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Concrete Pumping Effects on Entrained Air-Voids

CONCRETE PUMPING EFFECTS ON ENTRAINED AIR-VOIDS

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16. ABSTRACT

Pumping is a frequently used method of efficiently transporting concrete from the delivery vehicles to the formwork. Unfortunately, pumping concrete can affect the air content of a concrete mix. This has caused concern about the possible loss of resistance of the concrete to freezing and thawing. The actual effect of pumping on the air content measured for the concrete is not consistent; in some cases air content has increased, while in others it has decreased. Previous work has shown that pumping causes pressure in the concrete, and this pressure can alter the air-void system. The purpose of this work was to verify previously identified changes in the air-void system, and to examine the effect of pressure on concrete mixes containing various admixture combinations.

The stability of an air-void system with respect to pressurization was found to depend upon both the actual air content and the admixture(s) used in the mix. Higher air contents improved resistance to changes from pressurization, while the use of lignosulfonate-based water-reducers decreased the stability. Type F flyash improved the stability. Air-entraining agent type appeared to also affect stability, but additional testing would be required to establish statistically significant effects based on air-entraining agent type.

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EXECUTIVE SUMMARY

Pumping is a frequently used method of efficiently transporting concrete from the delivery vehicles to the formwork. Unfortunately, pumping concrete can affect the air content of a concrete mix. This problem has caused concern about the possible loss of the concrete's resistance to freezing and thawing. The actual effect of pumping on the air content measured for the concrete is not consistent: in some cases air content has increased while in others it has decreased. Though the measured air content is often viewed as the important parameter when resistance to freezing and thawing is considered, the actual air void system correlates most closely with frost resistance. The important parameters of the air void system are the size and distribution of the bubbles, and the effect of pumping on the size and distribution of these bubbles is of greater significance than merely the effect on the cumulative volume of the bubbles.

Dyer* conducted an analytical study of typical pressures applied to concrete during the pumping process. He followed this analytical study with a laboratory study of the effects of pressure on the air void system. He examined a specific mix containing a lignosulfonate-based retarding water-reducer along with a vinsol resin air-entraining agent, and found that pressure magnitude had a major effect on the air void system. Duration of the pressure also had an effect, though the effect was less than that associated with the magnitude of the pressure. The effect that Dyer found was that pressurization, as from pumping, resulted in a coarsening of the air void system; both the sizes of the bubbles and the spaces between them increased. In extreme cases these effects could be detrimental to the resistance of the concrete to freezing and thawing.

A limitation of Dyer's work was that he tested a single concrete mix design. Questions arose concerning whether his "air void coarsening from pressure exposure"

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* Dyer, R.M., "An Investigation of Concrete Pumping Pressure and the Effects on the Air Void System of Concrete", Master's Thesis, Department of Civil Engineering, University of Washington, 1991.

mechanism would apply to all concrete mixes, or was a characteristic of only the mix he tested. Clarifications were also needed to explain how his mechanism related to observed field air content fluctuations, and how significant the effect of this coarsening of the air void system would be on resistance to freezing and thawing.

The study described in this report attempted to determine whether Dyer's air void coarsening mechanism applied to other concrete mix designs. In addition to admixture combinations, the effect of actual air content was also examined. A mix subjected to actual pumping in the field was also examined to determine both changes to the air void system from the pumping and changes in the resistance to freezing and thawing. A new mechanism is proposed that combines Dyer's air void coarsening mechanism with typical field practice to explain observed air content fluctuations.

This study validated Dyer's work and demonstrated that pressures of 300 psi or higher caused greater changes in the air void systems than pressures below 300 psi. The study found that the initial air content had a significant effect on the magnitude of changes in the air void system caused by pressurization. Higher initial air contents resulted in more stable air void systems; with higher air contents the same magnitude and duration of pressure caused less of a change in the air void system. Using a lignosulfonate-based water-reducing admixture increased the detrimental changes in the air void system. Replacing *by mass* a portion of the cement with Type F flyash in the mixes containing the lignosulfonate-based water-reducing admixtures decreased the magnitude of the detrimental changes and appeared to make the air void systems of these mixes slightly more stable than the mixes containing only air-entraining admixtures. A stability index was developed for the various mixes that allowed comparisons of the resistance to changes in the air void systems caused by pressurization.

A concrete mixture similar to the ones determined to have the highest stability (resistance to air void changes due to pressurization) was pumped in the field at placing rates in excess of 90 cubic yards per hour. Specimens for laboratory testing were prepared from samples taken both before and after pumping. The maximum pressure experienced by the concrete during pumping was estimated using Dyer's analytical procedures to be about 250 psi. This pressure, along with the high expected stability of the mix, would be expected to result in little or no change in the air void system. Actual analysis of specimens prepared from un-pumped and pumped samples showed no significant changes in the air void system. Results of laboratory freezing and thawing tests showed no difference in durability between the un-pumped and pumped specimens.

The study concludes that air-entrained concrete can be safely placed by pumping with no detrimental effect on expected resistance to freezing and thawing as long as some precautions are observed. These precautions include designing mixes to have high expected air void stabilities, and avoiding exposure of the concrete to pumping conditions that result in pressures substantially in excess of 300 psi.

CHAPTER 1
INTRODUCTION

Concrete pumping, which was first widely utilized in the 1930 s [1], has continued to gain popularity because of advantages it has over other methods of concrete placement, most notably the speed of placement and access. Some construction procedures, such as fast-tracking, are generally more easily accomplished when concrete is pumped. Because of its increased speed as well as its increased accessibility, the pumping method is often chosen by construction companies to transport concrete to bridge decks, tunnels, and buildings of all sizes.

One of the problems faced by engineers when designing a concrete mix is the problem of freeze-thaw resistance. In general, concrete which will experience repeated freezing and thawing in a moist environment should be protected. This protection is usually accomplished by the addition of entrained air into the concrete. The addition of air voids, properly spaced, sized, and of sufficient number, can substantially increase the mix's resistance to freezing and thawing. However, the only procedure currently available to judge the quality of the air void system of a concrete mix is performed on hardened concrete samples, not on fresh concrete. Therefore, to insure good resistance to freezing and thawing on-site, a concrete contractor should use an approved air entraining agent (ASTM C 260). After using the air entraining agent the fresh air content of the mix must fall within the range recommended by the American Concrete Institute [2].

Recently, persons involved with placing concrete by pumping have noticed that a substantial amount of the air content (generally, 1 to 3 percent) is occasionally lost. A corresponding loss in slump when pumping air entrained concrete has also been observed. The loss in air content and slump sometimes result in the mix being rejected after it has been discharged into the forms. At this point, however, the concrete contractor, pumping contractor, and possibly the structural contractor have all handled the mix, making it difficult to assign responsibility for the rejected mix. An understanding of how the air is being lost is needed to avoid these situations.

In 1991, Dyer [3] examined this problem of lost air. Dyer [3] attempted to isolate the mechanism of pressure in the pipeline. He first presented a quantification of the pressure experienced by a plug of concrete as it was being pumped under various conditions. He then performed a lab study that showed the effects of various levels and durations of static pressure on a concrete mix. His lab study, while conclusive, was performed on only one specific concrete mix. Other researchers questioned whether different types of admixtures and pozzolans will alter the observations. In addition, Dyer's [3] study covered a range of pressure from -12 psi to 1500 psi. A typical pumping pressure range is 0 psi to 500 psi.

This work attempts to both validate and expand upon the results presented by Dyer [3]. First, a lab study examined the effects of pressures of 0, 50, 150, 300 and 500 psi for durations of 5 sec and 30 sec on the air void system. This study more thoroughly details the effects of this pressure range. In addition, the study examines the effects of different air contents, admixtures, pozzolans, and fine aggregate gradation on the stability of the air void system.

Second, a field study attempted to correlate lab findings to a job site situation. A mix containing air entrainment, water reducer, and pozzolan was pumped in a manner in which air loss is often noticed. The maximum pumping pressure was calculated using Dyer's [3] equations, and the results (both freeze-thaw resistance and linear traverse) of the specimens were compared to similar lab mixes to see if the lab study could be correlated to field conditions.

Conclusions concerning the stability of the air void systems produced in the various mixes are presented in this report. These conclusions are used to develop recommendations concerning preferred mixes for pumping as well as suggested work to further clarify the loss-of-air mechanisms.

CHAPTER 2
BACKGROUND

GENERAL

The continued popularity of portland cement concrete (PCC) as a construction material, combined with the increasing use of pumping during concrete placing [1], has caused concerns about loss of air content in air entrained concrete due to pumping to become more widespread. Increases in air content have also been reported in a few cases. In general, though, losses of 1 percent to 3 percent in air content from truck to hose are reported. This air loss is normally accompanied by a corresponding slump loss. In some cases, concrete sampled at the pump hose has been rejected because of low air content, although the mix was properly designed and air entrained by the concrete supplier.

To combat the problem of lost air content, many suppliers have increased their air contents to counteract this pumping effect. This method has been somewhat successful; however, it is considered a 'band-aid' solution. The method does not attempt to understand what is happening to the air void system and the mechanism by which the air is being lost. In addition, problems attributable to the compressibility of the fresh concrete have been reported when pumping high air concrete mixes [4].

Description of Air Void Parameters

Although field problems have focused around the loss of total air content in fresh concrete, it is the smaller, entrained air voids that are important to freeze-thaw durability. The distribution of air voids in concrete consists of randomly sized, randomly spaced air bubbles in the paste of a concrete mix. The bubbles that make up the distribution are often considered entrained or entrapped. Entrained represents smaller, spherical bubbles and entrapped represents larger and generally non-spherical voids. Current theory suggests that spherical voids are stabilized by an air-entraining agent, while non-spherical voids are trapped in the mix by other means [5]. In general, entrapped voids are much larger than entrained voids. The 'quality,' in terms of freeze-thaw resistance, of an air void system is determined by how closely spaced the bubbles are to one another. In general, the closer the spacing of the air voids, the higher the system's quality and the better the system's resistance to freezing and thawing. There is no procedure, however, to determine the quality of the air void distribution in fresh concrete. Air void analysis can be done on hardened PCC specimens by the linear traverse method (ASTM C 457), which collects chord lengths of air voids. A linear traverse involves microscopically examining (magnification range - 30 x to 125 x) a flat specimen of sliced and lapped concrete and recording the chord lengths for air (entrained and entrapped), paste, and rock. Though ASTM C 457 requires only the cumulative length of air void chords along with the total length of traverse, if individual chords are recorded, the distribution can be analyzed. Roberts and Scheiner [6] found that the size distribution of the chord lengths of entrained air voids tends to conform to a zeroth order logarithmic distribution, as given by Equation 1:

$$P(c) = \frac{e^{[-(\ln(c) - \ln(c_m)^2)/(2\sigma_0^2)]}}{((2\pi)^{0.5})*\sigma_0*e^{[\sigma_0^2/2]}} \qquad \text{(Eq. 1)}$$

where

P(c) is the probability of encountering a chord of length c,

c_m is the modal chord length (μ), and

σ_0 is the zeroth order standard deviation.

A typical distribution is shown in Figure 1 [2].

In order to discuss the air void distribution in greater depth, it is necessary to define the parameters generally used to represent the quality of an air void distribution.

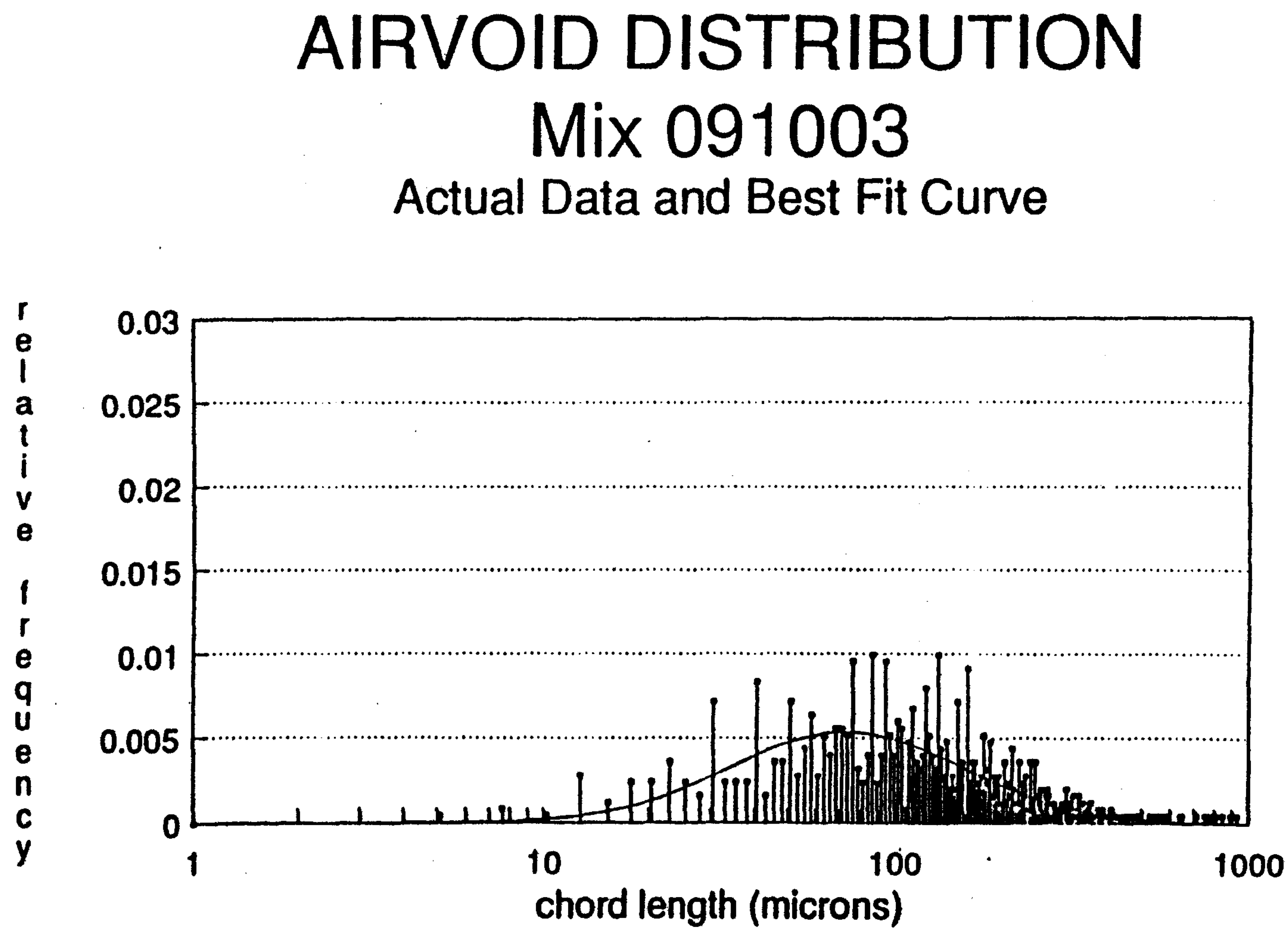

Figure 1. Typical Air Void Chord Distribution (Dyer [3]).

Hardened Air Content (A)

Air content (A) is defined as the volume of air per unit volume of hardened PCC and is normally determined for all air voids. Air content can also be determined for voids producing chords smaller than a specific size (e.g., 1 mm), which can be useful for removing the effect of the largest voids [7]. It is calculated as follows:

$$A = (L_v/L_t)*100\% \qquad \text{(Eq. 2)}$$

where

L_v is the cumulative air void chord lengths recorded (mm), and

L_t is the total length of traverse (mm).

A typical recommended value for an air content of PCC with good freeze-thaw durability that contains about 650 lb/yd^3 cement is 6.0 percent [8].

Specific Surface (α)

Specific surface (α) is a measure of the voids' surface area per unit volume of voids. A basic assumption of specific surface is that all voids are spherical; this makes α a function of average chord length alone [9]. Specific surface is, therefore, a good indicator of average void size. As average void size goes up, specific surface goes down.

The equation for determining specific surface is the following:

$$\alpha = 4 / l \qquad \text{(Eq. 3)}$$

where

l is the average chord intercept of the air voids (mm).

As a higher specific surface indicates smaller voids, which are better for freeze-thaw durability, the industry's generally accepted value of specific surface for good freeze-thaw durability is 23.6 mm^2/mm^3 or larger [10].

Spacing Factor ($\overline{L}$)

Spacing factor is an approximation of the largest distance to an air void. The following assumptions are made for this parameter: the voids are spherical and of equal size and the voids are evenly distributed in a simple cubic lattice throughout paste [8]. The equation for this parameter is in two parts, depending on the particular mix's ratio of paste to air. The spacing factor is calculated as follows:

when $p/A < 4.342$,

$$\bar{L} = p/(400n) \qquad \text{(Eq. 4a)}$$

and when $p/A > 4.342$,

$$\bar{L} = 3/\alpha\,[\,1.4\,(p/A + 1)^{1/3} - 1\,] \qquad \text{(Eq. 4b)}$$

where

p is the paste content (%),

A is the air content (%),

n is the number of voids, and

α is the specific surface of air voids (mm^2/mm^3).

The range of spacing factors is generally from 0.1 mm or less to approaching 1 mm for mixes that do not contain an air entraining agent. The generally accepted value for concrete with good resistance to freezing and thawing is about 0.2 mm or less [10].

Philleo Factor ($\bar{P}_{90}$)

In 1955, Philleo [11] developed an air void parameter in an attempt to eliminate the assumptions made for the spacing factor, namely that all voids are of equal size and spacing. His equation works on the concept that all voids are randomly sized and distributed and establishes a relationship between the air void distribution and the percentage of paste that is within a given distance of an air void. Philleo [11] utilized the work of Lord and Willis [12] to establish a relationship between linear data (air void chord lengths) and three dimensional data (voids per unit volume). This relationship is the cornerstone of his equations. Besides providing the percentage of paste protected, the equation can provide, alternatively, a value for the distance from an air void within which a given percentage of paste is located. This distance, called the Philleo factor, is often compared to the spacing factor. However, in actuality, the Philleo factor is more sensitive to the actual air void distribution rather than simply relying on just the air content, paste content, and number of voids as does the spacing factor.

The equation for the Philleo factor is as follows:

$$F' = 1 - e^{[-4.19(X_1)^3 - 7.80(X_1)^2(X_2)^{1/3} - 4.84(X_1)(X_2)^{2/3}]} \quad \text{(Eq. 5)}$$

with $X_1 \ \overline{P} N^{1/3}$

and $X_2 = -\ln(1-A)$

where

F' is the fraction of paste within distance $\overline{P}$ of the center of the nearest void,

$\overline{P}$ is the distance from the center of the nearest void (mm),

N is the void density in the paste (# of voids/mm^3), and

A is the fraction of air in the paste (volume of air/ volume of paste).

$\overline{P}_{90}$ is determined by using an F' value of 0.9 and solving for $\overline{P}$. Values for N and A can be determined from collected linear traverse data using procedures described by Lord and Willis [12].

The concrete industry has not been quick to accept this parameter as a measure of freeze-thaw durability potential, partially due to the industry's difficulty in acquiring the data necessary for calculation. No specific criteria for maximum $\overline{P}$ values for a given F' have been identified. An estimation, therefore, of the maximum Philleo factor at 90 percent protection was determined by examining linear traverse data for a number of mixes that had spacing factors of about 0.2 mm and specific surface values of about 23.6 mm^2/mm^3. This estimation was determined to be approximately 0.037 mm.

Errors Associated With Air Void Parameters

In 1992, Pleau and Pigeon [13] presented quantification of the possible errors that can result from the many facets of procedures used to determine the air void parameters in hardened PCC. These errors were grouped in the following categories: 1) the theoretical variability due to sampling size, 2) the heterogeneity of concrete, 3) the subjectivity of the operator, and 4) the differences among operators. Errors for each category were determined and combined to create an overall error range for a given level of confidence (i.e. 90 percent, 95 percent confidence).

A summary of the expected maximum errors for a typical, pumpable concrete mix (7 sack mix, 5 percent air, 4 in. slump, 3/4 in. max. agg. size) analyzed by the linear traverse method (ASTM C 457) is shown in Table 1. The errors were calculated by methods provided by Pleau and Pigeon [13], at 95 percent confidence, for various hardened air parameters.

Table 1. Predicted Errors from Linear Traverse, after Pleau and Pigeon [13]

Air Void Parameter	Typical Value	Max Error Expected @ 95% Confidence (% of value)
Paste Content	28.0 %	13 %
Air Content	5.0 %	21 %
Number of Voids	950	10 %
Specific Surface	33 mm^2/mm^3	10 %
Spacing Factor	.160 mm	9 %

Table 1 shows that the hardened air content is the most unreliable value attained from the linear traverse analysis, while the spacing factor, which incorporates air content in its calculations, shows a much smaller error range—less than one half of the expected error in air content. This inconsistency is likely due to the presence of large, entrapped voids in the concrete specimen that, while having a significant effect on the total hardened air content, have a much smaller effect on the spacing factor. No method of error quantification was derived for Philleo factor (but the error is expected to be less than that of the spacing factor because the curve fitting procedure used in the calculation of the Philleo factor.)

Proposed Mechanisms for Air Loss

The difficulty in assessing the effect pumping has on fresh concrete is partially due to the number of mechanisms that are assimilated in the process. The concrete falls through a grating in the pump hopper, is forced through a relatively small diameter pipe, moves through a series of bends, experiences changes in both elevation and pipe material (steel to rubber, generally), and is then released from pressure as it exits the pipe. This sequence of events makes it difficult to isolate the mechanism, if there is only one, that induces the loss (and occasional gain) in air content of air entrained concrete.

A number of authors have recently proposed mechanisms to explain the decrease in air content of fresh PCC that has been pumped. These proposed mechanisms can be called the vacuum, impact, and pressure-dissolution mechanisms, and are described below.

Vacuum Mechanism [14]

When PCC is placed by pumping for a wall or similar structure, it is often necessary to align the pump so that the latter half of the pipe has a long vertical section. The proposed mechanism suggests that, when the concrete travels down this long vertical section at a relatively slow rate, it can 'fall' as separate plugs of concrete, leaving an evacuated section of pipe behind it. This can cause air loss in the mix either by forming a pressure gradient through which the bubbles can escape more easily, or by causing the bubbles to expand and burst. Either of these effects will most likely cause a noticeable drop in air content.

Higher pumping rates will eliminate this phenomena and should eliminate or greatly reduce the air loss, if this were the only mechanism at work.

Impact Mechanism [14]

When concrete is being placed by pumping, the end of the hose occasionally is pulled out of the fresh concrete, allowing the concrete to drop rather than flow from the hose into the forms. The proposed impact mechanism states that even a small drop (5' or less) can result in air voids being 'knocked out' of the mix, lowering the total fresh air content. This impact can also occur between the truck and the hopper, or in a vertical section of pipe, which can result in an air loss even if the end of the hose is embedded in concrete. Little is known about the size of the voids that will be knocked out, though buoyancy effects, to be discussed in the section "Composite Mechanism for Air Loss," would suggest that larger voids will more likely be lost.

Pressure-Dissolution Mechanism [3]

This third theory of air loss takes into consideration the pumping action itself rather than special cases of vertical pipes and dropped PCC. During pumping, pressures in the mix frequently reach 300 psi to 500 psi. A fundamental law of fluid mechanics is the basis for this theory. Henry's Law [15] defines the solubility of a gas in liquid at equilibrium. The equation is defined as:

$$p = kC \qquad \text{(Eq. 6)}$$

where

- p is the partial pressure of gas,
- C is the concentration of the dissolved gas in solution at equilibrium, and
- k is a constant.

This equation shows that the concentration of the dissolved gas is directly proportional to the partial pressure of the gas out of solution. As the pressure of the fresh concrete increases, more of the entrained and entrapped air dissolves into the water, which effectively reduces the measurable air content.

The internal pressure of individual air bubbles in concrete can vary as well. Mielenz et al. [16] noted that the internal pressure of air bubbles in concrete can be described by the following equation:

$$P_i = P_o + 2\tau/R \qquad \text{(Eq. 7)}$$

where

P_i is the internal pressure of the air in a bubble,

P_o is the pressure of fluid surrounding the air bubble,

τ is the surface tension of the bubble film, and

R is the bubble radius.

This equation indicates that smaller bubble sizes have higher internal pressures. But for a fixed number of air molecules, increased pressure results in an even smaller bubble size (gas under higher pressure occupies less volume than gas under lower pressure).

The concrete's exit from the hose causes a depressurization of the concrete mix. The result is a reversal of the described dissolution process. The dissolved air, however, upon leaving solution, tends to come out on existing bubbles, as forming on existing bubbles as nucleation sites is easier than creating a new bubble. The effect on the mix is that the original air void distribution is reformed into a distribution of larger, more widely spaced voids. This shift will affect many of the critical air void parameters $\overline{L}$, $\overline{P}_{90}$ increase, α decreases), which may reduce the freeze-thaw durability of the concrete.

The distribution shift, while changing the characteristics of the air void system, will increase the total air content, as larger bubbles are under lower internal pressure than smaller bubbles. The decreased internal pressure allows the same number of air molecules to occupy a greater volume than before [17]. Problems also can occur when an air content test is performed. Air coming out of solution after depressurization of the PCC mix is a relatively slow process. If a specimen is consolidated in the air chamber before this reformation process is complete, the bubbles will be smaller and fewer air bubbles will be removed by consolidation. The mix will continue to gain air content after consolidation is complete. This will not occur if the dissolved air is allowed to reach equilibrium before the concrete is consolidated. In this latter case, consolidation is more likely to remove air, resulting in a lower measured air content, as the more of the reformed bubbles may be displaced. The result is that, after pumping, the air content can either increase measurably or decrease measurably over the unpumped mix. These possible opposite effects demonstrate the complex process that is occurring and how the air content in fresh concrete may not be a good indicator of the quality of the air void matrix for pumped concrete.

Composite Mechanism for Air Loss

From these three theories, all of which have some validity, a composite theory for the mechanism of air loss can be assimilated. To do this it is necessary to look at an air void individually to determine which characteristics make it susceptible to air loss. A key assumption made in this analysis is that all voids are perfectly spherical.

The best description of what makes an air bubble susceptible to loss is buoyancy. In concrete, as with all fluids, the buoyancy of a gas bubble is related to two parameters, the density differential between the two substances and the opposing frictional forces between the bubble wall and the fluid. The latter of the two parameters can be related to the viscosity of the fluid. The density differential represents the upward force on air in concrete and is related to the volume of the air void. The surface friction or viscosity represents the resistance to motion, hence a downward force on the bubble, and is related to the surface area of the void. As the ratio of surface area to volume, α, goes down, the air bubble is displaced more easily.

The relationship between increasing void size and decreasing α has already been established. Therefore, it can be concluded that larger air voids are more easily displaced from the mix. This displacement can be seen when consolidating fresh concrete by vibration; large bubbles will rise to the surface and escape [18].

The pressurization-dissolution mechanism, presented earlier, stated that the result of concrete pressurization is a shift in the air void distribution towards larger bubbles, but not necessarily a loss in air content. This increased bubble size, however, reduces the specific surface of the mix, thereby increasing the mix's susceptibility to air loss when vibrated or impacted. In addition, the air being lost is predominantly made up of larger bubbles, which, while accounting for a good amount of the total air content, represent a relatively small percentage of the actual number of voids. No significant change in the air void parameters will result from the bubbles' loss. The 'damage' to the distribution will occur from the pressurization itself, and will result in fewer, larger voids spaced farther apart. This 'damage' results in a decreased specific surface along with an increased spacing factor and Philleo factor, which may have an adverse effect on freeze-thaw durability.

RECENT LABORATORY AND FIELD STUDIES

Effect of Pumping on Air Content

In one of the most recent series of tests attempting to explain the loss in air content problem, Yingling et al. [14] performed experiments to quantify and isolate the percentage of air lost as a result of both pumping and simulated pumping. Their testing procedure was in two parts, a field test and a lab test. In both tests only 'pumpable' mixes were used (3-. to 4-in. slump, 5- to 7-percent air content).

The field test utilized an actual concrete pump with a 5 in. diameter pipe. The three most significant alignments for the pump boom were the following: a position with a long vertical section of pipe near the end, the vertical alignment with a series of 90 degree elbows at the end, and a completely horizontal position. For each pumping test, controlled and repeated pressure tests for determining air content were performed at both the chute and the hose. In addition, pumping rate and boom configuration were also recorded. A summary of the data collected is presented in Table 2.

Table 2. Loss of Air from Pumping PCC, after Yingling, et. al. [14]

Pump Configuration	Pumping Rate	Average Air Content		Change in Air Content
		Truck	Line	
Vertical	slow	7.7%	5.0%	-2.7%
	fast	7.3%	5.5%	-1.8%
Vertical w/90° elbows	slow	6.3%	5.2%	-1.1%
	fast	6.3%	5.2%	-1.1%
Horizontal	slow	6.4%	6.5%	+0.1%

Table 2 notes, with the vertical pipe alignment, a 2 percent to 3 percent loss in air content (about 25 percent to 35 percent of the original value) was noticed between the ends of the pump. This effect was lessened, however, when the elbows were added at the end of the hose. When the boom was flattened, no significant air loss was noticed.

To isolate this mechanism for air loss, the test was taken into the lab where fresh concrete samples were dropped from a constant height (14'-3") to determine if a loss in air content would also be experienced. Some specimens were allowed to free fall, while others were dropped down a 3 in. diameter shaft to simulate the drop through the end of a pump hose. There was a significant loss of air in all of the tests, with the smallest loss occurring when the concrete was dropped down a shaft and allowed to free fall less than 3 ft. A summary of the collected data is shown in Table 3.

Table 3. Loss of Air from Dropping PCC, after Yingling et. al. [14]

Description	Air Content		Change in Air Content
	Before	After	
Free fall - poured	8.9%	4.5%	-4.4%
Free fall - poured	8.0%	5.1%	-2.9%
Free fall - dumped	7.4%	5.0%	-2.4%
Drop 5' through pipe, free fall 14'-3"	8.2%	5.9%	-2.3%
Drop 17'-6" through pipe, free fall 2'-6"	8.7%	7.0%	-1.7%

The loss in air content by dropping concrete led Yingling et al. [14] to conclude that the impact mechanism was the major factor in the loss of air in fresh concrete. This did not explain, however, why the drop down the continuous 3 in. diameter pipe, the closest approximation to pumping, showed less air loss than the pumping study showed, as seen in Table 4. Microscopical analyses of the air void system in hardened PCC were not performed for any aspect of the study, so the effect of pumping concrete or dropping concrete on the air void distribution cannot be determined.

Table 4. Comparison of Loss of Air in Pumped and Dropped PCC, after Yingling et. al. [14]

Description	Average Air Content		Change in Air Content
	Truck	Line	
Pumping vertical—slow	7.7%	5.0%	-2.7%
Pumping vertical—fast	7.3%	5.5%	-1.8%
Pipe drop—long free fall	8.2%	5.9%	-2.3%
Pipe drop—short free fall	8.7%	7.0%	-1.7%

The loss of air content can be partially explained by this study. However, it is necessary to further explore the effect of pumping on a microscopic level, and to determine the effect pumping pressure has on the critical air void parameters for freeze-thaw durability.

<u>Effect of Pumping Pressure on the Air Void System</u>

In 1991, a master's thesis was submitted by Robert Dyer to the University of Washington [3] that attempted to shed more light on the problems of pumping air entrained concrete. The purposes of Dyer's [3] paper were:

- to discover if voids were being permanently lost or just transformed
- to determined the magnitude of loss or transformation for various pressures and times of pressurization, and
- to determine how this loss or transformation affects air void parameters $\overline{L}$, α, $\overline{P}_{90}$).

The procedure involved statically pressurizing a 'pumpable' mix (3 in. to 4 in. slump, at least 6 percent air content) to various pressures, ranging from -12 psi to 1500 psi, in an attempt to quantify effects for all currently possible ranges of pumping pressures. Concrete specimens were pressurized for 3 sec, 60 sec, and 300 sec in order to determine if any observed changes were time-dependent. In addition, one control specimen was prepared from the same mix with no pressurization. Fresh air contents were taken, by volumetric method (ASTM C 173), before and after pressurization to see if any air loss had occurred. After these specimens were cured they were sliced and prepared for analysis by ASTM C 457, "Standard Practice for Microscopical Determination of Air Void Content and Parameters of the Air Void System in Hardened Concrete." A summary of the collected data is in Table 5.

Table 5. Summary of Linear Traverse Results, after Dyer [3]

Pressure (psi)	Change in α (% of control)*	Change in $\overline{L}$ (% of control)*
50	-12%	+4.5%
150	-29%	+25%
500	-59%	+240%

* Specimens were held at noted pressures for 60 sec.
Signs indicate whether parameter increased or decreased.

The result of this study was that, with increased pressures, the modal chord length increased significantly and most pertinent air void parameters worsened, with the exception of air content. This was understandable because the specimens were undisturbed when they were pressurized and depressurized, which would result in no tendency to remove large air voids. Also, there was a significant worsening of parameters from 3 sec pressurization to 60 sec pressurization, but no significant change between 60 sec and 300 sec pressurization. Finally, it was noted that there was no consistent air loss among all of the specimens.

The major limitation in this study was that a single mix design was used for the tests. Repetitions of the same mix were used for all tests, and the mix contained an air-entraining admixture and a retarder. It is possible that one of these admixtures, or perhaps the combination of the two, may have caused or increased the effect noticed. It was recommended that a study be performed to test the effects of various combinations of air entraining agents, water reducers, and pozzolans on the pressurization effect.

Another concern with the study was the range of air contents in the mixes. It may be that higher air contents reduce or increase the effect of pressurization, and better control of the air content will be necessary to validate the tests and better examine the effect of pressure on the air void parameters. Also, although his study covered pressure ranges from -12 psi to 1500 psi and pressurized from 3 sec to 300 sec, Dyer's [3] study indicated that the greatest change in air void parameters occurred in the range of 0 to 500 psi and between 3 and 60 seconds. A narrower range of pressures and pressurization times is necessary to further examine these critical ranges.

CHAPTER 3
LABORATORY PROCEDURE

GENERAL

The testing procedure developed to analyze the effect of pressurization of fresh PC on the air void system included the following three parts: (1) mix design and batching, (2) pressurization of fresh PCC specimens, and (3) microscopical examination (modification of ASTM C 457) of both pressurized and non-pressurized hardened concrete specimens to determine air void parameters. In addition, one mix was actually pumped to check laboratory findings against field observations. This phase of the testing is described in Chapter 6. The pressures and pressurization times used were consistent for all mixes, with the exception of the mix that was actually pumped. The purpose of static pressure was to eliminate the complex dynamics of an actually pumped mix. Consistent pressure magnitude and duration were necessary to analyze the different effects upon mixes that, while having similar slumps and air contents, contained different types of air entraining admixtures, pozzolans, and aggregate gradations. A limited number of mixes with similar slumps and admixtures, but different air contents, were also analyzed.

MIX DESIGN AND BATCHING

The objective of the mix design was to obtain a mix that can potentially be pumped (i.e., a mix with well-graded aggregate, a slump of approximately 4 in., and a fresh air content of about 6 percent). In order to isolate the effects of the admixtures and pozzolans, only mixes within 3-1/2 to 4-1/2 in. slump and 5.5 to 6.5 percent air were accepted in most cases. The exceptions to this rule were mixes used for comparison of varying air contents.

Design

The mix designs for the specimens, while containing different amounts of admixtures and pozzolans, did not vary considerably. The amount of coarse aggregate and cementitious material was held constant for all mixes, while the sand, water, admixtures, and pozzolans were varied to insure a mix that met the slump and air content specifications. The saturated surface dry (SSD) weights for a typical mix, not including admixtures and pozzolans, were approximately the following:

Coarse Aggregate	1800 lb/yd^3
Fine Aggregate	1200 lb/yd^3
Type I-II Cement	660 lb/yd^3
Water	240 lb/yd^3

Complete mix designs can be found in Appendix A. The gradation curves for the normal and coarse sand can be found in Appendix B.

Mixing Procedure

The mixing procedure was similar to ASTM C 192. A detailed batching description can be found in Appendix C. Notable aspects are as follows.

A typical butter batch was 0.5 ft^3. The butter batch was first used to coat the mixer. The butter batch was used before a full batch to insure that the mixer was coated with the correct mortar. While not used for the actual pressurization, the butter batch had an air content test performed on it according to ASTM C 231. The procedure used for the air content test involved external vibration (5 sec @ 5000 Hz) on a vibrating table instead of rodding. As the mixes being batched were of constantly changing admixtures and pozzolans and the margin for error on slump and air content was small, the butter batch air content was used as initial guidance to estimate the dosages of both air entraining agent and/or water reducer, and the amount of mixing water to be added.

While slump was not measured on the butter batch (the air content test requires 0.25 ft^3 of the butter batch and there was not enough material left for a slump test), an estimate of the slump was made from a visual examination and from an assessment of its workability. Although it was not as influential as the air content test, this estimate was also used as a guide to adjust the water reducer dosage and the mixing water requirements.

After mixing a full batch, typically 1.2 ft^3, another air content test was performed. If the air content did not fall within the 5.5 percent to 6.5 percent range, the mix design was adjusted and rebatched. Occasional mixes not meeting this air content requirement were also tested to provide a mix with an air content outside the range.

A slump test was performed concurrent to the air content test in accordance with ASTM C 143. If the slump did not fall within the 3.5 in. to 4.5 in. range, the mix design was adjusted and rebatched.

When an acceptable mix was attained, a note was made of the time that mixing water was first added to keep a log of mix history.

Preparing Specimens

Ten pressurization specimens were prepared. The specimen containers, referred to as 'tubs', were made from vacuum-formed ABS plastic sheets, 0.09 mm thick. The tubs were cylindrical and their inside dimensions were 1-15/16 in. deep and 9-5/8 in. in diameter. This size was necessary for the specimen to fit into the pressure chamber, a procedure to be described later.

The specimens were prepared by filling each of the ten tubs with approximately 11 lbs. of concrete mix, as measured by a lab balance. The specimens were then consolidated on a vibrating table for 5 sec each (frequency was approximately 5000 Hz and the amplitude setting was 7 for the table used). This seemed to be enough time to allow the mix to consolidate. The specimens were then covered with a polyurethane film held in place by masking tape and transported to the pressurization area. The time at this point was also noted in the mix history log.

PRESSURIZATION OF SPECIMENS

Apparatus

The pressurization equipment was somewhat unique to this research. The pressure chamber was a modification of a commercially available chamber designed for moisture extractions from soils. Its commercial title was "100 Bar Pressure Membrane Extractor", manufactured by Soilmoisture Equipment Corporation. The following modifications were performed: (1) the perforated bottom plate was removed and replaced by a second solid top plate and (2) the plumbing was modified to enable pressure to be released at any desired rate. Compressed nitrogen provided the needed pressure, and the pressure was read from a dial gauge regulator. Drawings and photographs are shown in Figures 2 through 5.

Procedure

A hardened specimen was kept in the chamber between uses as a release rate calibration specimen. At the beginning of pressurization, pressure was applied, held, and released from the chamber containing the release rate calibration specimen. The time for the pressure to dissipate was then noted. The target release rate was around 30 $\pm$ 2 sec; if the time was not within the desired range, the nozzle was adjusted and the pressurization was repeated until the desired range was reached.

The procedure for placing specimens in the chamber was as follows:

1. Remove the bolts from the chamber.
2. Remove the lid and the middle ring of the chamber and place aside.
3. Remove the previous specimen from the chamber and place aside.
4. Clean the bottom of the chamber and the O-rings with a clean, damp towel.
5. Place the next specimen in the chamber and center it on the chamber bottom.
6. Place the bottom O-ring around the specimen, and center it.
7. Release any remaining pressure from the flexible line.

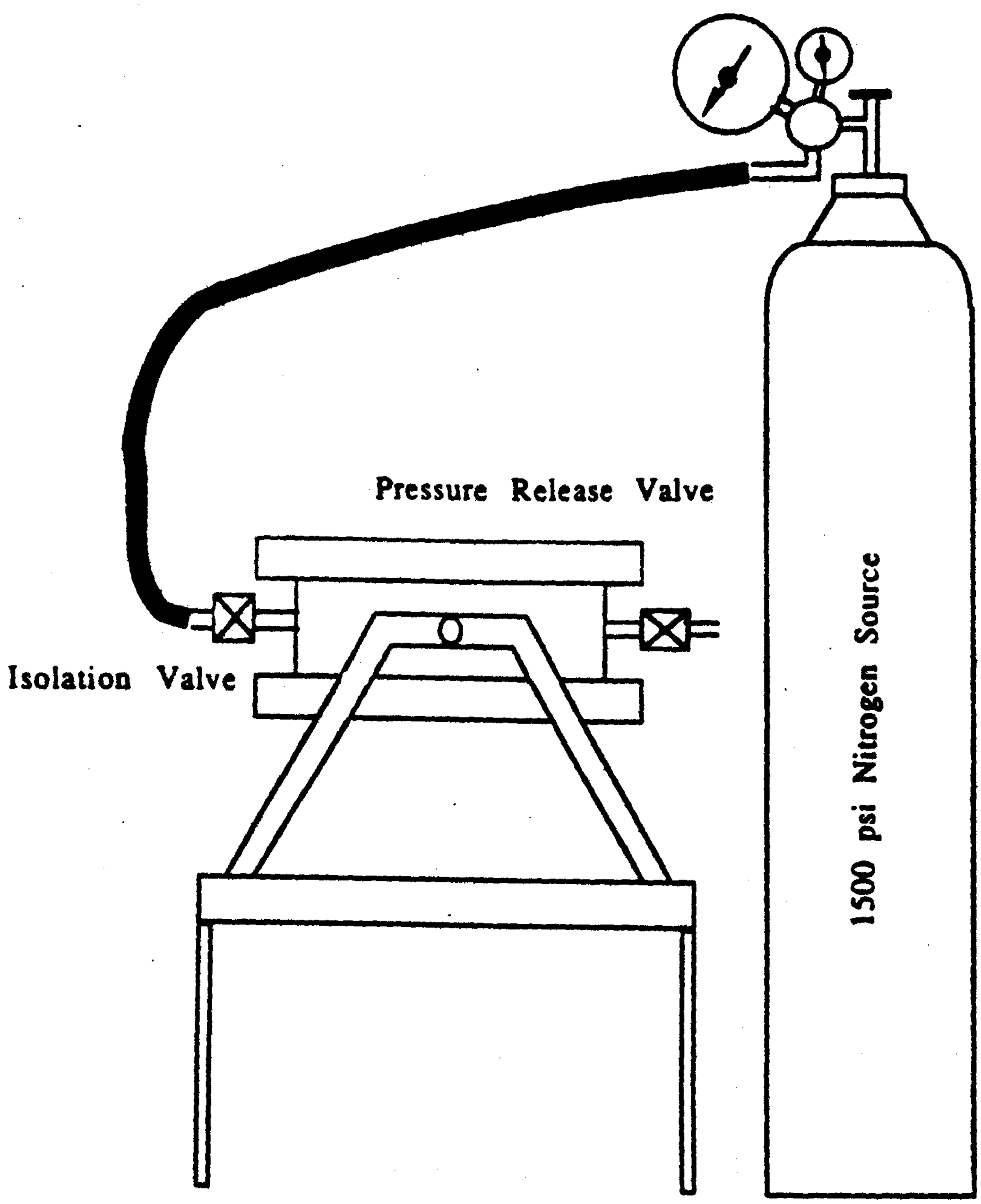

Figure 2. Schematic for Pressurization Apparatus (After Dyer [3]).

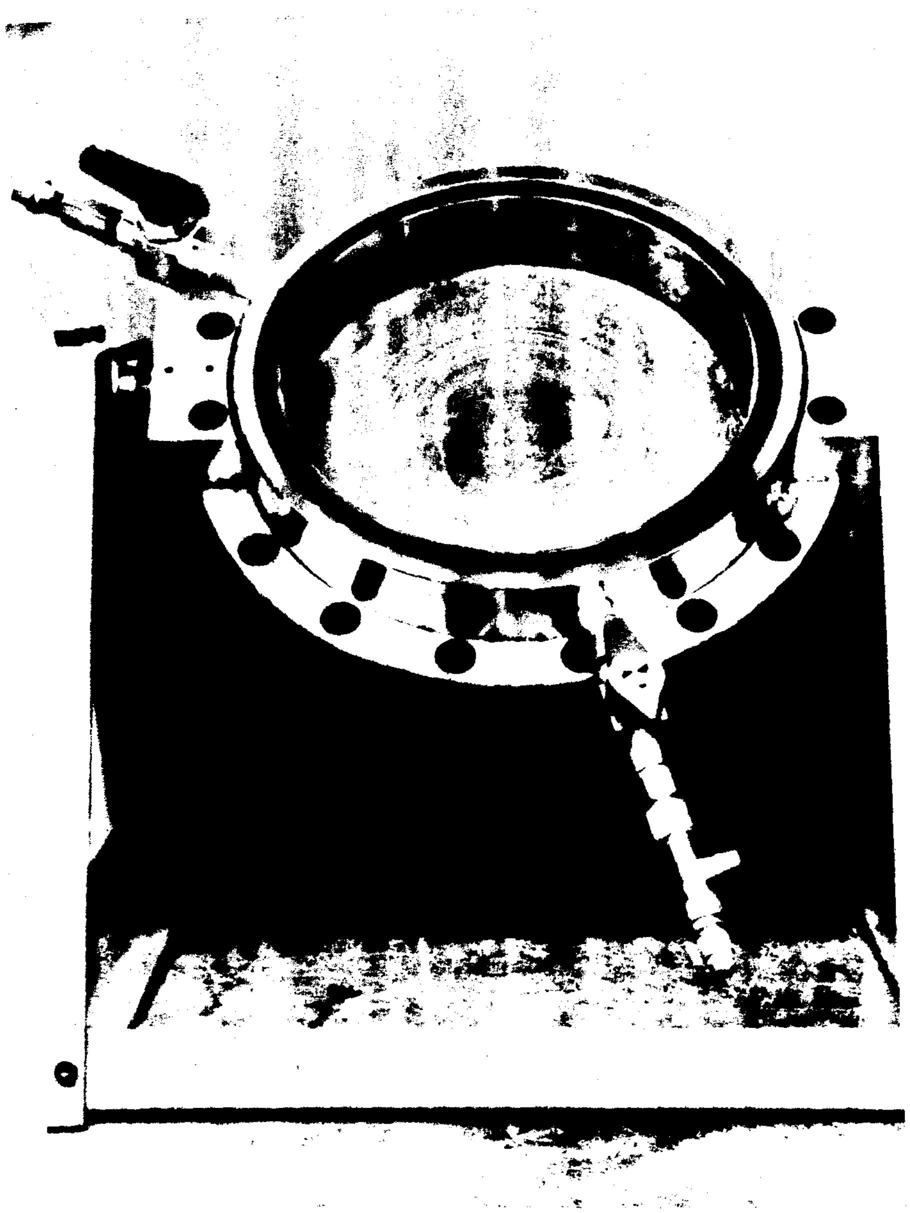

Figure 3. Photograph of Empty Pressure Chamber (Tilted for Better View).

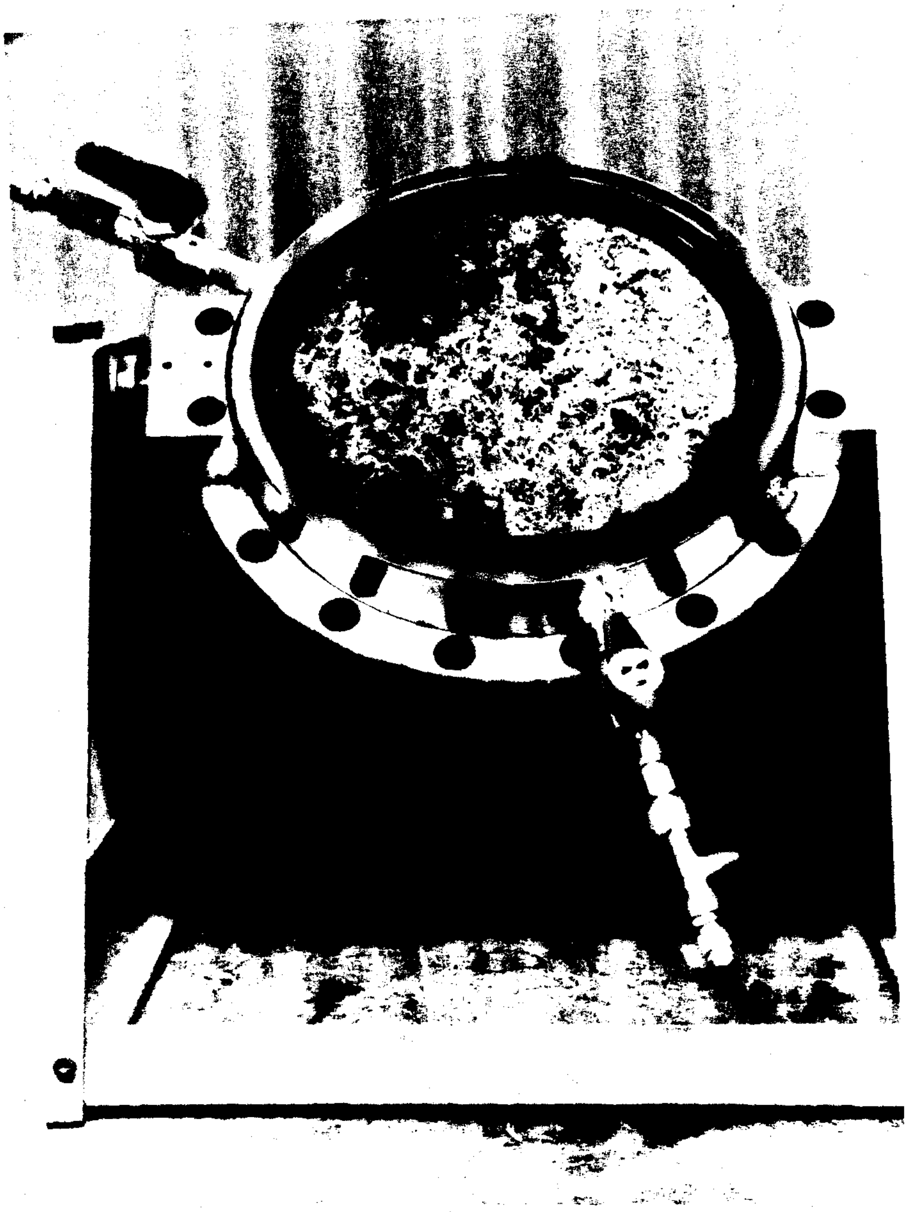

Figure 4. Photograph of Apparatus with Specimen (Tilted for Better View).

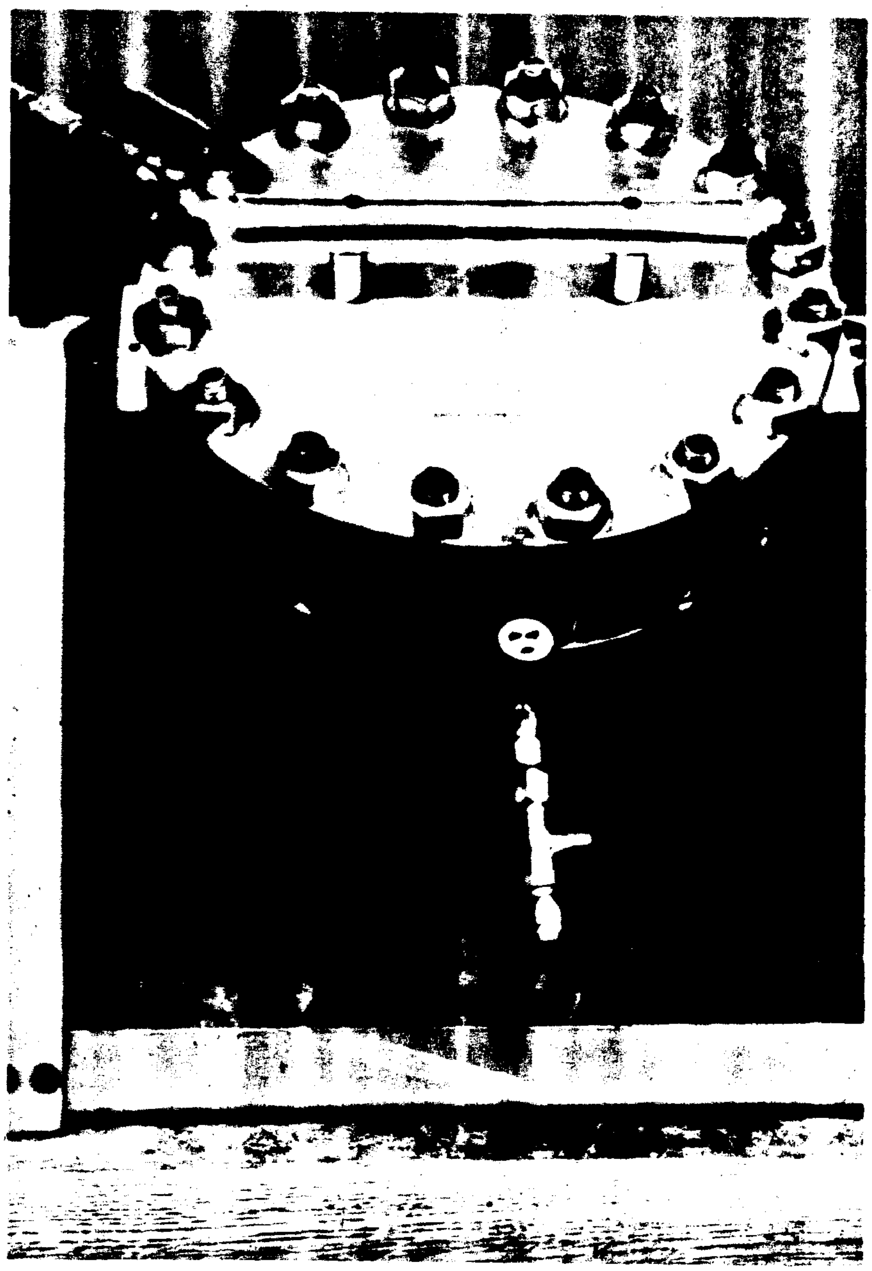

Figure 5. Photograph of Apparatus Bolted Shut, Ready for Pressurization (Tilted for Better View).

8. Replace the middle ring, and rotate it back and forth until it seats on the O-ring.
9. Place the top O-ring into the groove on top of the middle ring.
10. Replace the chamber's lid and bolts and tighten the bolts to finger tight.
11. Tighten the bolts in a crossing pattern with a torque wrench (60 to 80 in-lb).

The procedure for pressurizing the specimens was:

1. Adjust the regulator to the desired pressure level.
2. Open the chamber valve to pressurize the specimen. Keep the pressure on the specimen until 2 seconds before release time, then close the chamber valve. (Note: make sure the valve manipulations are clean and quick.)
3. Open the release valve at the release time.
4. Note the pressure and the pressurization time.
5. When all the pressure has dissipated, exchange the specimens by the previous procedure.

After the last fresh specimen was pressurized, the completion time was noted. The hardened control specimen was returned to the chamber and a final release rate was tested and noted. A typical order of pressurization is shown in Table 6.

Curing

Specimens were cured according to ASTM C 192 (95 percent to 100 percent humidity, 73°F) for at least 14 days. The duration of the cure was not important, as long as the specimens were cured enough to harden the paste to the point where they could be prepared for linear traverse.

Table 6. Typical Order of Pressurization

Specimen Number	Pressure (psi)	Time (sec)
Initial release	300 psi	N/A
1	300	30
2	50	30
3	150	30
4	500	30
5*	none	N/A
6	500	5
7	150	5
8	50	5
9	300	5
10**	300	30
Final release	300	N/A

* Control sample was not placed in the chamber, but other handling was the same.
** Repeat of #1, to check repeatability and time effects.

LINEAR TRAVERSE PROCEDURE

Preparing Specimens

The preparation of the specimens for microscopical analysis required a great deal of care. The specimens, after curing for at least 14 days (usually longer), were sawed and lapped, a procedure that was performed using successively finer grades of silicon carbide grit #220, #320, #600, #800, and #950. The specimens were treated with a solution of 50 percent Cutex fingernail hardener in acetone before the final lapping stage in order to further harden the paste.

Linear Traverse

The procedure used for linear traverse was in accordance with ASTM C 457, "Standard Practice for Microscopical Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete." The magnification during testing was 80x. All chord lengths, including paste and rock, were collected in the traverse procedure, and this data was analyzed to determine hardened air content (for all air and air under 1000 μ chord lengths), spacing factor ($\overline{L}$), specific surface (α), Philleo factor at 90 percent protection $\overline{P}_{90}$), and modal chord length (c_m).

CHAPTER 4
RESULTS

After the specimens were traversed, the data files created were analyzed by computer to determine the necessary air void parameters. Specifically the program determined conventional parameters (i.e., A, $\overline{L}$, α) for all air, air voids producing chord lengths less than 1 mm, and only voids identified as entrained (having a circular cross-section) by the operator. In addition, the program performed a zeroth order logarithmic curve fit for all three sets of voids and determined $\overline{L}$ and α from the best fit distribution. Philleo factors at 90 percent and 99 percent $\overline{P}_{90}$ and $\overline{P}_{99}$) were also determined for these best fit curves as well as the percentage of paste within 0.1 mm of an air void. When applicable, calculations were performed using paste contents from both the linear traverse data and the mix design data, for comparison.

Figure 6 shows a sample output from the linear traverse analysis program. A sample distribution of entrained air void chords, displayed in Figure 7, shows a curve conforming to the Roberts and Scheiner [6] equation, Equation 1. A complete record of all the samples tested can be found in Appendix D, along with a histogram of each sample's air void distribution.

Values were extracted from the linear traverse output sheets for air content (both total air and air under 1 mm), $\overline{L}$, α, and $\overline{P}_{90,}$ (all determined using mix design paste content), and modal chord length for chords under 1 mm; these values are summarized in Table 7. The results and values for each pressure are grouped by mix (P02, P06, etc.), and the mixes are organized according to air entraining agent (AEA1, AEA3, or AEA2).

INPUT FILE IS P025BET.AIR

MAXIMUM CHORD SIZE INCLUDED IN ENTRAINED AIR IS 1000 MICRONS

	ENTRAINED AIR ONLY	ALL AIR < 1000	ALL AIR
CALCULATED FROM ACTUAL DATA			
TOTAL LENGTH OF TRAVERSE (MM)	2334.3		
LINEAR TRAVERSE PASTE CONTENT (%)	28.4		
HARDENED AIR CONTENT (%)	2.1	3.3	4.3
PASTE TO AIR RATIO (LT PASTE)	13.2	8.5	6.6
AVERAGE AIRVOID CHORD LENGTH (MM)	.085	.091	.115
TOTAL NUMBER OF AIRVOIDS	588.	857.	869.
VOIDS PER MM TRAVERSE	.252	.367	.372
SPACING FACTOR (LT PASTE, MM)	.153	.134	.151
SPECIFIC SURFACE (SQ.MM/CU.MM)	47.0	44.1	34.9
CALCULATED FROM BEST FIT LOGNORMAL DISTRIBUTION			
AVERAGE AIRVOID CHORD LENGTH (MM)	.068	.064	.065
TOTAL NUMBER OF AIRVOIDS	740.	1212.	1529.
VOIDS PER MM TRAVERSE	.317	.519	.655
SPACING FACTOR (LT PASTE, MM)	.121	.095	.086
SPECIFIC SURFACE (SQ.MM/CU.MM)	59.1	62.3	61.4
# OF VOIDS PER CUBIC MM	124.3	201.8	252.2
2 PHILLEO FACTOR(S) DETERMINED			
PHILLEO FACTOR AT 90.% (LT PASTE, MM)	.041	.026	.020
PHILLEO FACTOR AT 99.% (LT PASTE, MM)	.069	.050	.042
1 SPACING(S) FOR WHICH PHILLEO PROTECTIONS HAVE BEEN DETERMINED			
% OF PASTE WITHIN .100 MM. (LT PASTE)	100.	100.	100.

Figure 6. Sample Output for Specimen P02-5 from Linear Traverse Analysis Program.

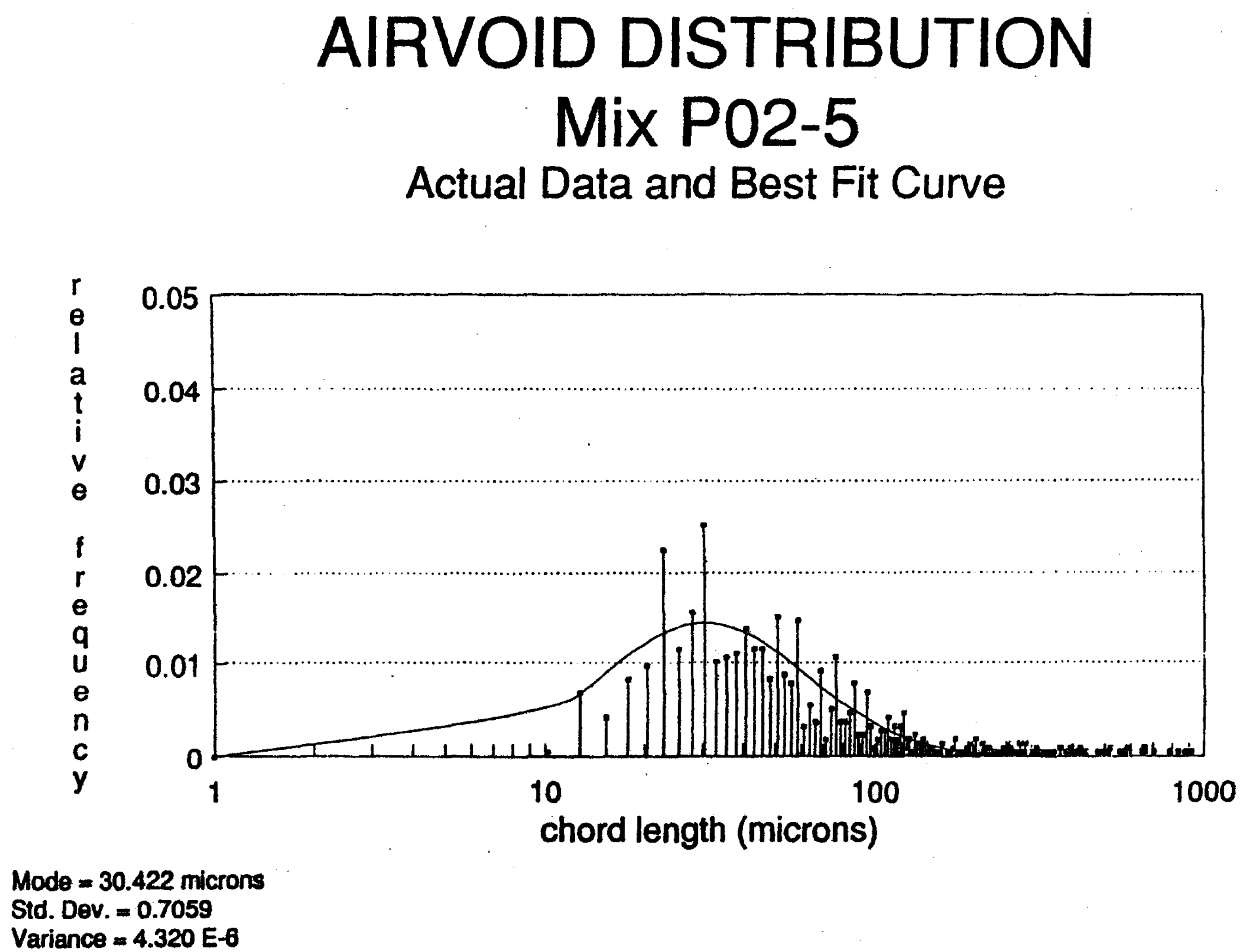

Figure 7. Air Void Chord Distribution for Specimen P02-5 from Linear Traverse Analysis Program.

Table 7. Summary of Linear Traverse Results.

Mix No.	Pressure (psi)	Duration (sec)	LTRAV Air < 1 mm (%)	LTRAV Total Air (%)	Spacing Factor Total Air (mm)	Specific Surface Total Air (mm^2/mm^3)	Philleo Factor @ 90% < 1 mm (mm)	Modal Chord Length < 1 mm (microns)
AEA1, Air = 4.0% (P08)								
	0	**0**	2.2	3.0	0.23	26	0.050	45
	150	**30**	2.8	3.9	0.23	23	0.052	63
	300	**30**	2.4	3.0	0.49	13	0.146	127
	500	**30**	2.8	3.9	0.63	9	0.181	173
AEA1, Air = 4.7% (P04)								
	0	**0**	3.7	4.2	0.17	31	0.030	43
	150	**30**	4.1	5.3	0.21	23	0.035	61
	300	**30**	3.6	4.2	0.39	14	0.103	158
	500	**30**	3.7	4.4	0.55	9	0.166	325
AEA1, Air = 5.9% (P16)								
	0	**0**	4.3	5.7	0.13	37	0.021	44
	150	**30**	5.2	7.0	0.13	31	0.019	56
	300	**30**	4.7	6.5	0.17	25	0.028	69
	500	**30**	4.6	5.2	0.34	14	0.075	141
AEA1, FM = 3.2 Air = 6.2% (P18)								
	0	**0**	4.9	5.4	0.11	43	0.019	50
	150	**30**	6.1	6.8	0.13	32	0.017	57
	300	**30**	5.7	7.7	0.14	26	0.019	66
	500	**30**	6.8	8.6	0.20	16	0.027	126

Table 7 (continued).

Mix No.	Pressure (psi)	Duration (sec)	LTRAV Air < 1 mm (%)	LTRAV Total Air (%)	Spacing Factor Total Air (mm)	Specific Surface Total Air (mm^2/mm^3)	Philleo Factor @ 90% < 1 mm (mm)	Modal Chord Length < 1 mm (microns)
AEA1, WRDA79 Air = 6.4% (P06)								
	0	0	5.3	6.3	0.15	28	0.019	44
	50	5	6.2	7.3	0.13	28	0.014	53
	150	5	4.5	5.8	0.21	21	0.034	67
	300	5	5.8	7.6	0.22	16	0.032	108
	500	5	5.8	7.6	0.25	14	0.037	122
	50	30	4.6	6.7	0.18	22	0.028	55
	150	30	4.9	6.2	0.21	20	0.032	79
	300	30	4.8	5.7	0.32	14	0.058	124
	300	30	5.2	6.7	0.28	14	0.047	119
	500	30	5.4	7.8	0.36	9	0.061	179
AEA1, WRDA79, Type F Air = 5.7% (P07)								
	0	0	3.5	4.7	0.19	27	0.037	52
	150	30	4.2	5.4	0.20	23	0.035	59
	300	30	3.6	3.9	0.27	20	0.068	85
	500	30	3.6	4.8	0.33	15	0.058	57
AEA3, Air = 5.6% (P20)								
	0	0	3.8	4.8	0.14	34	0.024	41
	150	30	4.4	5.7	0.19	23	0.033	64
	300	30	4.3	5.3	0.35	14	0.079	147
	500	30	3.9	5.6	0.55	8	0.133	226

Table 7 (continued).

Mix No.	Pressure (psi)	Duration (sec)	LTRAV Air < 1 mm (%)	LTRAV Total Air (%)	Spacing Factor Total Air (mm)	Specific Surface Total Air (mm^2/mm^3)	Philleo Factor @ 90% < 1 mm (mm)	Modal Chord Length < 1 mm (microns)
AEA2, Air = 5.0% (P02)								
	0	0	3.3	4.3	0.15	35	0.026	30
	50	30	4.0	4.7	0.15	33	0.025	43
	150	30	3.8	5.5	0.17	27	0.027	42
	300	30	3.9	4.6	0.19	26	0.042	68
	300	30	4.0	4.7	0.18	28	0.036	62
	500	30	4.1	4.9	0.43	11	0.109	183
AEA2, Air = 6.6% (P14)								
	0	0	5.0	5.8	0.10	48	0.015	39
	150	30	5.5	6.4	0.12	36	0.016	53
	300	30	5.4	6.4	0.12	36	0.017	52
	500	30	5.9	7.6	0.16	23	0.024	82
AEA2, MBL-82 Air = 5.6% (P09)								
	0	0	3.2	4.2	0.20	26	0.038	55
	150	30	3.3	4.9	0.26	18	0.047	63
	300	30	3.3	4.6	0.36	14	0.090	134
	500	30	3.0	4.2	0.58	9	0.136	213
AEA2, MBL-82, Type F Air = 5.5% (P17)								
	0	0	3.8	4.5	0.16	32	0.032	49
	150	30	3.8	4.4	0.18	29	0.036	58
	300	30	3.9	4.5	0.18	29	0.038	62
	500	30	4.1	5.1	0.22	22	0.051	91

CHAPTER 5
ANALYSIS

CHANGE IN THE AIR VOID DISTRIBUTION

The change in the air void distribution is the basis for the change in air void parameters by pressurization, as explained earlier. In order to understand the significance of the change in air void parameters, it is first necessary to show how pressure is altering the distribution of air voids in the paste matrix.

The pressure-dissolution theory presented earlier suggests that voids that have dissolved under pressure may come out of solution on existing voids. This will eliminate some smaller voids and make existing voids larger than before. The result of this will be a shift in the air void distribution, with larger pressures resulting in more pronounced shifts, for the same pressurization time.

Figure 8 shows a photomicrograph of cut and lapped sections of a control specimen (8a) and a specimen pressurized to 300 psi for 30 sec (8b). The decrease in frequency of small voids is quite apparent.

Mix P06, a mix containing an air entraining agent (AEA1) and water reducer (WR1), was analyzed by linear traverse for the specimens that were pressurized at 0, 50, 150, 300, and 500 psi for 30 sec, to see the change that different pressures had on the air void distribution. Figure 9 shows overlaid plots of all the distributions; all distributions are best fit curves of the actual data using Equation #1. The graph shows that, with increased levels of pressure, the air void distribution did shift towards larger chord sizes. This shift resulted in fewer voids and larger voids in pressurized specimens of the same air content.

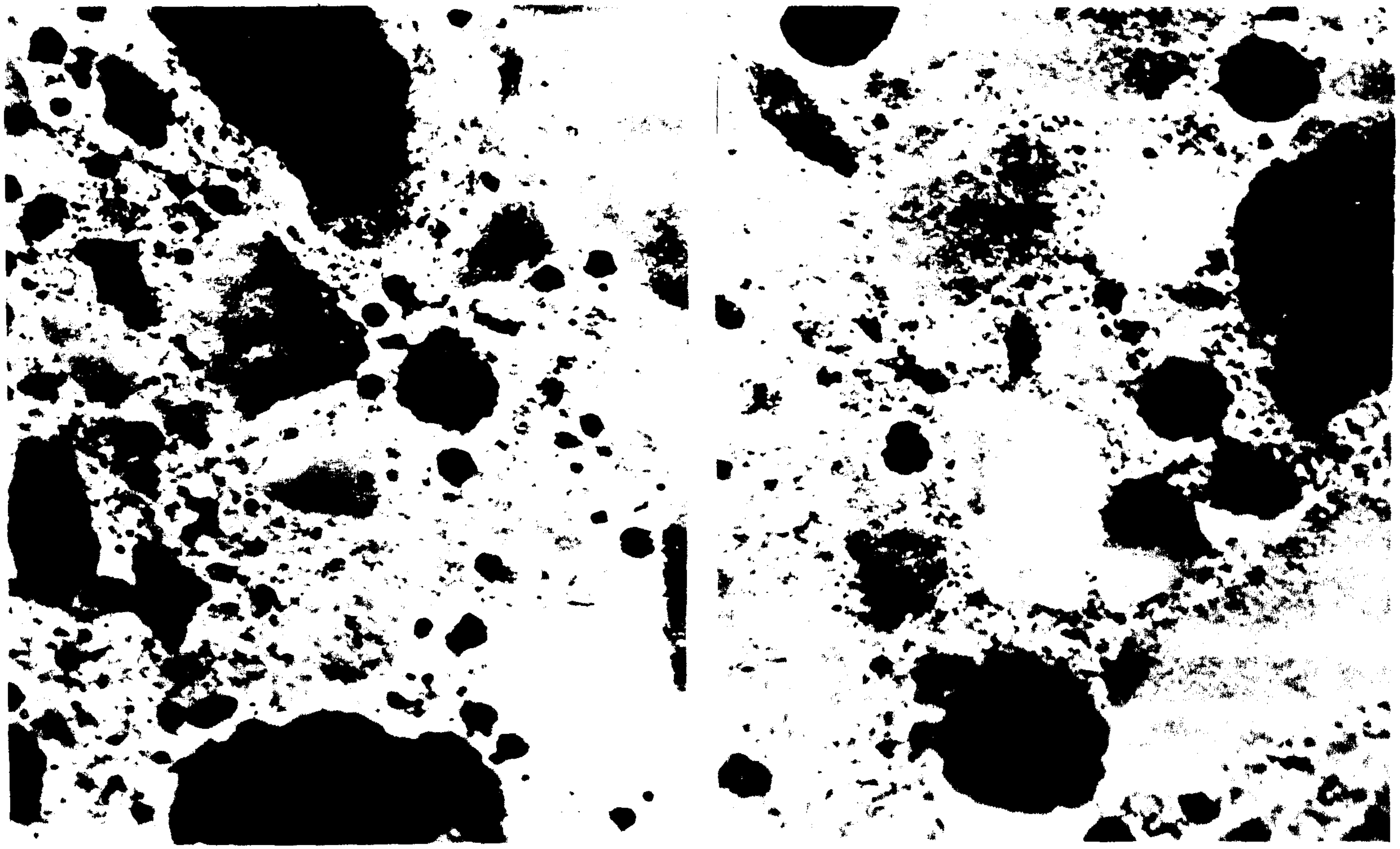

Figure 8. Photomicrograph of Cut and Lapped Sections of a Control Specimen (8a) and a Specimen Pressurized to 300 psi for 30 sec (8b).

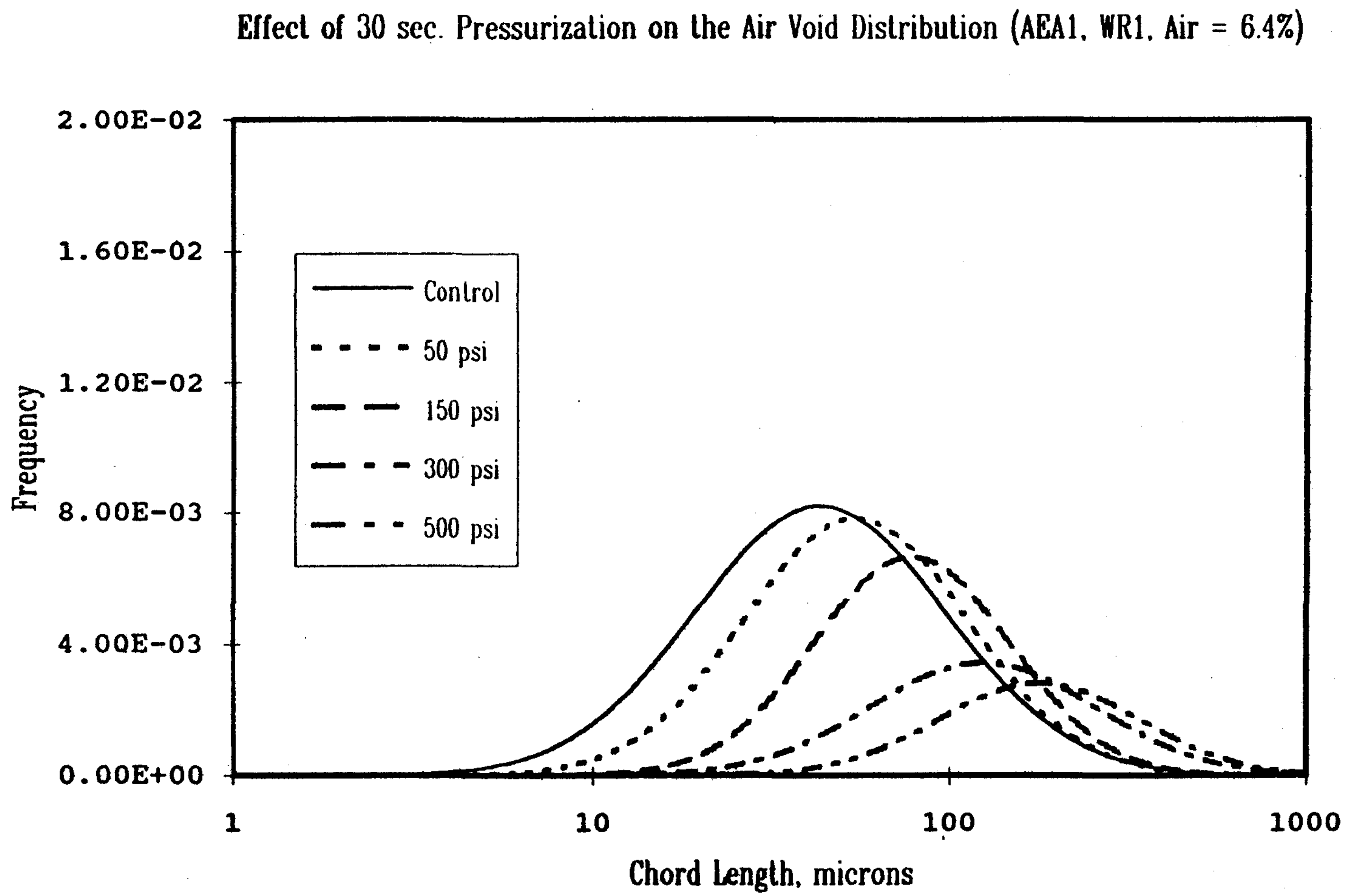

Figure 9. Change in Air Void Chord Distribution with Increasing Pressure.

EFFECT OF ORDER OF PRESSURIZATION

The effect of testing order on the magnitude of the shift in distribution was examined, as the process of pressurizing all of the specimens (ten, counting the non-pressurized control specimen) took nearly an hour to complete. All specimens were pressurized in the same order. It is important to determine if the delay in pressurization between specimens 1 and 10 had an effect on changes in the air void system.

The last specimen of each pressurized batch was a repeat of the first specimen, 300 psi for 30 sec. Two of the mixes analyzed were chosen to best demonstrate the effect of pressurization order. The first was a mix thought to be less likely to show any curing effects in one hour; the mix contained AEA1 (at 6.4 percent air) and WR1, a ligno-sulfonate based water reducer, that can have a retarding effect on the mix. The second mix was considered to have a greater chance of showing initial curing effects in one hour; the mix contained AEA2 (at 5.0 percent air) with no possible retarding admixtures.

Figures 10 and 11 show the distributions for each mix, and how the difference between the mixes compared to that of the control specimen. For each example, the effect of the order of pressurization was not as pronounced as the pressurization effect itself. Table 8 shows how this change in the distribution changed the air void parameters, as well as how the order of pressurization affected the parameters.

The range of parameter error along with the actual parameter value can be observed from this table. There is a 95 percent probability that the actual values for the spacing factor and the specific surface fall within the depicted ranges, given the measured value. Slight differences in the air void parameter values for the first and last pressurized specimens are overshadowed by the expected precision of the parameter (95 percent confidence range). The difference between the unpressurized and pressurized specimen parameters are, however, of interest.

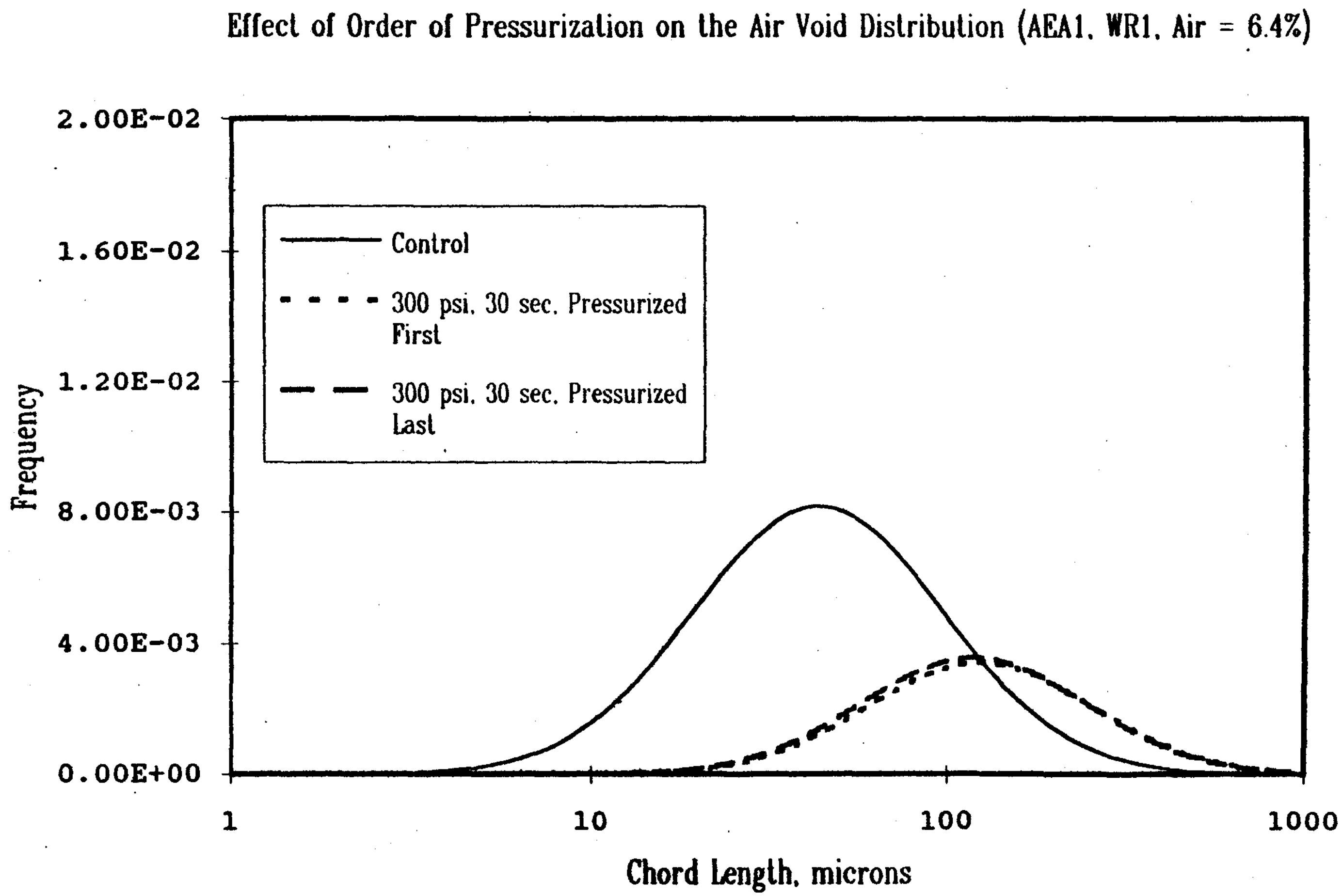

Figure 10. **Effect of Pressurization Order on the Air Void Chord Distribution for Mix Containing AEA1 and WR1.**

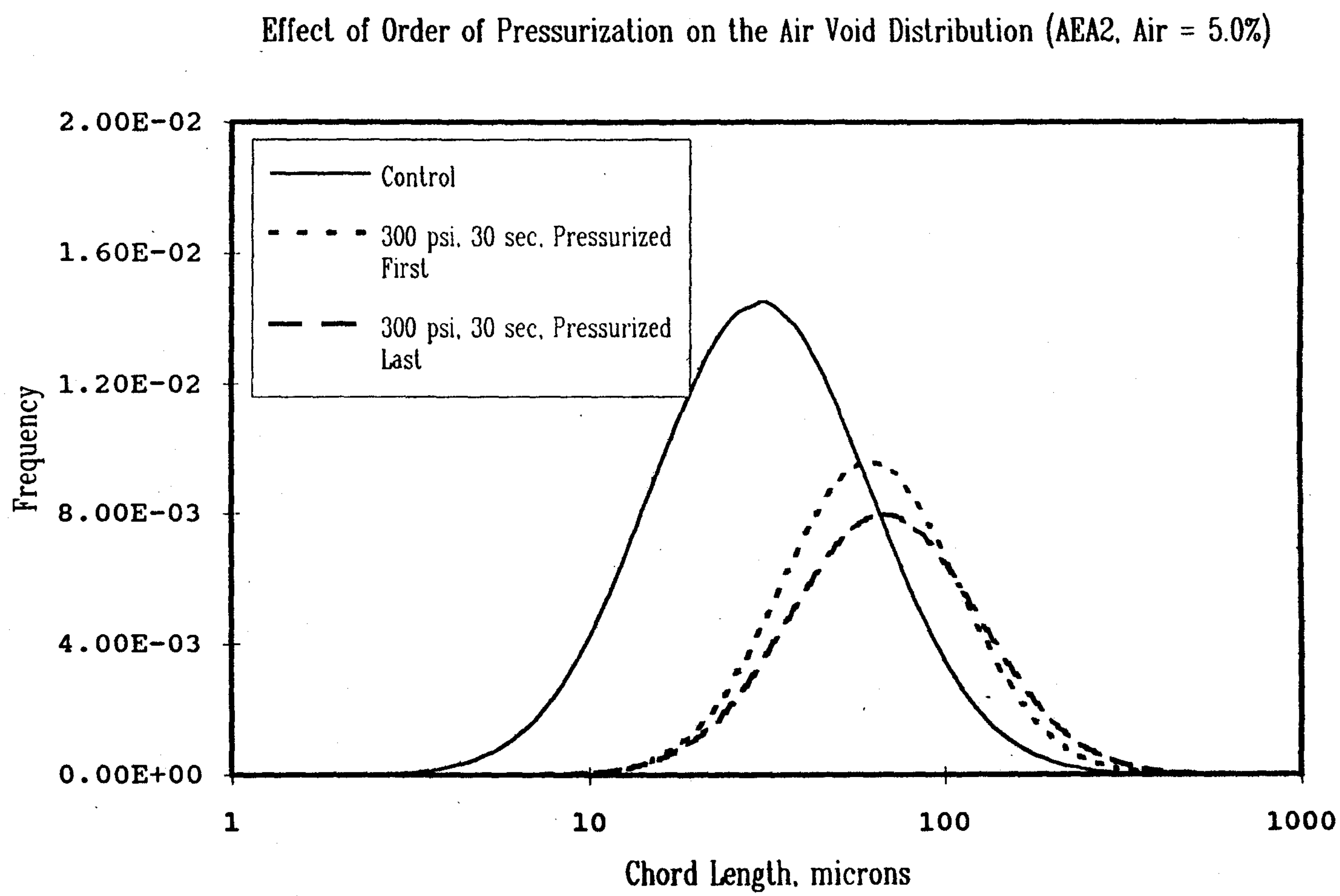

Figure 11. **Effect of Pressurization Order on the Air Void Chord Distribution for Mix Containing AEA2.**

Table 8. Effect of Pressurization Order

Mix	Specimen	Pressure (psi)	Time (sec)	$\overline{L}$ (95% range) (mm)	α (95% range) (mm)
AEA2	Control	---	---	0.15 (0.14 to 0.16)	35 (31 to 39)
	1st Press.	300	30	0.19 (0.17 to 0.21)	26 (23 to 29)
	Last Press.	300	30	0.18 (0.16 to 0.20)	28 (25to 31)
AEA1 WR1	Control	---	---	0.15 (0.13 to 0.16)	28 (25 to 31)
	1st Press.	300	30	0.32 (0.28 to 0.35)	14 (12 to 16)
	Last Press.	300	30	0.28 (0.25 to 0.31)	14 (12 to 15)

EFFECT OF PRESSURIZATION TIME ON AIR VOID PARAMETERS

The specimens, as noted earlier, were pressurized under various pressures and for a duration of either 5 sec or 30 sec. All specimens were traversed for one mix, a mix containing AEA1 and WR1 (air = 6.4 percent), to determine the effect of the pressurization period on the magnitude of the changes in air void parameters. The resulting changes in hardened air content (both total and for chord lengths under 1 mm), $\overline{L}$, α, and $\overline{P}_{90}$ can be seen in Figures 12 thru 15. Figure 12 shows the change in hardened air content for the different pressures. It also shows no noticeable trend between 5 sec and 30 sec pressurization. Although the remaining figures show the same general trends for all of the parameters, they illustrate that the effect on the 30 sec pressurization time is more pronounced than the 5 sec pressurization.

By establishing the influence of various pressures and times on the air void distribution, it is now possible to isolate which pressures and times seemed to be most

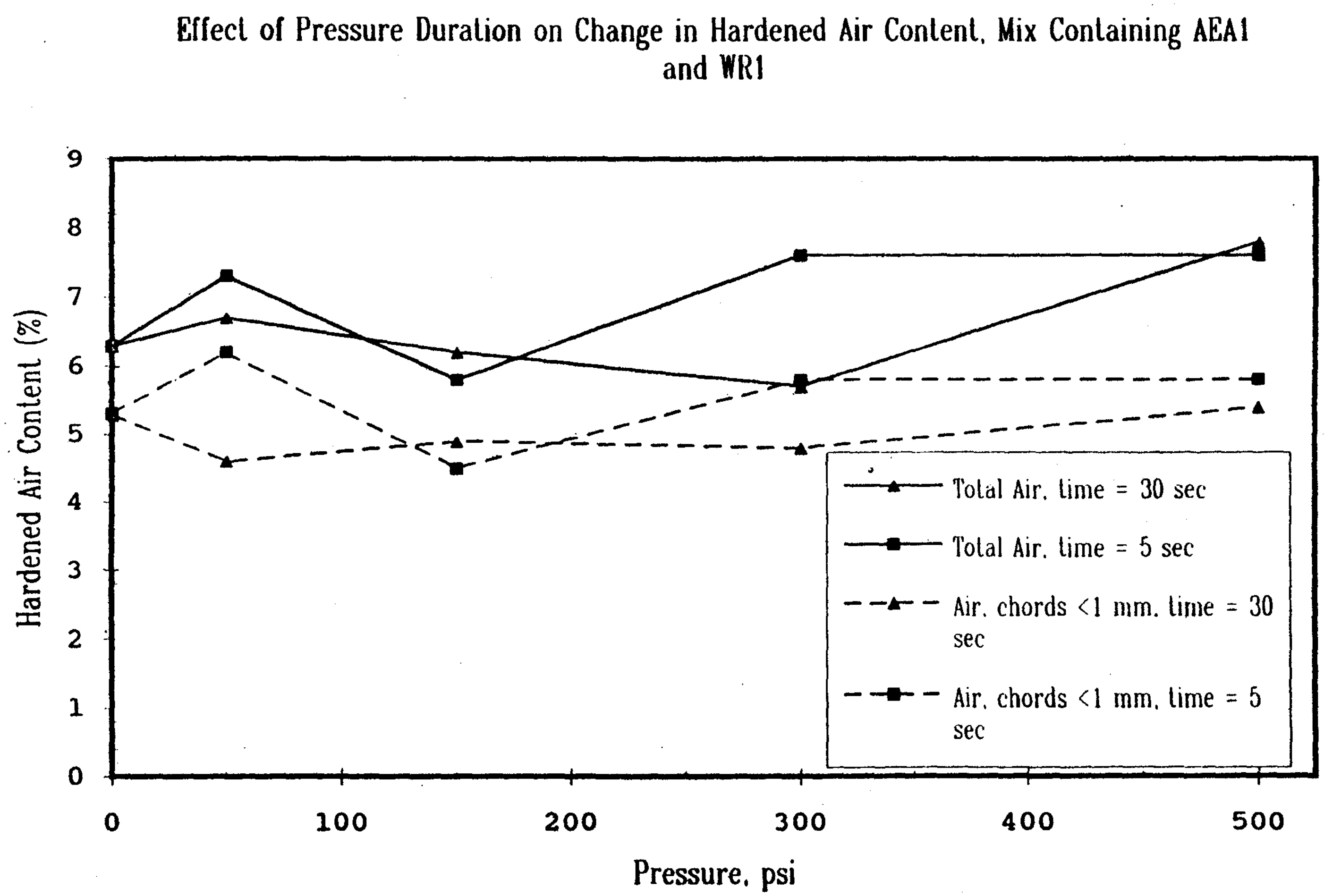

Figure 12. Influence of Pressurization Duration on the Effect of Pressurization on Hardened Air Content.

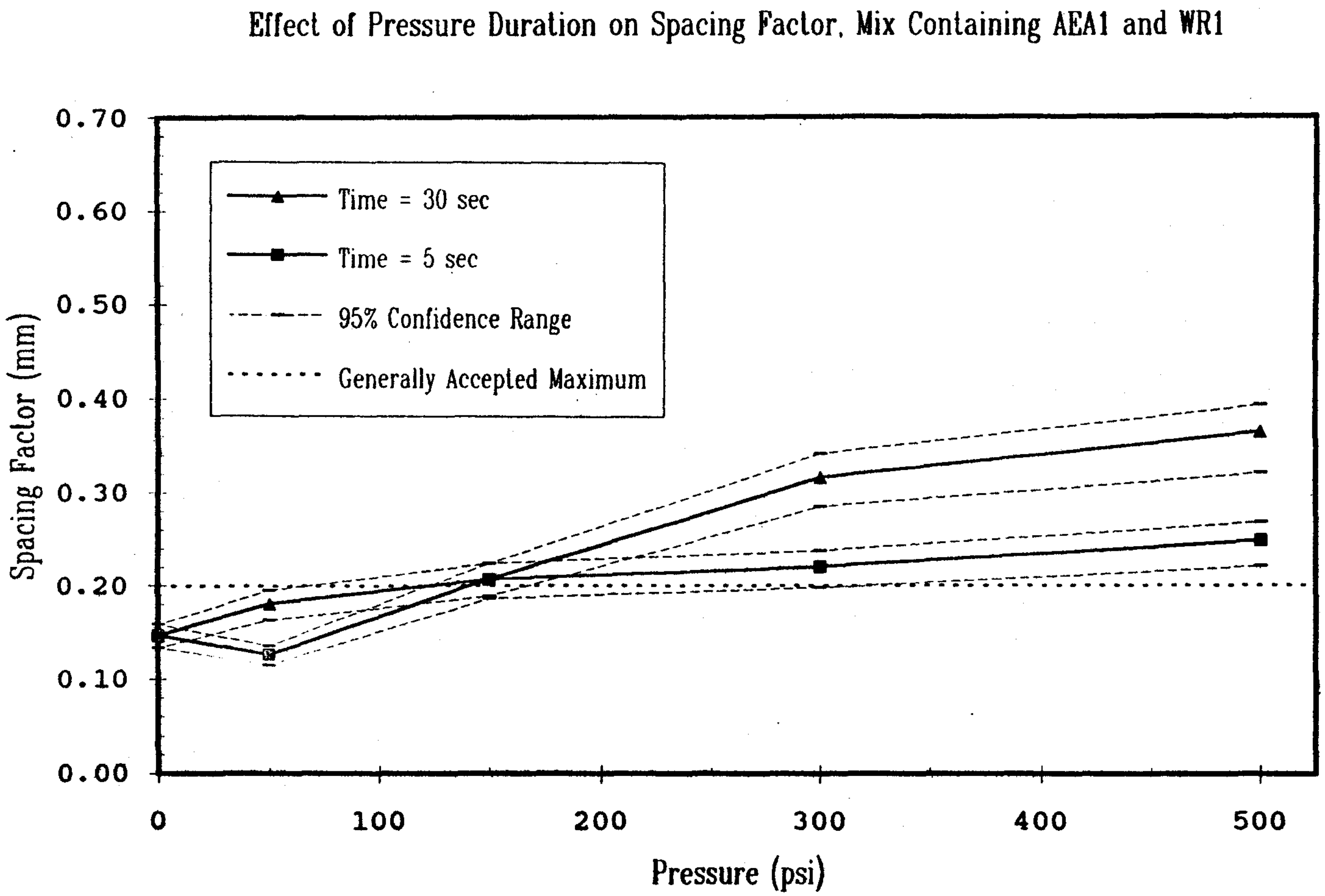

Figure 13. **Influence of Pressurization Duration on the Effect of Pressurization on Spacing Factor.**

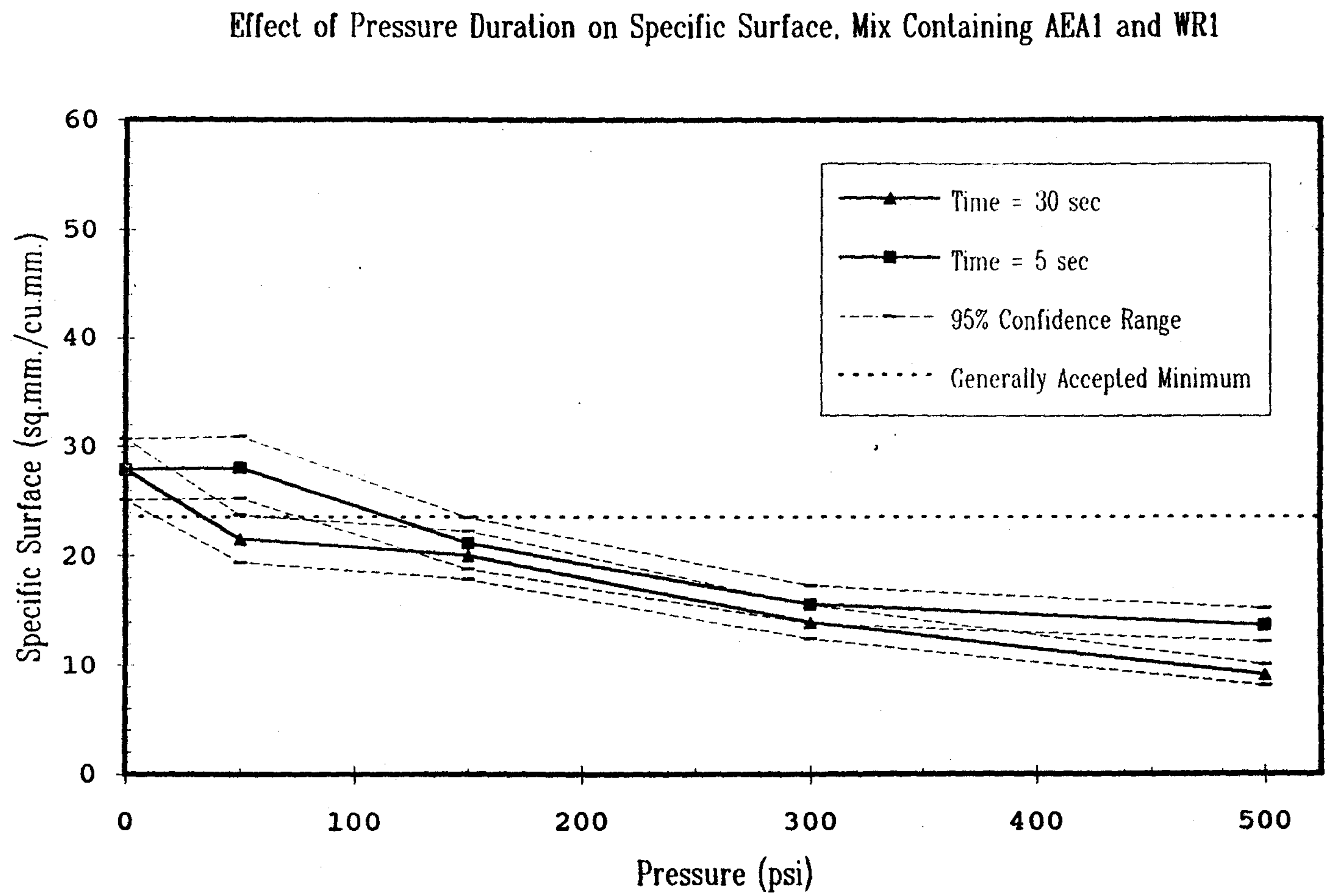

Figure 14. **Influence of Pressurization Duration on the Effect of Pressurization on Specific Surface.**

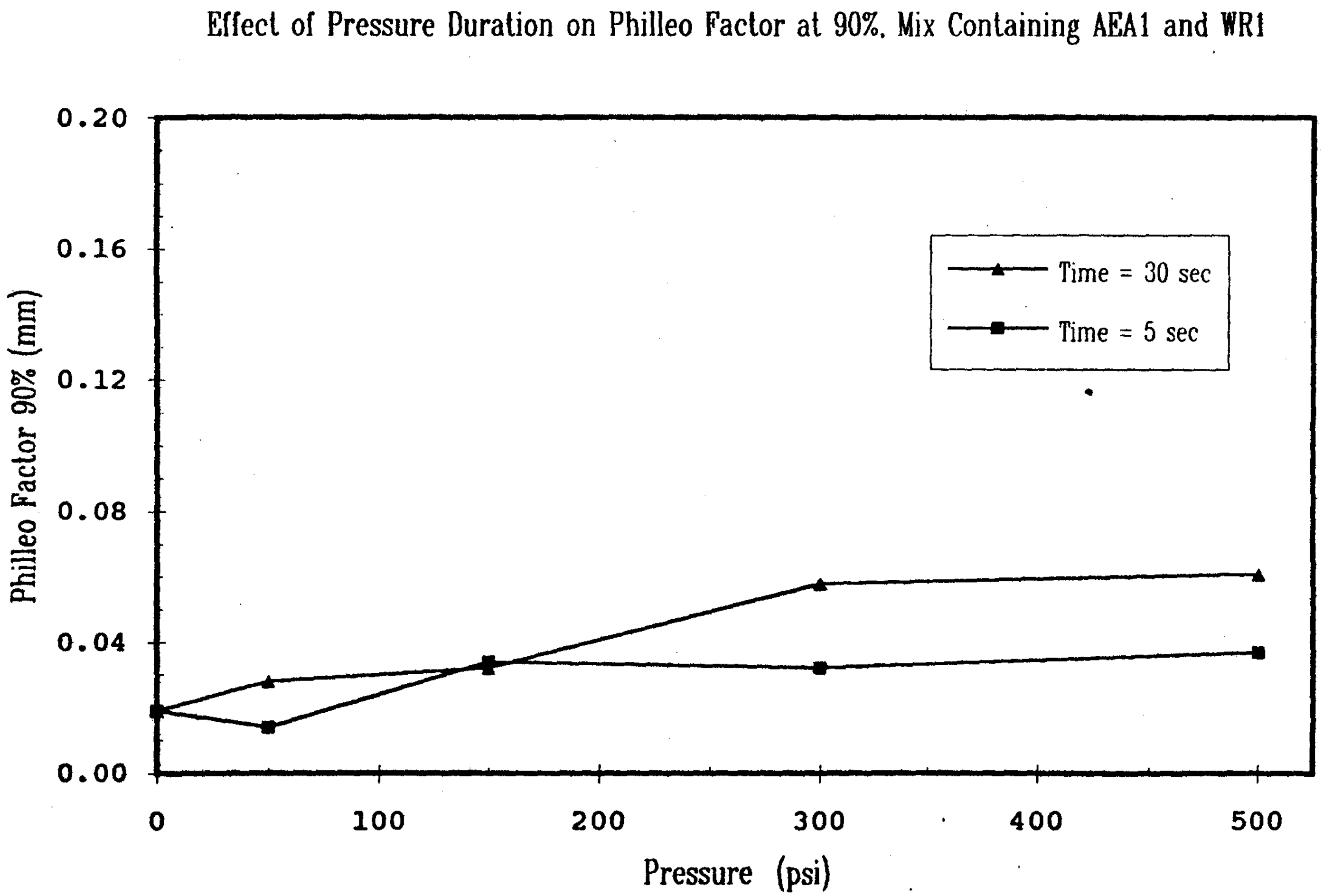

Figure 15. Influence of Pressurization Duration on the Effect of Pressurization on Philleo Factor at 90%.

important and to focus further study on those ranges. Figure 9 shows that 50 psi had a relatively small effect on the distribution, while 150, 300, and 500 psi had a definite impact. Therefore, for the remaining analysis, the 50 psi specimens will be omitted. Furthermore, as specimens pressurized for 30 sec showed better delineation among pressures, and were easier to produce consistently in a laboratory environment, 30 sec will be the pressure duration for which all of the specimens will be analyzed. A summary of the specimens that will be the focus of further study is as follows:

Control	0 sec
150 psi	30 sec
300 psi	30 sec
500 psi	30 sec

EFFECT OF DIFFERENT FRESH AIR CONTENTS

Mixes containing the same air entraining agent (no other admixtures) but different air contents were analyzed to show the effect of increasing the air content on the pressurization effect. This analysis was done for mixes containing either AEA1 or AEA2, with no other admixtures. For AEA1, which had fresh air contents of 4.0 percent, 4.7 percent, and 5.9 percent, Table 7 in Chapter 4 shows that, for higher air contents, a less dramatic change in modal chord length was noticed. Figures 16 through 19 illustrate the effects on air void parameters. The hardened air contents of the various specimens showed no distinguishable trends among the various fresh air content values, as shown by Figure 16. Figure 17, however, shows that the spacing factor for higher air contents required a higher pressure before change had begun to occur. A possible explanation for this requirement is that the water surrounding the air void became saturated with dissolved air when placed under pressure, and that this air could not diffuse away quickly enough to allow more air to dissolve out of the bubble. For higher air contents, then, there will still be a significant amount of air left in bubbles after pressure is applied, preserving a greater portion of the original distribution.

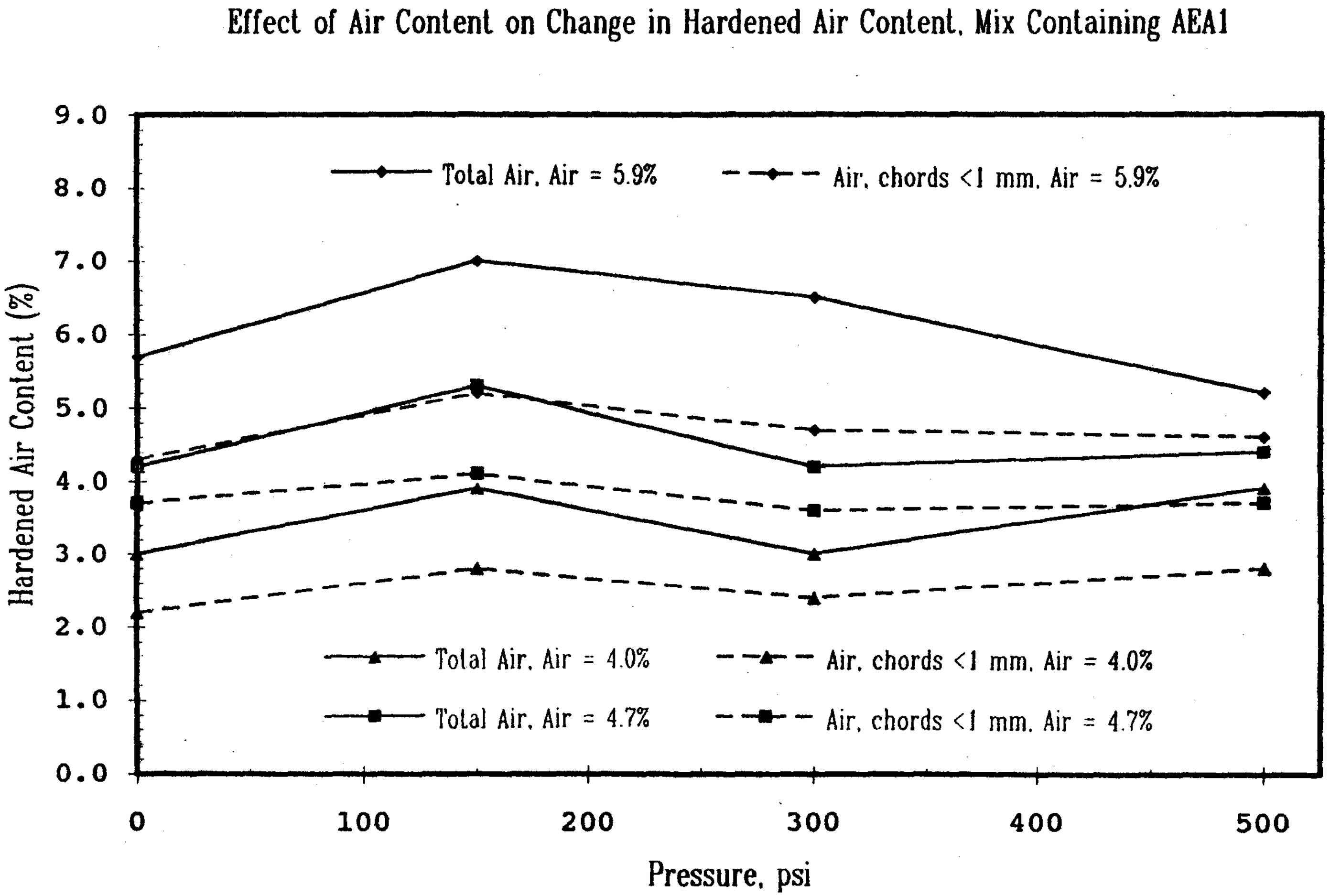

Figure 16. **Influence of Fresh Air Content on the Effect of Pressurization on Hardened Air Content, Mix Containing AEA1.**

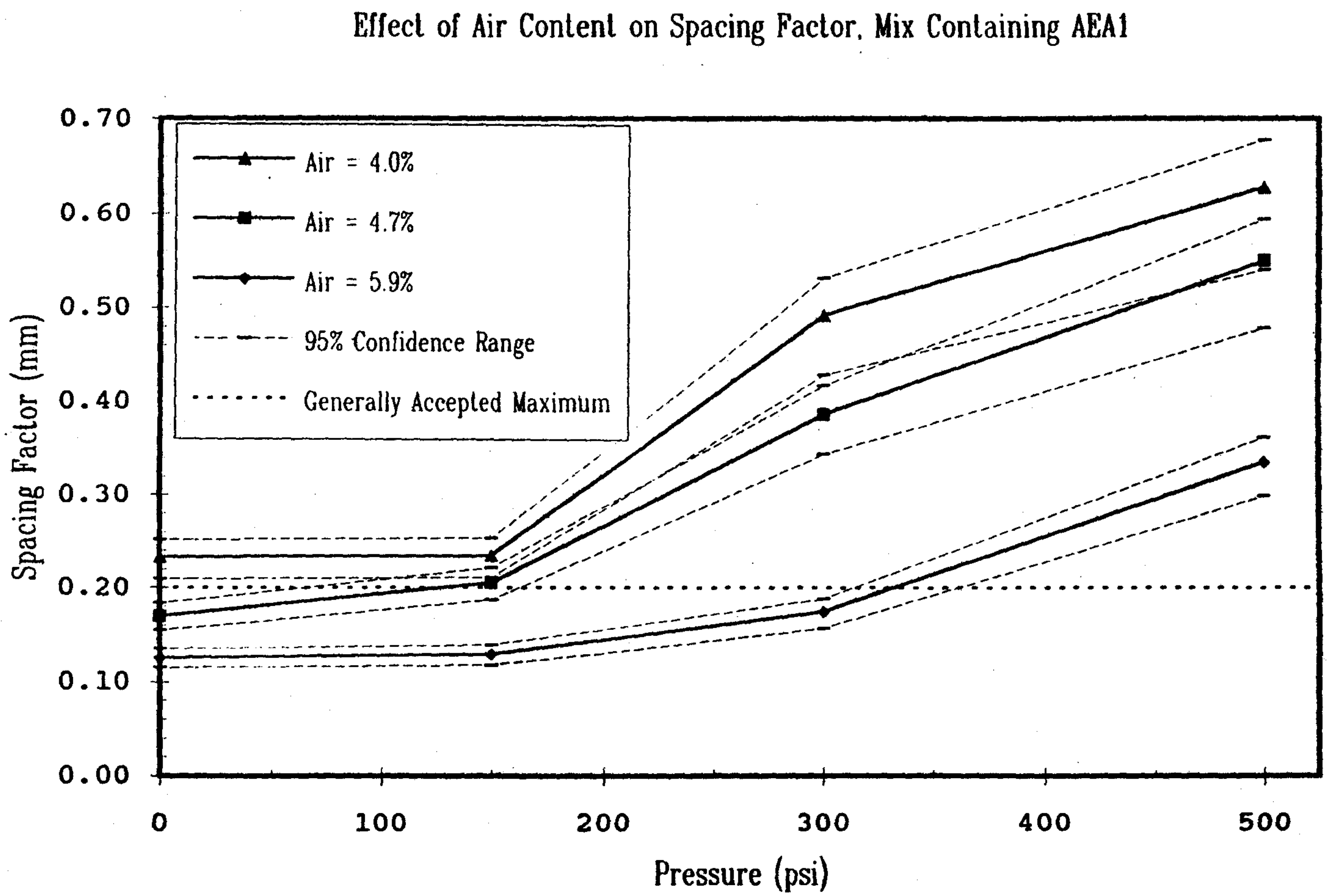

Figure 17. Influence of Fresh Air Content on the Effect of Pressurization on Spacing Factor, Mix Containing AEA1.

Figure 18 shows that the specific surface started higher (better) for higher air contents, but dropped at the approximately the same rate for all three mixes. This similar decline in rate suggests that though higher air content mixes had greater proportion of smaller bubbles, the total amount of air dissolving was about the same. Neither of the mixes showed greater or lesser resistance to the effects of pressurization.

The parallel changes in α for different air contents suggest a limited capacity to dissolve bubbles—this limitation possibly being the saturation of paste with dissolved air, as mentioned previously. Figure 19 shows that for the Philleo factor, as for the spacing factor, higher air contents had a greater resistance to the effect of pressurization than did lower air contents. The Philleo factor for the highest air content showed almost no significant change over the pressure range, while the lowest air content showed significant change over the range. This indicates, as was noted in the discussion of the spacing factor, that there may be a limit as to how much air can be dissolved into the mix under this pressure range. Mixes that had higher air contents kept more of their original distributions because of this limit.

For AEA2, the trends for modal chord length, hardened air content, spacing factor, specific surface, and Philleo factor were the same as the trends for AEA1. These trends are noted in Figures 20 through 23. This similarity not only shows the consistency of these trends, but also that the air content effect was independent of AEA type.

EFFECT OF DIFFERENT AIR ENTRAINING AGENTS

Limiting all other contributing factors as much as possible was necessary in order to analyze the effect of different air entraining agents on concrete mixes under static pressure. Therefore, for mixes containing AEA1, AEA2, and AEA3, no other admixtures were added and the air contents were not allowed to range more than 1 percent from each other. The mixes chosen for the three air entraining agents were, respectively, 5.9 percent, 6.6 percent, and 5.6 percent.

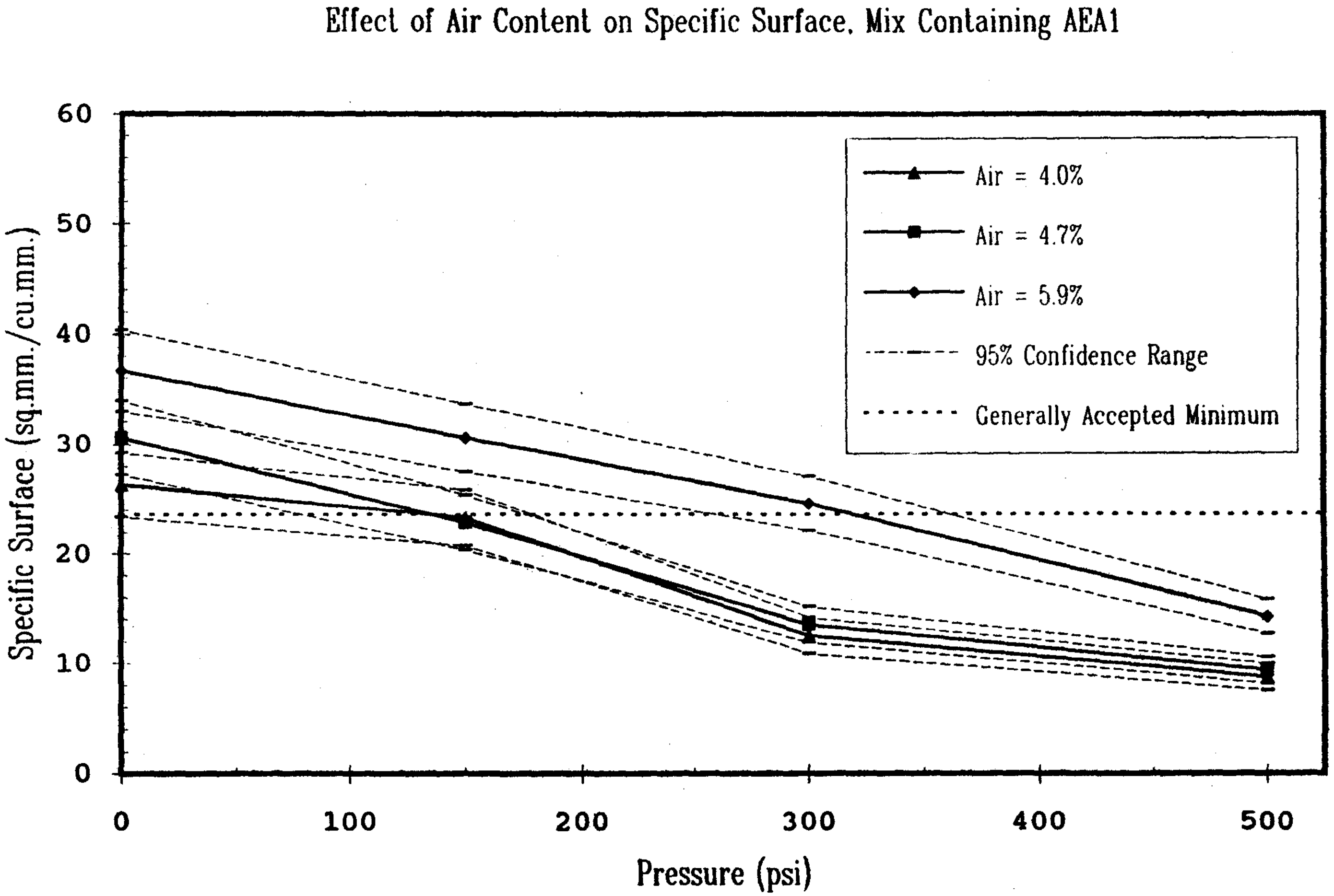

Figure 18. **Influence of Fresh Air Content on the Effect of Pressurization on Specific Surface, Mix Containing AEA1.**

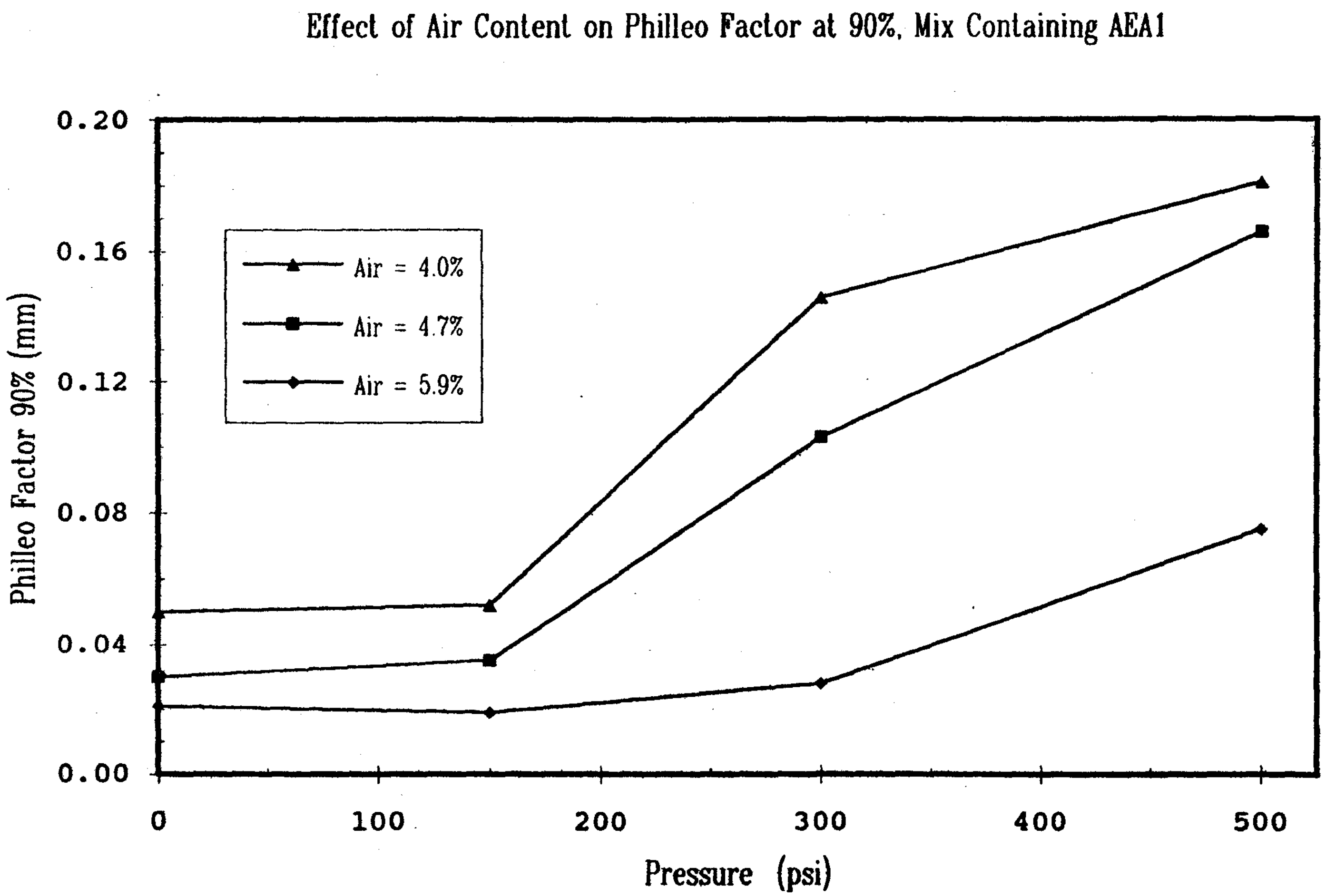

Figure 19. Influence of Fresh Air Content on the Effect of Pressurization on Philleo Factor at 90%, Mix Containing AEA1.

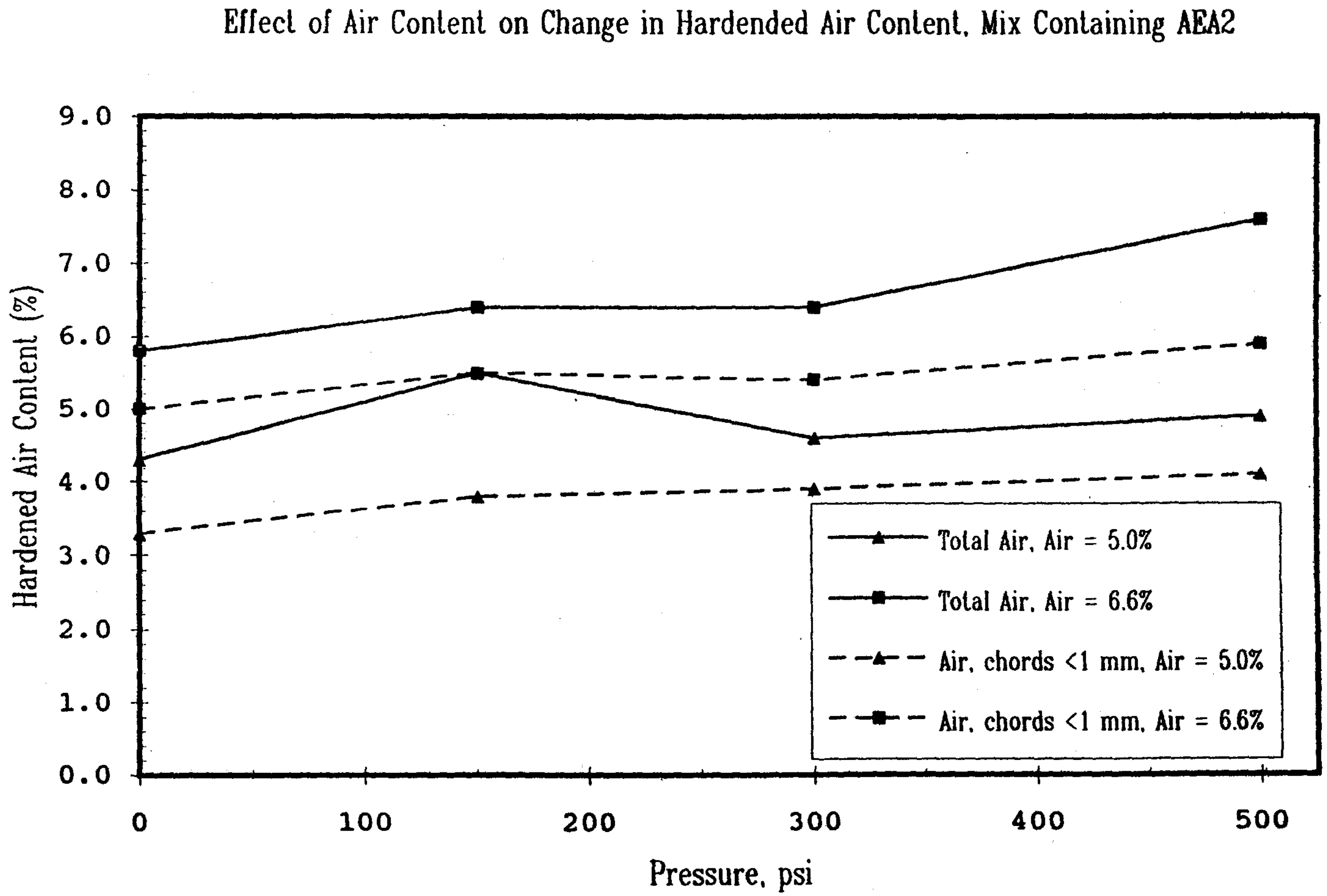

Figure 20. Influence of Fresh Air Content on the Effect of Pressurization on Hardened Air Content, Mix Containing AEA2.

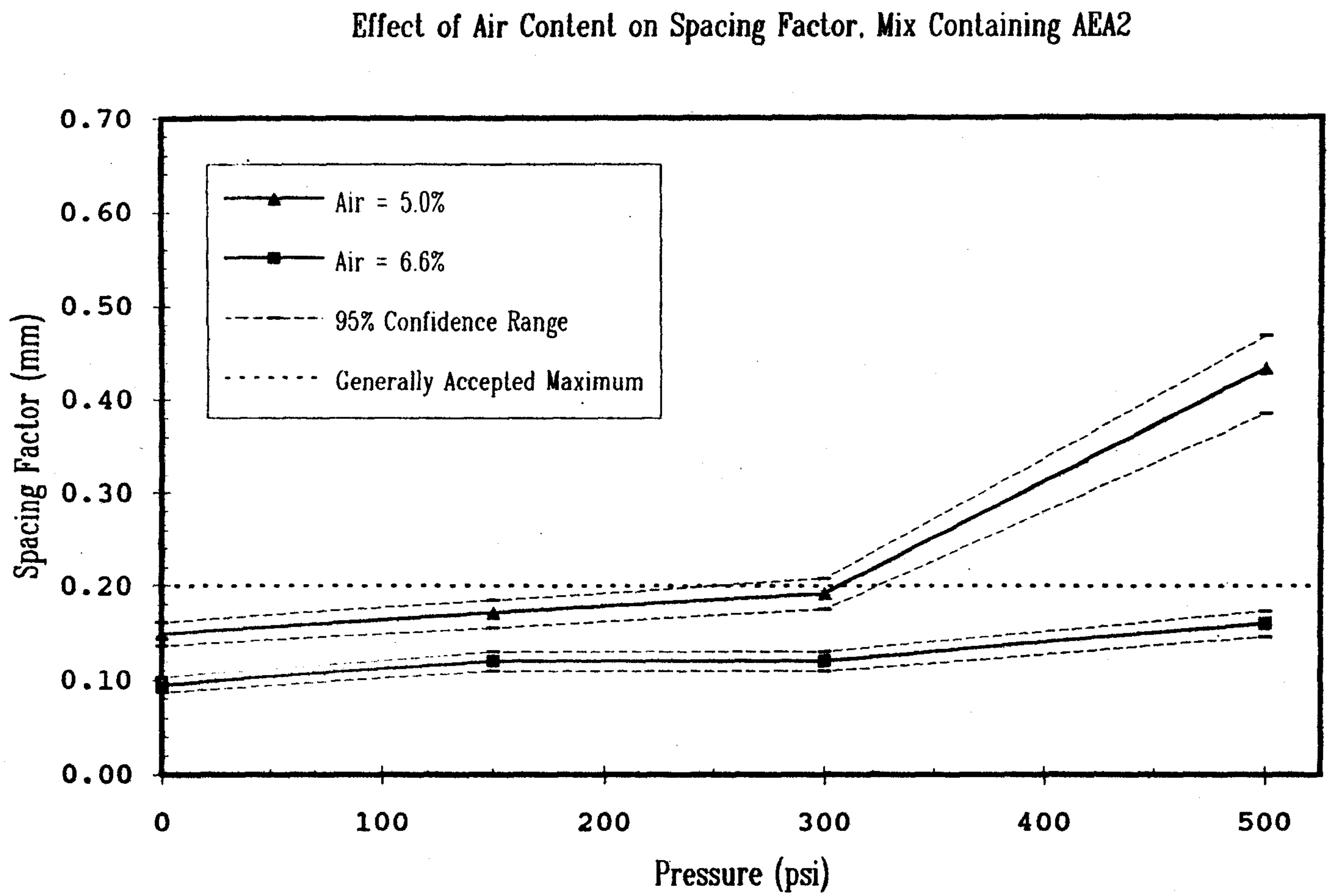

Figure 21. Influence of Fresh Air Content on the Effect of Pressurization on Spacing Factor, Mix Containing AEA2.

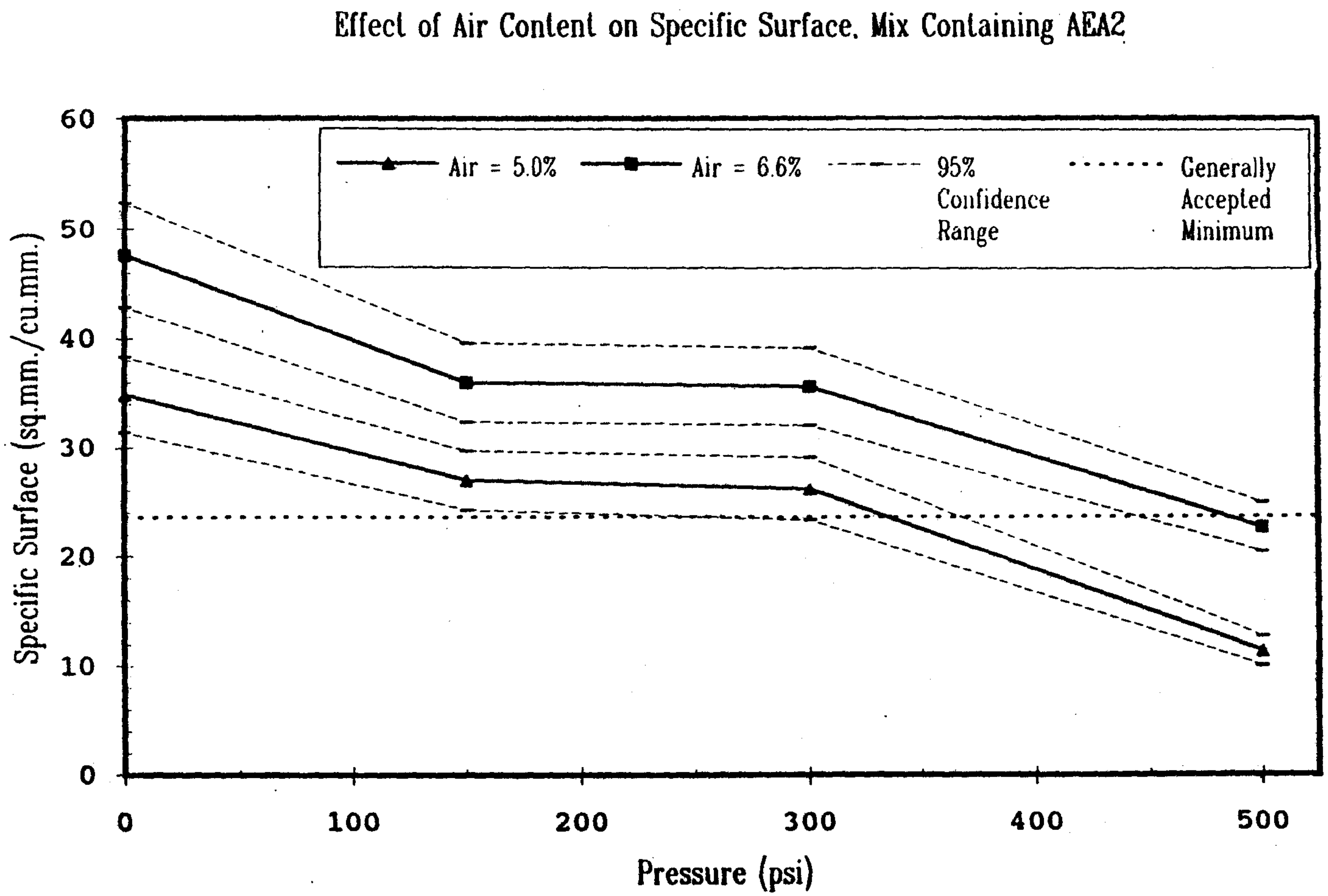

Figure 22. Influence of Fresh Air Content on the Effect of Pressurization on Specific Surface, Mix Containing AEA2.

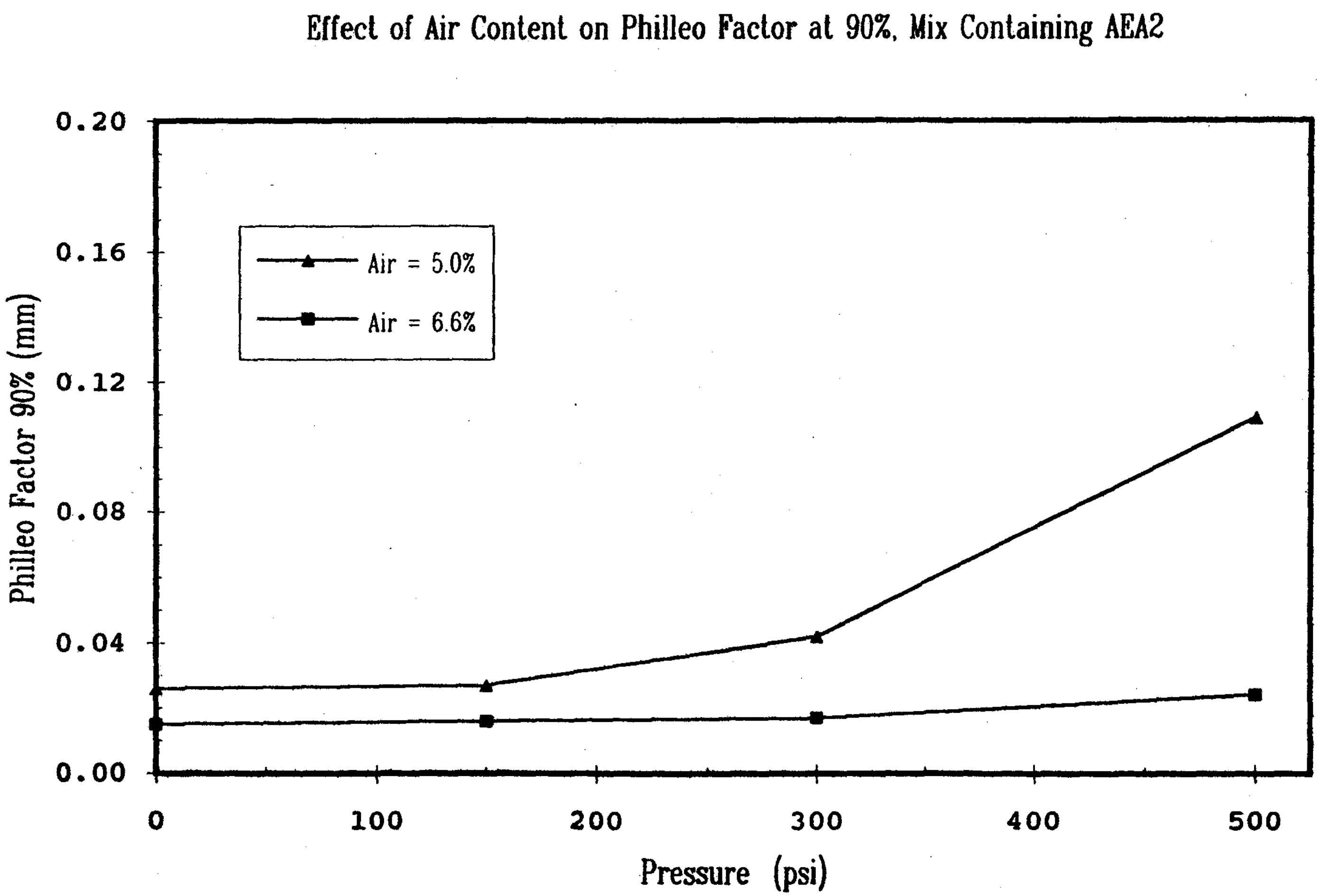

Figure 23. Influence of Fresh Air Content on the Effect of Pressurization on Philleo Factor at 90%, Mix Containing AEA2.

These air contents, while similar, do vary by a small amount. This should be kept in mind when making comparisons, as it was shown in the previous section that higher air contents can result in a more stable air void distribution.

The results of this comparison can be seen in Figures 24 through 27. Figure 24 once again shows that there was no significant trend in hardened air contents. Figure 25, however, shows that the spacing factor values changed significantly for the different agents. AEA2, the most stable agent, did not show significant change until around 500 psi (though this may be due in part to the higher air content). AEA1 was stable early, but showed a significant increase from 150 psi to 300 psi. AEA3, the most unstable agent, showed increases at the first level of pressurization.

The specific surface values, as shown by Figure 26, started at slightly different values, but, as with different air contents, dropped at very similar rates. The Philleo factors, displayed in Figure 27, showed similar trends to the spacing factor.

The following are possible explanations for the difference in air entraining agents: different agents create distributions with different initial numbers and sizes of voids and the agents create different levels of resistance to air passing through the bubble wall into solution. The mix containing AEA3, it should be noted, had the lowest air content of the three mixes, which may have made the mix more sensitive to the pressurization.

EFFECTS OF OTHER ADMIXTURES

As PCC often has other admixtures and pozzolans added along with air entrainment, mixes containing air entrainment with water reducer (WR1 and WR2), and air entrainment with water reducer and pozzolan (Fly ash Type F) were tested. A summary of the mixes used for this analysis is shown in Table 9. The effect of pressurization on all of these mixes can be seen in Figures 28 through 35.

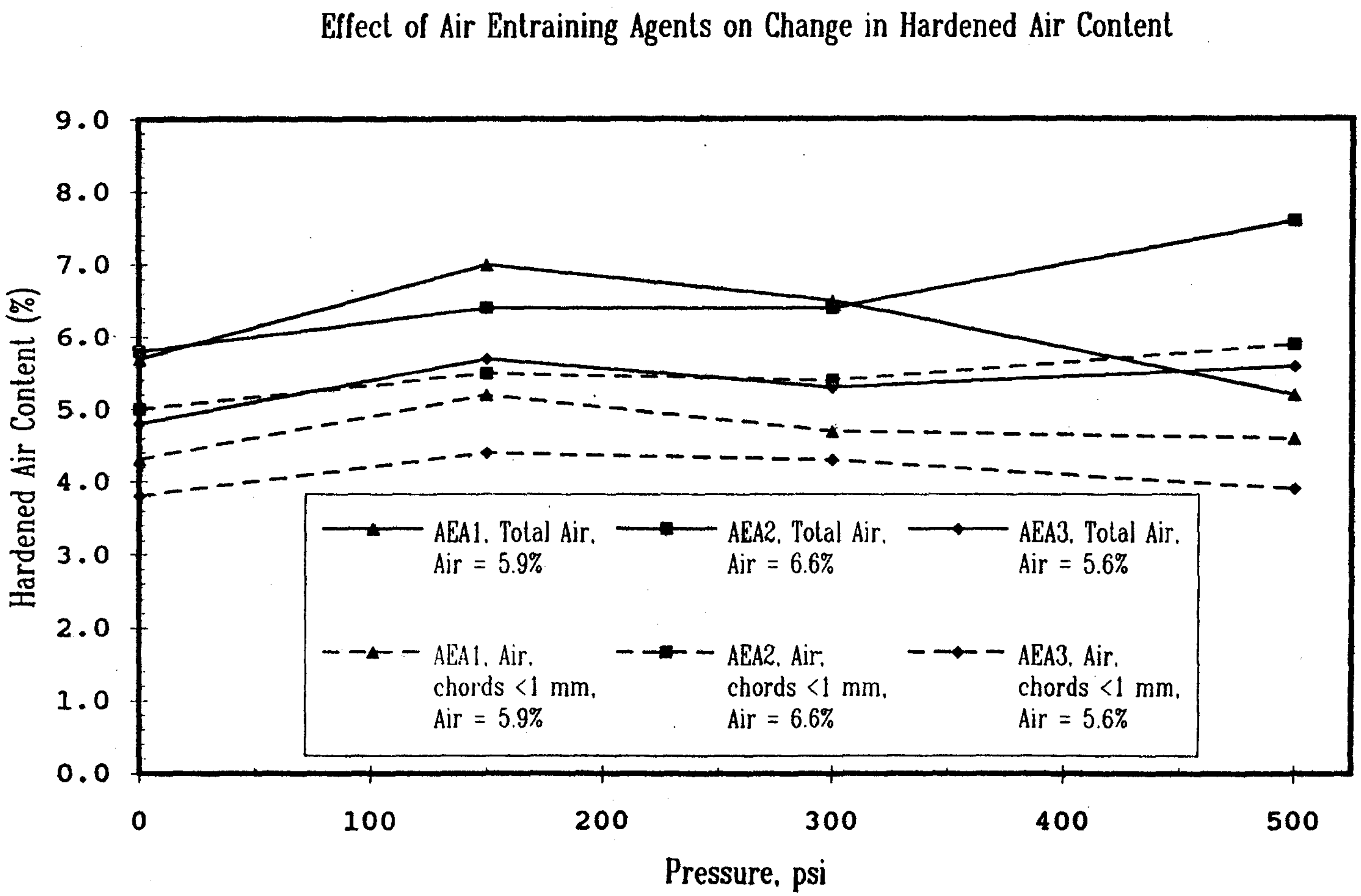

Figure 24. Influence of Air Entraining Agent on the Effect of Pressurization on Hardened Air Content.

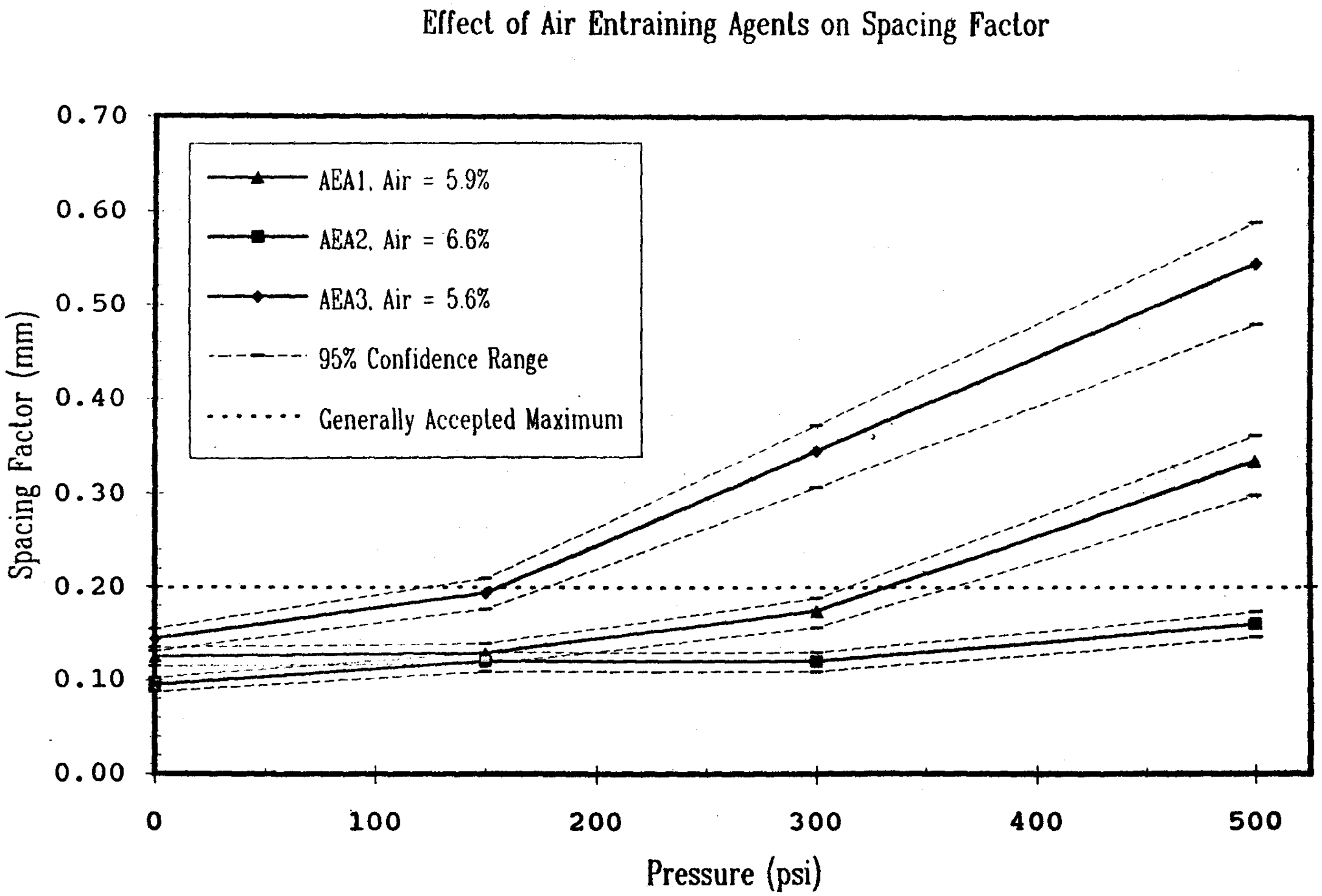

Figure 25. **Influence of Air Entraining Agent on the Effect of Pressurization on Spacing Factor.**

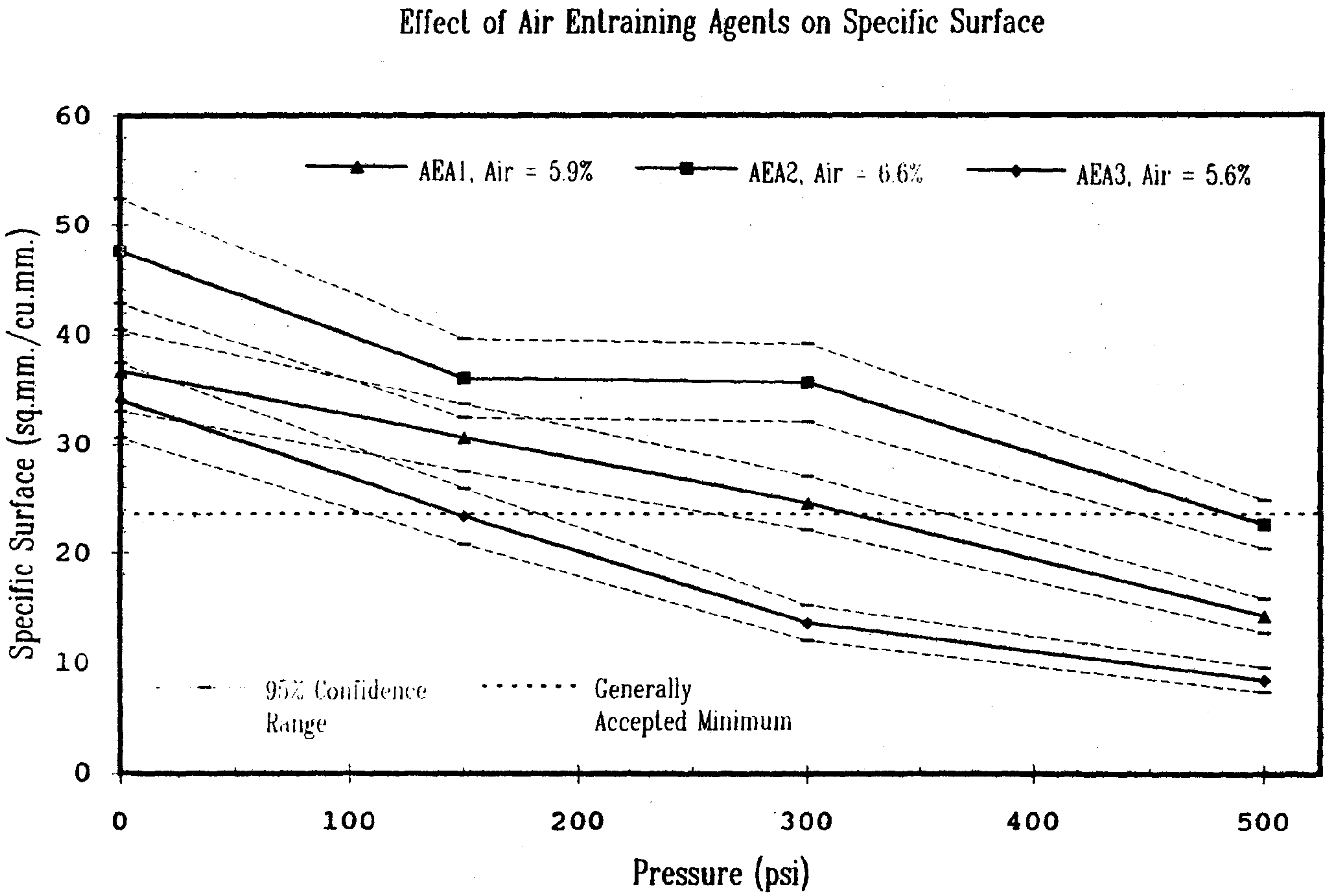

Figure 26. Influence of Air Entraining Agent on the Effect of Pressurization on Specific Surface.

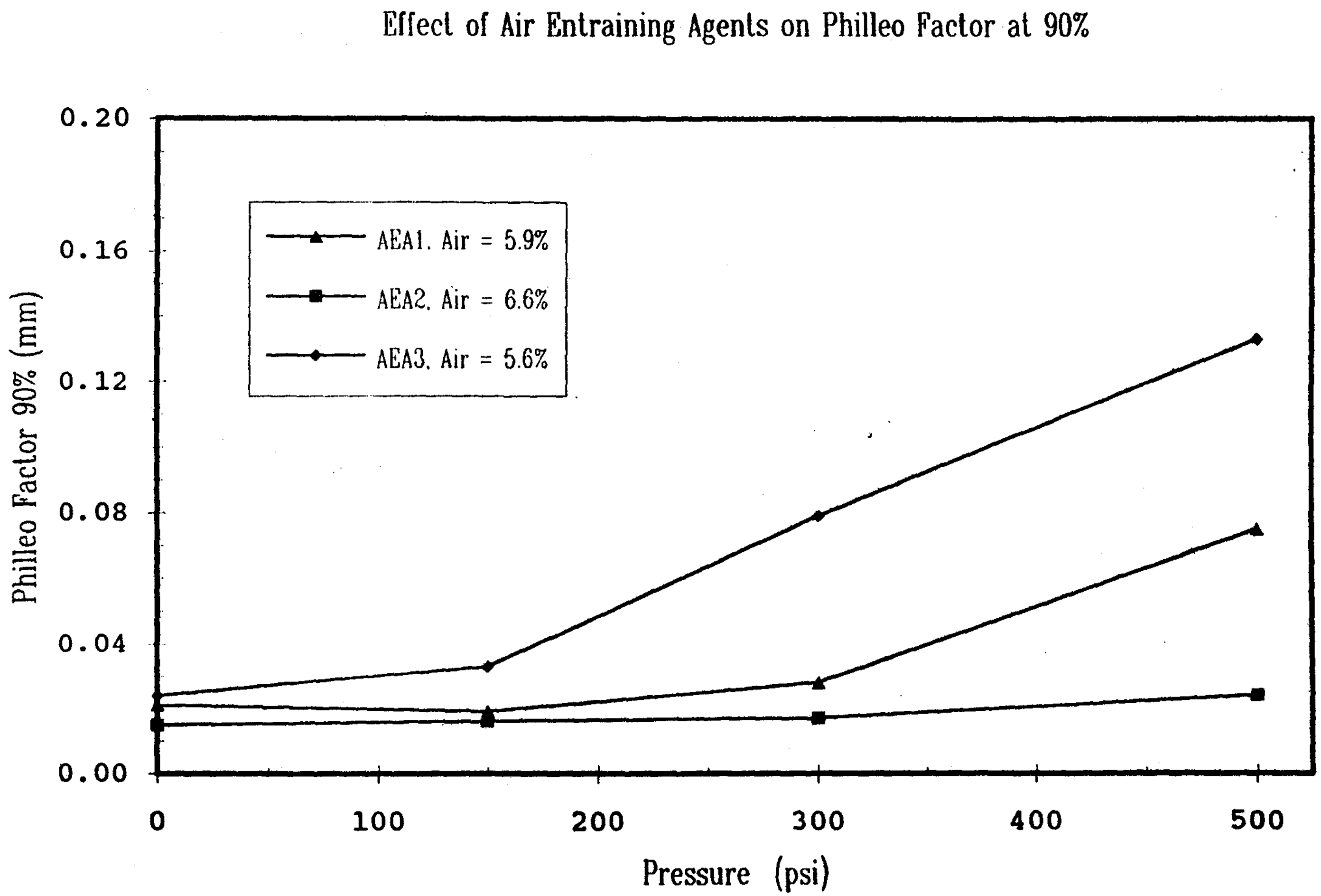

Figure 27. Influence of Air Entraining Agent on the Effect of Pressurization on Philleo Factor at 90%.

Table 9. Summary of Mixes Containing Fly Ash and Water Reducer

AEA1		AEA2	
AEA1 alone	Air = 5.9%	AEA2 alone	Air = 6.6%
AEA1 + WR1	Air = 6.4%	AEA2 + WR2	Air = 5.6%
AEA1 + WR1 + Type F	Air = 5.7%	AEA2 + WR2 + Type F	Air = 5.5%

For AEA1 and AEA2, as can be seen in Figures 28 and 32, the changes in hardened air content showed no significant trends.

Figure 29 shows that water reducer added alone with AEA1 caused the spacing factor to start climbing sooner than AEA1 alone, overriding the effect of the higher air content. When fly ash was added as well, however, stabilization of the spacing factor occurred. The spacing factor for the mix containing AEA1, WR1, and fly ash started out at the highest (least desirable) value, but changed at a much slower rate than did the others and ended up the smallest of the three at 500 psi. This result had even greater significance as the fly ash mix also had the lowest fresh air content; lower air content was expected to increase sensitivity to pressure.

The specific surface for the non-fly ash mixes, displayed in Figure 30, shows the same trends as have been seen before; the specific surface values, although starting at different values, dropped at similar rates. When fly ash was added, however, the specific surface was also stabilized; the fly ash mix started as the lowest (least desirable) value, but ended with the highest value at 500 psi.

The Philleo factor, displayed in Figure 31, showed trends that are similar to those of the spacing factor. For AEA1 alone, a rapid increase in the Philleo factor was shown. This was mirrored by the mix containing water reducer. The fly ash mix, however, again showed a more stable pattern, with the Philleo factor starting highest and finishing lowest (most desirable) across the 500 psi range.

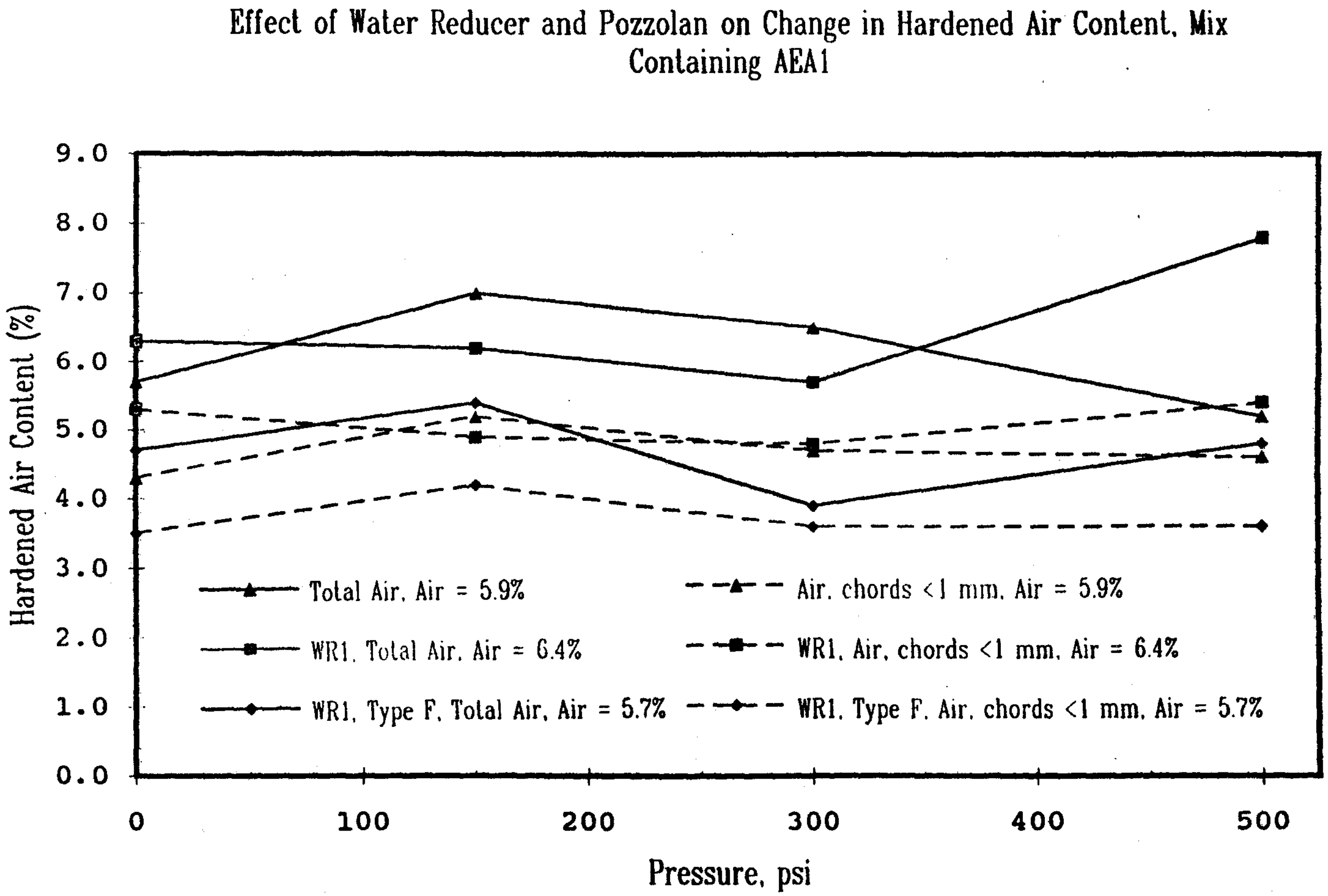

Figure 28. Influence of WR1 and Type F Fly Ash on the Effect of Pressurization on Hardened Air Content, Mix Containing AEA1.

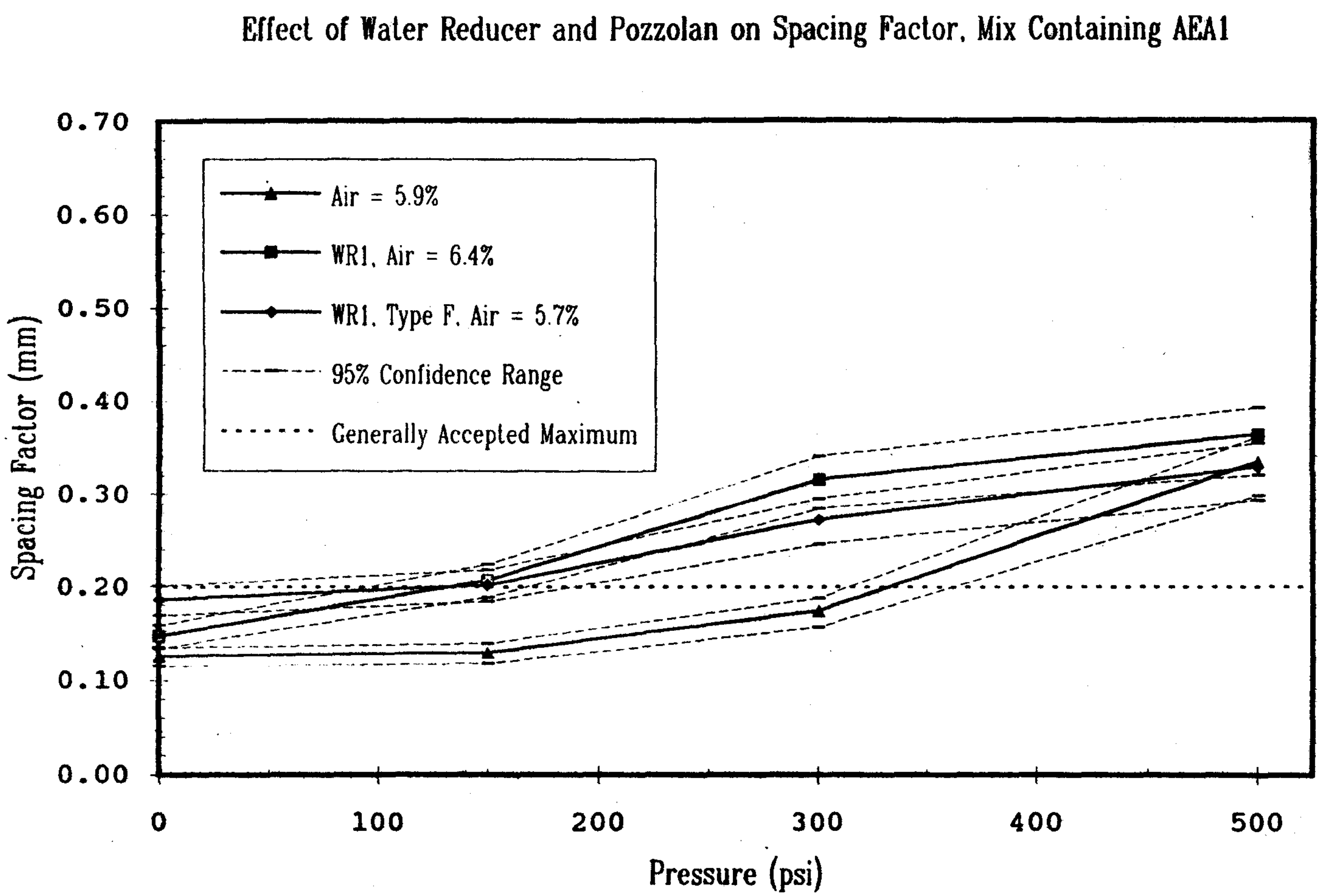

Figure 29. Influence of WR1 and Type F Fly Ash on the Effect of Pressurization on Spacing Factor, Mix Containing AEA1.

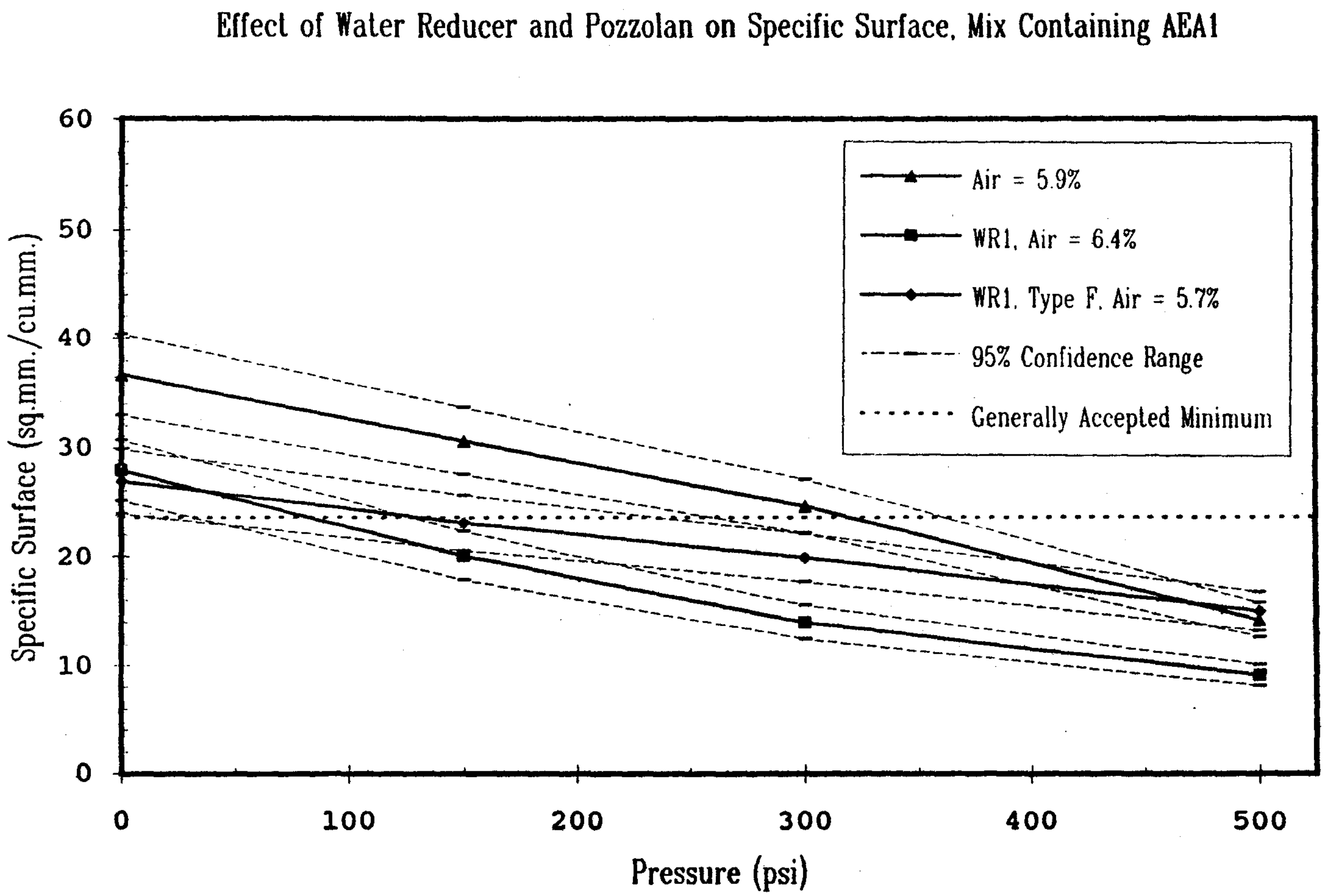

Figure 30. Influence of WR1 and Type F Fly Ash on the Effect of Pressurization on Specific Surface, Mix Containing AEA1.

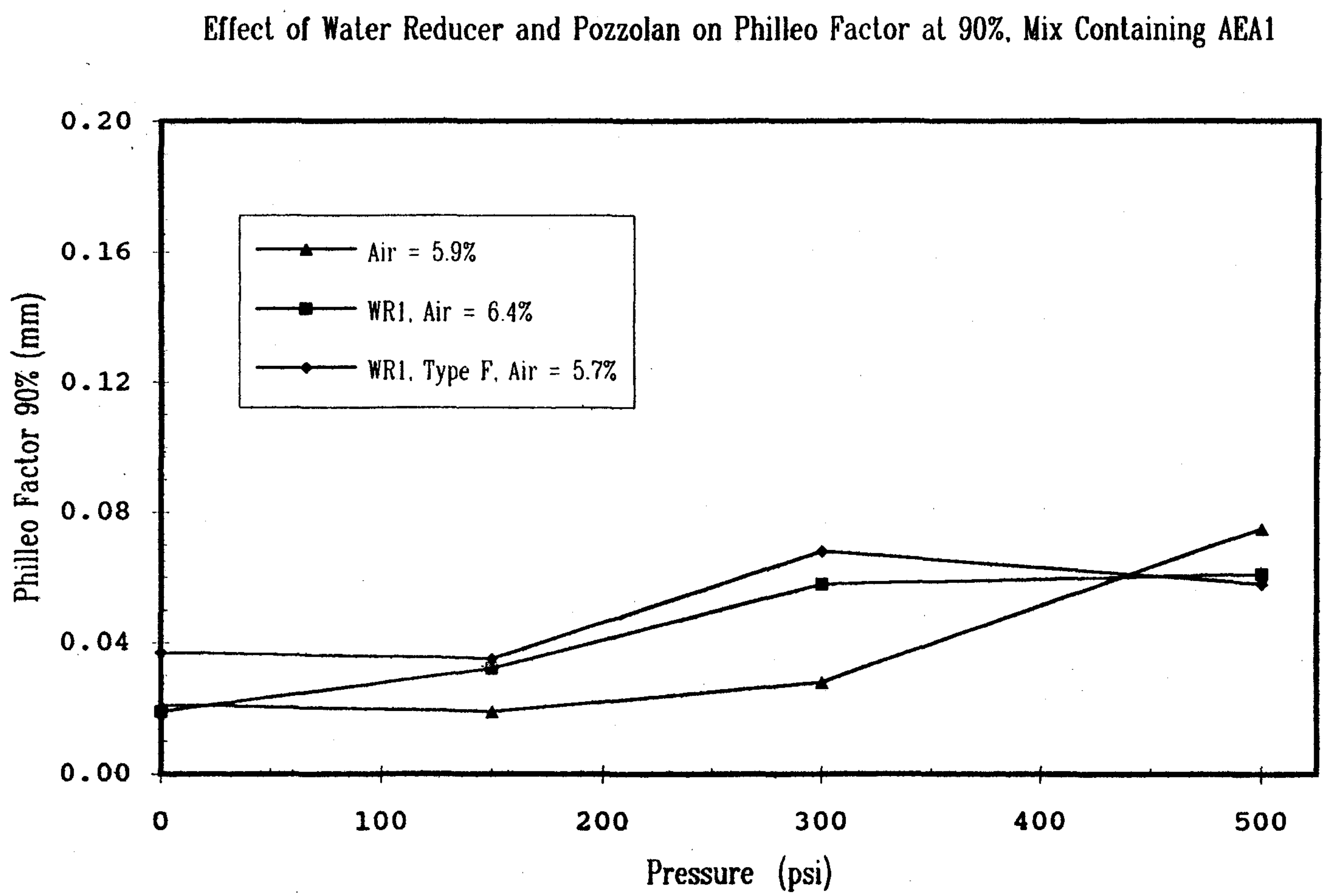

Figure 31. Influence of WR1 and Type F Fly Ash on the Effect of Pressurization on Philleo Factor at 90%, Mix Containing AEA1.

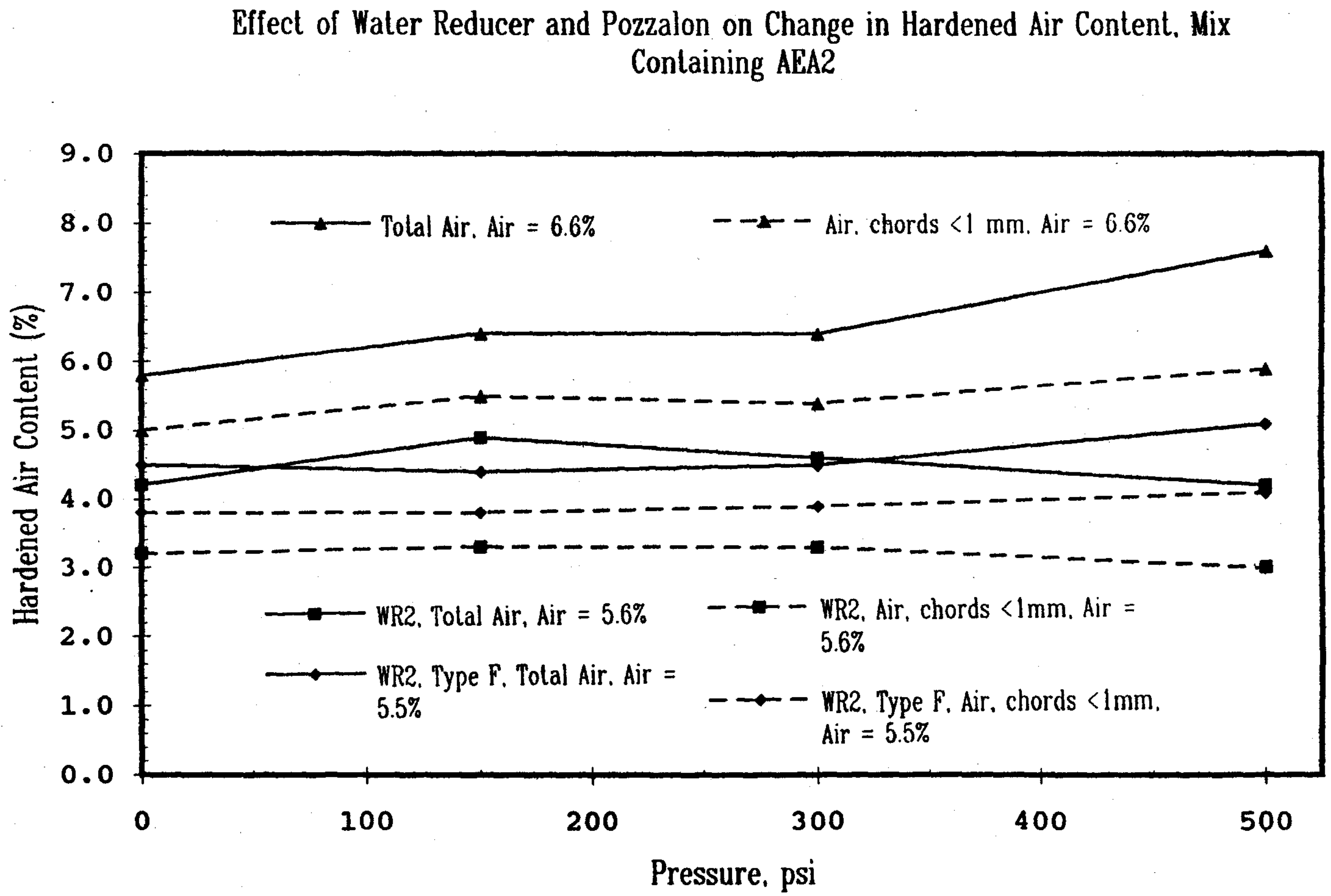

Figure 32. Influence of WR2 and Type F Fly Ash on the Effect of Pressurization on Hardened Air Content, Mix Containing AEA2.

Figures 33, 34, and 35, and the spacing factor, specific surface, and Philleo factor graphs, for AEA2 show trends that are very similar to the figures and graphs for AEA1. In both cases with the addition of water reducer (WR2) increased the mixes sensitivity to pressure while the addition of water reducer and fly ash decreased the sensitivity significantly.

A possible explanation for the water reducer effect is that water reducer makes it easier for air to dissolve into the mix water, and/or makes it easier for dissolved air near a void to diffuse away, thereby allowing more air to go into solution. This effect, however, was not related to workability, as all of the mixes had slumps between 3-1/2 in. and 4-1/2 in.

A possible explanation for the fly ash effect is that the increased amount of small particles (fly ash replaces a portion of the sand volume in the mix) reduces the diffusivity of the mix, preventing dissolved air from moving away from an air bubble, thereby preventing more air from dissolving.

EFFECT OF FINE AGGREGATE GRADATION

Two mixes, both containing AEA1 and no other admixtures, were designed and batched with sands of different gradations. A summary of the mixes is as follows:

AEA1, FM = 2.68, Air = 5.9%
AEA1, FM = 3.20, Air = 6.2%

The finer sand mix was the control, and was used in all other mixes.

The control mixes, the mixes with no pressure applied, showed differences in the critical air void parameters that were greater than had been expected from just the difference in air content. The coarse sand mix had values for $\overline{L}$ and α that were around 15 percent more desirable than the normal gradation mix. In addition, this initial difference continued

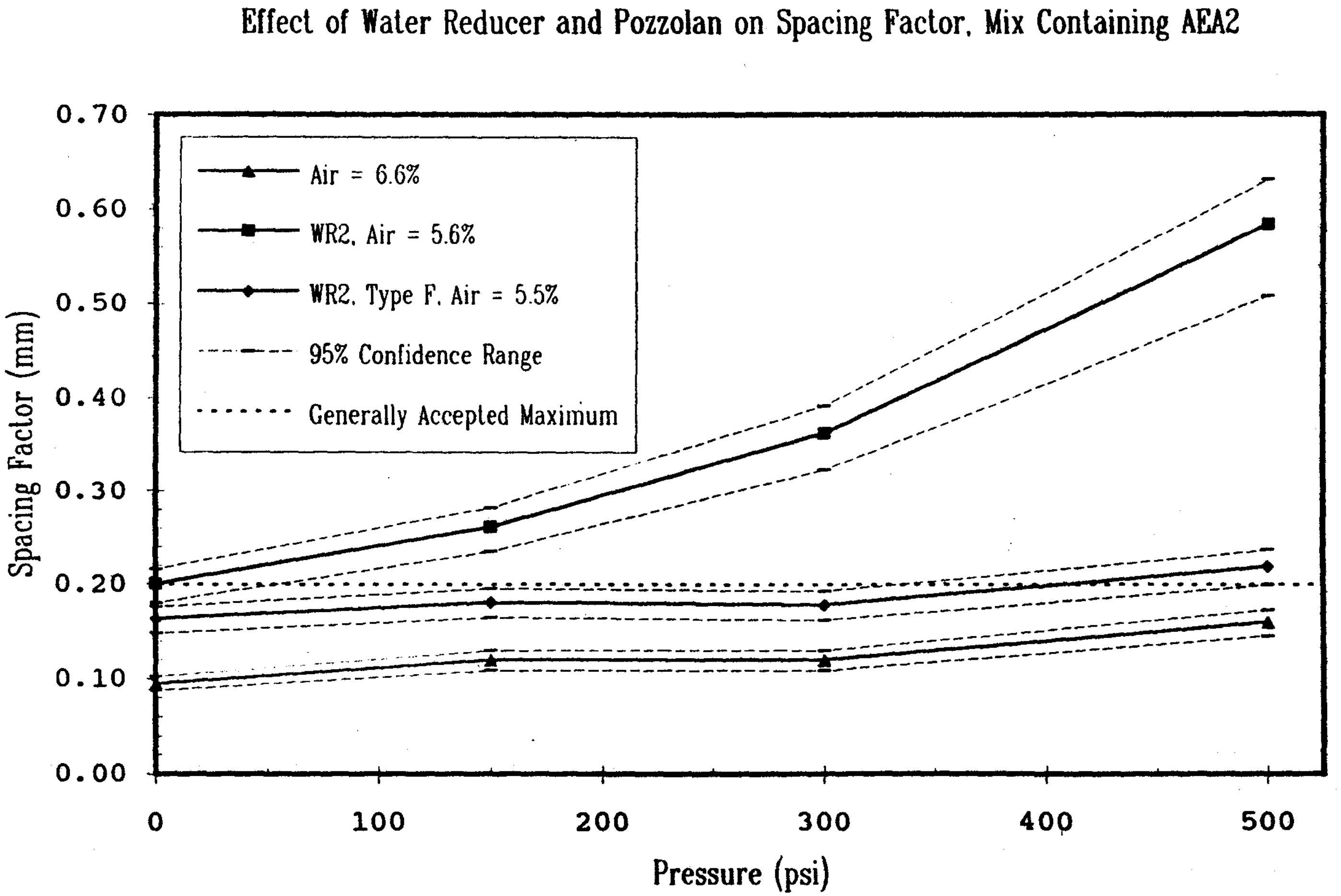

Figure 33. Influence of WR2 and Type F Fly Ash on the Effect of Pressurization on Spacing Factor, Mix Containing AEA2.

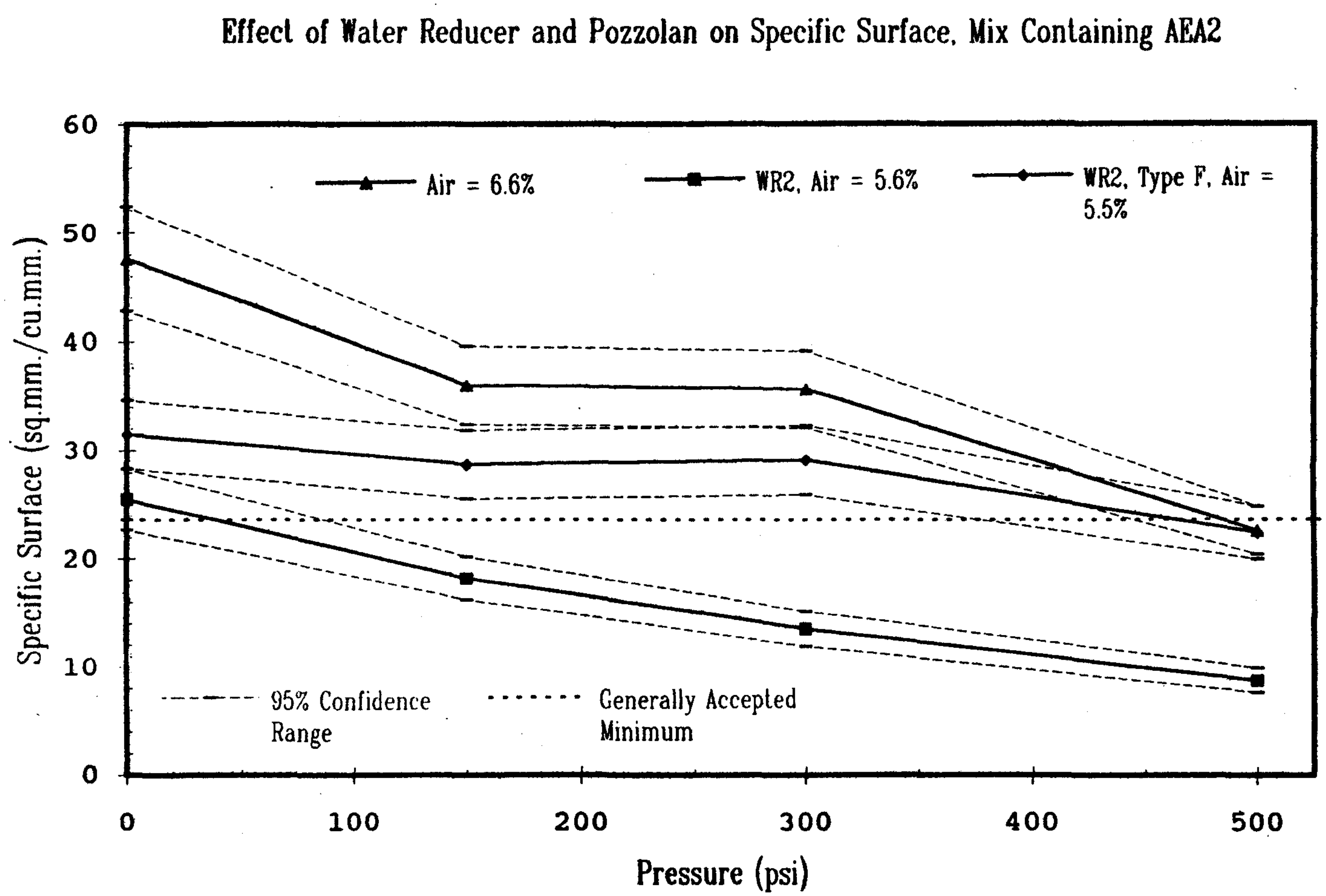

Figure 34. Influence of WR2 and Type F Fly Ash on the Effect of Pressurization on Specific Surface, Mix Containing AEA2.

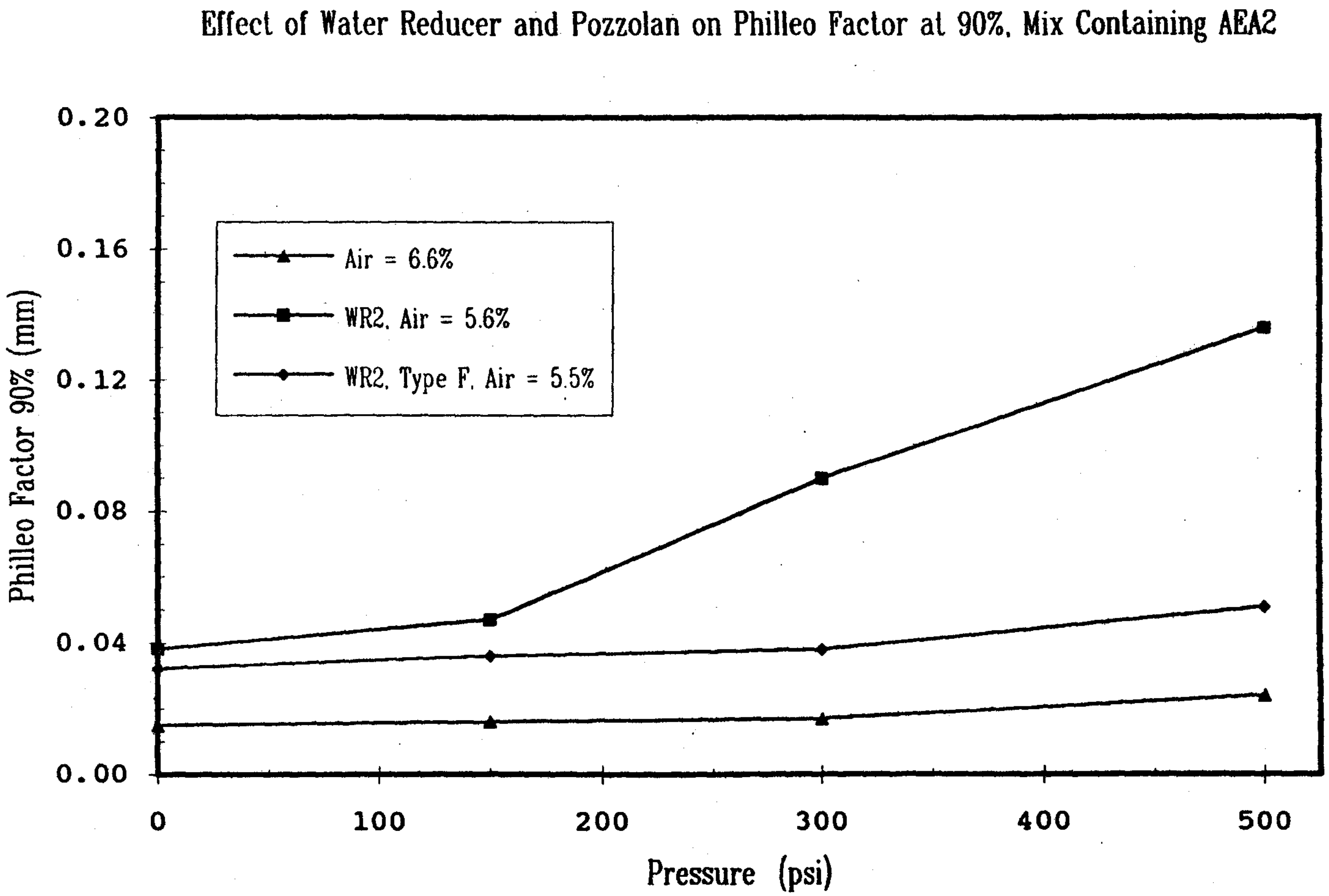

Figure 35. Influence of WR2 and Type F Fly Ash on the Effect of Pressurization on Philleo Factor at 90%, Mix Containing AEA2.

and even increased as applied pressure was increased. This comparison can be seen in Figures 36 through 39.

Total air content showed no significant trend again, as noted by Figure 36. Figure 37 shows that the spacing factor for the coarse sand mix experienced a lesser change in the spacing factor for all the pressures tested than the fine sand mix. Figure 38 shows that both sand gradations had the same trends for the specific surface. Philleo factor had trends that were similar to the spacing factor, as Figure 39 shows. The coarser sand mix had a slightly higher air content, and had been expected to be more stable. The actual difference in stability, however, was much greater than would be expected from just higher air content.

AIR VOID STABILITY

Because the terms stable and unstable have been repeatedly used to characterize many of the mixes that have been analyzed, a quantitative method for determining the stability of an air void distribution with respect to pressurization should be established. The spacing factor was chosen as the basis for this stability index as its trends were the most clearly defined and it was the air void parameter most often associated with resistance to freezing and thawing.

The method for calculating the stability index, graphically presented in Figure 40, is as follows:

1. Determine the area enclosed by the spacing factor graph (A1). The horizontal range is from 0 psi to 500 psi, while the vertical range is from the spacing factor at 0 psi to the spacing factor at 500 psi.
2. Normalize this area by A2, which has a vertical range from the spacing factor at 0 psi to a spacing factor at 500 psi of 1 mm. A2 is a value that was chosen to represent the spacing factor of non-air entrained concrete.

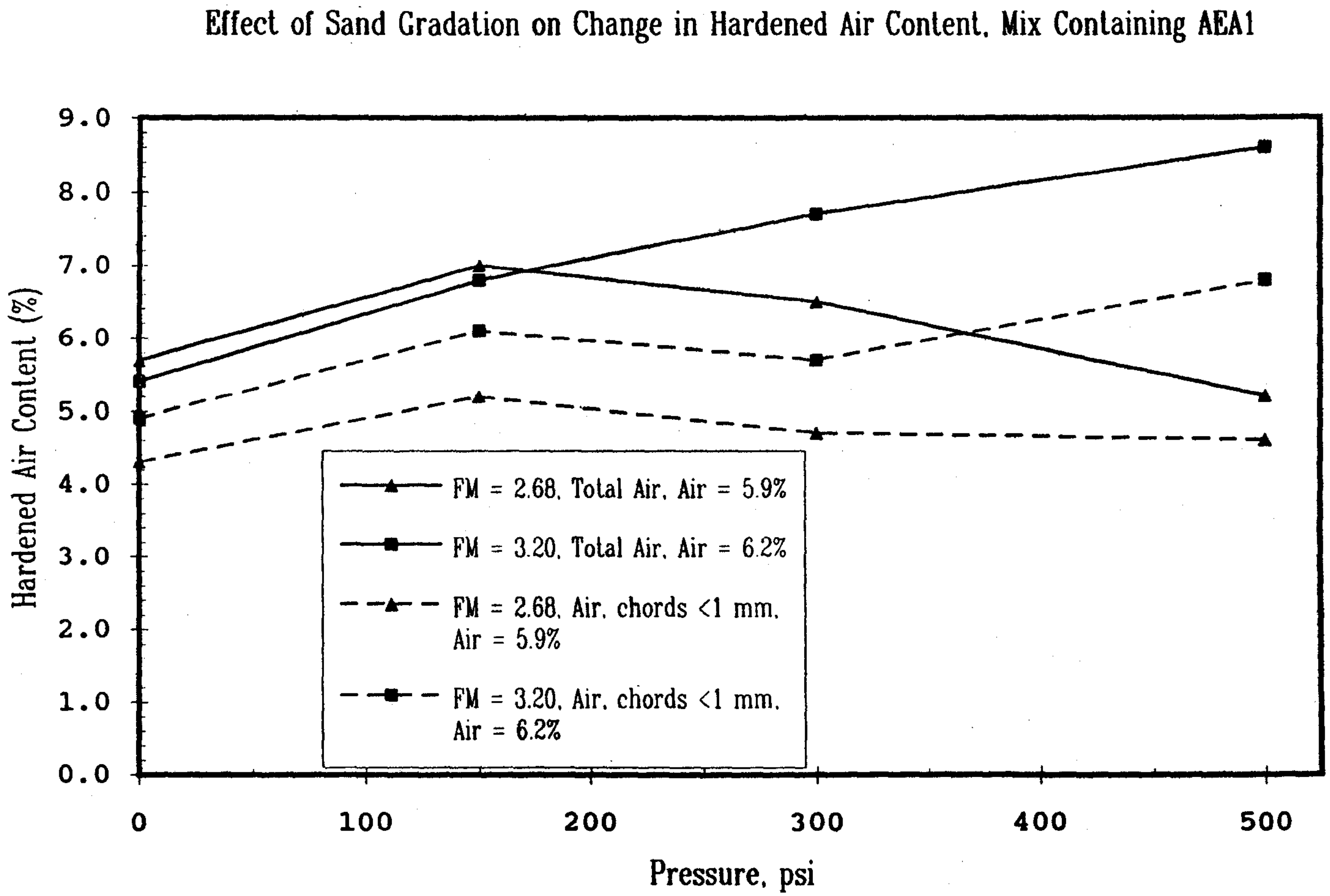

Figure 36. Influence of Fine Aggregate Gradation on the Effect of Pressurization on Hardened Air Content, Mix Containing AEA1.

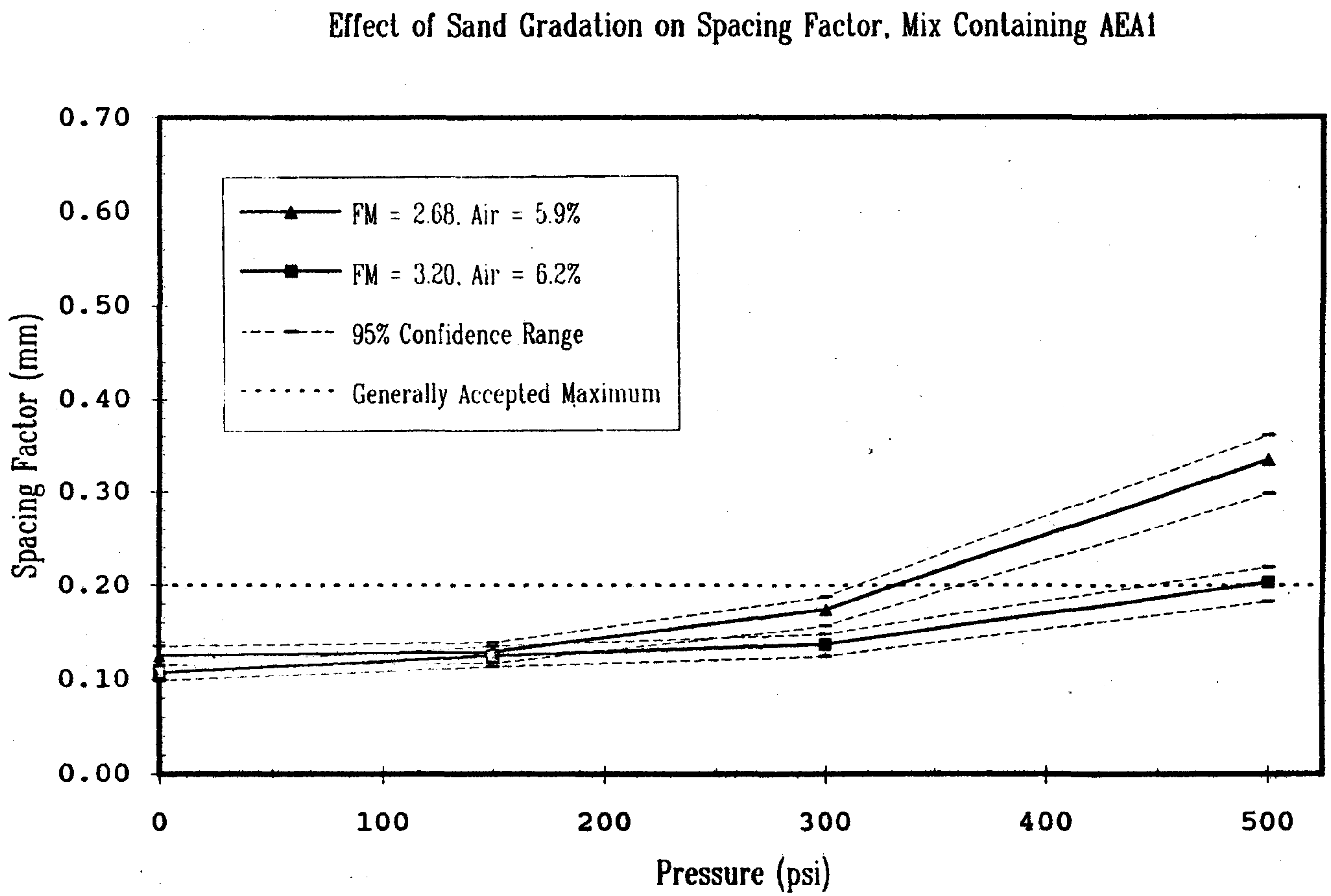

Figure 37. Influence of Fine Aggregate Gradation on the Effect of Pressurization on Spacing Factor, Mix Containing AEA1.

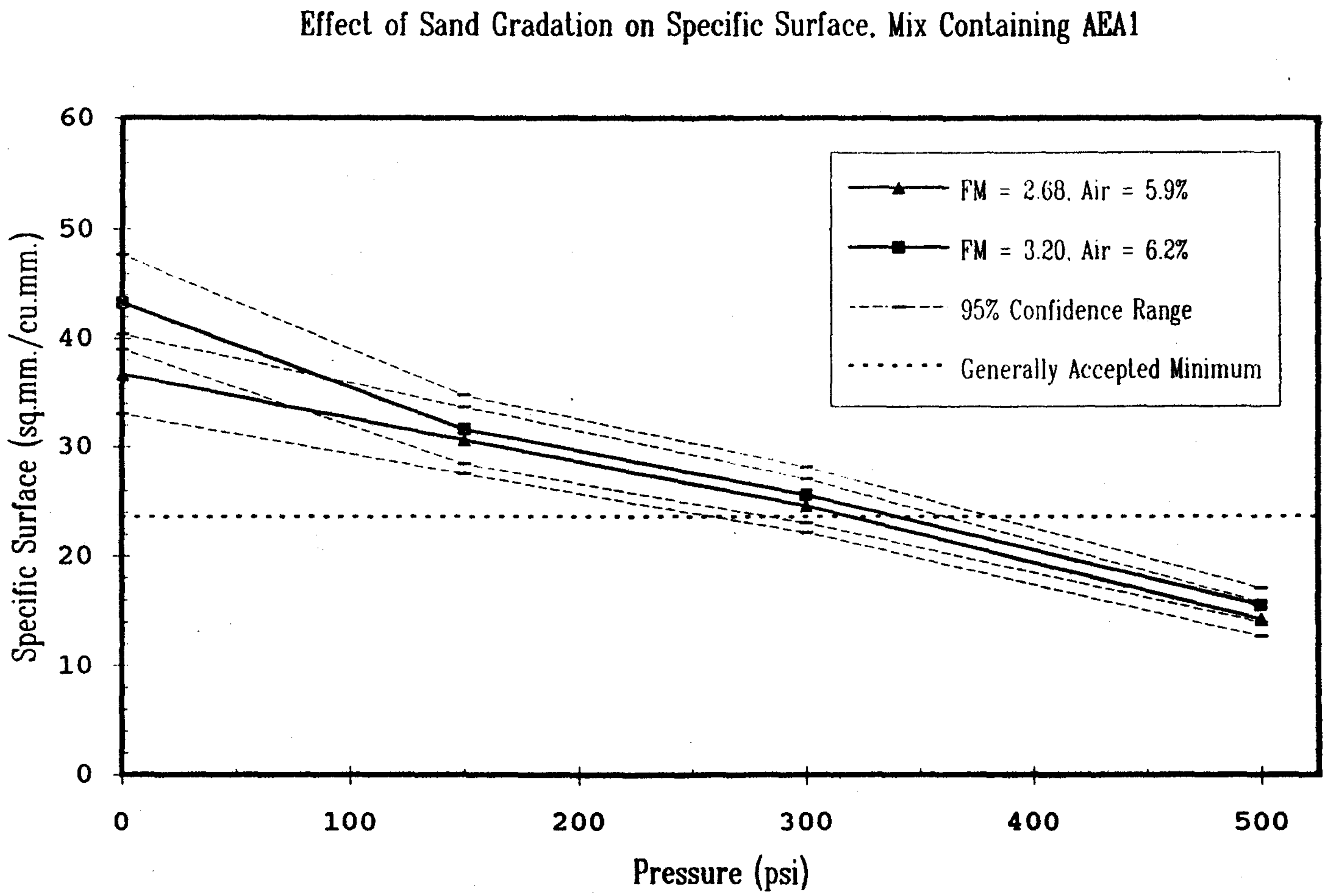

Figure 38. Influence of Fine Aggregate Gradation on the Effect of Pressurization on Specific Surface, Mix Containing AEA1.

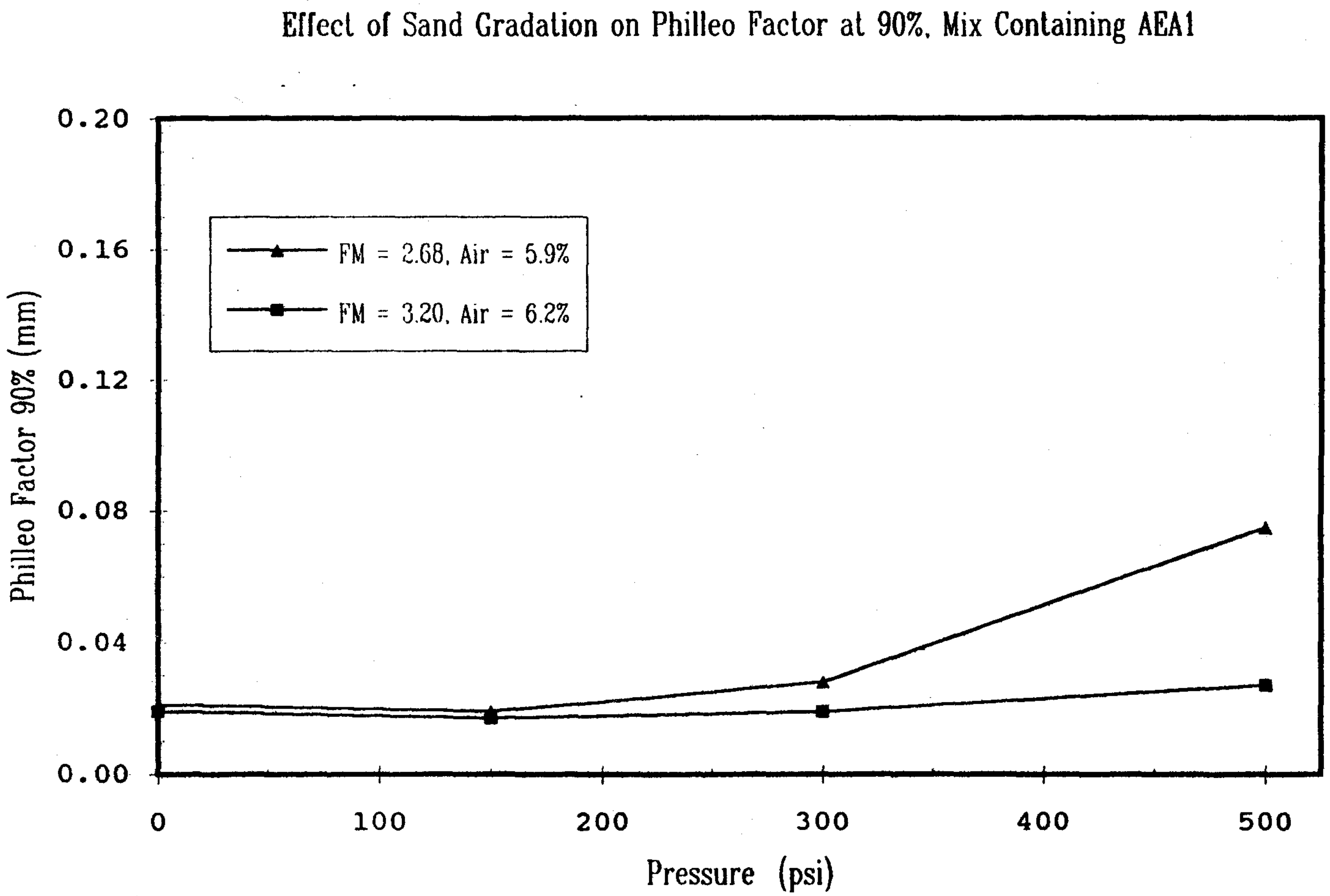

Figure 39. Influence of Fine Aggregate Gradation on the Effect of Pressurization on Philleo Factor at 90%, Mix Containing AEA1.

3. Perform the calculation shown in Figure 40, which gives a stability index as a percent, ranging from 0 to 100, with higher numbers representing a more stable mix.

A summary of the calculated stability indices for all of the mixes analyzed can be seen in Figures 41 and 42. Figure 41 shows that, for increasing air contents, both AEA1 and AEA2 had increasing stability indices, indicating that higher air contents made a PCC mix less sensitive to pressure changes.

Figure 42 is a bar graph showing the effect different types of admixtures, pozzolans, and sand gradations had on the stability index. As was noted earlier, the addition of water reducer, in either a mix containing AEA1 or AEA2, substantially increased the mix's sensitivity to pressurization. This effect, however, was all but eliminated when the water reducer was combined with Type F fly ash. This study also showed that, though many stability differences can be attributed to the initial air content, the actual air entraining agent may also have an effect on AEA3, appearing less stable under static pressure than the other two air entrainment types.

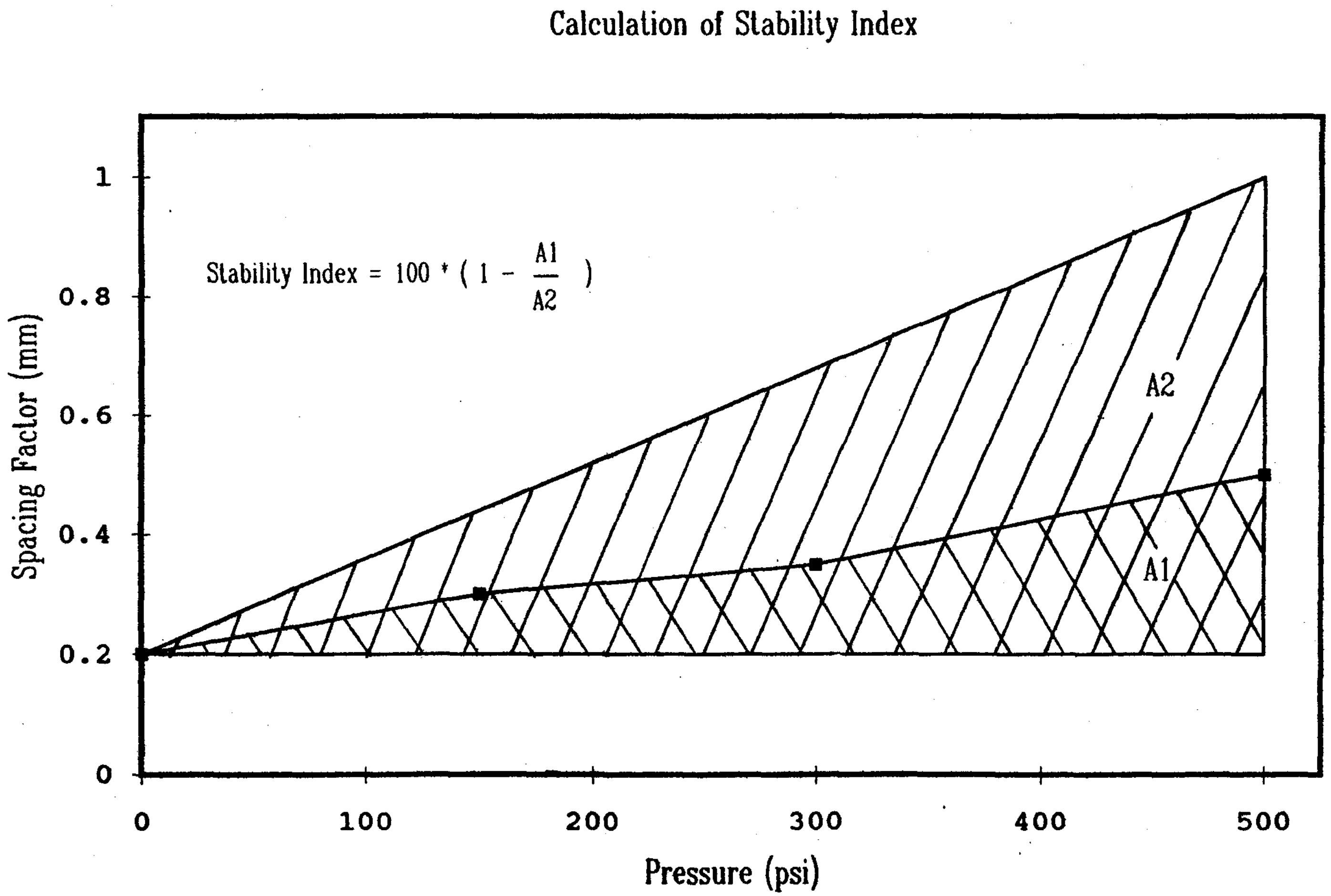

Figure 40. Calculation of Stability Index.

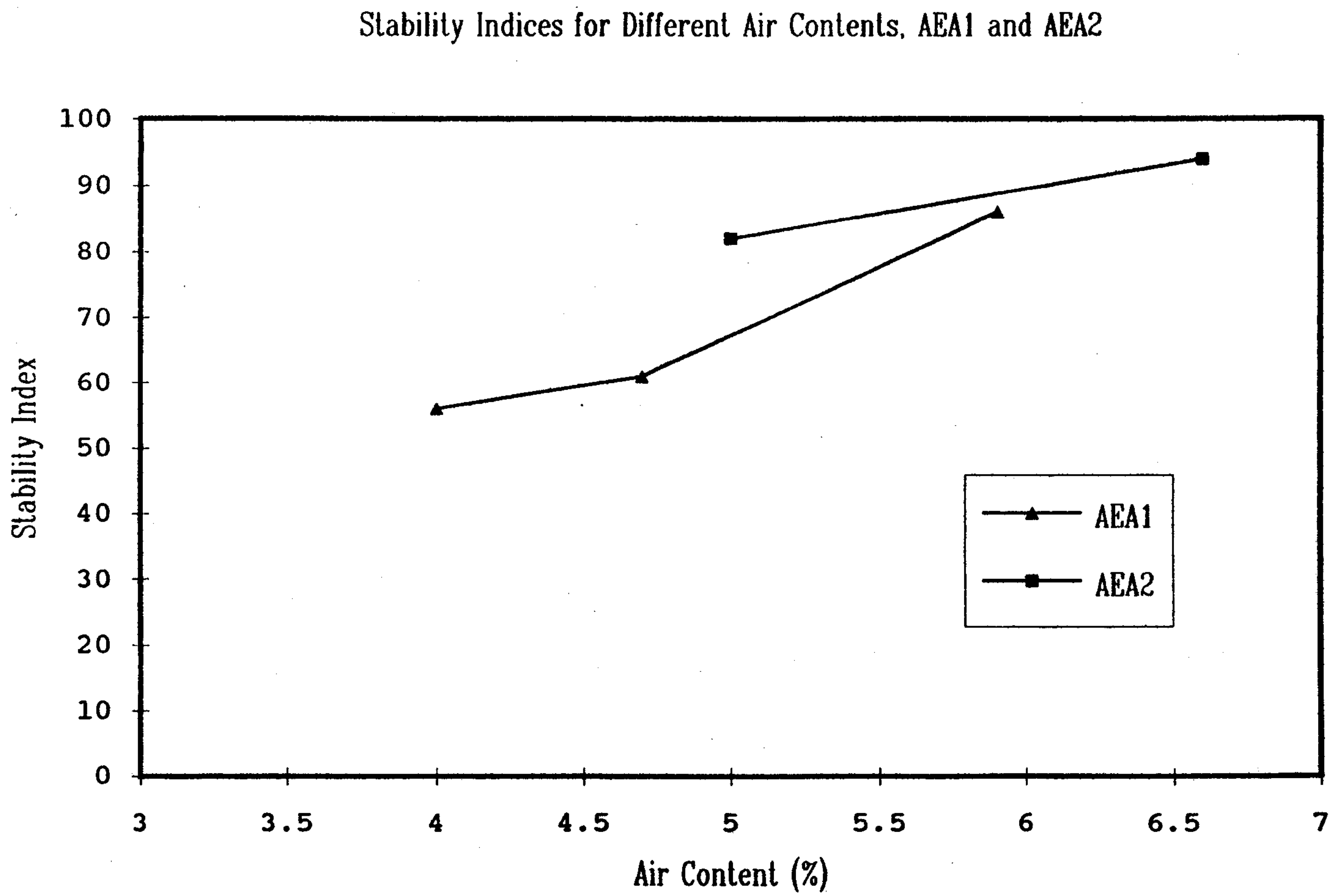

Figure 41. Comparison of Stability Indices for Mixes Containing AEA1 and AEA2, for Various Air Contents.

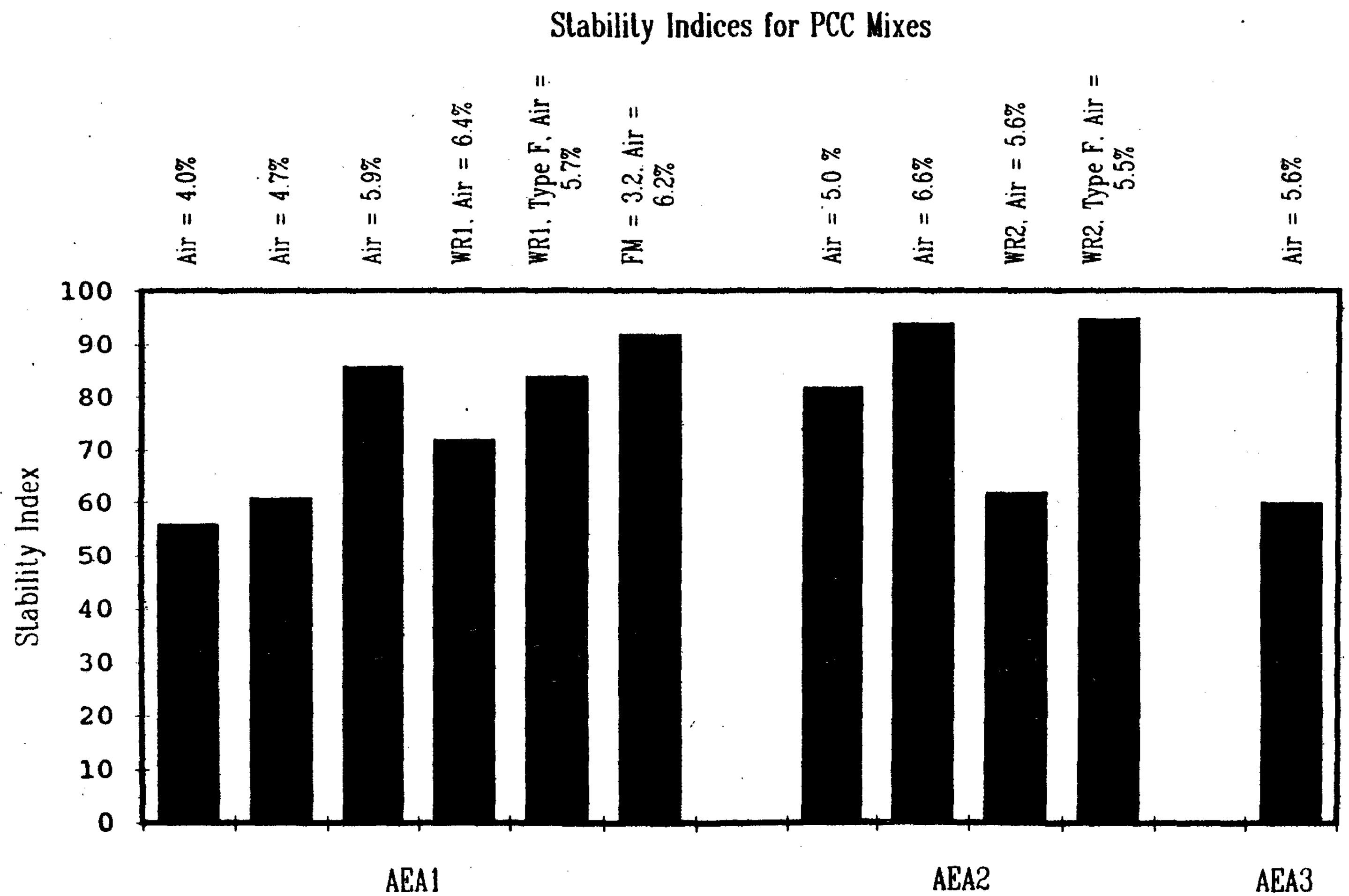

Figure 42. Influence of Air Content and Chemical and Mineral Admixtures on Stability Indices.

CHAPTER 6
FIELD STUDY

Previous work [3] had examined the magnitude of pressure that can be produced by pumping concrete. This work has shown the magnitudes of changes caused by pressures that can be expected in air void parameters for various admixture combinations. In an attempt to provide field validation of the lab results, a mix that was actually pumped* was examined to determine changes in air void parameters caused by pumping, as well as to determine if the pumping caused a change in resistance to freezing and thawing.

PROCEDURE

Equipment

The pump used for this study was a Schwing KVM 36 with articulated joints and a 1200 pump kit. This combination contained a 36 m long, 5 in. diameter steel pipe, with an 11 ft long, 4 in. diameter rubber hose at the end. The pump was aligned nearly vertical; the alignment had been previously suggested [14] to cause the greatest air loss. The discharge was a short distance from the pump hopper.

Mix Design

The PCC mix design used for the study met the WSDOT criteria for a 5000 psi design (Cadman Mix # 741783). The mix proportions per cubic yard were as follows:

Type II Cement	600 lb
Ash	100 lb
Coarse Aggregate	1768 lb

---

* Cadman, Inc. concrete supplier, Issaquah, WA, June 15, 1992. Field procedures and tests as well as specimen preparation were under the direction of Mr. Robert Dyer, Washington State Department of Transportation (WSDOT). All field information provided by Mr. Dyer.

Fine Aggregate	1189 lb
Water (maximum)	266 lb
AEA1	7.5 oz
Water Reducer	56 oz

The mix was dry batched at the plant, and the water was added on-site. This mix was expected to show good air void stability, based on the lab results for a mix with AEA1, water reducer, and fly ash, shown in Chapter 4.

Batching

A total of 9 yd^3 of concrete was mixed in two separate batches. In order to simulate the time it would take for the truck to arrive on-site after the concrete had been batched in the plant, the truck was driven around for a half an hour. This was also done to allow the concrete to "settle down." Upon returning, the pumping procedure was initiated.

The first 1/2 yd^3 was used to prime the pump. This portion was then wasted, as was the second 1/2 yd^3. The second cubic yard and third cubic yard were pumped at an approximate rate of 98 yd^3/hr, and specimens were taken from the third cubic yard. The specimens taken were as follows:

3 - 6" x 12" cylinders
6 - 3" x 4" x 16" beams

In addition, measurements of air content (by the pressure method), slump, and temperature were taken from the third cubic yard as well.

The fourth cubic yard was used for the collection of non-pumped specimens. The same number and type of specimens were taken for the non-pumped samples as were for the pumped samples. Also, air content, slump, and temperature readings were taken to compare to those of the pumped samples. These fresh concrete measurements are shown in Table 10.

Table 10. Summary of Fresh PCC Measurements

	Before Pumping	After Pumping
Temperature (°F)	72	74
Average Air Content (%)	5.15	5.4
Average Slump (in.)	2 - 3/4	2 - 3/8

These numbers initially indicated that, noting the small change in both air content and slump, the fly ash mix was behaving in a stable manner, as expected. The slight increase in air content may have been due to a shift in the air void distribution from smaller to larger voids which were more easily detected by the pressure meter (Chapter 2). The increase may have also been due to air coming out of solution after the air chamber had been consolidated, thereby increasing the measured air content.

The tests were completed at this point, and the remaining 5 yd^3 of concrete were wasted. Once finished, the specimens were then covered with plastic and left undisturbed for two days. They were then moved to the University of Washington and placed in a lime water bath for the rest of the 28-day curing period.

RESULTS AND ANALYSIS

Maximum Pressure Calculation

In 1991, Dyer [3] presented an idealized method for determining the pressure experienced by a PCC mix while being pumped. Working on the principle that fresh concrete behaves as a Bingham fluid, he devised a method using the energy equation along with mix parameters (e.g., slump), pump boom configuration, and pipe data (material, length, and diameter) to calculate the pressure history of a plug of concrete moving along the pipe boom. From the data provided by the field study and utilizing this method, the maximum pressure experienced by the concrete was determined to be approximately 250 psi. This magnitude of pressure, as noted from the lab study, was not expected to substantially change the air void distribution, as mixes containing fly ash proved to be the most stable tested.

Freeze-Thaw Testing

Five of the six beams for both the pumped and non-pumped concrete mixes were tested for resistance to freezing and thawing in accordance with ASTM C 666. The testing period lasted around 350 cycles of freezing and thawing. Figures 43 and 44 show the change in relative dynamic modulus (RDM) during the testing period for the unpumped and pumped mixes. The figures show the individual readings for each of the five samples from either mix, along with a best fit line indicating the average change in the RDM. Both figures show that, after 300 cycles, almost no change in the RDM occurred. This resulted in very high durability factors, as noted by Table 11. These results suggest that, for mixes determined to have high stability (i.e. containing fly ash), the effects of pumping were not severe enough to affect the mixes' resistance to freezing and thawing.

Table 11. Summary of Durability Factors Determined by ASTM C 666

	Durability Factor
Unpumped Concrete	101
Pumped Concrete	100

Linear Traverse

The remaining beam from each group was sliced and prepared for linear traverse, a procedure described in Chapter 3. The results of the linear traverse procedure are shown in Table 12.

From these results, it can be seen that the air void distribution did experience a small shift in modal chord length, as noticed in the lab study. The shift did not, however, have a strong effect on either α or $\overline{L}$, which was understandable because these parameters

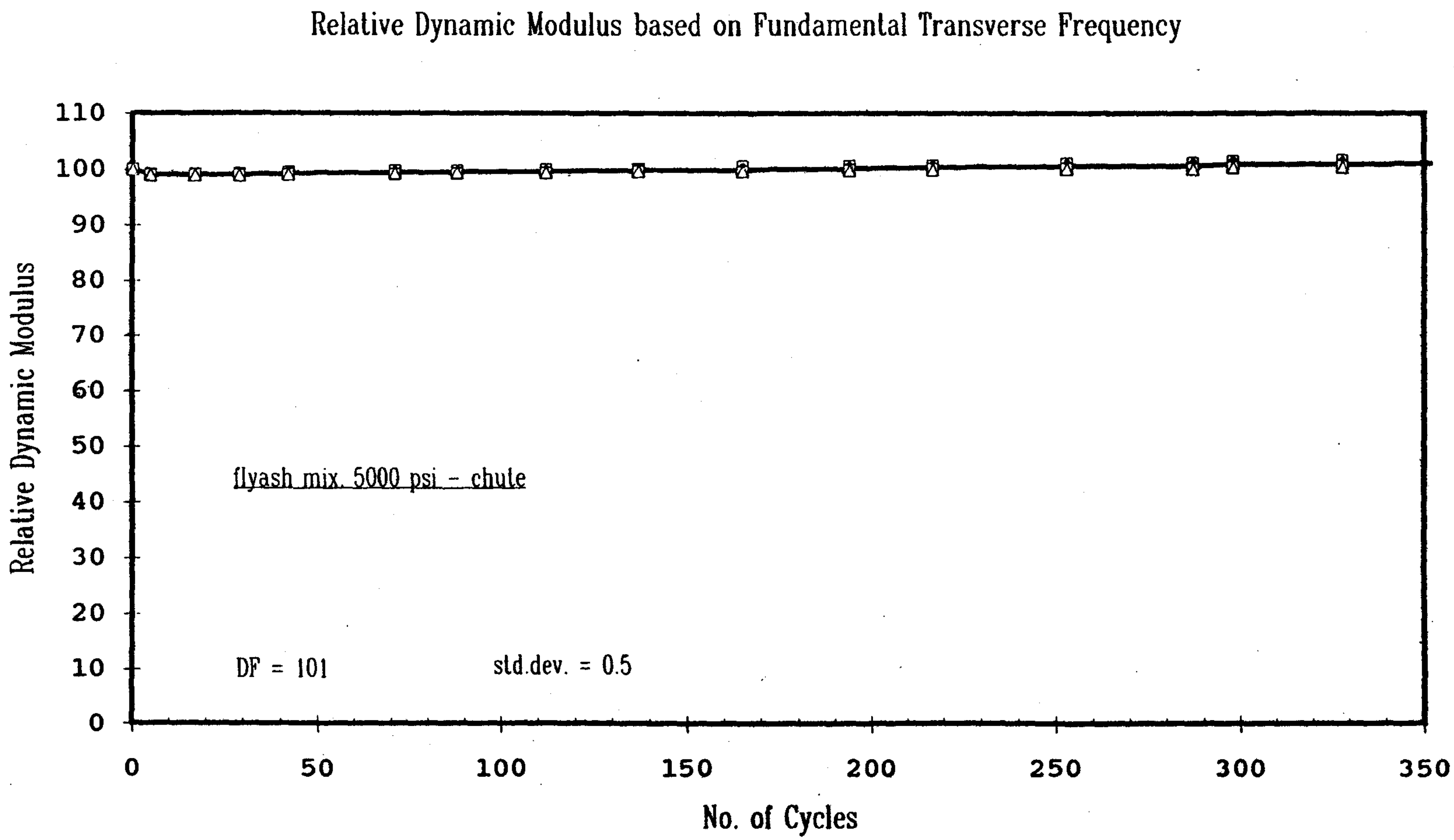

Figure 43. Relative Dynamic Modulus vs. Cycles of Freezing and Thawing for Non-Pumped Specimens.

Relative Dynamic Modulus based on Fundamental Transverse Frequency

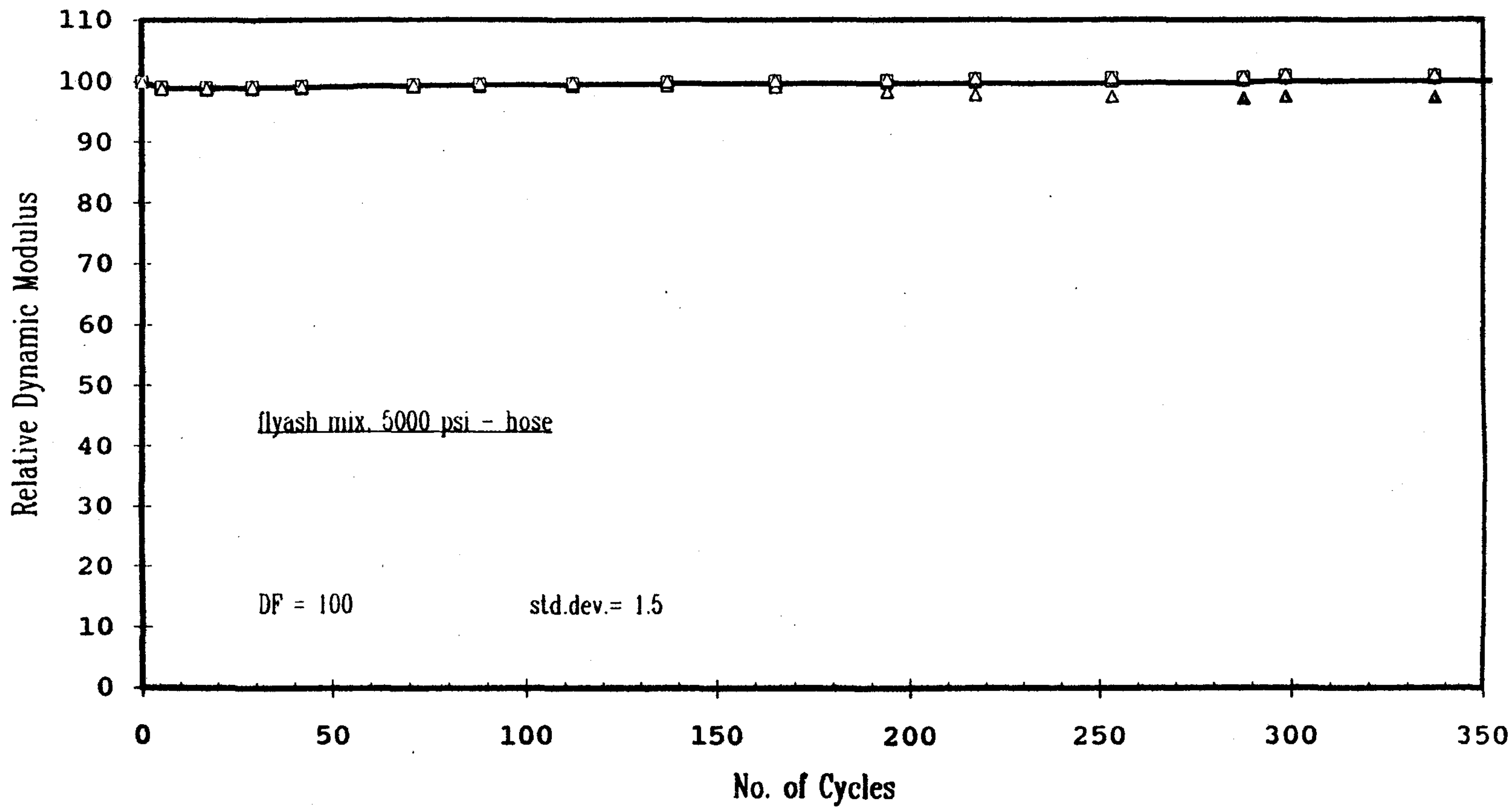

Figure 44. Relative Dynamic Modulus vs. Cycles of Freezing and Thawing for Pumped Specimens.

were not directly related to the air void distribution and, as such, may have not responded to subtle changes in the void system. The Philleo factor, however, did show an increase similar in magnitude to the modal chord length, because of its sensitivity to the air void distribution.

Table 12. Summary of Linear Traverse Results, Field Study

	Before Pumping	After Pumping
Hard Air Content— total air (%)	4.3 (3.3 - 4.3)*	4.0 (3.0 - 4.0)*
Hard Air Content— chords < 1 mm (%)	3.5**	3.7**
Specific Surface (α)— total air (mm)	32 (28 - 35)*	35 (31 - 38)*
Spacing Factor ($\overline{L}$)— total air (mm)	0.17 (0.15 - 0.18)*	0.16 (0.14 - 0.17)*
Philleo Factor ($\overline{P}_{90}$)— chords < 1 mm (mm)	0.029**	0.034**
Modal Chord Length— chords < 1 mm (microns)	38**	49**

* Numbers in parentheses indicate a 95% confidence range, Pleau and Pigeon [13].
** Pleau and Pigeon [13] did not present quantification for the errors associated with these parameters.

The laboratory study of the effect of pressurization on the air void system in a PCC mix in Chapter 4 found that the addition of fly ash substantially reduced the sensitivity of the mix to pressurization and that for lower pressures (0 psi to 300 psi), very little change in the critical void parameters was noticed. Therefore, it is reasonable to expect that, in a field setting, a mix containing fly ash will not show substantial change in air void parameters as a result of pressurization. The change in modal chord length and $\overline{P}_{90}$, however, suggested that the pressure-dissolution mechanism is valid and that, under higher pressures, a larger change in the void system, and critical parameters, should be expected.

The field mix that was actually pumped showed no significant change in air content, $\overline{L}$, and α, as expected. Values for $\overline{L}$ and α were better than the accepted maximum and minimum values of 0.2 mm and 23.6 mm^2/mm^3, respectively, for good resistance to freezing and thawing. $\overline{P}_{90}$, as well, was below the recommended value of 0.037 mm, as suggested in Chapter 2.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This study looked at the effect of pressurization on the air void system in portland cement concrete. By using different levels and durations of pressure, mixes of different air contents, mixes that contained different types and amounts of air entraining agents and water reducers, and mixes that included fly ash, the pressure sensitivity of the critical parameters of the air void system $\overline{L}$, α, and $\overline{P}_{90}$) was examined. One may conclude that the pressure stability of the air void system was altered by these different types of mixes. This study also attempted to correlate these laboratory findings with data from a field study that involved the comparison of two sets of specimens, one set prepared after the concrete was pumped, and one set prepared from an unpumped control. Some general conclusions can be drawn from this study of various PCC mixes:

1. The shift in air void distribution to larger voids and the worsening of the critical air void parameters with the application of increasing levels of static pressure, identified by Dyer [3] for one specific mix design, was upheld among the several mixes tested that contained various admixtures and pozzolans.

   At higher pressures (300 psi to 500 psi), the effect was very noticeable for the mixes studied. At lower pressures (0 psi to 150 psi) this effect was usually not distinctive.

2. The duration of the static pressure on fresh PCC contributed to the shift in the air void distribution and worsening of the associated parameters. However, this effect is not as large as that of increasing pressure. This effect was also noticed by Dyer [3] and was consistent among the different mixes tested.

An air void stability index, using change in $\overline{L}$ with increasing pressure as an indicator of stability, was developed. Using this concept, the following specific conclusions regarding factors affecting air void stability were developed:

1. Increasing the total air content of a concrete mix increased the mix's stability to pressurization.
2. Mixes containing water reducers had air void systems that were less stable when subjected to pressurization than either those without water reducer or those with both water reducer and fly ash.
3. The addition of fly ash to a mix substantially increased the stability of the air void matrix, when compared to a similar mix without fly ash.

An implication of the pressure-dissolution mechanism is that the time-dependance of the dissolved air coming out of solution can have an effect on the measured air in fresh concrete. Consolidating the concrete in the air meter soon after pumping, before the air has come completely out of solution, could result in an increase in measured air content. (The air would come out of solution after consolidation, but before the air content test was completed.) Delaying consolidation of the concrete in the air meter until after the air has come out of solution, however, would allow the removal of the larger voids by the consolidation process, resulting in a lower measured air content. Thus, the measured air content in the field would be more dependent upon the timing of the air content test for pumped concrete than for non-pumped concrete.

This study also examined the effect of different air entraining agents on the stability of the air void system; initial results suggest that differences may exist. A greater number of tests at different air contents are needed before final conclusions can be drawn. In addition, the pumped field mix showed the expected shift in distribution and the high stability that was expected of a mix with fly ash. However, a more precise pumping pressure history is needed before one can try to closely correlate lab pressurization to field pumping.

RECOMMENDATIONS

The following recommendations concerning concrete pumping are offered:

1. Mixes pumped at high rates and/or pressures which are to be exposed to cycles of freezing and thawing should be those that have been shown to have more stable air void systems. Mixes with higher air contents (over 6 percent) and mixes that contain fly ash have been shown to have higher stability than mixes which have low air contents and/or do not contain fly ash.
2. Pumping mixes that have been shown to have lower stability should be avoided, or limited to pumping rates not likely to subject PCC to pressures in excess of 150 psi. Mixes with low air contents and mixes that contain water reducer and no pozzolanic material have appeared to be the least stable.
3. Further study is necessary for concrete with different types of air entraining agents and/or other admixture combinations. Research will help to determine how entrainment type and/or other admixtures affect the stability of the air void system.
4. Further study is necessary to correlate lab and field data. Actual pumping pressure histories need to be collected to check the validity of the pipe flow equations developed by Dyer [3]. Duplication of these pressure histories in the lab will help solidify the comparison.
5. Further study is needed to discover the significance of time of consolidation after pumping on measured air content. This effect should be examined by the following method: 1) consolidating an air content specimen as soon as a

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