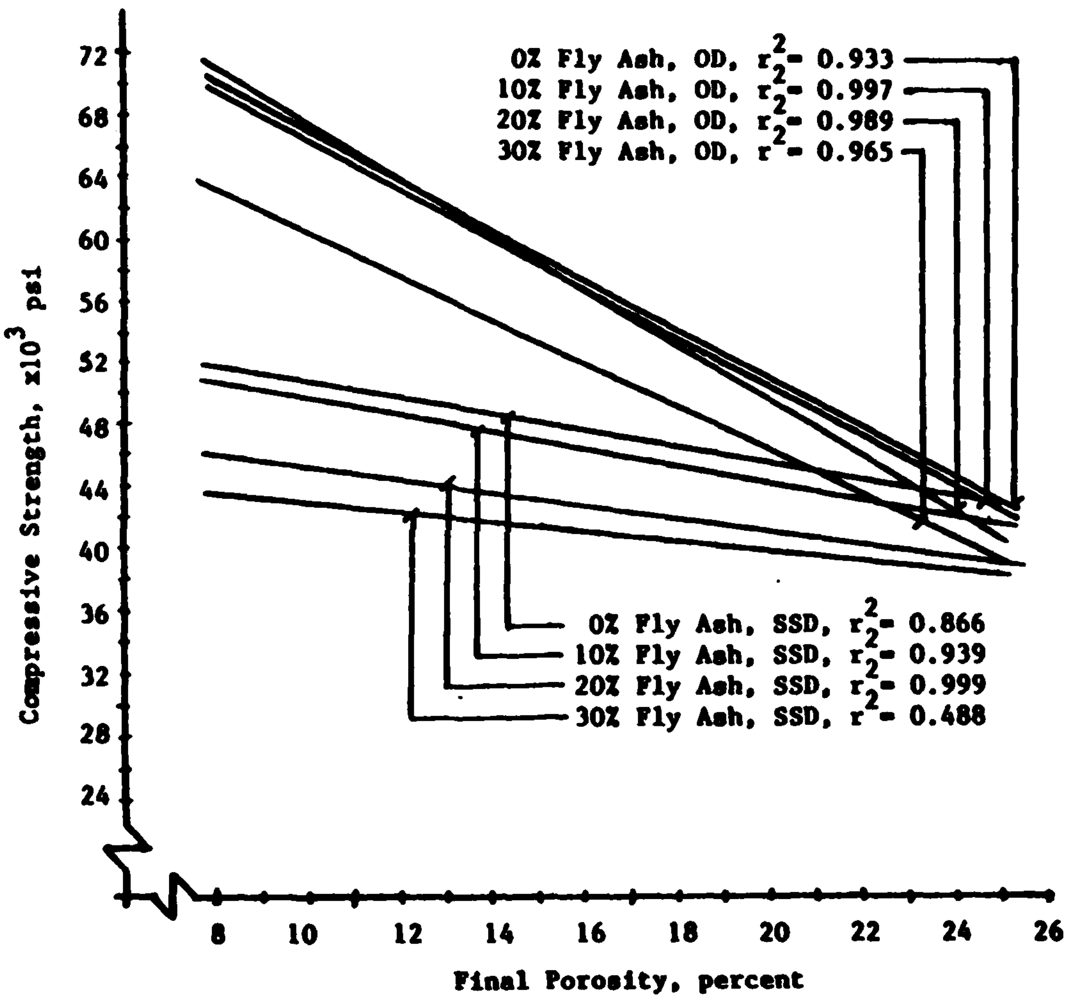


Figure 29. SSD and OD Compressive Strength vs. Final Porosity Relationships at 28 Days of Age for Compacts Containing 0, 10, 20, and 30 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

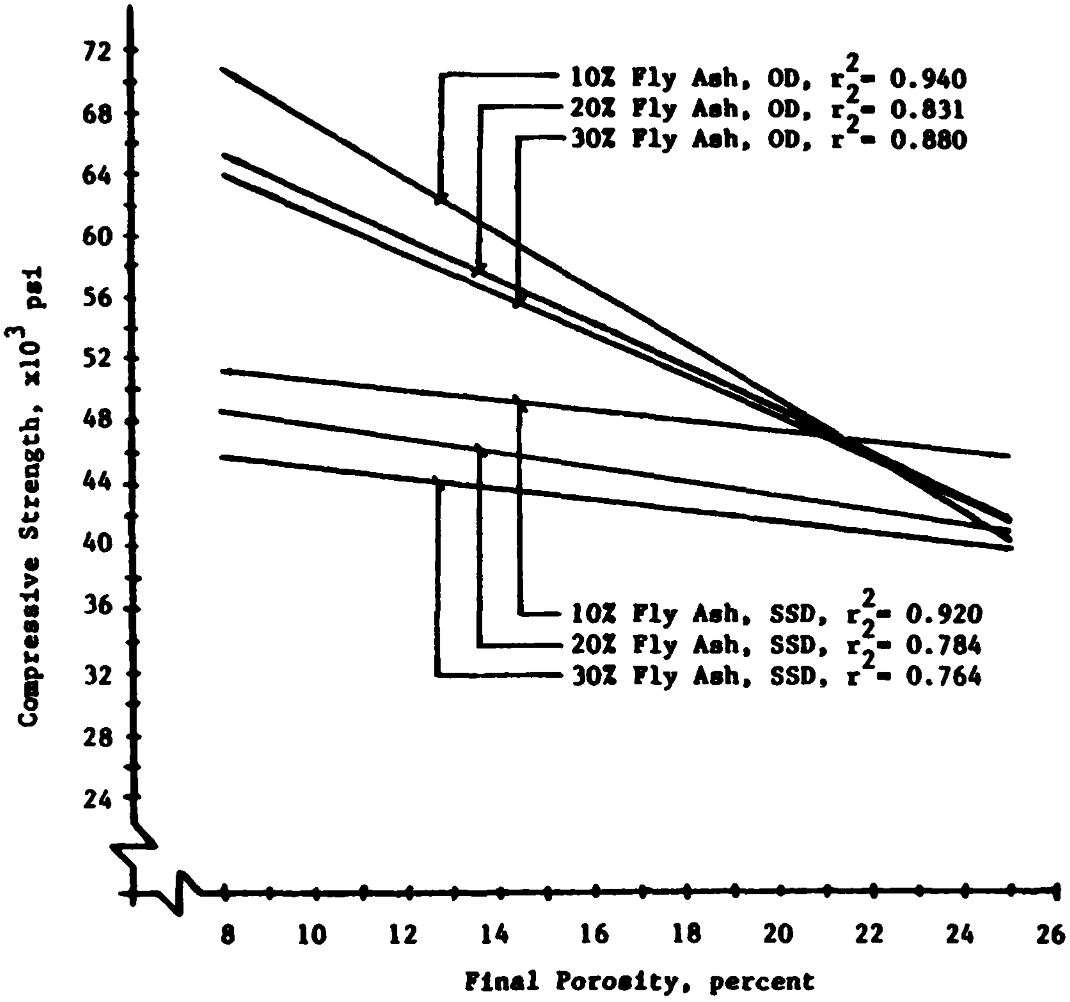


Figure 30. SSD and OD Compressive Strength vs. Final Porosity Relationships at 90 Days of Age for Compacts Containing 10, 20, and 30 Percent Fly Ash (Note: 1 psi = 0.006895 MPa)

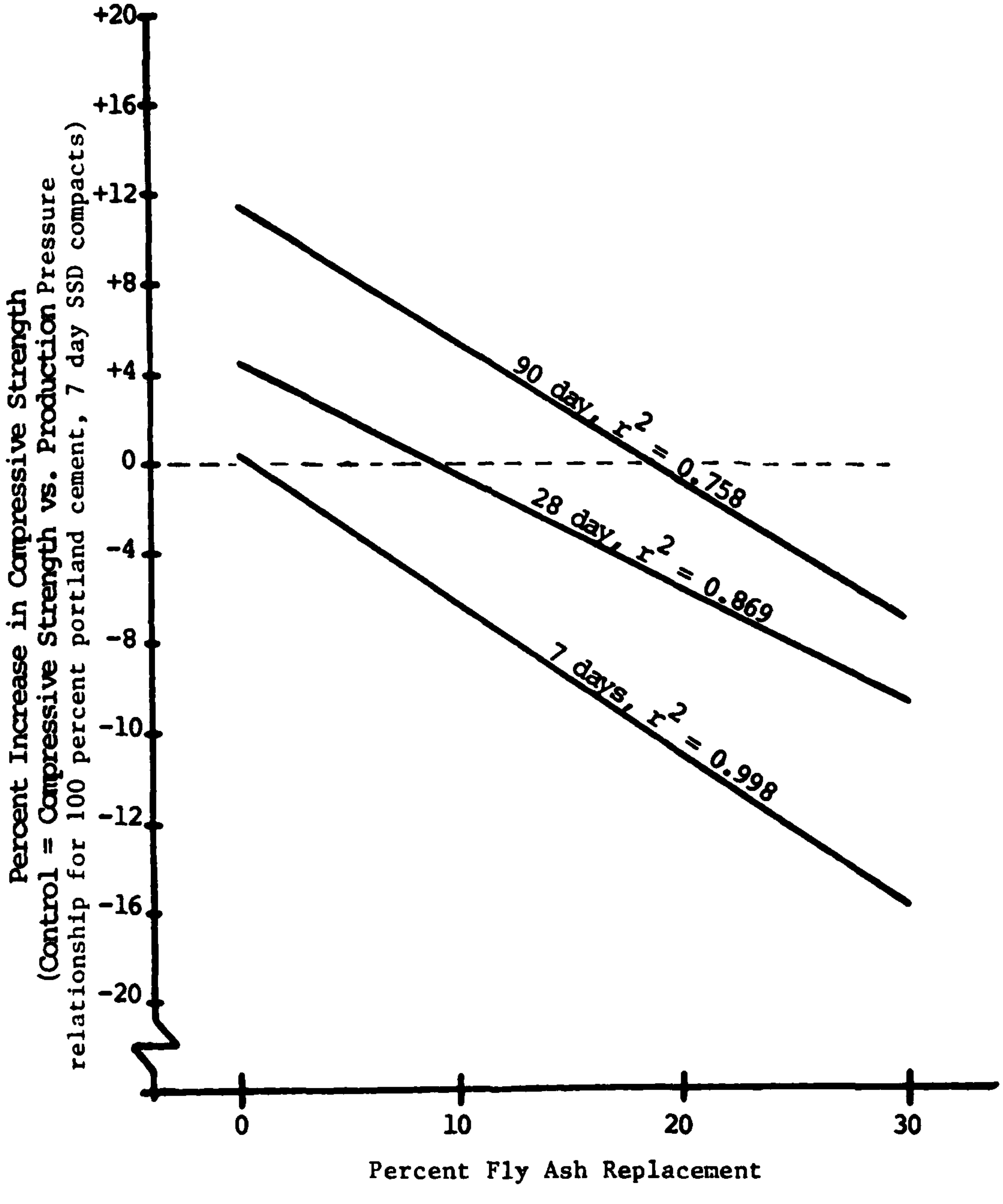


Figure 31. Percent Increase in SSD Compressive Strength vs. Percentage Fly Ash Replacement Relationships at 7, 28, and 90 Days of Age

of primary importance. As shown, the fly ash had an adverse effect on the strength of the compacts at all percentages of replacement. Figure 31 shows the marked effects of fly ash on the reduction of SSD compressive strength in the prepared compacts at all ages investigated. This is also a normalized relationship in that the SSD compressive strengths used for determination of the relationships included all production pressures.

Generally the figure shows that, for all production pressures, the SSD compressive strength increased approximately 12 percent of the 7-day strength from 7 to 90 days; regardless of the percentage of fly ash in the compact. The figure also shows that for each 10 percent of fly ash replacement in the compacts, 6 to 7 percent of the SSD compressive strength was lost at all curing durations, regardless of production pressure.

The influence of fly ash can be further established by entering the figure at the control point of zero percent increase in SSD compressive strength and compare the strengths of the of the fly ash replacements at the various durations. From this exercise, for approximately 10 percent fly ash cured for 28 days, the strength is the same for 100 percent portland cement cured for 7 days. Likewise for the 20 percent fly ash value, 90 days curing is required to achieve the same SSD compressive strength as 100 percent portland cement cured for 7 days. For 30 percent fly ash, curing periods up to 90 days were insufficient to produce strengths equal to 7 day strengths of 100 percent portland cement.

Therefore, in terms of SSD compressive strength, no optimum percentage of fly ash existed for up to 90 days of moist curing. At least no particular percentage of fly ash resulted in an increase in strength over that of the 100 percent portland cement compacts. At all durations up to 90 days, increasing percentages of fly ash produced incrementally lower SSD compressive strengths. It appears, although not conclusively, that fly ash replacement up to 10 percent had a less significant effect on reducing strength than replacement percentages of greater than 20 percent. Perhaps the 90-day curing duration utilized was insufficient to allow for the pozzolanic reaction to fully become established or, as discussed earlier, perhaps the high-pressure compaction process had a negative effect on the pozzolanic reaction.

Because of the excellent linear relationships which existed, multiple linear regression analyses were performed. The resulting equation, determined by combining all of the various parameters, is:

$$\begin{aligned} \text{SSD } f'c = {} & -303.8\ \text{FA} + 4401.7\ \text{Log}_{10}\ \text{Age} + \\ & 4441.5\ \text{Log}_{10}\ \text{PP} - 497.1\ P_i - 2666.4\ P_f \\ & - 66072.5\ \text{Den}_i - 26286.3\ \text{Den}_f + 291693.0 \end{aligned} \tag{6}$$

where SSD f'c is the predicted SSD compressive strength based on the parameter values supplied,

FA is the percentage of fly ash in the compact in percent,

Log_{10} Age is the base 10 logarithm of the curing age in days,

Log_{10} PP is the base 10 logarithm of the production pressure in psi,

P_i is the initial porosity of the compact in percent,

P_f is the final porosity of the compact in percent,

Den_i is the initial density of the compact in grams per cubic centimeter,

Den_f is the final density of the compact after removal of free water by oven drying at 220°F (105°C) for 48 hours, in units of grams per cubic centimeter.

The multiple R or the multiple coefficient of correlation for this equation is 0.950. This equation was developed from all the SSD data obtained from the various series.

Concerning this equation, two important points must be made. First, logarithmic values of the curing duration and production pressure must be used with the other data collected to obtain a high degree of correlation. Second, this equation was developed from a very definite range and combination of values as contained in Appendix E. Chief among these is the influence of production pressure on the porosity and density conditions as shown in Figures 12 through 17. The multiple-regression equation discussed here is based on the relationships shown in these figures. The equation is based on the fact that higher production pressures will produce corresponding lower-porosity conditions and resulting higher densities. Concerning typical values, the above-mentioned figures should be consulted. For a production pressure of approximately 185,000 psi (1,275 MPa), the initial porosity used must be in the 20 to 21 percent range with an initial density in the range of 2.4 to 2.5 g/cm^3. Conversely, for a production pressure of approximately 14,000 to 15,000 psi, a corresponding initial porosity of 32 to 33 percent and initial density of 2.0 to 2.1 g/cm^3 must be used for correct application of the equation. Realistic values for the final porosity and final density, depending on the curing duration and percentage of fly ash must also be used to achieve reliable strength predictions.

A satisfactory predictive equation of the SSD compresive strength of compacts prepared with the die was developed using only a few of the parameters involved. Multiple linear regression analysis yielded:

$$\text{SSD } f'c = -248.7 \text{ FA} + 5904.7 \text{ Log}_{10} \text{ Age} + 4552.8 \text{ Log}_{10} \text{ PP} + 17329.9 \qquad (7)$$

The multiple R or coefficient of multiple correlation for this particular equation is 0.924. Again, as with the previous equation, this equation was developed from data on all the SSD compacts and series tested.

The use of a realistic relationship between a higher production pressure producing a greater initial density is extremely important for a correct compressive strength prediction. Figures 14 through 17 show the typical relationships resulting between production pressure and initial density achieved, depending on the percentage of fly ash. Initial porosity was not necessary in this prediction equation, because of the excellent inverse relationship which exists between porosity and the production pressure. Parameters chosen for this equation have values which are readily available once a compact has been prepared and make this equation quite useful for the miniature compacts, keeping in mind the proper interrelationships and limitations on density and porosity.

Turning now to the OD compressive strengths, and using the same parameters, the following equation was developed by multiple linear regression:

$$\text{OD } f'c = -261.8 \text{ FA} + 1746.7 \text{ Log}_{10} \text{ Age} + 15981.2 \text{ Log}_{10} \text{ PP} - 20814.2 \qquad (8)$$

The multiple R or coefficient of multiple correlation for this particular equation is 0.955. This equation was developed from data on all the OD compacts tested and, as with Equations (6) and (7), must be used with realistic, interrelated values.

Figure 32 illustrates relative influence of age and accelerated OD curing on predicted compressive strengths of 100 percent portland cement compacts. Several important results can be seen from an examination of the figure. First, extremely high strengths are achieved very rapidly in these pressed compacts. The 3-day predicted strengths (earliest age measured) are 42,900 psi (300 MPa) for the SSD curing conditions and 59,900 psi (410 MPa) for the OD curing conditions. If the relationship remains linear for even earlier ages, it could mean 1-day strengths of 40,100 psi for the SSD curing conditions and 59,100 psi (410 MPa) for the OD curing condition. These are remarkable values, to say the least, and raise interesting possibilities for the rapid production of ultra-high-strength cement products. Second, since the vast majority of the strengths are achieved at a very early age, relatively small increases in strength occur from continued

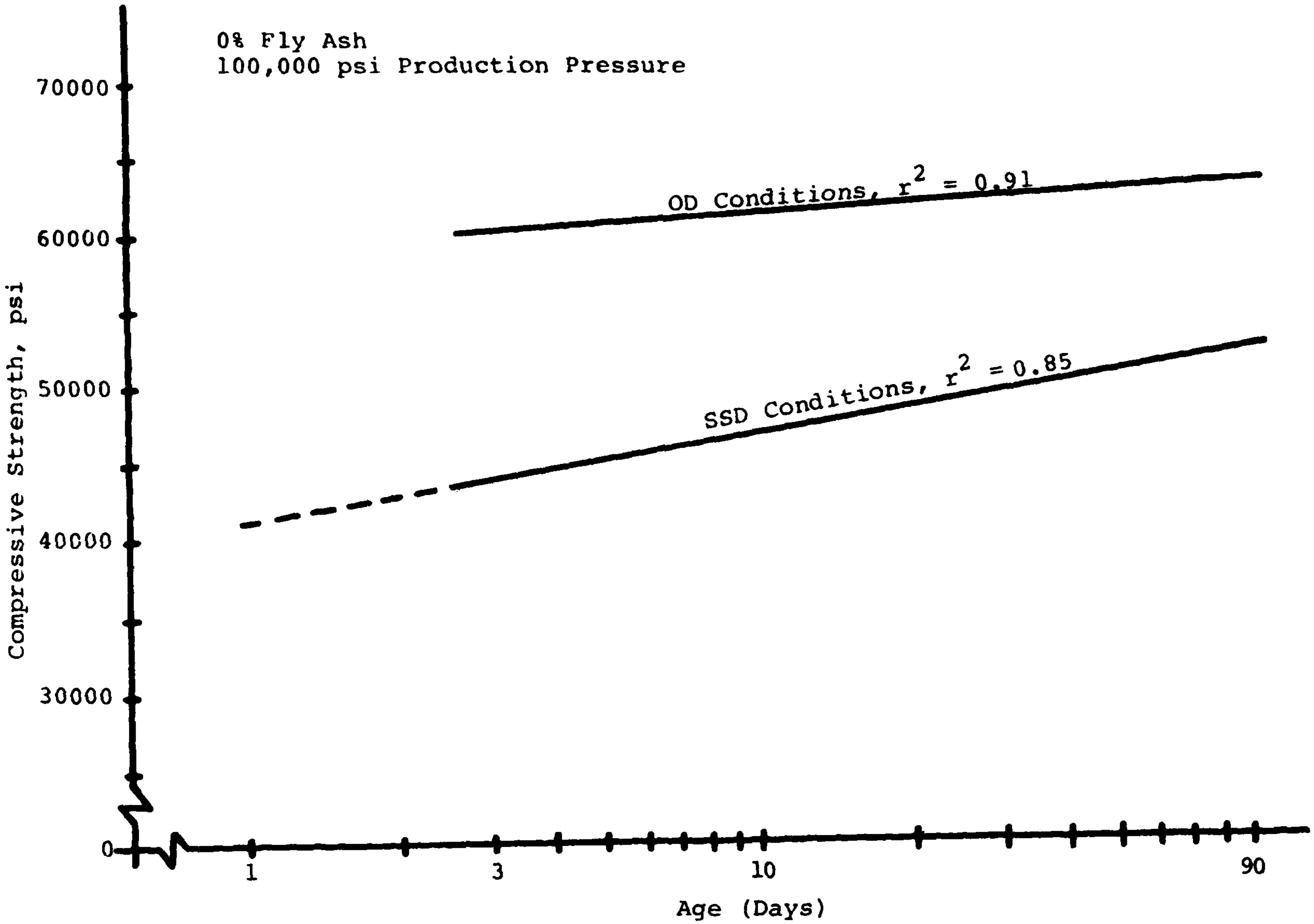


Figure 32. SSD and OD Compressive Strength vs. Age for Compacts Containing 100 Percent Portland Cement and Compacted Under 100,000 psi Pressure (Note: 1 psi = 0.006895 MPa)

curing. According to Equation (7), the SSD compressive strengths increase by about 5,900 psi (40 MPa) with each order-of-magnitude increase in age (1 to 10 days, 10 to 100 days, etc). According to Equation (8), the OD compressive strengths increase by only about 1,750 psi (10 MPa) with each order-of-magnitude increase in age. Third, the accelerated curing by oven-drying following water immersion dramatically increased strength, even though the specimens were being dried, but the rate of continued hydration with age was reduced. The OD equation predicts a 100-day strength of 62,500 psi (430 MPa). (If steam curing were utilized, the results should be even more dramatic.) Finally, caution should be exercised when using these equations for predictive purposes (especially Equation (8)) as they were developed for one brand of Type III cement cured under specific conditions. Thus, the results should not be generalized.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The following conclusions were drawn from an analysis of the literature surveyed and the laboratory investigation performed.

1. High-pressure compaction has been shown to be an excellent means of producing a low-porosity condition which results in ultrahigh compressive strengths in cementitious materials, especially at early ages.

2. The level of porosity present in prepared portland cement compacts, both initially and at the completion of curing, exhibited a linear relationship with the ultimate compressive strength (for the 20 to 32 percent initial porosity and the resulting 8 to 20 percent final porosity range).

3. In all instances, the greater the reduction of initial porosity due to high-pressure compaction, the greater the resulting strength, even though less hydration occurred.

4. In all instances, the higher the initial porosity the greater the amount of porosity present upon completion of curing. For compacts with a greater initial porosity, a greater amount of hydration product formed which resulted in a much greater <u>percentage</u> strength increase in the compact.

5. Over time, the strength of the compacts prepared at higher initial porosities appears to approach the strengths of the compacts prepared at lower porosity levels.

6. The high-pressure consolidation of portland cement and the Class "C" fly ash can be accomplished with excellent results. Compatibility of the materials, however, must be considered in the preparation of compacts containing fly ash. The use of a fly ash passing an ASTM 100 sieve produced a more stable compact than the use of the coarser raw fly ash material.

7. An optimum percentage of fly ash replacement of the cement in the miniature compacts could not be determined. Increasing replacement of the cement with fly ash resulted in decreasing compressive strengths at all ages of water curing. On a percentage basis, approximately 5 to 6 percent loss in strength was experienced at all durations with each 10 percent replacement of cement with fly ash.

8. The expected increased strength from the pozzolanic reaction was not realized when fly ash was used. Evidently the pozzolanic reaction required longer time or the high-pressure compaction process hindered the formation of needed calcium hydroxide.

9. Oven-drying of the prepared compacts to determine the amount of free water present as a measure of the final porosity produced significant compressive strength increases in the compacts tested, probably caused by the accelerated water diffusion rates driving additional hydration.

10. A multiple linear regression analysis of the SSD data yielded the following predictive equation for SSD compressive strength:

$$\text{SSD } f'c = -248.7\ \text{FA} + 5904.7\ \text{Log}_{10}\ \text{Age} + 4552.8\ \text{Log}_{10}\ \text{PP} + 17329.9 \qquad (9)$$

The multiple coefficient of correlation for this equation is 0.924.

11. A multiple linear regression analysis of the OD data yielded the following predicitve equation for OD compressive strength:

$$f'c = -261.8\ \text{FA} + 1746.7\ \text{Log}_{10}\ \text{Age} + 15981.2\ \text{Log}_{10}\ \text{PP} - 20814.2 \qquad (10)$$

The multiple coefficient of correlation for this equation is 0.955.

12. These compressive strength prediction equations are only valid for values encountered in this study. They predict very high early strengths, accelerated significantly by oven-drying, and relatively slow increases in strength over time.

B. RECOMMENDATIONS

The following recommendations are offered:

1. Careful consideration should be given to the order in which the compacts are prepared. For this particular study, all compacts for a particular duration were prepared before the compacts of another duration. Because of the data variability, the determination of successive changes in porosities and densities for the various durations was not possible. Excellent results, however, were obtained at each duration when the compacts cured for that duration where compared for porosity and density change relationships. Because of data variability, the actual intent of the laboratory investigation should be considered when determining the order in which to prepare the compacts.

2. Even though excellent relationships were determined concerning compressive strength and the various other parameters, the authors think that the strength results in terms of

consistency and uniformity could be improved by using a special device designed specifically for testing of the miniature cubicle compacts.

3. Exposing the freshly prepared compacts to a fine mist for initial periods of hydration and compact stabilization before complete immersion could help to reduce the quantity of compacts which fail prematurely in the curing solution.

C. FUTURE RESEARCH

This project raised the possibility of further research topics relating to the preparation of high-strength materials through high-pressure compaction.

1. Since the initial intent of this study was to determine the effects of fly ash on producing a higher-strength material by exposure to pozzolanic reaction, future efforts might consider increasing the time in which the compacts are moist-cured so that the full pozzolanic reaction can occur.

2. Additional work should be performed to investigate the effects of high-pressure compaction on the pozzolanic reaction. This will help determine the feasibility of utilizing fly ash in a high-pressure compaction system.

3. Considerable work needs to be done concerning the proper combination of a range of particle sizes to produce a higher-strength material through high-pressure compaction. Determination of the degree of particle crushing which occurs at the high production pressures is also critical to this determination of the optimum particle gradation involved in the high-pressure compaction process.

4. Considerable work also remains pertaining to the amount and type of hydration products formed in compacts having low porosities.

5. More effort should be directed at the effects of accelerated curing using elevated temperature and possibly steam. The authors find it intriguing that compressive strengths in excess of 72,000 psi (500 MPa) were achieved by oven-drying the specimens after water-curing. If hot-pressing and steam-curing were employed, the compressive strengths could even be higher.

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APPENDIX A

MATERIAL DATA

TABLE A-1. CEMENT COMPOSITION AND PROPERTIES

Midlothian TXI Type III Cement	
Physical Test Results as reported by TXI	
NC	26.5
% H_2O Cubes	48.5
% Flow	112
% Air	9.0
% Passing #325 Sieve	98.6
Blaine (cm^2/gm)	5350
Wagner (cm^2/gm)	2550
Gilmore Setting Time Initial/Final (hrs:min)	2:35/4:15
Vicat Setting Time Initial/Final (hrs:min)	0:50/3:20
% Fed. False Set	7.1
Autoclave Expansion	
D.O.P. (mm)	
1	50
2	50
3	50
4	50
5	50
Compressive Strengths (2"x2" cubes)	
1 day	3592 psi
3 day	5425 psi
7 day	6242 psi
28 day	7575 psi
Specific Gravity	3.13

TABLE A-1. CEMENT COMPOSITION AND PROPERTIES (CONCLUDED)

Chemical Analysis / X-Ray Analysis		
SiO_2	20.11	
Al_2O_3	4.38	
Fe_2O_3	3.52	
CaO	64.66	
MgO	0.78	
SO_3	3.34	
P_2O_5	0.23	
TiO_2	0.22	
Cr_2O_3	0.00	
Mn_2O_3	0.30	
Na_2O	0.29	
K_2O	0.38	
Total		98.20
C_3S	63.40	
C_2S	9.80	
C_3A	6.80	
C_4AF	10.70	

C_3A calculations include Al_2O_3, P_2O_5, and TiO_2

TABLE A-2. FLY ASH COMPOSITION AND PROPERTIES

Gifford-Hill Class "C" Fly Ash

Physical properties

	Sample	Specification
Fineness, +325 Sieve, % Retained:	18.3	34.0 max.
PAI (28 days), % Control	101.4	75.0 min.
Water Requirement, % Control	90	105.0 max.
Autoclave Soundness, %	0.218	0.8 max.

		Sample	Specification
Specific Gravity:	unsieved	2.71	....
	sieved	2.75	....

Chemical Properties

	Sample	Specification
Silicon Dioxide	32.03	
Aluminum Oxide	17.10	
Ferric Oxide	7.25	
Total	56.38	50.0 min.
Calcium Oxide	29.88	
Magnesium Oxide	6.34	
Sulfur Trioxide	3.61	5.0 max.
Sodium Oxide	2.08	
Potassium Oxide	0.26	
Loss on Ignition	0.88	6.0 max.
Moisture Content	0.07	3.0 max.
Total	99.50	
Sodium Oxide Equivalent	2.25	

TABLE A3. AGGREGATE DATA

Item	Fine Aggregate	Coarse Aggregate
Sieve Analysis (% Retained) as per ASTM C33		
3/4 in.		
1/2 in.		0.1
3/8 in.		3.8
No. 4	0.0	84.4
No. 8	0.7	96.3
No. 16	39.3	97.3
No. 30	64.0	
No. 50	80.0	
No. 100	93.5	
No. 200	99.4	
Dry loose unit wt (lb/ft^3)	-	101.0
S.G. (Dry Bulk)	2.60	2.91
Absorptions (%)	0.56	0.96

APPENDIX B

LABORATORY PROCEDURES FOR THE HIGH-PRESSURE PREPARATION OF CEMENT AND FLY ASH COMPACTS

A. PREPARATION OF THE POWDER MATERIAL

After the weight determinations for the proper proportions had been made, the cement and fly ash material were each weighed in separate containers and then mixed in a larger container. The powder needed for each individual compact was taken from this mixture. Generally 50 to 100 grams of combined powder was mixed at one time, depending upon the quantity of compacts to be prepared at that time. To provide for more meaningful data, enough powder was mixed at this point to provide a series of compacts for both the wet surface dry and oven-dried test conditions for a given combination of parameters. The percentage of fly ash in the mix also influenced the amount of powder which was initially mixed, because of the higher percentage of premature compact failures during the compaction process with increasing amounts of fly ash.

The powder material was mixed with a glass stirring rod until no visible segregation of the powder material existed. The combined powders were placed in a closed container, and mixed by vigorous shaking and tumbling.

Two other methods of powder preparation were not used for this work, but deserve mention. One method is the mixing of the powders for each individual compact. This procedure takes too long, has a greater probability of error, and variation among the individual compacts. The method recommended for future studies is a one-time mixing of the cement and fly ash material which would save a tremendous amount of time, permit mechanical mixing and improve the consistency in the mixed powder.

Once mixed, the powder was weighed for each of the individual compacts. This was done on a Sartorious Model 2442 scale which could be read to 0.0001 grams. The powder material for each of the individual compacts was placed in a paper cup container until placed in the die.

It is very important that the weighed powder, as well as the supply material, be protected from moisture in the air. Moisture can have disastrous effects on the overall quality of the compaction tests performed by affecting the powder weights causing inaccurate density considerations, and forming premature hydration reactions. For these reasons, all materials were kept covered in a minimum moisture exposure condition until use.

B. ADDITION OF POWDER TO THE DIE

Once the die is assembled and checked (see Figure 5), the ram is removed and the powder carefully placed into the die chamber. The die is placed on a table or platform vibrator for preliminary consolidation of the powder material. Once the die and vibrating table are in the proper working arrangement, a small glass funnel is placed in the die for the transfer of the powder from the paper cup holder to the die.

The powder is placed in the funnel slowly and continuously so that it does not accumulate at the neck of the funnel. Light brushing of the paper cup with a small fine bristled brush while it is held over the funnel removes all of the powder. Then the die, powder, and funnel are vibrated by the table vibrator for approximately 15 seconds or until the powder is uniformly distributed in the die. After the vibration, the glass funnel is removed from the die and wiped clean with a cloth.

C. COMPACTION OF THE POWDER

Once the ram is properly placed in the die, the spacer is then placed around the ram. The purpose of this spacer piece, as discussed in Section III, is to produce a constant nominal compact volume at full compaction and provide for manual control over the amount of compaction force applied to the powder material.

The full compactive effort is reached when the spacer piece is no longer free to move around the ram, because the ram head has come into contact with the spacer piece.

With the ram and spacer piece in place, the die is then placed in a press for actual compaction of the material. The die has a spherical seat and washer which allows for the proper distribution of compactive effort from the press through the ram to the powder material.

The powder material is then preloaded with a compactive load of approximately 500 pounds (2.22kN). A loading/displacement rate of the press platens of 0.05 inches (1.27 mm) per minute was used for this investigation. Once obtained, the maximum load was maintained for 1 minute, then released.

D. REMOVAL OF THE COMPACT

Once the compactive force is released, the prepared powder compact is removed and readied for curing. The extremely high compaction forces cause the die segments to experience some degree of radial displacement wedging them firmly into the clamp ring. A puller bar is required to "break down" the die. The clamp ring is freed by tightening the two bolts on the puller bar. By tightening these bolts, a vertical lifting force is applied to the clamp ring while the die segments are held in place. Once free, the clamp ring is then removed by hand and the four interior segments of the die are peeled carefully away from the prepared compact sitting on the center hub. The prepared compacts at this point are generally stable enough to be handled gently by hand.

E. THE CURING REGIME

Following removal from the die, then measured and weighed, the freshly prepared compacts are ready to begin the curing process for the desired duration. The fresh compacts, in an open container, were placed in a controlled atomosphere of 73°F (22.8°C) at 100 percent humidity for a period of approximately 30 minutes during which time they became acclimated to an abundance of moisture for hydration. During this 30-minute procedure, the container holding the compacts gradually collected water until the compacts were immersed. The time at initial placement of the compacts in the 100 percent humidity environment was recorded as the beginning of the curing period.

The compacts were then removed from this initial curing exposure and placed in supersaturated lime and distilled water solution at a constant temperature of 70°F (21 +/- 1/2°C) for the remainder of the desired curing period.

APPENDIX C

POWDER WEIGHT DETERMINATION PROCEDURES

A. INTRODUCTION

The purpose of this Appendix is to cover in detail the procedure for determining the amount of powder material needed to produce a desired porosity. As mentioned in the report, because of the principle on which the die operates, the amount of powder placed in the die chamber controls the resulting initial porosity. From laboratory experimentation, the relationship between the two was found to be linear, making possible the determination and use of a simple factor accounting for the variation in specific gravity of the fly ash material and the amount of fly ash in the compact.

B. LABORATORY RESULTS

To determine the initial relationship between the weight of powder material used and the porosity obtained, 10 experimental trial series, consisting of three to eight samples each, were prepared from the Type III anhydrous cement powder. The results of these trials are listed in Table C-1.

The calculated initial porosities shown in this table were determined with the following equation:

$$P_i = 1 - (W_t/(V_t((SG_c)(\%C) + (SG_{fa})(\%FA))) \qquad (C-1)$$

where: P_i is the calculated initial porosity,

W_t is the total weight of the prepared compact,

V_t is the total volume of the prepared compact,

SG_c is the specific gravity of the cement,

SG_{fa} is the specific gravity of the fly ash,

$\%C$ is the percentage of the cement powder used, and

$\%FA$ is the percentage of the fly ash powder used.

Using the calculated initial porosity and powder weight values shown in Table C-1, a linear regression analysis yielded the following equation:

$$\text{Porosity} = -17.8013\ (\text{Powder Weight}) + 71.2672 \qquad (C-2)$$

where :

Porosity refers to the calculated initial porosity, and

Powder weight refers to the weight of anhydrous cement powder material placed in the die for compaction, not the weight of the compact after compaction.

The coefficient of determination (r^2) for this equation was 0.994.

TABLE C-1. PRELIMINARY DATA USED TO DETERMINE THE RELATIONSHIP BETWEEN POWDER WEIGHT AND CALCULATED INITIAL POROSITY

Series No.	No. of Samples	Powder Weight (g)	Initial Density (g/cm^3)	Calculated Initial Porosity (percent)
P3	6	2.5386	2.3145	26.05
P4	8	2.7290	2.4136	22.89
P5	6	2.8469	2.4723	21.02
P7	6	2.4673	2.2814	27.11
P8	6	2.5939	2.3508	24.89
P9	3	2.3250	2.1870	30.13
P10	4	2.6500	2.3875	23.72
P11	3	2.3750	2.2186	29.12
P12	4	2.4200	2.2458	28.25
P13	4	2.7500	2.4392	22.07

Because of the excellent relationship between the initial powder weight and the calculated initial porosity for anhydrous cement powder, this equation was used to determine the powder weights needed to produce a desired initial porosity condition for the various percentages of fly ash replacing the cement, using factor which relates the weight to volume of the fly ash.

For example, if 2.8700 grams of anhydrous cement material produces a porosity of 20 percent, the values of %C and %FA in Equation (C-1) are 1.0 and 0.0, respectively. If fly ash is introduced into the system, a proportional specific gravity is used to calculate the porosity depending on the percentages of fly ash and cement in the system (with all other factors held constant). The control weight of the cement may be adjusted by multiplying a factor determined by:

$$((SG_c)(\%C) + (SG_{fa})(\%FA))/SG_c \qquad \text{(C-3)}$$

this will determine the powder weight needed for a material containing a given percentage of fly ash.

From these considerations, the following factors were determined for the different percentages of fly ash as shown.

Percent Fly Ash	Calculations		Factor
0% Fly Ash	(Cement Only Control)	=	1.0000
10% Fly Ash	((3.13x0.9)+(2.75x0.1))/3.13	=	0.9877
20% Fly Ash	((3.13x0.8)+(2.75x0.2))/3.13	=	0.9754
30% Fly Ash	((3.13x0.7)+(2.75x0.3))/3.13	=	0.9631

When these factors were initially determined, Equation (C-1) was developed from an intuitive approach by considering the relationships between porosity, density, specific gravity, percent cement and percent fly ash. However, the actual mathematical derivation of the relationship between porosity, density, specific gravity, percent cement, and percent fly ash produced a slightly different equation. This derived equation is developed in Appendix D.

From the laboratory results however, it appears that the considerations discussed in this Appendix are adequate for determining quantities of powder containing various percentages of fly ash to be used in producing a desired target initial porosity, provided the fly ash specific gravity is correct. For actual initial porosity calculations, the derived equation of Appendix D is the correct mathematical relationship and was used for determining the calculated initial porosity content of the compacts prepared for this investigation.

APPENDIX D

CALCULATED INITIAL POROSITY FORMULA DERIVATION

A. INTRODUCTION

The calculated initial porosity is a measure of the volume of a prepared compact which is void space before exposure to moisture and subsequent hydration occurs. The determination of this value depends on the specific gravity of the material, the volume, and the weight of the prepared compact. This Appendix contains the derivation of the relationship between these variables.

B. ONE-COMPONENT SYSTEM

A one-component system refers to the use of only one type of powder material for the compact preparation (in this case, Type III cement powder). Initially the compact has a total volume consisting of the volume of cement (V_c) and the volume of the voids between the cement particles (V_{air}). The total weight (W_t) of the compact is the weight of cement powder (W_c) composing the compact. In equation form, these relationships are:

$$V_t = V_c + V_{air} \qquad \text{(D-1)}$$

$$W_t = W_c \qquad \text{(D-2)}$$

Dividing Equation (D-1) by the total volume (V_t) of the compact, the equation becomes:

$$1 = V_c/V_t + V_{air}/V_t \qquad \text{(D-3)}$$

The ratio of V_{air}/V_t is defined as the fraction of the total compact volume which is void space or porosity (P_i). Equation (D-3) can then be written as:

$$1 = V_c/V_t + P_i \qquad \text{(D-4)}$$

Using the relationship of specific gravity, the volume of cement (V_c) can be written as:

$$V_c = W_t/SG_c \qquad \text{(D-5)}$$

where SG_c is the specific gravity of the cement material. Equation (D-4) then becomes:

$$1 = (W_t/SG_c)(1/V_t) + P_i \qquad \text{(D-6)}$$

Solving for P_i, the equation then becomes:

$$P_i = (1-(W_t/V_t)(1/SG_c)) \times 100 \qquad (D-7)$$

where P_i is the initial porosity of the compact on a percentage basis. Realizing that W_t/V_t is the density of the prepared compact, the calculation of the initial porosity for one component system is accomplished.

C. TWO-COMPONENT SYSTEM

Initially the volume of a prepared compact, in the case of this work, is the volume of cement, the volume of fly ash and the volume of void space. In equation form this relationship is:

$$V_t = V_c + V_{fa} + V_{air} \qquad (D-8)$$

Dividing through by the total volume V_t, the equation becomes:

$$1 = V_c/V_t + V_{fa}/V_t + V_{air}/V_t \qquad (D-9)$$

Again the ratio V_{air}/V_t can be defined as the initial porosity (P_i) or void space as a fraction of the total volume. Equation (D-9) then becomes:

$$P_i = 1 - (V_c + V_{fa})/V_t \qquad (D-10)$$

Concerning the weight relationship in a two-component prepared compact, the total weight (W_t) equals the weight of the fly ash (W_{fa}) plus the weight of the cement material (W_c). In equation form this becomes:

$$W_t = W_c + W_{fa} \qquad (D-11)$$

Dividing through y the total weight (W_t), the equation becomes:

$$1 = W_c/W_t + W_{fa}/W_t \qquad (D-12)$$

The ratios of the weights of the individual component materials may be defined as:

$$\%C = W_c/W_t \text{ and } \%FA = W_{fa}/W_t \qquad (D-13)$$

Also, using the specific gravity of each of the inidividual components, the volumes of cement and fly ash can be written as:

$$V_c = W_c/SG_c \qquad (D-14)$$

$$V_{fa} = W_{fa}/SG_{fa} \qquad (D-15)$$

Equation (D-10) then becomes:

$$P_i = 1 - (1/V_t)(W_c/SG_c + W_{fa}/SG_{fa}) \qquad \text{(D-16)}$$

However, this equation is impractical, because only the final density of the prepared compacts is known and not the individual weight values for each of the two powders. In order to have a more usable equation the following modification is made:

$$P_i = 1 - (W_t/V_t)((1/SG_c)(W_c/W_t) + (1/SG_{fa})(W_{fa}/W_t)) \qquad \text{(D-17)}$$

As defined by the equations of (D-13), W_c/W_t and W_{fa}/W_t are the known percentages of cement (%C) and fly ash (%FA) by weight in the mix used to prepare the compact. From this consideration then, the calculated initial porosity of the two component anhydrous system may be determined by:

$$P_i = (1 - ((W_t/V_t)(\%C/SG_c + \%FA/SG_{fa}))) \times 100 \qquad \text{(D-18)}$$

where: P_i is the calculated initial porosity,

W_t/V_t is the density of the prepared compact,

%C is the percentage of cement by weight in the mixed powder used for the compact,

%FA is the percentage of fly ash by weight in the mixed powder used for the compact,

SG_c is the specific gravity of the cement, and

SG_{fa} is the specific gravity of the fly ash material.

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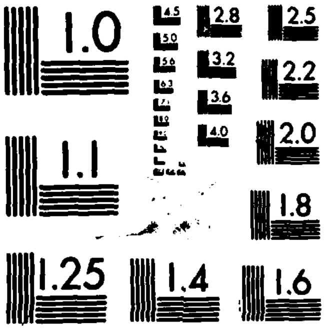

MICROCOPY RESOLUTION TEST CHART
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APPENDIX E

LABORATORY DATA

Complete laboratory data for all compacts are given in Tables E-1 through E-39.

TABLE E-1. LABORATORY DATA FOR SSD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 3 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)	Calc. Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
B11	$\bar{X}$ =	182,000	1,255	2.8684	1.1477	2.4992	20.15	3.1252	1.1567	2.7019	10.51	44,300^{c}	305^{c}
	σ =	3700	25	0.0006	0.0012	0.0027	0.08	0.0011	0.0012	0.0030		800	6
B12	$\bar{X}$ =	121,000	834	2.7093	1.1191	2.4209	22.65	2.9894	1.1277	2.6510	13.00	40,500^{b}	279^{b}
	σ =	3000	19	0.0007	0.0012	0.0028	0.08	0.0013	0.0018	0.0037		1000	7
B13	$\bar{X}$ =	70,300	485	2.5382	1.0910	2.3266	25.67	2.8513	1.0971	2.5989	16.01	39,500^{b}	272^{b}
	σ =	3100	22	0.0013	0.001	0.002	0.06	0.0018	0.0012	0.0023		1900	13
B14	$\bar{X}$ =	35,400	244	2.3714	1.0679	2.2206	29.05	2.7195	1.0736	2.5329	19.38	37,100^{c}	256^{c}
	σ =	1400	9	0.0003	0.001	0.0021	0.06	0.0008	0.0011	0.0027		1700	12
B15	$\bar{X}$ =	14,200	98	2.2083	1.0516	2.0998	32.91	2.5930	1.0569	2.4534	23.23	35,000^{b}	242^{b}
	σ =	300	2	0.0005	0.001	0.0019	0.05	0.0018	0.0016	0.0029		500	3

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 6

c. sample size = 7

TABLE E-2. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 3 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm)
b11	$\bar{X}$ =	174,200	1,201	2.8670	1.1468	2.4999	20.13	3.1282	1.1549	2.7087
	σ =	600	4	0.002	0.0015	0.0023	0.07	0.0022	0.0015	0.0028
b12	$\bar{X}$ =	117,800	812	2.7069	1.1174	2.4226	22.60	2.9901	1.1240	2.6603
	σ =	2700	19	0.0026	0.0008	0.0018	0.05	0.0022	0.0011	0.0037
b13	$\bar{X}$ =	68,800	475	2.5406	1.0911	2.3285	25.61	2.8561	1.0982	2.6007
	σ =	2000	14	0.0006	0.0015	0.0032	0.09	0.0017	0.0019	0.0038
b14	$\bar{X}$ =	33,300	230	2.3718	1.0674	2.2222	29.00	2.7203	1.0732	2.5349
	σ =	1100	8	0.0004	0.0007	0.0015	0.04	0.0011	0.0013	0.0033
b15	$\bar{X}$ =	14,400	99	2.2064	1.0500	2.1013	32.87	2.5940	1.0556	2.4575
	σ =	300	2	0.0024	0.0007	0.0031	0.09	0.0014	0.0011	0.0034

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation

TABLE E-3. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 3 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
b11	$\bar{X}$ =	3.0150	3.0069	3.0079	1.1505	2.6145	10.42	64,900[b]	448[b]
	σ =	0.0020	0.0019	0.0019	0.0013	0.0031		2000	14
b12	$\bar{X}$ =	2.8554	2.8468	2.8467	1.1178	2.5468	12.76	61,600[c]	424[c]
	σ =	0.0025	0.0027	0.0028	0.0009	0.0036		1400	10
b13	$\bar{X}$ =	2.6865	2.6799	2.6780	1.0899	2.4571	16.22	55,300[b]	381[b]
	σ =	0.0009	0.0008	0.0008	0.002	0.0046		1500	10
b14	$\bar{X}$ =	2.5110	2.5119	2.5103	1.0631	2.3613	19.57	48,900[b]	337[b]
	σ =	0.0004	0.0004	0.0005	0.001	0.0021		1700	12
b15	$\bar{X}$ =	2.3523	2.3539	2.3517	1.0438	2.2530	22.95	42,900[b]	296[b]
	σ =	0.0026	0.0025	0.0026	0.0008	0.0035		1600	11

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 6

c. sample size = 7

TABLE E-4. LABORATORY DATA FOR SSD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]	Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)	Calc. Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
C11R $\bar{X}$ =	182,900	1,261	2.8672	1.1468	2.5001	20.13	3.1304	1.1572	2.7052	10.64	49,000	338
σ =	3600	25	0.0006	0.001	0.0024	0.07	0.0016	0.0013	0.0022		1700	12
C12R $\bar{X}$ =	122,600	845	2.7089	1.1160	2.4272	22.45	2.9896	1.1240	2.6599	12.65	48,000[b]	331[b]
σ =	2,700	19	0.0022	0.0006	0.0014	0.04	0.0022	0.0019	0.0046		600	4
C13R $\bar{X}$ =	70,700	487	2.5382	1.0896	2.3293	25.58	2.8505	1.0967	2.5991	15.36	45,000[b]	310[b]
σ =	3,700	26	0.0032	0.0011	0.0026	0.07	0.0027	0.0014	0.0024		400	3
C14R $\bar{X}$ =	33,300	229	2.3725	1.0679	2.2217	29.02	2.7208	1.0735	2.5345	18.34	44,900[b]	310[b]
σ =	1,000	7	0.0003	0.0011	0.0023	0.07	0.0011	0.0010	0.0018		900	6
C15R $\bar{X}$ =	13,800	95	2.2073	1.0506	2.1010	32.87	2.5956	1.0574	2.4547	21.68	41,900[c]	289[c]
σ =	500	3	0.0003	0.0005	0.0011	0.03	0.0007	0.0012	0.0024		400	3

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 7

TABLE E-5. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)
cl1r	$\bar{X}$ =	183,600	1,266	2.8680	1.1474	2.4996	20.14	3.1339	1.1587	2.7047
	σ =	3,000	20	0.0006	0.0005	0.0011	0.03	0.001	0.0015	0.0029
cl2r	$\bar{X}$ =	124,000	855	2.7099	1.1186	2.4226	22.60	2.9947	1.1251	2.6618
	σ =	2,000	14	0.0003	0.0012	0.0025	0.07	0.001	0.0007	0.0011
cl3r	$\bar{X}$ =	72,000	496	2.5388	1.0899	2.3294	25.58	2.8552	1.0975	2.6016
	σ =	1,200	8	0.0035	0.0009	0.0023	0.07	0.0028	0.0011	0.0027
cl4r	$\bar{X}$ =	35,700	246	2.3724	1.0680	2.2214	29.03	2.7222	1.0744	2.5337
	σ =	1,000	7	0.0004	0.0009	0.0020	0.06	0.0017	0.0008	0.0019
cl5r	$\bar{X}$ =	14,600	101	2.2065	1.0505	2.1005	32.89	2.5948	1.0569	2.4550
	σ =	500	3	0.0027	0.0007	0.0024	0.07	0.0021	0.0006	0.002

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

TABLE E-6. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
cl1r	$\bar{X}$ =	3.0129	3.0087	3.0084	1.1552	2.6042	10.83	67,900[b]	468[b]
	σ =	0.0011	0.0010	0.0010	0.0011	0.0023		1,100	8
cl2r	$\bar{X}$ =	2.8619	2.8538	2.8529	1.1205	2.5460	12.60	62,400[b]	430[b]
	σ =	0.0016	0.0017	0.0015	0.0009	0.0025		2,300	16
cl3r	$\bar{X}$ =	2.6949	2.6874	2.6876	1.0910	2.4634	15.27	60,800[b]	419[b]
	σ =	0.0040	0.0049	0.0041	0.0015	0.0046		1,300	9
cl4r	$\bar{X}$ =	2.5289	2.5248	2.5248	1.0656	2.3694	18.37	50,900[c]	351[c]
	σ =	0.0028	0.0026	0.0025	0.0005	0.0026		2,200	15
cl5r	$\bar{X}$ =	2.3672	2.3646	2.3649	1.0466	2.2595	21.75	47,700[c]	329[c]
	σ =	0.0029	0.0029	0.0029	0.0007	0.0018		1,300	9

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 7

TABLE E-7. LABORATORY DATA FOR SSD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 28 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)	Calc. Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
D11R	$\bar{X}$ =	184,300	1,271	2.8668	1.1470	2.4994	20.15	3.1321	1.1590	2.7025	10.10	49,400[b]	341[b]
	σ =	3,100	21	0.0010	0.0007	0.0019	0.05	0.0014	0.0012	0.0026		3,000	21
D12R	$\bar{X}$ =	125,100	863	2.7091	1.1186	2.4219	22.62	2.9975	1.1278	2.6579	12.35	49,700[b]	342[b]
	σ =	1,800	12	0.0006	0.0006	0.0013	0.04	0.0005	0.0011	0.0026		700	5
D13R	$\bar{X}$ =	72,700	501	2.5390	1.0913	2.3267	25.67	2.8570	1.0981	2.6017	15.14	48,300[b]	333[b]
	σ =	1,600	11	0.0019	0.0010	0.0034	0.10	0.0012	0.0013	0.0025		3,000	21
D14R	$\bar{X}$ =	37,800	261	2.3727	1.0685	2.2205	29.06	2.7259	1.0765	2.5321	18.24	47,200	325
	σ =	700	5	0.0009	0.0008	0.0020	0.06	0.0015	0.0010	0.0016		1,700	12
D15R	$\bar{X}$ =	15,500	107	2.2078	1.0506	2.1016	32.86	2.6001	1.0596	2.4538	21.72	43,400	299
	σ =	300	2	0.0006	0.0005	0.0012	0.03	0.0010	0.0011	0.0024		1,500	10

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 6

TABLE E-8. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 28 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	(MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)
d11r	$\bar{X}$ =	184,900	1,275	2.8679	1.1469	2.5007	20.11	3.1334	1.1578	2.7064
	σ =	1,800	12	0.0006	0.0003	0.0008	0.02	0.0004	0.0011	0.0025
d12r	$\bar{X}$ =	124,000	855	2.7093	1.1193	2.4206	22.66	2.9969	1.1270	2.6591
	σ =	3,500	24	0.0007	0.0013	0.0025	0.07	0.0015	0.0018	0.0031
d13r	$\bar{X}$ =	73,500	507	2.5390	1.0912	2.3268	25.66	2.8555	1.0982	2.6002
	σ =	1,800	12	0.0010	0.0008	0.0021	0.06	0.0008	0.0013	0.0032
d14r	$\bar{X}$ =	36,600	252	2.3729	1.0682	2.2213	29.03	2.7241	1.0741	2.5362
	σ =	1,000	7	0.0007	0.0005	0.0012	0.04	0.0012	0.0008	0.0016
d15r	$\bar{X}$ =	15,800	109	2.2069	1.0508	2.1003	32.90	2.5985	1.0580	2.4561
	σ =	700	5	0.0016	0.0013	0.0024	0.07	0.0021	0.0014	0.0031

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

TABLE E-9. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 28 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and	Statistic[a]	24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
d11r	X =	3.0234	3.0159	3.0141	1.1538	2.6124	10.30	69,200^{c}	477^{c}
	o =	0.0015	0.0013	0.0011	0.0012	0.0030		800	5
d12r	X =	2.8660	2.8609	2.8606	1.1227	2.5479	12.09	61,400^{b}	424^{b}
	o =	0.0015	0.0013	0.0013	0.0014	0.0024		2,700	18
d13r	X =	2.6980	2.6908	2.6909	1.0921	2.4638	14.99	57,200^{b}	394^{b}
	o =	0.0012	0.0014	0.0012	0.0007	0.0014		2,800	19
d14r	X =	2.5308	2.5260	2.5255	1.0649	2.3717	18.49	54,000^{c}	372^{c}
	o =	0.0008	0.0008	0.0006	0.0010	0.0021		1,900	13
d15r	X =	2.3720	2.3685	2.3690	1.0461	2.2646	21.69	48,700	336
	o =	0.0016	0.0015	0.0016	0.0011	0.0029		1,500	10

Note:

a. X = sample average and o = sample standard deviation

b. sample size = 6

c. sample size = 7

TABLE E-10. LABORATORY DATA FOR SSD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 90 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure		Initial Weight	Initial Volume	Initial Density	Calc. Initial Porosity	SSD Weight	SSD Volume	SSD Density	Calc. Final Porosity	Compressive Strength	
		(psi)	(MPa)	(g)	(cm^3)	(g/cm^3)	(percent)	(g)	(cm^3)	(g/cm^3)	(percent)	(psi)	(MPa)
E11	$\bar{X}$ =	192,000	1,323	2.8666	1.1513	2.4899	20.45	3.1127	1.1572	2.6898	10.25		
	σ =	3,000	21	0.0009	0.0017	0.0039	0.11	0.0029	0.0015	0.0022			
E12	$\bar{X}$ =	125,500^{c}	866^{c}	2.7063^{c}	1.1177^{c}	2.4214^{c}	22.64^{c}	2.9746^{c}	1.1227^{c}	2.6495^{c}	12.09		
	σ =	6,100	42	0.0012	0.0012	0.0024	0.07	0.0028	0.0009	0.0031			
E13	$\bar{X}$ =	68,800	474	2.5360	1.0906	2.3253	25.71	2.8288	1.0958	2.5815	14.67		
	σ =	3,900	27	0.0019	0.0016	0.0033	0.09	0.0060	0.0017	0.0030			
E14	$\bar{X}$ =	33,300	229	2.3701	1.0676	2.2200	29.07	2.7030	1.0745	2.5156	17.50		
	σ =	1,500	10	0.0004	0.0013	0.0026	0.07	0.0030	0.0018	0.0024			
E15	$\bar{X}$ =	13,500^{b}	93^{b}	2.2051^{b}	1.0525^{b}	2.0952^{b}	33.06^{b}	2.5861^{b}	1.0580^{b}	2.4443^{b}	20.85		
	σ =	900	6	0.0008	0.0025	0.0045	0.12	0.0026	0.0021	0.0030			

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 9
Compressive strength data not available.

TABLE E-11. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 90 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)
e11	X =	179,900	1,240	2.8667	1.1510	2.4906	20.43	3.1133	1.1579	2.6887
	o =	8,200	56	0.0008	0.0032	0.0072	0.21	0.0038	0.0029	0.0044
e12	X =	127,700	880	2.7075	1.1191	2.4193	22.71	2.9787	1.1243	2.6495
	o =	3,500	24	0.0007	0.0018	0.0036	0.10	0.0032	0.0027	0.0055
e13	X =	72,700	501	2.5368	1.0914	2.3244	25.74	2.8323	1.0967	2.5826
	o =	2,300	16	0.0018	0.0013	0.0024	0.07	0.0051	0.0010	0.0033
e14	X =	33,700[b]	232[b]	2.3705[b]	1.0689[b]	2.2176[b]	29.15[b]	2.7062[b]	1.0739[b]	2.5199[b]
	o =	1,400	10	0.0014	0.0019	0.0040	0.11	0.0039	0.0024	0.0039
e15	X =	14,700	102	2.2046	1.0503	2.0990	32.94	2.5834	1.0559	2.4466
	o =	400	3	0.0015	0.0013	0.0035	0.10	0.0023	0.0011	0.0030

Note:
a. X = sample average and o = sample standard deviation
b. sample size = 8

TABLE E-12. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 100 PERCENT PORTLAND CEMENT AND CURED FOR 90 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength (psi)	(MPa)
e11	$\bar{X}$ =	3.0091	2.9969	2.9949	1.1540	2.5952	10.23		
	σ =	0.0022	0.0024	0.0027	0.0029	0.0059			
e12	$\bar{X}$ =	2.8534	2.8439	2.8425	1.1191	2.5399	12.11		
	σ =	0.0032	0.0029	0.0030	0.0025	0.0052			
e13	$\bar{X}$ =	2.6775	2.6707	2.6696	1.0877	2.4543	14.84		
	σ =	0.0044	0.0050	0.0047	0.0013	0.0028			
e14	$\bar{X}$ =	2.5263[b]	2.5210[b]	2.5192[b]	1.0629[b]	2.3701[b]	17.41[b]		
	σ =	0.0025	0.0026	0.0026	0.0019	0.0033			
e15	$\bar{X}$ =	2.3696	2.3641	2.3637	1.0427	2.2669	20.81		
	σ =	0.0023	0.0024	0.0026	0.0016	0.0047			

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 8

Compressive strength data not available

TABLE E-13. LABORATORY DATA FOR SSD COMPACTS CONTAINING 10 PERCENT SIEVED FLY ASH AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]	Production Pressure		Initial Weight	Initial Volume	Initial Density	Calc. Initial Porosity	SSD Weight	SSD Volume	SSD Density	Calc. Final Porosity	Compressive Strength	
	(psi)	(MPa)	(g)	(cm^3)	(g/cm^3)	(percent)	(g)	(cm^3)	(g/cm^3)	(percent)	(psi)	(MPa)
C21S $\bar{X}$ =	176,300	1,215	2.8310	1.1534	2.4546	20.48	3.1055	1.1653	2.6649	11.72	45,100[b]	311[b]
σ =	1,900	13	0.0007	0.0019	0.0041	0.12	0.0019	0.0019	0.0030		700	5
C23S $\bar{X}$ =	63,800[d]	440[d]	2.5077[d]	1.0946[d]	2.2909[d]	25.78[d]	2.8286[d]	1.1030[d]	2.5644[d]	16.51	44,600[c]	308[c]
σ =	700	5	0.0026	0.0012	0.0020	0.06	0.0027	0.0023	0.0041		1,000	7
C25S $\bar{X}$ =	12,900	89	2.1801	1.0517	2.0729	32.84	2.5754	1.0624	2.4241	22.89	38,800[c]	267[c]
σ =	0	0	0.0005	0.0016	0.0032	0.09	0.0013	0.0010	0.0021		500	3

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 7
d. sample size = 9

TABLE E-14. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 10 PERCENT SIEVED FLY ASH AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)
c21s	$\bar{X}$ =	175,600	1,211	2.8320	1.1519	2.4587	20.35	3.1012	1.1602	2.6731
	σ =	2,500	17	0.0012	0.0009	0.0026	0.08	0.0011	0.0015	0.0035
c23s	$\bar{X}$ =	64,300	443	2.5090	1.0927	2.2963	25.61	2.8258	1.0982	2.5731
	σ =	1,700	11	0.0027	0.0014	0.0026	0.07	0.0030	0.0025	0.0043
c25s	$\bar{X}$ =	13,500	93	2.1793	1.0513	2.0729	32.84	2.5690	1.0565	2.4316
	σ =	300	2	0.0006	0.0005	0.0010	0.03	0.0006	0.0008	0.0017

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation

TABLE E-15. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 10 PERCENT SIEVED FLY ASH AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
c21s	$\overline{X}$ =	2.9781	2.9690	2.9676	1.1560	2.5671	11.52	66,300[b]	457[b]
	σ =	0.0009	0.0006	0.0006	0.0012	0.0028		1,700	12
c23s	$\overline{X}$ =	2.6501	2.6438	2.6445	1.0903	2.4254	16.51	56,600[b]	390[b]
	σ =	0.0033	0.0030	0.0031	0.0023	0.0051		1,900	13
c25s	$\overline{X}$ =	2.3313	2.3282	2.3278	1.0443	2.2290	22.83	42,800[b]	295[b]
	σ =	0.0005	0.0006	0.0005	0.0009	0.0020		1,500	10

Note:

a. $\overline{X}$ = sample average and σ = sample standard deviation

b. sample size = 6

TABLE E-16. LABORATORY DATA FOR SSD COMPACTS CONTAINING 10 PERCENT SIEVED FLY ASH AND CURED FOR 28 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)	Calc. Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
D21SR	$\bar{X}$ =	175,500	1,210	2.8319	1.1508	2.4608	20.28	3.1023	1.1609	2.6722	11.18	49,300	340
	σ =	2,800	19	0.0021	0.0005	0.0015	0.04	0.0009	0.0019	0.0045		1,200	8
D23SR	$\bar{X}$ =	63,500^{d}	438^{d}	2.5073^{d}	1.0940^{d}	2.2919^{d}	25.75^{d}	2.8319^{d}	1.1025^{d}	2.5686^{d}	15.69	45,500^{b}	314^{b}
	σ =	2,100	15	0.0038	0.0007	0.0036	0.10	0.0024	0.0023	0.0045		1,400	10
D25SR	$\bar{X}$ =	14,600^{c}	101^{c}	2.1797^{c}	1.0507^{c}	2.0745^{c}	32.79^{c}	2.5739^{c}	1.0589^{c}	2.4308^{c}	21.49	43,500^{c}	300^{c}
	σ =	300	2	0.0011	0.0005	0.0013	0.04	0.0016	0.0010	0.0022		900	6

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 6

c. sample size = 7

d. sample size = 9

TABLE E-17. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 10 PERCENT SIEVED FLY ASH AND CURED FOR 28 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)
d21sr	$\bar{X}$ =	174,500[b]	1,203[b]	2.8320[b]	1.1528[b]	2.4566[b]	20.41[b]	3.1075[b]	1.1632[b]	2.6716[b]
	σ =	1,700	12	0.0025	0.0009	0.0032	0.09	0.0027	0.0015	0.0028
d23sr	$\bar{X}$ =	64,000	441	2.5083	1.0958	2.2891	25.84	2.8500	1.1113	2.5646
	σ =	1,500	10	0.0021	0.0021	0.0042	0.12	0.0037	0.0021	0.0030
d25sr	$\bar{X}$ =	14,400	99	2.1802	1.0504	2.0755	32.76	2.5770	1.0603	2.4304
	σ =	600	4	0.0009	0.0013	0.0028	0.08	0.0009	0.0004	0.0012

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 9

TABLE E-18. POSTDRYING LABORATORY DATA FOR OD COMPACT CONTAINING 10 PERCENT SIEVED FLY ASH AND CURED FOR 28 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
d21sr	$\bar{X}$ =	2.9811[c]	2.9760[c]	2.9754[c]	1.1595[c]	2.5661[c]	11.36	64,500[b]	445[b]
	σ =	0.0034	0.0031	0.0031	0.0011	0.0024		1,700	11
d23sr	$\bar{X}$ =	2.6863	2.6774	2.6762	1.1047	2.4226	15.64	56,700[b]	390[b]
	σ =	0.0035	0.0035	0.0036	0.0022	0.0043		2,000	14
d25sr	$\bar{X}$ =	2.3494	2.3464	2.3488	1.0506	2.2357	21.52	47,800	329
	σ =	0.0019	0.0018	0.0016	0.0005	0.0020		1,400	10

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 6

c. sample size = 9

TABLE E-19. LABORATORY DATA FOR SSD COMPACTS CONTAINING 10 PERCENT SIEVED FLY ASH AND CURED FOR 90 DAYS (SAMPLE SIZE = 9 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)	Calc. Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
E21S	$\bar{X}$ =	183,500[e]	1,265[e]	2.8328[e]	1.1556[e]	2.4513[e]	20.59[e]	3.1077[e]	1.1632[e]	2.6716[e]	11.70	49,400[d]	341[d]
	σ =	3,200	22	0.0008	0.0013	0.0028	0.08	0.0017	0.0016	0.0026		2,000	14
E22S	$\bar{X}$ =	125,600	866	2.6762	1.1246	2.3796	22.91	2.9743	1.1320	2.6276	13.64	49,300[c]	340[c]
	σ =	1,500	10	0.0010	0.0015	0.0028	0.08	0.0025	0.0018	0.0023		1,200	8
E23S	$\bar{X}$ =	76,900	530	2.5090	1.0960	2.2893	25.84	2.8353	1.1031	2.5703	16.08	48,800[c]	336[c]
	σ =	2,600	18	0.0015	0.0013	0.0018	0.05	0.0022	0.0010	0.0027		700	5
E24S	$\bar{X}$ =	36,500	252	2.3439	1.0712	2.1881	29.11	2.7055	1.0780	2.5097	18.80	47,100[d]	325[d]
	σ =	900	6	0.0004	0.0010	0.0021	0.06	0.0010	0.0008	0.0012		1,400	10
E25S	$\bar{X}$ =	15,800	109	2.1800	1.0519	2.0724	32.86	2.5814	1.0603	2.4345	21.92	46,700[b]	322[b]
	σ =	500	3	0.0006	0.0008	0.0015	0.04	0.0014	0.0006	0.0014		600	4

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 7
d. sample size = 8
e. sample size = 10

TABLE E-20. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 10 PERCENT PORTLAND CEMENT AND CURED FOR 90 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)
e21s	$\bar{X}$ =	184,400	1,271	2.8332	1.1566	2.4497	20.64	3.1107	1.1644	2.6715
	σ =	3,900	27	0.0005	0.0016	0.0034	0.10	0.0016	0.0016	0.0023
e22s	$\bar{X}$ =	125,000[c]	862[c]	2.6776[c]	1.1256[c]	2.3789[c]	22.93[c]	2.9754[c]	1.1314[c]	2.6299[c]
	σ =	3,900	27	0.0003	0.0014	0.0027	0.08	0.0015	0.0018	0.0031
e23s	$\bar{X}$ =	75,400	520	2.5090	1.0957	2.2898	25.82	2.8359	1.1026	2.5719
	σ =	2,200	15	0.0006	0.0009	0.0018	0.05	0.0013	0.0017	0.0030
e24s	$\bar{X}$ =	36,500[b]	252[b]	2.3424[b]	1.0714[b]	2.1862[b]	29.17[b]	2.7045[b]	1.0786[b]	2.5074[b]
	σ =	1,600	11	0.0017	0.0009	0.0020	0.06	0.0018	0.0010	0.0022
e25s	$\bar{X}$ =	15,100	104	2.1803	1.0525	2.0715	32.89	2.5808	1.0580	2.4393
	σ =	600	4	0.0006	0.0009	0.0020	0.06	0.0011	0.0007	0.0012

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 8

c. sample size = 9

TABLE E-21. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 10 PERCENT SIEVED FLY ASH AND CURED FOR 90 DAYS (SAMPLE SIZE = 10 UNLESS OTHERWISE NOTED)

Series and Statistic^{a}		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^{3})	48 Hour OD Density (g/cm^{3})	Measured Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
e21s	$\overline{X}$ =	2.9850	2.9777	2.9766	1.1606	2.5648	11.52	65,100^{b}	449^{b}
	σ =	0.0010	0.0009	0.0009	0.0018	0.0043		2,200	15
e22s	$\overline{X}$ =	2.8298^{d}	2.8226^{d}	2.8211^{d}	1.1269^{d}	2.5034^{d}	13.64	62,000^{b}	427^{b}
	σ =	0.0008	0.0007	0.0007	0.0016	0.0033		1,500	11
e23s	$\overline{X}$ =	2.6660	2.6573	2.6572	1.0948	2.4270	16.57	54,700^{b}	377^{b}
	σ =	0.0009	0.0007	0.0007	0.0014	0.0032		2,000	14
e24s	$\overline{X}$ =	2.5087^{c}	2.5045^{c}	2.5032^{c}	1.0691^{c}	2.3413^{c}	18.66	49,100^{b}	338^{b}
	σ =	0.0024	0.0023	0.0024	0.0012	0.0035		2,400	17
e25s	$\overline{X}$ =	2.3553	2.3495	2.3494	1.0471	2.2436	21.87	48,100^{c}	331^{c}
	σ =	0.0008	0.0008	0.0009	0.0011	0.0023		1,700	12

Note:

a. $\overline{X}$ = sample average and σ = sample standard deviation

b. sample size = 6

c. sample size = 8

d. sample size = 9

TABLE E-22. LABORATORY DATA FOR SSD COMPACTS CONTAINING 20 PERCENT SIEVED FLY ASH AND CURED FOR 7 DAYS (SAMPLE SIZE = 9 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)	Calc. Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
C31S	$\bar{X}$ =	168,800[d]	1,164[d]	2.7956[d]	1.1580[d]	2.4143[d]	20.70[d]	3.0763[d]	1.1694[d]	2.6307[d]	13.13	42,900[b]	296[b]
	σ =	3,900	27	0.0009	0.0010	0.0025	0.07	0.0019	0.0013	0.0028		500	3
C33S	$\bar{X}$ =	61,300	422	2.4771	1.0976	2.2568	25.87	2.8043	1.1082	2.5306	17.45	40,600[c]	280[c]
	σ =	2,500	17	0.0016	0.0006	0.0014	0.04	0.0018	0.0029	0.0058		900	6
C35S	$\bar{X}$ =	12,900	89	2.1522	1.0516	2.0465	32.78	2.5464	1.0605	2.4011	23.21	36,200[c]	250[c]
	σ =	0	0	0.0007	0.0004	0.0011	0.03	0.0011	0.0012	0.0032		600	4

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 7
d. sample size = 8

TABLE E-23. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 20 PERCENT SIEVED FLY ASH AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure		Initial Weight	Initial Volume	Initial Density	Calc. Initial Porosity	SSD Weight	SSD Volume	SSD Density
		(psi)	(MPa)	(g)	(cm^3)	(g/cm^3)	(percent)	(g)	(cm^3)	(g/cm^3)
c31s	$\bar{X}$ =	169,600[b]	1,169[b]	2.7963[b]	1.1587[b]	2.4133[b]	20.74[b]	3.0792[b]	1.1684[b]	2.6354[b]
	σ =	3,100	21	0.0004	0.0011	0.0022	0.06	0.0016	0.0014	0.0019
c33s	$\bar{X}$ =	65,000	448	2.4775	1.0973	2.2578	25.84	2.8049	1.1056	2.5369
	σ =	2,900	20	0.0005	0.0011	0.0025	0.07	0.0027	0.0029	0.0068
c35s	$\bar{X}$ =	13,300	92	2.1517	1.0513	2.0468	32.77	2.5459	1.0601	2.4016
	σ =	300	2	0.0020	0.0005	0.0019	0.06	0.0019	0.0005	0.0009

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 7

TABLE E-24. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 20 PERCENT SIEVED FLY ASH AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength	
								(psi)	(MPa)
c31s	$\bar{X}$ =	2.9356[c]	2.9291[c]	2.9287[c]	1.1622[c]	2.5199[c]	12.88	62,000[b]	428[b]
	σ =	0.0013	0.0009	0.0011	0.0013	0.0024		1,500	11
c33s	$\bar{X}$ =	2.6104	2.6073	2.6068	1.0981	2.3740	17.92	51,900[c]	358[c]
	σ =	0.0023	0.0025	0.0024	0.0030	0.0084		1,900	13
c35s	$\bar{X}$ =	2.3048	2.3012	2.3022	1.0482	2.1963	22.99	39,100[b]	270[b]
	σ =	0.0020	0.0019	0.0018	0.0005	0.0018		1,100	8

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 7

TABLE E-25. LABORATORY DATA FOR SSD COMPACTS CONTAINING 20 PERCENT SIEVED FLY ASH AND CURED FOR 28 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure		Initial Weight	Initial Volume	Initial Density	Calc. Initial Porosity	SSD Weight	SSD Volume	SSD Density	Calc. Final Porosity	Compressive Strength	
		(psi)	(MPa)	(g)	(cm^3)	(g/cm^3)	(percent)	(g)	(cm^3)	(g/cm^3)	(percent)	(psi)	(MPa)
D31SR	$\bar{X}$ =	175,000	1,206	2.7967	1.1568	2.4175	20.60	3.0806	1.1694	2.6343	13.01	44,100[b]	304[b]
	σ =	2,700	19	0.0007	0.0015	0.0030	0.09	0.0016	0.0016	0.0028		1,000	7
D33SR	$\bar{X}$ =	61,800[d]	426[d]	2.4776[d]	1.0964[d]	2.2597[d]	25.78[d]	2.8084[d]	1.1091[d]	2.5322[d]	17.25	42,500[c]	293[c]
	σ =	1,100	8	0.0010	0.0014	0.0032	0.09	0.0025	0.0041	0.0076		1,600	11
D35SR	$\bar{X}$ =	12,900	89	2.1512	1.0500	2.0487	32.71	2.5505	1.0607	2.4046	22.93	40,600[b]	280[b]
	σ =	0	0	0.0022	0.0006	0.0025	0.07	0.0021	0.0013	0.0036		300	2

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 6

c. sample size = 7

d. sample size = 9

TABLE E-26. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 20 PERCENT SIEVED FLY ASH AND CURED FOR 28 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)
d31sr	$\bar{X}$ =	172,300	1,188	2.7949	1.1565	2.4167	20.62	3.0780	1.1681	2.6351
	σ =	3,600	24	0.0031	0.0017	0.0023	0.07	0.0035	0.0036	0.0062
d33sr	$\bar{X}$ =	63,000[b]	434[b]	2.4771[b]	1.0962[b]	2.2597[b]	25.78[b]	2.8074[b]	1.1110[b]	2.5269[b]
	σ =	1,900	13	0.0004	0.0009	0.0018	0.05	0.0014	0.0030	0.0067
d35sr	$\bar{X}$ =	13,400	93	2.1520	1.0512	2.0473	32.76	2.5511	1.0614	2.4035
	σ =	200	1	0.0005	0.0008	0.0015	0.04	0.0008	0.0013	0.0029

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 9

TABLE E-27. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 20 PERCENT SIEVED FLY ASH AND CURED FOR 28 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength (psi)	(MPa)
d31sr	$\bar{X}$ =	2.9364	2.9280	2.9269	1.1628	2.5172	12.94	63,100	435
	σ =	0.0028	0.0026	0.0028	0.0044	0.0099		1,300	9
d33sr	$\bar{X}$ =	2.6206[c]	2.6144[c]	2.6140[c]	1.1012[c]	2.3739[c]	17.41	53,300[b]	367[b]
	σ =	0.0016	0.0018	0.0016	0.0029	0.0075		1,900	14
d35sr	$\bar{X}$ =	2.3135	2.3089	2.3080	1.0483	2.2017	22.90	45,000[b]	310[b]
	σ =	0.0006	0.0006	0.0004	0.0012	0.0025		1,100	8

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 6

c. sample size = 9

TABLE E-28. LABORATORY DATA FOR SSD COMPACTS CONTAINING 20 PERCENT SIEVED FLY ASH AND CURED FOR 90 DAYS (SAMPLE SIZE = 9 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)	Calc. Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
E31S	$\bar{X}$ =	181,300^{e}	1,250^{e}	2.7982^{e}	1.1597^{e}	2.4130^{e}	20.75^{e}	3.0841^{e}	1.1678^{e}	2.6410^{e}	12.76	46,100^{d}	318^{d}
	σ =	4,000	28	0.0004	0.0009	0.0018	0.05	0.0014	0.0027	0.0048		2,100	14
E32S	$\bar{X}$ =	118,600	818	2.6437	1.1288	2.3420	23.08	2.9499	1.1365	2.5955	14.56	45,500^{b}	314^{b}
	σ =	2,800	19	0.0014	0.0012	0.0022	0.06	0.0017	0.0017	0.0027		1,200	8
E33S	$\bar{X}$ =	66,800	461	2.4778	1.0970	2.2588	25.81	2.8123	1.1088	2.5363	16.66	45,800^{c}	316^{c}
	σ =	1,200	8	0.0005	0.0005	0.0009	0.03	0.0012	0.0030	0.0062		2,000	13
E34S	$\bar{X}$ =	30,400	210	2.3154	1.0714	2.1611	29.02	2.6812	1.0799	2.4828	19.13	44,700^{c}	308^{c}
	σ =	1,000	7	0.0005	0.0010	0.0018	0.05	0.0011	0.0014	0.0027		1,500	11
E35S	$\bar{X}$ =	12,800^{e}	89^{e}	2.1525^{e}	1.0519^{e}	2.0462^{e}	32.79^{e}	2.5592^{e}	1.0620^{e}	2.4098^{e}	22.04	41,500^{c}	286^{c}
	σ =	200	2	0.0010	0.0005	0.0016	0.05	0.0009	0.0012	0.0030		1,200	8

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 7
d. sample size = 8
e. sample size = 10

TABLE E-29. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 20 PERCENT SIEVED FLY ASH AND CURED FOR 90 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic^a		Production Pressure (psi)	(MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)
e31s	$\bar{X}$ =	179,500^c	1,238^c	2.7965^c	1.1594^c	2.4121^c	20.78^c	3.0833^c	1.1688^c	2.6380^c
	σ =	2,800	19	0.0004	0.0006	0.0013	0.04	0.0021	0.0030	0.0051
e32s	$\bar{X}$ =	117,900^b	813^b	2.6430^b	1.1287^b	2.3416^b	23.09^b	2.9517^b	1.1377^b	2.5944^b
	σ =	1,600	11	0.0007	0.0012	0.0021	0.06	0.0032	0.0017	0.0039
e33s	$\bar{X}$ =	67,800	467	2.4774	1.0971	2.2581	25.83	2.8129	1.1077	2.5395
	σ =	1,100	8	0.0006	0.0007	0.0015	0.04	0.0014	0.0025	0.0048
e34s	$\bar{X}$ =	31,300	216	2.3139	1.0713	2.1598	29.06	2.6799	1.0799	2.4816
	σ =	900	6	0.0017	0.0005	0.0019	0.06	0.0013	0.0013	0.0031
e35s	$\bar{X}$ =	12,900^c	89^c	2.1528^c	1.0518^c	2.0468^c	32.77^c	2.5599^c	1.0613^c	2.4120^c
	σ =	0	0	0.0014	0.0005	0.0014	0.04	0.0013	0.0007	0.0012

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 9
c. sample size = 10

TABLE E-30. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 20 PERCENT SIEVED FLY ASH AND CURED FOR 90 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
e31s	$\bar{X}$ =	2.9434[e]	2.9380[e]	2.9369[e]	1.1649[e]	2.5213[e]	12.53	57,900[c]	399[c]
	σ =	0.0014	0.0012	0.0012	0.0027	0.0065		1,200	8
e32s	$\bar{X}$ =	2.7928[d]	2.7861[d]	2.7849[d]	1.1322[d]	2.4597[d]	14.66	54,600[b]	377[b]
	σ =	0.0015	0.0015	0.0014	0.0015	0.0031		2,400	17
e33s	$\bar{X}$ =	2.6325	2.6243	2.6245	1.0989	2.3883	17.01	55,900[b]	386[b]
	σ =	0.0011	0.0010	0.0010	0.0022	0.0053		2,000	14
e34s	$\bar{X}$ =	2.4792	2.4740	2.4736	1.0705	2.3108	19.10	51,700	357
	σ =	0.0015	0.0013	0.0014	0.0006	0.0021		1,200	8
e35s	$\bar{X}$ =	2.3324[e]	2.3287[e]	2.3274[e]	1.0499[e]	2.2168[e]	21.91	44,200	304
	σ =	0.0016	0.0017	0.0017	0.0009	0.0018		2,000	14

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 7
d. sample size = 9
e. sample size = 10

TABLE E-31. LABORATORY DATA FOR SSD COMPACTS CONTAINING 30 PERCENT SIEVED FLY ASH AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Stastistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)	Calc. Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
C41SR	$\bar{X}$ =	166,000	1,145	2.7619	1.1611	2.3788	20.80	3.0529	1.1739	2.6006	14.89	37,100[b]	256[b]
	σ =	4,300	29	0.0018	0.0012	0.0016	0.05	0.0024	0.0017	0.0029		1,100	8
C43SR	$\bar{X}$ =	60,200[c]	415[c]	2.4472[c]	1.0974[c]	2.2301[c]	25.75[c]	2.7785[c]	1.1101[c]	2.5029[c]	18.57[c]	38,200[c]	263[c]
	σ =	2,300	16	0.0009	0.0010	0.0026	0.08	0.0006	0.0031	0.0069		1,600	11
C45SRR	$\bar{X}$ =	12,600	87	2.1249	1.0530	2.0180	32.81	2.5208	1.0607	2.3764	23.82	32,400[c]	223[c]
	σ =	400	3	0.0006	0.0008	0.0018	0.05	0.0009	0.0014	0.0035		1,500	11

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 6

c. sample size = 7

TABLE E-32. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 30 PERCENT SIEVED FLY ASH AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure		Initial Weight	Initial Volume	Initial Density	Calc. Initial Porosity	SSD Weight	SSD Volume	SSD Density
		(psi)	(MPa)	(g)	(cm^3)	(g/cm^3)	(percent)	(g)	(cm^3)	(g/cm^3)
c41s	$\bar{X}$ =	170,100[b]	1,173[b]	2.7608[b]	1.1634[b]	2.3730[b]	20.99[b]	3.0511[b]	1.1753[b]	2.5962[b]
	σ =	3,200	22	0.0019	0.0008	0.0027	0.08	0.0013	0.0022	0.0045
c43sr	$\bar{X}$ =	61,400	424	2.4451	1.0978	2.2273	25.85	2.7779	1.1080	2.5071
	σ =	800	6	0.0017	0.0013	0.0032	0.09	0.0019	0.0023	0.0047
c45sr	$\bar{X}$ =	12,700[c]	88[c]	2.1248[c]	1.0512[c]	2.0213[c]	32.71[c]	2.5195[c]	1.0598[c]	2.3774[c]
	σ =	300	2	0.0022	0.0005	0.0017	0.05	0.0018	0.0016	0.0027

Note:

a. $\bar{X}$ = sample average and σ = sample standard deviation

b. sample size = 7

c. sample size = 9

TABLE E-33. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 30 PERCENT SIEVED FLY ASH AND CURED FOR 7 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
c41s	$\bar{X}$ =	2.8784[c]	2.8748[c]	2.8746[c]	1.1682[c]	2.4608[c]	15.02	55,700[b]	384[b]
	σ =	0.0028	0.0026	0.0026	0.0029	0.0080		900	6
c43sr	$\bar{X}$ =	2.5732	2.5711	2.5712	1.0997	2.3381	18.66	47,400[b]	327[b]
	σ =	0.0025	0.0022	0.0022	0.0026	0.0068		2,300	16
c45sr	$\bar{X}$ =	2.2720[d]	2.2680[d]	2.2679[d]	1.0480[d]	2.1641[d]	23.74	37,900[b]	261[b]
	σ =	0.0020	0.0020	0.0021	0.0011	0.0028		1,700	12

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 7
d. sample size = 9

TABLE E-34. LABORATORY DATA FOR SSD COMPACTS CONTAINING 30 PERCENT SIEVED FLY ASH AND CURED FOR 28 DAYS (SAMPLE SIZE = 7 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)	Calc. Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
D41SR	$\bar{X}$ =	171,900[d]	1,185[d]	2.7602[d]	1.1610[d]	2.3774[d]	20.85[d]	3.0529[d]	1.1739[d]	2.6006[d]	14.13	40,700	281
	σ =	2,000	14	0.0006	0.0010	0.0021	0.06	0.0017	0.0018	0.0035		900	6
D43SR	$\bar{X}$ =	56,300	388	2.4460	1.0979	2.2280	25.82	2.7828	1.1131	2.5001	17.94	42,000[b]	289[b]
	σ =	800	6	0.0006	0.0015	0.0033	0.10	0.0022	0.0039	0.0072		1,800	12
D45SR	$\bar{X}$ =	12,800[c]	88[c]	2.1258[c]	1.0510[c]	2.0227[c]	32.66[c]	2.5290[c]	1.0624[c]	2.3804[c]	23.18	38,400	265
	σ =	200	2	0.0005	0.0003	0.0008	0.02	0.0011	0.0008	0.0022		700	5

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 8
d. sample size = 9

TABLE E-35. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 30 PERCENT SIEVED FLY ASH AND CURED FOR 28 DAYS (SAMPLE SIZE = 6 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)
d41sr	$\bar{X}$ =	169,000	1,165	2.7590	1.1592	2.3800	20.76	3.0546	1.1757	2.5982
	σ =	2,300	16	0.0006	0.0011	0.0024	0.07	0.0016	0.0029	0.0055
d43sr	$\bar{X}$ =	56,300	388	2.4464	1.0988	2.2263	25.88	2.7846	1.1166	2.4938
	σ =	1,100	7	0.0005	0.0008	0.0016	0.05	0.0025	0.0043	0.0082
d45sr	$\bar{X}$ =	12,300[b]	85[b]	2.1232[b]	1.0505[b]	2.0212[b]	32.71[b]	2.5278[b]	1.0656[b]	2.3723[b]
	σ =	200	2	0.0008	0.0010	0.0020	0.06	0.0017	0.0014	0.0032

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 8

TABLE E-36. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 30 PERCENT SIEVED FLY ASH AND CURED FOR 28 DAYS (SAMPLE SIZE = 6 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^3)	48 Hour OD Density (g/cm^3)	Measured Final Porosity (percent)	Compressive Strength	
								(psi)	(MPa)
d41sr	$\bar{X}$ =	2.9331	2.8972	2.8916	1.1690	2.4736	13.86	54,200	374
	σ =	0.0018	0.0013	0.0010	0.0025	0.0057		1,800	12
d43sr	$\bar{X}$ =	2.2587	2.5800	2.5798	1.1080	2.3284	18.34	50,100	346
	σ =	0.0018	0.0015	0.0016	0.0050	0.0115		1,500	10
d45sr	$\bar{X}$ =	2.2992[b]	2.2840[b]	2.2820[b]	1.0517[b]	2.1698[b]	23.07	41,400	285
	σ =	0.0017	0.0017	0.0017	0.0013	0.0026		800	5

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 8

TABLE E-37. LABORATORY DATA FOR SSD COMPACTS CONTAINING 30 PERCENT SIEVED FLY ASH AND CURED FOR 90 DAYS (SAMPLE SIZE = 9 UNLESS OTHERWISE NOTED)

Series and Statistic[a]	Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)	Calc. Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
E41S $\bar{X}$ =	175,500	1,210	2.7614	1.1634	2.3735	20.98	3.0594	1.1748	2.6041	14.41	43,400[b]	299[b]
σ =	2,800	19	0.0011	0.0009	0.0019	0.06	0.0022	0.0032	0.0056		1,300	9
E42S $\bar{X}$ =	116,200[c]	801[c]	2.6083[c]	1.1310[c]	2.3062[c]	23.22[c]	2.9234[c]	1.1413[c]	2.5614[c]	16.13	42,900[b]	296[b]
σ =	3,100	21	0.0010	0.0013	0.0024	0.07	0.0022	0.0019	0.0029		1,000	7
E43S $\bar{X}$ =	68,700	474	2.4468	1.0996	2.2251	25.92	2.7896	1.1118	2.5091	18.21	43,300[b]	299[b]
σ =	1,600	11	0.0005	0.0009	0.0018	0.05	0.0009	0.0021	0.0040		1,000	7
E44S $\bar{X}$ =	31,200[c]	215[c]	2.2844[c]	1.0718[c]	2.1313[c]	29.04[c]	2.6565[c]	1.0808[c]	2.4580[c]	20.61	42,400[b]	292[b]
σ =	700	5	0.0009	0.0005	0.0012	0.03	0.0038	0.0006	0.0037		1,100	7
E45S $\bar{X}$ =	12,600[d]	87[d]	2.1240[d]	1.0516[d]	2.0198[d]	32.75[d]	2.5327[d]	1.0603[d]	2.3886[d]	23.46	40,200	277
σ =	500	3	0.0014	0.0006	0.0019	0.06	0.0015	0.0008	0.0019		1,600	11

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 8
d. sample size = 10

TABLE E-38. PREDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 30 PERCENT SIEVED FLY ASH AND CURED FOR 90 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic[a]		Production Pressure (psi)	Production Pressure (MPa)	Initial Weight (g)	Initial Volume (cm^3)	Initial Density (g/cm^3)	Calc. Initial Porosity (percent)	SSD Weight (g)	SSD Volume (cm^3)	SSD Density (g/cm^3)
e41s	$\bar{X}$ =	174,000	1,200	2.7599	1.1633	2.3725	21.01	3.0585	1.1741	2.6050
	σ =	3,200	22	0.0018	0.0010	0.0019	0.06	0.0024	0.0024	0.0045
e42s	$\bar{X}$ =	112,100[b]	773[b]	2.6079[b]	1.1313[b]	2.3053[b]	23.25[b]	2.9241[b]	1.1437[b]	2.5567[b]
	σ =	2,100	14	0.0014	0.0011	0.0019	0.06	0.0024	0.0024	0.0037
e43s	$\bar{X}$ =	66,700	460	2.4451	1.0996	2.2236	25.97	2.7872	1.1125	2.5054
	σ =	2,000	14	0.0017	0.0011	0.0029	0.09	0.0022	0.0032	0.0062
e44s	$\bar{X}$ =	31,000[c]	214[c]	2.2841[c]	1.0726[c]	2.1296[c]	29.10[c]	2.6553[c]	1.0812[c]	2.4559[c]
	σ =	1,300	9	0.0013	0.0013	0.0030	0.09	0.0025	0.0022	0.0031
e45s	$\bar{X}$ =	12,500[b]	86[b]	2.1237[b]	1.0510[b]	2.0207[b]	32.72[b]	2.5320[b]	1.0592[b]	2.3906[b]
	σ =	500	3	0.0007	0.0007	0.0014	0.04	0.0018	0.0012	0.0016

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 9
c. sample size = 10

TABLE E-39. POSTDRYING LABORATORY DATA FOR OD COMPACTS CONTAINING 30 PERCENT SIEVED FLY ASH AND CURED FOR 90 DAYS (SAMPLE SIZE = 8 UNLESS OTHERWISE NOTED)

Series and Statistic^{a}		24 Hour OD Weight (g)	42 Hour OD Weight (g)	48 Hour OD Weight (g)	48 Hour OD Volume (cm^{3})	48 Hour OD Density (g/cm^{3})	Measured Final Porosity (percent)	Compressive Strength (psi)	Compressive Strength (MPa)
e41s	$\bar{X}$ =	2.8901	2.8891	2.8891	1.1680	2.4736	14.43	56,100^{b}	386^{b}
	σ =	0.0023	0.0022	0.0020	0.0026	0.0055		900	6
e42s	$\bar{X}$ =	2.7405^{d}	2.7357^{d}	2.7355^{d}	1.1346^{d}	2.4110^{d}	16.49	54,900^{c}	379^{c}
	σ =	0.0016	0.0017	0.0015	0.0018	0.0033		900	6
e43s	$\bar{X}$ =	2.5956	2.5877	2.5868	1.1017	2.3481	18.01	49,100^{b}	338^{b}
	σ =	0.0027	0.0023	0.0023	0.0021	0.0056		1,300	9
e44s	$\bar{X}$ =	2.4367^{e}	2.4340^{e}	2.4355^{e}	1.0702^{e}	2.2758^{e}	20.33	46,800	323
	σ =	0.0015	0.0018	0.0017	0.0020	0.0043		700	5
e45s	$\bar{X}$ =	2.2835^{d}	2.2793^{d}	2.2806^{d}	1.0470^{d}	2.1783^{d}	23.73	45,200^{b}	311^{b}
	σ =	0.0017	0.0021	0.0016	0.0012	0.0023		900	6

Note:
a. $\bar{X}$ = sample average and σ = sample standard deviation
b. sample size = 6
c. sample size = 7
d. sample size = 9
e. sample size = 10

APPENDIX F

LINEAR REGRESSION SUMMARY DATA

The purpose of this Appendix is to provide additional pertinent data concerning each of the linear regression analyses performed for this report. The data presented have been sorted by the figure which contains the linear relationship in question. Additional data presented include the units to be used for the X and Y axis values, the slope of the developed regression equation, the Y-intercept of the regression line, the number of data points used for the equation development or degrees of freedom and the coefficient of determination for each equation. Linear regression data are given in Table F-1.

TABLE F-1. LINEAR REGRESSION SUMMARY DATA

Figure Number	Line Description	Axis Units		Degrees of Freedom	Slope of Regression Line	Y-Intercept of Regression Line	Coefficient of Determination
		Y	X				
10	0% Fly Ash	grams	percent	40	-0.051	3.887	0.993
	10% Fly Ash	grams	percent	22	-0.052	3.887	0.994
	20% Fly Ash	grams	percent	22	-0.053	3.877	0.993
	30% Fly Ash	grams	percent	22	-0.053	3.857	0.992
11	0% Fly Ash	grams	$\log_{10} X$, psi	40	0.59	-0.28	0.978
	10% Fly Ash	grams	$\log_{10} X$, psi	22	0.58	-0.27	0.976
	20% Fly Ash	grams	$\log_{10} X$, psi	22	0.56	-0.18	0.983
	30% Fly Ash	grams	$\log_{10} X$, psi	22	0.55	-0.16	0.983
12		percent	$\log_{10} X$, psi	106	-10.9	78.2	0.991
13	0% Fly Ash	percent	$\log_{10} X$, psi	20	-10.5	65.9	0.979
	10% Fly Ash	percent	$\log_{10} X$, psi	11	-9.5	61.9	0.983
	20% Fly Ash	percent	$\log_{10} X$, psi	11	-8.6	58.1	0.980
	30% Fly Ash	percent	$\log_{10} X$, psi	11	-7.9	55.7	0.987
14	SSD	g/cm^3	$\log_{10} X$, psi	40	0.22	1.5	0.991
	OD	g/cm^3	$\log_{10} X$, psi	40	0.32	0.9	0.994
	Initial	g/cm^3	$\log_{10} X$, psi	20	0.36	0.6	0.994
15	SSD	g/cm^3	$\log_{10} X$, psi	22	0.22	1.5	0.992
	OD	g/cm^3	$\log_{10} X$, psi	11	0.30	1.0	0.995
	Initial	g/cm^3	$\log_{10} X$, psi	22	0.35	0.6	0.991
16	SSD	g/cm^3	$\log_{10} X$, psi	22	0.20	1.6	0.995
	OD	g/cm^3	$\log_{10} X$, psi	11	0.28	1.1	0.992
	Initial	g/cm^3	$\log_{10} X$, psi	22	0.32	0.7	0.997

TABLE F-1. LINEAR REGRESSION SUMMARY DATA (CONTINUED)

Figure Number	Line Description	Axis Units		Degrees of Freedom	Slope of Regression Line	Y-Intercept of Regression Line	Coefficient of Determination
		Y	X				
17	SSD	g/cm^3	$\log_{10}$ X, psi	22	0.19	1.6	0.994
	OD	g/cm^3	$\log_{10}$ X, psi	11	0.26	1.1	0.995
	Initial	g/cm^3	$\log_{10}$ X, psi	22	0.31	0.7	0.996
18	Initial	percent	$\log_{10}$ X, psi	106	-10.93	78.2	0.991
	Final	percent	$\log_{10}$ X, psi	48	-9.18	60.5	0.919
19	14,000 psi	percent	percent	12	-0.19	34.4	0.679
	70,000 psi	percent	percent	12	-0.39	41.7	0.918
	175,000 psi	percent	percent	12	-0.57	48.4	0.944
20	3 day	psi	$\log_{10}$ X, psi	5	7,731.7	2,336	0.929
	7 day	psi	$\log_{10}$ X, psi	5	6,053.3	16,870	0.933
	28 day	psi	$\log_{10}$ X, psi	5	5,691.2	20,291	0.912
21	7 day	psi	$\log_{10}$ X, psi	3	5,797.9	15,464	0.898
	28 day	psi	$\log_{10}$ X, psi	3	5,211.7	21,412	0.922
	90 day	psi	$\log_{10}$ X, psi	5	2,877.0	34,445	0.936
22	7 day	psi	$\log_{10}$ X, psi	3	6,041.7	11,453	0.997
	28 day	psi	$\log_{10}$ X, psi	3	3,066.9	27,940	0.996
	90 day	psi	$\log_{10}$ X, psi	5	3,643.6	27,415	0.807
23	7 day	psi	$\log_{10}$ X, psi	3	4,566.1	14,439	0.699
	28 day	psi	$\log_{10}$ X, psi	3	2,227.7	29,902	0.478
	90 day	psi	$\log_{10}$ X, psi	5	2,575.1	30,213	0.807
24	7 to 28 days	percent	$\log_{10}$ X, psi	11	-1.3	10.1	0.996

TABLE F-1. LINEAR REGRESSION SUMMARY DATA (CONTINUED)

Figure Number	Line Description	Axis Units		Degrees of Freedom	Slope of Regression Line	Y-Intercept of Regression Line	Coefficient of Determination
		Y	X				
25	7 to 28 days	percent	$\log_{10}$ X, psi	11	-2.4	19.0	0.996
	7 to 90 days	percent	$\log_{10}$ X, psi	11	-8.7	53.4	0.996
26	7 to 28 days	percent	$\log_{10}$ X, psi	11	-8.6	47.1	0.996
	7 to 90 days	percent	$\log_{10}$ X, psi	11	-8.0	49.6	0.996
27	7 to 28 days	percent	$\log_{10}$ X, psi	11	-8.0	55.5	0.996
	7 to 90 days	percent	$\log_{10}$ X, psi	11	-8.3	51.5	0.996
28	0% Fly Ash,SSD	psi	percent	5	-621.5	55,539	0.946
	10% Fly Ash,SSD	psi	percent	3	-582.6	52,760	0.869
	20% Fly Ash,SSD	psi	percent	3	-670.0	51,913	0.991
	30% Fly Ash,SSD	psi	percent	3	-565.8	46,702	0.679
	0% Fly Ash,OD	psi	percent	5	-1868.7	87,399	0.957
	10% Fly Ash,OD	psi	percent	3	-2082.4	90,537	0.997
	20% Fly Ash,OD	psi	percent	3	-2265.3	91,618	0.996
	30% Fly Ash,OD	psi	percent	3	-2030.4	85,862	0.997
29	0% Fly Ash,SSD	psi	percent	5	-512.9	55,555	0.866
	10% Fly Ash,SSD	psi	percent	3	-552.4	55,004	0.939
	20% Fly Ash,SSD	psi	percent	3	-351.8	48,637	0.999
	30% Fly Ash,SSD	psi	percent	3	-280.3	45,529	0.488
	0% Fly Ash,OD	psi	percent	5	-1612.3	83,111	0.933
	10% Fly Ash,OD	psi	percent	3	-1635.9	82,791	0.997
	20% Fly Ash,OD	psi	percent	3	-1805.8	85,853	0.989
	30% Fly Ash,OD	psi	percent	3	-1394.0	74,248	0.965

TABLE F-1. LINEAR REGRESSION SUMMARY DATA (CONCLUDED)

Figure Number	Line Description	Axis Units		Degrees of Freedom	Slope of Regression Line	Y-Intercept of Regression Line	Coefficient of Determination
		Y	X				
30	10% Fly Ash,SSD	psi	percent	5	-299.8	53,185	0.920
	20% Fly Ash,SSD	psi	percent	5	-451.9	52,416	0.784
	30% Fly Ash,SSD	psi	percent	5	-319.9	48,378	0.764
	10% Fly Ash,OD	psi	percent	5	-1804.3	85,485	0.940
	20% Fly Ash,OD	psi	percent	5	-1325.4	75,447	0.831
	30% Fly Ash,OD	psi	percent	5	-1269.9	74,038	0.880
31	7 day	percent	percent	24	-0.7	0.6	0.988
	28 day	percent	percent	24	-0.5	4.7	0.869
	90 day	percent	percent	18	-0.6	11.6	0.758

END

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