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16. Abstract


Pumping of concrete can be an economical and versatile method of placement. However, the mix design process of a pumpable concrete should account for factors related to pumping operations. Various difficulties may be experienced at the construction site, such as difficulty in pumping, blockages, air loss, and changes in the air void system of the concrete. These problems are addressed on a fundamental level to provide a basis for construction guidelines to avoid or minimize such problems during pumping operations.

The air entraining mechanism and the instability of the air void system in the fresh concrete is detailed. The various factors such as resistance to flow, flow velocity of concrete, and pressure on concrete are examined in terms of workability, pumpability and the air loss mechanism. The mechanical and pressure aspects of air loss and changes in the air void system are discussed in detail.

Factorial designs are used to formulate an empirically based prediction model for air loss based on the factors, such as, Coarse Aggregate Factor (CAF), Intermediate Aggregate (IA), type of Air Entraining Admixture (surface tension), and the pumping boom angle. The effect of surface texture and shape of the aggregate in terms of workability and pumpability is examined. Linear traverse results are analyzed to study the effect of pumping on the air void characteristics.

Optimized mix design concepts lead to reduced flow resistance, reduced pumping pressures by improving workability characteristics, avoid or minimize pumping difficulties and improve construction productivity.


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# EXAMINATION OF AIR ENTRAINMENT STABILITY FACTORS OF PUMPED CONCRETE

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## IMPLEMENTATION STATEMENT

This report summarizes the findings pertaining to the effects of various factors on the pumping of air-entrained Portland Cement Concrete and the circumstances surrounding the loss of air that can occur during the pumping of fresh concrete. The mechanism of entraining concrete with air is presented to focus on the instability of the air bubbles while concrete is in a fresh state in terms of the effect of the pumping operation and the air bubble system. Various laboratory and field experiments conducted by others are examined and considered in the development of an approach to address pumping and air entrainment difficulties in a broader perspective.

The most common factors that affect the air loss are identified as:

1. Slump of the concrete (water to cement ratio),
2. Maximum pressure on the concrete due to pumping,
3. Coarse Aggregate Factor (CAF),
4. Use of Intermediate Aggregate (IA),
5. Type of Air Entraining Admixture (AEA),
6. The shape and texture of the aggregate,
7. Workability of the concrete.

Minor factors include the boom angle and concrete placing and finishing operations (vibration, screeding, etc.).

A factorial design was used to examine the effect of CAF, IA, type of AEA (in terms of surface tension), and the boom angle. The results of the experiment were analyzed to formulate an empirically based prediction model for air loss. The linear traverse method was used to analyze the hardened concrete samples to supplement the pressure method results and also to consider various air void characteristics.

Specific guidelines are provided to minimize air loss and change in the air void system of pumped concrete. Optimized mix design air loss is suggested. Potential factor which cause pumping problems are addressed and recommendations are made to avoid such problems.

Implementation of the results and recommendations of this study will help the State improve concrete pumping techniques and reduce the incidence of pumping difficulties during construction operations. Implementation of the results can reduce the loss of air and the detrimental change in the air void system of the concrete and improve the quality of the concrete in terms of durability and strength.

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# CHAPTER I
# INTRODUCTION AND STUDY OBJECTIVES

Concrete pumping is commonly accepted as the primary method of transporting concrete to final placement. Conventional methods of placement such as crane and skip, hoists and conveyors, may not match the advantages of pumping. Placement by concrete pumps is typically accomplished more quickly, at greater distances and more efficiently than other methods. A concrete pump provides flexible solutions to work around obstacles and reduces costs with overall construction time savings. Pumps can maintain continuous flow rates when placing at different heights, something not possible using other methods. The pipeline serves to protect the flowing concrete and maintain quality in adverse conditions, irrespective of the transported length. The use of concrete pumps is increasing throughout the world since concrete pumps have become more functional. However, the advantages of concrete pumping can be realized only if the fresh concrete has the requisite workability for pumping [1].

Concrete placed by pumping is conveyed through hoses (either rigid or flexible) and released directly into construction forms. A steady supply of pumpable concrete must be readily available for satisfactory pumping. Pumpable concrete use dictates good quality control, i.e., uniform aggregate grading, (along the pump line) uniform batches and through mixing. With current equipment, pumping rates can vary from 10 to 90 cubic yard (cu yd) per hour. Pumping ranges vary horizontally from 300 to 1000 feet, and vertically 100 to 300 feet [2]. Maximum capabilities of modern pumps are: vertical reach of over 1,400 feet, pressures of over 3,300 pounds per square inch and volumes of over 170 cu yd/per hour [3].

Although the purposes and background will be presented later in this report, the objectives of this study are presented now for the convenience of the reader:

a) To indicate the affect of aggregate type and air entraining admixture type on air content of concrete when placed by pumping and to suggest best type of aggregate and air entraining admixture.

b) To detail the pumping effects on air void system from delivery to placement) in terms of aggregate effects, type of air entraining admixture, and mix design requirements for pumpable concrete.

c) To indicate with respect to quality control when, where, and how air content testing should be conducted for pumped concrete.

**Air Entrainment in Concrete**

Air entrainment is the process of incorporating small air bubbles into concrete within the matrix that binds the aggregate together in the hardened concrete. Consequently, it is recognized that the air bubbles are dispersed throughout the hardened cement paste. The inclusion of air in concrete is accomplished by the use of an air entraining agent (AEA). If a component of concrete (such as an AEA) is added to concrete during the mixing process, it is referred to as an admixture; if interground with cement, it is referred to as an additive [4]. The use of air-entraining admixtures in concrete has greatly increased the durability of concrete pavements and other structures and has improved workability characteristics. However, the function of entrained air in concrete is that of protecting the paste against freeze-thaw damage. The aggregate is unprotected except to the degree that protecting the paste protects the aggregate. Therefore, apart from designing and producing air-entrained concrete, selecting durable aggregates is also critical to long term performance [5].

The actual mechanisms involved in the protection of concrete due to air entrainment is explained by two theories.

a) Hydraulic Pressure
b) Gel Water Diffusion (osmosis)

Hydraulic Pressure: Early attempts to understand the failure of concrete by freezing centered on the expansion of water when it solidifies (a volume increase of approximately nine percent). The calculated pressure to prevent freezing is about 1800 psi per degree celsius. Therefore, concrete, with a tensile strength of about 1000 psi, will fail within a fraction of a degree of subcooling if forced to restrain the pressure generated by the expansion. This thinking lead to the concept of a critical degree of saturation for porous materials in freezing. It therefore follows that, if the pore space is less than ninety percent saturated with water, damage due to freezing should not occur. Enough free space will exist to accommodate the volume increase that occurs on freezing creating no generation of disruptive pressure.

The hydraulic pressure hypothesis was developed to explain this phenomenon. Water in a critically saturated pore that is subjected to freezing may force some unfrozen water out into and through the as yet unfrozen pore system of the cement paste. The flow rate of the water is inversely proportional to the length of the flow path and directly proportional to the permeability of the porous medium and the flow pressure. Excess pressure generated in too long of a flow path will exceed the strength of the material, and may result in cracking.

Considering reasonable values of flow (freezing) rate and permeability, the critical length, which cannot be exceeded without disruptive pressure being generated, is of the order of 0.008 inches. This small measure is the result of the extremely low permeability of the cement paste, on the order of $1.55 \times 10^{-17}$ $in^2/sec$. The purpose of the entrained air is to provide a great many small, closely spaced, voids for the excess water when freezing occurs. If the voids in the paste are no further than twice the critical distance from another void, disruptive pressures cannot be generated, and the paste durability increases in freezing and thawing [4].

<u>Gel Water Diffusion</u>: Powers and Helmuth [7] later proposed a theory relating to gel water diffusion. Based on observations of cement paste dimensional changes over time, (the temperature being held at some subfreezing level, it was observed that saturated, non air entrained pastes continued to expand. Air entrained pastes however, did not expand

but rather contracted during cooling at an even greater rate than could be accounted for by the coefficient of thermal contraction.

They postulated that the gel, entrained with air bubbles, protected it against freezing distress by presenting an alternative path to the unfrozen water. The unfrozen water has two paths: either it can travel to an air bubble or to an ice filled pore. If the unfrozen water travels to an ice filled pore, pressure in the pore increases and hence expansion follows. If the unfrozen water travels to an air bubble there might be a small amount of ice which is not under pressure, and the unfrozen water can be accommodated in the air bubble and not create excess pressure. The thermodynamic impulse influences the water to move to the air bubble. If no pressure increase occurs then no expansive stresses are induced. Therefore, the air voids protect the paste against disruption from both the gel water diffusion mechanism and the hydraulic pressure mechanism [4]. The factors affecting frost resistance are shown in the Figure 1 [8].

**Typical Percentage of Air Entrainment**

Initial experience with air entrained concrete indicated that approximately 3 percent air was required to provide adequate freeze-thaw resistance. However, greater amounts of air entrainment were used to ensure that a 3 percent minimum was achieved. Typically, air contents on the order of 4½ percent were used but over the years a 6 percent maximum has been used to maintain sufficient strength levels. Some instances have occurred where concrete mixtures have required greater percentages of air than what others have needed. These particular mixes may have had a small sized coarse aggregate or a fine cement grind such as may occur with a Type III cement. Experience has also indicated that variability of the level of air content causes the volume of entrained air to vary from point to point. Consequently, material engineers have come to understand in both laboratory and field mixtures that at a constant dosage rate the air content is subject to variations due to various factors beyond their control [5].

At a constant dosage rate of air entraining agent, it has been noted that the air content varied if the cement content, the consistency of the

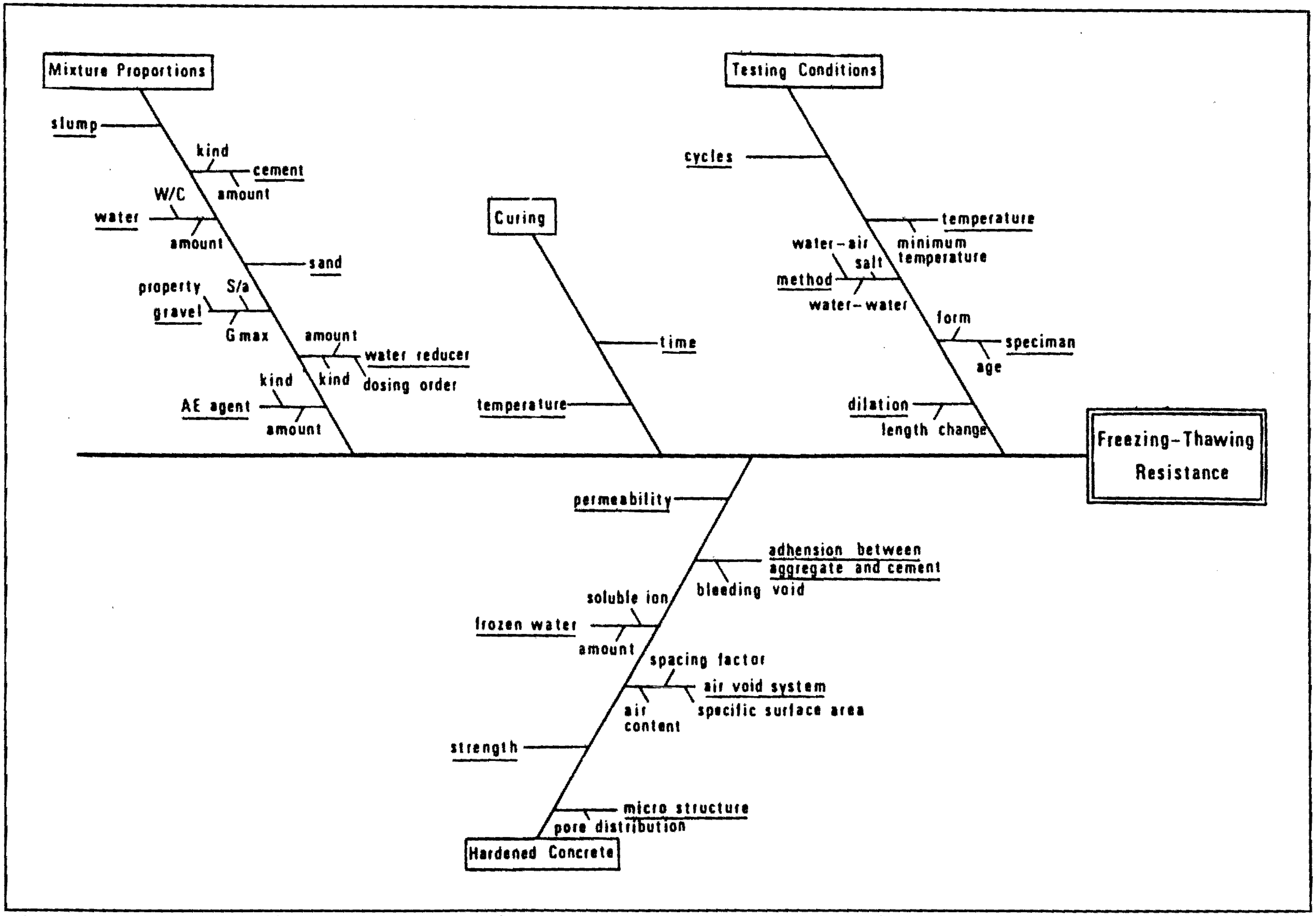


Figure 1. Factors Affecting Freezing-Thawing Resistance of Concrete [8].

mix, the method and time of mixing of the concrete, the grading and amount of the aggregate, (especially the sand) and if the ambient temperature varied. It is believed that all variations in air content have the same effect on frost resistance as variations produced by changing the amount of air entraining agent. Although not founded on field data, this thinking led to the practice of attempting to offset each variation in air content by manipulating one factor or another known to influence the air content. The production of air entrained concrete by attempting to a maintain a fixed total air content under all conditions is not practical. The method of control of the air entrained concrete involves adopting a void-spacing factor (discussed later) as the basis for specifying and controlling air entrained concrete [5].

**Entrained and Entrapped Air**

The volume of air contained within fresh concrete is considered to be of two types: air which is entrained and air which is entrapped. "Entrapped air" is air which is "normally" found in a given mixture of concrete and entrained air is considered to be air in "excess" of entrapped air, present because of the air entraining agent. However, this is probably not an accurate distinction. All "air" that is in the mixture (excludes air voids produced by segregation of coarse material or by incomplete filling of forms by a stiff mixture) is held by the same mechanisms. When an air entraining agent is present it is safe to assume that all the air carries film due to the agent, whether the bubbles appear spherical or not. Therefore, the term "intentionally entrained air" only indicates an increase of air content to a preselected value by means of a suitable agent. Some of the "entrained" air may seem to be contained by entrapment [9].

**Pumping Effects on Air Entrainment**

The ingredients of both pumped and unpumped concrete mixes are similar except that greater emphasis is placed on the quality control of the proportioning and use of a pumpable mix. Pumpability is affected by the pumping equipment, the operators, the amount of ingredients in the mixture, batching and mixing control, and the knowledge and experience of the project personnel [2].

Since concrete pumping became popular more than 30 years ago, questions about the effect of pumping on the properties of the plastic concrete have existed. Should the fresh concrete be tested at the pump or at the discharge end? [10]. General experience over the years has been that there is loss of air of about 1 to 1½ percent and loss of slump of about ¼ to ½ inch due to pumping.

When pumping air entrained concrete the volume of the air is less at discharge than at the pump due to the loss of air displaced when pumping. On the average, the original volume of air lost is about 20 percent. Increasing the amount of entrained air may adjust for the above noted loss of air, but overcompensation may result in the concrete failing to be pumped. This effect may be due to the compressibility of air where a part of each pump stroke may be used to overcome, to some extent, the cushion provided by the entrained air which can inhibit the movement of concrete through the pipeline. Therefore, if the dosage of an air entraining admixture is too high there can be difficulties experienced in pumping. Generally, adding up to 2 percent to the specified dosage when pumping above 150 feet has normally compensated for the line loss without creating any pumping difficulties.

As an additional note, several factors may affect the effectiveness of an air entraining admixture (AEA), such as other admixtures, cement fineness, amount of water, batch size, and the length of mixing. Concrete mixtures which incorporate other admixtures besides an AEA may require special care. Fine ground cements (such as Rapid Hardening Cement), are finer than Ordinary Portland Cement (OPC), which may dictate the need to increase the dosage to obtain the required amount of air entrained into the mix (typically up to twice the normal dose). An increase in water content may also increase the amount of air entrained. Within limits, more air is entrained with longer mixing times or smaller batches. Due to these variables, trail mixes are recommended when using air entraining admixtures in this manner [1].

**On-Site Pumping**

On site concrete pumping difficulties may consist of excessive loss of air content in the concrete which typically is associated with the loss of construction productivity. Improper mix designs can create high resistance to the flow of the concrete through the pump line and consequently causes high pumping pressures to transport the concrete. The most common remedy to this situation is to increase the water content (or the slump) of the concrete mix. This solution may remedy this situation, but the effect on the other properties of concrete, such as strength or durability, may be detrimental when such solutions are applied. As previously pointed out, it is common to increase the dosage of the air entraining admixture in an effort to compensate the loss of air.

On Project MA-F 784(20) on US 54 in El Paso County, Texas, in 1989, air loss and pumping productivity difficulties were experienced during the phase of construction involving the placement of the bridge deck [11]. The concrete was difficult to pump possibly due to improper mix design (grading and proportioning of the aggregates). Where this difficulty affected the production rate of the concrete placement, tests for air content and slump indicated that there was a loss of about 1½ to 3 percent of entrained air, while there was little change in the slump. After the change in the air content was noted, it was decided to increase the dosage of the air entraining admixture so as to compensate for the loss of air. However, when air entraining admixture dosage was increased considerably, the concrete mix became so difficult to pump that it eventually blocked the pipelines thus impeding the placement operation. Although there was loss of air when tested immediately after pumping, the air seemed to return or was recovered after the concrete was placed and finished. This was observed based on tests made on (fresh) concrete samples taken from the finished bridge deck. Since the desired air content was recovered and seemed to be normal after placing, it was then decided to use a normal (manufacture recommended) dosage of air entraining admixture and to test the concrete before pumping rather than afterwards. The appropriateness of this decision was based upon the fact that the measured air loss eventually diminished, however the actual effect of pumping on the air entrainment (air content and air-void system) was not fully understood at that time, thus creating the need for additional research to more fully understand the nature of this problem. Hardened concrete samples obtained later on from the deck were tested for the air void characteristics using the linear traverse technique (discussed in Chapter 2) with the summarized results provided in Table B-10 (Appendix B).

The linear traverse results showed in Table B-10 indicate that the air void characteristics were adequate. The specific surface are of the bubbles was over 600 $in^{-1}$ and the spacing factor is less than 0.008 inches, which provide sufficient protection against frost damage. However, the measured high air content most likely reduced the strength of the concrete considerably. This predicament clearly illustrates the need for good pumpable mix designs and proper measures to control the air content variations.

The factors that may influence air entrainment are water content, cement type and content, type of admixture and dosage, mixing procedure, type of coarse aggregate, surface texture of aggregate, type of fine aggregate and the quantity used, and the use of other admixtures. In addition to transportation, placing methods and finishing operations also affect the entrainment of air in concrete. When pumping of concrete is involved, the factors that influence the air entrainment includes all of the above and factors that involve the pump itself. These factors, apart from influencing air entrainment individually, affect the air void system in combination with the other previously mentioned factors. The factors that relate to pumping are the resistance of flow, pressures on the concrete, shear force acting on the concrete mix as it moves through the pipeline, vibrations and vortex actions in the bend sections, and the boom configuration among others. This phenomenon is quite involved and careful evaluation and extensive research has allowed certain conclusions to be made. This study attempts to identify the major factors involved and to provide a basis for guidelines to overcome the difficulties and to control the apparent loss of air entrainment more efficiently.

This report proceeds to first identify all the possible factors that may affect the air void system in pumped concrete. Chapter II presents an extensive literature survey. The information presented in this chapter points out the factors, that influence the air void characteristics of pumped concrete and the mechanism of air entrainment. In Chapter III, pumping effects and the theoretical aspects of the apparent air loss are considered. Chapter IV describes an experimental setup of the field tests to examine factors pointed out in the previous chapters and the associated test results. Chapter V provides the analysis of the test results. The framework for implementation of findings is provided in Chapter VI.

# CHAPTER II
# QUALITATIVE ASPECTS OF AEA IN CONCRETE

This literature survey is aimed at providing a review of current available information concerning the use and effects of air entrainment in the Portland Cement Concrete (PCC). The information presented in this chapter is compiled into different sections; namely air entraining admixtures, mechanism of air entrainment, factors influencing air entrainment, air-void characteristics, instability of air bubbles, and tests to measure for air content in both fresh and hardened concrete. This literature survey, although extensive, may not be entirely complete. However, the objective of this review is to provide a basis in which to address difficulties in the control of air entrainment in pumped Portland Cement Concrete and to suggest directions to develop solutions for the same.

## Air Entraining Admixtures

All air entraining admixtures can be classified as general surface-active agents (surfactants) which are subjected to a physio-chemical process occurring at the surface of constituent materials used in concrete mixtures. Much of the information available today on surfactants have been developed by the detergents industry. Surfactants are used as air entraining agents in concrete to produce a stable dispersion of bubbles of suitable size and spacing. This requires the reduction of the surface energy of the water molecules which are dipoles that have a strong affinity for each other (Figure 2). Consequently, a great amount of energy is needed to separate these molecules. A surfactant may be described as a long chain molecule, with a "skeleton" of linearly configured carbon atoms with one end repelling water (hydrophobic) and the other end attracting water (hydrophilic). When a surfactant is added to water, the molecules in it tend to orient themselves on the surface as shown in Figure 3. Due to the orientation of the molecules of a surfactant, the attraction between them is less than that between water molecules, causing a reduction in the surface energy [13].

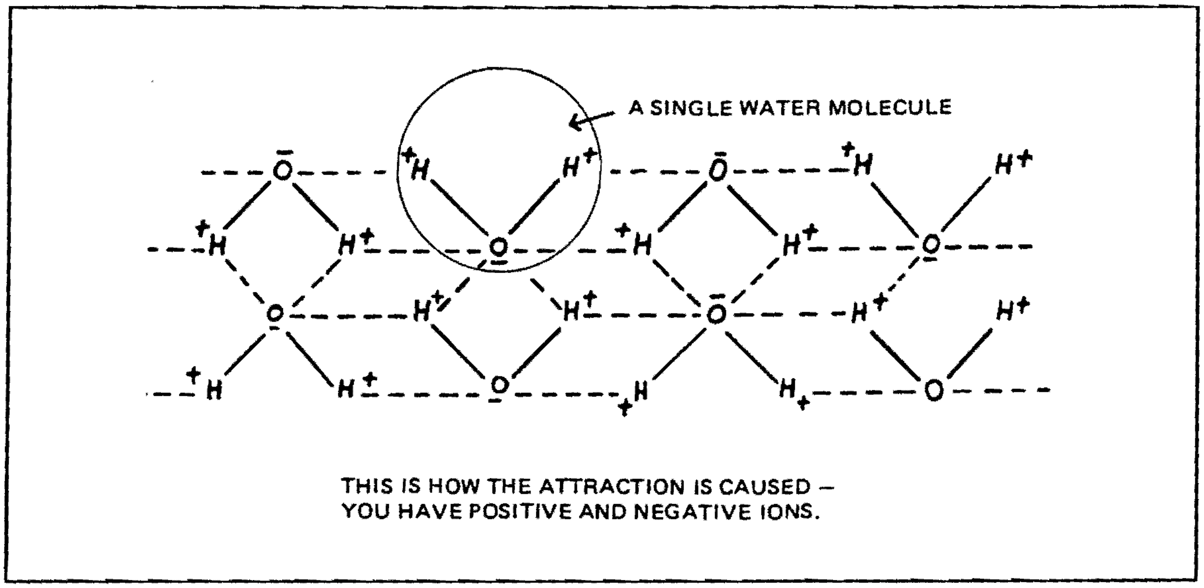


Figure 2. Representation of Attraction Between Water Molecules [13].

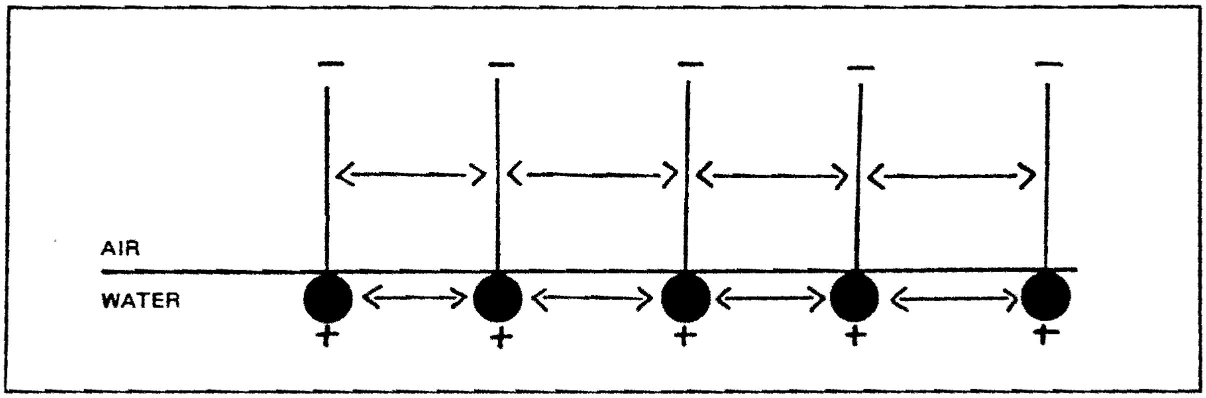


Figure 3. Orientation of Surfactant [13].

Commercial usage of air entraining agents comprises of only a small group of surfactants. A list of TxDOT approved AEA's and their classification is provided in FHWA/TX-92/1254-1 [11] in Table 3 and are associated with the following categories listed in reference 4:

1. Salts of wood resins
2. Synthetic detergents
3. Salts of sulfonated lignin
4. Salts of petroleum acids

5. Salts of proteinaceous materials
6. Fatty and resinous acids and their salts
7. Organic salts of sulfonated hydrocarbons.

Salts of wood resins also known as "neutralized vinsol resin" and are widely used as air entraining agents (AEA) in concrete today. Synthetic detergents, which generally consist of alkyl aryl sulfonates, make up a large class of surfactants. Salts of sulfonated lignin which are by-products of the paper industry are mostly used as retarders and water reducers. Due to their poor air entraining capabilities, they are not used widely used as air entrainment agents. Salts of petroleum acids are by-products of petroleum refining and are neutralized usually with sodium hydroxide. Water soluble sulphonates which are contained in the sludge, upon neutralization with sodium hydroxide, produces another group of surfactants, namely, "organic salts of Sulfonated Hydrocarbons". The next group of surfactants are "salts of proteinalean materials" which are the products of animal hide processing industries. These type of air entraining agents are few when compared with other types of AEA. Fatty and resinous acids and their salts are a group of surfactants which are produced from various materials such as soaps, vegetable oils, etc. On account of the presence of insoluble calcium salts, these sufactants contribute little to the air entrainment in concrete mixtures. Most existing air entraining agents are inexpensive which warrants general usage. New agents found through research that indicate a superior level of performance are expected to be adopted on a wide basis [4].

**Mechanism of Air Entrainment**

The air bubbles in concrete are formed by mixing action. The function of the air entraining agent is to stabilize the bubbles that are formed; it does not generate them. Powers et. al. analyzed the details of the air entrainment process [9].

The mixing action consists of two processes. One is an infolding of air by a vortex action where the shearing action (as that produced by mixer blades in the mixer) causes the air in the vortex to dissolve and break up into smaller bubbles. In pan type mixers, the mixing blades pass through the mass and create the vortices. In drum mixers, the vortices exist at the ends of shelves. In order that vortices to occur, the mass must be more or less fluid; kneading action causes the infolding of air in dryer mixes [4].

The second process of the mixing action explains the strong influence of aggregate on development of the entrained air void system. In this process, aggregate particles essentially act as a "three dimensional screen" to entrap and hold air bubbles during the mixing. Essentially, these two processes are responsible for development of the air void system. As stated previously, the air entraining agents ensure the stability of the smaller air bubbles in the concrete. The air entraining agent is presumed to achieve this in several ways. Although considerable research has been done on these processes, the details are not clear. In the absence of an air entraining agent, the air bubbles incorporated in fresh concrete by the mixing are lost relatively soon. They tend to merge to form larger bubbles as they come close to each other during mixing. Also, any larger bubbles that reach the surface of the fresh concrete by their buoyancy and the mixing action may burst and escape from the concrete [4]. See Appendix F for further information on the factors influencing the entrainment of air in concrete.

**Role of Air Entrainment Agents**

Air entraining agents tend to stabilize the air bubbles formed by the processes refered to above. The stabilizing action of an AEA is due to its adsorption at the bubble surface (Figure 4). A film of the adsorbed molecules is formed at the interface of water and air with their polar heads oriented in the water phase. When molecules in a medium carry a particular charge, the air bubbles within that medium will acquire this charge at their surfaces. Any two bubbles approaching each other during mixing will experience an electrostatic repulsive force which will keep them apart as they would otherwise come together or merge (Figure 4). This action is similar to that of an emulsifying agent which stabilizes and prevents the breaking of an emulsion. Another type of stabilizing action is the orientation of a layer of water around the bubbles, probably as thick as several molecules. This phenomenon is

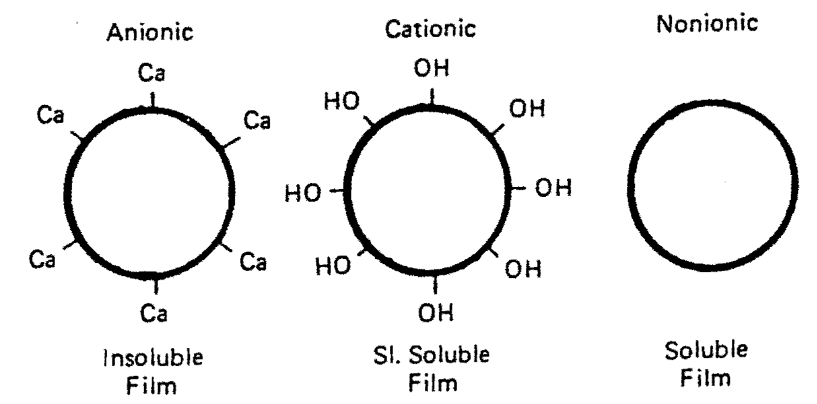


Figure 4. Nature of AEA Film Around the Entrained Air Void [22].

sometimes referred to as a "hydration sheath" which separates, stabilizes, and deflocculates the system of air bubbles. This type of action is also seen in the case of adsorbed layers of nonionic agents that do not change the bubble attraction characteristics or potential. It may be significant to note that nonionic agents generate poorer air entraining action resulting in larger bubble sizes than those which result from the use of ionic agents [4].

The action of anionic air entraining agents seems to be dependent also on the extent to which it is precipitated by the constituents of the aqueous phase of the concrete. In general, calcium salt is insoluble. As the hydration process develops, the concentration of calcium increases in solution and becomes supersaturated with respect to calcium hydroxide after only a few minutes. If the calcium salt of the agent is more insoluble than calcium hydroxide, it should be precipitated from solution. If anionic molecules are adsorbed and located at the surfaces of the air bubbles, it is evident that such precipitates should form there in large amounts. Mielenz et al [14] stated that such films which form at the bubble surface are of sufficient thickness and strength to help stabilize the air bubbles and prevent their coalescence. These "precipitate" films essentially act as a protective colloid that maintains dispersion and prevents coalescence. They achieve this by a "steric" effect which essentially prevents bubbles from approaching each other. Low weight foamed concretes are stabilized by adding animal products which form similar films around the bubbles.

If the air entraining agent is precipitated completely, little would remain to lower the surface tension of water in the concrete mix. The results of some experimental studies showed that air entrainment could be obtained with apparently all of the agent precipitated out of solution. Other studies showed that a residual of the agent left in the solution was important for satisfactory air entrainment in concrete. It may be significant to note that many air entraining agents are complex mixtures. Some parts of these mixtures produce insoluble precipitates, which are adsorbed at the bubble surfaces and lower the surface tension. The other components are left in the solution [4].

Although cationic and nonionic surfactants cannot form insoluble precipitates in a concrete system, they do cause air entrainment. Anionic agents whose calcium salts are soluble also serve adequately as air entrainers. Thus, it can be seen that insoluble film mechanism, though important to the process, is not essential [4].

Air entraining agents also stabilize the bubble system by adsorption on to the cement particles (Figure 5) [17]. Generally speaking, cement particles, upon contact with the water, rapidly become coated with a hydration product, a finely divided calcium silicate hydrate. This coating is relatively impermeable to water which cause the hydration reaction to cease and the dormant period follows until initial set, during which the bubble system is fixed. Due to the adsorption of calciumious, the hydration product bears a positive surface charge. It is believed that the air entraining agent (anionic) is adsorbed on to the surface of the hydration product with the non polar portion of the molecule extending out into the water that surrounds the molecule. This creates a "hydrophobic" particle that results in the attachment of the cement particles to the air bubbles. Since the cement particle size is smaller than the bubbles, a "coating" consisting of the cement particles on the bubbles provides an anchor for bubbles in the mass and prevents their ascension and coalescence. The action is similar in many aspects to the flotation of minerals that is carried out to concentrate ores. Bruere [18] used such flotation tests for evaluating air entraining agents in cement pastes. He concluded that bubble attachment to the cement particles was important. On the other hand, it is difficult to see how this mechanism can apply to cationic or nonionic agents. After the bubble formation and their subsequent stabilization against loss, a further action which influences its final form in hardened concrete is thought to take place.

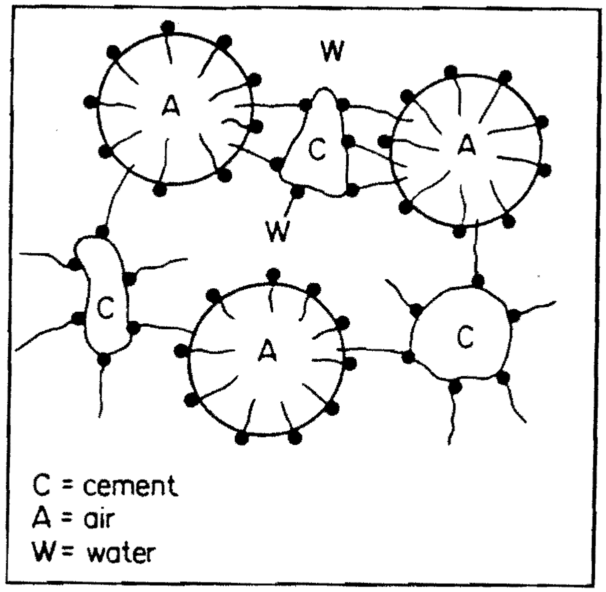


Figure 5. Interactions Between Cement, Air, Water and Molecules of Air Entraining Agent [17].

**Air Void Characteristics**

Protection of hardened concrete from destruction by freezing action, the primary function of air entrainment in concrete, can be achieved by providing a sufficient number of bubbles per unit volume of paste. This produces a cellular structure wherein the cell walls are composed of hardened paste that are about a few thousandths of an inch thick. For a given percentage of air, the average wall thickness between bubbles is indirectly proportional to the mean bubble diameter and inversely proportional to the number of bubbles. Hence, it is important to consider the quantity of entrained air, and the characteristics of the air void system; the bubble size distribution in particular. It is interesting to point out as a side note that the measurement of air void characteristics in fresh concrete has recently been facilitated by the development of a new device known as the air void analyzer [11]. Prior to this development, it was assumed that the casts of bubbles found in the hardened paste of concrete are representative of the bubbles that existed in the fresh state [9]. It is expected that assumptions such as this along with others similar in nature can now be considered in greater detail leading to enhancing the understanding of the characteristics of air voids and their variations in fresh concrete.

The parameters of the air void system that are important for frost resistance are specific surface, spacing factor, air content, and bubble size distribution. Among parameters mentioned above, spacing factor ($\bar{L}$) is generally considered as the most significant indicator of the durability of the cement paste matrix to freezing and thawing exposure of concrete. The maximum value of the spacing factor, under the above explained conditions, for moderate concrete exposure is usually taken as 0.008 inches (0.20 mm). The standard definitions of the air void characteristics as per ASTM C457 are provided below for the convenience of the reader [19]:

**Air Content ($A$)**: The proportion of the total volume of the concrete that is air voids; expressed as percentage by volume.

**Average Chord Length ($\bar{l}$)**: The average length of the chords formed by the transection of the voids by the line of traverse; the unit is length.

**Paste-air ratio ($p/A$)**: The ratio of the volume of hardened cement paste to the volume of the air voids in the concrete. The paste-air ratio is usually in the range of 4 to 10.

**Paste Content ($p$)**: The proportion of the total volume of the concrete that is hardened cement paste expressed as percentage by volume.

**Specific Surface ($\alpha$)**: The surface area of the air voids divided by their volume, expressed in compatible units so that the unit of specific surface is a reciprocal length. The specific surface is usually in the range of 600 to 1100 in.$^{-1}$ (23.6 to 43.3 mm$^{-1}$). The higher the specific surface, the greater the durability to frost.

**Spacing Factor ($\bar{L}$)**: A parameter related to the maximum distance in the cement paste from the periphery of an air void; the unit is a length. The spacing factor is dependent on the paste content. The spacing factor ($\bar{L}$) is usually in the range of 0.004 to 0.008 in. (0.10 to 0.20 mm).

Void Frequency (*n*): Voids per unit length of traverse; the number of air voids intercepted by a traverse line divided by the length of that line. The unit is a reciprocal length.

**Tests for Air Content and Air Void Characteristics**

TxDOT employs three methods for determining the air content in freshly mixed concrete. They are as follows:

1. Pressure method,
2. Volumetric method, and
3. Gravimetric method.

A fourth method, the Chase Air Indicator method, provides only an approximate air content of freshly mixed concrete. All the above methods measure the in situ volume of air and are discussed in the report 1254-1 [11]. Petrographic analysis can be done on hardened concrete samples to determine the parameters of the air void system. The two tests most commonly used are:

1. Linear Traverse Method and the
2. Modified Point Count Method.

Linear Traverse Method: The current method of determining the air content of hardened concrete is the Linear Traverse Method. The air content is determined by means of microscopic method (Figure 6) [20]. The air-void content, and the spacing factors are determined by standard procedure ASTM C457 (American Society for Testing and Materials). Microscopic analysis is an accurate measure of the air content since it measures bubbles of all sizes; bubbles of less than 50 microns diameter are not likely to be read by pressure meter method.

This procedure consists of the determination of the volumetric composition of concrete by summing the distances traversed across a given component along a series of regularly spaced lines in one or more planes intersecting the sample. The data gathered are the total length traversed ($T_t$), the length traversed through air voids ($T_a$), the length

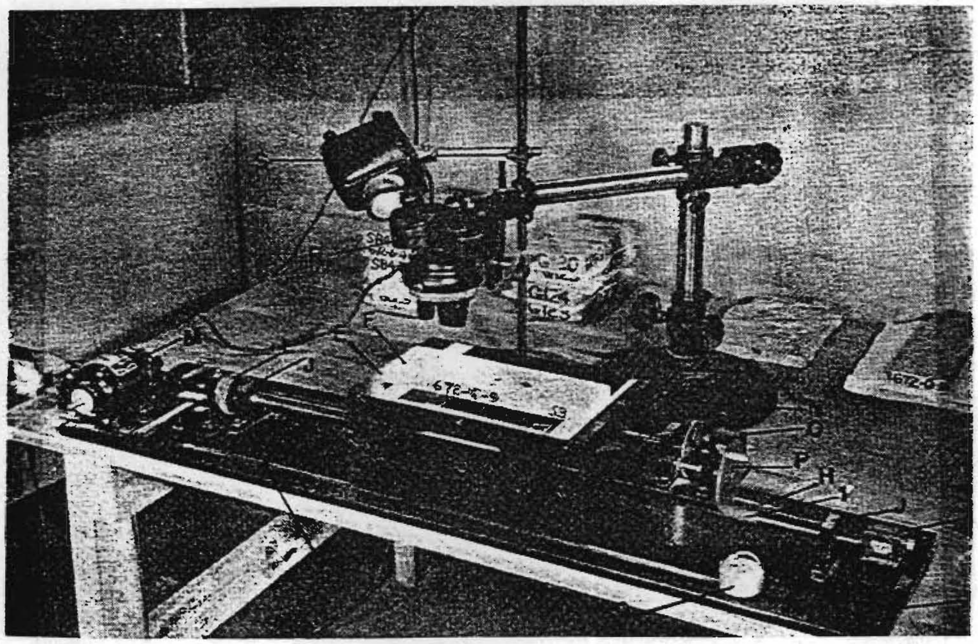

Figure 6. Apparatus Used in the Linear Traverse Method [19].

through the paste ($T_p$), and the number of air voids (N) intersected by the traverse line. These data are used to calculate the air content and various parameters of the air void system. If only the air content is desired, only $T_a$ and $T_t$ need be determined [19].

The equations for the various air void characters are listed below for the convenience of the reader [19]:

Air Content (A), in percent:

$$A = \frac{T_a \times 100}{T_t} \tag{1}$$

Void Frequency (n):

$$n = \frac{N}{T_t} \tag{2}$$

Average Chord Length ($\bar{l}$):

$$\bar{l} = \frac{T_a}{N} \tag{3}$$

or

$$\bar{l} = \frac{A}{100\ n} \tag{4}$$

Specific Surface ($\alpha$):

$$\alpha = \frac{4}{\bar{l}} \tag{5}$$

or

$$\alpha = \frac{4N}{T_a} \tag{6}$$

Paste Content (p), in percent:

$$p = \frac{T_p \times 100}{T_t} \tag{7}$$

Paste-Air Ratio (p/A):

$$\frac{p}{A} = \frac{T_p}{T_a} \tag{8}$$

Spacing Factor ($\bar{L}$):

When p/A is less than or equal to 4.342

$$\bar{L} = \frac{T_p}{4N} \tag{9}$$

When p/A is greater than 4.342

$$\bar{L} = \frac{3}{\alpha}\left[1.4\left(1 + \frac{p}{A}\right)^{1/3} - 1\right] \tag{10}$$

Modified Point Count Method: This procedure consists of the determination of the content of a specific component of the concrete on a volumetric basis. The volume of a given component is estimated by observation of the frequency in which the areas of the component coincide with a regular grid system. Consequently, the observed frequency distribution is based on a sample observed along the lines defined by the grid system. These points may be in one or more planes intersecting the sample. The data gathered are the linear distance between stops along the traverse (I), the total number of stops ($S_t$), the number of stops in air voids ($S_a$), the number of stops in paste ($S_p$), and the number of air voids (N) intersected by the line of traverse over which the component data is gathered. From these data, the air content and various parameters of the air void system are calculated. If only the air content is desired, only $S_a$ and $S_t$ need be determined [19]. This method is less accurate but much faster than the linear traverse method.

**Effect of Air Entrainment on Concrete**

As noted above, air entrainment agents can influence the plastic properties of fresh concrete. Slump and workability, bleeding and segregation, and finish ability are the properties that may be affected by air entrainment. At the same water content, air entrained concrete result in higher slump than the non air entrained concrete. This change in slump signifies an improvement in workability. Workability can be defined as the ease with which concrete can be placed, consolidated, and finished with little segregation [9]. The increase in workability caused by air entrainment is generally attributed to a sort of "ball bearing" action of the air bubbles particularly since the air bubbles are numerous, roughly on the order of a quarter of a million per cubic centimeter of cement paste. The tiny bubbles are compressed under the forces that the concrete is subjected to during placement where this deformation contributes to an increased workability. Air entrained concrete is also subjected to less bleeding and segregation than a non-air entrained concrete. Finishability is not a problem if proper tools are used and a suitable delay is observed before starting the finishing operations.

Although air entrainment in concrete does not affect its setting time [4], the addition of air entraining agents increases the yield. In other words, a 5% air content only 95% of the concrete constituent materials normally used will be required to produce a given volume of concrete [13].

The properties of hardened concrete that are typically affected by air entrainment are unit weight, resistance to frost, compressive strength, modulus of elasticity, shrinkage and creep, and permeability. Entrainment affects the unit weight because the unit weight is inversely related to the yield. The ratio of the unit weight of the air entrained concrete to that of the non-air entrained is one minus the fractional air content. The strength of air entrained concrete is reduced (Figure 7), but usually this is compensated by the reduction of water cement ratio allowed by the presence of air. The advantage of the reduction in water cement ratio provided by air entrainment will be more than compensated for the amount of entrained air in the hardened concrete, up to 5 percent to 6 percent air. This is especially true for lean mixture concretes. After the range of 5 to 6 percent air is exceeded, the reduction in water cement ratio cannot compensate for the number of voids within the paste. Thus, the compressive strength of the concrete drops sharply. Another cause for this decrease in strength is the tendency of the air voids to collect at the surface of the large aggregate. When their number exceeds a certain range, the strength of the paste to aggregate bond is reduced. Elastic modulus is also reduced to some degree as the compressive strength in an air entrained concrete. That is, the presence of entrained air does not alter the usual relationship between strength and modulus [4]. Air entrained concrete have been found not to affect either creep or shrinkage to a great extent. The permeability and the rate of capillary adsorption are smaller for properly air entrained concrete than for non-air entrained concrete [4].

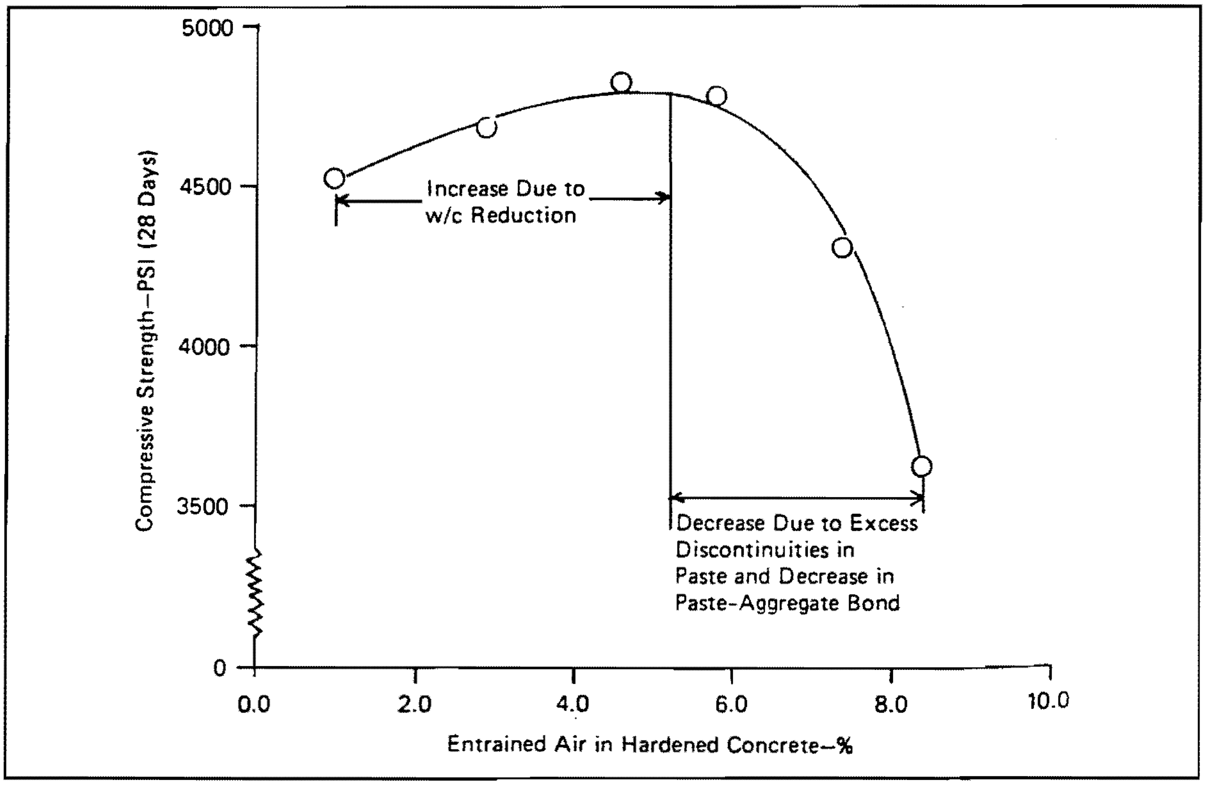


Figure 7. Effect of Entrained Air Content on the 28-Day Compressive Strength of Concrete [22].

In comparison with non air entrained concrete, the proportioning of air entrained concrete is achieved in light of: 1) the increase in slump due to the air bubbles 2) the concomitant increase in workability of the concrete (Figure 8) and 3) the affect on strength of concrete (due to the change in consistency, at a constant slump, less water is needed for the air entrained mixture). The decrease in water demand amounts to roughly ten percent less than the water demand found in ordinary mixes, according to the ACI (American Concrete Institute) recommended practice. The increase in air volume in the concrete mix is offset by a decrease in the volume of water and by the decrease in the volume of fine aggregate (Figure 9), (based on absolute volume method) [4].

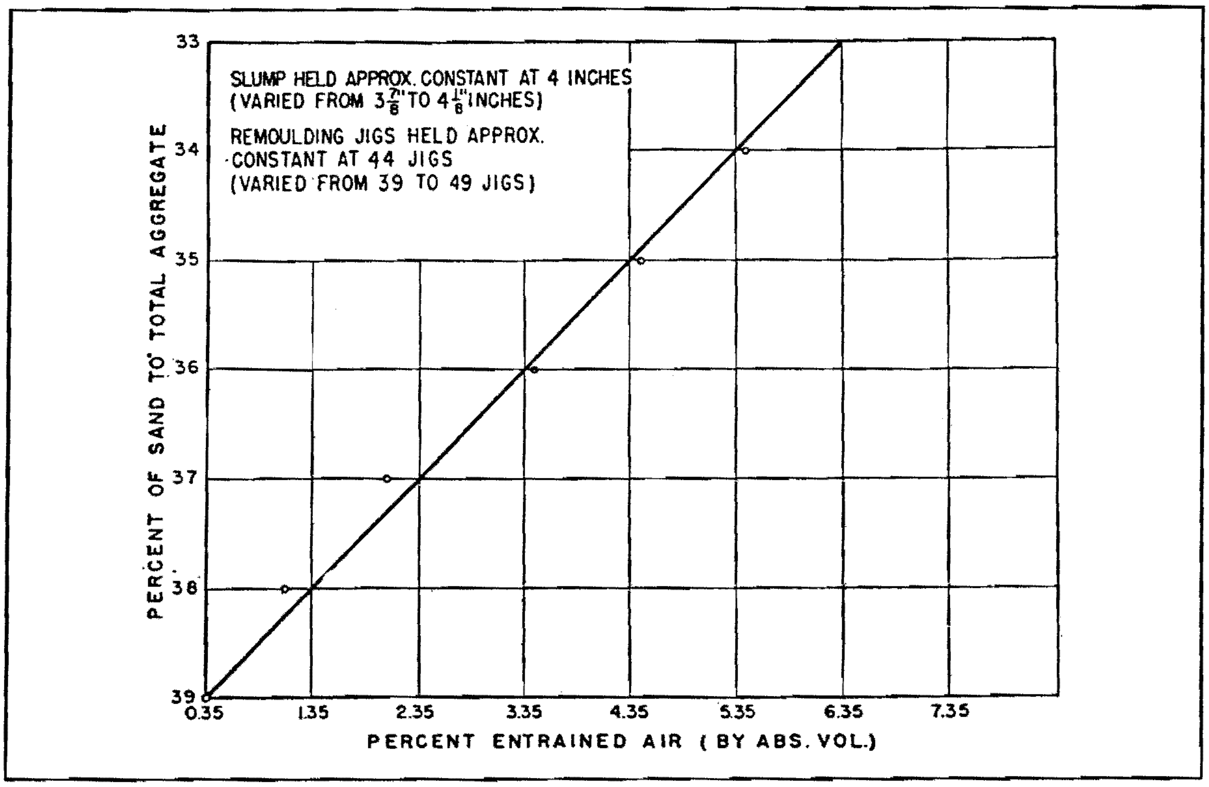


Figure 8. The Workability and Slump Remain About the Same if the Percent of Sand is Reduced by One Percent for Each Percent Increase in Air Content [30].

For rich concrete mixtures, there may be an increase in strength due to the lowered water/cement ratio. As pointed out above, this is offset by the decrease in strength due to the entrained air. In some cases, in order to maintain a constant strength, additional cement may need to be added. On the other hand, for leaner concrete mixes that are proportioned with higher water/cement ratios, and exhibit lower concrete strengths, a similar water content decrease due to air entrainment may cause a greater reduction in the water/cement ratio and consequently a larger relative increase in concrete strength. Thus, the weakening effect of the entrained air will be nearly offset with the result that additional cement is required for constant strength to be maintained [4].

**Dissolution of Air Bubbles**

The air pressure inside air bubbles formed in fresh concrete may be greater than air pressure at atmospheric conditions due to [14]:

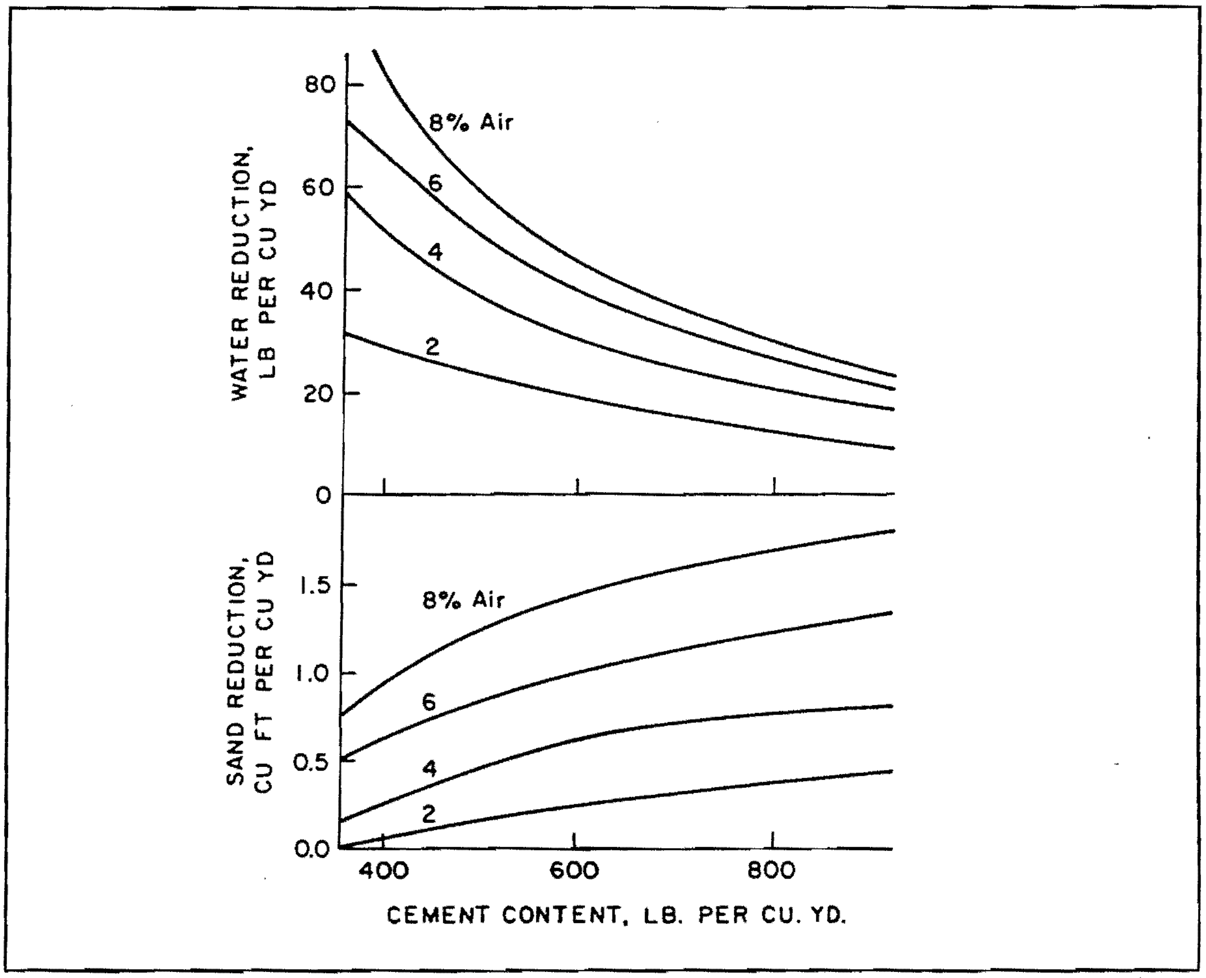


Figure 9. Reduction in Water and Sand Contents Made Possible by Various Percentages of Entrained Air Content [21].

1) Overburden hydrostatic pressure caused by the weight of overlying concrete, and
2) The natural curvature associated with the air-water bubble interface.

Hydrostatic pressure referred to in 1) above typically will be about 1 psi per foot of concrete depth. The pressure (independent of pressure due to overburden) within a bubble is given by the expression:

$$P = \frac{4\gamma}{D} \tag{11}$$

where

$P$ = Excess pressure resulting from surface tension at the air-water interface in fresh concrete,
$\gamma$ = Surface tension of the water referred to above and
$D$ = Air bubble diameter.

As shown in Figure 10, the air pressure within a bubble (in water) increases rapidly as the diameter of the bubble decreases (particularly, in the range less than 100 microns) [14]. This increase is apparently enhanced for bubble diameters less than 10 microns. In other words, while concrete is in a fresh state, the air in bubbles less than 10 microns will be more extensively affected by re-distribution (as described below through loss of air and dissolution into larger bubbles) than the air in bubbles larger than 10 microns. The distribution of bubbles with diameters less than 10 microns will be reduced considerably due to the dissolution of air. Consequently, the entire range of air voids will be affected by excessive pressure manifest initially by a general reduction size and then an increase in size of a certain range of bubble diameters. To the extent this is reflected in the hardened concrete will depend on the rate of hardening with respect to the rate of dissolution of air [14]. This concept is particularly important in terms of objective b) stated in Chapter I. A dissolution process as described above is related to pumping effects on the air void system and is elaborated further in Chapter III.

While the concrete is in a plastic or fresh state, the air in the smaller bubbles (which was forced into water) will tend to move into the bubbles of larger diameters as the air is released from the water. As a result of this dissolution process, the air content of the concrete will increase relative to the noted air content prior to the release of air from the water. The air content may nearly equal the amount of air prior to pressurization less any air that may escape (as being permanently lost) into the atmosphere from the exposed surfaces of the concrete. The relative gain in air content can be characteristically expected as a part of the dissolution process. Parenthetically speaking, if entrained air bubbles of 20 microns in diameter were subjected to dissolution it would

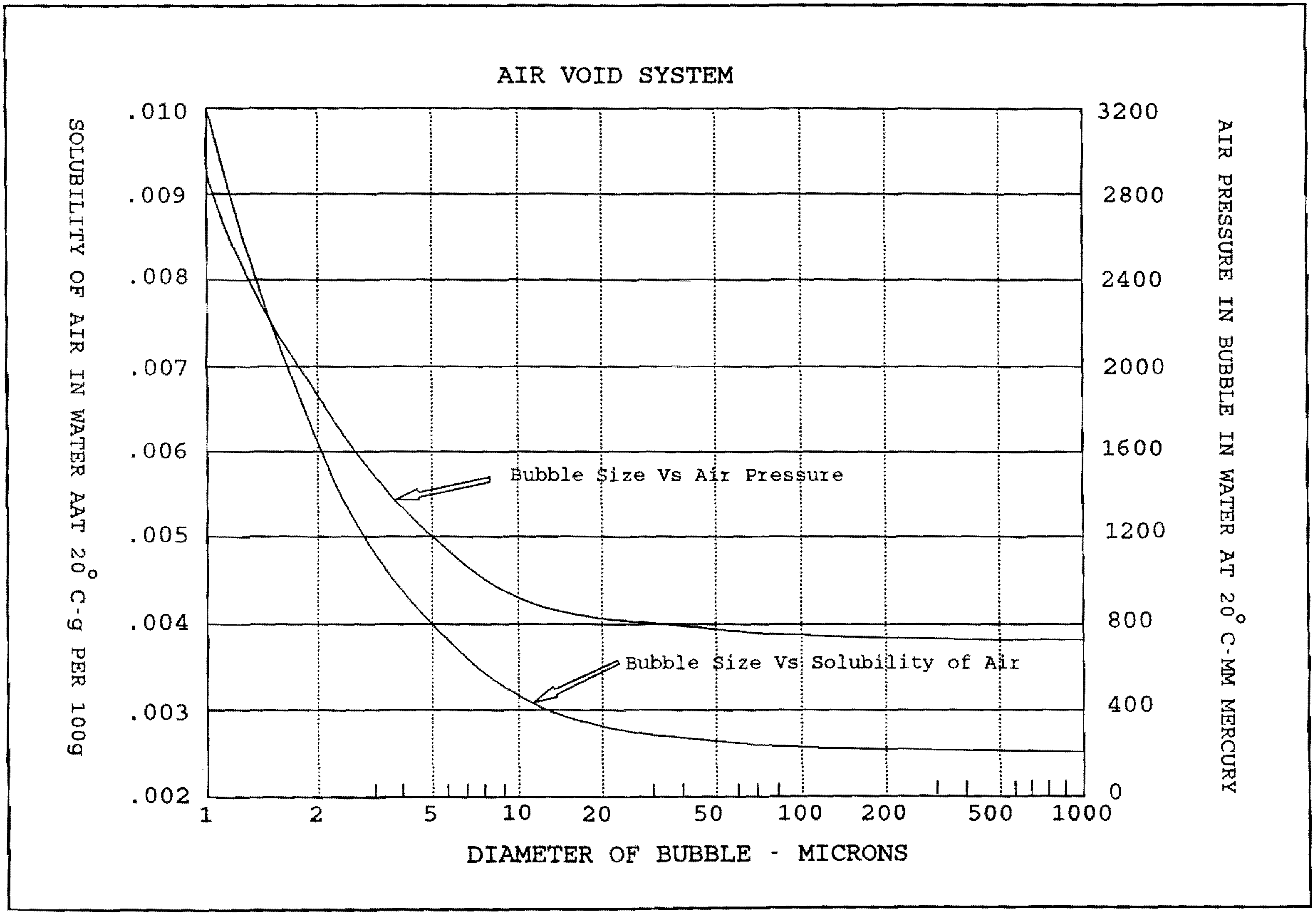


Figure 10. Relationship of Solubility of Air and Internal Pressure to the Size of an Air Bubble in Water at 20°C [14].

occupy about 2/3 more volume when transmitted to voids 1mm in diameter [14].

It has been noted [14], that the flow of air associated with the above described dissolution process is a function of the following factors: 1) area of the air-water interface, 2) the pressure differential established between bubbles losing air and those gaining air, 3) the solubility of air in water, 4) the rate of diffusion of air through the water, and 5) distance through which the diffusion occurs. The air flow (B) between a bubble of diameter $d_1$ and a large bubble of diameter $d_2$ is proportionately related as:

$$\frac{dB}{dt} \propto \frac{aD\gamma}{T}\left[\frac{1}{d_1} - \frac{1}{d_2}\right] \qquad (12)$$

where

a = area of the surface of the bubbles gaining or losing air,
T = average distance between the surface of the bubbles,
D = diffusion factor, and
$\tau$ = surface tension of the AEA.

The diffusion factor represents the rate of bubble (i.e. the air) transmission through water. For a given air-void system, several factors can affect the flow of air through a volume of concrete. These factors are the size distribution of the bubbles, the specific surface ($\alpha$), and the distance between the surface of the bubbles which varies directly with the spacing factor $\bar{L}$ [14]. With respect to Objective a) stated in Chapter I, equations 11 and 12 are significant in describing how the admixture characteristics relate to the air void system of concrete when subject to pumping pressures.

Mielenz [14] proposed and defended the above theory but Bruere [31] presented contradictory evidence. Theoretically, Mielenz's mechanism seems to be appropriate, and any barrier to the passage of the air would offset the dissolution process. Bubbles with low permeability of air would produce smaller bubbles [32]. It may be possible that the air entraining agents Bruere used were of low permeability and consequently no diffusion or change in the air void characteristics were observed. However, in terms of the primary focus of this study, high pressures in the pipeline of a concrete pump will accelerate the diffusion process, even if the process of diffusion does not occur at atmospheric pressure. This diffusion process apparently plays a major part in the transportation of the air bubbles (air) in the pumped concrete.

The consequences of the dissolution process may be manifest in its effect on the freeze-thaw resistance of concrete. The rate of dissolution may also be and the air-void system may be affected by the amount of air entraining agent. The average size of the air voids and the spacing factor tend to decrease with an increasing proportion of air entrainment agent at a constant water-cement ratio. The spacing factor decreases with decreasing water-cement ratio within the range of workable mixtures at constant air content [33].

Other factors affecting the dissolution process are related to the water-cement ratio and the intensity of vibration (previously discussed). The viscosity of the cement paste influences the size distribution of air voids and the air content of the cement paste which is related to the water cement ratio. Therefore, the viscosity of the cement paste increases as the water-cement ratio decreases causing a decrease of the air content. As would be expected, the diffusion process is (and the permanent loss of air) slowed with an increased viscosity of the cement paste. The same affect occurs as the distance between the bubbles increases [34].

## CHAPTER III

## FUNCTIONAL ASPECTS OF AIR LOSS IN PUMPED CONCRETE

In pumping any flowable material there is necessarily a pressure gradient which decreases in the direction of flow, caused by pipeline resistance which reduces the pressure head. This is another way of stating that the material must be capable of transmitting sufficient pressure to overcome all resistances throughout the length of the pipeline. Of all the ingredients in concrete, water is the only pumpable ingredient in its natural state. It is water that transmits pressure to all the other concrete constituents during subjection to pumping pressure. The solids of the mix must interact in such way that the water can transmit pressure through out the mix while confining the water from escaping from the mix. A blockage in the pumpline may occur due to lack of water transmission. This often occurs due to water escaping from the mixture. Pump vibrations contribute very little towards air loss. The loss of air bubbles is dependent on the resistance to flow and concrete pressure. Higher resistance to flow requires higher pressures to pump the concrete. The influence of resistance is mechanical and the influence of pressure is hydraulic on the air bubbles. Aggregate and gradation effects are also considered to be important, which indirectly affect the pressures which develop during pumping.

### Resistance to Flow

Concrete in a pipeline flows in the form of a plug. A layer of water, cement, and fine particles lubricates the insides of the pipe to facilitate the flow. The plug comprises of aggregate, sand, and cement particles separated by a continuous water layer which is hydraulically connected to the lubricating layer. The velocity of flow is nearly constant across the width of the plug, i.e., there is no relative velocity between the aggregate particles. The velocity drops rapidly across the lubricating layer to zero at the pipe wall as shown in Figure 11.

The resistance to concrete flow is explained by hydraulic shearing of the layer and the friction of the solid particles in contact with the pipe wall. The effectiveness of frictional resistance is dependent on the level of concrete saturation [36]. When concrete is in a saturated state (i.e., when there is sufficient water in the mix to overfill the voids within the dry materials) the magnitude of frictional resistance is negligible compared with that found when the concrete is in an unsaturated state. Tobin [37] illustrated this fact by measuring the flow resistance of concrete (for one mix design) with a varying water cement ratio. The results are illustrated in Figure 12 [39]. Flow resistance is inversely proportional to the magnitude of the water-cement ratio. In view of this fact, there is a critical level of water cement ratio, in this case 0.45, below which the frictional resistance increases dramatically. The sudden increase in resistance to flow may be attributed to the change from the saturated to the unsaturated condition.

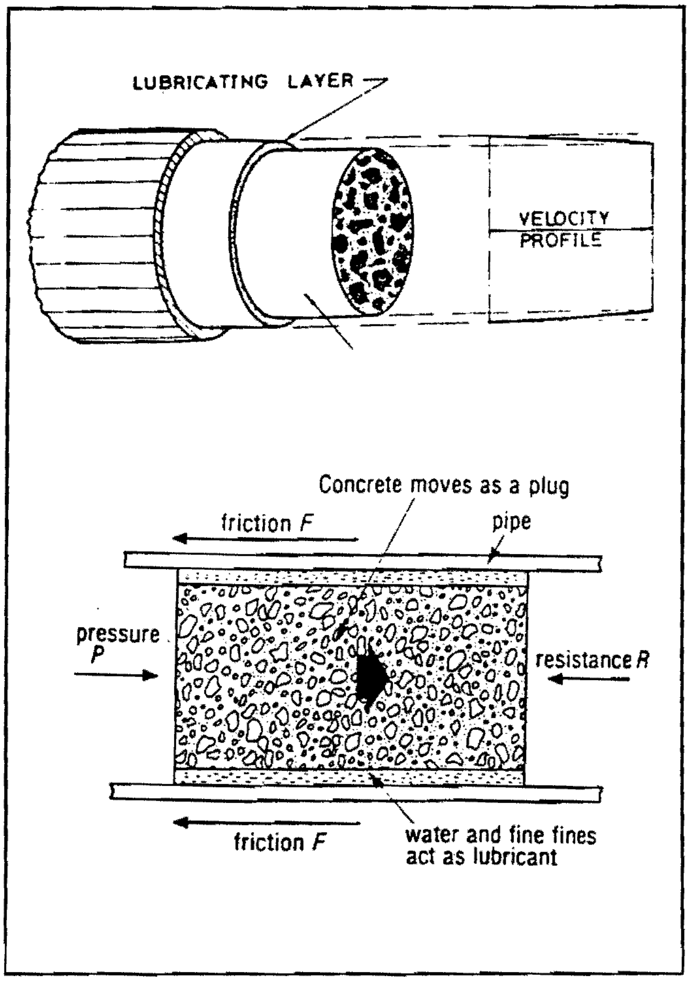


Figure 11. Representation of Plug Flow [36, 38].

There are two reasons for concrete failure to flow under the pressure provided by a pump:

a) When the void spaces are not small enough or intricate enough to provide sufficient internal friction within the mix to overcome the resistance of the pipeline and the water bleeds through the mix without moving the mass.

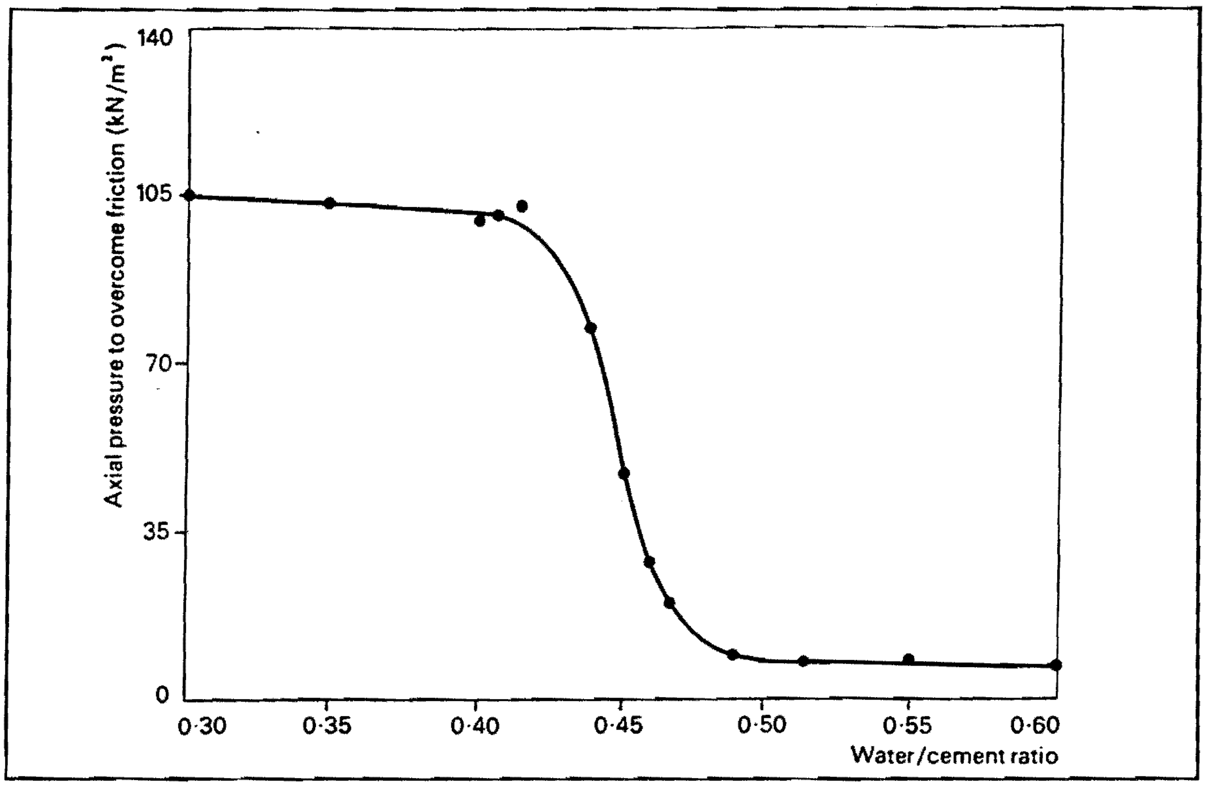


Figure 12. Relationship Between the Water Cement Ratio of Concrete and Pumping Pressure [39].

b) When the solids of the concrete are such that they produce a high pipeline friction that the pressure exerted by the piston through the water phase is not sufficient to move the mass.

Condition (a) will occur generally with medium and low strength mixes and (b) with high strength mixes, or mixes containing a high proportion of very fine materials such as fly ash, stone dust, etc. The factors contributing to these conditions in (a) are high voids caused by irregular or gap grading, and in (b) the high surface area of the solids produced by excess fines (Figure 13) [38].

Fine materials which have a large number of small individual voids offer a greater resistance to the flow of water than coarse materials with their large individual voids. The fines are essential to create the "block filter" effect which allows the water phase to transmit pressure but not to escape from the mix. They also generate high frictional

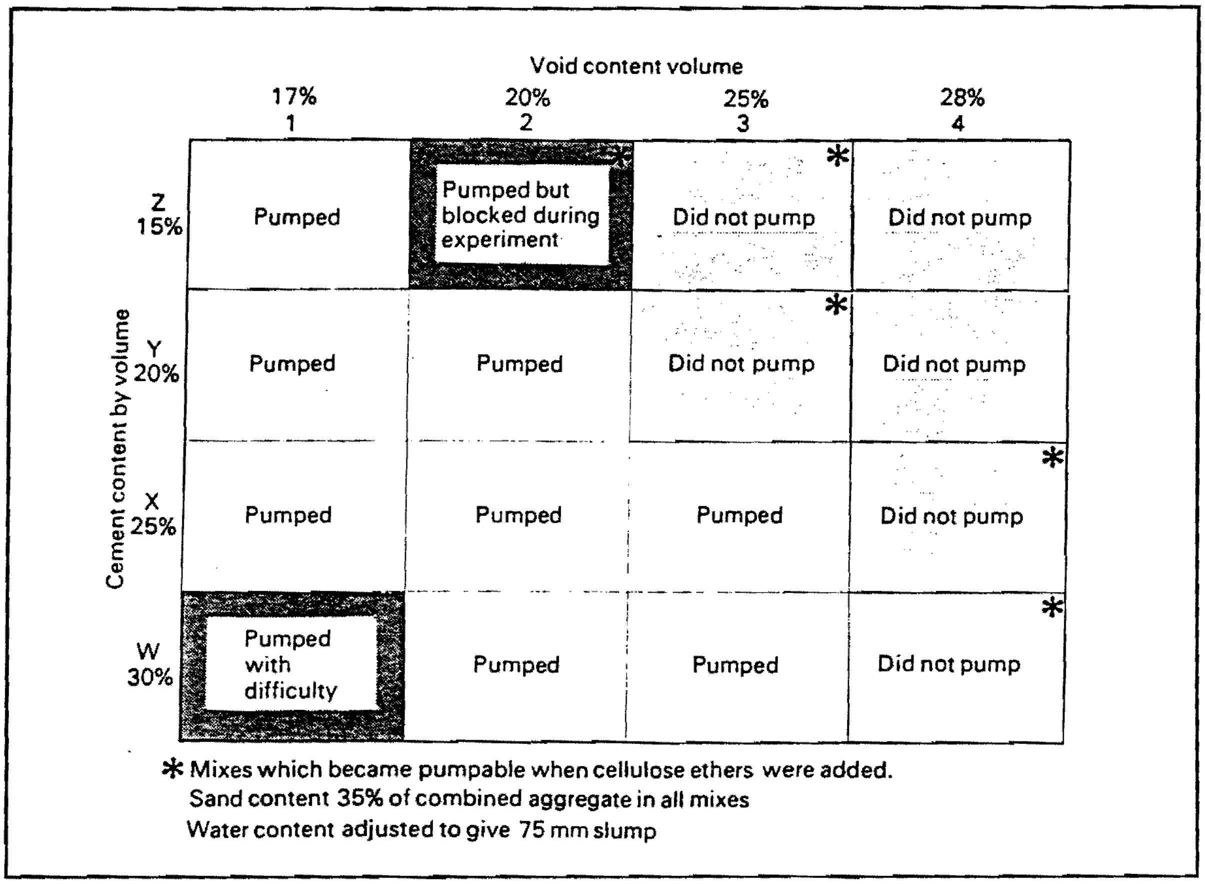


Figure 13. Adjustments to Produce Pumpable Concrete Mixes [38].

resistance in the pipe, due to the high surface area. Therefore, the goal is to produce maximum frictional resistance within the mass of the mix with minimum void sizes and minimum frictional resistance to the walls of the pipe with a low surface area of aggregates. It has been suggested that a high proportion of coarse material should be used to produce a low void content with minimum fines to produce the block filter effect [35].

The void volume within a coarse aggregate is reduced by grading with particles of smaller sizes with the intent of filling interparticle voids with particles of varying sizes. In the random packing of a typical coarse aggregate there is no consistent void size. The materials are graded in such a way that they do not fill the voids but are continuously reduced in size as in 0.75 inch, 0.63 inch, 0.47 inch, etc. (19mm, 16mm, 12mm) and so on where the voids are not filled but are continuously reformed, producing voids of smaller individual size and less total void volume (Figure 14). By continuous grading, minimum total voids are achieved with the minimum surface area of aggregate. This also produces a mass composed of a variety of particle sizes. This locks together particles providing not only small individual voids but intricate and tortuous passages for water to pass through the material [35].

There is a wide variety of grading shape and surface texture of aggregates. Although it is difficult to develop gradation data relative to a particular void size distribution, some combinations of different proportions of aggregates of various nominal grades are more useful than others in providing certain results. The following guidelines are helpful for improved concrete mix proportioning with respect to pumping:

If frictional resistance is excessive [38]:

1. Decrease cement content.
2. Adjust aggregate coarse/fine ratio to increase voids.
3. Increase water content.

If segregation and bleeding are excessive:

1. Increase cement content.
2. Adjust aggregate coarse/fine ratio to reduce voids, usually by adding a third aggregate.
3. Add fines (e.g. rock dust or flyash).
4. Use flocculating agent admixture.

The increase in frictional resistance is due to the presence of excessive fine particles in the concrete mix. The remedial measures suggested will reduce the quantity of the fines in the concrete mix, and thus the frictional resistance is reduced. Bleeding and segregation are a function of the larger void sizes in the concrete mix which also allows water to leave the concrete matrix. Including, a third aggregate consisting of sizes lying between the fine and coarse aggregate fractions will minimize the voids sizes in the concrete mix resulting in a more

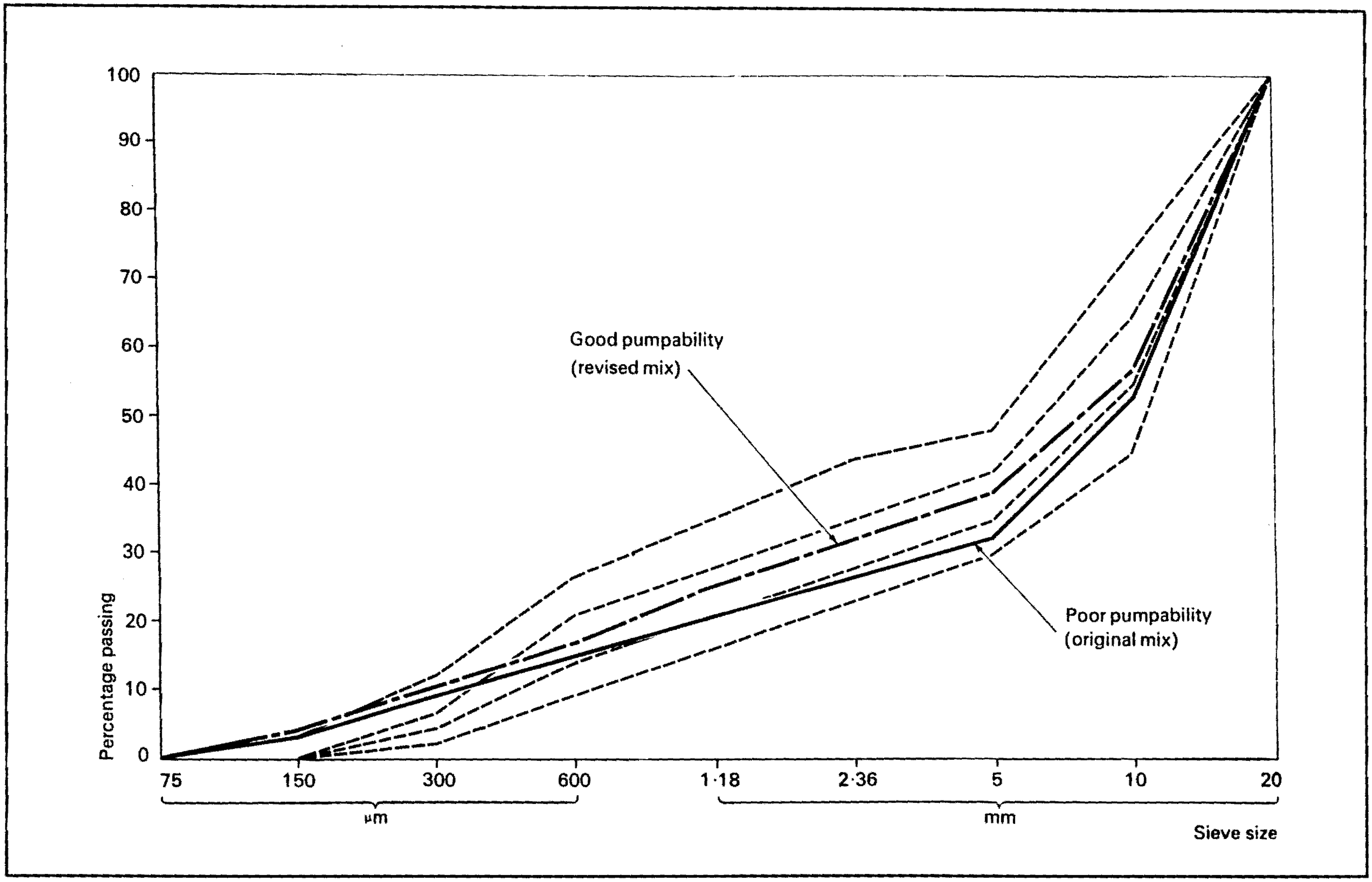


Figure 14. Grading Curves for the Unpumpable Mix and for the Modified Mix [39].

uniform void distribution of void sizes that tends to limit the loss of moisture from the fresh concrete matrix.

**Flow Velocity of Pumped Concrete**

The resistance of concrete to flow while in the hydraulic state is affected by the concrete velocity through the pipeline and to a lesser extent by the concrete workability. Results of field tests indicate an approximately linear relationship between flow resistance and concrete velocity as shown in Figure 15 [36]. Results obtained by Weber [40], using a laboratory piston rig, by Alekseev using a rotary viscometer, and by Ede in reference 37 (authored by Tobin) using a sliding compression apparatus, have also been included in Figure 15, for comparison. Data presented in Figure 15, was obtained by measuring the pressure drop down a pipeline and converting the results to flow resistance using the equation:

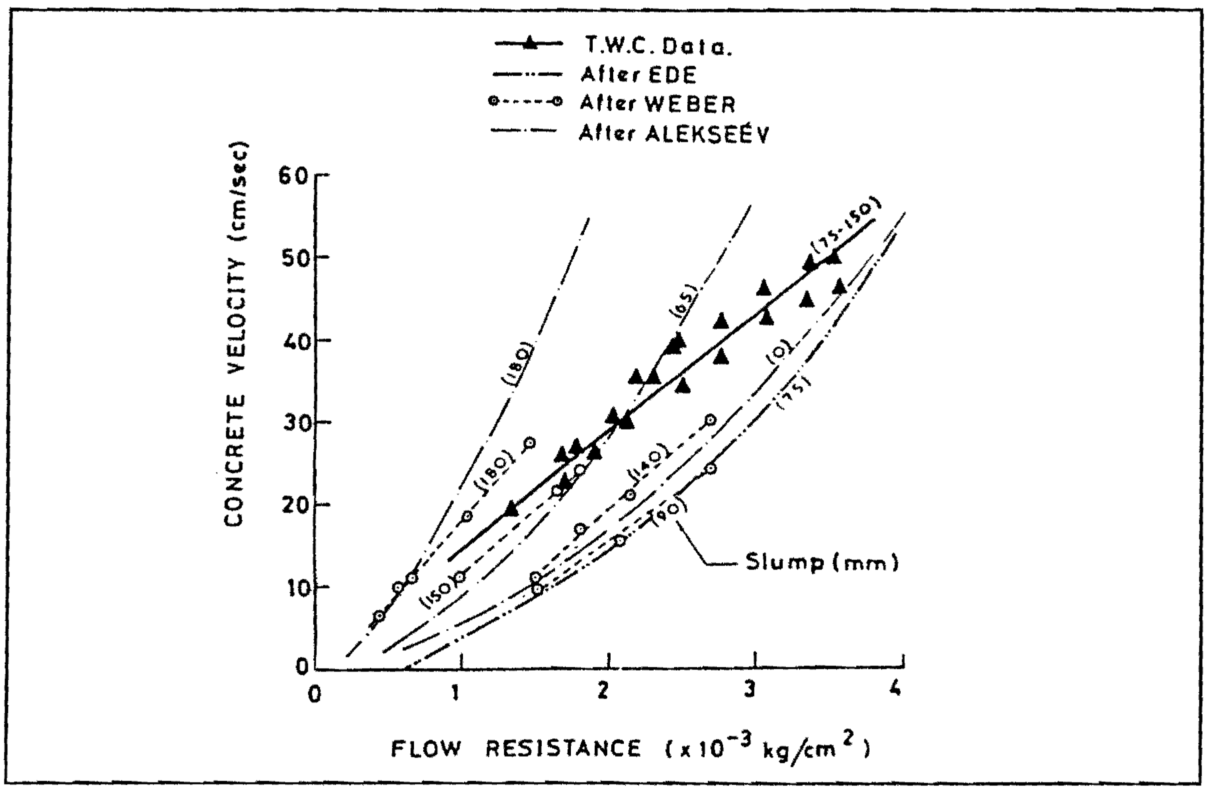


Figure 15. Relationship Between Flow Resistance and Concrete Velocity [36].

$$R = \frac{(P_1 - P_2)}{L} \frac{D}{4} \tag{13}$$

where $P_1$ and $P_2$ are the pressures at two positions along a pipe of internal diameter D, at a distance L apart. The plot shows concrete transport velocity $V_t$ against flow resistance R. The value of $V_t$ has been defined as follows [36]:

$$V_t = \frac{S}{T} \tag{14}$$

where

S = Stroke length of the pump
T = Time for a single pressure stroke

Where the piston and pipeline diameters ($D_1$ and $D_2$, respectively) are not equal, the velocity of flow in the line is corrected for the change in cross section as follows:

$$V_t = \left( \frac{D_1}{D_2} \right)^2 \frac{S}{T} \tag{15}$$

An understanding of the concrete velocity during the pressure pulse (refer to subsequent discussion on analysis of traces) is of value (with respect to resistance to flow and associated flow pressure) in investigating pumping difficulties and the influence of admixtures on pumping performance. The transport velocity ($V_t$) of concrete in the pipeline can be estimated using the following equation [36]:

$$V_t = \left(\frac{D_1}{D_2}\right)^2 \left( \frac{S}{(T_c/2) - T_v} \right) \tag{16}$$

where

$D_1$ = Piston diameter
$D_2$ = Pipeline diameter
S = Length of piston stroke
$T_c/2$ = Half cycle time (i.e., the time for one piston stroke)
$T_v$ = Valve change time

The value of $(T_c/2) - T_v$ is equivalent to the value of T given in Equation (15). The values of $T_c$ and $T_r$ can be obtained from pumping pressure traces (discussed later) along with information regarding flow properties of the concrete and the efficiency of the pump.

**Pressure on Concrete**

High pressures are required to pump concrete if the resistance to flow is high. Pumping pressure is also related to the saturation condition of the concrete. The pressure distribution in a pipeline filled with fresh concrete in either a saturated or unsaturated state is expressed as follows [36]:

Saturated (Hydraulic) Flow: The pipeline pressure loss is linear when concrete is saturated (Figure 16), where the pressure at any point in the pipeline is described by the expression:

$$P = P_o - \frac{4\ R\ x}{D} \tag{17}$$

where

| | | |
|---|---|---|
| P | = | Pressure in the pipeline at a distance x from the pump (under saturated conditions, axial=radial pressure) |
| $P_o$ | = | Pressure at the pump end of the line (i.e., when x=0) |
| D | = | Internal pipe diameter |
| R | = | Flow resistance/unit area of pipe |

The flow resistance is divided into two components, the adhesion resistance (A), which is present even when the concrete is stationary, and a factor related to the velocity (V) of flow in the pipeline and is given by the equation [36]:

$$R = A + K\ V^n \tag{18}$$

where K and n are constants for a particular concrete and are related to the mix proportions and workability.

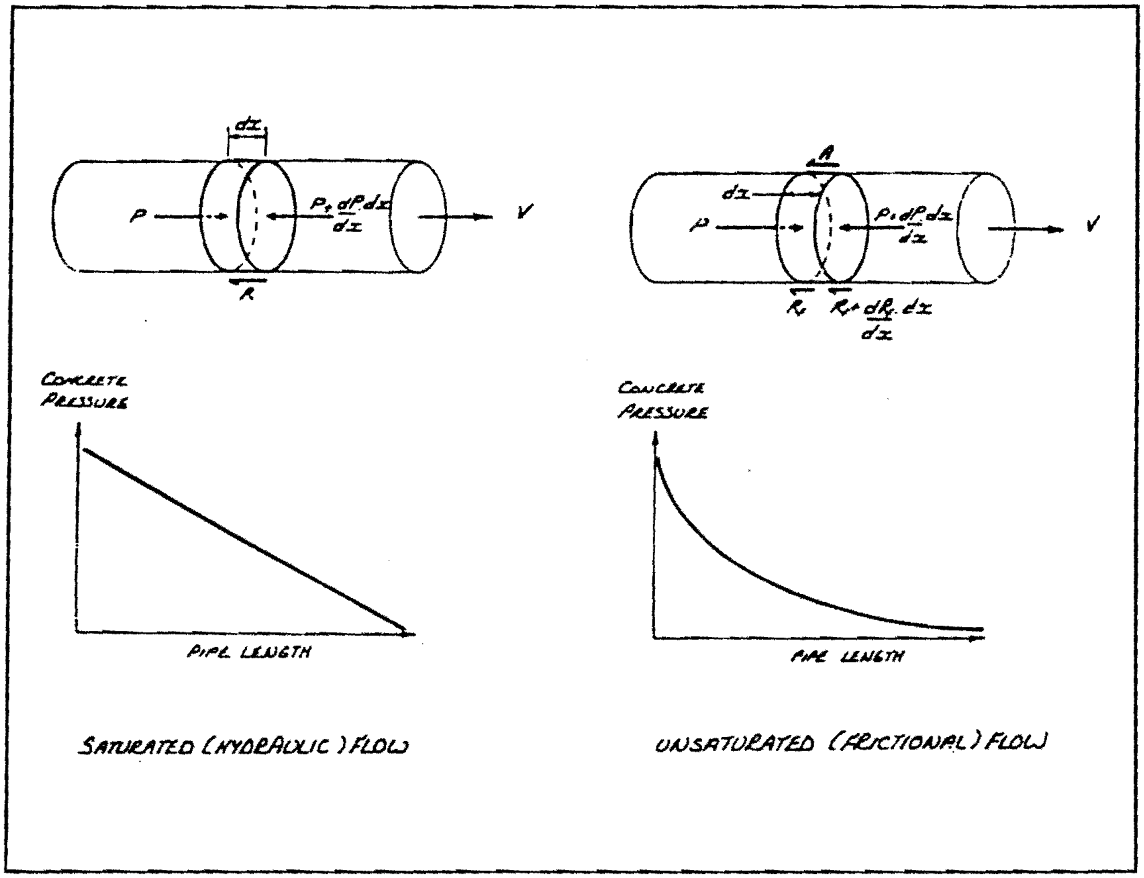


Figure 16. Saturated (Hydraulic) Flow and Unsaturated (Frictional) Flow [36].

Unsaturated (Frictional) State: The pressure loss in the pipeline is not a linear function when concrete is unsaturated (Figure 16). Research has shown it to follow a more exponential relationship. Under these conditions of frictional flow, the resistance R is related to the radial pressure $P_r$ in concrete by the following equation:

$$R = A + \mu P_r \tag{19}$$

where

A = Adhesion resistance (R = A when $P_r$ = 0)
$\mu$ = Coefficient of friction between the concrete and the pipe wall

The general term for flow resistance, however, should not be used in this case. Not only is the value of R related directly to radial pressure, but also the relationship between the axial and radial pressures vary with change in pump pressure. The various factors, therefore, should be considered separately [36].

Analysis of Traces: Pipeline pressures were determined under field conditions by Weber [40], a typical pressure trace is shown in Figure 17, and a trace with increased chart speed is shown in Figure 18. A detailed analysis of pressure traces will show that useful information may be obtained related particularly to concrete workability and also efficiency of the pumping system. The peak pressure $P_p$ occurs when the piston hits the concrete in the cylinder and is the impact and initial pressure required to move the concrete. The constant velocity pressure $P_{cv}$ is the pressure required to keep the concrete in motion.

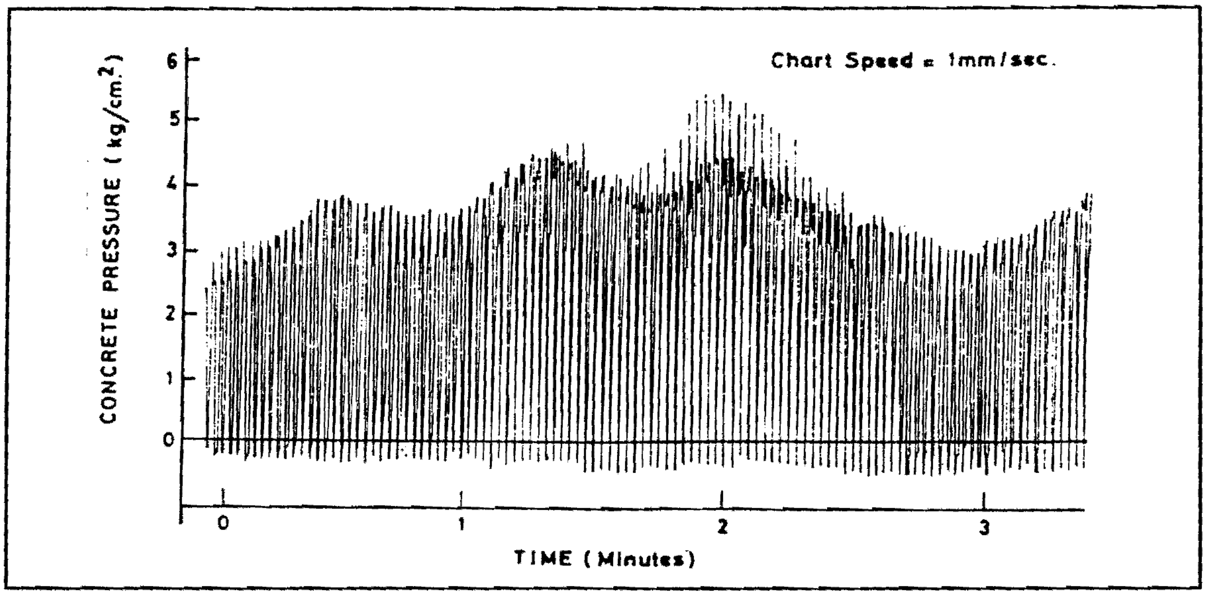


Figure 17. Continuous Pressure Trace [36].

During one cycle (i.e., the time taken for both pistons to complete one stroke), some of the time is ineffective in moving the concrete. This "dead time" is taken up by the valve change time $T_v$, and also the time taken for the piston to hit the concrete, $T_p$. $T_p$ is related to the design of the cylinder inlet valve (i.e., the filling efficiency of the cylinder) and also to the workability of the concrete.

The filling efficiency is defined as that proportion of a piston stroke during which the piston is in contact with the concrete. The time for a single piston stroke is $(T_c/2) - T_v$; thus the filling efficiency can be defined by the equation:

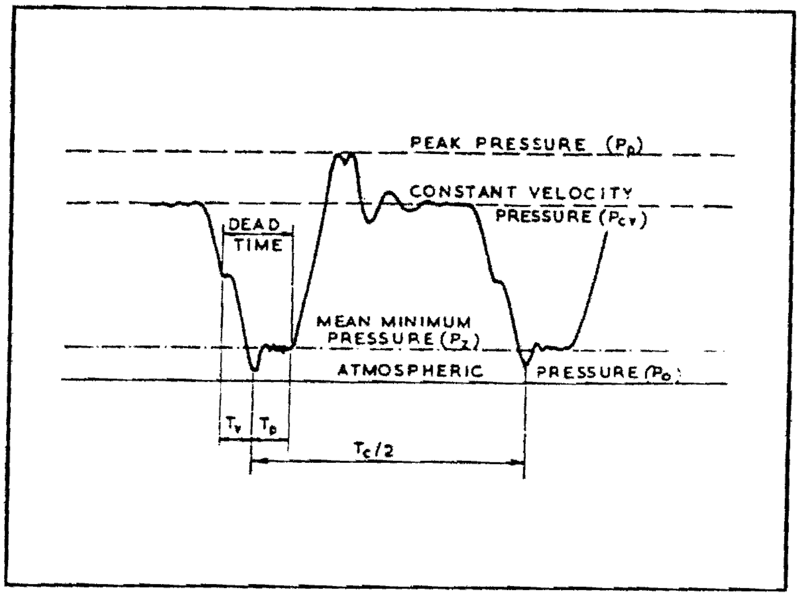


Figure 18. Analysis of a Pressure Pulse [36].

$$Efficiency\ (\%) = \left[1 - \frac{T_p}{(T_c/2) - T_v}\right] X\ 100 \tag{20}$$

For a given pump, the value of $T_p$ is directly related to the workability of the concrete, being defined by its ability to flow into the pump cylinder. This is illustrated clearly in Figure 19.

<u>Pipe Diameter</u>: Concrete flow resistance is a function of the pipeline diameter. The flow velocity and consequently the flow resistance increases with decreasing diameter. The use of larger pipe diameters results in higher delivery outputs, reduce pumping pressures, and lower pipeline wear. It is important to choose the correct diameter and wall thickness of the pipeline to match the pump and the required placing rate. For long horizontal lines involving high pumping pressures larger diameter pipes are recommended as there will be less resistance to flow. For vertical pumping of concrete, the weight of concrete in the line must be considered. It is suggested that the smallest possible size pipe

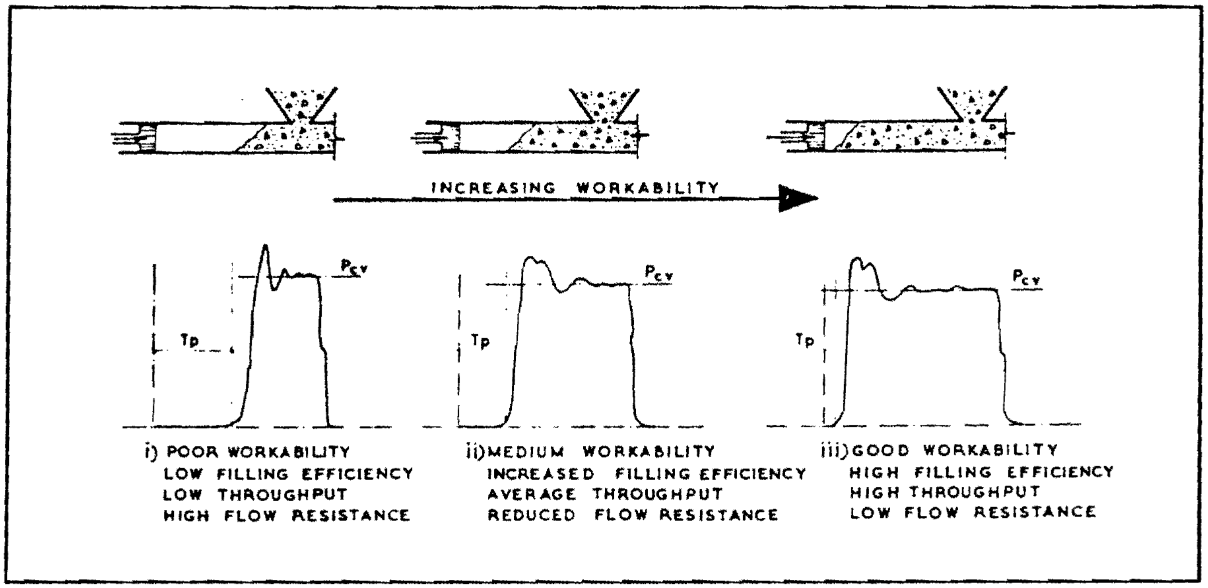


Figure 19. Effect of Concrete Workability on Pumpability and Pump Efficiency [36].

should be used. Besides these considerations, the use of small diameter pipelines offers advantages in easier handling of the corresponding smaller diameter end hoses. This will also alleviate segregation problems due to bleeding and air pocket resistance. The designated pipe diameter should be considered when proportioning the mix. The pipe diameter should be at least 3 to 4 times the maximum size of the aggregate that is used in the concrete mix [1].

Distance Pumpable: The affect of concrete mix consistency on the pumpable distance can be demonstrated as follows. For a given pump pressure of 500 psi (35 kgf/cm$^2$) and pipeline diameter of 4 inches (10 cm), the maximum distance that saturated and unsaturated concrete may be pumped can be calculated. Calculations have shown that for saturated flow the concrete can be pumped over a distance of 820 feet (250 m) [36]. In the case of an unsaturated condition, the distance is reduced to 3.6 feet (1.1 m). Hence, if for any reason, more than a length of 3.6 feet of concrete flow became unsaturated, the pump pressure would be exceeded by the pressure required to move the concrete, causing blocking. Blockages may be caused by "dewatering" of the concrete over a relatively short length of pipelines (see Figure 20). Such occurrences can be avoided if the concrete has low permeability to the flow of its own mix water.

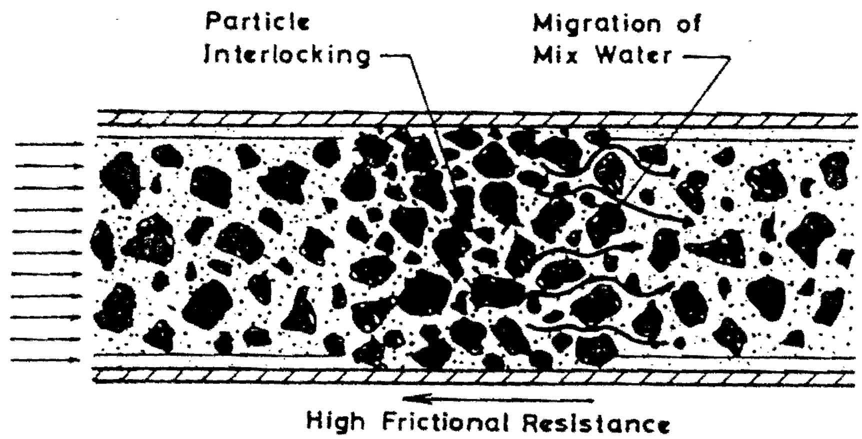


Figure 20. Dewatering in Pipeline [4].

Concrete Workability: Concrete workability is a function of the water content, cement content, aggregate content fine and coarse), aggregate grading, aggregate shape, size and texture. The effect of water, cement and the aggregate content on the workability is well documented. However, the actual effect of the aggregate grading, shape and the texture of the aggregate particles is not well described quantitatively. The shape and the texture of an aggregate can be characterized by several methods most of which are subjectively based. A promising method recently developed [42] at the Texas Transportation Institute to characterize aggregate shape and texture is based upon fractal concepts. Fractals are a set of mathematical functions which describe the deviations of natural objects from their topological ideals. The characteristic which defines a fractal is called the fractal dimension. This concept has found its application in the shape and texture analysis of natural aggregates. Li et. al. [42] have determined the fractal dimension (fd) numbers for shape and texture of aggregates. Fractal dimension for shape range from 1.05 (circle) to 1.15 (elongated). For texture of the aggregates, the fractal dimension numbers range from 0.15 (limestone) to 0.09 (uncrushed river gravel). Fractals provide new mathematical tools and image processing techniques which can be used to describe natural shape and structure that is irregular, rough or fragmented.

As a demonstration of this concept, three different coarse aggregates with different fractal dimensions were used in different mixtures using the same concrete mix design. The workability of each mixture was observed in terms of measured slump [41, 42]. The three different aggregates used were Crushed Limestone Rock (CLR - fd = 1.28), Uncrushed River Gravel (URG - fd = 1.1), and Synthetic Glass Marbles (SGM - fd = 1.0). These materials were chosen to achieve the widest disparity possible between the macro shape and micro texture of the surface. Two concrete mix designs were used where one had no intermediate aggregate (Design A) and the other had an intermediate aggregate (Design B). The mix proportions (which consisted of 3 coarse aggregates and 2 mix designs A and B) are summarized in Table 1.

The results of these experiments relate the fractal dimension for the coarse aggregate (shape) and the slump of the concrete (as a measure of workability). The results are presented in Figure 21 and Figure 22. Design A is modelled after a concrete mix equivalent to a standard TxDOT pumping mix used in bridge decks. Design B is a modification of the same concrete mix, but uses an intermediate aggregate to fill the voids in the aggregates used in design A. The intermediate aggregate improved the mix workability (less the effect of the increase in w/c) while at the same time reducing the amount of paste in the mix.

The results indicate that aggregates with low fractal dimension yield higher slumps for the water cement ratio (Figure 21). Since Design A had no intermediate aggregate to fill the available void space in the

Table 1. Textural Mix Design Factorial.

| Coarse Aggregate Type | | Design A Cu.ft./Cu.yd. | Design B Cu.ft./Cu.yd. |
|---|---|---|---|
| CLR fd 1.28 | Cement | 2.39 CF | 2.39 CF |
| | Sand | 7.17 CF | 7.45 CF |
| URG fd 1.1 | Coarse Aggregate | 11.36 CF | 8.27 CF |
| SGM fd 1.0 | Intermediate Aggregate | ---- | 3.06 CF |
| | Water (35) | 4.73 CF | 4.48 CF |
| | Total Air 5% +/-1% | 1.35 CF | 1.35 CF |
| | Total | 27.00 CF | 27.00CF |

aggregate gradation, the slump increased very quickly with the decrease in the fractal dimension. The effect of aggregate macro shape and micro texture can have an erratic behavior in the material workability if an intermediate aggregate is missing from the aggregate gradation. At the job site any attempt to increase the slump by adding the calculated correct amount of water may produce concrete with more slump than required. By using an aggregate with a lower fractal dimension, slump and workability are increased while minimizing any change to the water cement ratio or strength.

The effect of the intermediate aggregate is apparent in Figure 22, the slope of the trend line is more uniform and linear. The fractal dimension of 1.1 is significant from the standpoint that the trend for Design A becomes almost linear at this point in Design B, with the presence of an intermediate aggregate tends to eliminate erratic behavior in the workability. Research has shown that slump change is greater for aggregates with a low fractal dimension for the same amount of change in the water quantity [41, 42].

As previously discussed, the optimum combination of concrete materials occurs when the internal friction within the concrete is a

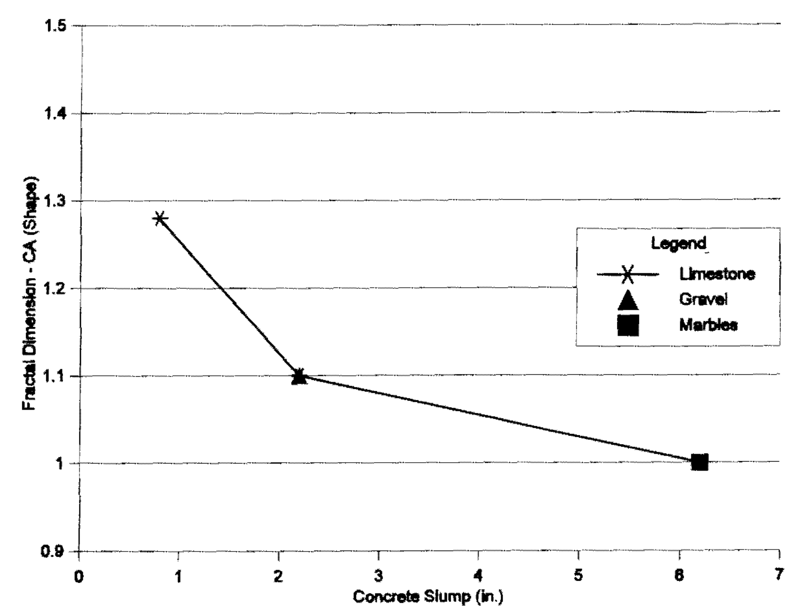


Figure 21. Relationship Between Fractal Dimension and Slump (Design A, w/c=0.48) [41].

maximum and the friction with pipe wall is a minimum. Aggregates with high fractal dimension (in either shape or texture) have more mechanical interlock and give greater resistance to any movement within the mix. But this high resistance may not be beneficial in concrete that is subjected to pumping, even though this type of mix provides maximum amount of internal friction since the friction with the pipe wall may also be maximum. Concretes with low fractal dimension aggregates in both shape and texture like the Uncrushed River Gravel (URG), produce concrete with low internal resistance and greater workability. It may appear that this type of mix design is not suitable for pumping since internal resistance within the concrete is less. However, the internal resistance can be increased by adding a third (intermediate) aggregate yet minimizing the pipe wall friction resistance.

With regard to the surface texture, aggregates with rough surface texture may not require an intermediate aggregate in the case of pumped

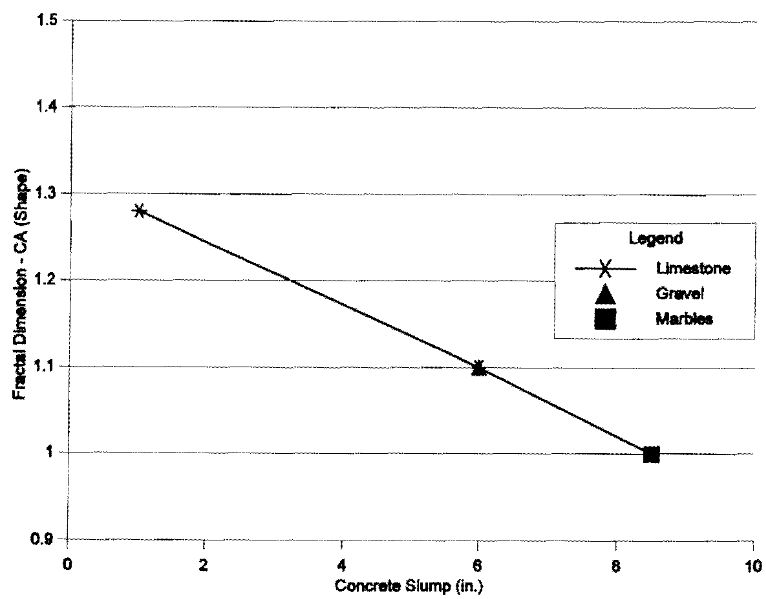


Figure 22. Relationship Between Fractal Dimension and Slump (Design B, w/c=0.48) [41].

concretes as these surfaces increase the internal friction within the concrete. The ideal aggregate for pumped concrete may be aggregates with round shapes (low shape fractal dimension) and rough surface texture. This is because the round shape improves the workability and the surface increases the internal friction, which is important for transmitting pressure without segregating the mix water. Other aspects of aggregate texture are subsequently discussed. Using an intermediate aggregate in the mix proportions produces small voids for maximum surface area and decreases water segregation due to the pressure in the pipeline. The use of fractal dimension concepts in combination with mix workability to characterize the effect of the coarse aggregate shows potential towards indicating the best combinations of aggregate and gradations to minimize air loss in pumped concrete and should be further researched. However, it is obvious that several workable combinations may be available to the design engineer with regard to the proportioning and material selection for pumpable concrete.

**Mechanical Aspects of Air Loss**

The mechanics of air loss when pumping concrete can be explained by following the path of concrete through the pump. For information regarding the functions of a concrete pump refer to Appendix A. Pumping concrete begins with the fresh concrete being placed into the hopper of the concrete pump. In the hopper, concrete cascades through the remix screw and the paddles. These paddles vibrate at a low frequency to consolidate concrete to facilitate easy flow of concrete into the pump. Due to the low vibration frequency, the air loss may be insignificant and only larger bubbles are expected to be affected. From this point, concrete is sucked into the piston which draws the concrete by creating a vacuum in the cylinder. The negative pressure is usually about 0.789 atm (0.80 bar) and may not affect the smaller air bubbles significantly [43]. The air pressure in bubbles due to surface tension only and ranges from 0.0045 atm for bubble diameter of 640 microns to 1.15 atm for bubble diameter of 2.5 microns [9]. Negative pressure may burst the larger bubbles. Its effect on the smaller bubbles is to increase their size and lower the pressure inside the bubble. If the concrete mix has good workability and internal resistance to deformation and maintains its integrity inside the cylinder, the negative pressure may not affect the smaller size bubbles. The peak pressure ($P_p$) occurs when the piston impacts the concrete in the cylinder while developing the initial pressure required to move the concrete. This pressure compresses the concrete and pushes the concrete as a whole unit into the pipeline.

If the piston cylinder diameter is greater than the pipeline diameter, a reducer is used to reduce the diameter gradually. When concrete passes through the reducer there is a rapid change of velocity. An enormous amount of internal friction is developed due to deformation or change in shape which takes place within the plug of concrete. To conform to this reshaping effect, a concrete mix must be plastic. The cement, sand, and gravel particles must be so proportioned that they can be rearranged in position without interfacing with movements of one another. This is called "particle interface" and pump mixes should always be proportioned to avoid this problem. A mix may have acceptable properties for plug flow in a straight pipe but may have unacceptable properties with respect to movement through a reducer [37].

The key to affective pumping is to maintain the integrity of the concrete within the mixture. In other words, the internal friction within the concrete mass should be kept to a maximum and the friction between the pipe wall and the concrete to a minimum as explained previously. In terms of air loss, this is more important because of the effect it has on the rupture of air bubbles. It should be noted that the internal friction within the concrete mass will subject the bubbles to a shearing force that may tend to stretch and possibly break them. Unlike the shearing force during mixing, the concrete movement will actually break up the bigger bubbles into smaller sizes (the shearing force tears the bubble). The continuous flow of the concrete in the pipeline does not serve to reform the bubbles.

The reduction of friction internal to the concrete mass also affects the flow of the concrete plug. Fines within the concrete tend to move towards the pipe wall and the coarser aggregates tend to move to the center of the plug. As a result, the fines and/or the paste is subject to shearing force at the edges and hence any bubbles within this area are affected. The rotational motion of coarse aggregate which accompanies the movement to the center also shears the paste and pulls the bubbles apart. This effect is more pronounced if the coarse aggregate surface texture is rough and may deform the bubble by stretching the bubble film, resulting in a reduced thickness and greater susceptibility to breakage. Adding a third aggregate to the mix maximizes the within concrete friction by minimizing the air voids and limits the exposure of the air bubbles to the shearing action within the mix.

An additional factor which may enhance the bubble stability with respect to these forces is the surface tension. Air entraining admixtures with high surface tension may produce bubbles with greater stability and thus with greater resistance to the shearing action previously described. During a cycle of the pump stroke, when surface tension (stress on the bubble film) is greatest, the bubble film may stretch and compress according to the position of the pump stroke. When admixtures with higher surface tension are used it is expected that air loss is reduced.

The next vulnerable area for air loss in the pipeline is at the bends and elbows. An additional source of head loss is attributed to bends and elbows. Concrete particles moving along the outside portion of the curve must travel faster and or at higher velocities than those on the inside to travel through the curve in the same span of time. This differential in velocity can be a source of increased pipe friction. Deflections of concrete flow result in a pressure increase. Bends with radius of 3 feet (1 m) and deflection of 90 degrees have a resistance equivalent to that of a horizontally laid pipe section approximately 10 feet (3 m) in length. An elbow (pipe bend) with radius of 10 inches (250 mm), as it is used in pumping booms, has a resistance equivalent to that of a horizontally laid pipe, approximately 3 feet (1 m) in length. The turbulence created by the change in direction of the flow of concrete combined with the increased resistance increase the affect on the air bubble system. After passing the bend, a vortex motion is created within the pipeline. Any air lost from the bubbles due to this effect may form air pockets in the concrete flow which may escape at the discharge end of the pipeline. At discharge, if concrete is subsequently dropped from a certain height, may cause a loss of air (permanently) upon impacting the concrete forms [10].

**Pressure Aspects of Air Loss**

It has been made clear that pumped concrete can be subjected to high pressures. High pressure may affect the air void system in several ways particularly with respect to diffusion. Mielenz et al. [14] pointed out that a system of bubbles in fresh concrete is intrinsically unstable thermodynamically. To explain further, thermodynamic equilibrium (at a given temperature) requires that 1) pressure transmitted through the water to the air bubble be equal in all directions and 2) that the water must be saturated with a certain amount of air depending on the temperature. Such a condition cannot prevail in fresh concrete, since water is never completely saturated with air. In air entrained concrete, the principal areas of contact between water and air are at the boundaries of bubbles. The amount of air required to saturate water depends on pressures at the bubble boundaries.

At a given level below the top surface of a mass of fresh concrete, the air pressure in a bubble is equal to the hydrostatic pressure at that level plus the pressure due to surface tension [9]; thus

$$P = P_h + P_y = P_h + \frac{4\lambda}{D} \tag{21}$$

Where P is the air pressure in the bubble, $P_h$ is the hydrostatic pressure, $P_y$ is the pressure due to surface tension, $\gamma$ is the coefficient of surface tension, and D is the diameter of the bubble. It is evident from the equation that internal air pressure is generally higher than the external air pressure. At any exposed surface, some air passes from the water (in air entrained concrete) to the atmosphere. Such a possible loss of air should be insignificant in comparison with the possible rate of transfer of air from one bubble to another [9].

Bubble diameters in a freshly formed system in fresh concrete may range initially from 2 or 3 microns up to 2000 microns [9] or more. Table 2 illustrates the fact that pressures in adjacent bubbles may differ by as much as 1 atm or even more. Solubility of air in the water depends on pressure and (Figure 10); solubility increases as the pressure increases. If water surrounding a small bubble should become saturated with respect to the pressure in the small bubble, it will become supersaturated with respect to the water surrounding a larger bubble. Air in the smaller bubbles is at a higher pressure than air in the larger bubbles. Air diffuses through the water from the smaller to the larger bubbles, reducing the smaller bubble and enlarging the larger bubble. The average pressure on the air will have diminished; hence the total volume of air will have increased.

As previously discussed in Chapter II and elaborated further here, entrained air in concrete placed under pressure during pumping may be subject to a diffusion process. Air is the only compressible ingredient in the concrete mix. Part of this pressure is taken up by these bubbles.

Table 2. Air Pressure in Bubbles Due to Surface Tension Only [9].

| Bubble Diameter ($\mu$) | $P_\gamma$ | |
|---|---|---|
| | Atm | psi |
| 640 | 0.0045 | 0.066 |
| 320 | 0.009 | 0.132 |
| 160 | 0.018 | 0.264 |
| 80 | 0.036 | 0.528 |
| 40 | 0.072 | 1.06 |
| 20 | 0.144 | 2.11 |
| 10 | 0.288 | 4.22 |
| 5 | 0.576 | 8.45 |
| 2.5 | 1.150 | 16.9 |

The pressure on the air inside the bubble increases tremendously. At this pressure, the water surrounding the bubble is not saturated and air under pressure diffuses into the water surrounding the air bubbles. Though it may appear that larger bubbles will be under more pressure than the smaller bubbles, the air in the larger bubbles is under a lower degree of pressure and is easily compressible. In contrast, air in the smaller bubbles is already compressed, and any additional pressure will drive air out of the bubble and the unsaturated condition of the water; the increased pressure surrounding smaller bubbles will promote the diffusion of air from them. The diffusion of air is at the same time accompanied by the release of the air into larger bubbles as pressure applied on concrete is in a pulsating manner as previously described. At peak pressures, the air is diffused from the small air bubbles into the water and at the dead times (pressure just above atmosphere pressure, Figure 18) air is released into the larger bubbles. The level of diffusion is directly proportional to the pressure on the bubbles and the saturation level of water at that pressure, and inversely proportional to the distance between the bubbles. The distance between the bubbles is critical for frost resistance, the only variables that can be altered to decrease the air loss are obviously the pressure and the water that is saturated. Since water saturation is dependant on the water availability, any decrease in water in the mix will decrease the diffusion process. Greater air loss is possible when pressures are high and when water to cement ratio is high.

A large portion of the dissolved air in water is released in the pipeline but sometimes it is possible for the air to be released after the concrete has been placed. This is possible since it is not necessary that the rate of diffusion or dissolution of air be the same at its release. Air can be dissolved in the water at a much faster rate due to pressure than it is released when the pressure is removed. An analogy can be seen in the process of opening a coke can or a beer bottle. Even after vigorous agitation and consequent opening of the can or the bottle, air can be seen to be released long after the initial rush of the released air. The same phenomenon is possible with respect to the air gain after pumping. It is possible for the air to be released long after the concrete is placed and thus air content can be expected to increase, when compared to the air content immediately after pumping. Due to the release of dissolved air into the larger bubbles there is an increase in air content. This dissolved air is from the smaller bubbles, and hence the number of smaller bubbles decrease and the number of larger bubbles increase. Thus, the air content increases since the air in smaller bubbles is under higher pressure and occupies lesser volume when compared to the larger bubbles. In the cases of concretes with slumps more than 7 inches (where water content may be on the high side), it is possible that the air loss is more due to the release of air into the atmosphere (which is permanently lost) from the surface of the exposed concrete. It is clear that to reduce air loss, pumping pressures on the concrete should be low (low resistance to flow) and water cement ratio should be low. Apart from this, the bubble film characters of the admixture will also play an important role. Admixtures producing films with low diffusion coefficient (low permeability to air) and thick bubbles, prevent diffusion and may minimize changes in the air void characteristics.

Another aspect of pressure effect on the air loss may be due to the boom angle. Boom angle is the smallest angle made by two consequent pipelines of the pump. Concrete pumped up over a sharp boom angle and then downward (as if in a free fall situation due to gravity) may experience a considerable amount of air loss (which is permanent in nature since evidence presented in Chapter V shows that this air does not return and is lost to the atmosphere). As a result of these conditions, the air loss may be greater when the boom angles are small or sharply configured [10]. This requires high pump pressures to pump the concrete against gravity apart from the resistance of the flow. At the peak angle of the boom, there is sudden release of pressure, due to the concrete falling freely and creating a vacuum (negative pressure) by gravity. Since the bubbles are subject to high pressure in the ascending angle, the sudden release of this pressure may burst the bubbles, just like the bubbles released from a beer bottle opened after shaking vigorously. The vacuum created also contributes to this effect. The steep down angle imparts greater acceleration to the concrete, and consequently, it may have tremendous impact as the concrete that passes through an elbow. This impact may release air bubbles from the concrete which causes the permanent loss of air referred to above.

When concrete is pumped at high pressures, the concrete velocity may be high at discharge and hence may have more residual pressure at the discharge point than necessary. This residual pressure is released suddenly as soon as the concrete comes out of the pipeline, expanding the bubbles rapidly and hence may burst the bubbles.

Use of superplasticizers in concrete may reduce the air loss due to the dissolution process. This is made possible by lower pumping pressures and water demand. Hence, the use of superplasticizers may reduce the apparent loss of air, but at the same time the combined use of air entraining admixture and superplasticizer may produce an inferior air void system. The use of superplasticizer for pumpable concrete may not be functional in all circumstances. The effect of pumping on the air void system when air entraining admixture and superplasticizers are used is an area for further research.

**Laboratory and Field Experiments Investigating Air Loss**

The following sections discuss the various laboratory and field experiments on air loss performed by different groups.

WACA Tests: Washington Aggregates and Concrete Association (WACA) conducted some field tests to determine the factors that may affect variations in air entrainment in pumped concrete [44]. The major variable of interest was the boom configuration. Four different boom configurations were studied [12]. Air content was tested by the pressure method and also linear traverse method (hardened concrete).

It was observed that configurations with steep increase and decrease of boom angle indicated a little air loss, but when the concrete was dropped from a height in this configuration, considerable air loss was observed. In the horizontal position the boom had no effect on the air and slump. In all cases except for one, it was observed from petrographic analysis, that the average bubble size and the spacing factor increased due to pumping. It appears that whenever a turbulent flow of concrete occurred through the elbow joints in the pipeline (under apparent "free-fall" conditions), a decrease in air content was observed. When the pipeline was kept full there was little change or even an increase in measured air content.

NRMCA Tests: National Ready Mix Concrete Association (NRMCA) conducted some tests to determine the effect of boom configuration and the effect of impact of falling concrete on the air loss in cement concrete [10]. Air content was recorded for mixes pumped with different boom and pump line configurations and different pumping rates in order to study the effect of pressure head, pressure change, rate of pumping, and impact on the air loss. Six tests were conducted for each run at the pump discharge and averaged to obtain the line air content. The pumping tests were conducted by recycling the concrete from the previous tests. Different mix designs were developed by adding the required amount of the coarse or fine aggregate to the previously tested concrete mix. A recycling admixture was used and appropriate amount of water was added to compensate for the loss of water in the pump. Concrete was pumped at three different pumping rates assigned as slow (8 to 10 strokes/min), medium (12 to 15 strokes/min), and fast (20 to 25 strokes/min). Laboratory tests were conducted to determine the effect of impact on falling concrete on the air content. Figure 23 shows the test set up and also the air loss for the tests [10].

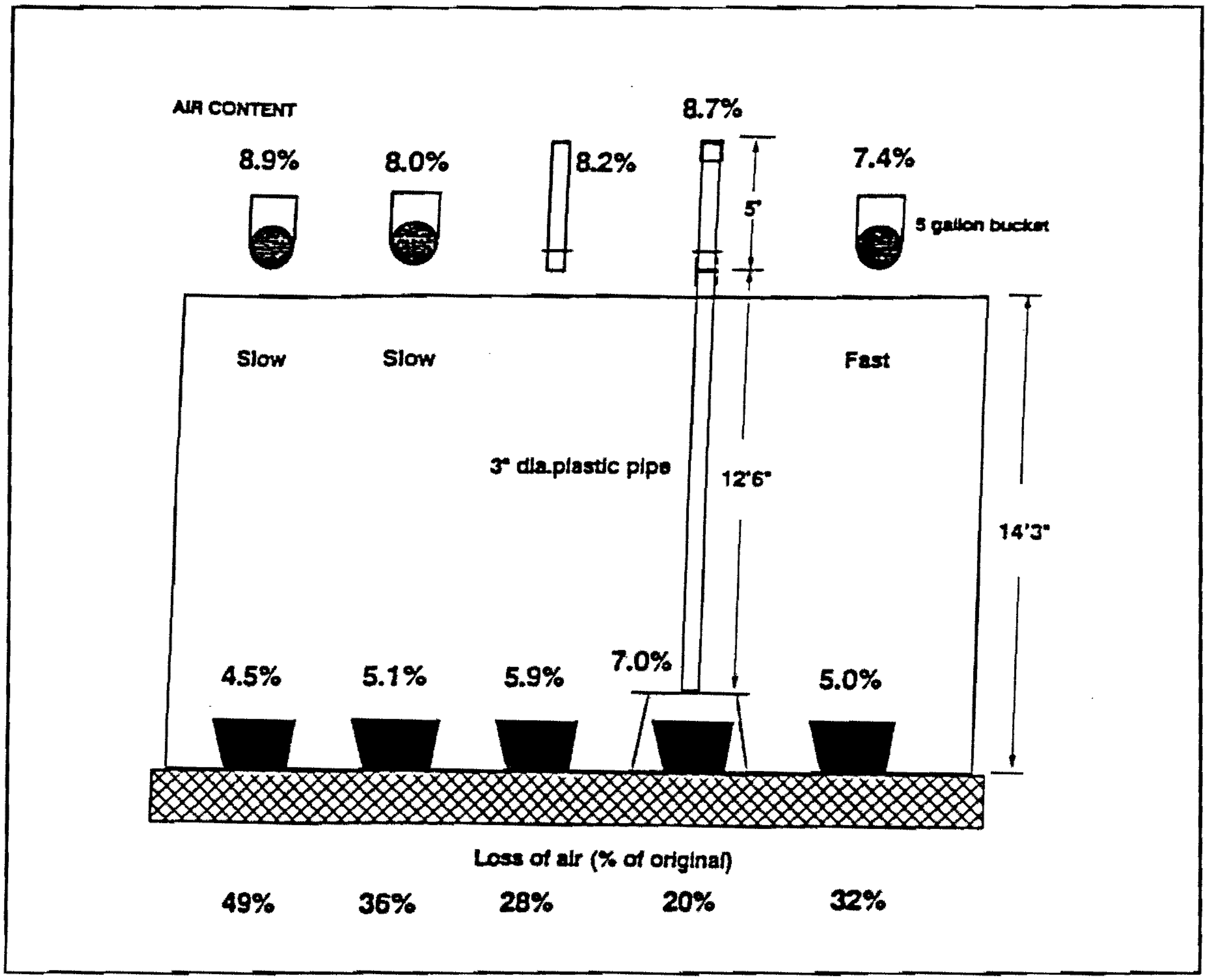


Figure 23. Effect of Dropping Concrete on Air Content [10].

The tests revealed that significant air loss occurred when concrete was pumped. However, air loss was minimum while pumping was conducted in a horizontal position of the boom, or at low boom angles. The influence of boom angle (difference between horizontal and vertical boom configuration) was not studied, but during the tests it was possible to hear concrete falling down a vertical boom section and impact on the

90-deg elbows that form the swivel at the end of each boom section. The impact of rapidly moving concrete appears to be a major factor in the permanent loss of air entrainment. It may be possible that a vacuum forming in the pump line or excessive pressure due to high boom angle and a sudden change in pressure at the discharge end may contribute to the air loss as previously described. In all the tests, slump was an important variable (Figure 24). The air entraining agent used (neutralized vinsol resin) was effective in stabilizing the air bubbles formed by remixing the concrete after pumping. Laboratory tests done for studying the effect of impact on concrete showed that air loss was maximum when concrete was simply dropped from the top and minimum when allowed to slide down a pipe (Figure 23).

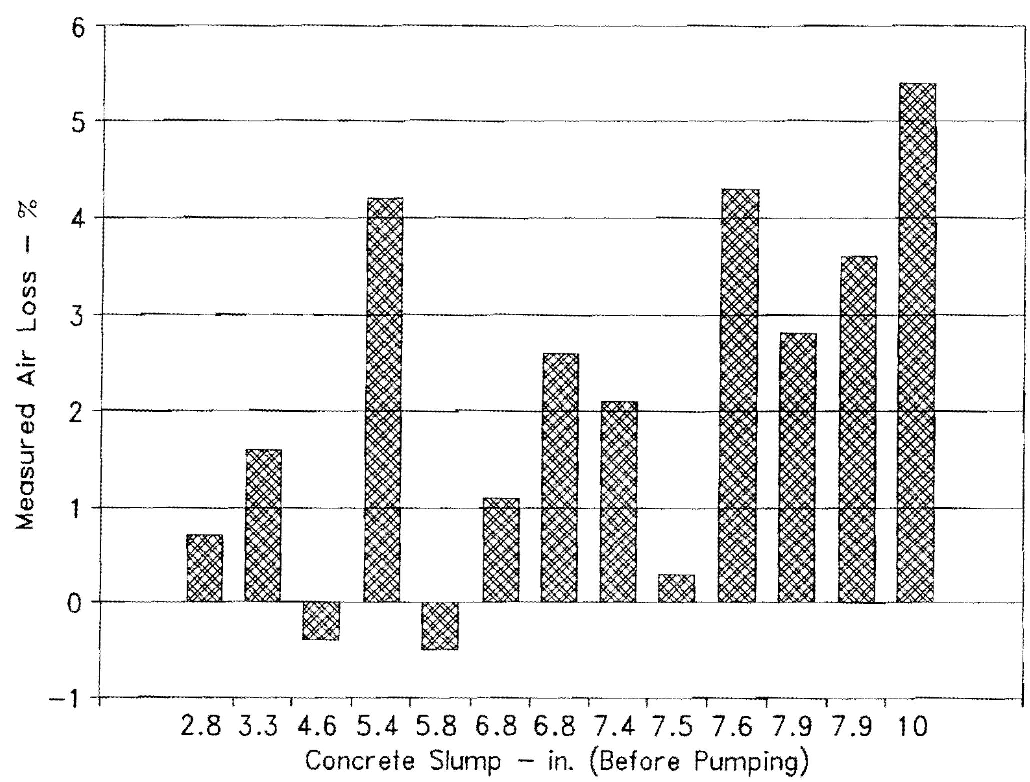


Figure 24. Effect of Slump in NRMCA Test Results.

Schwing America, Inc.: The effect of pumping on air loss was examined by conducting pumping tests by Schwing America, Inc. in White Bear, Minnesota. Different concrete mix designs were tested, and it was observed that slump of the concrete was the most significant factor affecting the air loss [12]. Use of a turbulator (described in Chapter IV) at the end of the pipeline also helped in reducing the air loss, perhaps due to the possible creation of back pressure to the concrete preventing a free fall effect. Dropping concrete from a height increased the air loss, and was proportional to the height of the drop. The impact of the concrete may permanently knock air out from the concrete mix.

Washington University: Laboratory experiments were designed and tested for the pressure effect on pumped concrete [45]. The tests were conducted to consider the effect of pumping pressure, more significantly the magnitude of the pressure and the duration of the pressure. Various pressures and durations were used to examine the effect. A modified chamber originally designed for moisture extraction from soils was used to pressurize fresh concrete. Pressure was provided by bottled nitrogen, with pressure magnitude read from the dial gage on the regulator attached to the nitrogen bottle. A schematic diagram is shown in Figure 25. In addition, the effect of negative pressure (vacuum) was studied. The vacuum was provided by a commercially available vacuum pump and read with mercury manometer.

The tests were conducted for single mix design with a slump of 4 inches and targeted air content of 7 percent. The concrete was tested for five different pressures (1500, 500, 150, 50, 12 psi), for three different durations (300, 60, 3 seconds) at each pressure. A retarding admixture was used in all the concrete mixes that were tested. The concrete mix design used for the tests is listed below:

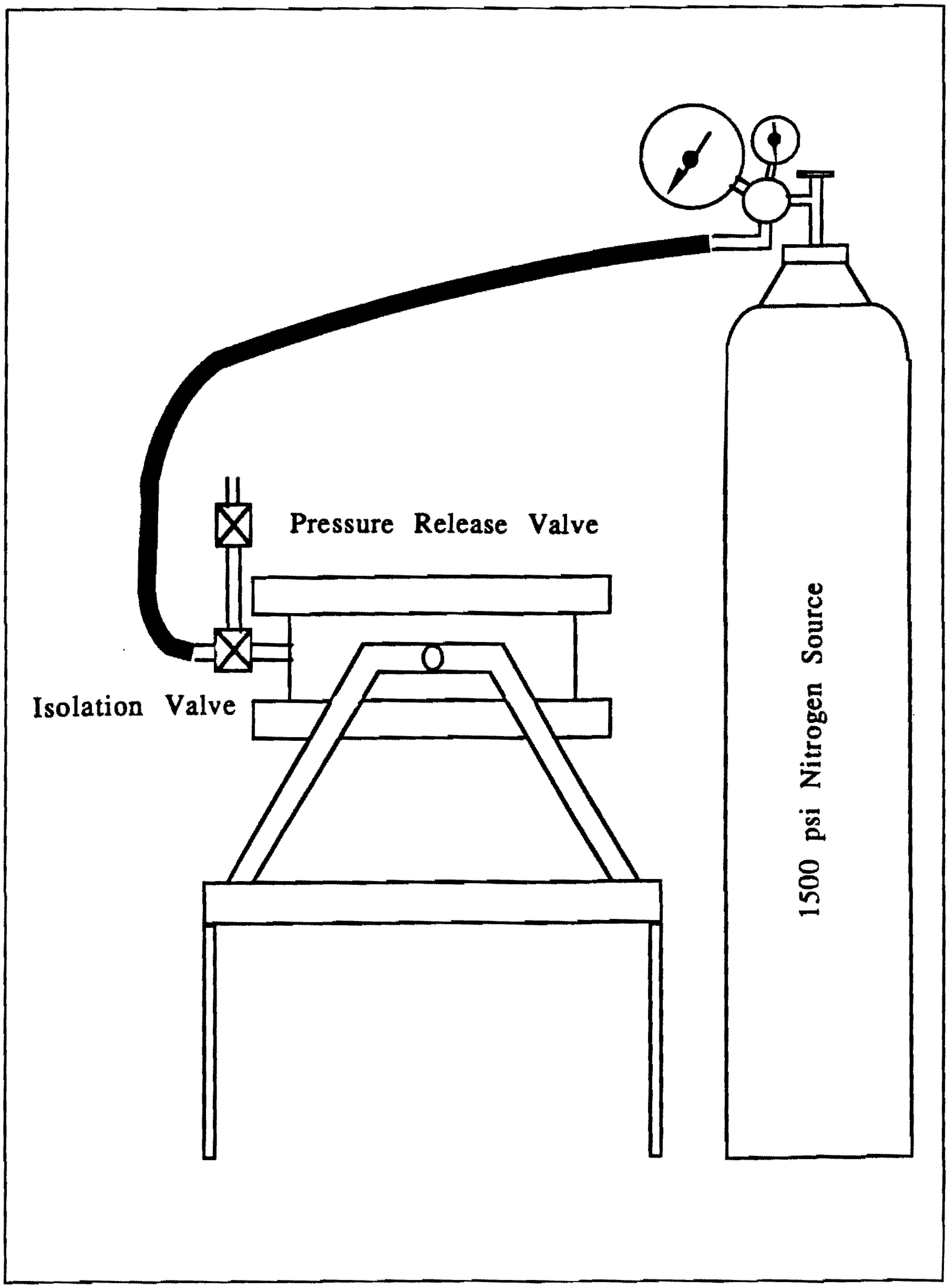


Figure 25. Schematic for Pressurization Apparatus [45].

| | Weight lbs/yd3 |
|---|---|
| Cement, Type I-II | 660 |
| Water | 240 |
| Fine Aggregate (SSD) | 1250 |
| Bulk S.G. SSD = 2.64 | |
| Adsorption = 2.1 % | |
| Coarse Aggregate (3/4") SSD | 1810 |
| Bulk S.G. SSD = 2.68 | |
| Adsorption = 1.1 % | |
| Air Entraining Admixture | 1.1 oz/c wt |
| Retarder | 5.5 oz/c wt |
| Water Cement Ratio | 0.36 |
| Target Air Content | 7 % |
| Target Slump | 4 inches |

The conclusions from this study are as follows [45]:

1. "Pressurization at constant pressures, in the range of pressures and for the durations tested, changes the air void system of concrete. Spacing factor tends to increase, and specific surface tends to decrease. The magnitude of these changes in job pumping conditions is expected to be less".

2. "Magnitude of constant pressure contributes more to the change in air void system than duration of pressure, over the range of magnitudes and durations tested. Time of pressurization has a minor effect".

3. "Air content can increase or decrease as a result of pressurization. This depends on a variety of variables, including time of testing, inherent properties of the mix, and degree of consolidation".

**Chord Length Distribution and Air Loss**

In the linear traverse method of measuring air content and the air void characteristics in hardened concrete, it is possible by a slight modification in the procedure to obtain actual chord lengths of the traversed air voids. Actual chord length data may be useful in developing distributions of chord length to examine correlations between chord length distribution parameters and air loss characteristics due to dissolution. Subsequent discussion in this section considers on the average the potential of such correlations. Typically, the chord lengths of the air bubbles are added cumulatively in each of the traverse lengths, but by noting the individual chord lengths, the chord length distributions are obtained for a sample of hardened concrete. The chord length distribution may be represented by log normal distribution [27]. A typical distribution curve is shown in the Figure 26. The density function of the chord length is given as:

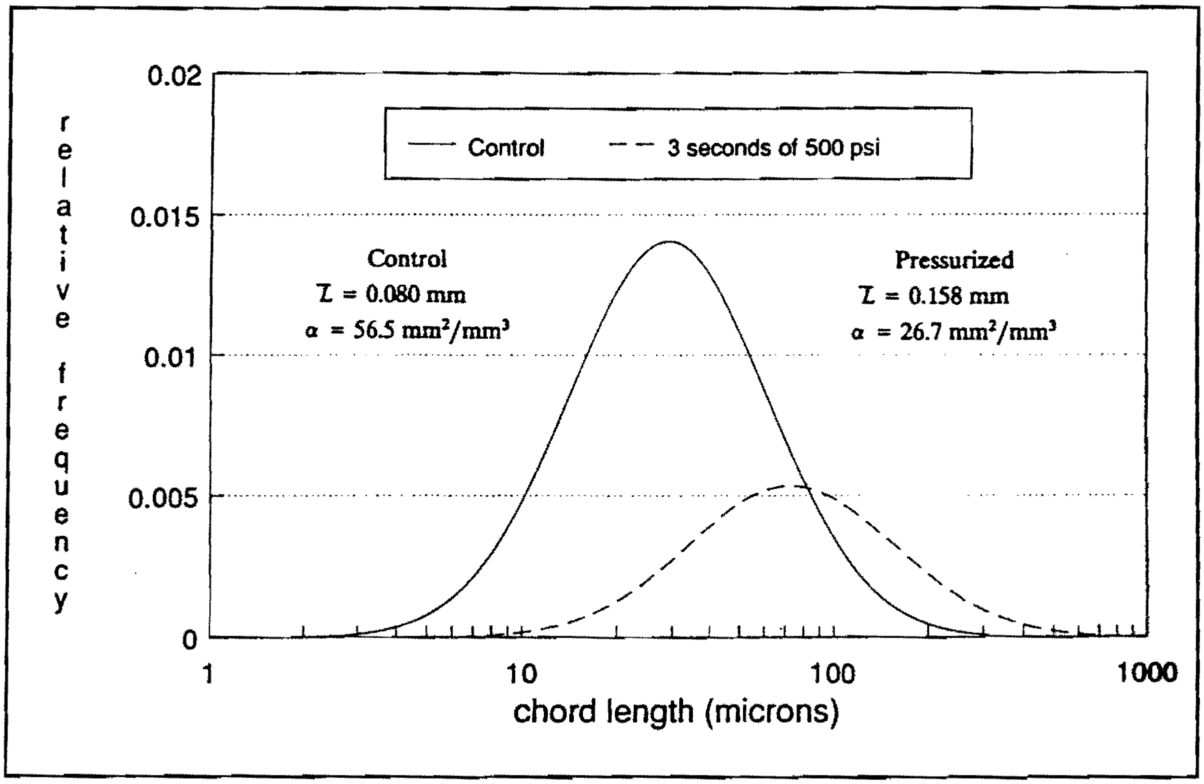


Figure 26. Typical Chord Length Distribution [45].

$$f_x(X) = \frac{1}{\sqrt{2}\ \pi \xi X}\ exp\left[\frac{-1}{2}\left(\frac{\ln x - \gamma}{\xi}\right)^2\right]\ 0 \le X < \infty \qquad (22)$$

where:

x = chord length,
$\xi$ = $\sqrt{}$var(ln X standard deviation, and
$\lambda$ = E(ln X) mean.

The chord length distribution can be characterized by the two parameters

$\lambda$ and $\xi$. The distribution of the chord lengths can be important in understanding the characteristics of an air void system. Also, it may be possible to associate the percentage of the air content lost to dissolution within a given interval between chord lengths where the potential of predicting the amount of air lost due to dissolution is considered subsequently by associating the area between two chord lengths on the abscissa. Accordingly, the parameters $\lambda$ and $\xi$ are related to the average chord length and the standard deviation of the chord length distribution. The average chord length and the standard deviation can be obtained from data obtained from the linear traverse method. It may be possible to correlate this data to the mix design and admixture type if sufficient data should be available to develop such calibrations. The chord length standard deviation can be obtained by standard procedures for the individual chord length data obtained in the linear traverse method. Determining the two parameters for a given sample distribution may provide a basis, subsequently explained, to estimate the air loss in fresh concrete due to pumping pressure. In other words, the distribution function, assuming that it represents the bubble distribution in fresh concrete, is used to examine the effect of pressure on the air bubbles in the concrete. To elaborate further, the data from the Washington University laboratory tests [45] is used since the maximum pressure data was not recorded for the pumping tests conducted in this study.

According to Mielenz, et. al. [14], the air bubbles in the fresh concrete with diameters less than 10 microns will not be preserved because of rapid dissolution of air bubbles as previously described. Therefore, 10 microns is used as a threshold bubble diameter for the evaluation of the potential correlation being air loss in pumped concrete and predicted air loss as illustrated in Figure 27. The before bubble distribution curve (with mean $D_1$) temporarily shifts to the left where the sizes of the bubbles (with mean $D_2$) decrease due to the pumping pressure. The distribution may not be the same under the application of the pressure, since compression of the bubbles is not a linear function of the applied pressure. However, the initial bubble size which is reduced to a bubble size of 10 microns ($D_2$) or less are assumed for purposes of

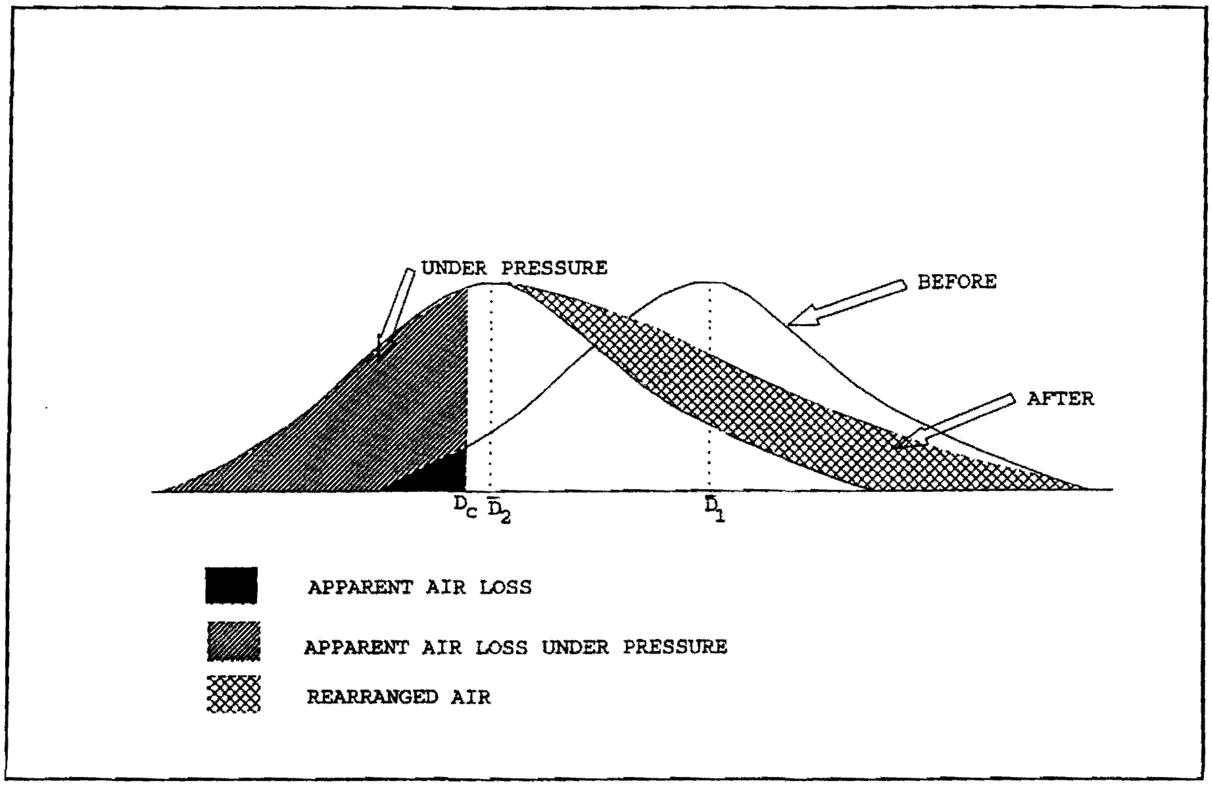


Figure 27. Air Loss Process in Concrete.

simplification to contain the volume of air lost in the dissolution process.

The actual compression of the bubbles can be obtained by applying Boyle's law of gasses. If the temperature is constant, we have:

$$P_1V_1 = P_2V_2$$

where

$P_1$ = Initial pressure in the bubble,
$V_1$ = Initial volume of the bubble before applying pressure,
$P_2$ = Initial pressure + additional pressure applied, and
$V_2$ = Resulting volume due to the increased pressure.

The initial pressure in the bubble, as previously pointed out, is the sum of the pressures due to the overlaying concrete, atmospheric pressure, and the pressure due to surface tension of air water interface (Equation 11). Neglecting the atmospheric and the overlaying concrete pressures, the initial pressure will be only due to the surface tension. Thus we have for the average bubble:

$$\overline{P}_1 = 4\gamma/\overline{D}_1 \qquad V_1 = \pi\overline{D}_1^3/6$$

$$\overline{P}_2 = \Delta P + 4\gamma/\overline{D}_2 \qquad V_2 = \pi\overline{D}_2^3/6$$

where $\Delta P$ is a pressure increase, $\overline{P}_i$ is the average bubble pressure, $\overline{D}_1$ is the initial average bubble diameter and $\overline{D}_2$ is the average bubble diameter under the applied pressure. Rearranging the above equation we obtain:

$$\overline{D}_1 = \overline{D}_2 \left(1 + \frac{\Delta P}{4\gamma} \overline{D}_2\right)^{1/2} \tag{23}$$

Applying the analogy of Mielenz with regard to the process of dissolution, in the case of concrete under pumping pressure, the bubbles which are compressed to a size less than 10 microns are dissolved into the water, as stated previously. The volume of air contained in these bubbles is rearranged in the form of larger bubbles after the pressure is removed where the size distribution of bubbles consists of bubbles greater than 10 microns as a result of bubble dissolution and re-arrangement of the air, as illustrated in Figure 27.

The initial bubble size before pressure is applied can be calculated from Equation (23), by substituting in a value for $D_2$ and knowing the pressure applied and the surface tension of the admixture. In effect, it may be possible to calculate the air lost by dissolution from the chord length distribution. However, the noted calculations are provided in terms of bubble diameter, requiring the bubble diameter distribution to be estimated from the measured chord data. A method to accomplish this is suggested by Lord and Willis [46] based on data obtained from the linear traverse method and theory of probability. It was noted by these authors that, as the chord interval becomes small, the chord distribution approaches the true bubble diameter distribution. Consequently, the data from the Washington University results shown in Figure 26 (where the chord intervals approach zero in the form of a continuous function), in terms of the Lord and Willis approach, may be taken as the bubble diameter distribution. The area under the curve that represents the air lost due to dissolution by the effect of the additional pressure due to pumping is indicated in Figure 27.

The critical bubble diameter under which air is lost may not be 10 microns as assumed; it may be greater if the pumping pressures are too high. Extensive data of chord lengths distributions of different concrete samples subject to pressure should be obtained to determine how the critical diameter may vary with pressure. It stands to reason that it is possible that air lost may occur from bubbles larger than 10 microns in diameter, and this air loss may be decrease proportionally as the critical bubble diameter decreases.

In Figure 27, the total air loss as shown may include the air that is permanently lost to the atmosphere and the air that is rearranged into larger bubbles. However, the bubble size frequency distribution may be different than that shown. It is important to measure air loss or air transfer in terms of mass, since air in the bubbles occupy different volumes for the same mass depending on the diameter of the bubble, as discussed earlier. The difference in the mass of the total air loss and the mass of the air that is rearranged in larger bubbles is the air that is lost to the atmosphere and is not recoverable. This loss is termed as permanent loss of air and is mostly due to the mechanical aspects of pumping or due to placement and finishing operations. The mass of air that is rearranged into the larger bubbles is the apparent loss, which is not lost to the atmosphere but is shifting within the air-void system. This air occupies, as previously pointed out, a larger volume due to relatively less pressure in the larger size bubbles, and hence air content may increase after applying pressure. The permanent air loss may not be critical in terms of frost resistance, since larger bubbles contribute little to the frost resistance. The bubble sizes that are affected due to the mechanical aspects of pumping are usually large (about 200 microns) in diameter. The contribution of the smaller bubbles to frost resistance is relatively greater, and hence loss of these bubbles may reduce frost resistance considerably. The apparent loss of air that occurs due to pumping pressures reduces the number of smaller bubbles and hence relative to the mechanical loss may be more critical.

Equation (23) gives the relation between the pressure, the surface tension of the admixture, and their effect on the air loss in terms of the initial bubble diameter which reduces in size after application of pressure. The relationship is graphically represented in Figure 28. From the figure, as the surface tension of the admixture increases, the initial diameter of the bubble decreases, i.e., apparent loss of air increases, assuming that the initial distribution and the critical diameter obtained for both low and high surface tension admixture mixes are the same. These assumptions may not hold true if high surface tension admixture produces considerably larger proportions of smaller bubbles (less than 50 microns). In this case, the area under the curve (less than $D_c$) may be more since the initial diameter $D_1$ for the high surface tension admixture is less. The expression shown in Equation 23 may suggest that $D_c$ would not be the same for AEA's with different $\gamma$'s and as a consequence, the use of high surface tension admixtures in combination with low pumping pressures should reduce the apparent loss of air (the $D_c$ in Figure 26 appears to be approximately 8 microns).

The data from Washington University tests are used to estimate the apparent air loss on the basis of $D_c$ equal to a 10 micron diameter. It should be noted that this calculated air loss is not the same as the actual observed air loss. The estimated air loss is the percent of air that is subjected to the dissolution process. The estimated apparent air loss is shown in Table 3. From the table, it is observed that the actual air loss in the case of low pressures appears to be relatively much more than predicted which may indicate the permanent loss in air apparently makes up a large portion of the actual air loss. This may be due to several reasons such as the small sample size used in the test and the concomitant loss of air to the atmosphere. Handling of a small size concrete sample increase the air loss to the atmosphere if sufficient time is not provided for the dissolved air to be released in the larger bubbles. The negative air loss may be due to excessive rearrangement of air (apparent air loss) within the concrete. Based on this analysis, it

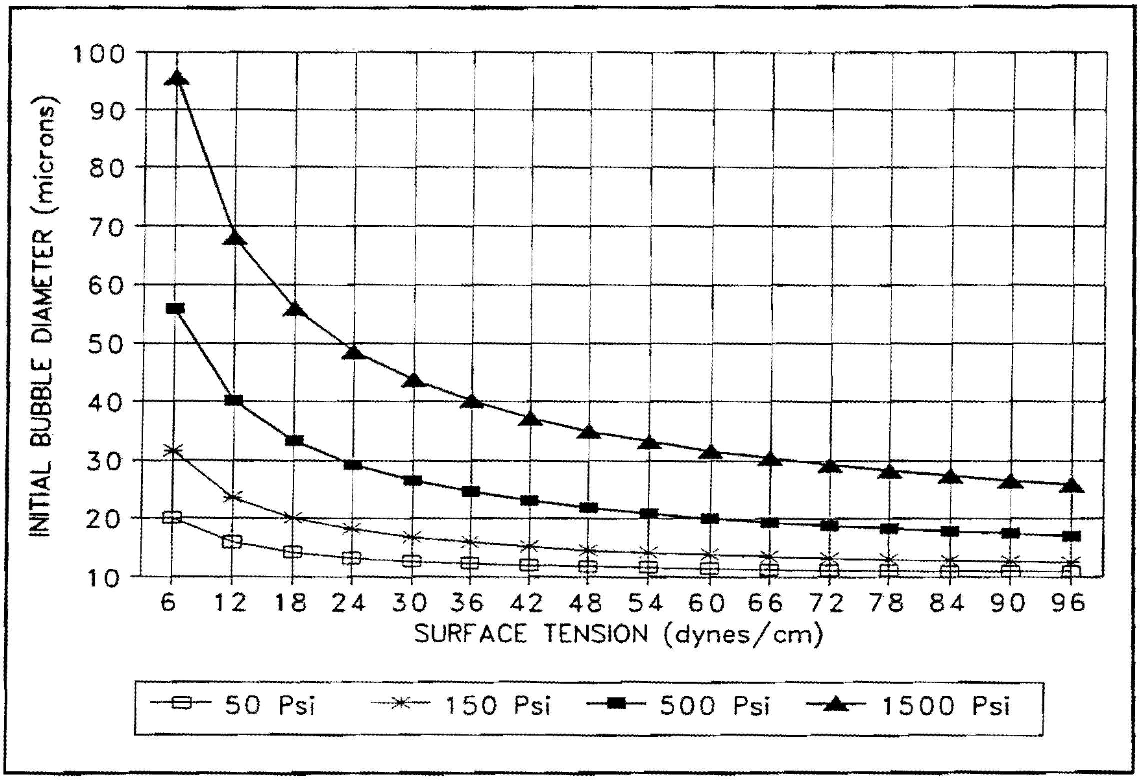


Figure 28. Relationship Between Pressure, Surface Tension of Admixture and the Initial Diameter of the Bubble.

does not appear that this procedure of estimating and calibrating air loss may not give accurate results. Consequently, no further results are presented on test samples obtained under the test program described in Chapter IV.

Table 3. Estimation of Air Loss by Dissolution.

| Max Press. Psi | Time Secs | Surface Tension dyn/cm | Avg. Chord microns | $D_1$ | $D_2$ | Initial Air Content% | Final Air Content% | Air Loss % | Est. Air Loss % | Air % |
|---|---|---|---|---|---|---|---|---|---|---|
| 50 | 3 | 36 | 81.1 | 12.26 | 10 | 9.6 | 8.2 | 1.4 | 0.05 | 0.55 |
| 50 | 60 | 36 | 70.2 | 12.26 | 10 | 6.0 | 6.0 | 0.0 | 0.05 | 0.82 |
| 50 | 300 | 36 | 66.1 | 12.26 | 10 | 6.3 | 5.7 | 0.6 | 0.04 | 0.71 |
| 150 | 3 | 36 | 78.9 | 15.84 | 10 | 9.0 | 7.7 | 1.3 | 0.10 | 1.16 |
| 150 | 60 | 36 | 78.9 | 15.84 | 10 | 7.6 | 8.1 | -0.5 | 0.15 | 1.98 |
| 150 | 300 | 36 | 60.9 | 15.84 | 10 | 4.8 | 6.4 | -1.6 | 0.11 | 2.38 |
| 150 | 300 | 36 | 73.4 | 15.84 | 10 | 7.6 | 7.9 | -0.3 | 0.12 | 1.57 |
| 500 | 3 | 36 | 66.2 | 24.57 | 10 | 6.0 | 6.5 | -0.5 | 0.50 | 8.35 |
| 500 | 60 | 36 | 73.2 | 24.57 | 10 | 7.2 | 6.7 | 0.5 | 0.49 | 6.82 |
| 500 | 300 | 36 | 82.6 | 24.57 | 10 | 9.2 | 7.2 | 2.0 | 0.21 | 2.25 |
| 1500 | 300 | 36 | 73.4 | 40.13 | 10 | 5.9 | 6.2 | -0.3 | 1.27 | 21.49 |

# CHAPTER IV
# EXPERIMENTAL DESIGN FOR PUMPING TESTS

The effect of various factors on the loss of entrained air in pumped concrete is the major part of this study. In order to quantify the significant factors affecting the loss of entrained air, a fractional factorial design (FFD) experiment was developed and conducted which incorporated concrete pumped under actual field conditions using a full-sized concrete pump, as explained later in this chapter.

As a result of preliminary investigations of variations of measured air content of pumped concrete conducted under this project, it appeared that there were four variables significantly affecting the air entrainment in the Portland Cement Concrete. These four variables are coarse aggregate factor, intermediate aggregate, surface tension of the admixture, and boom configuration (characterized by the apex angle of the boom). In order to reduce the number of tests to a manageable level, a partial factorial design was adopted to allow an efficient means of interpreting the test data.

## Significance of Pumping of Factors

The percent of coarse aggregate and the intermediate aggregate which are used for the mix design influence the flow resistance and the pressure required to pump concrete. Since it was shown in Chapter III that the effect on air entrainment due to pumping is directly related to pumping pressures and flow resistance of concrete, the aggregate gradation is considered to be a major factor. The coarse aggregate is characterized by the coarse aggregate factor. The coarse aggregate factor (CAF) is the ratio of loose volume of coarse aggregate to a unit volume of the concrete mix, which is typically a specified mix design parameter. The TxDOT nominal limits of CAF is 0.68 at the minimum and 0.82 at the maximum. The intermediate aggregate (IA -rounded pea gravel sized material) is the aggregate that falls in between the size of coarse aggregate and fine aggregate gradations and tends to fill the gap that occurs between the 3/8 inches to the #16 sieve sizes. The author's experience has shown that intermediate aggregate seems to reduce the pump pressures during pumping of fresh concrete and that concrete mixes with CAFs greater than about 0.74 are too difficult to pump and can significantly reduce pumping productivity.

The surface tension of the admixture (ADMIX) is related to the bubble stability, since bubbles are subject to pressures and shearing forces due to friction within and with the pipe wall. Under these conditions, obviously a more stable bubble is expected to survive the pressure variations. The formation of air bubbles in the concrete during mixing is largely dependent upon the reduction of surface tension of water. Each particular surface active compound differs as regards its ability to reduce the surface tension of water. The ability of the bubble to regain its shape when subject to deformation is dependent on the surface tension of the bubble film; hence surface tension of the admixture is an important factor. The boom angle of a pump has been observed to be a factor with regard to the air loss in several of the field experiments conducted by various groups, which were discussed in the previous chapter.

Consequently, the four variables (coded as $X_1$ through $X_4$) that were selected to be included in the partial factorial design based on their anticipated relative effect on the variation of entrained air in pumped concrete are:

- $X_1$: Coarse aggregate factor (CAF),
- $X_2$: Intermediate aggregate (IA gravel material),
- $X_3$: Surface tension of the air entraining admixture (ADMIX), and
- $X_4$: Boom configuration (BOOM).

**Laboratory Test for Surface Tension**

The surface tension of the various state approved admixtures was determined by the capillary rise method. The results are shown in Table B-9 in Appendix B. The surface tension of a liquid by the capillary tube method is determined by the following expression:

$$h = \frac{2\gamma}{r\rho g} - \frac{r}{3} \tag{24}$$

where

$h$ = Height of the capillary rise (L)
$\gamma$ = Surface tension (F-L)
$r$ = Radius of the capillary tube (L, $r = 0.0285$ cm)
$\rho$ = Density of the liquid ($Ft^2L^{-4}$)
$g$ = Acceleration due to gravity ($Lt^{-2}$)

and a procedure referred to as the "single capillary rise" method pointed out in reference 49. The procedure is relatively straightforward, consisting of the placement of a capillary tube of a prescribed radius vertically into a liquid and measurement of the height of capillary rise above the free surface of the liquid. T is calculated from the expression shown in Equation 24.

**Test Procedures**

The testing procedure referred to above that was followed to carry out the field experiments associated with the test conditions of the factorial design is detailed in Figure 29. The figure is self-explanatory as to the types and sequencing of tests conducted during the field work. Generally speaking, the testing process involved the determination of air contents and slumps before the concrete was pumped and immediately and 30 minutes after pumping. Air content tests were measured using the Type B pressure meter and repeated 3 times (simultaneously by a team of trained Laboratory workers) to establish a mean and standard deviation of the test parameter. In addition, placement operations were simulated by means of vibrating 1 cubic foot concrete samples for 10 to 15 seconds after pumping to examine the effect of vibration on air loss. The vibrator consisted of an electric handheld immersion type vibrator. Air content tests were also conducted for concrete pumped while a turbulator was connected to the end of the pump hose. The turbulator is an experimental device constructed by

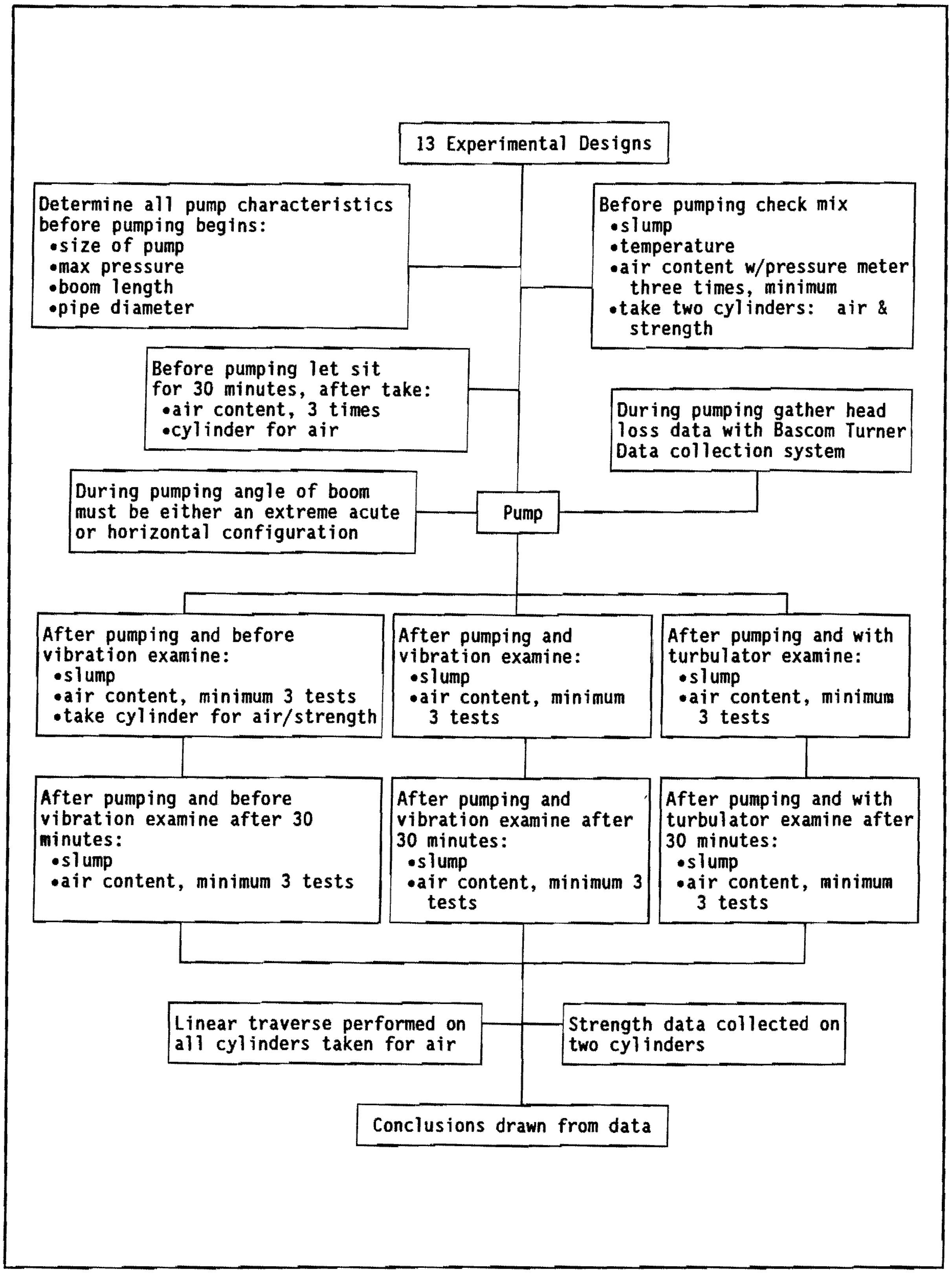


Figure 29. Experimental Procedure for Pumping Tests.

Construction Forms, Inc., of Cederburg, Wisconsin, and is shown in Figure 30. The effect of this device is to provide some backpressure to the flow of concrete as it exits the pump hose. The turbulator consists of steel spiral bevels (as shown in Figure 32) on the inside to slow the flow of concrete at the end of the hose where it is attached.

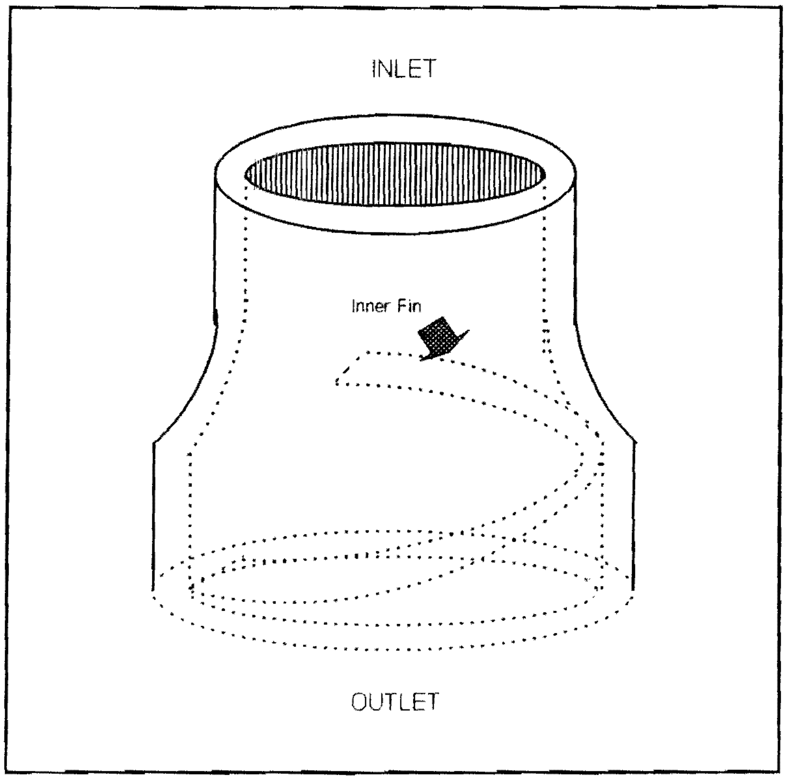


Figure 30. Turbulator Manufactured by Construction Forms Inc.

**Fractional Factorial Design**

Statistical methods for experimental designs are an invaluable asset when used properly. One method of such experimental design is the factorial design, which is useful when it is necessary to study the effect of various factors involved in a particular phenomenon. Factorial designs constitute a powerful way to simultaneously experiment with several factors, revealing the extent and nature of variable interactions in a straightforward manner. Appendix C describes the details of a $2^n$ factorial design referred to later in this section. However, the results of a $2^n$ factorial design can be conducted geometrically and can be easily interpreted. The tests are conducted by choosing values for low and high level of each factor, i.e. the affect of each factor can be studied when its level increases from a low level to a higher level. By this method, apart from the main effect, the interactions of the factors can also be estimated. The main effects are represented as $E_x$ and the interactions are represented as $E_{xx}$.

A basic factorial design is the $2^n$ factorial design with n factors involved and requires $2^n$ tests for a full factorial design. A complete $2^3$ factorial design requires 8 tests. A complete $2^4$ factorial requires 16 tests, and if only 8 tests are available (due to budget restrains, etc.) then the factorial design becomes a $2^{4-1}$ Fractional Factorial Design (FFD). A factorial design, in which only a fraction of tests are conducted, is called a fractional factorial design. The purpose of fractional factorial designs are to eliminate the insignificant factors so that with the remaining factors a full factorial design can be set up and analyzed. The analysis process involved with a $2^3$ factorial design results in the computation of main ($E_x$) and interaction effects ($E_{xx}$). If a main effect is significant, then the sign of the effect describes how the variable it is associated with changes, on the average, from a low level to a high level while the magnitude of the effects tells the strength of the effect. If an interaction effect is significant, then it describes how the average effect of two or more variables changes from a low level to a high level due to the variable interaction. As for the structure of a $2^{4-1}$ FFD, some main effects or interaction effects will be confounded with each other until the unimportant variables can be eliminated. Therefore, the analysis process associated with the use of an FFD is to screen significant variables to be included in a $2^3$ mathematical model.

On this basis, the focus of FFDs is to conduct experiments on the broadest scope possible at the least amount of cost (using only 8 tests), as was the case for the pumping experiment. A $2^{4-1}$ FFD was designed to limit the number of test runs but a few extra tests were conducted for replication purposes and to produce enough data to "un-confound" the main effects in the screening process. All totaled, there were 12 experimental combinations run in the experiment, as indicated in Appendix B, Table B-1. Experimental test runs 7a, 8a, and 12a serve as replicated tests. As pointed out before, the results in Table 5 are grouped into two sets of 8 tests. The second group serves as a "mirror image" [50] of the first group to aid in the calculation and the "un-confounding" of the main effects.

The computations involved with a $2^{4-1}$ FFD are similar to those associated with a $2^3$ factorial design, which is illustrated in Appendix C and consequently is not elaborated here other than to point out that an FFD assumes that some interaction effects are not as important as others. With this premise, some of the main effects can be assigned to the interaction effects. The analysis in Appendix C suggests that the $E_{12}$ interaction is not significant which means, in terms of the FFD, that the variable $X_4$ (boom configuration) can be assigned to the $E_{12}$ interaction. As noted in Appendix C, the $E_{12}$ interaction was also not significant when a turbulator was used.

Different types of data pertaining to the pumping experiment and the experimental design are listed in Appendix B. Tables B-1 to B-9 list general information, mix design data, and concrete pumping and air tests results. Three types of concrete mix designs were used in the experiment. Every pump test consisted of using a mix design which had certain characteristics with respect to coarse aggregate factor (CAF), intermediate aggregate (IA), admixture type (Admix different air entraining agents [AEA] depending on the measured surface tension), and boom configuration (Boom) which were held at one of two levels high or low. These levels are tabulated in Table 4.

Table 4. Design Factorial Test Conditions.

| Variable | Coarse Aggregate Factor CAF | Intermediate Aggregate IA | Surface Tension ADMIX | Boom BOOM |
|---|---|---|---|---|
| Factor | $X_1$ | $X_2$ | $X_3$ | $X_4$ |
| Unit | Percent | Pounds | Dyne-cm | Angle |
| Low Level | 0.57 | 0 | 26 | 170 |
| High Level | 0.72 | 560 | 34 | 30 |

One set or combination of test levels constitutes a an experimental run. The list of experimental runs and their associated combinations or designs are listed in Table 5. Table 5 shows two standard orders (one being the mirror image design [50]) consisting of 8 tests each, which will be explained subsequently, but the test results associated with these numbered runs are given in Appendix B, Table B-7 and Table B-8.

The concrete mix designs, shown in Appendix B, are associated with 3 different combinations of CAF and IA shown in Table 6. It should be pointed out that the high level combination for both CAF and IA could not be pumped; consequently, a mix design for this combination was not included in the experimental tests. However, values were assigned (discussed later) in the analysis of the factorial data to complete the matrix of data points in the calculation process.

Slump Correction: In most instances where air loss was encountered during the execution of the factorial design, relatively high slumps were measured for the concrete mix. It was of interest in the analysis to minimize the effect of slump in the variation of the measured air contents. For the range of slumps considered, an adjustment of the test data was made due to the slump effect. From data collected at a bridge construction site over the Houston Ship Channel on SH 146 and from other previous studies indicate that slump is also a factor in the amount of air loss which may occur during pumping operations (Figure 31). Due to this effect, it was of interest to correct the pumping data (in terms of percent air loss) to a common slump of 5 inches. An expression was developed which relates percent air loss to the slump of the concrete and was used in correcting the test data ($r^2$ = 0.55, see = 0.275):

$$\%\text{Air Loss (Y)} = \exp\,(a + b/\text{slump}) \tag{25}$$

where

| | | |
|---|---|---|
| a | = | 1.26 |
| b | = | -2.98 |
| Note: see | = | standard estimate of the error |

Table 5. Factorial Design and Corresponding Measured Air Loss (%).

| Order | Test # | $X_1$ CAF | $X_2$ IA | $X_3$ Admix | $X_{4=12}$ Boom | Air Loss % B - A | Adj Air Loss % | Air Loss % B - AT | Adj Air Loss % |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | - | - | - | + | 0.067 | 0.936 | 0.166 | 0.703 |
| 2 | 10 | + | - | - | - | 3.333 | 2.907 | 1.500 | 1.08 |
| 3 | 6 | - | + | - | - | 0.333 | 1.077 | -0.217 | 0.480 |
| 4 | 15 | + | + | - | + | | 2.032 | | 2.58 |
| 5 | 4 | - | - | + | + | 0.116 | -0.169 | 0.216 | -0.07 |
| 6 | 9 | + | - | + | - | 0.530 | 0.171 | 0.400 | 0.041 |
| 7 | 8 | - | + | + | - | 0.520 | 0.439 | 1.517 | 1.44 |
| 8 | 13 | + | + | + | + | | 0.700 | | 0.567 |
| 1 | 14 | + | + | + | - | | -0.014 | | 1.75 |
| 2 | 5 | - | + | + | + | 0.900 | 0.415 | 1.200 | 0.715 |
| 3 | 11 | + | - | + | + | -0.367 | 0.116 | -0.700 | -0.22 |
| 4 | 1 | - | - | + | - | 0.500 | 0.624 | -0.400 | -0.28 |
| 5 | 16 | + | + | - | - | | 2.637 | | 0.707 |
| 6 | 7 | - | + | - | + | 0.959 | 1.154 | 0.925 | 1.12 |
| 7 | 12 | + | - | - | + | 2.050 | 1.814 | 2.150 | 2.16 |
| 8 | 3 | - | - | - | - | 1.633 | 1.348 | 1.133 | 0.848 |

Table 6. Major Mix Design Factorials.

| Mix Design | CAF | IA | Factorials |
|---|---|---|---|
| 1 | - | - | 1 - 4 |
| 2 | - | + | 5 - 8a |
| 3 | + | - | 9 - 12a |

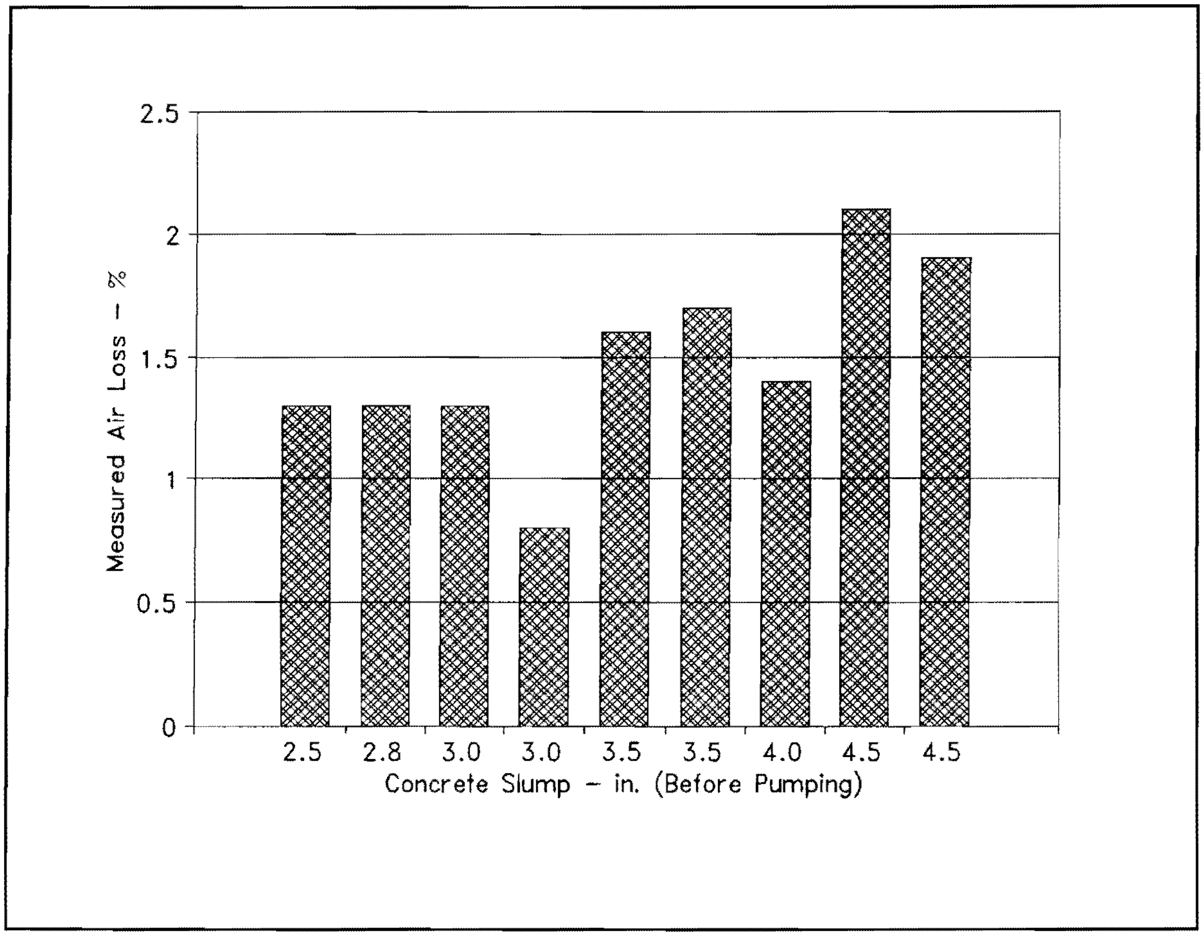


Figure 31. Effect of Slump on Loss of Air.

A slump of 5 inches was selected since it was close to the average slump of the factorial mixes.

<u>Missing Data Estimation</u>: It was pointed out previously that test runs containing certain combinations of CAF and IA (high level combinations of each - factorial designs 13 through 16) could not be pumped. With this limitation, missing data points resulted in the factorial matrix. When this occurs in the course of an experiment, one option is to drop an entire block or combination of variable levels from the analysis. However, this option is somewhat unappealing from the standpoint that some useful information is available in the remaining combinations (in this instance, this is the data pertaining to a high level of CAF and low

level of IA); therefore, a procedure is used to estimate the missing experimental data. The sole purpose of using such a procedure is to facilitate the factorial analysis, thus salvaging the remaining data in the block where the missing observations are located. Therefore, the results of certain test runs were combined to develop what was expected to be the measured percent of air loss for the test run combinations which could not be conducted in the field. To explain further, if test run 4 was subtracted from test run 5 and 11 and then these differences added to test run 4, then test run 13 would result, as shown below:

| | $X_1$ | $X_2$ | $X_3$ | $X_4$ |
|---|---|---|---|---|
| Run 5: | - | + | + | + |
| Run 4: | - | - | + | + |
| | 0 | + | 0 | 0 |

plus

| | $X_1$ | $X_2$ | $X_3$ | $X_4$ |
|---|---|---|---|---|
| Run 11: | + | - | + | + |
| Run 4: | - | - | + | + |
| | + | 0 | 0 | 0 |
| plus Run 4: | - | - | + | + |
| equal Run 13: | + | + | + | + |

Following this process, air loss percentages were determined for test runs 13, 14, 15, and 16 by combining the test runs listed in Table 7.

Table 5 also lists air loss (percent) results by comparing the after (A) pumping measured air contents (using the pressure 'B' type meter) to the measured air contents before (B) pumping. The difference between these conditions is the

Table 7. Estimation Process for Missing Data Points.

| Factorial | Combination |
|---|---|
| 13 | (5 - 4) + (11 - 4) + 4 |
| 14 | (8 - 1) + ( 9 - 1) + 1 |
| 15 | (7 - 2) + (12 - 2) + 2 |
| 16 | (6 - 3) + (10 - 3) + 3 |

computed or measured air loss in percent. The pumping conditions when a turbulator was connected to the end of the line are also included in Table 5. Both of the resulting air loss computations were adjusted to a common slump of 5 inches and provided in the table.

**Measurement of Line Pressure**

In addition to the air content and slump tests, an attempt was made to measure the in line concrete pressure. A pressure transducer was used to at record pressure data (Figure 32). It was connected in line with the pipeline, line, about 10 feet from the reducer. The method consists of measuring the line pressure continuously by the strain developed in the short section of calibrated pipe line. The results are recorded in terms of voltage change from a bridge of electrical resistance strain gages mounted on a reduced section of the pipe wall. A strip chart pen recorder was used to monitor the results, allowing adjustment of the chart speed and enabling instantaneous observation of the data (Figure 33).

**Gravimetric Method**

Gravimetric Method of air content measurement uses the unit weight of the concrete to determine the percentage of air content. The unit weight of the concrete for each of the concrete batches was measured by weighing the base of the pressure meter filled with concrete. The data collected is shown in Table B-8 Appendix B. The air content calculated by this method is compared with the pressure method results in Figures E-1 to E-8. In all, it was observed in the results of the pressure method and the gravimetric methods that similar trends in terms of the air content were evident and hence statistical analysis of the gravimetric method were not performed.

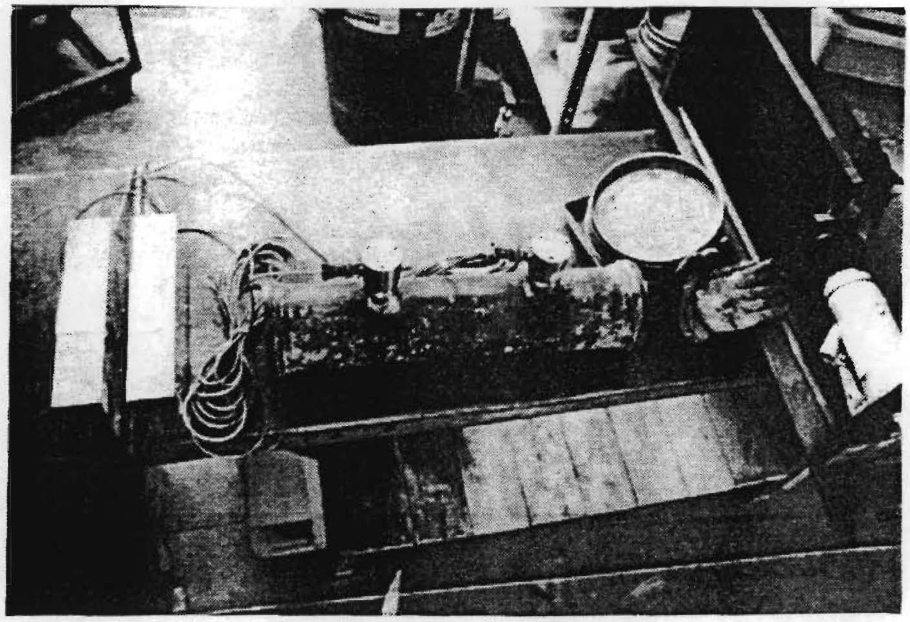

Figure 32. Pressure Transducer.

**Linear Traverse Method**

Petrographic analysis using linear traverse method was performed on the samples of factorial numbers 1, 2, 5, 9, and 10. The results are summarized in Table 8. It should be noted that the high slumps were obtained due to the use of higher water cement ratio only, as other admixtures were not used for the concrete mixes tested.

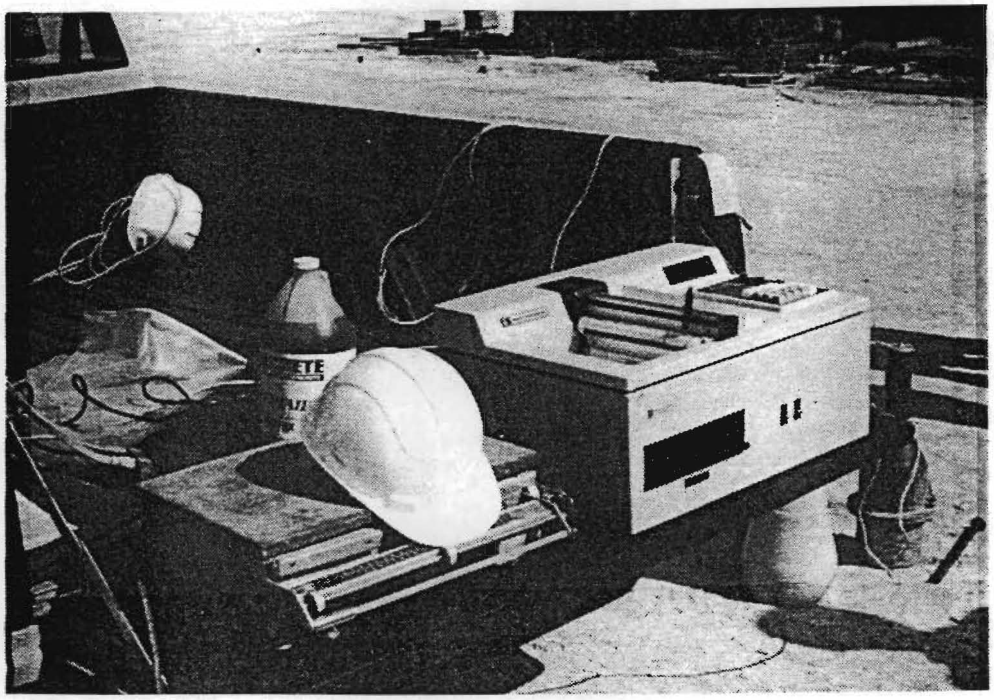

Figure 33. Strip Chart Recorder.

Table 8. Linear Traverse Results.

| # | Design | | Slump in | Air Content A | Voids per Inch n | Avg. Chord Ī | Paste Percent P | P/A Ratio | Specific Surface @ | Spacing Factor [ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | - - + - | B | 4.500 | 4.589 | 5.331 | 0.0086 | 25.58 | 5.573 | 464.625 | 0.0105 |
| | | A | 4.875 | 3.411 | 6.123 | 0.0056 | 26.06 | 7.640 | 717.912 | 0.0078 |
| 2 | - - - + | B | 2.500 | 3.972 | 2.575 | 0.0154 | 23.74 | 5.978 | 259.361 | 0.0194 |
| | | | 2.375 | 4.033 | 2.884 | 0.0134 | 24.42 | 6.054 | 286.053 | 0.0177 |
| 5 | - + + + | B | 7.750 | 7.120 | 9.599 | 0.0074 | 25.92 | 3.640 | 539.275 | 0.0068 |
| | | A | 7.500 | 4.588 | 6.761 | 0.0068 | 27.99 | 6.102 | 589.416 | 0.0086 |
| 9 | + - + - | B | - | 6.886 | 12.01 | 0.0057 | 20.81 | 3.021 | 700.117 | 0.0043 |
| | | A | - | 6.303 | 9.092 | 0.0069 | 26.08 | 4.137 | 576.952 | 0.0072 |
| 10 | + - - - | B | 7.500 | 5.271 | 9.462 | 0.0056 | 26.52 | 5.032 | 718.044 | 0.0065 |
| | | A | - | 6.330 | 8.612 | 0.0073 | 26.68 | 4.215 | 544.737 | 0.0079 |

Note : Design indicates the level of each factor in the order CAF, IA, ADMIX, and BOOM.
- Indicates a low level,
+ Indicates a high level, and
# Indicates factorial number.
B - Before pumping.
A - After pumping.

## CHAPTER V
## RESULTS AND SUMMARY OF RESULTS

In this chapter the results obtained by the linear traverse method and the pressure method are analyzed. Fractional factorial design of experiments was used to determine the key factors that control the air loss mechanism; with unimportant factor(s) eliminated from further analysis, a full factorial design was adopted to characterize the remaining factors. The results of linear traverse method were used to understand the mechanism of air loss. Finally a comparison of the pressure method and the linear traverse method is presented, and the possible reasons for the variations are discussed.

**Two Level Fractional Factorial Designs (FFD)**

Table 9 lists the variable effects used in the screening analysis and their confounding effect in which the 3 factor interactions ($E_{xxx}$) are assumed to be insignificant. In the table, B - A refers to the air loss

Table 9. Results of FFD Analysis.

| Factor | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_{12}$ | $E_{13}$ | $E_{23}$ | $E_{123}$ |
|---|---|---|---|---|---|---|---|---|
| Confounding Effect | $E_{24}$ | $E_{14}$ | $E_{1234}$ | $E_{12}$ | $E_4$ | $E_{234}$ | $E_{134}$ | $E_{34}$ |
| B - A | 0.315 | 0.014 | 0.0 | 0.0 | - | -.651 | 0.113 | 0.417 |
| B - AT | 0.033 | 0.260 | -.069 | 0.069 | - | -.448 | 0.542 | -.421 |

in concrete due to pumping and B - AT denotes the air loss in concrete after pumping with turbulator connected at the discharge end. Due to the number of extra tests that were conducted during the field testing, all of the main effects were unconfounded. Apparently neither of the effects of boom configuration or admixture are strongly significant in the screening process. Neither of these effects appear to be more significant than the other in the $E_{13}$, $E_{23}$, and the $E_{34}$ interactions. Both of these are alternatively considered with respect to the development of a mathematical model as subsequently explained.

With the elimination of either the boom effect or the admixture effect, the test runs can be re-ordered to increase the number of replications based on 8 test conditions and the percent air losses associated with B - A and B - AT can be re-computed, as shown in Table 10. As previously explained, the differences shown in Table 10 are based upon adjusted air losses due to slump. Table 10 and Table 11 list the resulting equation coefficients for the mathematical model given in Appendix C using the CAF, IA, and Admix main effects and for the CAF, IA, and Boom main effects, respectively. The mathematical models represented in these tables seem to fit the field observations reasonably well since the residual errors (difference between the estimated Y and measured y) appear to be randomly distributed as shown in Figure 34. Listed in tables are the levels of significance associated with each equation coefficient.

Table 10. Standard Order Based on Screened Results.

| Order | Factorial | $X_1$ | $X_2$ | $X_3$ | % Air Loss B - A | % Air Loss B- AT |
|---|---|---|---|---|---|---|
| 1 | 2 & 3 | - | - | - | 1.142 | 0.775 |
| 2 | 10 & 12 | + | - | - | 2.362 | 1.618 |
| 3 | 6 & 7 | - | + | - | 1.116 | 0.801 |
| 4 | (15 & 16) | + | + | - | 2.335 | 1.643 |
| 5 | 1 & 4 | - | - | + | 0.228 | -0.173 |
| 6 | 9 & 11 | + | - | + | 0.144 | -0.088 |
| 7 | 5 & 8 | - | + | + | 0.427 | 1.076 |
| 8 | (13 & 14) | + | + | + | 0.344 | 1.160 |

Table 11. Mathematical Model and Test of Significance (CAF, IA, and Admix).

| Factor | $b_o$ | $b_1$ | $b_2$ | $b_3$ | $b_{12}$ | $b_{13}$ | $b_{23}$ | $b_{123}$ |
|---|---|---|---|---|---|---|---|---|
| B - A | 1.012 | .284 | .043 | -.727 | 0 | -.326 | .057 | .153 |
| B - AT | 0.852 | .232 | .319 | -.319 | 0 | -.190 | .306 | .105 |
| $\alpha_A$ | - | < 1% | N/S | < 1% | - | < 1% | 49% | 7.5% |
| $\alpha_{AT}$ | - | < 1% | < 1% | < 1% | - | 2% | < 1% | 21% |

Note: N/S = Not Significant.

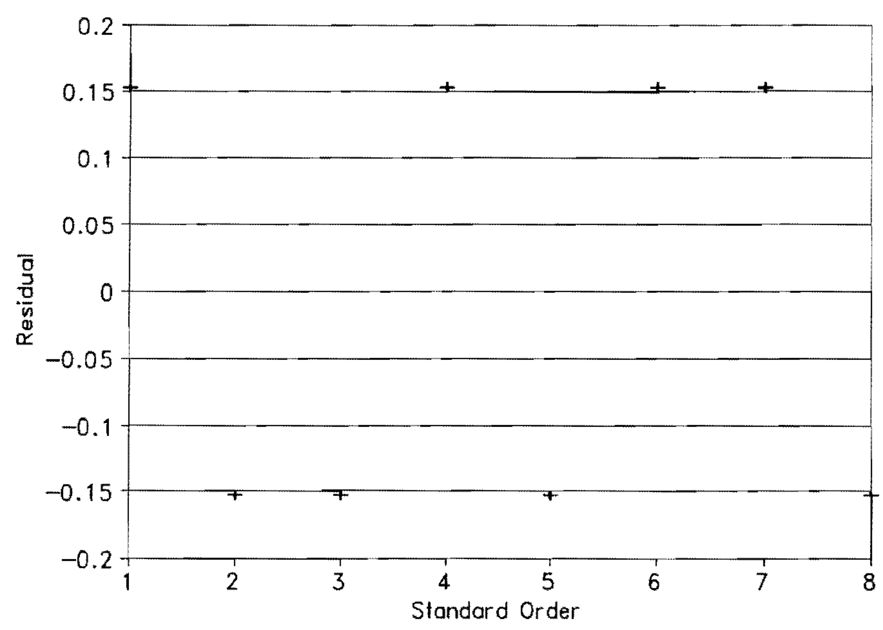


Figure 34. Residual Error for B - A Mathematical Model.

The test of significance ($\alpha$) was based on the calculated variance of the variable effects (V[E]):

$$
\begin{aligned}
V[E] &= V[1/12\{y_{a2} - y_{b2} - y_{c2} - \ldots - y_{a7} - y_{b7} - y_{c7}\}] \\
&= 1/144\ \{\sigma^2 + \sigma^2 + \ldots + \sigma\} \\
&= 24/144\ \{\sigma^2\} = \sigma^2/6
\end{aligned}
$$

The variance of all the effects is assumed to be equal and is determined from the pooled sample variance ($S^2_p$ - shown later in equation 26 and the variance of the difference ($S^2_{\bar{d}}$) between the mean percent air losses that are listed in Table 12. The calculated V[E] for the B - A mathematical model is 0.025 and for the B - AT model 0.021. The values given in Table 11 are provided since the effect of the boom configuration was nearly as significant as admixture based on the screening results.

Table 12. Mathematical Model and Test of Significance (CAF, IA, and Boom).

| Factor | $b_o$ | $b_1$ | $b_2$ | $b_4$ | $b_{12}$ | $b_{14}$ | $b_{24}$ | $b_{124}$ |
|---|---|---|---|---|---|---|---|---|
| B - A | 1.012 | 0.284 | 0.043 | -0.137 | 0 | 0 | .157 | .069 |
| B - AT | 0.852 | 0.232 | 0.319 | 0.094 | 0 | 0.096 | -.02 | .034 |
| $\alpha_A$ | - | < 1% | N/S | 10% | - | - | 7% | 43% |
| $\alpha_{AT}$ | - | < 1% | < 1% | 27% | - | 26% | N/S | N/S |

Note: N/S = Not Significant.

On the average, the concrete pumped using a turbulator experienced a decreased amount of air loss as indicated by the $b_o$ term in the equation. However, some combinations (CAF, IA, and Admix or Boom) will cause a greater amount of air loss to result. The models shown in Table 10 and Table 11 indicate that the effect of including an intermediate aggregate in the mix design will cause a greater amount of air loss due to pumping. This result is very surprising and appears to be contradictory to the experience during the field testing. Based on the effect that including the intermediate sized material had on friction loss and pump pressure, it was anticipated that the value of $E_2$ should carry a negative sign. However, the value of $E_2$ appears to be insignificant (except for where a turbulator is used) as indicated by the results shown in Table 10, Table 11 and Table B-7 in Appendix B. The effect of CAF appears to be significant and in all instances a lower amount of air loss was experienced with low CAF's, and therefore, it may be appropriate to consider some modifications, in this regard, to the current mix design specifications for pumpable concrete.

Table B-7 in Appendix B lists other categories of data collected during the controlled field testing. Mathematical models are not developed from these groups of data but are analyzed from a "hypothesis test" perspective. Hypothesis testing is one way to examine the significance of a difference in air content between two different treatments or categories of data. A test of a hypothesis is a comparison of assumed direction in the test results to the actual trends noted in the collected data. The hypothesis is accepted only if the test results are consistent in the assumed direction. One treatment that was investigated was the assumption that the air content of the concrete from the truck (before pumping) was assumed to be different (greater) from the air content of the unpumped concrete, after a 30 minute delay. The other conditions for which air contents were compared and tested in the hypothesis analysis are:

- Air content immediately after pumping to air content 30 minutes after pumping,
- Air content immediately after vibrating pumped concrete to air content 30 minutes after the pumped concrete was vibrated,
- Air content after concrete was pumped with turbulator attached to the pipeline to 30 minutes after,
- Air content immediately after pumping to air content immediately after vibrating, and
- Air content 30 minutes after pumping concrete to air content 30 minutes after vibrated.

Table 13. Pooled Sample Variance of Effects Data.

| Run # | Before | | After | | | | After Turbulated | | |
|---|---|---|---|---|---|---|---|---|---|
| | Obs. | $\sigma$ | Obs. | $\sigma$ | $S^2_p$ | $S_{\bar{d}}$ | $\sigma$ | $S^2_p$ | $S_{\bar{d}}$ |
| 1 | 3 | 0.231 | 3 | 0.404 | 0.108 | 0.269 | 0.473 | 0.139 | .304 |
| 2 | 3 | 0.351 | 3 | 0.173 | 0.077 | 0.277 | 0.289 | 0.103 | .263 |
| 3 | 3 | 0.330 | 3 | 0.351 | 0.107 | 0.267 | 0.115 | 0.052 | .185 |
| 4 | 3 | 0.535 | 3 | 0.115 | 0.150 | 0.316 | 0.153 | 0.155 | .321 |
| 5 | 3 | 0.361 | 3 | 0.700 | 0.310 | 0.455 | 0.000 | 0.087 | .269 |
| 6 | 3 | 0.361 | 3 | 0.981 | 0.546 | 0.603 | 0.764 | 0.357 | .488 |
| 7 | 3 | 0.321 | 3 | 0.419 | | | 0.539 | | |
| 7a | 3 | 0.321 | 3 | 0.000 | 0.095 | 0.356 | 0.058 | 0.125 | .408 |
| 8 | 3 | 0.208 | 3 | 0.115 | | | 0.874 | | |
| 8a | 3 | 0.351 | 3 | 0.351 | 0.076 | 0.318 | 0.000 | 0.233 | .557 |
| 9 | 3 | 0.400 | 3 | 1.137 | 0.726 | 0.696 | 0.693 | 0.320 | .462 |
| 10 | 1 | 0.000 | 3 | 0.289 | 0.084 | 0.334 | 0.000 | 0.000 | .000 |
| 11 | 3 | 0.346 | 3 | 0.379 | 0.132 | 0.296 | 1.131 | 0.506 | .649 |
| 12 | 3 | 0.173 | 2 | 0.000 | | | 0.058 | | |
| 12a | 3 | 0.551 | 3 | 0.404 | 0.142 | 0.461 | 0.058 | 0.085 | .337 |

A 't' distribution was assumed for the test data collected in order to evaluate the significance of the difference and the assumed trend in the data. A pooled or common variance ($S^2_p$) was determined, assuming that the results for two different conditions were unpaired and the variances are equal. The formula used to calculate the common variance is:

$$S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{(n_1 - 1) + (n_2 - 1)} \tag{26}$$

$$S_1^2 = \frac{\sum (Y_1 - \overline{Y_2})^2}{n_1 - 1} \tag{27}$$

$$S_2^2 = \frac{\sum (Y_2 - \overline{Y_2})^2}{n_2 - 1} \tag{28}$$

where

$S_1^2$ = Before sample variance (or first condition), and

$S_2^2$ = Variance of the second condition

In this way the information from the first sample (i.e., the $Y_{1i}$) and the second sample (i.e., the $Y_{2i}$) is pooled to provide a single estimate of common variance. Standard deviation is calculated from the variance, and the value of 't' is calculated by using the equation:

$$t = \frac{(\overline{Y_1} - \overline{Y_2}) - \mu_D}{S_{\overline{D}}} \tag{29}$$

where

$S_{\overline{D}}$ is the standard deviation

For most of the conditions described above, the calculated 't' values were in the range between 0.5 and 0.6 which correlate to an $\alpha$ value from the student's t statistics table greater than 50 percent where 5 percent is normally an acceptable level of $\alpha$. The calculated 't' values are far beyond the range of accepting the proposed hypothesis that there is a significant change in the air content. In other words, the difference of the air content is not significant for the above mentioned conditions except for cases when the concrete was vibrated. The calculated 't' values for these conditions ranged from 1.00 to 1.75. The tabulated $\alpha$ values for the 't' values obtained ranged from 20 to 40 percent for the vibrated concrete, which shows that the air loss was significant to some extent.

The hypothesis tested may show that the difference between the air content before and after pumping is not significant statistically speaking. However, it is interesting to observe that in almost all the field conditions the difference or the change in the air content due to pumping has alarmed construction engineers to take corrective steps. Statistically, the results may not show any significance, but structurally, many aspects of the air void system have repeatedly caused durability problems in air entrained concrete due to frost damage.

Petrographic analysis using linear traverse method can show these differences in the air void system which are important in the frost resistance mechanism.

**Pressure Method Results**

The results of the pressure tests are presented in the Figure 35. From the figure it is clear that in most of the cases air loss is more for concrete with higher slump and less for the concrete with lower slump. Placing operations (vibration) usually in a reduction in the air

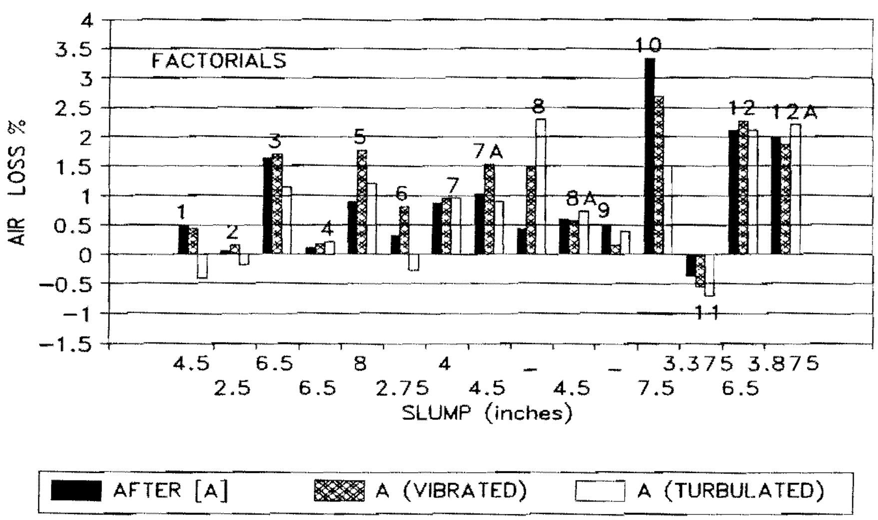


Figure 35. Air Loss in Concrete Due to Pumping (After, Vibrated, and Turbulated).

content. The variations in air loss are due to several reasons, among which water content, i.e., slump, is an important factor. Placing operations (vibration) usually reduce the air content (~1%). The loss of air in high slump concretes may be higher, since air is lost as concrete is vibrated. The use of a turbulator seems to reduce the air loss in most of the cases, and in four cases an increase is observed. The reason for such an increase could be that the turbulator reduces the residual pressure and subjects the concrete to a form of mixing action which tends to retain air. In the case of free falling, fresh concrete (in the pumpline below the Apex angle) the turbulator should tend to reduce the effect of free fall by building up back pressure so as to avoid negative pressure due to gravity flow.

**Pumping Pressures**

Pressure transducers were not used to test all of the concrete mix designs in the factorial design. A single mix design was used to measure the pressure variations in the pipeline. Five batches of concrete (five truck loads) were used and the pressure variations are plotted by the strip chart in Figure 36. Air content tests were not done for these batches of concrete. The five distinct parts can be identified in the graph representing the five batches of concrete which were all relatively easy to pump. However, the first batch showed the greatest variations in the maximum and minimum pressure. The pressure shown in Figure 36 is in psi and is above the atmospheric pressure. The next batch of concrete was adjusted to increase the workability by adjusting the aggregate gradation. The variations in the maximum and the minimum pressure was reduced considerably and the concrete pumped smoothly. The third batch had slightly higher variations in the pressure since it had lower slump than the second batch. The initial high pressure shows that the concrete pumping was restarted after a gap in the pumping. The fourth batch shows an unsteady flow of concrete, mainly due to the variations within the batch of the concrete. Mix integrity may have been lost in this batch; any excessive variations would have created a blockage in the pipeline. The fifth batch was pumped relatively smoothly when compared to the fourth batch of concrete.

**Linear Traverse Results**

Various characteristics of the air void system were determined by the linear traverse method. These were the air content, spacing of the bubbles, specific surface, average chord length, and spacing factor. These results are presented graphically in the following sections. Slumps can be observed from Figure 38 for comparative purposes for Figures 37, 39, and 40.

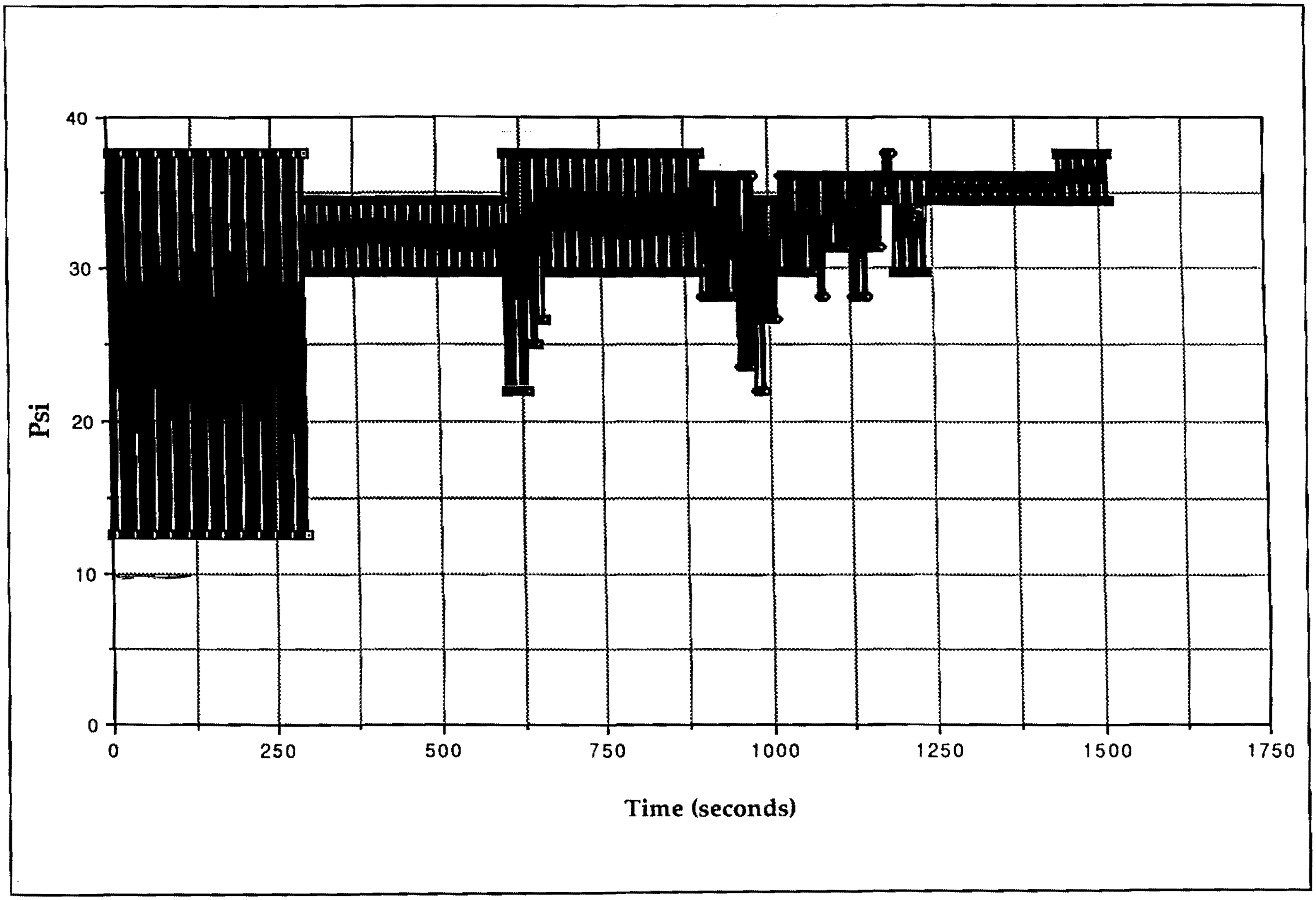


Figure 36. Pressure in Pipeline.

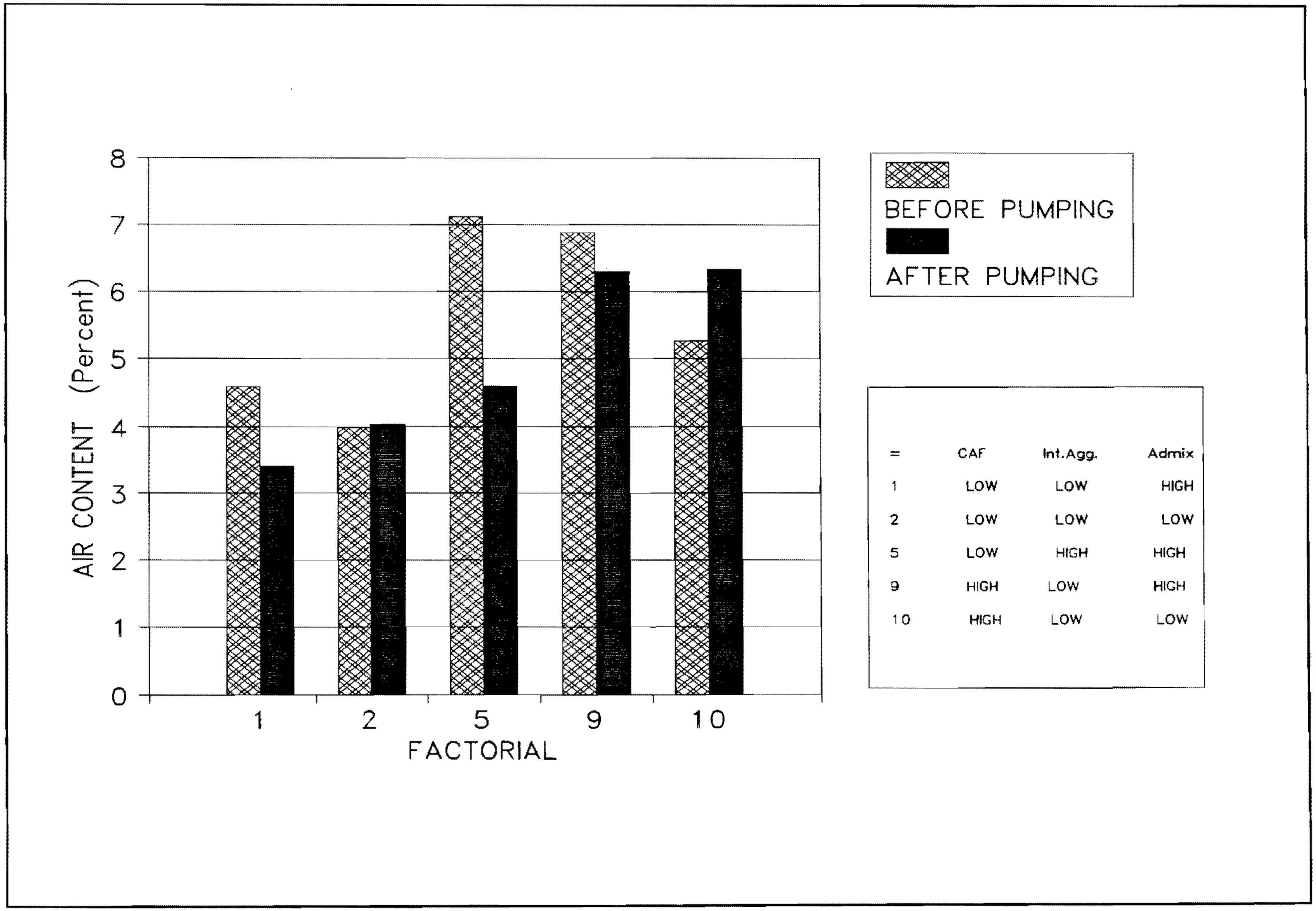


Figure 37. Air Content of Unpumped and Pumped Concrete (Linear Traverse Method).

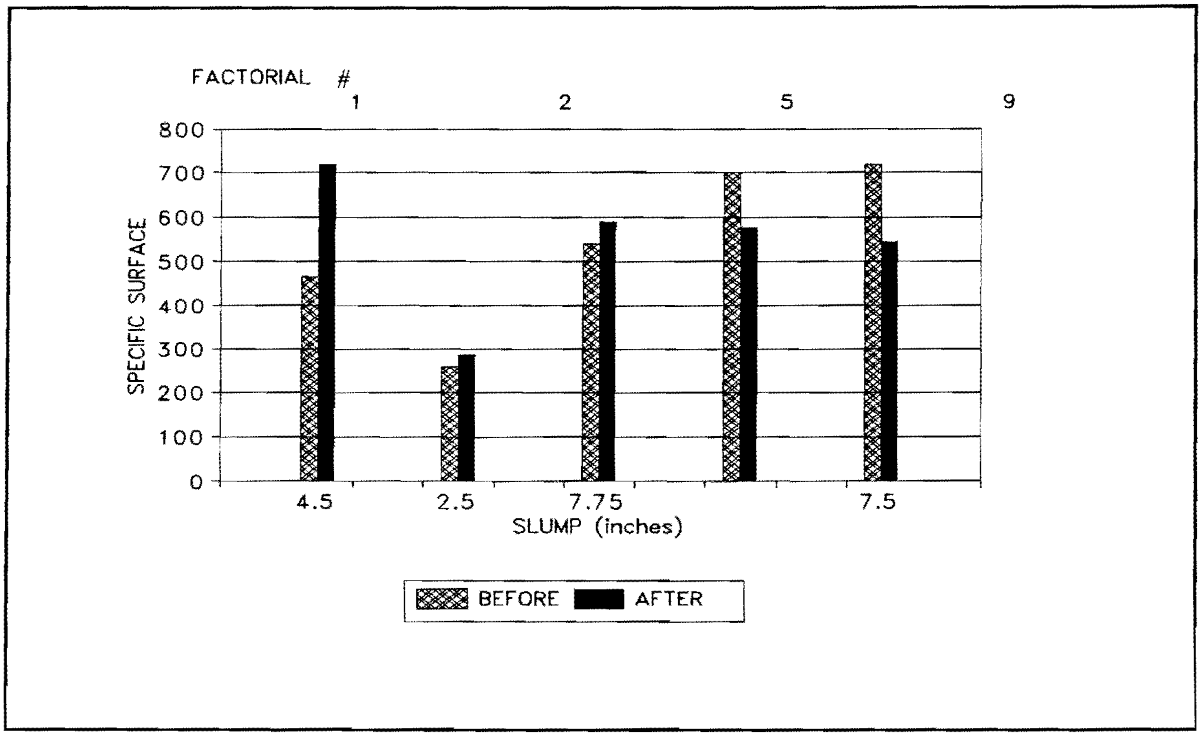


Figure 38. Specific Surface of the Bubbles, Unpumped and Pumped Concrete.

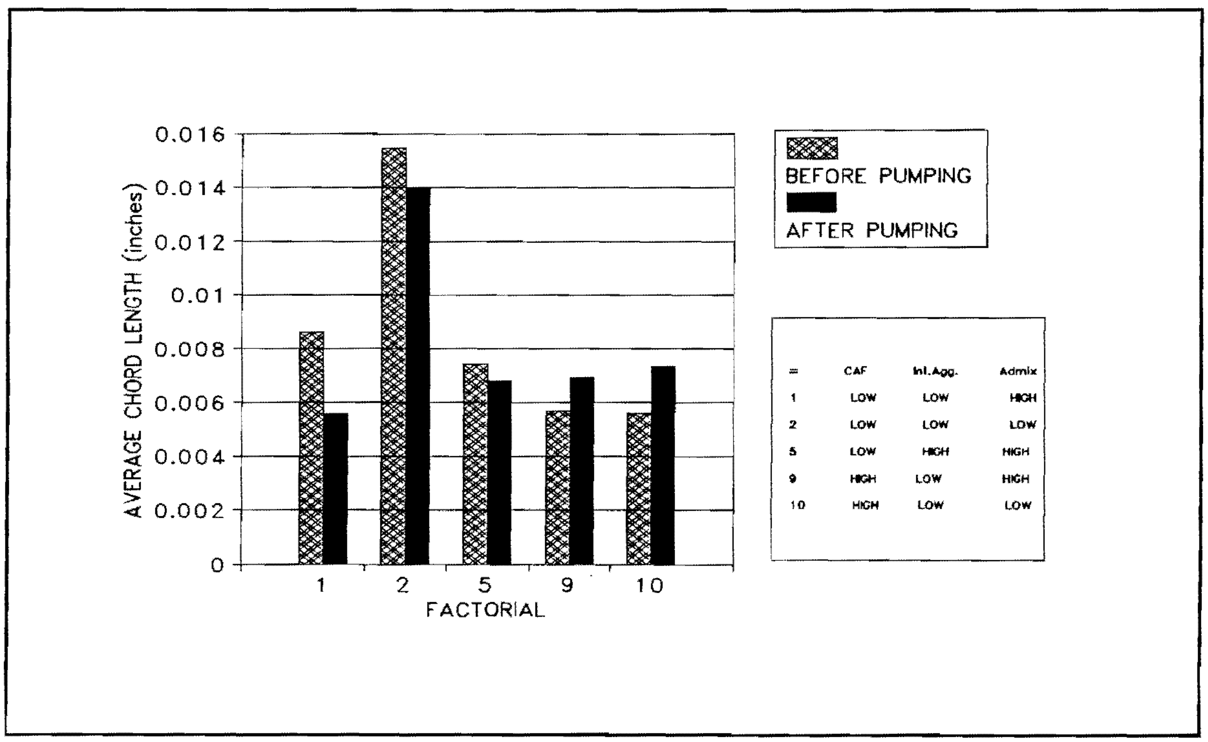


Figure 39. Average Chord Length of Bubbles in Unpumped and Pumped Concrete.

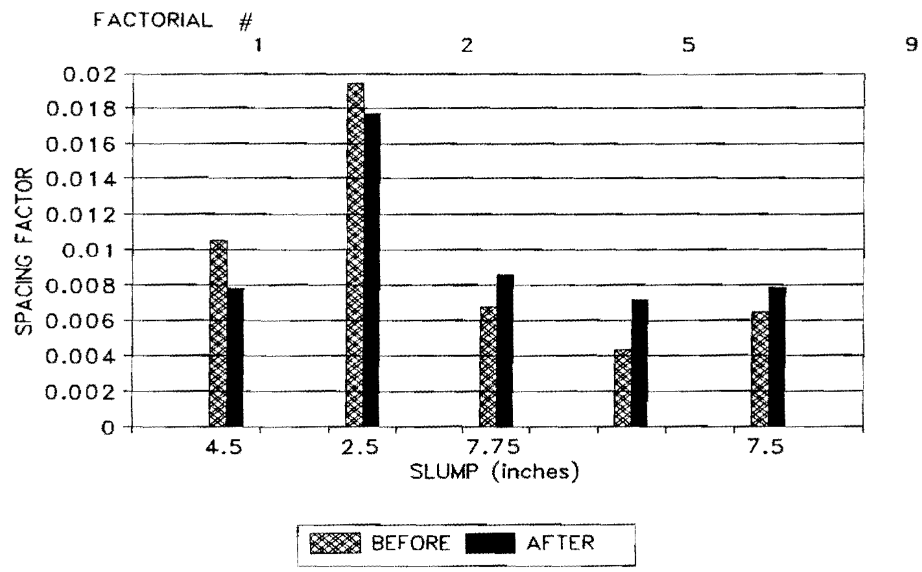


Figure 40. Spacing Factor of Bubbles in Unpumped and Pumped Concrete.

<u>Air Content</u>: In all the cases (Figure 37), the air content has either decreased or has not changed significantly, except in the case of test run 10. In this case, a large air void (entrapped air) has influenced the actual air content, consequently showing higher air content than what it might be. Figure 37 shows the air contents of the before pumping and the after pumping samples. Highest loss of air content (which did not return) is observed in the case of test run number 5 (high boom configuration). It is interesting to note that the slump was also very high in this case (Figure 38). This factorial seems to represent the case where a permanent loss of air occurs as referred to previously.

<u>Spacing of Bubbles</u>: Spacing of bubbles refers to the number of bubbles (voids) that are encountered in a unit length (inch) of linear traverse. The spacing or the number of total bubbles has decreased for concretes with high slump (test run 5, 9 and 10), while in the case of low slump there is an indication of increase in the number of bubbles. Higher slumps may tend to promote loss of air bubbles.

Specific Surface Area: The specific surface area of the bubbles decreases for the mixes with high slump, except for the factorial number 5, which shows nearly no change in the specific surface area (Figure 38). The low slump concrete mixes showed an increase in the specific area. Higher specific surface area means smaller bubbles in the concrete, and can be important to have higher specific areas in terms of concrete durability.

Average Chord Length: In Figure 39, the average chord length of bubbles in high slump concretes increased, while in the low slump concretes, there is an indication of chord length decrease. The best combination with respect to the average chord length is the test run number 5, which has low CAF, high IA, and high ADMIX, since there is little change in the chord lengths (Figure 39). It may appear that test run number 1 is a good combination in terms of specific surface area and chord length. The chord length is also important in terms of frost resistance and concrete durability since it is related to the spacing factor and the air content. Test run 2 was a stiff mix which produced large bubble sizes, indicating that too stiff a mix makes air entrainment difficult.

Spacing Factor: Spacing factor is the most critical aspect of air entrainment, since a low spacing factor produces concrete that is durable to frost damage. In Figure 40, low slump concretes show an increase in the spacing factor which is not desirable. It can be seen that the initial spacing factor before pumping for the high slump concretes is well below the critical spacing factor of 0.008, and it tends to increase as a result of pumping. The reason for the decrease of spacing factor in low slump concretes as indicated by Figure 40 is not clearly understood. The stiff mix (factorial number 2) shows a very high spacing factor which indicates that it is difficult to entrain air in stiff mixes.

**Comparison of Linear Traverse and Pressure Method Results**

> "Discrepancy between the results of linear traverse method (hardened concrete) and the pressure method (fresh concrete) may be due to the inaccuracy of the pressure meter in measuring the total air content of concrete mixes with small entrained air bubbles. It has been qualitatively proposed that the air meter becomes increasingly less accurate as the bubbles become smaller, due to the high pressure of the air within extremely small bubbles. This is because the smaller bubbles are less compressible than larger bubbles, particularly at the relatively low pressure applied by a typical air meter" [47] (Also discussed reference [48] by Hover).

The results of pressure method and the linear traverse method are illustrated in Figure 41. These results are useful for determining the air content variations from the time when the concrete was fresh to the time of setting. From Figure 41 for the low slump concretes, the air content by linear traverse method (or hardened concrete air content) is

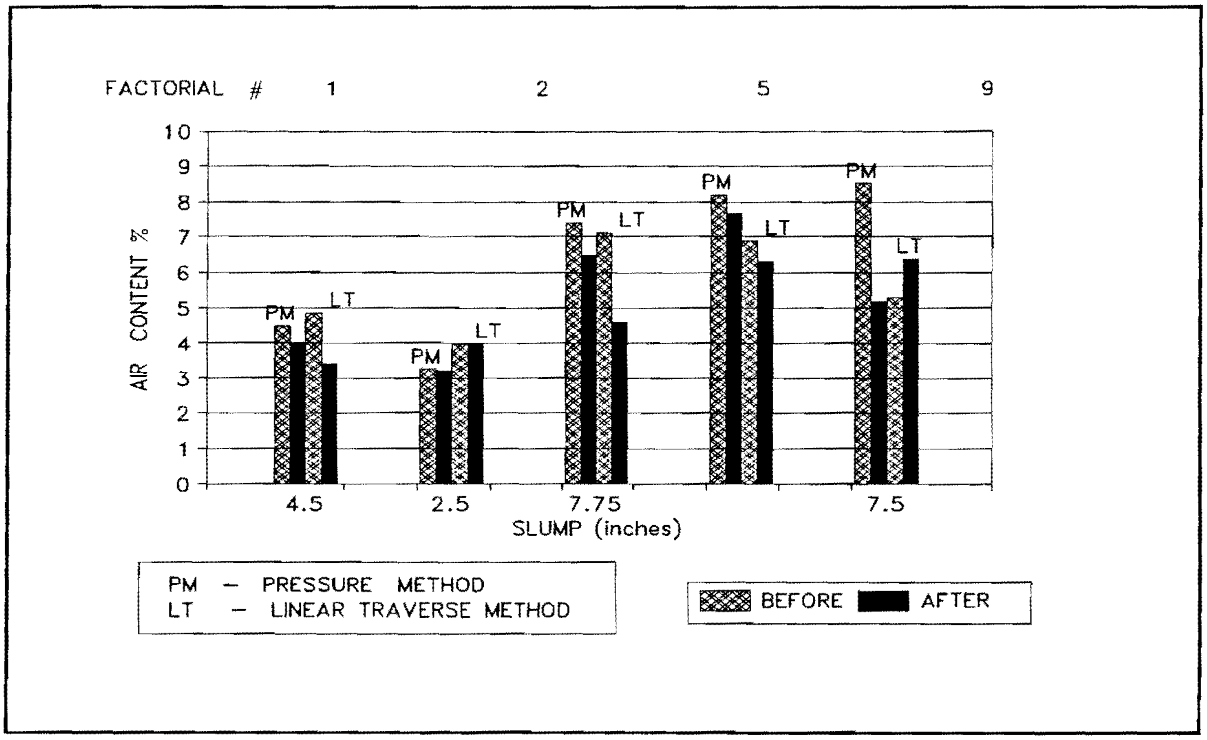


Figure 41. Comparison of Pressure Method and Linear Traverse Method Results.

higher than the air content obtained by pressure method (fresh concrete). For concretes with high slump, the hardened concrete air content is less than the fresh concrete air content. In the case of low slump the difference may be attributed to the inability of the pressure method to measure smaller sized bubbles, since the air loss is difficult to detect with the pressure meter method in this case. Hence, the pressure method indicates a lower percentage of air than hardened concrete. Air loss is expected to be more in the case of the concretes with high slump, and diffusion process is also expected to be more; hence the pressure method would show more accurate (compared to low slump concrete) air content measurement, since diffusion process would reduce the number of smaller bubbles. The data presented here is too limited to make any conclusions regarding the process of air loss until the time of setting (hardening of concrete), after which concrete is relatively too stiff to cause any changes in the air void system.

# CHAPTER VI
# FRAMEWORK FOR IMPLEMENTATION OF FINDINGS

## Conclusions

This study makes the following conclusions:

1) As slump increases (high water cement ratio) an apparent air loss (since the lost air eventually returns) increases. Additionally, changes in the air void characteristics of high slump mixes are more prominent due to the dissolution process (apparent loss of air), particularly when placed under pressure. On the other hand, air entrainment in stiff mixes (low slump mixes) is difficult to attain, and these mixes are hard to pump. Concrete mixes with slumps between 4 to 5 inches are ideal with regard to pumping.
2) Based on the review of the literature, noted related studies, and experience gained from this study, high pressure and excessive variations in the pressure (pressure pulses), cause bubble rearrangement and lead to apparent loss of air content.
3) High CAFs ( > 0.74) in the concrete mix design require high pumping pressures due to high resistance to flow, which in turn increases the air loss. High CAFs may cause bleeding of water in the pipeline, consequently blocking the concrete flow.
4) Intermediate aggregate (rounded middle fractions) improves within concrete friction and reduces plug flow affect (mix integrity is maintained). The increased density will prevent the escape of water from the mix, and hence blockages in the pipeline can be avoided. Crushed aggregates may not function well as an intermediate aggregate because their fractal dimension may be too high.
5) Admixtures with high surface tension tend to produce bubbles that are more stable and cause less bubble rearrangement and less apparent loss of air.
6) The effect of boom angle is not obvious, but seems to indicate that air is lost when the boom angle is high. This may be particularly true for high slump mixes, since the impact created in the pipeline may knock out the bubbles, thus causing a permanent loss of air.

7) Although data collected in this study indicated little loss of air due to vibration, placing and finishing operations (such as vibration) may cause loss of air which should not be attributed to pumping operations.
8) Use of turbulator at the end of the pipeline seems to reduce the apparent loss of air.
9) Based on experience gained in the field testing program, air may be regained after placing operations, but the air void characteristics are expected to change, possibly affecting the durability of the pumped concrete.
10) The use of fractal dimension concept shows promise in characterizing aggregate shapes, texture, and gradation in classifying aggregates in terms of workability and pumpability.

The conclusions are summarized in Table 14.

Table 14. Conclusions.

| CONCLUSIONS | APPARENT LOSS | PERMANENT LOSS |
|---|---|---|
| High Slump (W/C Ratio) | Increases | Increases |
| High Pressure | Increases | - |
| High CAFs | Increases | Increases |
| Intermediate Aggregate Use | Decreases | Decreases |
| High Surface Tension Admixture | Decreases | Decreases |
| High Boom Angle | - | Increases |
| Placing & Finishing | - | Increases |
| Turbulator Use | - | Decreases |

## Recommendations

The key to effective control of air entrainment is by using improved mix design concepts as described in this report. High water cement ratios (and possibly superplasticizers) should be avoided for pumpable mixes while achieving the prerequisite workability as to reduce the pressure required to pump the concrete. Use gap graded aggregates should be avoided in pumped concrete as this may lead to bleeding of water from the mix during pumping and possibly to blockage of the pumpline and loss of production. When pumping problems are experienced, common remedies such as increasing the water content and admixture dosage should be avoided (Objective b). These measures most likely will not solve the immediate problem, and in the long run, the durability of the concrete can be affected. A combination of high boom angle and slumps greater than 5 inches should be avoided. The following recommendations are made with regard to the mix design:

1) Low CAF factors should be used in the mix design (TxDOT specifies CAF factors of 0.68 at the minimum and 0.82 at the maximum.) High CAF factors should be avoided: CAF factors between 0.57 and 0.64 should be considered. The pumping pressures should be lower when low CAF factors are used. The maximum size of the coarse aggregate should be less than one-fourth the pipe diameter of the pump (best pumpability) and never more than one-third the pipe diameter.
2) Intermediate aggregate addition in the mixture should increase the workability of the concrete and minimize bleeding of water and the chances of blockage. Intermediate aggregate (rounded middle fractions) of sizes between 3/8 inch and #8 size sieve are recommended.
3) Use of high surface tension admixture is recommended as these produce more stable bubbles (Objective a).

With respect to Objective c (stated in Chapter I), using the above recommendations, air measurements can be made prior to pumping (and verified at the point of discharge) as frequently as necessary using the standard available test methods since the variations in the entrained air content should be held to a minimum. Use of improved mix design should help to curtail the loss of air void characteristics and because of improved workability it may be pumpable for slumps between 3 to 4 inches (TxDOT recommendation for pumping is between 4 to 5 inches of slump).

**Implementation**

The implementation of these recommendations for pumping concrete should be initiated on an experimental basis, perhaps over a construction season. Close monitoring at the construction site using both improved and standard mix designs and adequate tests (on fresh and hardened concrete) should be done to clearly establish the effect of these changes in the mix design. Tests using recently developed equipment such as the air void analyzer will provide information at the job site on the air void system of fresh concrete. In addition, linear traverse tests and freeze thaw tests are also required to assess the long-term durability of the new mix design. Also, additional research work should be considered to develop the use of fractal dimension to improve the mix design as a function of the aggregate characteristics for pumpable concrete. Other tests should be done before pumping, after pumping and after placing. Availability of testing data from various construction sites will help to better understand the facts of air content variations due to pumping. Further research is required in quantitizing the effect of pumping concrete and to predict the changes in the air void system. For this purpose, additional pumping tests should be performed in the field to further calibrate the effect of each of the important factors that pertain to air entrainment due to pumping.

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# APPENDIX A

# CONCRETE PUMPING

## Pumping of Concrete

Recently pumping has become one of the most popular and utilized methods of placement for concrete materials for building and bridge deck construction. It is interesting to note that although concrete pumping was developed in the 1930s, it was a method of placement that was relatively uncommon in the late 60s and early 70s. This has changed dramatically in recent years. Concrete pumping is a very versatile method of placement that is particularly useful where space and maneuverability are limited which is typical of most concrete construction projects. Concrete can be pumped successfully over large distances typically more than 1500 feet horizontally and 500 feet vertically. However, these distances have been recently exceeded since pumping equipment and technology have improved with experience. Even though concrete pumping may not be the best option for concrete placement, it offers certain advantages over other methods such as placement by skip crane, hoists, and conveyors [1].

## Historical Development of Concrete Pumping

Concrete pumping was first patented in the USA in 1913 but was developed initially in Germany. In the early 1930's, a German firm started producing a single cylinder mortar pump. Early research and development lead to continued improvement in pump design and distribution of pumps in several countries such as the U.S., France, Holland and the U.K. During this period, the sliding plate value was developed to replace the less efficient ball value [1].

Pump development and research continued, particularly in Europe after World War II, even though pumps were mechanically driven. The next generation of pumps were hydraulically driven. During the rapid rebuilding of West Germany during the 1950s and 1960s, concrete pumping was widely used which is one reason why the West Germans are world leaders in the manufacture of concrete pumps [1]. Other countries have not had the same perspective on concrete pumping as the West Germans. For instance, West Germans place nearly 40 percent of their concrete by pumping, while countries such as the UK place only 10 percent. Concrete pumps are used in West Germany because of the construction expediency associated with them while in the UK a reluctance persists to use pumping that was perceived to be more costly than the traditional crave and skip method. Users in the UK, immediately after the second Word War, experienced problems in pumping which were not unlike the problems experienced today. Users complained of pump reliability and several difficulties were experienced with line blockages which can be related to the mix design. Improvements in the valve design may have helped overcome some problems associated with line blockages.

Today, in many countries around the world, concrete pumping is an integral part of the planning and organization of a wide variety of construction projects. However, some reservations may still persist to use pumping only if placement of the concrete cannot be carried out by any other method. Pumping can be very beneficial to the progress of the project since it is typically a much quicker method of placing the concrete and it will not tie up other equipment that can be used for other construction activities [1].

It is also interesting to note that after the disaster at the Chernobyl nuclear power station in 1986, concrete pumps were used to place several thousand cubic yards of concrete as part of the remedial work to encase the damaged reactor. More than ten concrete pumps from four manufacturers were used in the pumping operations [1]. Workmen and operators were permitted only two hours of exposure to radiation which meant that additional operators needed to be trained in order to maintain the pumping to continue both day and night. The emergency situation at Chernobyl is an indication of the durability and high output performance that a concrete pump can provide. Speed of placement was of the essence in the encasement of the reactor, and it is interesting to note that the main concrete placing option chosen was pumping.

Several manufacturers are involved today in the production of concrete pumps. The competition among these manufacturers provides the motivation to continue to improve the efficiency and the performance of modern concrete pumps.

**Concrete Pumping Equipment**

The nature of equipment used for the pumping of concrete was discussed previously to some extent in reference 11 and 12. Although some information may be repeated here, it is provided for convenience. Two early versions of the concrete pump were the mechanically driven and the pneumatic placers. The mechanical pump worked on a two-strobe basis using either single or double pistons. The mechanical pumps were relatively simple devices which consisted of a receiving hopper, an inlet and an outlet valve, a piston and a cylinder. A mechanical pump is illustrated in Figure A-1. The concrete is pulled into the cylinder with the suction stroke and pushed forward into the pipeline as the inlet valve closes and the outlet valve opens. These pumps are often powered by a diesel engine and incorporate similar principles that are evident in modern day pumps.

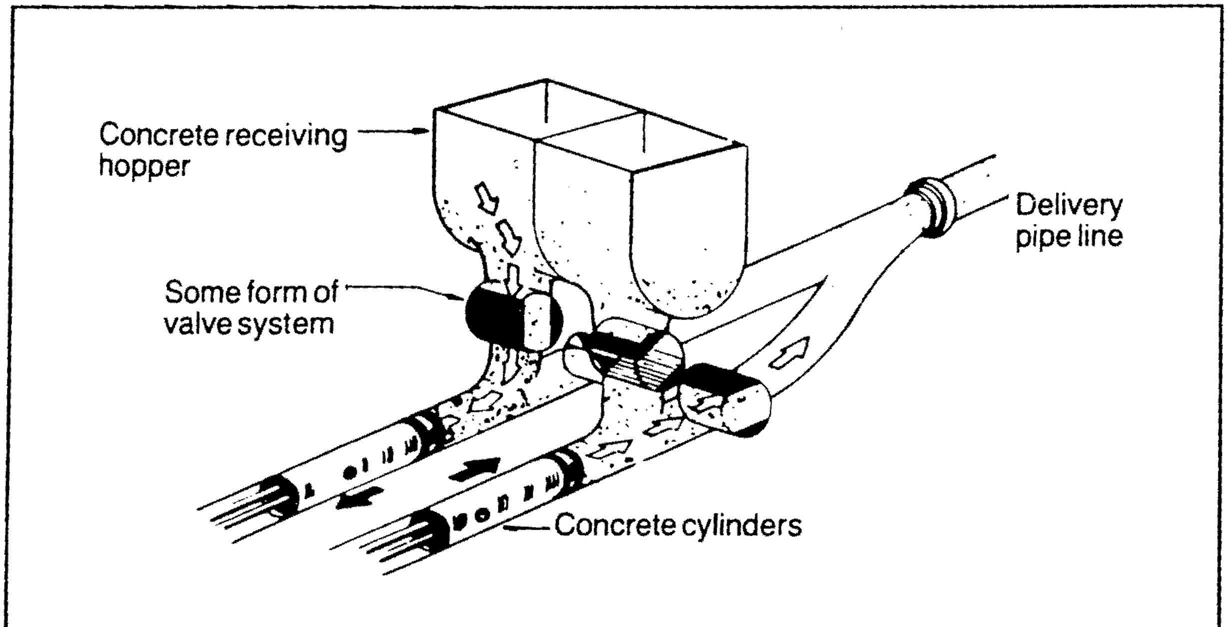


Figure A-1. Principle of Mechanical Concrete Pump; After [1].

Pneumatic placers pressurize the concrete to move it through the pipeline. Most of the earlier versions of this model created problems due to the high pressures required to move the concrete. Even though many of these problems have been overcome, very few of this type of pumps are used today to transport concrete.

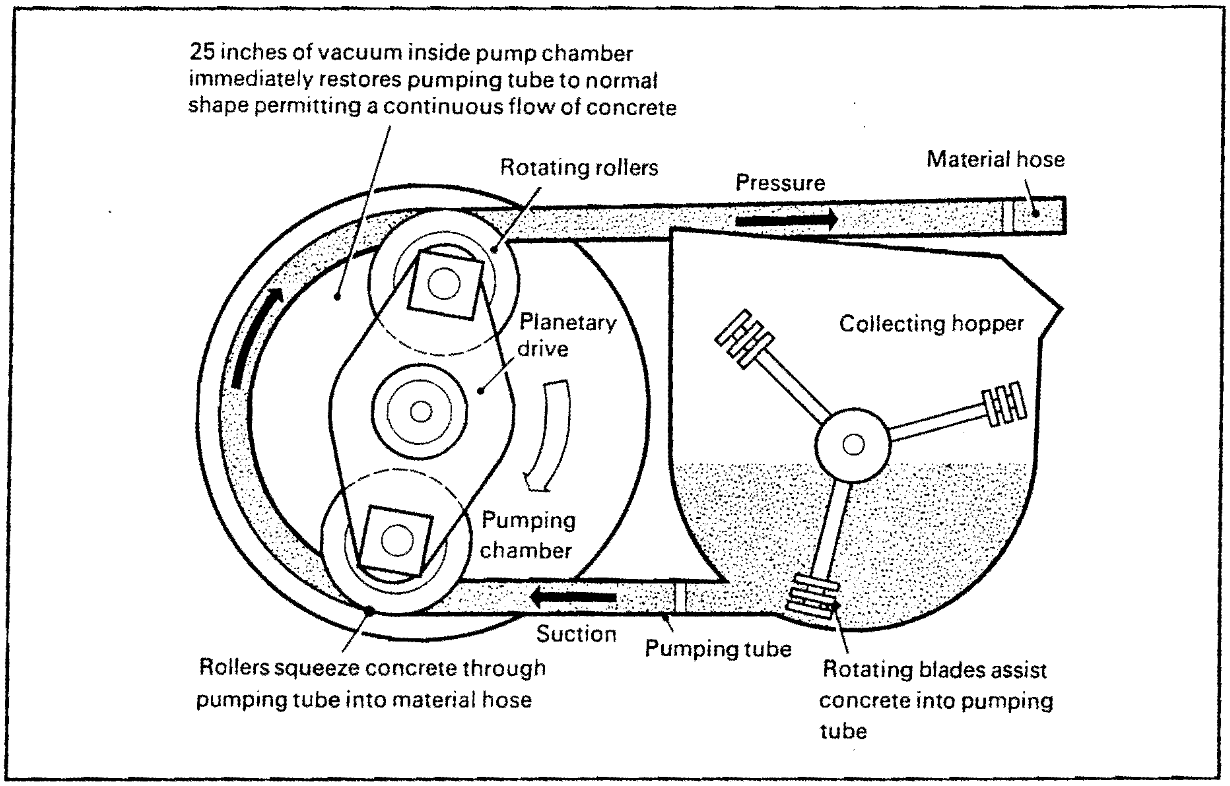


Figure A-2. Principle of the Peristaltic Pump [39].

A pump which was developed in the United States is the peristaltic or squeeze type pump illustrated in Figure A-2. These pumps operate by forcing the fresh concrete through a rubber tube located within a chamber by rotating rollers. The advantage of these pumps is the continuous smooth flow of concrete that is provided at a lower operational pressure.

The hydraulic piston pump is the most popular of the modern pumps used in concrete construction. However, it works on a concept similar to earlier versions of the mechanical pump. This pump is adaptable to most construction applications. A hydraulic piston pump consists of three parts: a concrete receiving hopper, a valve system, and a power transmission system. The design of the pump may vary to some degree depending upon the use of the pump.

Most hydraulic pumps, which are vehicular mounted, use oil as the working fluid. These pumps typically have twin cylinders in which the pistons within each cylinder are connected to a double-acting hydraulic ram. Oil is applied under pressure to the ram by the main oil pump which may be driven by the vehicle's engine. The action of the two pistons is synchronized in such a way that as concrete is discharged from one cylinder, it is charged into the other cylinder.

Some hydraulic pumps use water instead of oil as the working fluid. These pumps are available in twin-cylinder models in which the pistons are connected by a steel cable rather than piston rods.

A concrete pump may be mobile, trailer mounted or static, or a mortar pump. All these pumps are mounted on a carrier for transportation purposes and have a placing boom which is connected or independent of the pump.

**Pump Valve Systems**

Valves play an important role in the operation of a concrete pump. They are designed to provide a minimum of restriction to flow on the suction stroke and loss of pressure on the concrete in the pipeline. The types of valves are [39]:

a. Flat Gate Valve: This valve slides to block entry of concrete from the hopper during the discharge stroke and *visa versa* during the suction stroke. These valves are used with both single-cylinder and twin-cylinder pumps (Figure A-3).

b. Spade Valve: The concrete inlet and outlet values are separate in a spade valve system. These valves have a curved profile to facilitate the flow of the concrete (Figure A-4). The advantage provided by this system is that both outlet valves can be closed during delays in pumping to relieve back pressure on the cylinders.

c. Flapper Valve: This type of valve performs the function of both inlet and outlet in twin cylinder pumps (Figure A-5). It can be pivoted either vertically or horizontally to allow concrete to pass on both sides of the blade. However, on one side the concrete flows into the cylinder, and on the other it flows into the pipeline. These types of valves are low in maintenance cost but may not be conducive to high production pumping.

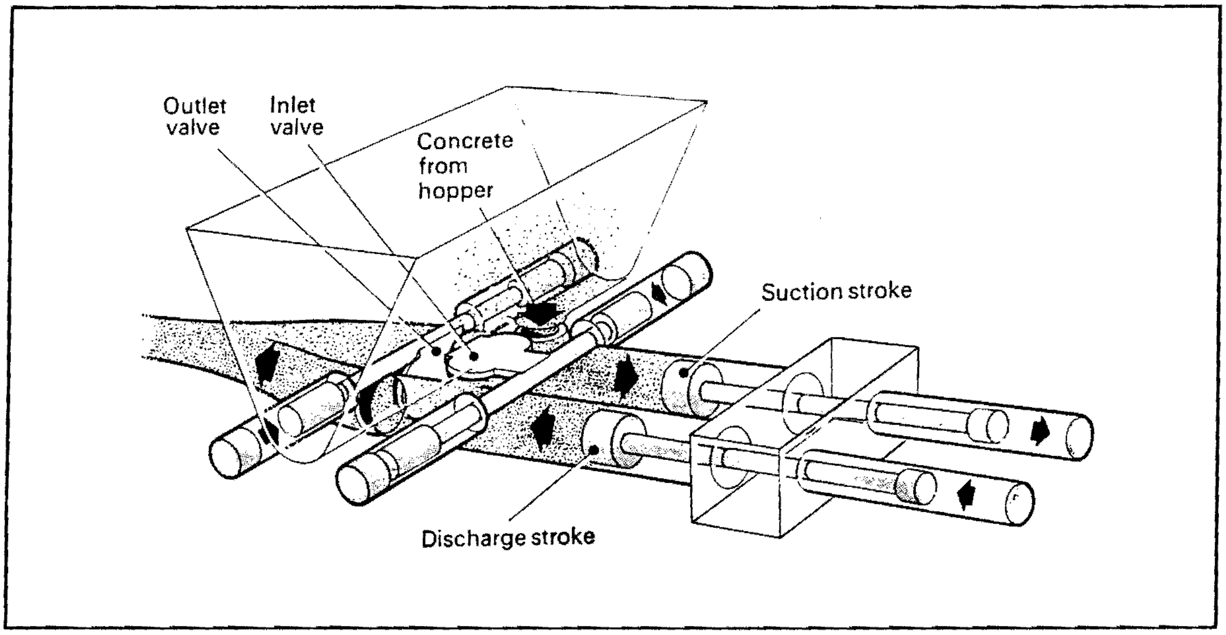


Figure A-3. Flat Gate Valve System in Concrete Pump [39].

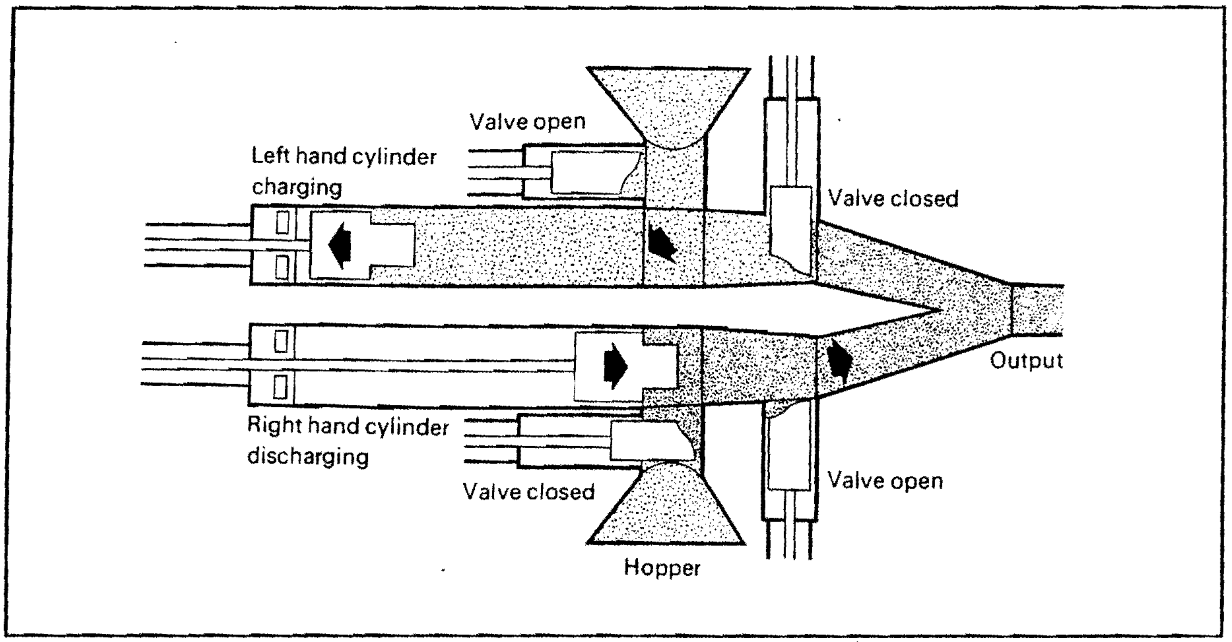


Figure A-4. Typical Spade Valve System with Four Curved Profile Values [39].

d. Rotary Valves: A rotary valve can be used in both mechanically driven and hydraulically driven pumps. Apparently, these valves do not close completely during operation to prevent

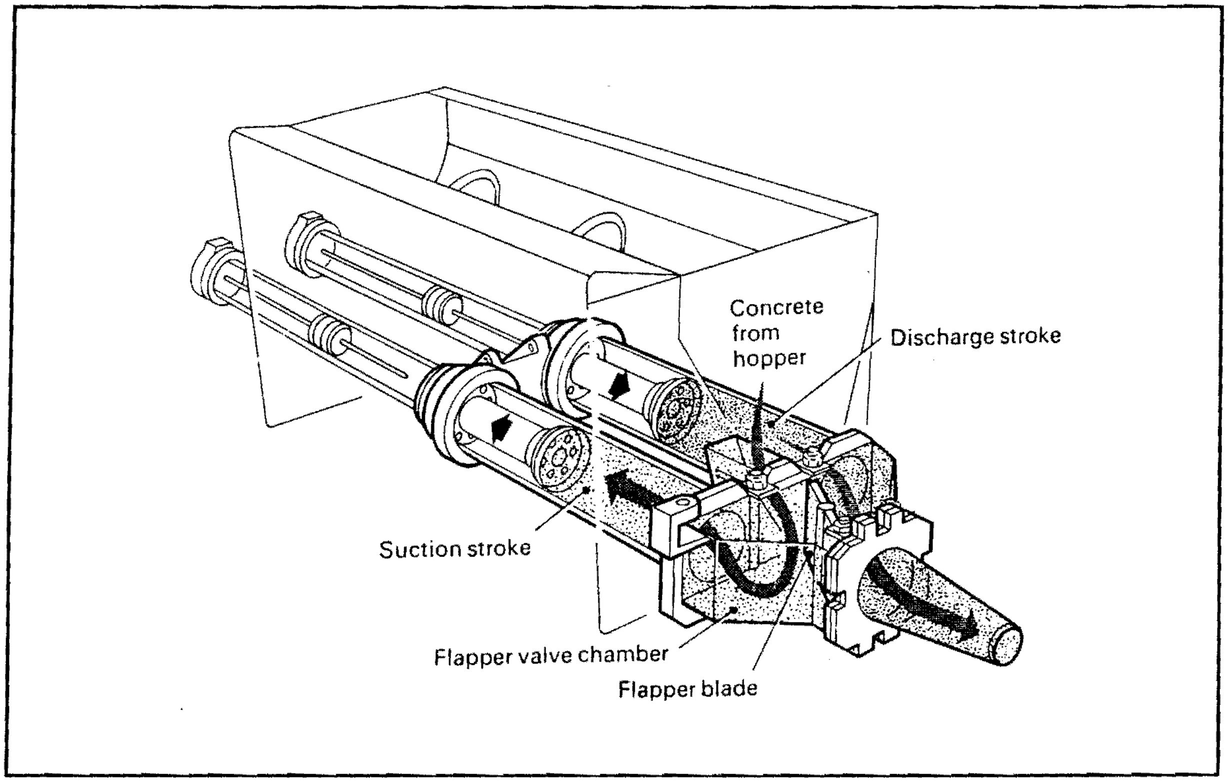


Figure A-5. Flapper Valve System [39].

damage due to aggregates becoming jammed in the valve. In fact, the valves can be adjusted depending on the size of aggregate in the pumped concrete.

e. Hollow Transfer Tube Valves: This valve, illustrated in Figure A-6, rotates back and forth between dual cylinders that use a cutting ring which constantly maintains contact with a wearing plate to provide a proper seal. The wearing parts can be easily replaced and can be readily cleaned and maintained.

**Pipes and Accessories**

Steel Pipeline: Most pipelines are of seamless steel construction in approximately 10ft lengths. They are capable of withstanding three times the working pressure when new and are highly resistant to abrasion. The 4 inch bore pipes normally have a wall thickness of 1/4 inch. The ends of the pipes are prepared to suit the type of coupling used.

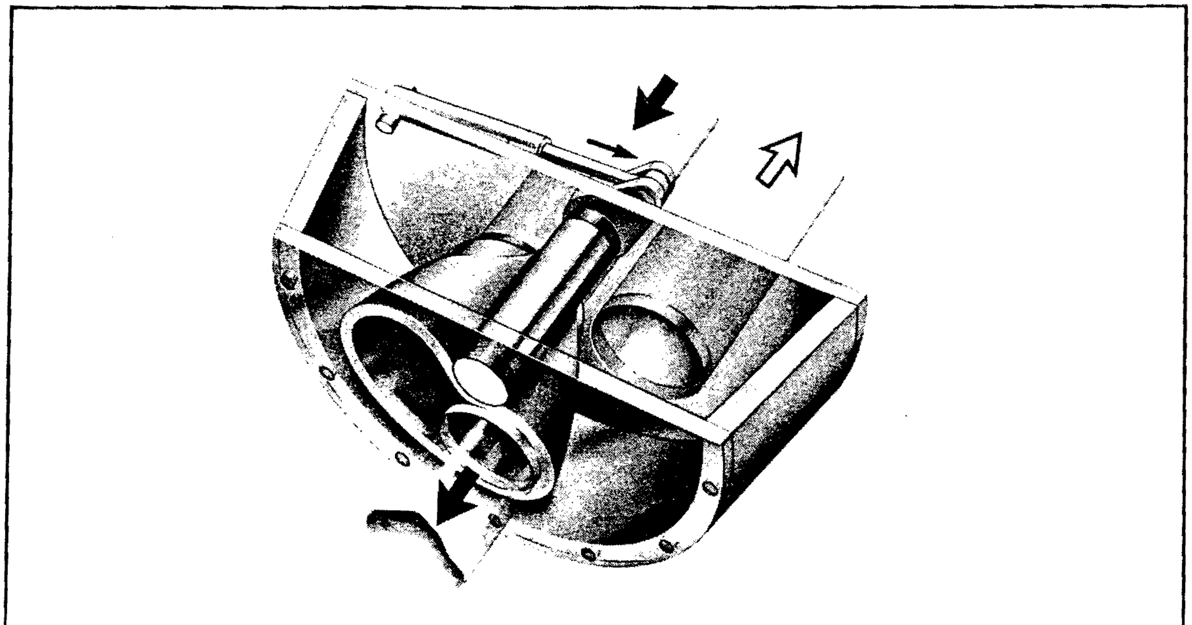

Figure A-6. Hollow Transfer Tube Valve; After [1].

Pipe bends should have large radii (usually 3-6 feet) to minimize drag and wear. Standard angles are 90°, 45° and 22 1/2°. Rigid steel bends are preferable to flexible hose since they are more durable and offer less resistance to flow. Tapered pipes are used to connect pipelines to the larger diameter outlets of pumps.

Bore diameter of the pipeline should be in accordance with the pump manufacturer's recommendations. The following circumstances affect the bore size used:

1. For speed in erecting pipeline - 3 or 4 inch diameter bore
2. For great distance horizontally - a large diameter bore up to 7 inches
3. For great distance vertically - the smaller diameter bores (3 to 4 inches) are satisfactory
4. For concrete with high frictional resistance - the larger diameter bores
5. For aggregate size - bore diameter should be at least four times to maximum size of the aggregate, although three times aggregate size is acceptable for the larger pipes.

Aluminum and plastic pipes: An advantage of aluminum and plastic pipes is that they are lighter than steel. Aluminum alloy pipes have been used successfully but under certain circumstances, with long pipelines, it is possible that the chemical interaction between concrete and aluminum will cause hydrogen to be released into the concrete in sufficient quantities to cause damage. This could occur in hot weather when pumping at high pressure through a long pipeline.

Plastic pipes normally require reinforcement and the ends need strengthening to receive couplings. Experience with this type of pipe is limited.

Flexible hoses: Apart from the special squeeze-tubes in peristaltic pumps, flexible hoses are used on booms and at the delivery end of pipelines. Delivery hoses do not have to withstand high pressures and can be more flexible than those used on booms. The inner lining of the hose must give low resistance to flow and high resistance to wear. Punctures or tears in the lining can cause high pressures or blockages.

Flexible hose can be reinforced with helical wire to prevent kinking. Corrugated covers also help to give flexibility but tend to reduce wear resistance because sympathetic corrugations can develop internally if the hose is kept in one configuration for a period and then bent to another shape.

Pipe coupling and special fittings: Some examples of the various proprietary methods used for connecting the pipes are shown in Figure A-7, Figure A-8, and Figure A-9 [39].

Some of the special fittings are:

**Rotary distributor** - Two 90° bends connected by a swivel coupling that allows 360° movement between the two bends.

**Discharge pocket** - A length of pipe incorporating a valve which allows concrete to be discharged at the side of the pipe, or to continue up the pipe.

**Shut-off valve** - A short length of pipe incorporating a valve which can be placed at the bottom of a vertical pipeline.

**Adjustable pipe supports** - These support the pipeline clear of form work or reinforcement.

**Wash-out gun** - A short length of pipe with one end blanked-off and a

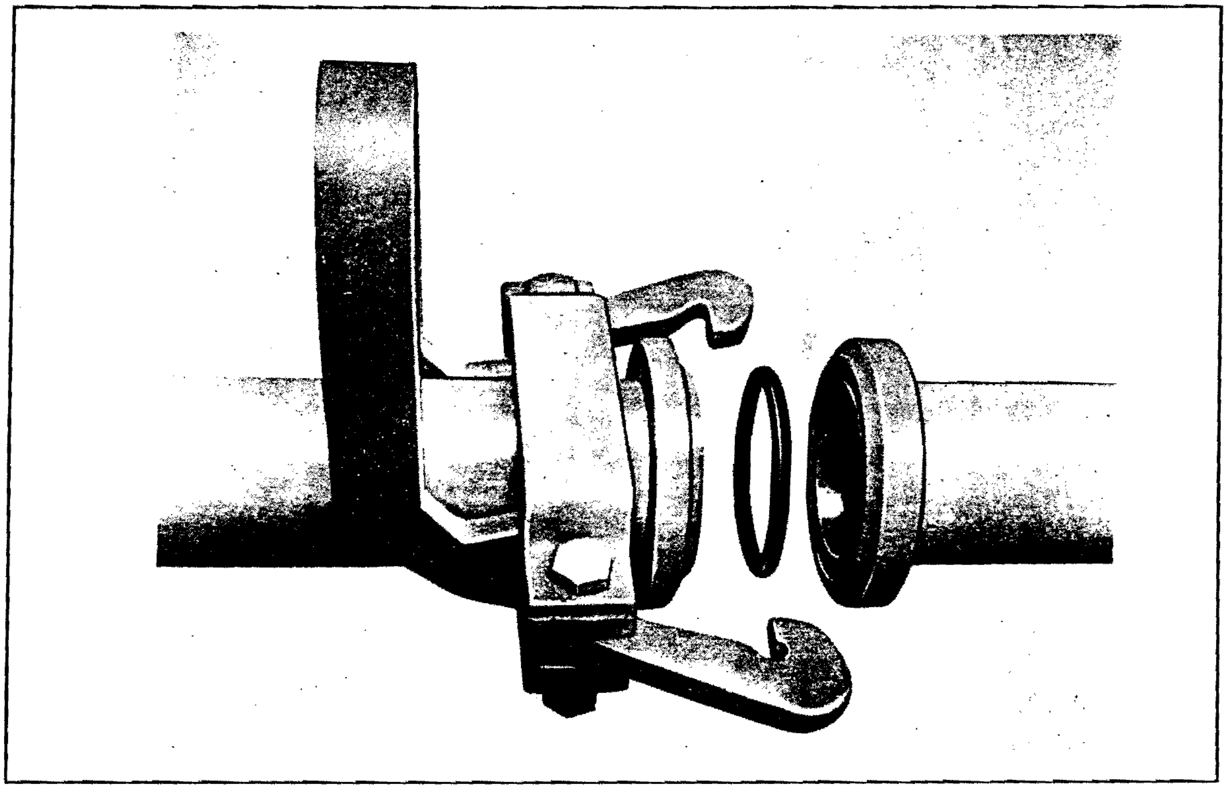

Figure A-7. Quick-Action Pipe Coupling Tightened by Pivoting a Lever [39].

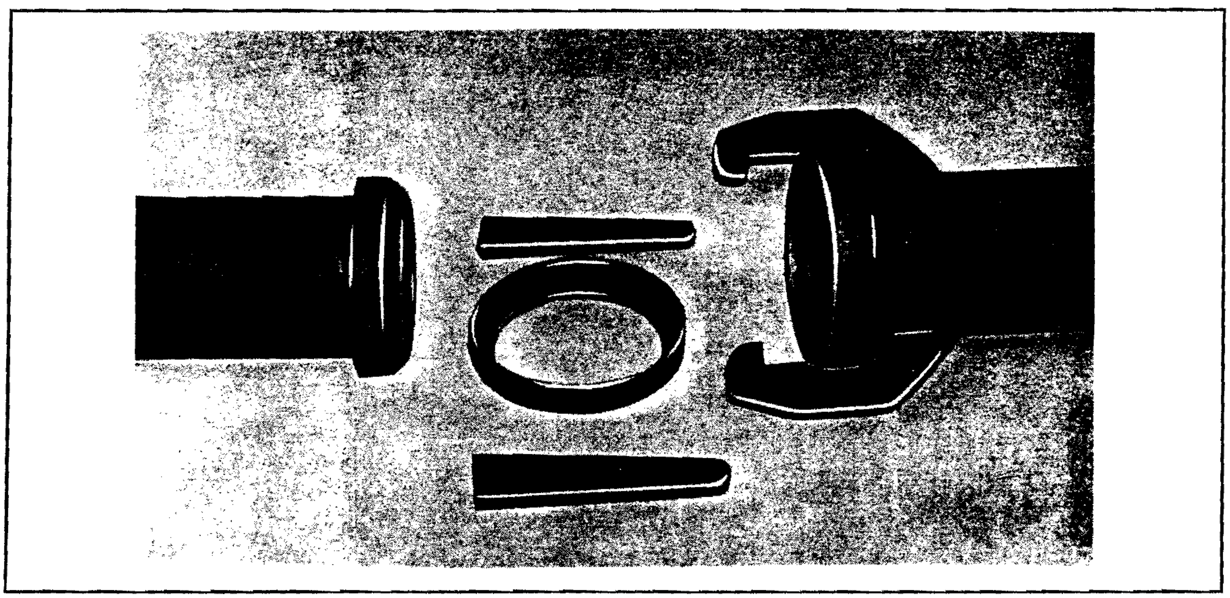

Figure A-8. Toggle-Type Pipe Coupling in Closed and Open Positions [39].

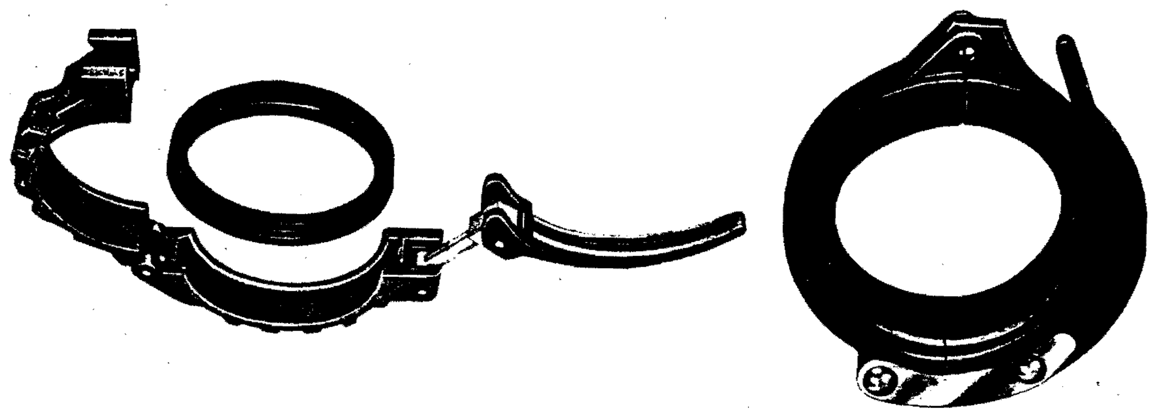

Figure A-9. Quick-Action Pipe Coupling Tightened by Driving on Two Wedges [39].

connection for a water hose which is joined to the pipeline to clean out the concrete after use. Water is normally supplied by a pump mounted on the machine. A similar gun equipped with an air release cock and a pressure gauge is used for cleaning pipelines by compressed air.

**Trap basket** - A device fitted to the end of the pipeline, when the wash-out gun is used, to catch the sponge rubber ball used in this operation.

**Pump Mountings and Booms**

Most hydraulically operated pumps are mounted on truck chassis as shown in Figure A-10. Vehicles that carry booms require additional stability to avoid overturning, and lorry mounted pumps are fitted with two or four outriggers.

Booms are capable of supporting about 20 to 60 feet of pipeline that can be slewed and derricked to alter the position of the delivery hose,

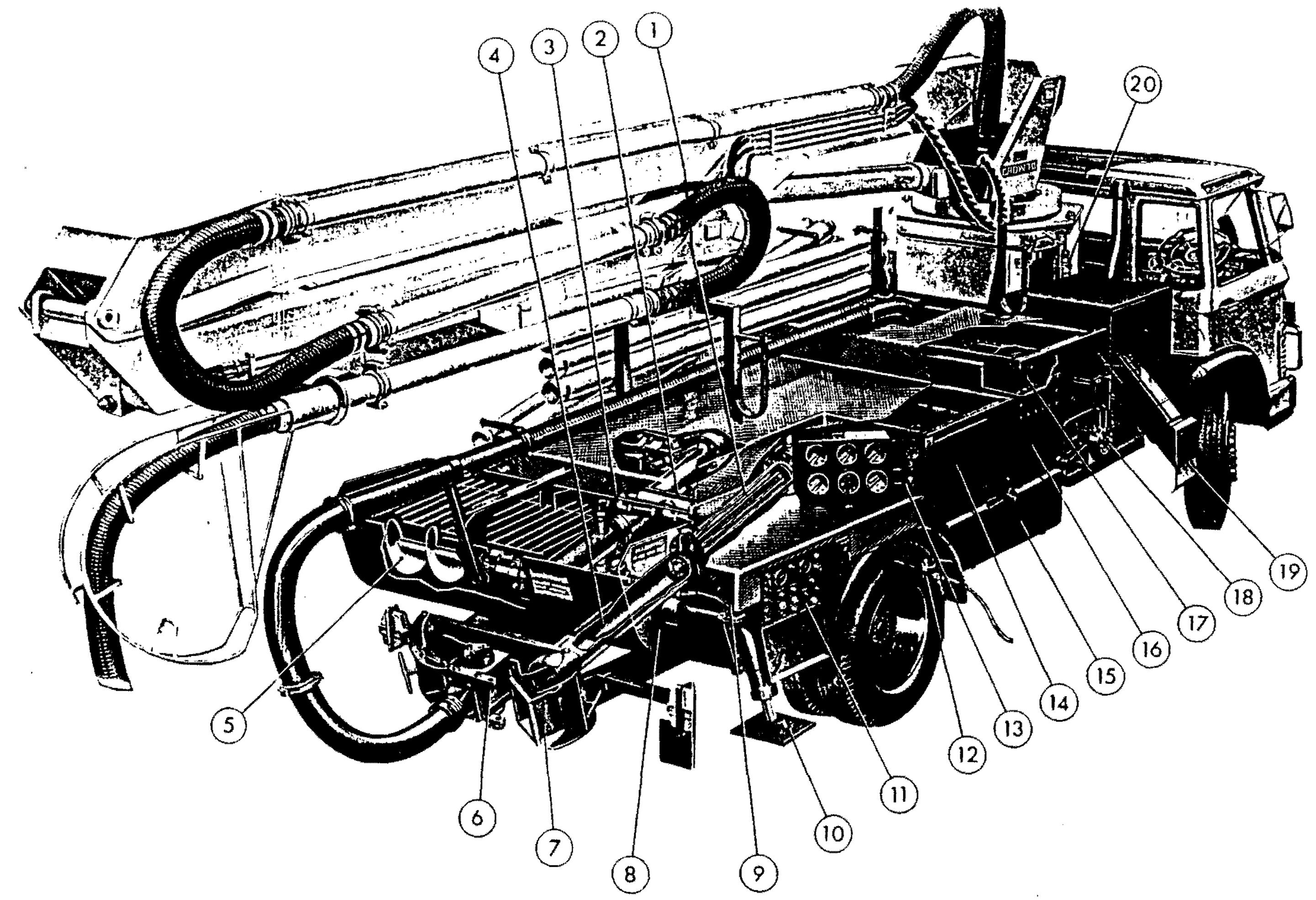


Figure A-10. A Typical Mobile Pump with Hydraulically Articulated Boom [39].

which greatly increases the efficiency of concrete placing. The lattice type boom eliminates the need for rigging vertical pipelines and attaching them to the building or scaffolding, but, as the boom is transported in sections, it requires manual erection on site. Articulating booms with permanently rigged pipeline can achieve heights up to 90 feet. These booms are unfolded from the travelling to the working position in a few minutes by hydraulic rams, the movements of the boom being controlled from the vehicle or with a remote control box. From observation of Figure A-10, one can discern what path the concrete takes as part of the delivery process involved in pumping. In mechanically operated concrete pumps, once the concrete is placed in the receiving hopper it is stirred by the remixing blades to agitate the concrete. The concrete moves from the hopper with the help of vibration in the hopper into the cylinder by the inlet valve while the outlet valve is closed preventing concrete from moving into the pipeline. The suction caused by the piston moving back draws the concrete into the cylinder with the aid of gravity. On the forward stroke the inlet valve closes while the outlet valve opens to allow a length or a "plug" of concrete to be discharged into the pipeline. This action causes the concrete to move within the pipeline in a pulsating flow, which subjects the concrete to peak pressure pulses until it is extruded from the pipeline. To allow for double cylinder action, a "y" piece is inserted into the line to accommodate both cylinders.

Hydraulic pumps offer some advantages such as longer pump stokes, controlled pumping speed, and controlled pump pressures over mechanical pumps. Other than these differences, the path of concrete in the process of pumping is similar in both pumps.

# APPENDIX B

# CONCRETE PUMPING FACTORIAL DATA

## Appendix Notation

| | |
|---|---|
| F#,FACT# : | Factorial Number |
| CAF : | Coarse Aggregate Factor |
| IA : | Intermediate Aggregate |
| ADMIX : | Air Entrainment Admixture |
| BOOM : | Boom Configuration |
| AIR% : | Measured Air Content (Type B Pressure Meter) |
| STD : | Standard Deviation |
| SLUMP : | Measured Concrete Slump |
| U.WT. : | Sample Weight |
| B : | Before Pumping |
| A : | After Pumping |
| 30 : | 30 Minutes After Discharge |
| V : | Vibrated Concrete Sample |
| T : | Concrete Pumped with Turbulator Connected to End of Line |

**Table B-1. Experimental Factorial Design Data.**

| FACTORIAL DESIGN # | DESIGN PARAMETERS: CAF | IA | ADMIX | BOOM | DATE OF TEST | AVERAGE TEMP. | TYPE OF PUMP | PIPE DIAMETER | BOOM LENGTH |
|---|---|---|---|---|---|---|---|---|---|
| 1 | - | - | + | - | 02-02-92 | 65 F | Schwing 1200/32 | 5" | 32 m |
| 2 | - | - | - | + | 02-02-92 | 60 F | " | 5" | 32 m |
| 3 | - | - | - | - | 02-08-92 | 60 F | " | 5" | 32 m |
| 4 | - | - | + | + | 02-08-92 | 60 F | " | 5" | 32 m |
| 5 | - | + | + | + | 01-20-92 | 78 F | " | 5" | 32 m |
| 6 | - | + | - | - | 01-20-92 | 78 F | " | 5" | 92 ft |
| 7 | - | + | - | + | 02-08-92 | 60 F | " | 5" | 32 m |
| 7A | - | + | - | + | 02-08-92 | 60 F | " | 5" | 32 m |
| 8 | - | + | + | - | 01-20-92 | 57 F | " | 5" | 32 m |
| 8A | - | + | + | - | 02-08-92 | 55 F | " | 5" | 32 m |
| 9 | + | - | + | - | 01-20-92 | 60 F | " | 5" | 32 m |
| 10 | + | - | - | - | 01-20-92 | 78 F | " | 5" | 32 m |
| 11 | + | - | + | + | 02-08-92 | 55 F | " | 5" | 32 m |
| 12 | + | - | - | + | 01-20-92 | 78 F | " | 5" | 32 m |
| 12A | + | - | - | + | 02-08-92 | 55 F | " | 5" | 32 m |
| 13 | + | + | + | + | * | * | * | * | * |
| 14 | + | + | + | - | * | * | * | * | * |
| 15 | + | + | - | + | * | * | * | * | * |
| 16 | + | + | - | - | * | * | * | * | * |

## Table B-2. Mix Design Group II Fact# 5, 6, 7 (Jan 20, 1992).

Texas Highway Department
Construction Form 309

County: ____
Project: ____
Date: ____

**CONCRETE DESIGN WORK SHEET**
(NATURAL AGGREGATES)

AGGREGATE CHARACTERISTICS:

Factorial Design No: 5, 6, & 8
Group No: II

| | SP. GR | SSD Unit Wt. Lbs./Cu.Ft. | % Solids | F.M. |
|---|---|---|---|---|
| Fine Aggregate (FA) | 2.63 | 101.00 | 0.615 | 2.51 |
| Coarse Aggregate (CA) | 2.57 | 93.01 | 0.580 | |

SOURCE
Water ____
Cement ____
Fly Ash ____

DESIGN FACTORS:
Cement Factor (CF). 5 Sacks per cubic yard of concrete
Coarse Aggregate Factor (CAF) 0.57
Water Cement Ratio (WCR) 5.0 ga. per sack of cement
Air Factor (AF) 5.0 %
Percent-Fly Ash 17.33 % Sp. Gr. (Fly Ash) 2.55

BATCH FACTOR:
$\frac{\text{Size of Batch (Full Size)}}{\text{Yield for 1-Sk. Batch}} = \frac{27}{5.4} = 5$

| BATCH DESIGN (ONE SACK) | VOLUMES 1-SK. BATCH (CU. FT.) | | VOL. TO WT. (LB.) VOL. X 62.5 X SP. GR | 1-SK. BATCH WTS. | FULL SIZE BATCH | |
|---|---|---|---|---|---|---|
| 1. Concrete Yield = Cu. Ft. per Cu.Yd. / CF | 27 / 5 = 5.4 | | | | | |
| 2. Volume CA = Yield X CAF X Solid | 5.4 X 0.57 X 0.58 = | 1.79 | X 62.5 X 2.57 = | 288 | 5 | 1440 |
| 3. Volume Mortar = Yield - Vol. Ca. | 5.4 - 1.79 = 3.61 | | | | | |
| 4. Volume Water = WF / Gal. Water per Cu. Ft. | 5.0 / 7.5 = | 0.667 | X 62.5 X 1.00 = | 41.69 | 5 | 208.45 |
| 5. Volume Fly Ash .485 X % Fly Ash / 100 | .485 X 17.33 % Fly Ash / 100 = | 0.084 | X 62.5 X 2.55 = | 13.39 | 5 | 66.95 |
| 6. Volume Cement = .485 - Vol. Fly Ash | .485 - 0.084 = | 0.401 | X 6.25 X 3.10 = | 7.77 | 5 | 38.85 |
| 7. Volume Entrained Air = Yield X AF | 5.4 X 0.05 = | 0.27 | | | | |
| 8. Volume Paste = Water + Fly Ash + Vol. Cem. + Air | 0.667 +0.084+0.401 + 0.27 = 1.422 ... | | | | | |
| 9. Volume FA = Vol. Mortar - Paste | 3.61 - 1.422 = | 2.188 | X 62.5 X 2.63 = | 360 | 5 | 1800 |
| 10. Yield (Summation of 2, 4, 5, 6, 7 & 9 to Check No. 1 Above) | | = 5.4 | | | | |

11. Fine Aggregate Factor = $\frac{\text{Vol. Fa}}{\text{FA Solids X Vol. Mortar}} = \frac{2.188}{0.615 \text{ X } 3.61} = 0.986$

* Correct for Free Moisture or Absorption
** Specific Gravity of Fly Ash from Source to be Used
** Sum of Steps 4, 5, 6, & 7

| Fact# | ADMIXTURE DOSAGES (Description) | (Amt./Batch) |
|---|---|---|
| 5. | Concentrate AES | 40.0 oz. |
| 6. | Relcrete Air 30 | 40.0 oz. |
| 8. | AIR-TITE | 32.0 oz. |

Remarks: Volumes in Above are Absolute Unless Otherwise Noted.
Water Added of Mixer Must Include the Liquid of the Admixtures.

## Table B-3. Mix Design Group III Fact# 9, 10, 12 (Jan 20, 1992).

Texas Highway Department
Construction Form 309

County: ________
Project: ________
Date: ________

CONCRETE DESIGN WORK SHEET
(NATURAL AGGREGATES)

AGGREGATE CHARACTERISTICS:

Factorial Design No: 9, 10, & 12
Group No: III

| | SP. GR | SSD Unit Wt. Lbs./Cu.Ft. | % Solids | F.M. |
|---|---|---|---|---|
| Fine Aggregate (FA) | 2.63 | 101.00 | 0.615 | 2.51 |
| Coarse Aggregate (CA) | 2.57 | 93.01 | 0.580 | |

| | SOURCE |
|---|---|
| | |
| | |
| Water | |
| Cement | |
| Fly Ash | |

DESIGN FACTORS:
Cement Factor (CF). 5 Sacks per cubic yard of concrete
Coarse Aggregate Factor (CAF) 0.716
Water Cement Ratio (WCR) 5.78 ga. per sack of cement
Air Factor (AF) 5.0 %
Percent-Fly Ash 0.0 % Sp. Gr. (Fly Ash) -

BATCH FACTOR:
Size of Batch (Full Size) / Yield for 1-Sk. Batch = 27 / 5.4 = 5

| BATCH DESIGN (ONE SACK) | VOLUMES 1-SK. BATCH (CU. FT.) | | VOL. TO WT. (LB.) VOL. X 62.5 X SP. GR | 1-SK. BATCH WTS. | FULL SIZE BATCH | |
|---|---|---|---|---|---|---|
| 1. Concrete Yield = Cu. Ft. per Cu.Yd. / CF | 27 / 5 = 5.4 | | | | | |
| 2. Volume CA = Yield X CAF X Solid | 5.4 X 0.716 X 0.58 = | 2.24 | X 62.5 X 2.57 = | 360 | 5 | 1800 |
| 3. Volume Mortar = Yield - Vol. Ca. | 5.4 - 2.24 = 3.16 | | | | | |
| 4. Volume Water = WF / Gal. Water per Cu. Ft. | 5.78 / 7.5 = | 0.771 | X 62.5 X 1.00 = | 48.20 | 5 | 241.0 |
| 5. Volume Fly Ash .485 X % Fly Ash / 100 | .485 X 0 / 100 % Fly Ash = | 0 | X 62.5 X - = | 0 | 5 | 0 |
| 6. Volume Cement = .485 + Vol. Fly Ash | .485 + 0 = | 0.485 | X 6.25 X 3.10 = | 9.40 | 5 | 47 |
| 7. Volume Entrained Air = Yield X AF | 5.4 X 0.05 = | 0.27 | | | | |
| 8. Volume Paste = Water + Fly Ash + Vol. Cem. + Air | 0.771 + 0 + 0.485 + 0.27 = 1.526 ... | | | | | |
| 9. Volume FA = Vol. Mortar - Paste | 3.16 - 1.526 = | 1.634 | X 62.5 X 2.63 = | 269 | 5 | 1345 |
| 10. Yield (Summation of 2, 4, 5, 6, 7 & 9 to Check No. 1 Above) = | | 5.4 | | | | |
| 11. Fine Aggregate Factor = Vol. Fa / FA Solids X Vol. Mortar | = 1.634 / 0.615 X 3.16 = | 0.841 | | | | |

* Correct for Free Moisture or Absorption
** Specific Gravity of Fly Ash from Source to be Used
** Sum of Steps 4, 5, 6, & 7

| Fact# | ADMIXTURE DOSAGES (Description) | (Amt./Batch) |
|---|---|---|
| 9. | Sika-AER | 32.0 oz. |
| 10. | Relcrete Air 30 | 40.0 oz. |
| 12. | Reicrete Air 30 | 40.0 oz. |

Remarks: Volumes in Above are Absolute Unless Otherwise Noted. Water Added of Mixer Must Include the Liquid of the Admixtures.

# Table B-4. Mix Design Group I Fact# 1, 2, 3, 4 (Feb 08, 1992).

Texas Highway Department
Construction Form 309

County: ______
Project: ______
Date: ______

CONCRETE DESIGN WORK SHEET
(NATURAL AGGREGATES)

Factorial Design No: 1, 2, 3, & 4
Group No: I

AGGREGATE CHARACTERISTICS:

| | SP. GR | SSD Unit Wt. Lbs./Cu.Ft. | % Solids | F.M. |
|---|---|---|---|---|
| Fine Aggregate (FA) | 2.63 | 101.00 | 0.615 | 2.51 |
| Coarse Aggregate (CA) | 2.57 | 93.01 | 0.580 | |

SOURCE
Water
Cement
Fly Ash

DESIGN FACTORS:
Cement Factor (CF). 5 Sacks per cubic yard of concrete
Coarse Aggregate Factor (CAF) 0.64
Water Cement Ratio (WCR) 6.4 ga. per sack of cement
Air Factor (AF) 5.0 %
Percent-Fly Ash 0.0 % Sp. Gr. (Fly Ash) -

BATCH FACTOR:
Size of Batch (Full Size) / Yield for 1-Sk. Batch = 27 / 5.4 = 5

| BATCH DESIGN (ONE SACK) | VOLUMES 1-SK. BATCH (CU. FT.) | | VOL. TO WT. (LB.) VOL. X 62.5 X SP. GR | 1-SK. BATCH WTS. | FULL SIZE BATCH | |
|---|---|---|---|---|---|---|
| 1. Concrete Yield = Cu. Ft. per Cu.Yd. / CF | 27 / 5 = 5.4 | | | | | |
| 2. Volume CA = Yield X CAF X Solid | 5.4 X 0.64 X 0.58 = | 2.0 | X 62.5 X 2.57 = | 322 | 5 | 1610 |
| 3. Volume Mortar = Yield - Vol. Ca. | 5.4 - 2.0 = 3.4 | | | | | |
| 4. Volume Water = WF / Gal. Water per Cu. Ft. | 6.4 / 7.5 = | 0.853 | X 62.5 X 1.00 = | 53.31 | 5 | 266.55 |
| 5. Volume Fly Ash .485 X % Fly Ash / 100 | .485 X 0 / 100 % Fly Ash = | 0 | X 62.5 X - = | 0 | 5 | 0 |
| 6. Volume Cement = .485 + Vol. Fly Ash | .485 + 0 = | 0.485 | X 6.25 X 3.10 = | 9.40 | 5 | 47 |
| 7. Volume Entrained Air = Yield X AF | 5.4 X 0.05 = | 0.27 | | | | |
| 8. Volume Paste = Water + Fly Ash + Vol. Cem. + Air | 0.853 + 0 + 0.485 + 0.27 = 1.608 ... | | | | | |
| 9. Volume FA = Vol. Mortar - Paste | 3.4 - 1.608 = | 1.792 | X 62.5 X 2.63 = | 295 | 5 | 1475 |
| 10. Yield (Summation of 2, 4, 5, 6, 7 & 9 to Check No. 1 Above) = | | 5.4 | | | | |

11. Fine Aggregate Factor = Vol. Fa / FA Solids X Vol. Mortar = 1.792 / 0.615 X 3.4 = 0.857

* Correct for Free Moisture or Absorption
** Specific Gravity of Fly Ash from Source to be Used
** Sum of Steps 4, 5, 6, & 7

| Fact# | ADMIXTURE DOSAGES (Description) | (Amt./Batch) |
|---|---|---|
| 1. | DARAVAIR | 12.5 oz. |
| 2. | BRYCO | 24.0 oz. |
| 3. | BRYCO | 26.0 oz. |
| 4. | DARAVAIR | 10.0 oz. |

Remarks: Volumes in Above are Absolute Unless Otherwise Noted.
Water Added of Mixer Must Include the Liquid of the Admixtures.

## Table B-5. Mix Design Group II Fact# 7, 7A, 8A (Feb 08, 1992).

Texas Highway Department
Construction Form 309

County: ____
Project: ____
Date: ____

CONCRETE DESIGN WORK SHEET
(NATURAL AGGREGATES)

AGGREGATE CHARACTERISTICS:

Factorial Design No: 7, 7A, 8A
Group No: II

| | SP. GR | SSD Unit Wt. Lbs./Cu.Ft. | % Solids | F.M. |
|---|---|---|---|---|
| Fine Aggregate (FA) | 2.63 | 101.00 | 0.615 | 2.51 |
| Coarse Aggregate (CA) | 2.57 | 93.01 | 0.580 | |

SOURCE
Water ____
Cement ____
Fly Ash ____

DESIGN FACTORS:
Cement Factor (CF). 5 Sacks per cubic yard of concrete
Coarse Aggregate Factor (CAF) 0.63
Water Cement Ratio (WCR) 6.2 ga. per sack of cement
Air Factor (AF) 5.0 %
Percent-Fly Ash 0.0 % Sp. Gr. (Fly Ash) -

BATCH FACTOR:
Size of Batch (Full Size) / Yield for 1-Sk. Batch = 27 / 5.4 = 5

| BATCH DESIGN (ONE SACK) | VOLUMES 1-SK. BATCH (CU. FT.) | | VOL. TO WT. (LB.) VOL. X 62.5 X SP. GR | 1-SK. BATCH WTS. | FULL SIZE BATCH | |
|---|---|---|---|---|---|---|
| 1. Concrete Yield = Cu. Ft. per Cu.Yd. / CF | 27 / 5 = 5.4 | | | | | |
| 2. Volume CA = Yield X CAF X Solid | 5.4 X 0.63 X 0.58 = | 1.97 | X 62.5 X 2.57 = | 316 | 5 | 1580 |
| 3. Volume Mortar = Yield - Vol. Ca. | 5.4 - 1.97 = 3.43 | | | | | |
| 4. Volume Water = WF / Gal. Water per Cu. Ft. | 6.2 / 7.5 = | 0.827 | X 62.5 X 1.00 = | 51.69 | 5 | 258.45 |
| 5. Volume Fly Ash .485 X % Fly Ash / 100 | .485 X 0 / 100 % Fly Ash = | 0 | X 62.5 X - = | 0 | 5 | 0 |
| 6. Volume Cement = .485 + Vol. Fly Ash | .485 + 0 = | 0.485 | X 6.25 X 3.10 = | 9.40 | 5 | 47 |
| 7. Volume Entrained Air = Yield X AF | 5.4 X 0.05 = | 0.27 | | | | |
| 8. Volume Paste = Water + Fly Ash + Vol. Cem. + Air | 0.827 + 0 + 0.485 + 0.27 = 1.582 ... | | | | | |
| 9. Volume FA = Vol. Mortar - Paste | 3.43 - 1.582 = | 1.848 | X 62.5 X 2.63 = | 304 | 5 | 1520 |
| 10. Yield (Summation of 2, 4, 5, 6, 7 & 9 to Check No. 1 Above) . = | | 5.4 | | | | |

11. Fine Aggregate Factor = Vol. Fa / FA Solids X Vol. Mortar = 1.848 / 0.615 X 3.43 = 0.876

* Correct for Free Moisture or Absorption
** Specific Gravity of Fly Ash from Source to be Used
** Sum of Steps 4, 5, 6, & 7

| Fact# | ADMIXTURE DOSAGES (Description) | (Amt./Batch) |
|---|---|---|
| 7. | BRYCO | 24.0 oz. |
| 7A. | BRYCO | 26.0 oz. |
| 8A. | DARAVAIR | 12.5 oz. |

Remarks: Volumes in Above are Absolute Unless Otherwise Noted.
Water Added of Mixer Must Include the Liquid of the Admixtures.

## Table B-6. Mix Design Group III Fact# 11, 12A (Feb 08, 1992).

Texas Highway Department
Construction Form 309

County: ______
Project: ______
Date: ______

CONCRETE DESIGN WORK SHEET
(NATURAL AGGREGATES)

AGGREGATE CHARACTERISTICS:

Factorial Design No: 11, 12A
Group No: III

| | SP. GR | SSD Unit Wt. Lbs./Cu.Ft. | % Solids | F.M. |
|---|---|---|---|---|
| Fine Aggregate (FA) | 2.63 | 101.00 | 0.615 | 2.51 |
| Coarse Aggregate (CA) | 2.57 | 93.01 | 0.580 | |

| | SOURCE |
|---|---|
| | |
| | |
| Water | |
| Cement | |
| Fly Ash | |

DESIGN FACTORS:
Cement Factor (CF). 5 Sacks per cubic yard of concrete
Coarse Aggregate Factor (CAF) 0.73
Water Cement Ratio (WCR) 6.2 ga. per sack of cement
Air Factor (AF) 5.0 %
Percent-Fly Ash 0.0 % Sp. Gr. (Fly Ash) -

BATCH FACTOR:
Size of Batch (Full Size) / Yield for 1-Sk. Batch = 27 / 5.4 = 5

| BATCH DESIGN (ONE SACK) | VOLUMES 1-SK. BATCH (CU. FT.) | | VOL. TO WT. (LB.) VOL. X 62.5 X SP. GR | 1-SK. BATCH WTS. | FULL SIZE BATCH | |
|---|---|---|---|---|---|---|
| 1. Concrete Yield = Cu. Ft. per Cu.Yd. / CF | 27 / 5 = 5.4 | | | | | |
| 2. Volume CA = Yield X CAF X Solid | 5.4 X 0.73 X 0.58 = | 2.29 | X 62.5 X 2.57 = | 368 | 5 | 1840 |
| 3. Volume Mortar = Yield - Vol. Ca. | 5.4 - 2.29 = 3.11 | | | | | |
| 4. Volume Water = WF / Gal. Water per Cu. Ft. | 6.2 / 7.5 = | 0.827 | X 62.5 X 1.00 = | 51.69 | 5 | 258.45 |
| 5. Volume Fly Ash .485 X % Fly Ash / 100 | .485 X 0 / 100 % Fly Ash = | 0 | X 62.5 X - = | 0 | 5 | 0 |
| 6. Volume Cement = .485 + Vol. Fly Ash | .485 + 0 = | 0.485 | X 6.25 X 3.10 = | 9.40 | 5 | 47 |
| 7. Volume Entrained Air = Yield X AF | 5.4 X 0.05 = | 0.27 | | | | |
| 8. Volume Paste = Water + Fly Ash + Vol. Cem. + Air | 0.827 + 0 + 0.485 + 0.27 = 1.582 ... | | | | | |
| 9. Volume FA = Vol. Mortar - Paste | 3.11 - 1.582 = | 1.528 | X 62.5 X 2.63 = | 251 | 5 | 1255 |
| 10. Yield (Summation of 2, 4, 5, 6, 7 & 9 to Check No. 1 Above) = | | 5.4 | | | | |

11. Fine Aggregate Factor = Vol. Fa / FA Solids X Vol. Mortar = 1.528 / 0.615 X 3.11 = 0.799

* Correct for Free Moisture or Absorption
** Specific Gravity of Fly Ash from Source to be Used
** Sum of Steps 4, 5, 6, & 7

| Fact# | ADMIXTURE DOSAGES (Description) | (Amt./Batch) |
|---|---|---|
| 11. | DARAVAIR | 12.5 oz. |
| 12A. | BRYCO | 26.0 oz. |

Remarks: Volumes in Above are Absolute Unless Otherwise Noted.
Water Added of Mixer Must Include the Liquid of the Admixtures.

## Table B-7. Measured Air and Slump Test Data.

| F# | B AIR% | B STD | B SLUMP | B-30 AIR % | B-30 STD | A AIR % | A STD | A SLUMP | A-30 AIR % | A-30 STD | AV AIR % | AV STD | AV-30 AIR % | AV-30 STD | AT AIR % | AT STD | AT-30 AIR % | AT-30 STD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.467 | 0.231 | 4.5" | 4.317 | 0.501 | 3.967 | 0.404 | 4.88" | 4.533 | 0.153 | 4.033 | 0.404 | _ | _ | 4.867 | 0.473 | _ | |
| 2 | 3.267 | 0.351 | 2.5" | 3.367 | 0.252 | 3.200 | 0.173 | 2.38" | 3.450 | 0.229 | 3.100 | 0.100 | _ | _ | 3.433 | 0.289 | _ | |
| 3 | 5.800 | 0.300 | 6.5" | 5.900 | 0.141 | 4.167 | 0.351 | 4.38" | 4.400 | 0.200 | 4.100 | 0.265 | _ | _ | 4.667 | 0.115 | _ | |
| 4 | 3.683 | 0.535 | 6.5" | 3.550 | 0.132 | 3.567 | 0.115 | 4.38" | 3.767 | 0.153 | 3.500 | 0.000 | _ | _ | 3.467 | 0.153 | _ | |
| 5 | 7.400 | 0.361 | 7.75" | 6.967 | 0.153 | 6.500 | 0.700 | 7.5" | 6.800 | 0.819 | 5.633 | 0.321 | 5.400 | 1.015 | 6.200 | 0.000 | | |
| 6 | 6.400 | 0.361 | 2.75" | 7.667 | 0.289 | 6.067 | 0.981 | _ | 6.400 | 0.849 | 5.583 | 0.382 | 6.267 | 0.475 | 6.667 | 0.764 | | |
| 7 | 3.967 | 0.321 | 4.0" | 3.767 | 0.321 | 3.083 | 0.419 | 2.75" | 3.000 | 0.231 | 3.017 | 0.325 | _ | _ | 3.017 | 0.539 | _ | |
| 7A | 4.133 | 0.321 | 4.5" | 3.900 | 0.707 | 3.100 | 0.000 | 4.88" | 3.150 | 0.071 | 2.600 | 0.265 | _ | _ | 3.233 | 0.058 | _ | |
| 8 | 7.570 | 0.208 | _ | 6.270 | 0.208 | 7.130 | 0.115 | _ | 6.430 | 0.208 | 6.070 | 0.208 | 6.630 | 0.252 | 5.270 | 0.874 | | |
| 8A | 5.233 | 0.351 | 4.5" | 5.033 | 0.252 | 4.633 | 0.351 | 4.25" | 4.567 | 0.379 | 4.667 | 0.451 | _ | _ | 4.500 | 0.000 | _ | |
| 9 | 8.200 | 0.400 | _ | 6.600 | 2.078 | 7.670 | 1.137 | _ | 8.270 | 0.404 | 8.030 | 0.058 | 7.130 | 1.159 | 7.800 | 0.693 | | |
| 10 | 8.500 | 0.000 | 7.5" | 12.00 | 1.000 | 5.167 | 0.289 | _ | 5.100 | 0.141 | 5.833 | 0.289 | 6.667 | 0.577 | 7.000 | 0.000 | | |
| 11 | 3.400 | 0.346 | 3.38" | 3.367 | 0.321 | 3.767 | 0.379 | 3.13" | 4.200 | 0.283 | 3.933 | 0.379 | _ | _ | 4.100 | 1.131 | _ | |
| 12 | 8.100 | 0.173 | 6.25" | _ | _ | 6.000 | 0.000 | 6.5" | 5.867 | 0.306 | 5.833 | 0.153 | 6.000 | 0.917 | 6.000 | 0.000 | | |

## Table B-8. Measured Sample Weight Data.

| FACT # | B | B-30 | A | A-30 | AV | AV-30 | AT | AT-30 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | U.WT | STD | U.WT | STD | U.WT | STD | U.WT | STD | U.WT | STD | U.WT | STD | U.WT | STD | U.WT | STD |
| 1 | 32.467 | 0.115 | 32.733 | 0.200 | 32.667 | 0.115 | 32.600 | 0.115 | 32.667 | 0.306 | - | - | 32.600 | 0.306 | - | - |
| 2 | 33.400 | 0.306 | 33.600 | 0.231 | 33.467 | 0.306 | 33.667 | 0.115 | 33.467 | 0.416 | - | - | 33.533 | 0.200 | - | - |
| 3 | 31.667 | 0.115 | 31.492 | 0.566 | 33.000 | 0.115 | 32.800 | 0.306 | 33.000 | 0.306 | - | - | 32.533 | 0.200 | - | - |
| 4 | 33.733 | 0.346 | 33.333 | 0.200 | 33.533 | 0.200 | 33.200 | 0.115 | 33.467 | 0.231 | - | - | 33.533 | 0.000 | - | - |
| 5 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 6 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 7 | 33.600 | 0.231 | 33.667 | 0.115 | 33.894 | 0.231 | 33.761 | 0.200 | 33.933 | 0.400 | - | - | 33.925 | 0.252 | - | - |
| 7A | 33.200 | 0.115 | 33.092 | 0.000 | 33.600 | 0.115 | 33.292 | 0.000 | 33.733 | 0.200 | - | - | 33.533 | 0.000 | - | - |
| 8 | 32.294 | 0.287 | 31.933 | 0.437 | 31.867 | 0.477 | 32.000 | 0.333 | 32.000 | 0.520 | 31.667 | 0.527 | 32.800 | 0.202 | 32.600 | 0.225 |
| 8A | 32.667 | 0.115 | 32.867 | 0.306 | 33.000 | 0.115 | 33.067 | 0.231 | 33.067 | 0.231 | - | - | 33.000 | 0.231 | - | - |
| 9 | 31.417 | 0.375 | 31.333 | 0.104 | 31.067 | 0.477 | 30.733 | 0.592 | 31.000 | 0.202 | 30.933 | 0.633 | 31.067 | 0.444 | 31.000 | 0.362 |
| 10 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 11 | 33.533 | 0.200 | 33.800 | 0.115 | 33.600 | 0.115 | 33.492 | 0.283 | 33.467 | 0.231 | - | - | 32.800 | 0.115 | - | - |
| 12 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

Table B-9. List of AEA's and Measured Surface Tension Results.

| PRODUCER | PRODUCT | DENSITY ($\rho$) | HEIGHT h cm. | SURFACE TENSION dynes-cm. |
|---|---|---|---|---|
| CORMIX | AIR-TITE | 1.01 to 1.06 | 2.20 | 31.196 to 32.74 |
| | AMEX 210 | 1.01 | 1.95 | 27.666 |
| W.R.GRACE | DARAVAIR-M | 1.02 to 1.09 | 2.50 | 35.783 to 38.238 |
| | DAREX AEA | 1.014 | 1.90 | 27.067 |
| PROKRETE | PROKRETE AES | 1.04 | 2.40 | 35.030 |
| | EVER AIR | 1.008 | 1.90 | 26.907 |
| | CONCENTRATE AES | 1.08 | 2.30 | 34.868 |
| MONEX | RELCRETE AIR30 | 1.02 | 2.05 | 29.366 |
| | SEPTAIR | 1.04 | 2.50 | 36.484 |
| SIKA-CORP | SIKA-AER | 1.048 | 2.35 | 34.567 |
| MASTER BUILDERS | PAVE AIR | 1.033 | 2.10 | 30.462 |
| | MB - VR | 1.033 | 2.15 | 31.184 |
| | MICRO - AIR | 1.007 | 1.80 | 25.473 |

Surface Tension of Water $\tau$ = 72 dyne-cm.

Table B-10. Linear Traverse Results - El Paso Samples.

| | | El Paso # 2 | El Paso # 5 |
|---|---|---|---|
| Distance From Pump | ft | 85.615 | 9.5099 |
| Total Length Traversed | in | 101.66496 | 96.3284 |
| Air Length in inches | | 8.09786 | 7.0985 |
| Number of Air Voids | | 1278 | 1125 |
| Aggregate Length in inches | | 56.4468 | 57.4219 |
| Number of Aggregate | | 1790 | 1591 |
| Paste Length in inches | | 37.1203 | 31.8080 |
| Air Void Spacing | n | 12.5707 | 11.6788 |
| Average Chord Length | $\bar{l}$ | 0.00633635 | 0.006309 |
| Air Content in | % | **7.97** | **7.37** |
| Paste Percentage | p | 36.51 | 33.02 |
| Specific Surface | @ | 631.28 | 634.015 |
| Paste / Air ratio | P/A | 4.581 | 4.481 |
| Spacing Factor | $\bar{L}$ | 0.0070491 | 0.0069481 |

# APPENDIX C

## DISCUSSION OF $2^3$ FACTORIAL DESIGN

## $2^3$ Factorial Design

The main purpose of using a designed experiment to examine the variations of measured air content in pumped concrete is to collect data in such a manner as to allow the development of a mathematical model to predict the measured variation in air under certain circumstances. Comparative experiments of this nature are an important means to discuss differences in the behavior of processes or other physical phenomenon, as various factors are altered in the environment and conditions of the mechanisms being considered.

Two-level factorial design consists of experiments run at two levels of each variable included in the experiment. A design may involve any number of variables, but most of them do not include more than 3 to 4 variables. The mathematical model which results from a three-variable experiment run at two-levels ($2^3$ factorial design) will have a form of:

$$Y_1 = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{123}X_1X_2X_3 \quad \text{(C-1)}$$

where

| | | |
|---|---|---|
| $Y$ | = | Predicted value |
| $X_i$ | = | Model variable |
| $b_i, b_{ij}, b_{ijk}$ | = | Variable coefficient or effect |

The analysis process related to a factorial design allows for the determination of the variable effects in the above mathematical model such that it may be used as a predictive tool. An example of the calculations involved with this analysis is provided subsequently which illustrates the development of a $2^3$ factorial design using the first three variables shown in Table C-1. The observations in the example will consist of the difference in measured air content between air tests taken before and after pumping of the concrete. This difference constitutes the loss in air content and is adjusted, as previously described, to a common slump of 5 inches based on the slump (Table B-7) that was recorded during each factorial run.

The factorial test conditions involve two levels for each variable based upon designated ranges. The "high" and "low" levels of the three variables are shown below in Table C-1. In order to adopt the notation of

Table C-1. Design Factorial Test Conditions.

| Variable | Unit | Low Level | High Level |
|---|---|---|---|
| Coarse Aggregate factor | Percent | 0.57 | 0.72 |
| Intermediate Aggregate | Pounds | 0 | 560 |
| Surface tension | dynes-cm | 26 | 34 |

pluses (+'s) and minuses (-'s) used to designate the different levels in factorial designs, transforming equations are incorporated to code the variables such that the high level will be denoted by +1 and the low level by -1. By doing so, the physical conditions represented by the two levels are transformed into the basic design of the two-level factorial design in the form of a simple arrangement of pluses and minuses. The transforming equations are listed as follows:

For coarse aggregate factor (CAF):

$$X_1 = \frac{0.645 - 0.72}{0.075} = -1 \qquad X_1 = \frac{0.72 - 0.645}{0.075} = +1$$

For intermediate aggregate (IA):

$$X_2 = \frac{0 - 280}{280} = -1 \qquad X_2 = \frac{560 - 280}{280} = +1$$

For Surface Tension (ST):

$$X_3 = \frac{26 - 30}{4} = -1 \qquad X_3 = \frac{34 - 30}{4} = +1$$

**Construction of the $2^3$ Factorial Design**

A complete $2^3$ factorial design requires $2^3$ = 8 tests. One systematic way of noting the eight sets of conditions in their coded form is to proceed as follows:

(1) For $X_1$, assign values -1, +1, -1, +1, -1, +1, -1, +1

(2) For $X_2$, assign values -1, -1, +1, +1, -1, -1, +1, +1

(3) For $X_3$, assign values -1, -1, -1, -1, +1, +1, +1, +1

A desired $2^3$ factorial design which consists of the eight distinct sets of coded test conditions is given below in Table C-2 and is represented geometrically in three dimensions in Figure C-1. The value of each of the variable combinations shown in Figure C-1 can be taken at either a high or low value of boom configuration.

**Table C-2. Standard Order of $2^3$ Factorial.**

| ORDER | CAF $X_1$ | IA $X_2$ | ST $X_3$ | CAF $(X_1)$ | Int.Agg $(X_2)$ | Surface Tension $(X_3)$ |
|---|---|---|---|---|---|---|
| 1 | -1 | -1 | -1 | 0.57 | 0 | 26 |
| 2 | +1 | -1 | -1 | 0.72 | 0 | 26 |
| 3 | -1 | +1 | -1 | 0.57 | 560 | 26 |
| 4 | +1 | +1 | -1 | 0.72 | 560 | 26 |
| 5 | -1 | -1 | +1 | 0.57 | 0 | 34 |
| 6 | +1 | -1 | +1 | 0.72 | 0 | 34 |
| 7 | -1 | +1 | +1 | 0.57 | 560 | 34 |
| 8 | +1 | +1 | +1 | 0.72 | 560 | 34 |

Presentation and Interpretation of Results: As pointed out previously, three air tests were conducted at each factorial shown in Table C-3. Obtaining replicated tests provide an estimate of the experimental error of the test method. The factorials 4 and 8 represented a set of test conditions which could not be pumped. The air loss to these test factorials was assigned based on the discussion previously provided. These assumptions are made to complete a $2^3$ factorial. The values from the different test conditions are represented geometrically in Figure C-2.

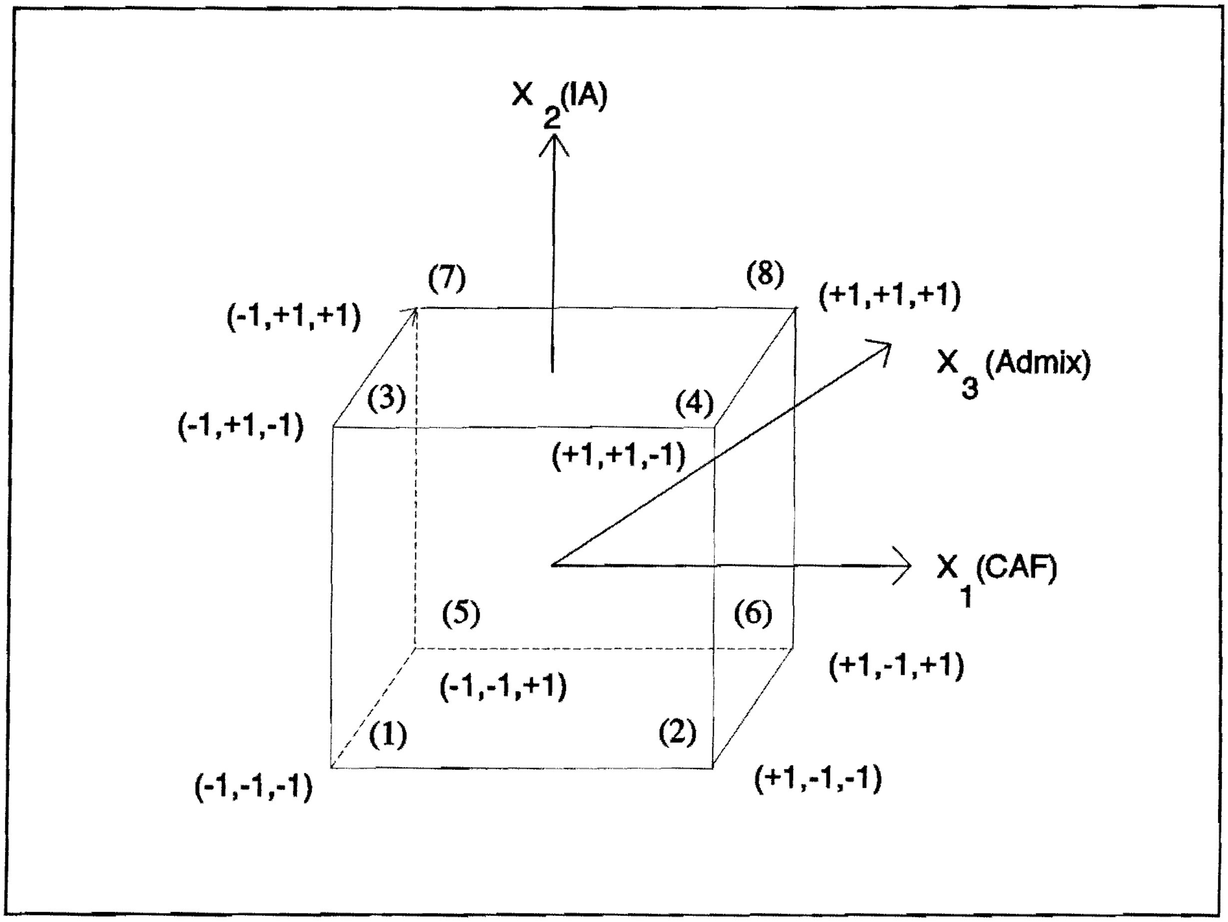


Figure C-1. Geometric Representation of the $2^3$ Factorial Design.

Table C-3. Average Factorial Test Results.

| Test No. | CAF | IA | ST | Loss of Air |
|---|---|---|---|---|
| 1 | - | - | - | 0.936 |
| 2 | + | - | - | 1.815 |
| 3 | - | + | - | 1.154 |
| 4 | + | + | - | 2.033 |
| 5 | - | - | + | -0.169 |
| 6 | + | - | + | 0.116 |
| 7 | - | + | + | 0.415 |
| 8 | + | + | + | 0.701 |

**Calculation of Variable Effects on Loss of Air**

The geometrical representation of the experimental design can be used to determine the value of each variable effect. The cube in Figure C-2 depicts the $2^3$ factorial geometrically. The average response for each test is given at the eight corners of the cube where the results of the tests are denoted as the corners of the cube.

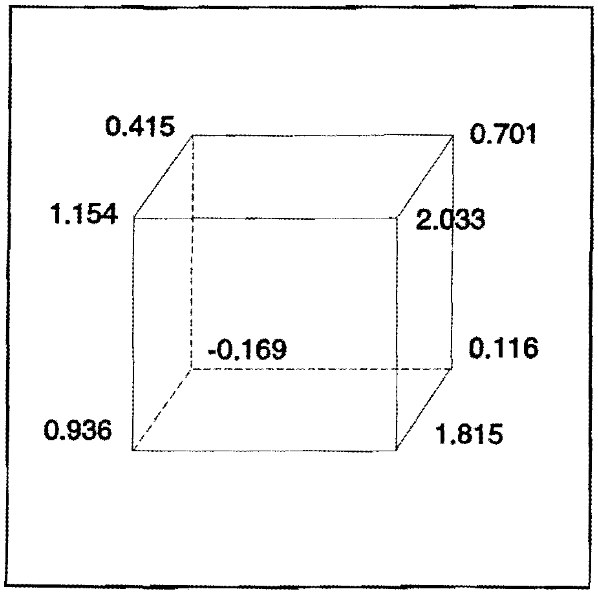


Figure C-2. Geometrical Representation of Replicated Tests.

Average/main effect of Intermediate Aggregate, $E_1$: In order to calculate how the air content changes with a change in any one of the three variables under consideration while the other two are held constant, a certain process is employed, as demonstrated in Figure C-3. A glance at the cube shown in this figure indicates that there are no less than four comparisons of test results or contrasts that can be made with respect to how the air content has changed when the coarse aggregate factor changes while the other two variables (the intermediate aggregate and the surface tension of the AEA) are held constant.

Comparison of the following pairs of tests are used to indicate the effect of CAF:

Tests 1&2: $Y_2-Y_1 = 1.815 - 0.966 = 0.849$

Tests 3&4: $Y_4-Y_3 = 2.033 - 1.154 = 0.879$

Tests 5&6: $Y_6-Y_5 = 0.116 - (-0.169) = 0.285$

Tests 7&8: $Y_8-Y_7 = 0.701 - 0.415 = 0.286$

The symbol Y indicates the difference in percent air loss for the experimental design conditions and combinations considered. To see the effect of Coarse Aggregate Factor (CAF) on the air entrainment alone we look across the cube from left to right. The differences in the results within each of the four pairs of tests just defined reflect the effect of coarse aggregate factor alone, on the amount of air loss.

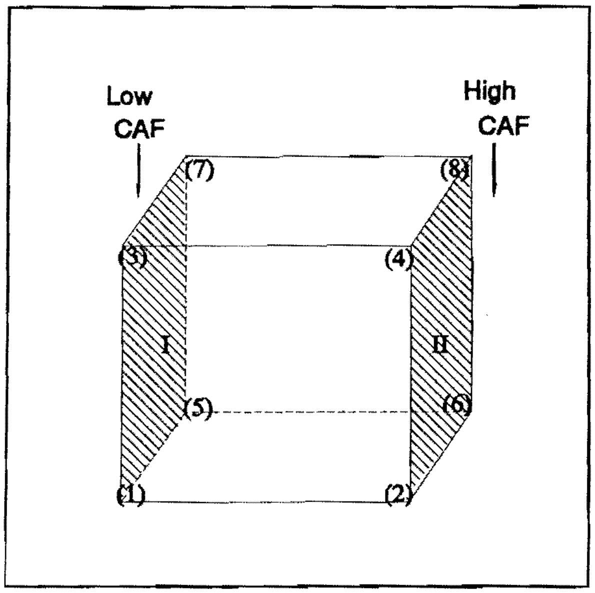


Figure C-3. Geometrical Representation of Average/Main Effect of CAF.

The average effect of the coarse aggregate factor, designated by $E_1$, is "by definition" the average of the above four differences. That is:

$$E_1 = 1/4\,[(Y_2-Y_1) + (Y_4-Y_3) + (Y_6-Y_5) + (Y_8-Y_7)]$$
$$= 1/4\,[0.849 + 0.879 + 0.285 + 0.286]$$
$$= 0.574$$

Geometrically, the average (main) effect of coarse aggregate, $E_1$, is the difference between the average test result on plane II (high level of coarse aggregate factor) and the average result on plane I (low level of coarse aggregate factor) as shown in Figure C-3. The average effect of lowering the coarse aggregate factor in the mix design is 0.574 percent which means that, on an average, a lower coarse aggregate factor will result in a lower amount of air loss due to pumping. Similarly, the effects of intermediate aggregate and the surface tension of AEA are calculated and are shown below.

<u>Average/main effect of Intermediate Aggregate, $E_2$</u>: Compare and contrast of the following pairs of tests reveals the effect of intermediate aggregate:

Tests 1 & 3 = $Y_3 - Y_1$ = 1.154 - 0.936 = 0.218

Tests 2 & 4 = $Y_4 - Y_2$ = 2.033 - 1.815 = 0.218

Tests 5 & 7 = $Y_7 - Y_5$ = 0.415 - (-0.169) = 0.584

Tests 6 & 8 = $Y_8 - Y_6$ = 0.701 - 0.116 = 0.585

And the average effect is:

$$E_2 = 1/4\,[(Y_3 - Y_1) + (Y_4 - Y_2) + (Y_7 - Y_5) + (Y_8 - Y_6)]$$
$$= 1/4\,[0.218 + 0.218 + 0.584 + 0.585]$$
$$= 0.401$$

Geometrically, the average effect of intermediate aggregate is the difference between the average result on plane IV (high level of intermediate aggregate) and the average result on plane III (low level of intermediate aggregate) and is represented by Figure C-4. The average effect of including an intermediate aggregate in the mix design is 0.401 which tells us that, on the average an intermediate aggregate will cause lower amount of air loss due to pumping.

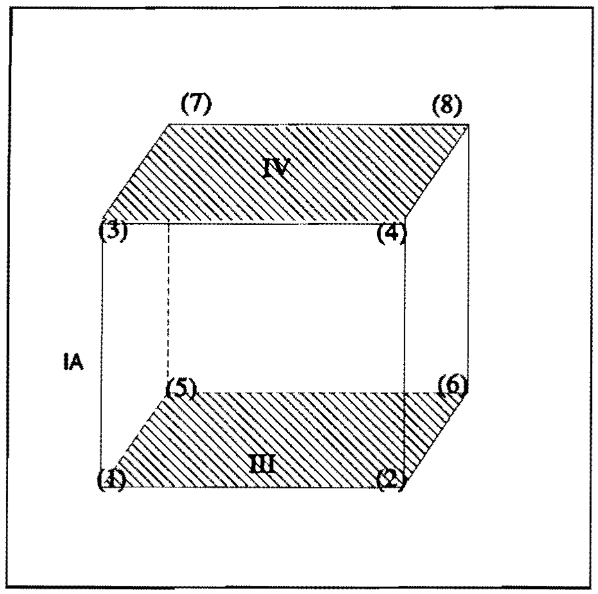


Figure C-4. Geometrical Representation of Average/Main Effect of IA.

Average/Main Effect of Surface Tension, $E_3$: Similarly, the average effect of the surface tension, $E_3$, is the corresponding comparison between plane IV (high level of surface tension) and plane V (low level of bar size) as indicated in the Figure C-5. A comparison of the following pairs of tests will illustrate the effect of surface tension of AEA:

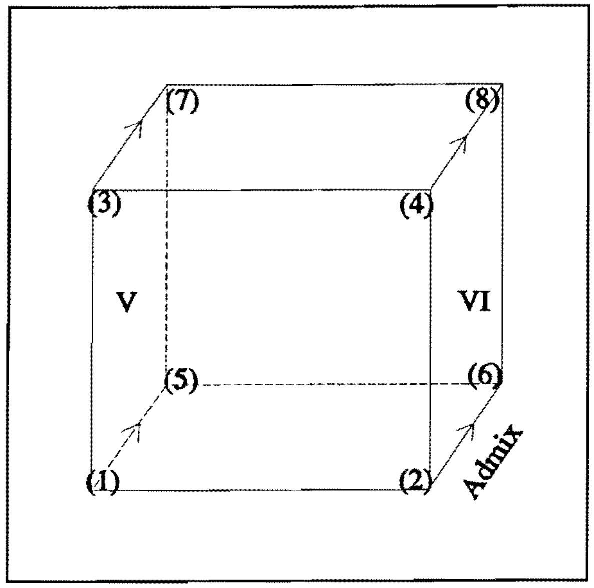


Figure C-5. Geometrical Representation of Average/Main Effect of Admix.

Tests 1 & 5 $\quad Y_5 - Y_1 =$

$(-0.169) - 0.936 = -1.1030$

Tests 2 & 6 $\quad Y_6 - Y_2 =$

$0.116 - 1.815 = -1.699$

Tests 3 & 7 $\quad Y_7 - Y_3 = 0.415 - 1.154 = -0.739$

Tests 4 & 8 $\quad Y_8 - Y_4 = 0.701 - 2.033 = -1.332$

and the average effect is:

$$E_3 = 1/4\ [(Y_5-Y_1) + (Y_6-Y_2) + (Y_7-Y_3) + (Y_8-Y_4)]$$
$$= 1/4\ [-1.1.050 - 1.699 - 0.739 - 1.332]$$
$$= -1.219$$

The average effect of the admixture is -1.219, which means that the use of high tension admixtures will result in a lower amount of air loss during pumping operations.

Interpretation of Average/Main Effects: The average or main effect of a variable is defined as the amount of change in the response, on the average, when only that variable changes from a low to a high level. It is an average effect because within the experimental design there are generally several comparisons/contrasts which can be made which measure the changes of response when only a certain variable changes. The average of all such contrasts across the entire experimental design is called the "average" or "main effect" of that factor. The sign of the variable indicates the direction of the effect and magnitude indicates the strength of the effect. Recalling the effect estimates:

$$E_1 = 0.574$$
$$E_2 = 0.401$$
$$E_3 = -1.219$$

**The Meaning of Variable Interactions**

In calculating the average/main effect of Coarse Aggregate Factor, the amount (and even direction) of change in air entrainment with change in coarse aggregate factor seemed to depend on the particular levels of intermediate aggregate and surface tension. The calculations are done as shown in Table C-4.

**Table C-4. Change in CAF Based on the Levels of IA and ST.**

| Intermediate Aggregate | Surface Tension | Effect of CAF |
|---|---|---|
| 0 | 26 | 0.849 |
| 560 | 26 | 0.879 |
| 0 | 34 | 0.285 |
| 560 | 34 | 0.286 |

Coarse Aggregate - Intermediate Aggregate Interaction: Looking closely at the above table, it can be said that the average effect of CAF varies little with the level of IA and the calculations are shown below:

without IA: $E_{CAF} = 1/2(0.849 + 0.285) = 0.567$

with IA: $E_{CAF} = 1/2(0.879 + 0.286) = 0.583$

The results indicate that the average effect of CAF is affected little with the presence of intermediate aggregate. The average effect of CAF is much different depending on the level of surface tension.

With low surface tension admixture:

$E_{CAF}$ = 1/2(0.849 + 0.879) = 0.864

With high surface tension admixture:

$E_{CAF}$ = 1/2(0.285 + 0.286) = 0.285

The effect of CAF on the loss of air seems to be:

1. Independent of the presence of intermediate aggregate, and
2. Dependent on the magnitude of surface tension of admixture.

The nature of the interaction that may exist between two factors can be examined with a 2-way diagram. To examine the interaction between CAF and IA, we compress the cube in Admix direction. Compressing the cube along a given axis into a square (Figure C-6) averages the response values for a given coarse aggregate factor and intermediate aggregate combination (at say, the (-)(-) levels) across the high and low levels of surface tension.

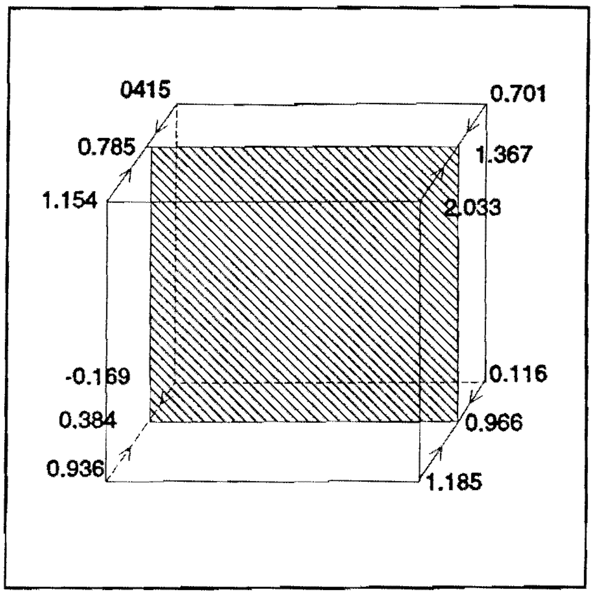


Figure C-6. Construction of Two Way Diagram for CAF and IA.

The square which resulted from the above calculations is represented in Figure C-7, and the calculations are done as shown below in the form of two way diagram.

$$E_{12} = 1/2\ [-0.583 - (-0.582)]$$
$$= 0$$

The value of $E_{12}$ shows that effect of CAF does not depend on level of intermediate aggregate.

<u>Coarse Aggregate - Admixture Interaction:</u> A similar analysis can be constructed for CAF and Admixture two factor interaction and is shown in the Figure C-8. The calculations are shown below:

$$E_{13} = 1/2\ [0.280 - 0.879] = 0.297$$

The results show that the effect of CAF depends strongly on admixture's surface tension.

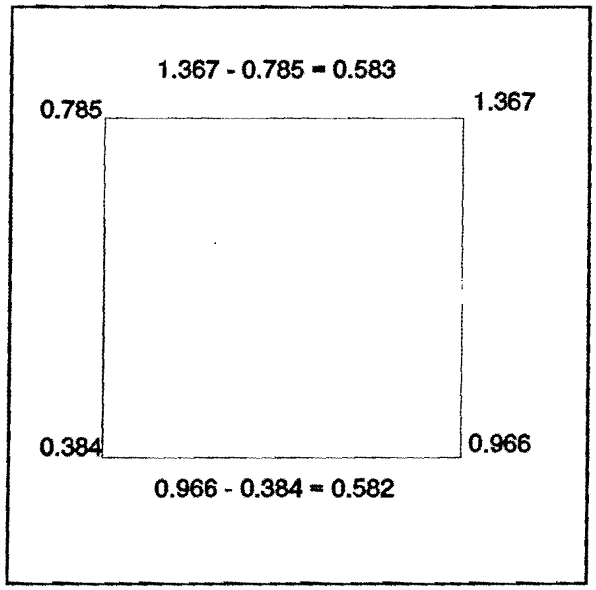


Figure C-7. Two Way Diagram for CAF and IA.

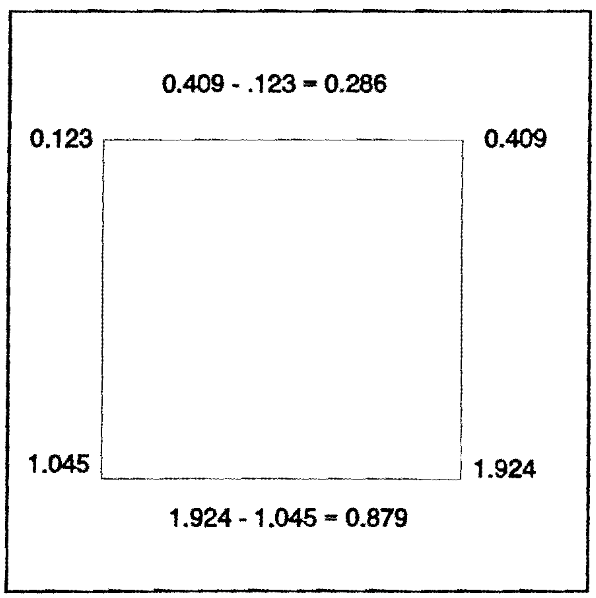


Figure C-8. Two Way Diagram for CAF and Admix.

Intermediate Aggregate - Admixture Interaction: Compressing the cube along CAF axis results in a square of two way diagram as shown in Figure C-9, and the calculations are done as shown below:

$$E_{23} = 1/2\ [-1.606 - (-1.403)] \qquad = 0.198$$

The results show that the effect of intermediate aggregate depends on the surface tension of the admixture.

Three Factor Interaction (CAF - Int.Agg. - Admix): Returning to the geometric representation of the $2^3$ factorial design, it was noted in the previous discussions of two factor interactions that the cube was averaged over the variable not under examination. Consideration of the two factor interaction "locally" that is, without compressing the cube along the surface tension axis, at the (-) level admixture, the calculation is:

$$E^{1}_{12} = 1/2[(0.936 - 1.154) - (1.815 - 2.033)$$

$$= 1/2[-0.218 -(-0.218)] = 0$$

At the (+) level of admixture the calculation is:

$$E^{11}_{12} = 1/2[(-0.169 - 0.415) - (0.116 - 0.701)]$$

$$= 1/2[-0.584 - (-0.585)] = 0$$

Since 2-factor interaction between CAF and intermediate aggregate does not depend on the level of surface tension, we say that a three factor interaction does not exist.

$$E_{123} = (E^{11}_{12} - E^{1}_{12})/2 = 0$$

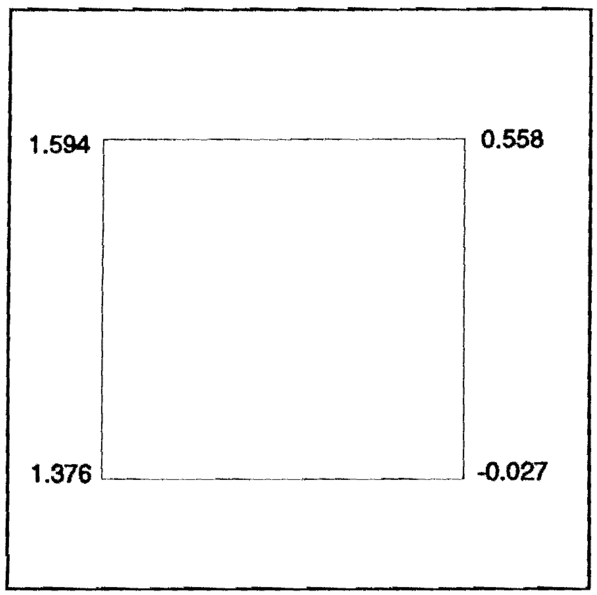


Figure C-9. Two Way Diagram for IA and Admix.

**Mathematical Modelling: Before Pumping vs After Pumping**

With the average/main and interaction affects calculations, the variable effects can now be determined as shown in Equation (C-1). The variable products in Equation (C-1) are summarized in Table C-5. The coefficients of the mathematical model are defined and provided in Table C-6 for two conditions of percent air loss immediately after pumping with (B - AT) and without (B - A) a turbulator connected to the end of the pump line. Substituting the values of b1, b2, b3, b12, b13, b23, and b123 in the mathematical model yields an estimate $\hat{Y}$ of Y at the high and low levels of boom configuration. The values of Y are shown in Table C-7.

**Table C-5. Mathematical Model Coefficients.**

| Factor | $X_4$ | $b_o$ | $b_1$ | $b_2$ | $b_3$ | $b_{12}$ | $b_{13}$ | $b_{23}$ | $b_{123}$ |
|---|---|---|---|---|---|---|---|---|---|
| Calc. | - | $\Sigma Y_i/8$ | $E_1/2$ | $E_2/2$ | $E_3/2$ | $E_{12}/2$ | $E_{13}/2$ | $E_{23}/2$ | $E_{123}/2$ |
| B - A | High | .875 | .291 | .200 | -.609 | 0 | -.148 | .092 | .110 |
| | Low | 1.15 | .277 | -.114 | -.844 | 0 | -.503 | .022 | .195 |
| B - AT | High | .945 | .327 | .301 | -.696 | 0 | -.401 | .091 | .182 |
| | Low | .758 | .136 | .336 | -.019 | 0 | .022 | .520 | .029 |

**Table C-6. Variable Products of Mathematical Model.**

| Test | $X_1$ | $X_2$ | $X_3$ | $X_1X_2$ | $X_1X_3$ | $X_2X_3$ | $X_1X_2X_3$ |
|---|---|---|---|---|---|---|---|
| 1 | -1 | -1 | -1 | +1 | +1 | +1 | -1 |
| 2 | +1 | -1 | -1 | -1 | -1 | +1 | +1 |
| 3 | -1 | +1 | -1 | -1 | +1 | -1 | +1 |
| 4 | +1 | +1 | -1 | +1 | -1 | -1 | -1 |
| 5 | -1 | -1 | +1 | +1 | -1 | -1 | +1 |
| 6 | +1 | -1 | +1 | -1 | +1 | -1 | -1 |
| 7 | -1 | +1 | +1 | -1 | -1 | +1 | -1 |
| 8 | +1 | +1 | +1 | +1 | +1 | +1 | +1 |

Table C-7. Measured and Calculated Air Loss (%).

| | Measured B - A | | Estimated B - A | | Measured B - AT | | Estimated B - AT | |
|---|---|---|---|---|---|---|---|---|
| Test | High Boom | Low Boom | High Boom | Low Boom | High Boom | Low Boom | High Boom | Low Boom |
| 1 | 0.936 | 1.348 | 0.826 | 1.153 | 0.703 | 0.847 | 0.521 | 0.818 |
| 2 | 1.815 | 2.908 | 1.925 | 3.103 | 2.160 | 1.075 | 2.342 | 1.103 |
| 3 | 1.154 | 1.077 | 1.264 | 1.272 | 1.121 | 0.480 | 1.303 | 0.508 |
| 4 | 2.033 | 2.637 | 1.923 | 2.442 | 2.579 | 0.707 | 2.397 | 0.679 |
| 5 | -.169 | 0.624 | -.059 | 0.819 | -.069 | -.276 | 0.113 | -.248 |
| 6 | 0.116 | 0.171 | 0.006 | -.024 | -.217 | 0.041 | -.399 | 0.012 |
| 7 | 0.415 | 0.439 | 0.305 | 0.244 | 0.715 | 1.436 | 0.533 | 1.408 |
| 8 | 0.701 | -.014 | 0.811 | 0.181 | 0.567 | 1.753 | 0.749 | 1.781 |

# APPENDIX D

# COMPARISON OF GRAVIMETRIC METHOD AND PRESSURE METHOD

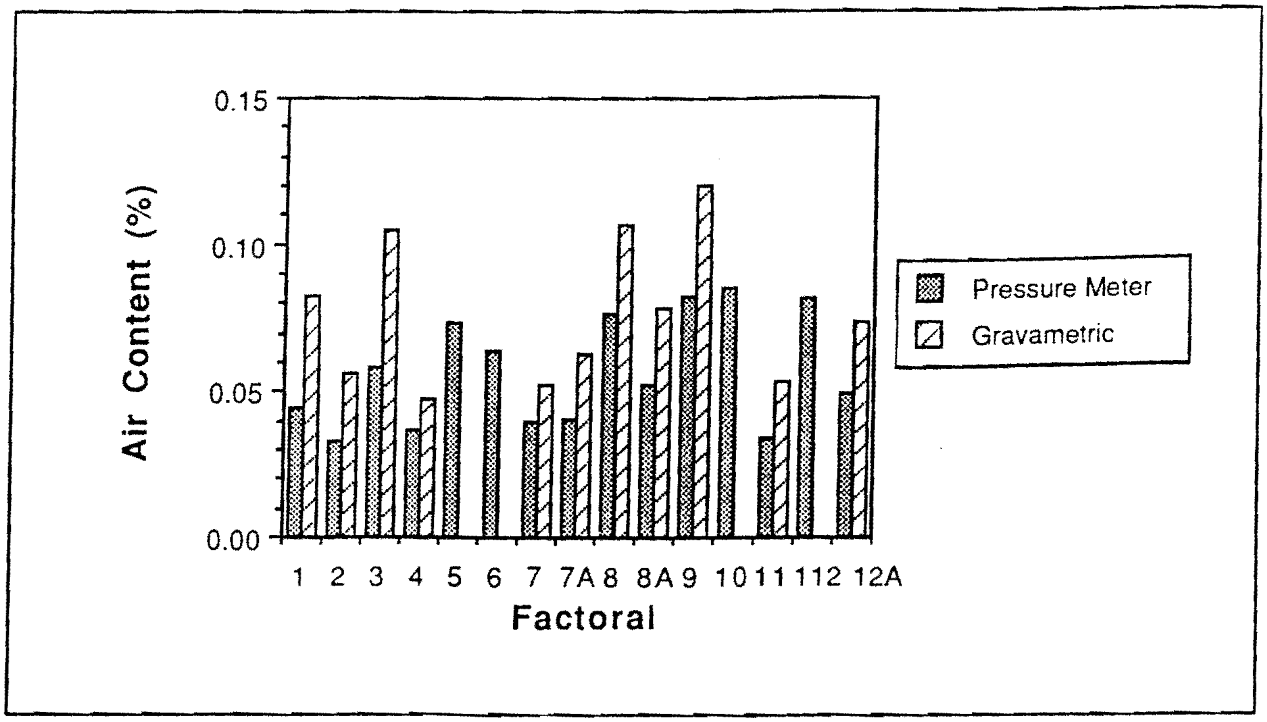


Figure D-1. Air Content - Gravimetric vs Pressure Method
[Before Pumping].

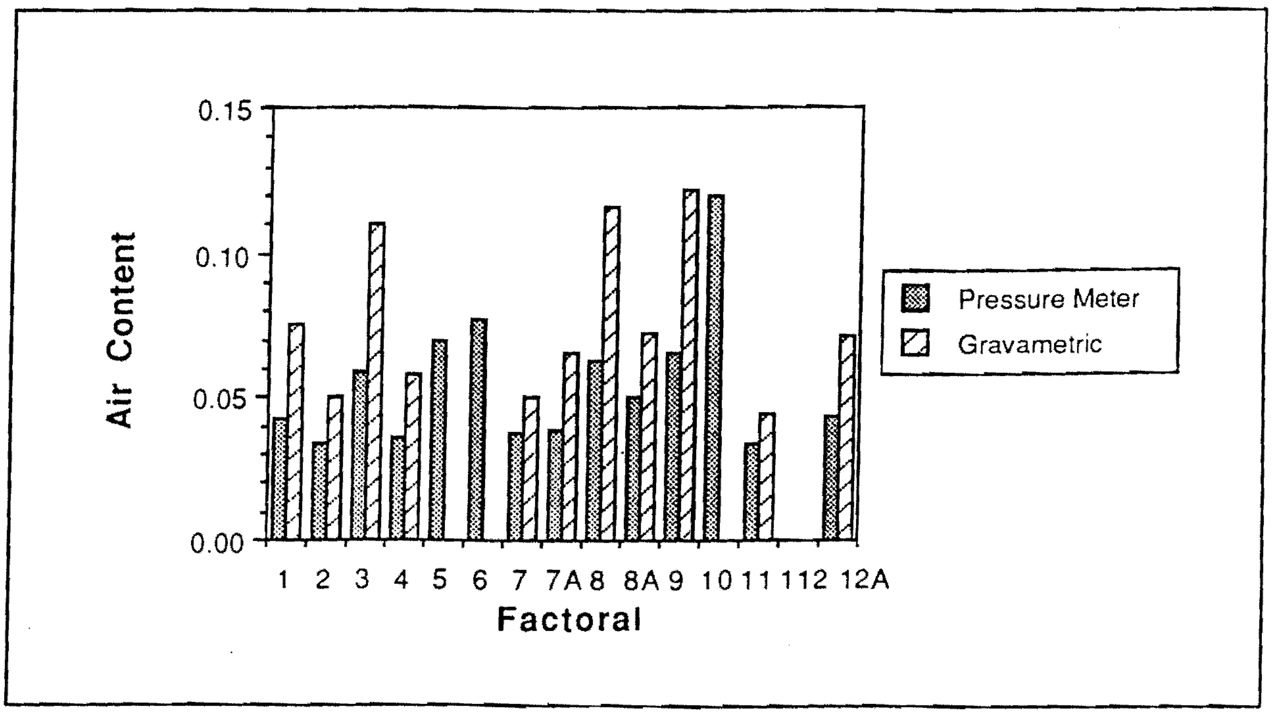


Figure D-2. Air Content - Gravimetric vs Pressure Method
[Before Pumping 30 Minutes].

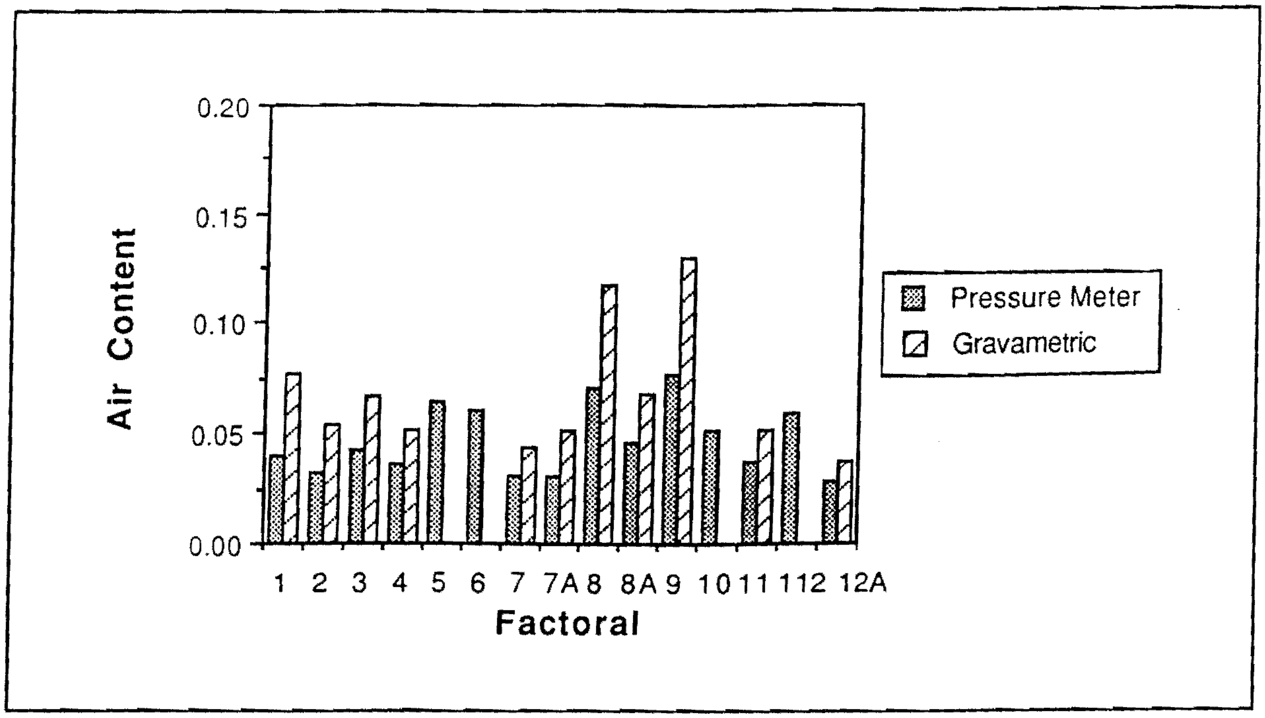


Figure D-3. Air Content - Gravimetric vs Pressure Method [After Pumping].

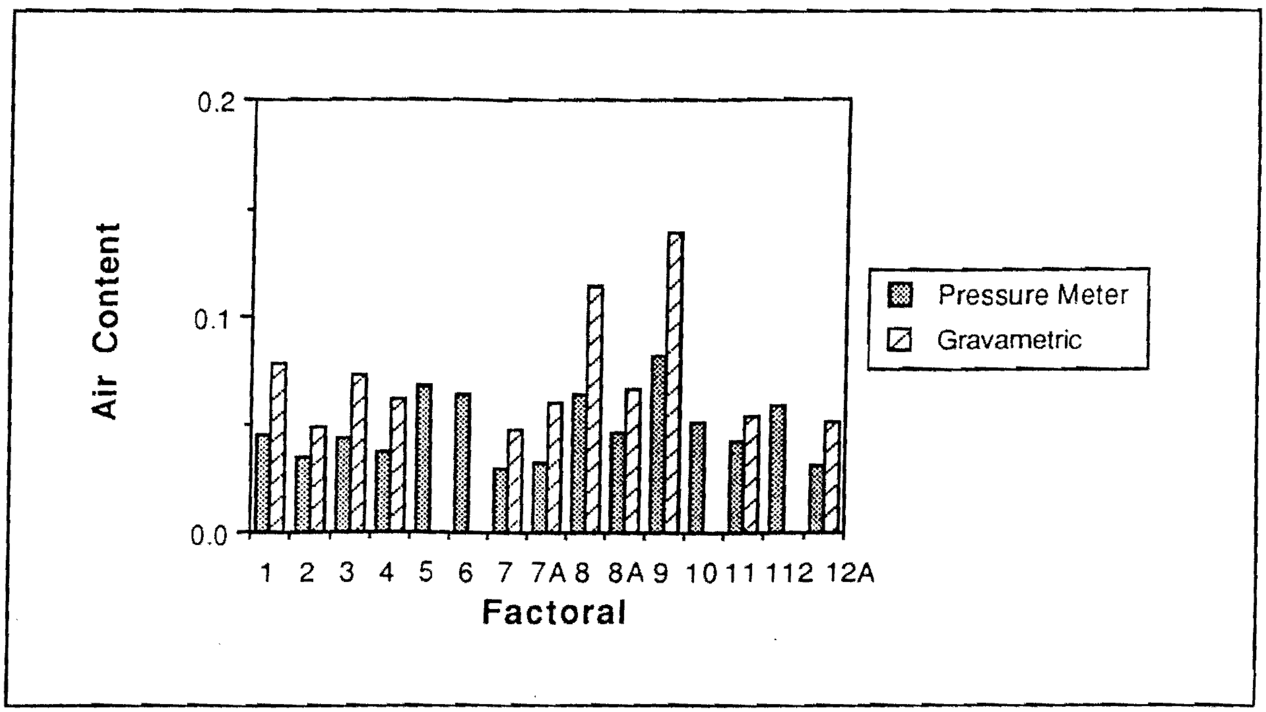


Figure D-4. Air Content - Gravimetric vs Pressure Method [After Pumping 30 Minutes].

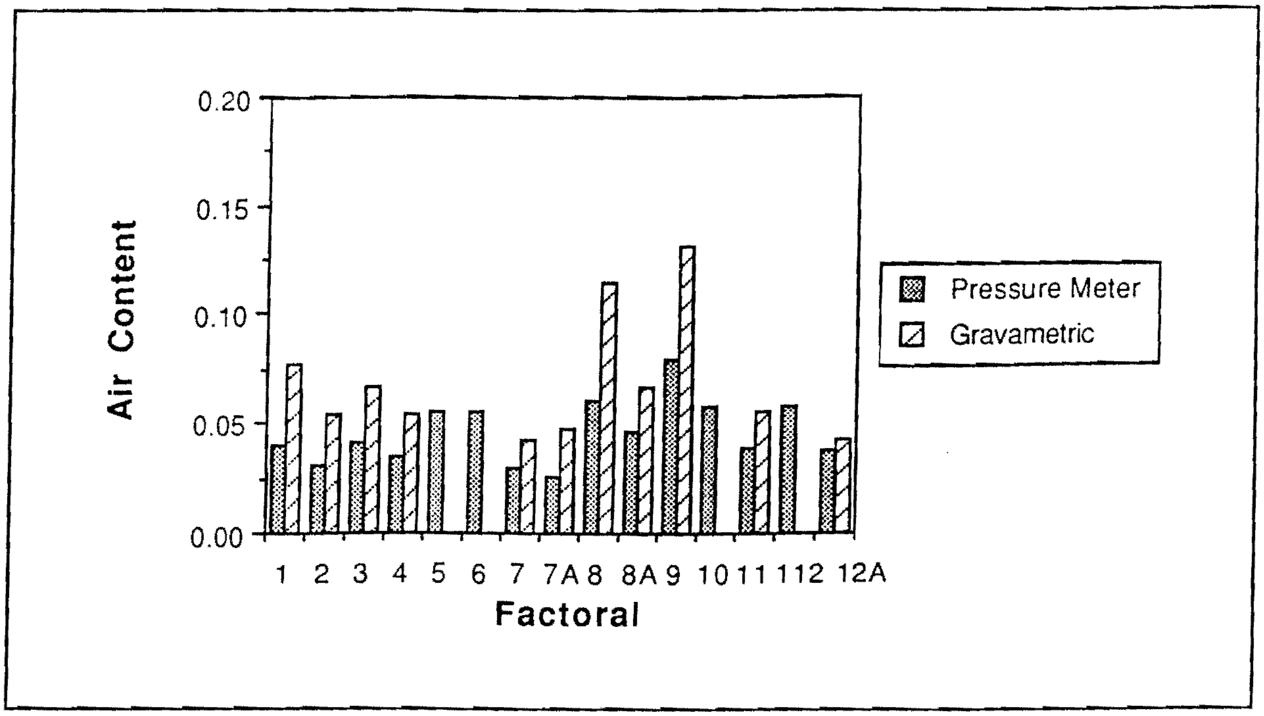


Figure D-5. Air Content - Gravimetric vs Pressure Method [After Pumping Vibrated].

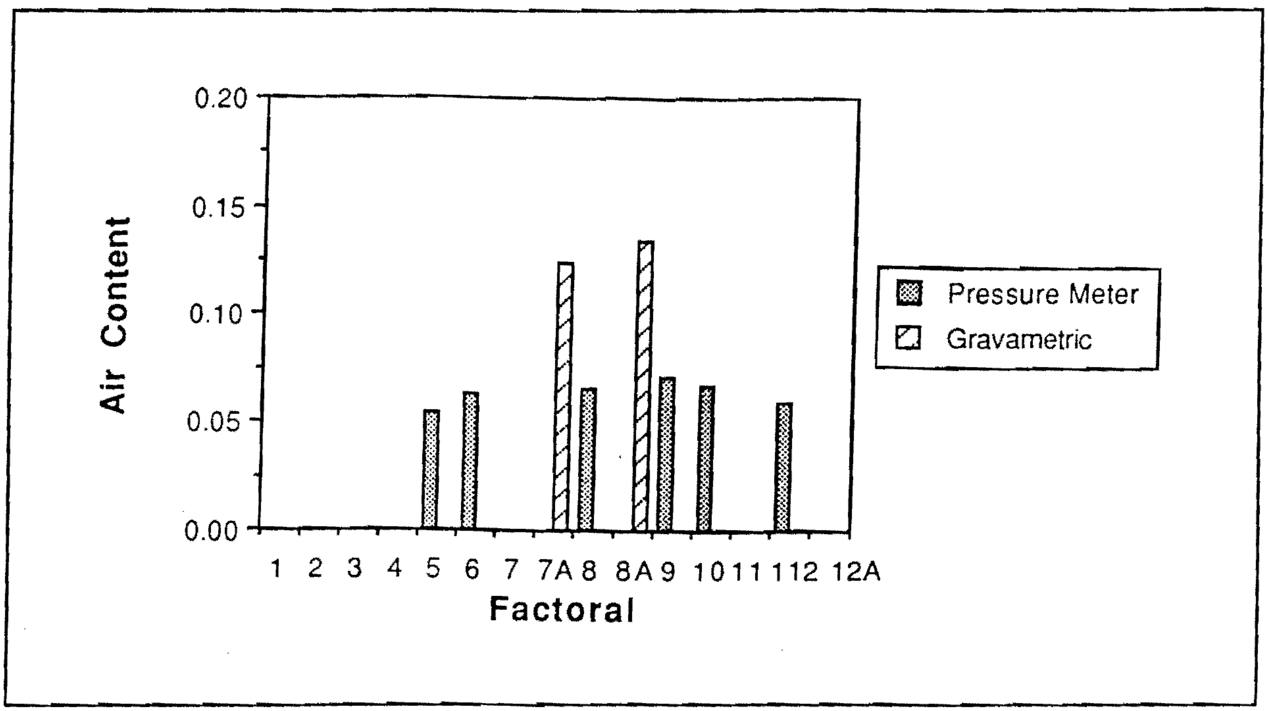


Figure D-6. Air Content - Gravimetric vs Pressure Method [After Pumping Vibrated 30 Minutes].

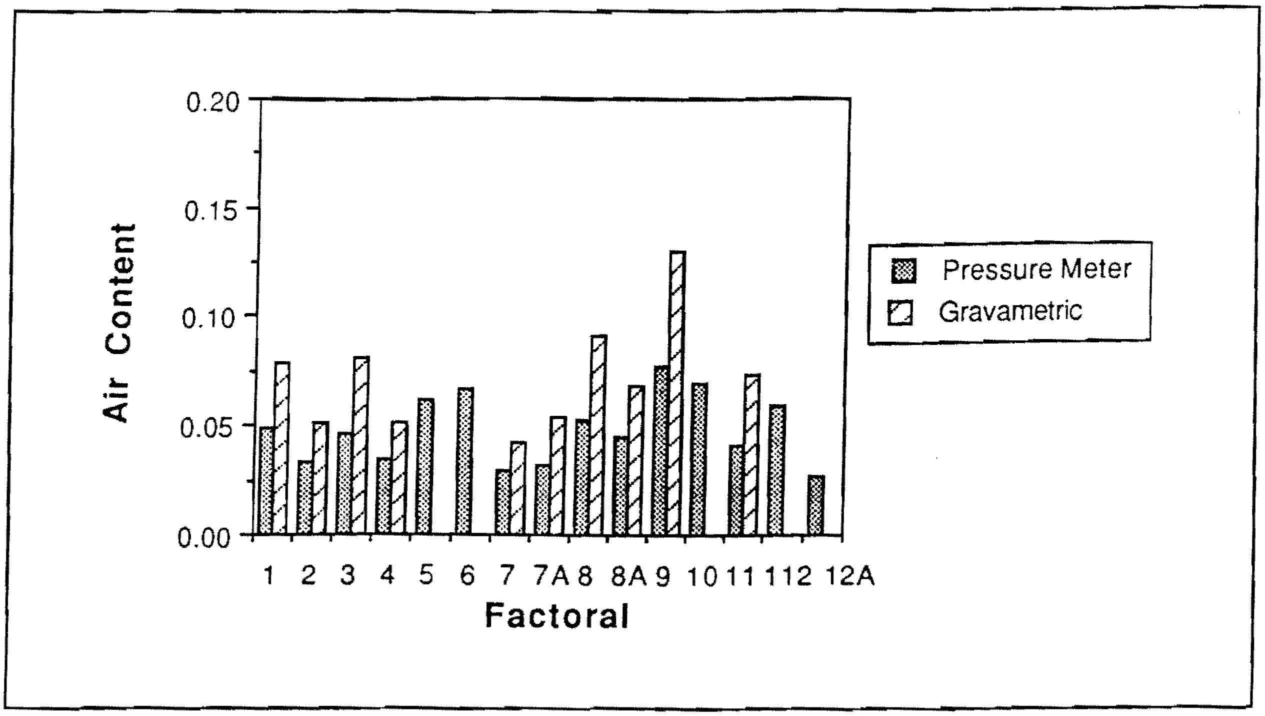


Figure D-7. Air Content - Gravimetric vs Pressure Method
[After Pumping Turbulated].

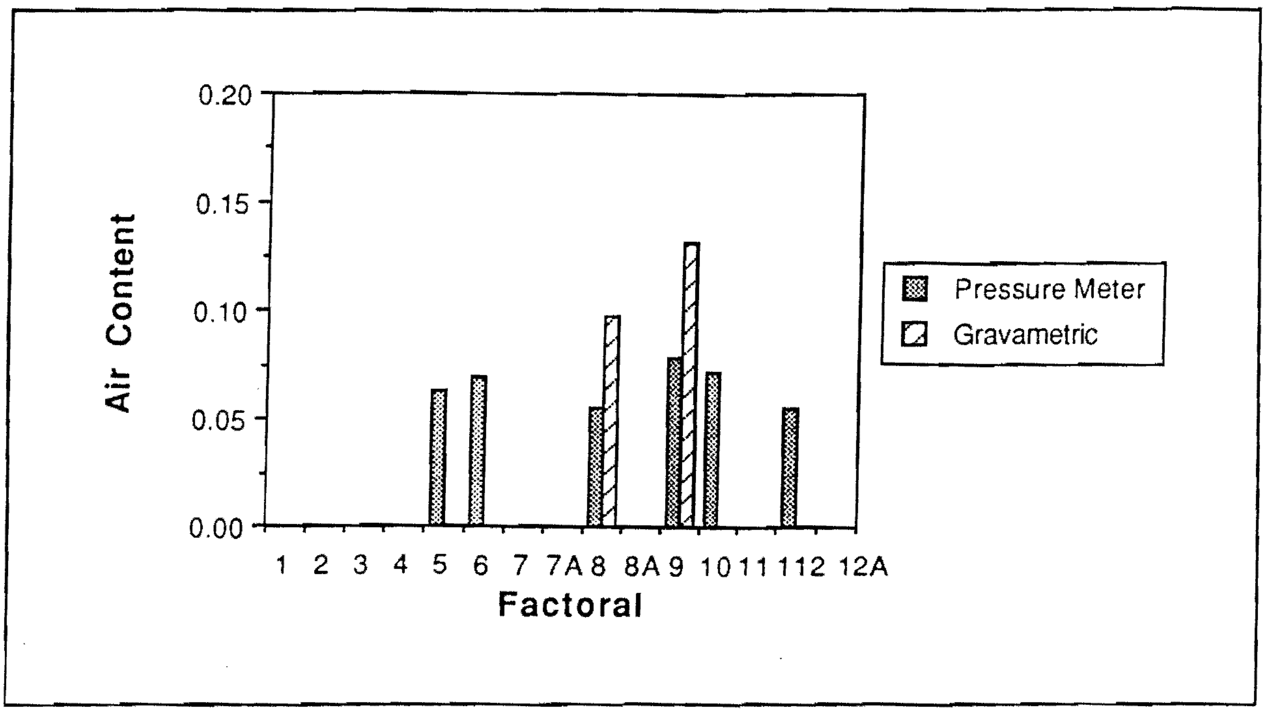


Figure D-8. Air Content - Gravimetric vs Pressure Method
[After Pumping Turbulated 30 Minutes].

# APPENDIX E

# IMPACT OF VARIOUS FACTORS ON AIR ENTRAINMENT

**Table E-1. Impact of Cement and Fine Aggregate on Air Entrainment and Corrective Actions [12,18].**

| EFFECT ON | | CORRECTIVE ACTION(S) |
|---|---|---|
| AIR CONTENT | AIR VOID SYSTEM | |
| Cement: | | |
| ● Decreases with increase in cement content.<br>● An increase in the alkali content of cement will increase air entrainment.<br>● Type III requires more AEA.<br>● Contaminants; oxidized oils increase air. Unoxidized oils decrease air.<br>● An increase in fineness of cement will decrease the air content. | ● Smaller and greater number of voids with increasing cement content.<br>● Type III and alkali effect not well defined.<br>● Little apparent effect when contaminated. | ● Increase AEA 50% for 200lb/yd$^3$ increase in cement.<br>● Increase AEA 10% or more for very rich, low slump mixtures.<br>● Use 50-100% more AEA for Type III. Decrease AEA dosage 20-40% for high alkali.<br>● Obtain certification on cement. Test for contaminants if problems develop. |
| Fine Aggregate: | | |
| ● Increases with increase in sand content. Organic impurities may increase or decrease air content.<br>● Well rounded particles are conductive to air entrainment.<br>● An increase in the fine fraction (passing the No. 100 sieve) will decrease the amount of air.<br>● An increase in the middle fractions (passing No. 16 but retained on No. 30 and No. 100 sieves) will increase the air content. | ● Surface texture may affect specific surface of voids. | ● Decrease AEA as sand content increases. Check sand with ASTM C40 prior to acceptance. |

Table E-2. Impact of Coarse Aggregate and Water on Air Entrainment and Corrective Actions [12,18].

| EFFECT ON | | CORRECTIVE ACTION(S) |
|---|---|---|
| AIR CONTENT | AIR VOID SYSTEM | |
| Coarse Aggregate: | | |
| • Decreases as max. size of aggregate increases. Crusher fines on coarse aggregate decrease air content.<br>• Dust on the aggregate will lower the air content.<br>• Crushed stone aggregate will entrain less air than a gravel concrete. | • Little effect. | • No action needed as required air decreases with increase in aggregate size. Hold percentage fines below 4 percent. |
| Water: | | |
| • Increases with increase in water content. Very fluid mixes show loss of air.<br>• Small quantities of household or industrial detergents in the water will increase the amount of entrained air.<br>• If hard water (well or quarry) is used to dilute the AEA prior to batching, the air content will be reduced.<br>• R/M truck wash water decreases air content. Algae increases air.<br>• Slump; An increase in slump from 3" to about 6" will increase the air content. Above this, the air becomes less stable and the air content drops. A decrease in slump beyond 3" makes air more difficult to entrain. | • Becomes coarser at high water content.<br>• Effect of wash water and algae unknown. | • 1-inch slump increases air by ½-1 percent. Decrease AEA accordingly.<br>• Do not use recycled wash waters. Test water supplies for algae and other contaminants prior to acceptance. |

**Table E-3. Impact of Chemical Admixtures on Air Entrainment and Corrective Actions [12,18].**

| EFFECT ON | | CORRECTIVE ACTION(S) |
|---|---|---|
| AIR CONTENT | AIR VOID SYSTEM | |
| Chemical Admixtures: | | |
| • Most chemical admixtures will increase the amount of air when added in conjunction with an AEA.<br>• Type C admixture usually do not affect the air content, although the addition of straight calcium chloride may tend to reduce the amount of entrained air.<br>• Delaying the addition of either the chemical admixture or the AEA by as little as 15 seconds will increase the amount of air. | | |
| Water reducers/retarders: | | |
| • Lignosulfonates increase air. Other types have less effect. | • Spacing factors increase at higher dosages. | • Decrease AEA 50-90 percent for lignosulfonates, esp at lower temperatures. Decrease AEA 20-40 percent for other types. Do not mix admixtures prior to batching. |
| Accelerators: | | |
| • $CaCl_2$ increases air content. Other types have little effect. | • Unknown. | • Decrease AEA when $CaCl_2$ is used. |
| Superplasticizers: | | |
| • Naphthalene-based materials increase air content. Highly fluid mixtures may lose air. | • Produces coarser void systems. Spacing factors increase. | • Use less AEA with naphthalene. Specify 1-2 percent higher air content if possible. |

Table E-4. Impact of Pozzolans, Oil and Mineral Admixtures on Air Entrainment and Corrective Actions [12,18].

| EFFECT ON | | CORRECTIVE ACTION(S) |
|---|---|---|
| AIR CONTENT | AIR VOID SYSTEM | |
| <u>Pozzolans</u>: | | |
| ● As the fineness of the pozzolan increases the amount of entrained air decreases.<br>● As the carbon content of the pozzolans increases, the amount of air decreases.<br>● An increase in the amount of pozzolanic material/$yd^3$ of concrete will decrease the amount of entrained air. | | |
| <u>Oil and/or Grease</u>: | | |
| ● Depending on their composition, they will either increase or decrease the amount of entrained air. These organic impurities usually occur in concrete as a result of poor lubricating practices at the cement plant or ready mix plant. | | |
| <u>Mineral Admixtures</u>: | | |
| <u>Fly Ash</u>:<br>● High L.O.I. or carbon decrease air content. Fineness of ash may have effect. | ● Little effect. | ● Increase AEA. May need up to 5 times more with high carbon ash. "foam index" test is useful check procedure. |
| <u>Pigments</u>:<br>● Carbon-black based may absorb AEA, depress air content. | ● Unknown. | ● Pre-qualification of pigment with job materials. |

Table E-5. Impact of Temperature and Production Procedures on Air Entrainment and Corrective Actions [12,18].

| EFFECTS | CORRECTIVE ACTION(S) |
|---|---|
| Temperature:<br>● Air content decreases with increase in temperature. | ● Increase AEA dosage as temperature increases. |
| Production Procedures: | |
| Batching Sequence:<br>● Simultaneous batching decreases air.<br>● Late addition of AEA raises air. | ● Avoid slurry-mix addition of AEA.<br>● Do not batch AEA onto cement. Maintain uniformity in batching sequence. |
| Mixer Capacity:<br>● Air increases as capacity is approached.<br>● The amount of air entrained by a given mixer (stationary, paving, transit) will decrease as the mixing blades become worn.<br>● Air content will increase if the mixer is loaded to less than capacity. However, in very small loads, such as a laboratory drum mixer, air becomes more difficult to entrain. | ● Run mixer close to full capacity, avoid overloading, clean mixer frequently. |
| Mixing Time:<br>● Central mixers - air increases up to 90 seconds. Truck mixers - air increases up to 10 minutes. Air decreases after optimum time is reached.<br>● The air content will increase with increased time of mixing up to about 2 minutes in stationary or paving mixers and to about 15 minutes in most transit mixers. | ● Establish optimum mixing time for particular mixer. Avoid over mixing. |
| Mixing Speed:<br>● Air increases up to approximately 20 rpm. decreases at higher speeds. | ● Avoid high drum speeds. |

Table E-6. Impact of Production Procedures and Construction Practices on Air Entrainment and Corrective Actions [12,18].

| EFFECTS | CORRECTIVE ACTION(S) |
|---|---|
| Production Procedures: | |
| Admixture Metering:<br>● Accuracy, reliability of metering system will affect uniformity of air content. | ● Avoid manual dispensing gravity-feed systems, timers. Positive displacement devices preferred. Establish frequent maintenance and calibration program. |
| Haul Time:<br>● Long haul times reduce air, especially in hot weather. | ● Optimize delivery schedules. Maintain concrete temperatures in recommended ranges. |
| Construction Practices: | |
| Retempering:<br>● Air content increases after retempering. In effect beyond 4 hours. | ● Retemper only to restore workability. Avoid addition of excess water. |
| Consolidation:<br>● Air content decreases under prolonged vibration or at high frequencies. | ● Do not over vibrate. Avoid high frequency vibrators. Avoid multiple passes of vibrating screeds. |
| Transportation:<br>● Some air (1-2%) normally lost during transportation. Air lost in pumping and on belt conveyors, especially at higher air contents. | ● Avoid high air contents in pumped concrete. Do not use aluminum conveyors. |
| Finishing:<br>● Air content reduced in surface layer by excessive finishing. | ● Avoid finishing bleed water still on surface. Avoid over finishing. Do not sprinkle surface prior to finishing. |

# APPENDIX F

# CONCRETE MATERIAL AND MIXTURE

**Factors Influencing Air Entraining**

One of the most important findings of this literature survey is the information reviewed on the importance of certain variables on the ability to achieve adequate control of air entrainment. These variables could be grouped into five major categories:

1) concrete materials,
2) concrete mix design,
3) production procedures,
4) construction practices, and
5) environmental conditions.

Each of the above listed categories consists of subsets of relatively greater or lesser importance. This helps the field engineer in decisions regarding the variables that should be closely controlled in production of air entrained concrete, and the ones which have a lesser impact. Thus, these subsets of information may serve a purpose to the field engineer in applying his working knowledge in considering some of these factors under field conditions.

The five major categories and their sub-variables are listed below and their impact on air entrainment is compiled in the tables listed in Appendix E. Whiting and Stark have compiled this information which is reproduced in this report for the convenience of the reader [21]. The categories of concrete materials and concrete mix design are combined to some degree in the tables.

1) Concrete Materials:

- Cement - alkali content, fineness
- Admixtures - air entraining, water reducers, pozzolans, accelerators
- Aggregates - sand, coarse aggregate
- Contaminants, fine materials
- Water - algae, wash water
- Pigments

(2) Concrete Mix Design:

- Cement content
- Water content - w/c ratio, slump
- Sand proportion
- Maximum aggregate size
- Sand gradation

(3) Production Procedures:

- Batching sequence
- Mixing time
- Mixing speed
- Admixture metering
- Haul time

(4) Construction Practices:

- Retempering
- Consolidation - vibration
- Transportation-conveyors, pumping
- Temperature
- Finishing

(5) Environmental Conditions:

- Temperature

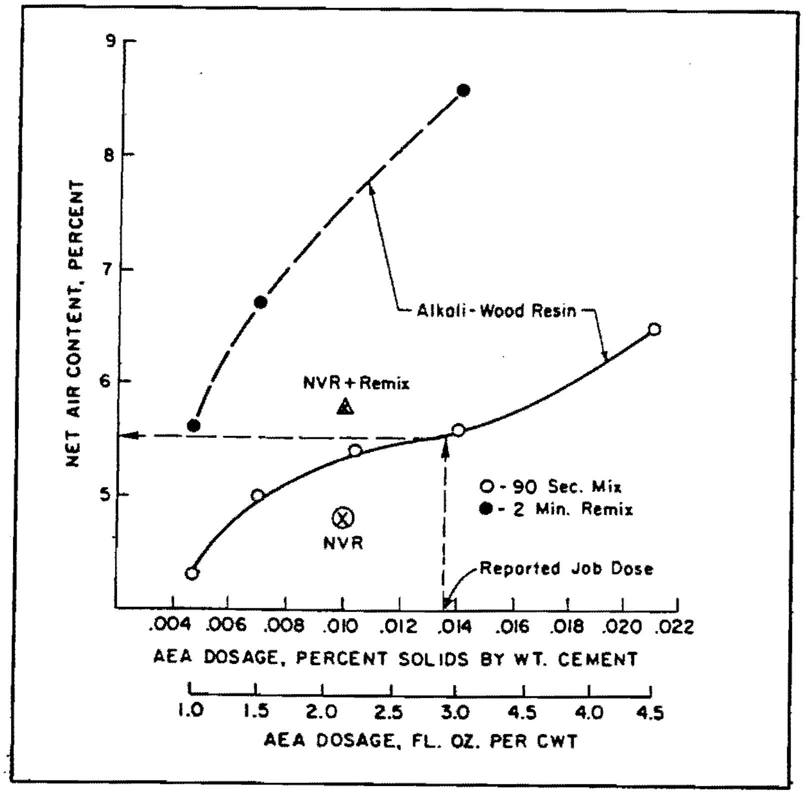


Figure F.1. Variation of Air Content With Dosage of Air Entraining Agent [21].

<u>Air Entraining Agent</u>: Within certain limits, the more air entraining agent that is used in the mixture, the higher will be its air content. In most cases, this increase is parabolic and tends to level off at higher levels of dosage. There is no apparent relationship between the amount of a agent used and the resulting air content of the concrete [4]. Some agents have been observed to be more "efficient" than others (Figure F.1).

Slump: Increase in concrete slump (up to about 6 inches) results in higher air content. Air contents tend to drop off at slumps greater than 6 inches. The variation of air content with slump is shown in Figure F.2. Higher water content results in a more fluid mixture into which the air can be entrained more easily by the mixing action. Air entrainment

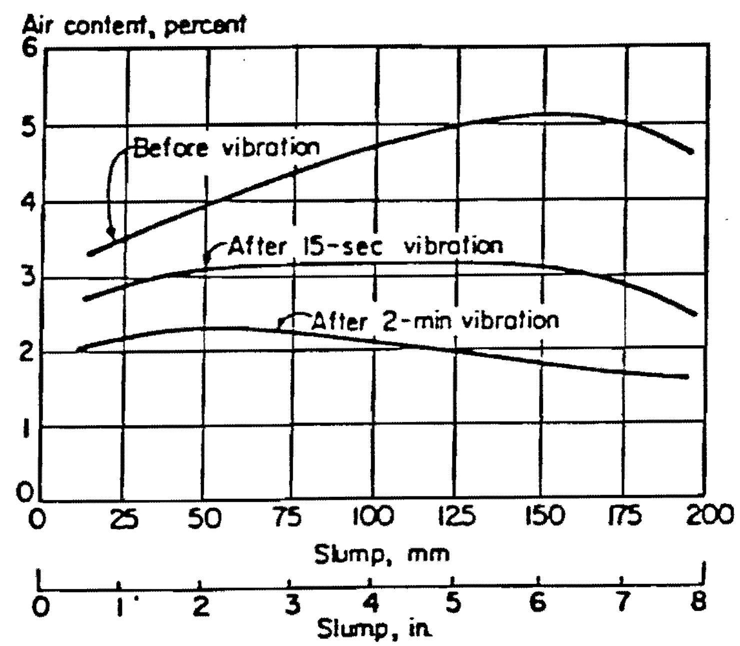


Figure F.2. Relationship Between Slump and Air Content of Concrete [4].

is difficult to achieve in stiffer mixtures. Bulking of sand, on account of additional water, creates more space for bubbles. Powers [9] discussed this in great detail. Higher slumps of about six inches results in increased fluidity of the mix. This permits an easier air loss during handling and placing; hence the value decreases slightly [4].

Fine Aggregate: The fine aggregate is that portion of the mixture which serves as a "three dimensional screen" and traps the air refered to in Chapter II. The fine aggregate provides interstices that can contain paste and air bubbles, so that air is generated more efficiently, and the air entraining agent stabilizes the bubbles so formed [9]. The higher the proportion of sand in the total aggregate, the greater the air content of the concrete. This effect is represented in Figure F.3. Apart from aggregate proportions, it seems that the aggregate size and range grading is important. The critical factors seem to be the amount of inter-particle space that aggregate grading contains (which serves as the locus of air bubbles) and the size of that space. The effect of aggregate is elaborated in Chapter 3.

Conventionally, the sand sizes, from about 600 micron (No. 30 sieve) to the 150 micron (No. 100 sieve), have been found to be more efficient in entraining air bubbles. The interstices of groups of particles in this size are of the size of a large proportion of the desirable bubbles in air entrained concrete, and this may be the reason for the importance of this size fraction. The influence of aggregate screen is of lesser importance in richer (greater cement contents) mixes [4].

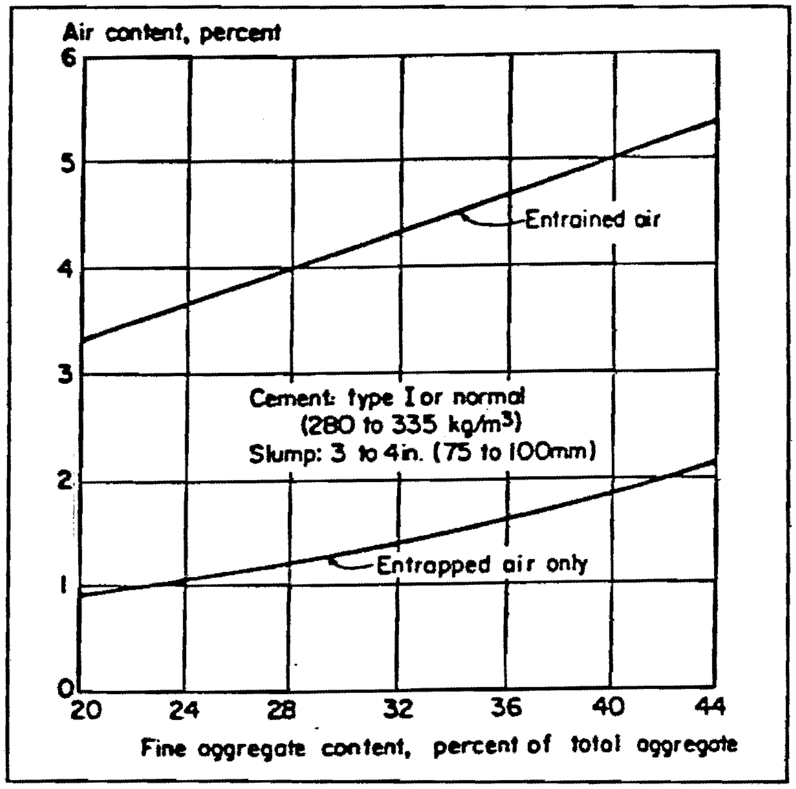


Figure F.3. Relationship Between Percentage of Fine Aggregate and Air Content of Concrete [4].

The effect of increase in cement-alkali content is shown in Figure F.4. Various concrete samples, were cast using different types of cements with varying alkali contents. In order to determine the amount of alkali contributed by each type of cement to the aqueous phase of

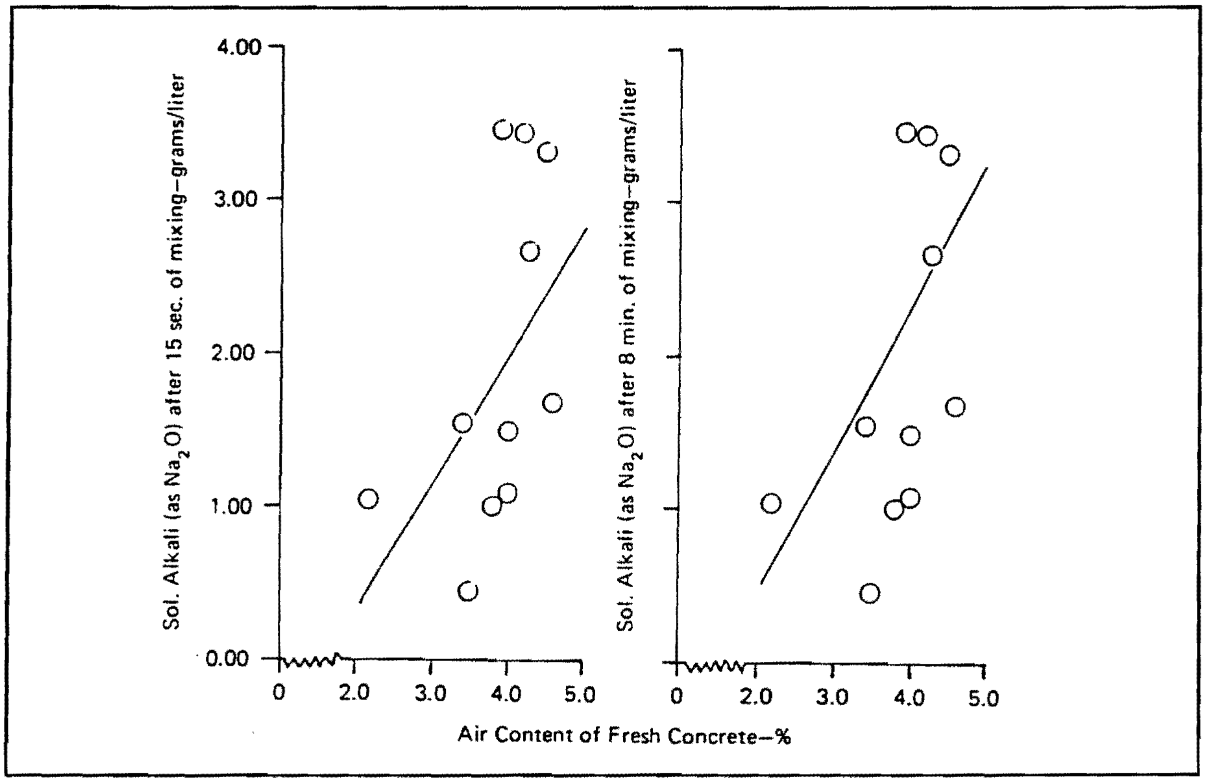


Figure F.4. Effect of Cement Alkali (Soluble) on Air Entrainment in Concrete [22].

constant). The best fit line through each set was a slope of 0.83 concrete, the cement and water were rapidly mixed in the noted study [22] for 15 seconds and for 8 minutes (while maintaining the water-cement ratio and 0.93 respectively. Though the data points are scattered, the trend shows an increase in air content as the alkali content in cement increases [22].

The effect of cement fineness is shown in Figure F.5 where the same cement was used for investigating the effect of fineness. A cement of fineness 3550 $cm^2/g$ was selected and was then ground in laboratory steel contributes to the loss ofball mills to three additional degrees of fineness and the products of those grinds were used for evaluation. The results show that increase in fineness of cement results in a lower entrained air content [22].

The vibration of concrete may cause considerable losses of entrained air particularly if the air-void system consists of large

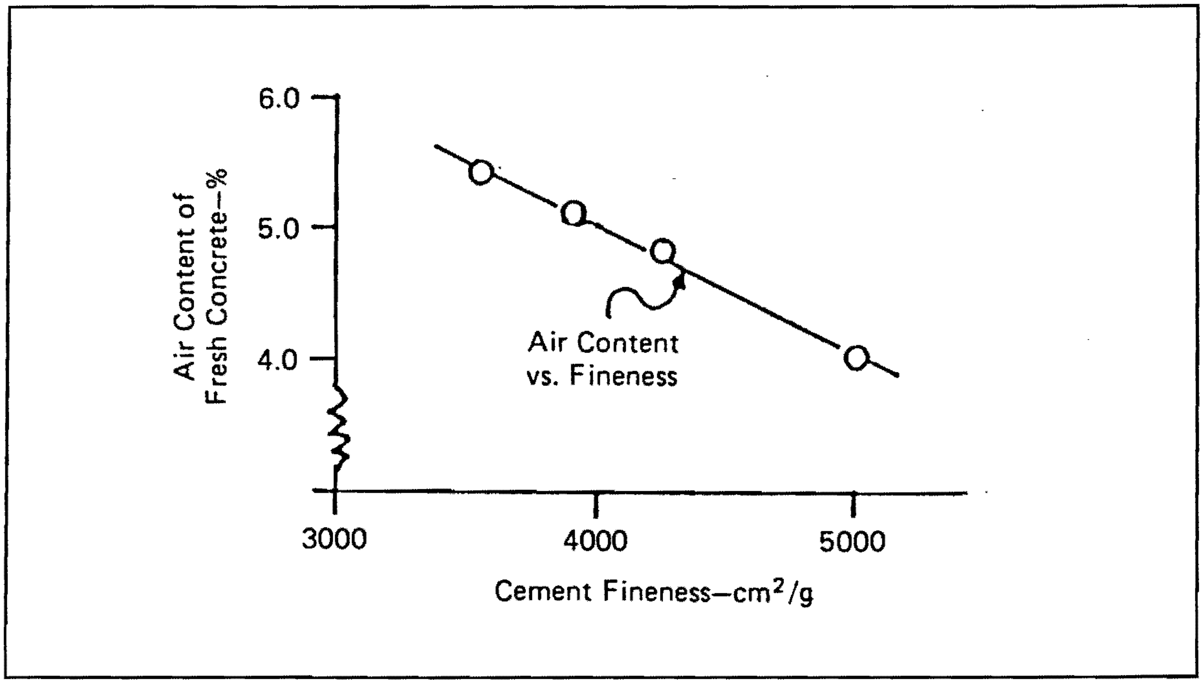


Figure F.5. Effect of Cement Fineness on Air Content of Fresh Concrete [22].

diameter air voids. However, this is typically considered not to be a widespread problem. Also, the void size distribution is altered, as shown in the Figure F.6 [17]. As the vibrating time increases an increase in the loss of air may occur. Also, the higher the vibrating frequency, the smaller is the bubble size that air.

Other Admixtures: When air entraining admixtures are used in conjunction with other admixtures, the air content and the air void system can be affected. If only air entrained admixture is used, the development of the air void system is unaffected by other admixtures that were added to the mixture. Experience of others has suggested the addition of AEA's at the end of the mixing cycle when more than AEA's are used. By adding the air entraining admixture with the mixing water, a higher total air content may result but the air void system may be of poorer quality. Air entraining admixtures generally work best without any combination of water reducers or superplasticizers in the concrete mixture [23].

Where water reducers are used with air entraining admixtures, they may increase the air content by a substantial amount. However, this may cause the bubbles to decrease and the spacing factors to generally increase. The delayed addition of water reducer relative to the air entraining admixture further reduces the stability of the air void system [23].

For the same water content, addition of superplasticizers result in concrete with greater slump and workability. However, after a period of time the slump can rapidly change but may be recovered by redosage with additional superplasticizer agent. When air entraining admixtures are used in conjunction with superplasticizers, the total air content is decreased with increased spacing factors. There is also a tendency for increased bubble coagulation where the specific surface of the bubbles is very low and the spacing factors are usually high and in general the stability of the air void system is reduced [24, 25, 26, 27]. It should be noted, however, that melamine based superplasticizer admixtures result

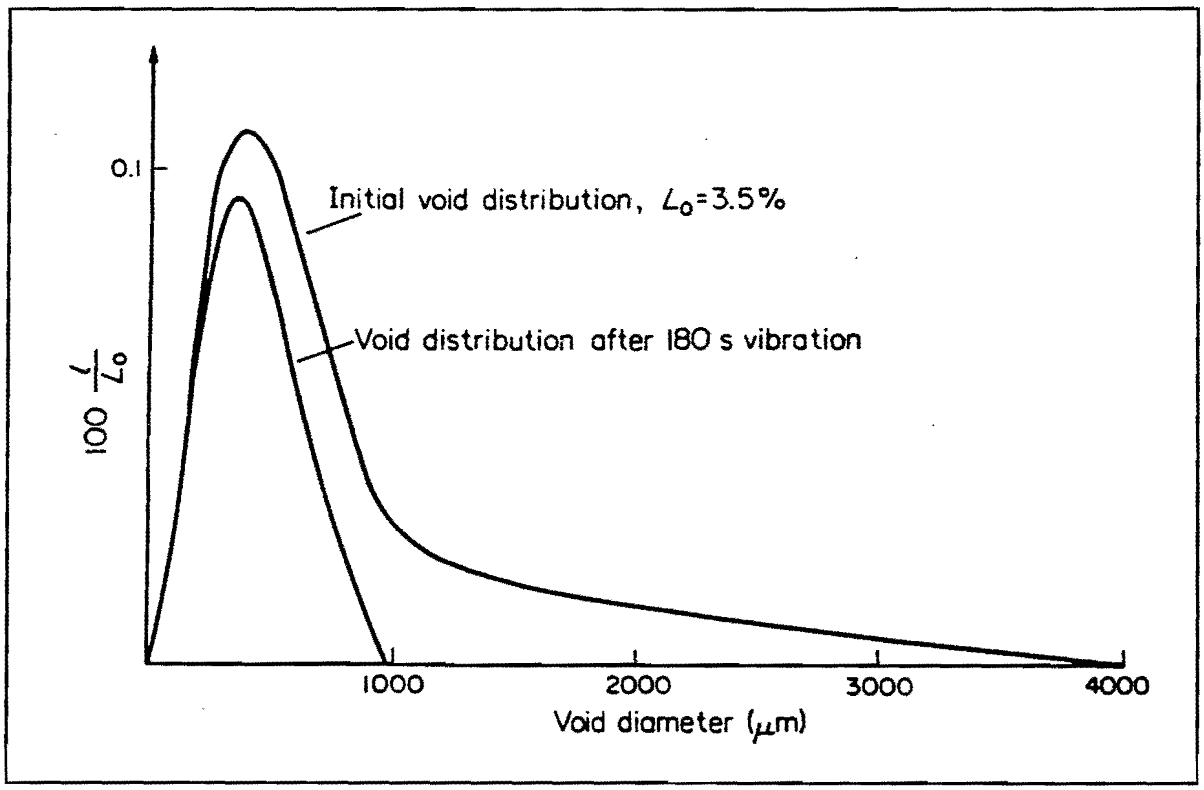


Figure F.6. Change in Void Size Distribution on Vibration of Air Entrained Concrete [17].

in a better air void system than naphthalene based admixture. In fluidized concrete, a superplasticized concrete may facilitate the escape of air to the atmosphere and may also coalesce air bubbles [23].

In spite of the inferior air void system produced by the superplasticizer in concrete, the resistance to damage by freeze thaw cycles is excellent [25]. The good resistance to freezing and thawing damage observed in the concrete may be due to the use of a low water cement ratio. Use of superplasticizers, as noted previously, increase workability of the fresh concrete and can reduce the maximum pressure required to pump concrete. The reduction in the pumping pressures may be about 30 percent. The increase in pumping resistance with the increase in pumping rate is less than that for conventional concrete [28, 29]. The topic is also elaborated further in Chapter III.