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16. Abstract

Experience in Texas suggests problems may occur in stabilizing the air content of entrained concrete during and after pumping operations. In one instance, normal air entraining dosage rates were significantly exceeded in an effort to maintain the desired amount of air content in the concrete immediately after discharge. It was determined subsequently from hardened samples that the loss air was fully recovered and actually was 50 percent greater than the desired levels.

Several factors have been noted in the literature to affect the level of entrained air in concrete. Factors such as cement content and fineness, coarse aggregate size, amount of fine aggregate, slump, type of admixture, etc. have been identified as factors affecting entrained air content.

Preliminary test results indicate an apparent loss of air occurs immediately after discharge from the pump and tends to return after a period of time. This noted variation of air follows a dissolution process suggesting a shifting of the air-void system from smaller bubbles to larger bubbles. A test program is suggested to identify significant factors in this process.

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EFFECTS ON AIR ENTRAINMENT ON PORTLAND CEMENT CONCRETE

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Research Report 1254-1
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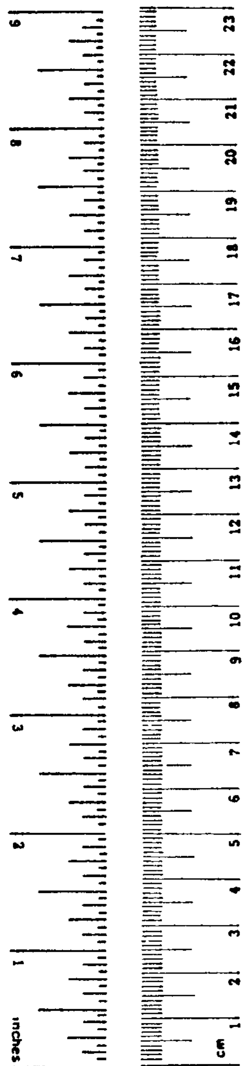
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

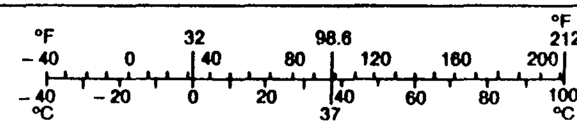
NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

IMPLEMENTATION STATEMENT

This report summarizes reviewed literature pertaining to the effects of various factors on the entrainment of air in portland cement concrete. The effect of various factors are discussed with respect to the loss of air during the pumping operations. However, preliminary conclusions are provided and will be developed as the study progresses. Recommendations with respect to changes in present specifications, test procedures and mix design to reduce the loss of air during the pumping operations will be forth coming in subsequent reports.

The most common factors that effect air entrainment in cement concrete are pump characteristics, types of aggregates, type of air entraining admixture (AEA), coarse aggregate factor (CAF), and concrete mix proportioning requirements for pumpable concrete. The other minor factors involved being cement, slump, vibration, etc.

The angle of the boom of the concrete pump, the type of the admixture, and the mix design factors (such as CAF) are believed to play an important role in this study. Work is being conducted both in the laboratory and in the field to formulate an empirically based prediction model for air loss based on the above factors. The air void system and the distribution of the bubbles in the cement concrete are also being considered.

It is anticipated that upon the completion of this study, findings will be provided which will indicate the appropriate changes and modification to existing mix design practice, testing procedure, and construction technique which may be less susceptible to air loss during the pumping operation.

Results of this study may be implemented to improve concrete placement techniques by pumping and should be helpful to the State in reduced pumping related problems while maintaining quality in the placed concrete in terms of durability and strength.

DISCLAIMER

The contents of this report reflect the view of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the State and Federal Highway Administration. This report does not constitute a standard, specifications, or regulation.

There is no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter and any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country. This report is not intended for construction, bidding, or permit purposes.

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CHAPTER 1

STUDY DESCRIPTION, OBJECTIVES, AND BACKGROUND

Introduction

The use of air entrainment is important in concrete since concrete can be badly damaged after only a few freeze-thaw cycles if the entrapped air/air content is too low. Fortunately, concrete can be made frost resistant by the addition of air entraining admixtures which are added primarily to improve the air void structure and the frost resistence. A desired level of air content should be achieved to meet certain design requirements along with a desired level of workability and concerns related to the concrete durability and strength. In order to achieve a desired degree of air content, a certain amount of air should be introduced into the concrete intentionally which is different from the "entrapped" air which is included unintentionally and occurs randomly during batching and mixing.

It is of interest to gain a better understanding of the effect that various construction related activities (such as pumping) may have upon the required air content and to examine the influence of entraining admixtures and the dosage which should be mixed to achieve the desired level of air. Adjustments of the air entraining admixture are typically necessary to account for loss of air when pumping concrete and resultant variations in air content between the delivered concrete and the pumped concrete at the discharged end. The basis upon which to make adjustments to the air entrainment admixture is complicated even further when material and aggregate effects may cause air content variations such as an apparent increase/decrease in the air content between the discharged concrete (after pumping) and the inplace concrete.

Project Objectives

The objectives associated with this study are:

(1) Review the process of air entrainment in concrete and the test procedures used to determine air content along with the principals upon which the procedures are based. This will include new technology developed from SHRP research.

(2) Determine the types of air-entrainment admixtures and aggregates used in pumped concrete in SDHPT projects.

(3) Detail the pumping and material effects on air-entrainment (from delivery to placement) in terms of the aggregate type, admixture type, and the mix requirements for pumpable concrete.

(4) Describe the effects in terms of testing specifications and procedures for pumpable concrete with respect to when and where air content testing should be conducted and what the expected range of air content which may be obtained for a given level of air entrainment.

Task Description

The work plan for this study is divided into several tasks. Each of the tasks are related to the objectives of this study arranged sequentially in a rational process towards determining the answers to some of the questions which have been raised with respect to air content testing. The tasks are actually broken down according to four phases. The first phase deals with a literature survey of current test procedures, recent testing developments, and available information on the factors which affect air entrainment, bubble size, distribution, spacing, and air content in fresh and hardened concrete. The second phase will consist of an in-depth study of material (aggregate, admixture, etc.) effects on air content using different test methods. The third phase will address field trials and testing of the findings from the second phase using different test methods for validation purposes. The fourth phase will develop the framework by which the findings of the study and be implemented in the form of modified specifications, test procedures and methodologies.

Task 1.1 Review Current Test Procedures

This task will concentrate on existing air content methods. Each procedure will be reviewed to detail the fundamental principles of the procedures and to understand the scientific and engineering differences between each one. Work under this task will endeavor to summarize the laws and scientific principles controlling the forming of air bubbles in fresh concrete due to both natural causes and air entraining agents and ultimately lead to distinguishing the characteristics of each agent. The factors which affect bubble size, distribution, and spacing will also be considered in this task.

Task 1.2 Review New Developments

Work under this task will concentrate on reviewing new developments in the determination of air content such as those developed from SHRP research. The scientific principles underlying these methods will also be examined. Following this procedure will allow comparison of each method on an equal basis which should aid in delineating the differences between methods along with illustrating the advantages and disadvantages of each one.

Task 1.3 Determine Aggregate and Admixtures Types

Different types of air entraining admixtures are used in SDHPT concrete construction projects and each may have different effects on the final air content. Different aggregates may also have an affect on the final air content and possibly even more so than admixture. Consequently, as a prelude to the examination of the effects of different aggregates and admixtures on air content, the various air entrainment admixtures and aggregate types used in Texas should be identified. Along with the identification of each type of air entrainment admixture and aggregate will be the review of information available in the literature with respect to effects on air content in concrete due to these factors.

Task 1.4 Interim Report

This task concludes the literature review phase of the study and will lead to a summary of the literature and available information on the factors which affect air entrainment and air content in concrete under pumping and other relevant conditions.

Task 2.1 Determine Air Content For Different Aggregate and Admixture Types

This will relate the underlying principles affecting and controlling the formation of air bubbles in concrete found in the literature to the actual mix designs and materials used in Texas concrete. Various test methods (current and newly developed) will be utilized in this portion of work. Current methods consist of Pressure Method, Volumetric Method, and the Gravimetric Method. The intent of examining in the laboratory the effect of different aggregate types, different admixtures, and different test procedures on air content is to develop comparisons of these factors to provide in-sight with respect the use of different materials and test procedures. For a given aggregate type, a factorial of tests will be conducted for each test procedure and for each air-entraining admixture used.

Contained within this factorial will be a set of tests examining the effect on air content in the paste as function of air entrainment agent. These test results will allow for comparison of the performance of various agents for the same mix design. The measured performance will be examined in terms of the surface-active agents and the forces which cause an air bubble to develop and stabilize in fresh concrete mix.

Task 2.2 Quantify Air Content In Terms of Pumping Pressure

This task will relate the results from each test method investigated in this study to the pressure ranges experienced during pumping (usually 300 to 500 psi excluding the weight of the concrete). Although some test methods may be used to approximate the pressures in the pumping line, actual pumping equipment must be used to check the air content before and after pumping. The concrete will be tested twice after discharging; once upon immediate discharge and again 30 minutes later. This work will be accomplished for each mix design used in Task 2.1.

As a result of this task and Task 2.1, a working model or mechanism describing the influence of critical factors affecting air content in concrete will be developed. Data analysis will be performed to illustrate the trends in air content due to material properties and the effects due to pumping. This model should also include how the results may change depending on the method used to measure the air content. As a result of these tasks, (2.1 and 2.2), the effect of aggregate, air-entrainment admixture, test procedure, and other critical factors on air content in pumped concrete will be quantified with respect to when and where testing should be conducted and what the measured results mean in terms of the final air content.

Task 3.0 Field Test Methods and Conclusions

This task will consist of an effort to field validate the work accomplished under the laboratory phase of this study. The validation can be made with similar aggregates and admixtures used in Task 2.1 and 2.2. Each test method will be used at each selected field site (which will be coordinated on a District level) to correlate the results of each method to the mechanism developed under Task 2.2.

Task 4.1 Develop Framework For Revised Air Content Testing Procedures

Work under this task will summarize the results of the literature review, laboratory program, and the field validation program to develop suggested changes or modifications to the testing procedures to measure the air content of pumped concrete. It is expected that the type and nature of the aggregate will have a significant input into these suggested modifications and that each test method will yield different results. It is expected that the variations in air content observed for pumped concrete are largely due to aggregate and test procedure effects which must be interpreted in terms of the final air content for any testing location in the pumping train.

Task 4.2 Final Report

The final report will provide a summary of the work accomplished under this study illustrating the mechanism factors affecting air entrainment efficiency and the air content of pumped concrete. The report will elaborate on suggested modifications to the current procedure followed to measure air content and layout a framework by which the modifications can be implemented.

Bridge Deck Construction

On Project MA-F 784(20) on US 54 in El Paso county, District 24 in 1989, problems were experienced in achieving the desired level of air (5 to 7 %) while using normal dosages of air entrainment agent (normal dosage rates are 2-3 oz/cwt for routine placement). The dosage rates on this particular project were as high as 10-11 oz/cwt in order to correct an apparent problem associated with placement by pumping. During the placement of the concrete, slump and air tests were conducted on each of the first three concrete deliveries and every sixth delivery thereafter to monitor the variation in the measured air content of the mix. The results are summarized in Table 1. Measured air content data was obtained at three different instances (1) prior to discharging the concrete into the pump, (2) at the end of the discharge pump line, (3) and after the completion of all placement and finishing operations (for both the upper 2 inches of the deck and over the full thickness of the deck).

The test results indicate that in the majority of the tests the percentage of entrained air of the concrete in its final location after all manipulations was equal at that point in time to that first tested at the truck before pumping (ie., The air content after the placement may be considered to fall within the population of the measured air contents before pumping). It may appear on the surface, the air content of the concrete before pumping (at the truck) is more or less the same as the air content of the concrete at full depth of the deck. However, subsequent spectrographic analysis of hardened concrete samples of the bridge deck indicated that the percent of air to be between 8 to 10 percent which may significantly reduce the strength of the concrete and the bridge deck.

The question is, what is the nature of the variation in air due to the pumping process and why did the air content increase after the placement and finishing operations were completed. Some concern may also exist with respect to what happens to the chemical admixture after pumping and whether or not air entraining agent become inert or is it reactivated by the handling and finishing operation. Lastly but certainly not least, is what role does the mix design and the method of pumping play in the observed variations in air content.

Table 1. Summary of Concrete Air & Slump Tests - Project MAF 784(20) Pump Concrete - Class "S" Bridge Deck.

Date May 18, 1989

Load & Truck	Slump At Truck	Air At Truck	Slump At Pump	Air At Pump	Slump Full Surf.	Air Full Surf.	Slump Full Depth	Air Full Depth	Conc. Temp.	Amb. Temp.	A.E.A. Oz./ CWT	Water Gal./ Load	Remarks
1) 102	3	8	4	5.5	5	1) 16 2) 9.2	5	8.0 7.9	65	78	8	0	1) Meter 278869 - Test conc. included paste at deck surface 2) Meter 322773 - Test conc. from 0" to 3"
2) 28	3½	8.8	3½	5.4	3¾	8.0	4	7.8	78	78	10	0	
3) 27	3¼	7.0	3¼	5.0	3½	8.0	3	7.5	80	78	11	0	
6) 107	2¾	6.8	3¼	5.5	3¼	8.3	3½	8.2	80	76		4	
12) 110	3¼	6.8	2¾	4.0	4½	6.7	1¼	5.4	79	74		0	
13) 102			4	5.5									Extra test for low air on prev. load
18) 107	3½	8.0	3¾	5.7	5½	10.0	4	8.0	78	68		0	
24) 110	2½	6.0	2¼	5.5	3¼	7.8	2¼	6.3	77	66		0	
30) 107	3	7.5	3	5.5	3¼	6.6	2¼	7.0	77	70		2	Truck tested 4:06 A.M. deck conc. tested 5:45 A.M.
36) 110	3	8.0	2¼	5.0					75	64		0	Concrete not tested in deck because finishing fell behind
42) 105	3	7.8	3¼	6.2	4¾	9.5	2	8.0	73	71	11	0	Truck tested 7:00 A.M. deck tested 8:15 A.M.

Mix Design: Class "S" Concrete using 1" Limestone aggregate (A.E.A. - Microair; C.D.A. - Pozzolith 100xR)

CAF: 0.73 Coarse Agg: 1801 lbs./cy (adj. to 1812 lbs.)
CF: 6.5 Cement Type II: 611 lbs./cy
WF: 5.0 Fine Agg: 1115 lbs./cy (adj. to 1158 lbs.)
AF: 6.0 Water: 32.5 gal./cy (adg. to 26.0 gal.)

Specs. - %Air = 6% ± 1½%
Specs. - Slump = 3" desired
Specs. = Slump = 4" Maximum

Obviously several critical factors need to be considered in this research study. In order to focus on the cause of air content variation during pumping and address testing procedures with respect to when, where, and how air content testing should be conducted for pumped concrete, consideration should be given to various factors such as:

1. Pump characteristics,
2. Type of aggregates,
3. Type of AEA,
4. Coarse aggregate factors, and
5. Concrete mix proportioning requirements for pumpable concrete.

Each of these properties will be briefly discussed below in order.

It has been observed that certain pumping characteristics may effect the loss of air during pumping. The instances where "boom" type pumps are used, the angle of boom play a very vital role in the loss of air during pumping operations. It has been observed [2] that the steeper the slope of the boom while placing the concrete, the greater is the loss of entrained air during pumping of the concrete which results in lower measured air contents at the discharge end of the pipe. It is suspected that a possible "free fall" affect on the concrete due to the steeper slope of the boom is related to the apparent loss of entrained air. It appears that in this configuration when ever a turbulent flow of concrete occurs through the elbow joints (where the concrete may impact against the wall of the elbow joint) in the pump line, a decrease in air content was observed (Table 2).

Certain aggregate types may absorb a portion of the entrained air during an agitated condition, such as the pumping process and cause

Table 2. The Physical Changes Measured After Pumping by W.A.C.A.

	1	2	3	4	5
Angle					
Slump Change	+2"	0"	+½"	-½"	+1¾"
% Air (Pressure)	-4.10%	+0.30%	+0.1%	-1.10%	-0.10%
% Air (Volumetric)	-3.75%	+1.25%	+0.50%	-1.00%	+1.00%
% Air (Petrographic)	-3.86%	+0.61%	+0.39%	-0.82%	+0.92%
% Air (SHRP)	-1.00%	+1.80%	-1.60%	N/A	N/A
Spacing Factor	+.0049"	+.0005"	-.0002"	+.0006"	+.0012"
Unit Weight	+4.25#	-0.48#	-2.12#	+0.75#	-0.16#

temporary changes in the intended entrained air content of the inplace concrete. Type of aggregates depends upon the source of origination, location and other conditions.

Air entraining agents of different chemical composition produce air voids of different size, distribution and spacing which will be discussed later in greater detail. The amount of agent also has an effect on the above parameters, such as the reduction in the air void size and spacing. Air entrainment agents used according to the dosage rates recommended by ACI [6] will usually provide a satisfactory air void system and satisfactory resistance to freezing and thawing.

Preliminary finding of this study indicate that the coarse aggregate factor of concrete mix may have an effect on the potential for the loss of air during pumping. The Texas DOT specifications (Item 421.11) currently require that the CAF range between 0.68 and 0.85 [4]. It is commonly accepted that mix designs based on high CAFs may cause the pumping of concrete to be more difficult and require greater pumping pressures for pumping concrete when compared to pumping concrete with lower CAFs. High pump pressures may cause a greater apparent loss of entrained air which may degenerate the air void system and the overall distribution of air bubbles. Little information has been documented verifying the effect of coarse aggregate factor on loss of air during pumping.

Concrete mix proportion characteristics involves the consideration of the effect the combined material gradation (coarse aggregate, fine aggregate and cement) may have on entrained air variation. There are three principal factors [1] related to mix proportions can be considered based on a given combination of aggregate characteristics:

1. The relationship between the coarseness of two larger aggregate fractions and the fine fraction,
2. Total amount of mortar, and
3. Aggregate particle distribution.

The sample particle distribution may be obtained from a multitude of aggregate combinations which may all influence the strength of the concrete the same way but there may be vast differences in the combinations in the rheological properties of the fresh concrete. It may be possible to optimize these combinations to where one may obtain the maximum strength and maximum workability. Normally, gap graded or near gap graded mixtures contain a greater amount of coarser particles which tends to have an adverse effect upon pumpability and finishability of the fresh concrete.

Literature reviews have indicated a simple theory which can be stated as "the amount of fine sand required to produce an optimum mixture is a function of the relation between the two larger fractions" [6]. The amount of fine sand needed to optimize a mixture is a function of the amount of cementitious materials in the mixture. The mixture with a low water-cement ratio possess the highest strength but it cannot be pumped or readily finished in the construction process. Since the water-cement ratio, fine aggregates, coarse aggregates, coarseness factor, and mortar factor affect the pumpability of concrete and consequently the air entrainment, there appears to be a need for the examination of alternate mix proportioning processes and considerations.

CHAPTER 2

LITERATURE REVIEW

Introduction

Pumping of concrete is universally accepted as one of the main methods of concrete distribution and placement. Advances in concrete technology have facilitated the continuous castings of the large pours for which concrete pumps have been recommended. Concrete placing rates can be maintained irrespective of the height and congestion in urban areas, thus providing the flexibility in overcoming access problems.

Factors Affecting Air Entrainment in the Cement Concrete

The several factors have identified to affect amount of air entrained in the concrete are:

1. Cement content
2. Coarse aggregate
3. Fine aggregate
4. Mixing water
5. Slump
6. Concrete temperature
7. Admixtures
8. Mixing action
9. Premature finishing

Cement Content: As cement content increases the air content decreases for a set dosage of air entraining admixture per unit of cement within the normal range of cement contents (Figure 1). The fineness and the

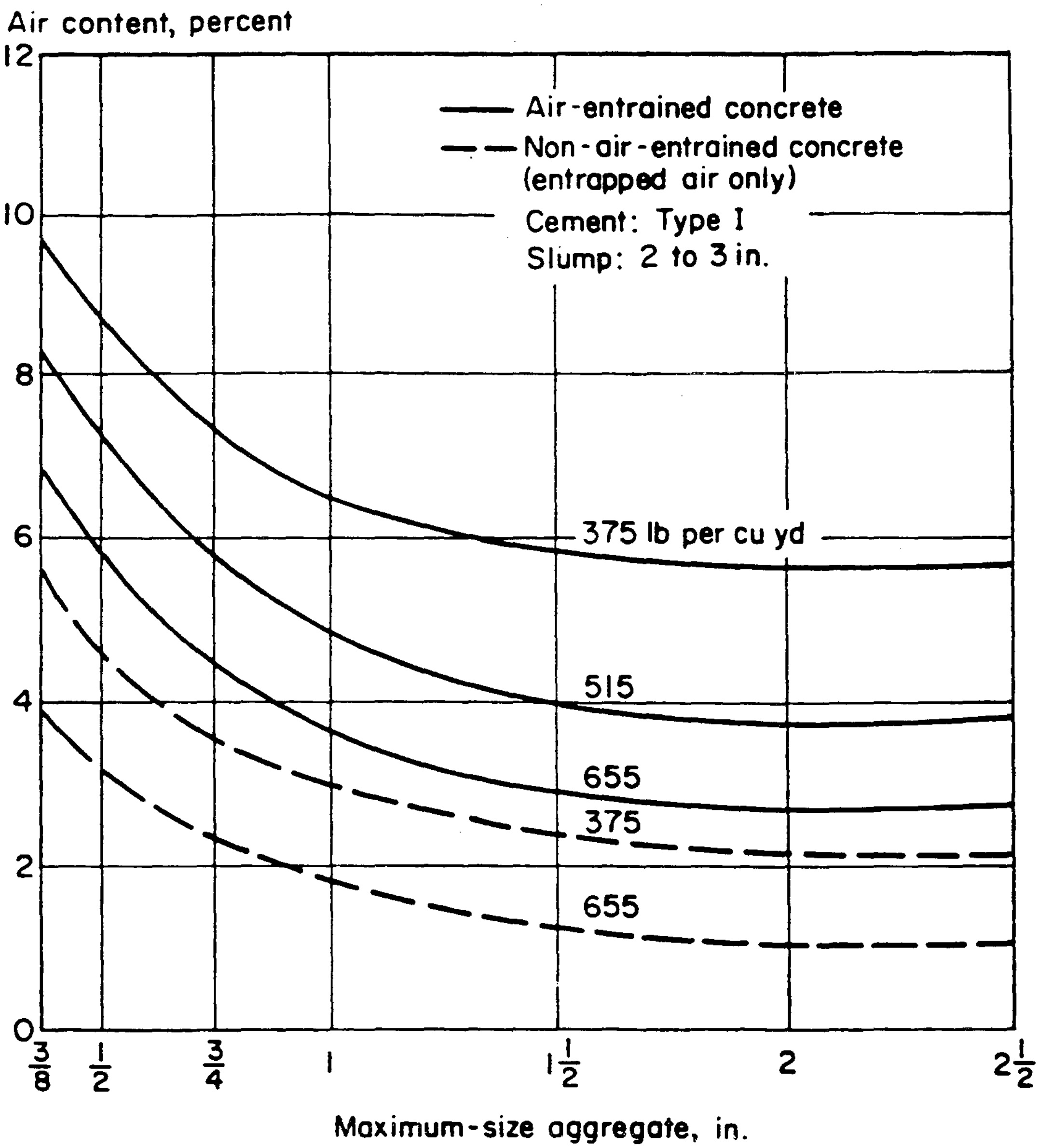


Figure 1. Relationship between aggregate size, cement content, and air content of concrete. The air-entraining admixture dosage per unit of cement was constant for air-entraind concrete. [14]

type of the cement can also affect the air content, an increase in cement fineness will result in decrease in the amount of air entrained. High alkali cements may entrain more air than a low alkali cement with the same amount of air entraining material.

Coarse Aggregates: The size of the coarse aggregate has a pronounced effect on the air content of the both entrained and non entrained cement concrete. But it is noted that there is a little effect when the aggregate size is increased above 1½ inches. As the aggregate size decreases the air content increases sharply with a constant admixture rate since the mortar volume increases.

Fine Aggregates: The fine aggregate content in the concrete affects the percentage of air entrained in both air entrained and non air entrained concrete. An increase in the amount of the fine aggregates increases the amount of air entrained (Figure 2). The fine aggregates passing through the No. 30 to No. 100 sieves are more effective in air entrainment than very fine or coarser particles. Difference in shape and texture of fine aggregates will also cause difference in air entrainment.

Mixing Water and Slump: An increase in the mixing water increases the air content in concrete corresponding to a slump increase up to 6 or 7 inches since more water is available for the generation of the air bubbles. An increase in the water content ratio from 0.4 to 1.0 can increase the air content by 4%. It has been noted that the increase in one gallon of water may increase the air content by approximately one-

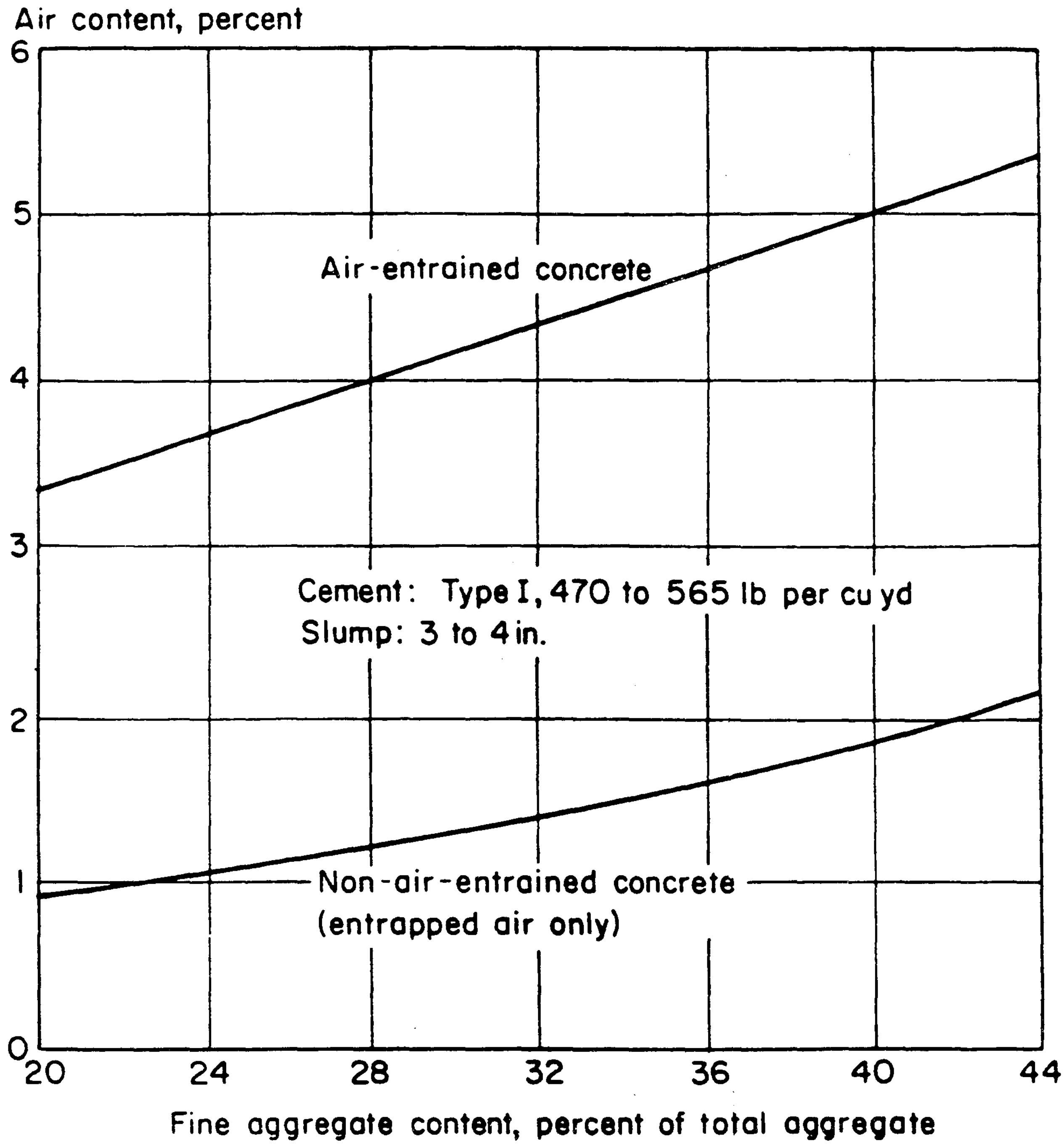


Figure 2. Relationship between percentage of fine aggregate and air content of concrete. [14]

half to one percent and a one inch increase in the slump. The quality of the water also has an effect on air content. Algae-contaminated water increases the air content. Hardness generally does not have effect, but very hard water may sometimes cause a decrease in the air content.

Vibration: Vibration will cause considerable reduction on air content. The greater the and longer the vibration time, the greater the percentage of reduction in air during the vibration (Figure 3). However, little air is lost if vibration is applied properly.

Concrete Temperature: Less air is entrained as the temperature is increased, particularly as the slump is increased (Figure 4). Increased concrete temperature during mixing may generally reduce air volume, but the spacing factor, and specific surface are only slightly affected.

Admixtures: Fly ash, coloring agents such as carbon black, or finely divided materials usually decrease the amount of air entrained. The admixtures used to increase the entrainment of the air are called air entraining admixtures. Air entraining agents contain surface-active agents, which help in bubble formation and stabilize once they are formed. All surface-active agents are not equally effective.

Mixing Action: The amount of entrained air varies with the type and condition of the mixture. The amount of the concrete being mixed and the rate and duration of mixing also effect the entrainment of air (Figure

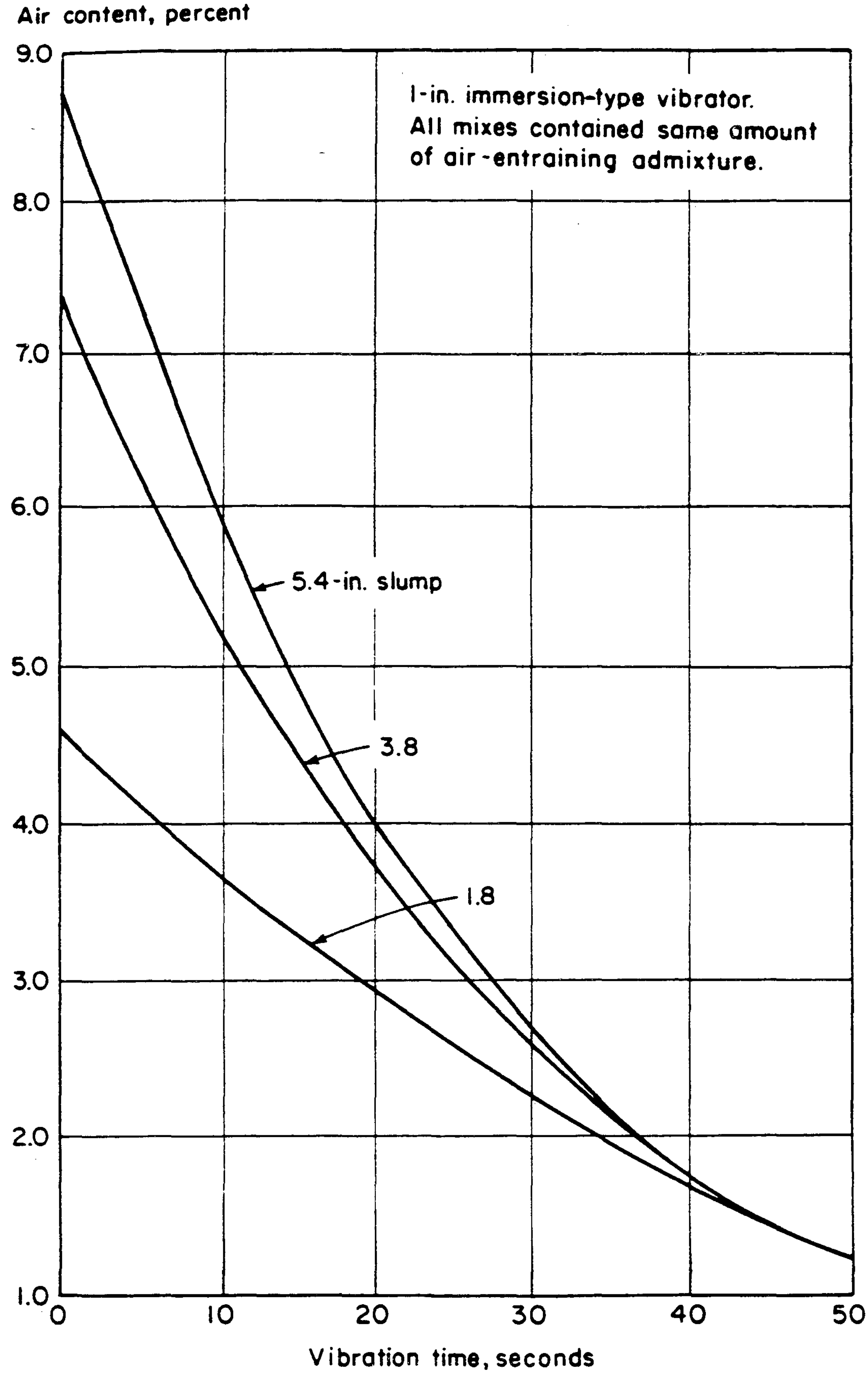


Figure 3. Relationship between slump, duration of vibration, and air content of concrete. [14]

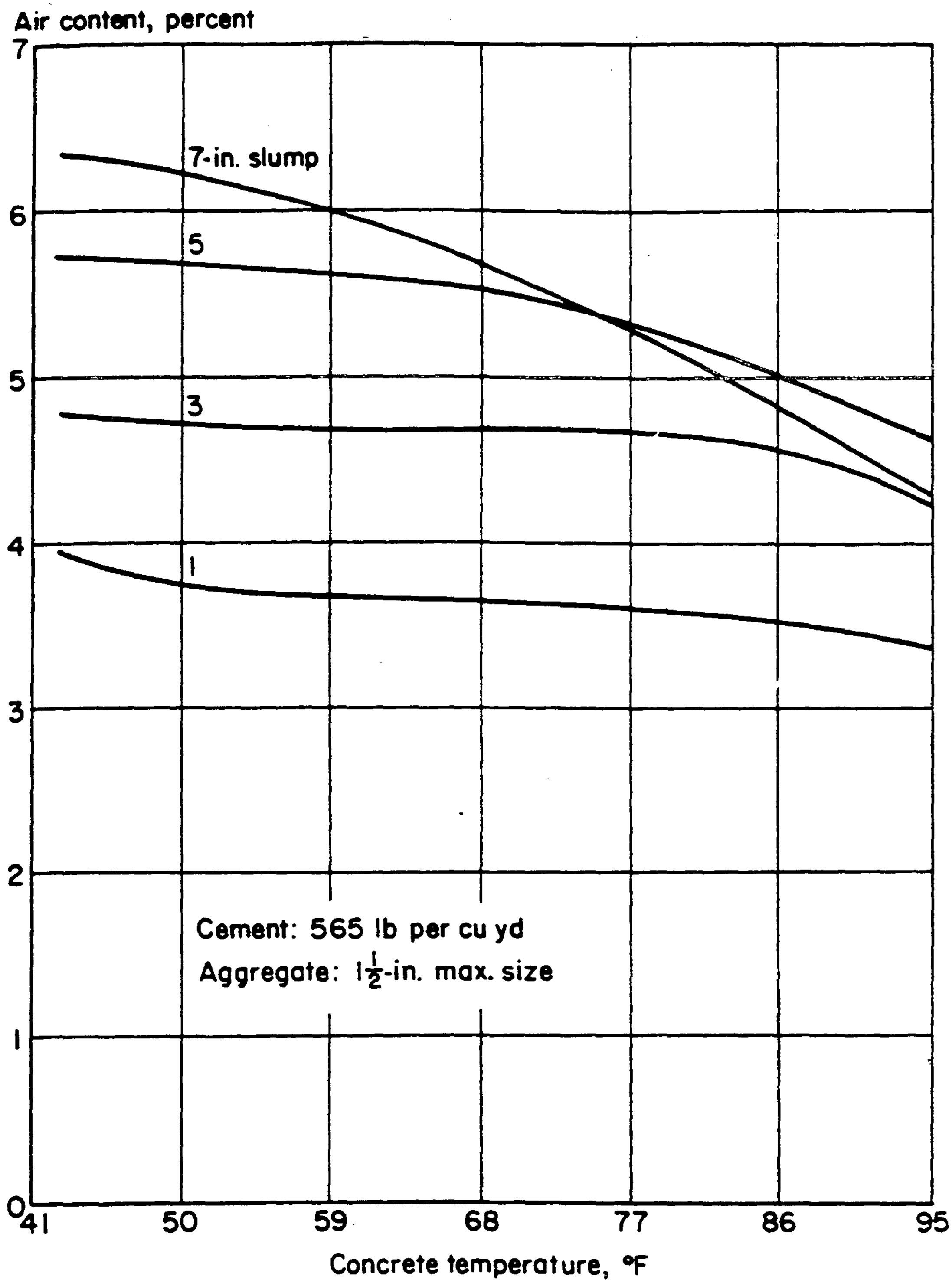


Figure 4. Relationship between temperature, slump, and air content of concrete. [14]

5). More air is entrained as the speed of the mixing is increased to about 20 rpm (beyond which entrainment of air decreases). A lesser amount of air is entrained in small batches made in a larger mixer.

Premature finishing: Premature finishing operations may reduce the amount of entrained air in the surface region which may cause the concrete surface vulnerable to scaling.

Pumping Factors

The modern concrete pump is a sophisticated, reliable and robust machine. It is produced in many shapes and sizes to suit the numerous applications and demands of the concrete site. A great development has taken place since the early days of the concrete pumping when the pumps were mechanically driven, incorporating single and double pistons [6].

The simple two stroke mechanical pump consists of a receiving hopper, an inlet and an outlet valve, a piston and a cylinder. The pumping action starts with a suction stroke drawing cement concrete into the cylinder as the piston moves backwards. During this operation the outlet valve is closed. On the pumping stroke the inlet valve closes and the outlet valve opens to allow the concrete into the delivery pipeline (Figure 6).

Pneumatic placers are another early form of concrete pump, consisting of a compressed air chamber which, when filled with concrete is sealed and compressed air added. This pressurizes the concrete to move it through the pipeline. These kinds of models are not used extensively because of their disadvantages in height and distance pumped

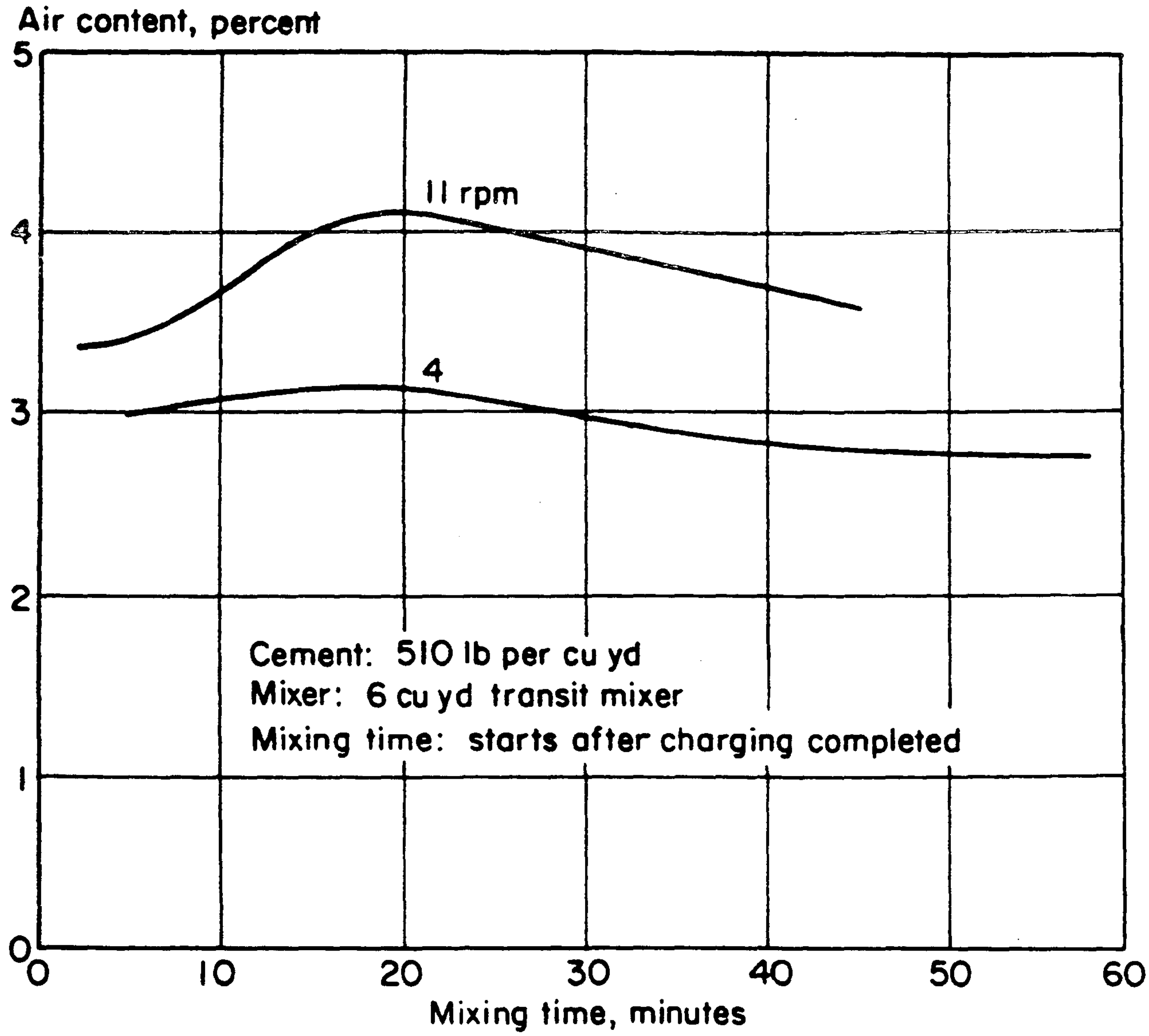


Figure 5. Relationship between mixing time and air content of concrete. [14]

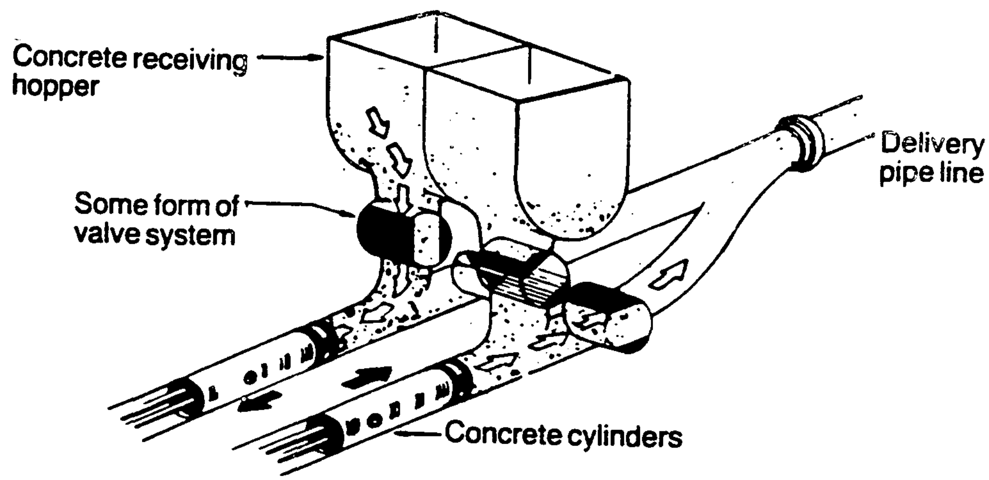


Figure 6. Principle of the Concrete Pump. [6]

and because higher slump concrete is required.

The most important part of any concrete pump is the valve system and several types have been developed over the years. The two main types of valves which are in extensive use are the flat gate valve and the rock valve. Flat gate valves (Figure 7) or rotating visor valves are well proven and can be very effective. Concrete from the two cylinders is brought together by means of a "Y" pipe. Rock valve (Figure 8) which is used extensively, offers a balanced changeover under any condition with high sealing efficiency.

The three main types of concrete pumps used extensively are mobile, trailer or static and screed or mortar. Mobile pumps consist of a concrete pump mounted on a vehicle chassis, which may have two, four, six or even eight axles depending on the size of the unit. These pumps are fully hydraulic and are extremely versatile, principally because of their mobility and adaptability. Trailer pumps can be towed from site to site as required and are mainly mounted on a single-axis chassis. There are

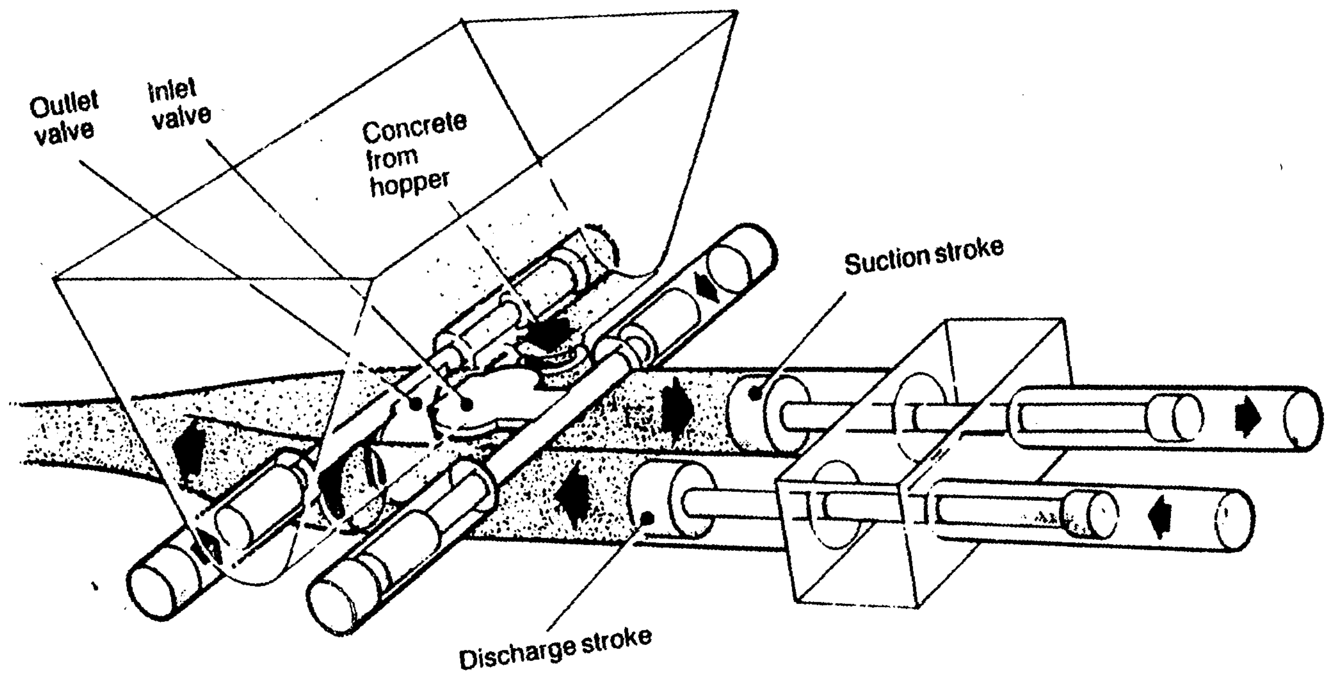


Figure 7. Flat Gate Valve. [6]

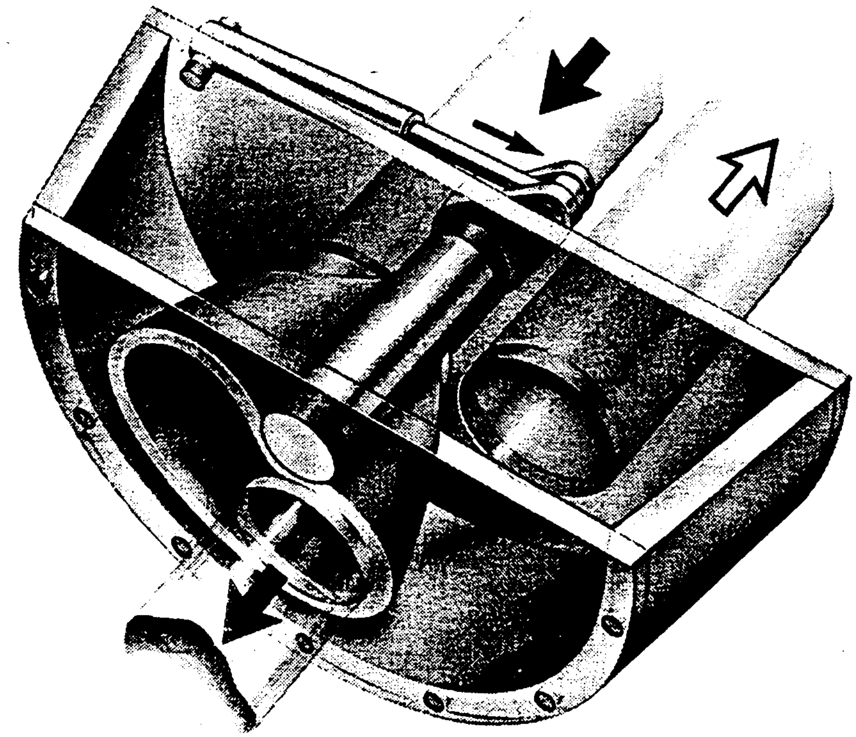


Figure 8. Rock Valve. [6]

several types of mortar pumps that are mainly single or double piston pumps.

To pump concrete the pressure exerted by the pump on the concrete has to overcome the pipeline wall friction, the resistance created at bends and tapers, the correct head when placing at a higher level than the pump, and the inertia of the concrete in the pipe. The physical flow state in the form of plug which is separated from the pipe wall by a thin lubricating layer consisting of cement paste. The water in the paste is hydraulically linked with the interparticle water layer in the plug. According to hydraulic theory, the plug flow velocity across the pipe is constant with respect to the velocity across the width of the plug, i.e; there is no relative velocity between the particles (Figure 9) [6]. The velocity drops across the lubricating layer to zero at the pipe wall.

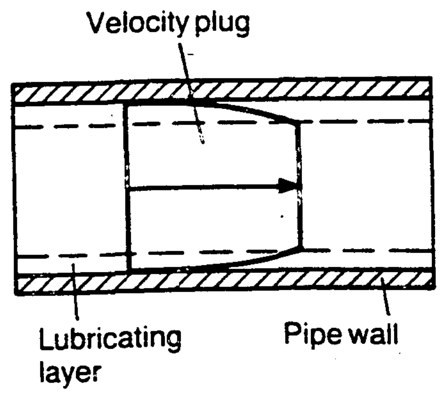


Figure 9. Velocity Profile for Plug Flow. [6]

The flow resistance is shown to be constant with respect to the pipe length and the concrete pressure decreases linearly down a straight horizontal pipe line. The flow resistance is given by

$$R = \frac{D}{4} \cdot \frac{dP}{dx} \tag{1}$$

where

"R" = flow resistance,

"D" = pipe line diameter, and

"dP/dx" = pressure gradient

R consists of two components, the hydraulic shearing of the lubricating layer and the friction of solid particles on the pipe wall. Both of these components are effected by the water-cement (w/c) ratio of concrete. The limitation being this is applicable to fresh concrete with sufficient mortar.

For continuous plug movement, the pressures generated by the flow resistance must not be greater than the pump pressure rating. However, if the concrete is too saturated the permeability of the concrete at certain pressures is such that water is forced out of the mix then excessive bleeding will create an increase in flow resistance and a possible flow blockage (Figure 10).

Therefore to enable the concrete to be pumped, both the permeability and the flow resistance, which are functions of mix proportions, must be balanced. The permeability is affected by the mix proportions and the aggregate type which in turn affects the pressure gradient. The pressure gradient is directly proportional to the flow resistance.

With permeability and flow resistance in mind, the mix must not only be able to bind all the constituent materials together under pump pressure, thereby avoiding segregation and bleeding. A pumpable mix must also facilitate the radial movement of sufficient grout to maintain the lubricating film initially placed on the pipe line wall. The mix deforms in the valve assembly, at bends and taper sections. To achieve this, the proportion of fines i.e; fines of cement and fine sand below #8 sieve size, is of prime importance and the quantities of between 30 and 36 lb/ft^3 are considered necessary for pumpable concrete. Not only is this required for maintaining the lubricant film, but it is important for quality and workability that there is enough grout to cover individual grains. The two main reasons for the occurrence of blockage are:

1. Water is being forced out of the mix creating bleeding and blockages by jamming, or
2. These is too much frictional resistance due to the nature of the ingredients of the mix.

Both conditions are caused by poor aggregate grading at opposite extremes on the scale. The first case is related to the existence of high voids which increases the flow resistance locally. The second case

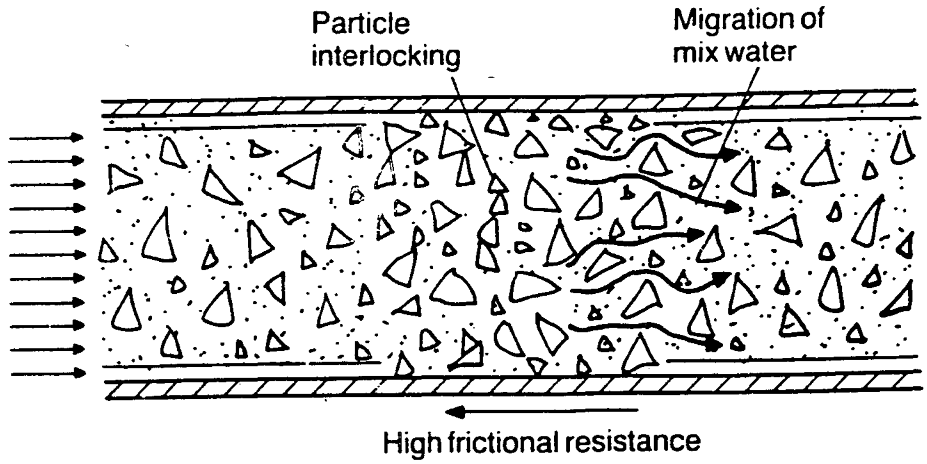


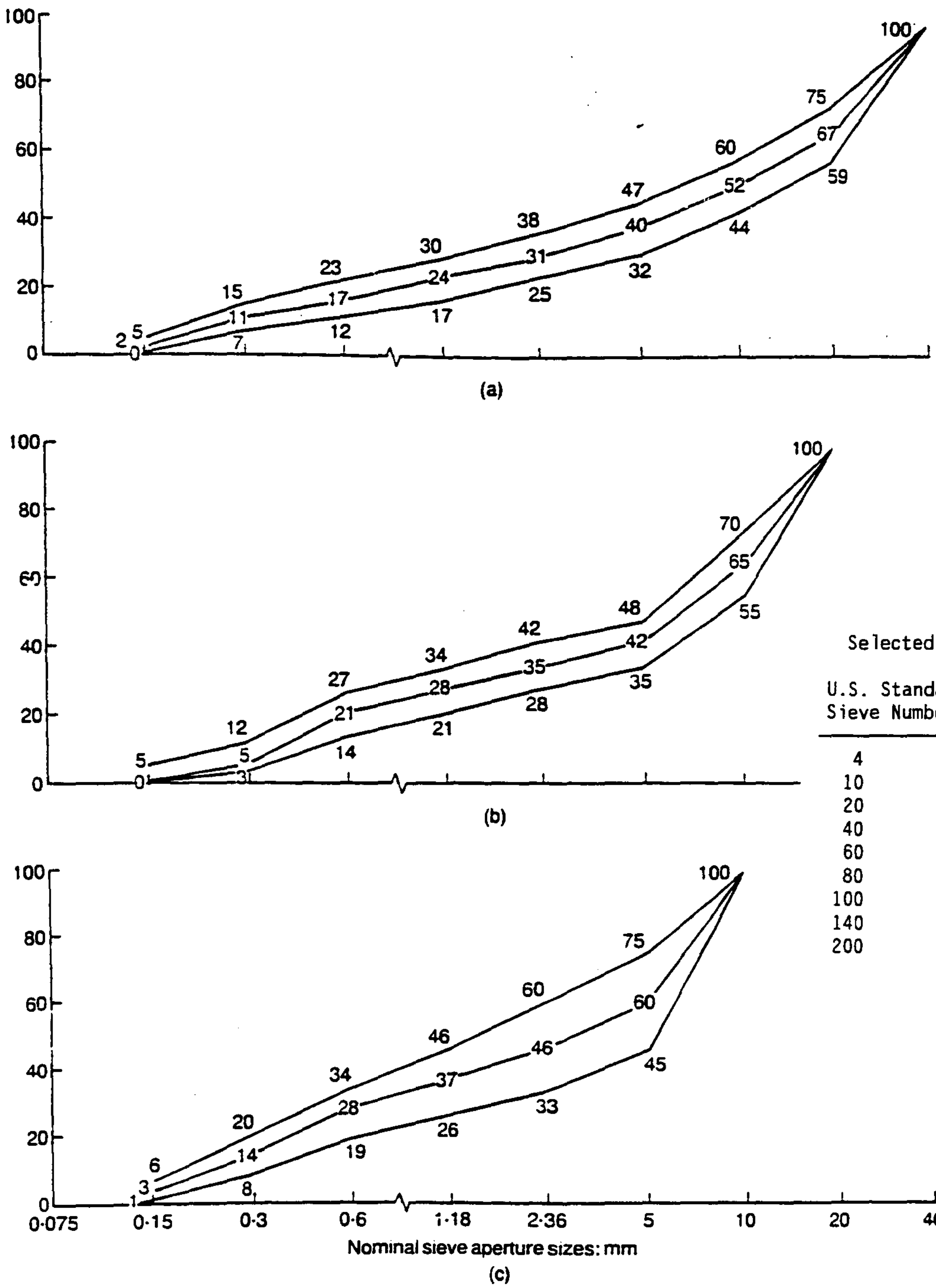
Figure 10. Effect of Dewatering in a Pipeline. [6]

is related to high proportions of very fine materials (#100 and above sieve sizes) which cause an increase in flow resistance. Excessive frictional resistance can be counteracted by (1) decreasing the cement content, (2) by adjusting the aggregate coarse/fine ratio (to increase voids), (3) by increasing water content, (but not so much to cause excessive bleeding and by using a wetting agent admixture). Excessive segregation and bleeding can be counteracted by increasing the cement content, by adjusting coarse/fine ratio to reduce voids, and by adding fines or by using a flocculent agent [8].

The increase in cement content to counteract the segregation can also cause high frictional resistance which is considered as poor grading. The adjustment of coarse/fine ratio (to reduce voids) also can cause frictional resistance. Hence, any adjustments made to the mix proportion should be done to minimize segregation since segregation can cause blocks and pump failure.

Aggregates vary in shape, grading and porosity according to their source and may in fact vary within the same source. The types and size of the aggregates are extremely important, particularly when designing a pumpable concrete. The concrete should be designed to suit different requirements and, for economic reasons, the concrete should also be made from materials which can generally be obtained locally. It may sometimes be impracticable to be specific about grading in designing a pumpable concrete. There may be some sands and gravels with natural gradings that gives low void contents and facilitate a pumpable mix design. Natural gravels are usually rounded and produce a better pump mixes than crushed rock aggregates. Crushed coarse aggregate materials may contain a proportion of dust, an excess of which could cause high pipeline friction.

The concrete mix proportion should be designed in light of the mechanics of concrete pumping as previously described. Not only must the hardened concrete meet the specification requirements of strength and other properties, but in its plastic state it must be pumpable. Pumpable quality means that the consistency must be such that it will pump without segregation or bleeding, that the slump normally be within the range of two to four inches and that the diameter of pipeline is at least 3-4 times the maximum size of aggregate. The grading of aggregate should be checked to determine the air void content and for adjustment of the proportions of coarse and fine aggregates to facilitate pumping. The grading of the aggregates should then be checked against the grading curves which are known to give pumpable mixes from the same sources. Typical grading curves are given in Figure 11. The recommended amount of



Selected sieve sizes

U.S. Standard Sieve Number	Opening (mm)
4	4.75
10	2.00
20	0.850
40	0.425
60	0.250
80	0.180
100	0.150
140	0.106
200	0.075

Figure 11. Typical Grading Curves for Pumpable Mixes. [6]

fine aggregate passing the #8 sieve is 10-20%. The adjustment of fines, adjustment of proportions of coarse and fine aggregates, amount of fine aggregates are the basic steps when designing a pumpable mix and it is also required at this stage that a check should be made for the specified strength and other requirements.

Adding an air entraining agent creates very small air bubbles through out the concrete, which will be elaborated under "admixtures". This alters the properties of the concrete both in its plastic and hardened state. As far as concrete pumping is concerned, air entraining increases the workability of the fresh concrete and the presence of air bubbles enables both the water content and the proportion of the fine aggregates to be reduced. The concrete is less liable to segregate and bleed. Therefore, there appears to be considerable advantages in pumping concrete which has entrained air in it.

If the air-entrainment agent dosage is too high then problems will arise in pumping. The entrained air is compressible such that a part of each piston stroke of

the pump is uselessly expended in overcoming the cushion formed by the entrained air which can inhibit the movement of concrete through the pipeline. The volume of air tends to be less at the discharge end than at the pump as some air is lost during the pumping. This is typically 20% or more of the volume of the air entrained (Figure 12) [6]. It is usual to allow for this by increasing the amount of air as was the case in District 24, but if this is over compensated for, the concrete may fail to be pumped. Generally, a 2% increase to the specified dosage (when pumping vertically 15 feet or more) can normally be allowed without

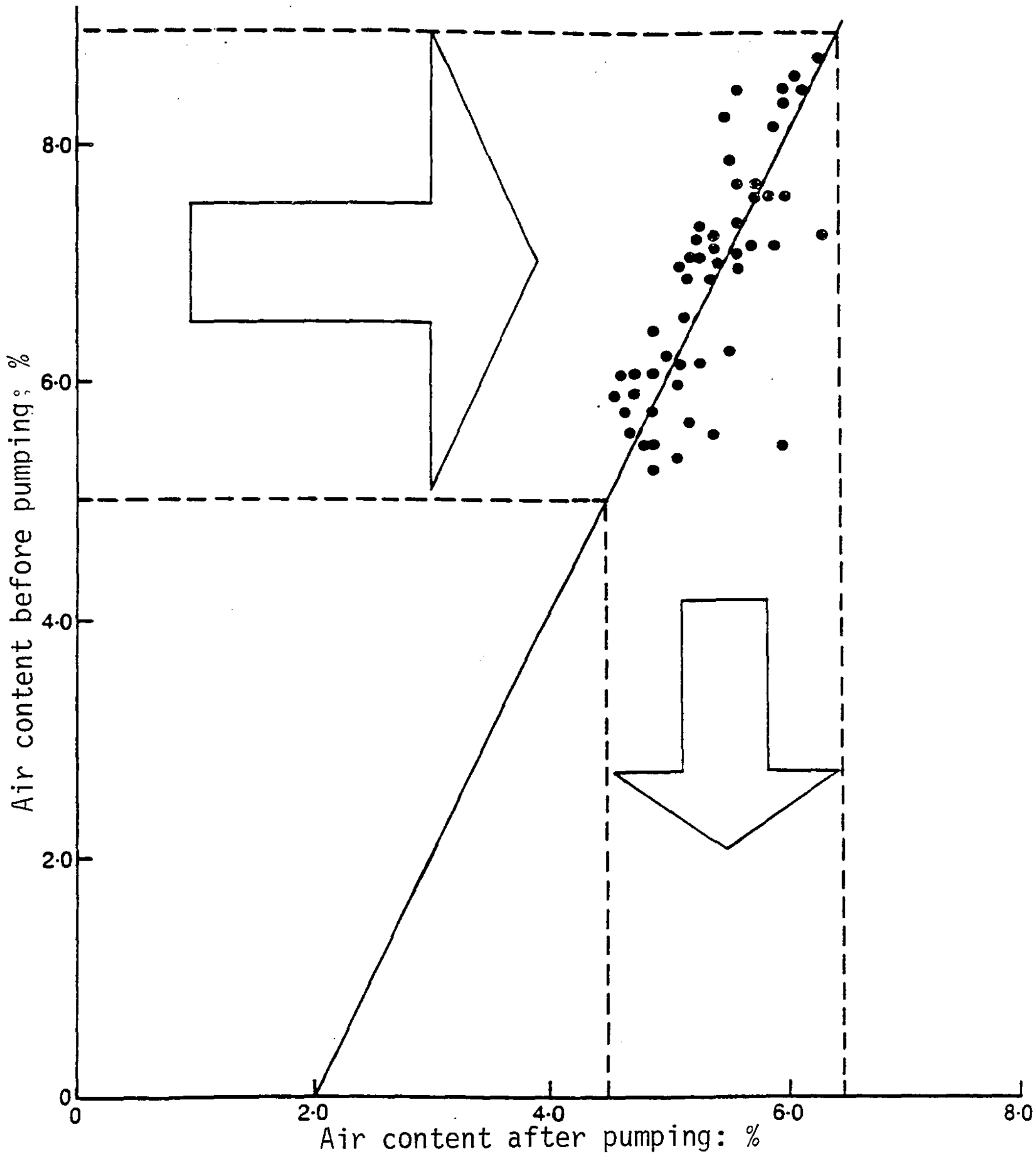


Figure 12. Air Content in Fresh Concrete Measured Before and After Pumping. [6]

causing any pumping problems. Special care should be taken when designing a mix which incorporates air entraining admixtures.

Effect of Pumping on Air Entrained Concrete

Factors associated with loss of air of pumpable mixes was studied by Washington Aggregates and Concrete Association (WACA) [2]. Tests were conducted in the studies to investigate not only the effects of pumping, but how different boom angles could change the air content between the truck discharge and pump discharge. Test results showed that there was a considerable change in the amount of air content between the truck discharge end and the pump discharge end. Four different configurations were tested.

Configuration I: The boom was oriented straight up and straight down (Figure 13) with the end of the rubber hose lifted up to create a back pressure, preventing the concrete from free falling within the boom. The amount of air content at the pump discharge was in fact found to be changed minimally when compared with the air content at the truck discharge; however, there was very slight drop in the unit weight and a slight increase in the spacing factor, with overall a minimal change in air content and void spacing.

Configuration II: The pump boom position is oriented in a straight out position as shown in Figure 14 to simulate a pump line of about 150 feet from pump to end of the hose, where the concrete was allowed a drop 2 feet. It was observed that there was very little change in the

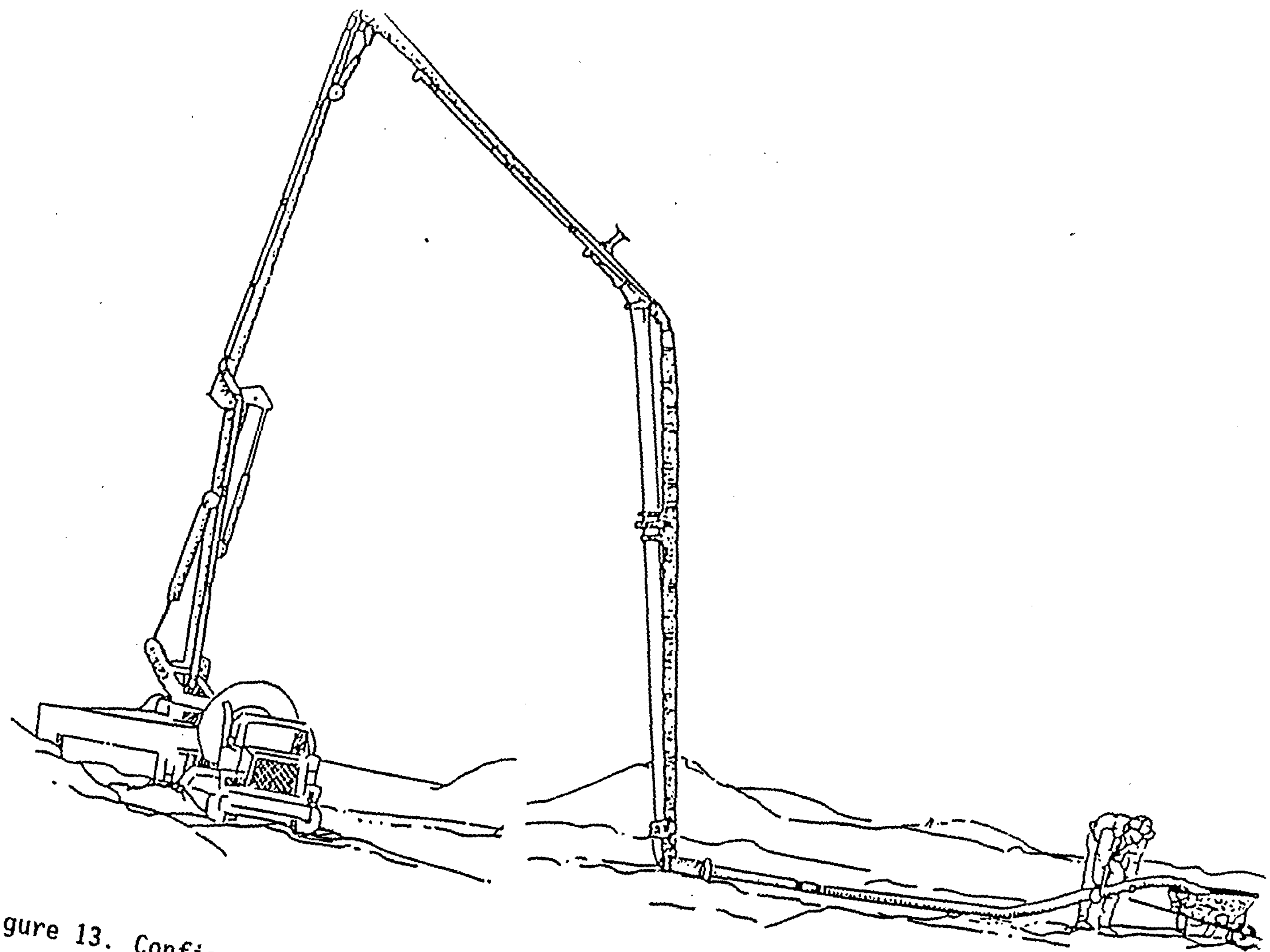


Figure 13. Configuration I. [2]

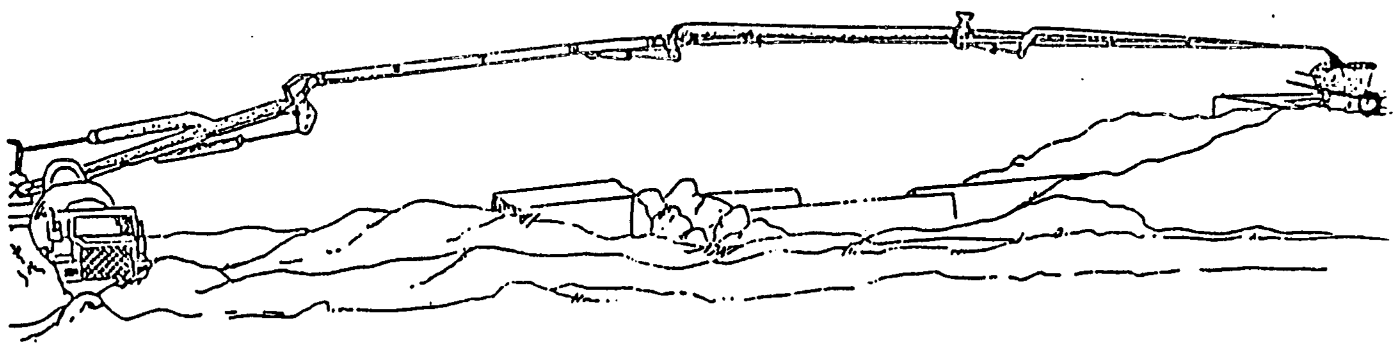


Figure 14. Configuration II. [2]

concrete properties. A drop of five feet also was not detrimental as it was clear during field tests (described later in chapter 3) conducted at Houston ship channel bridge construction site.

Configuration III: In this configuration the boom is positioned straight up and straight down allowing the concrete to fall freely (Figure 15). It was observed that there was a significant decrease in the air percentage. The spacing and unit weight also increased slightly which correlates to the loss in air.

Configuration IV: The pump boom was positioned at an angle to simulate pumping down hill, with rubber hose slightly curved up (Figure 16). While the petrographic and volumetric tests indicate about a 1% gain in air content, the pressuremeter showed no change. But there was a significant slump increase. This increase may be attributable to the additional mixing action in the pump to the increase in air content plus bubble size, indicated by the increased spacing factor.

It appears that whenever a turbulent flow of concrete occured through the elbow joints in the pipe line (under apparaent "free-fall" conditons), a decrease in air content was observed. Otherwise, if the pipe line was kept full there was little change or even an increase in measured air content. The bubble spacing factor increased in all but one of the WACA tests indicating that the bubble size increased with pumping [2].

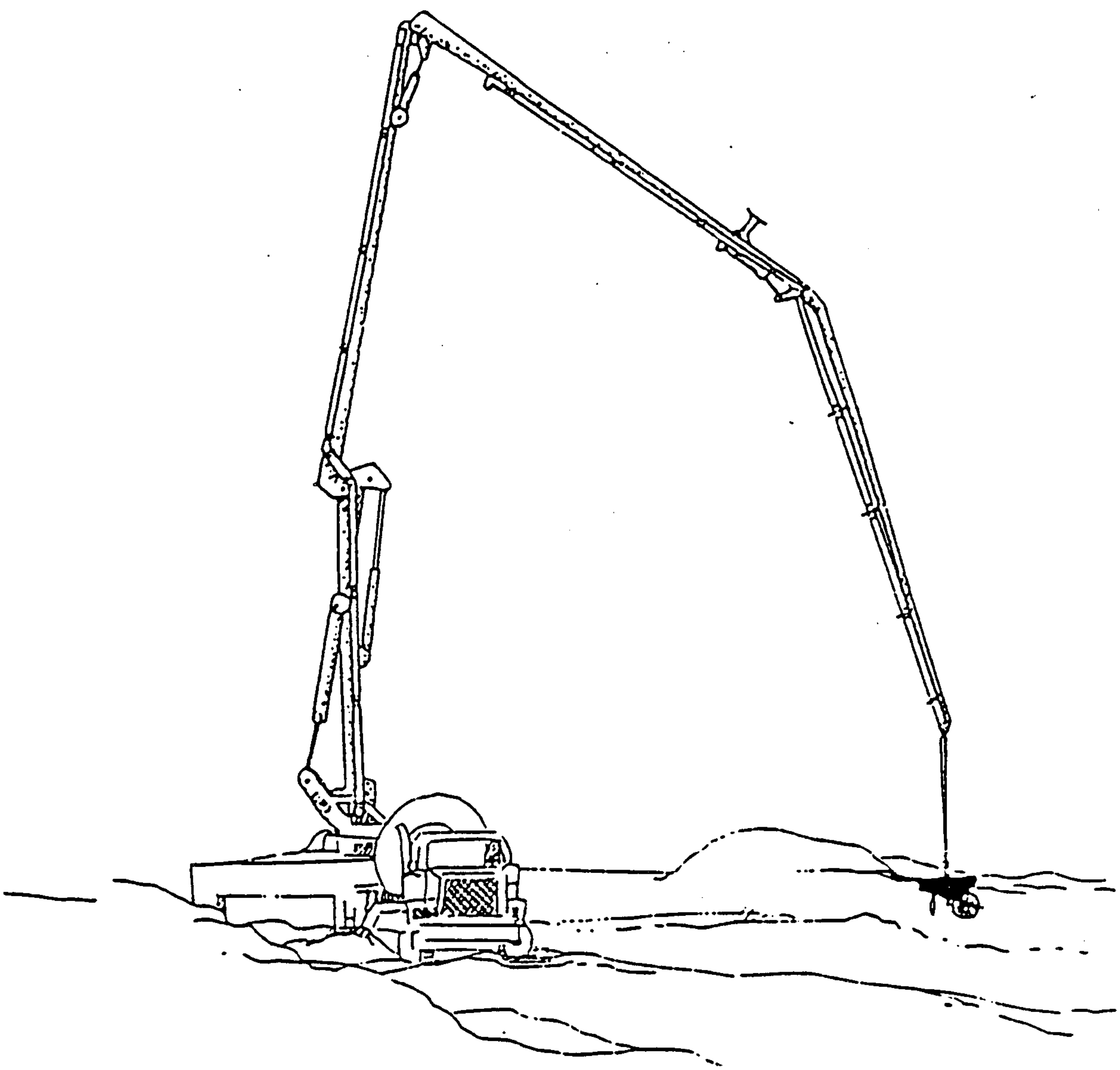


Figure 15. Configuration III. [2]

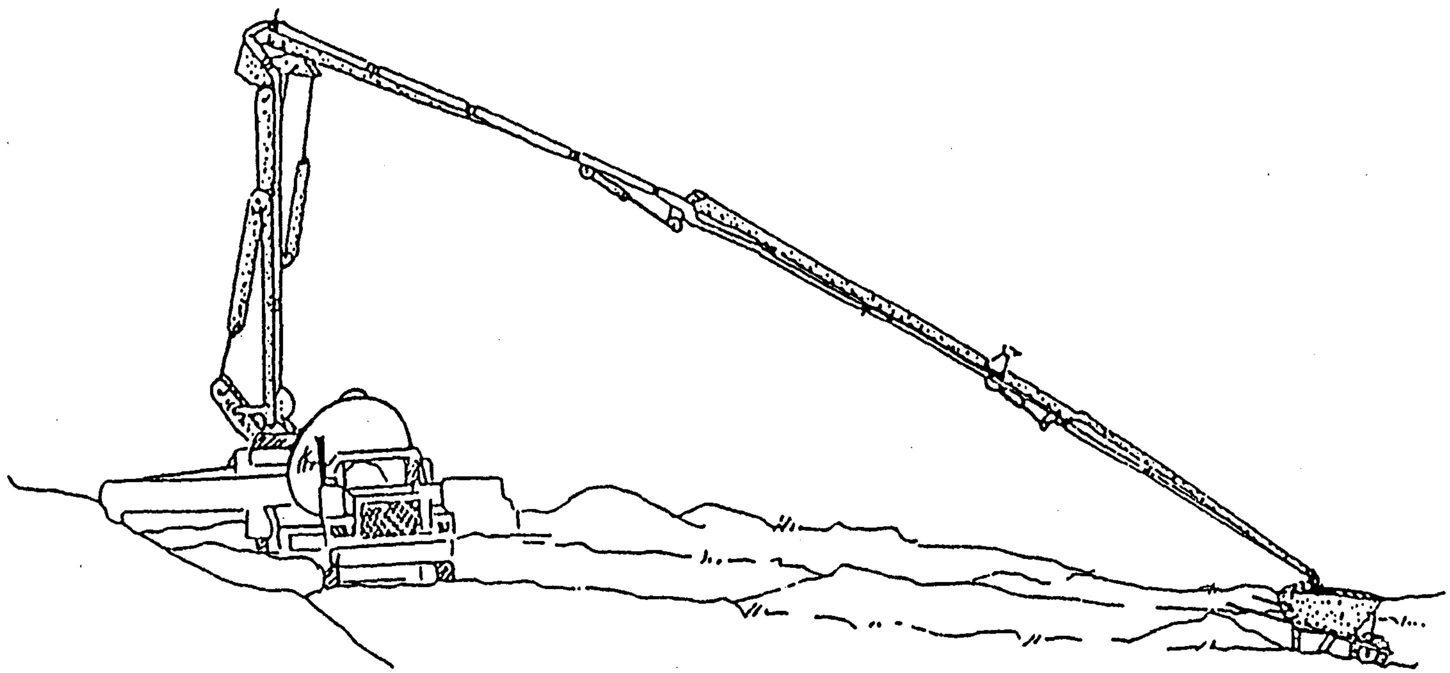


Figure 16. Configuration IV. [2]

Pumping Concrete and Associated Problems

Pumping of portland cement concrete is believed to cause an apparent loss of entrained air, which has been noted not only in Texas but, as pointed out previously, by others as well. It has been commonly accepted by pumping contractors to increase the dosage rate of the air entraining agent in order to compensate for the loss of air after pumping as was done in District 24. The exact reason for the loss of air is not yet fully understood. However, many factors such as slump, mix design, aggregates, type of admixtures, pump pressure can contribute for such a loss of air in cement concrete during the placement of concrete by the use of a pump.

Pumping of concrete seems to effect the air void system which develops in the concrete. Pumping may result in larger air bubbles and greater bubble spacing thus altering the concrete. Certain pump characteristics may contribute to the alteration of the air void system. They are:

1. Placing rate required(yd^3/hr),
2. Working factor of pump,
3. Horizontal length of pipeline,
4. Vertical length of the pipe line,
5. Number and radius of bends,
6. Diameter of the pipeline, and
7. Consistency (slump) of the mix.

The rated output of the pump has to be downgraded by what is described as a work factor. The reason for this is that the site conditions will dictate what level of performance the pump can achieve throughout the concrete placement (in comparison to ideal conditions). The level of performance may not necessarily be due to the pump capability itself. Therefore the output has to be rated by the work factor before taking anything else into consideration. A typical value of the work factor is 75.

As the pumping pressure will vary depending on the length, height and diameter of the pipeline as well as the number and radius of bends, these factors must be taken into consideration. Frictional pumping resistance in a pump line horizontally oriented is a function of the pipeline length and will be maximum at the pump reducing to zero at the discharge point. When pumping vertically an added increment of pressure is encountered due to an allowance has static pressure since concrete is approximately 2.5 times the weight of water; the increased pressure due to the vertical pipeline is about 0.08 bar/ft (1 bar = 760 mm q Hg).

Bends and tapers which invariably form a part of the pipeline, are points which cause the pressure to build up due to deformation of concrete. Pipeline diameter is also important. For a given flow rate, the velocity in the pipeline decreases as the pipeline diameter increases, with the result that the pressure will be lower. The choice of pipeline diameter is normally related pump size and to the aggregate size. The pipeline diameter always should be less than the pump cylinder diameter. With regard to aggregate size, a general rule is that the pipe diameter should be between three and four times the size of the largest aggregate.

The consistency of the mix will influence pumping pressure. The stiffer the concrete is, the higher the pressure required. The lower the concrete workability is, the higher the flow resistance is and consequently higher the pressure is. There are, of course, upper limits of slump such that a high water/cement ratio may lead to segregation and a blockage. Conversely, if the mix is too dry it cannot be pumped. Therefore, the slump of the mix is important and must be within the limits for pumpable concrete.

Air Entraining Admixtures

Air-entraining admixtures are materials which produce minute air bubbles in concrete during mixing with resultant improved workability, reduced segregation, lessened bleeding, lowered permeability, and increased resistance to damage from freezing and thawing cycles [28]. Each one percent of entrained air permits a reduction in mixing water of from 2 to 4 percent, with some improvement in workability and with no loss in slump. Entrained air generally will reduce the strength of most concretes [15]. In cases where the cement content can be held constant, some advantage can be taken of the reduced water requirement such that the air entrainment in lean concrete has negligible effect on strength and may slightly increase it. Among the different types of cements, Portland Cement is the best for air-entraining. Cements containing blast-furnace slag or fly ash are more difficult to entrain [18].

Types of Air-Entraining Agents

A large number of commercial formulations are currently available for use as air-entraining agents. Most admixtures are complex formulations which may include mixtures of more than one chemical. Perhaps the simplest, and most widely used products, are based on "Vinsol resin"

[16]. The classification of air-entraining agents is given in the Table 3 [19].

Resistance of Concrete to Frost

Concrete is considered to be frost-resistant to the degree that it is completely saturated with water under atmospheric pressure and can still retain its resistance to a large number of conventional cycles of freezing and thawing. Air-entrained concrete can be highly resistant to frost because generally its coefficient of saturation is correspondingly low.

The capillary system in the concrete is filled with water under atmospheric pressure (saturated condition), where as the air space of the concrete together with the air bubbles, are filled with water under an increased pressure (150 atm). The coefficient of saturation 's' is the relation of the weight of capillary water 'u' in saturated conditions under atmospheric pressure to the weight of the water 'v' obtained under increased pressure (about 150 atm).

$$s = \frac{u}{v}$$

The index of frost resistance is the coefficient of saturation 's'. The value (1-s) denotes the free air space in concrete saturated with water under normal conditions. The greater the frost resistance, the smaller the coefficient 's' and the greater the free air space.

Air-entraining admixtures change the structure of the cement grout in the concrete. In particular, they improve the entire capillary and pore system. The air is distributed in a manner different from that in concrete which has not been air-entrained. A considerable part of the

Table 3: Classification of Air-Entraining Agents.

GROUP	CLASSIFICATION	CHEMICAL TYPE(S)	BRAND NAME(S)
A	Salts of wood resins {Neutralized (Vensel) Resin}	Complex mixture of lignin derivatives (phenols), carboxy resin acids, aromatics, terpenes	NVX,Sika-AER*, Amex*,MBVR*, MBAE-10*, Daravir*, Protex-AES
B	Synthetic detergents	Alkyl-aryl sulfonates	Amex-210*, Microair*, Darex*
C	Salts of sulfonated lignins	Complex sulfate liquors (Ca lignosulfonates, reducing sugars, carbohydrates)	Not widely used at present for AEA
D	Salts of petroleum acids	Complex, highly sulfonated aromatic and saturated ring structures	No information
E	Salts of proteinaceous materials	Amino acids	Airsene-L
F	Fatty and resinous acids and their salts	C_{12} to C_{18} saturated acids, oleic acid, abietic acid, tall oil	Airalon, Airex-D, Septair*
G	Organic salts of sulfonated hydrocarbons	Triethanolamine salts of condensed petroleum acids	Pro-Air

* on approved Texas DOT list of admixtures

Note: The other approved admixtures are: Air-in, Air-Tite, Con Ad AEA, Pave-Air, Preston Air-20, Prokrete AES, Prokrete, Concentrate AES, Relcreate Air 30, Shepair-20, Solar AEA.

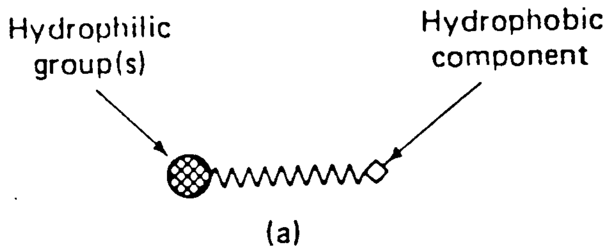
air is contained in the closed bubbles, which constitute a separate component of the concrete. For this reason, air-entrained concrete having a higher content of air has greater water tightness than plain concrete with a smaller content of air [18].

When a water-saturated, porous material freezes, macroscopic ice crystals form in the coarser pores and water, which is unfrozen in the finer pores, migrates to the coarser pores or the surfaces. The larger ice crystals feed on the small ice crystals, even when the large ones are under constraint. The pore structure of hardened cement pastes determines the amount of freezing of water contained in the pores. The pore structure depends largely on the initial water-cement (w/c) ratio and the degree of the hydration. In general, the pore structure is composed of pores having diameters ranging from 10,000 to 50 Å for nonmatured pastes and 1,000 to 50 Å for matured pastes. The higher the w/c ratio, the greater will be the volume fraction of larger pores. When these pores are saturated with water, a large amount of water will be able to freeze during cooling. A saturated concrete, prepared at a higher w/c ratio and with a lower degree of hydration, contains a greater amount of water. Larger dilation is not only due to water freezing in the larger pores but also due to water migrating from smaller pores, freezing in limited spaces and generating stress. When the rate of cooling is slow, there is enough time for water to vacate the small pores of the sample, causing a contraction due to drying shrinkage. Adding an air-entraining admixture to the paste, produces various quantities of air bubbles of uniform size (larger, relative to the size of the larger pores). Though concrete is saturated (except for the entrained space), the existence of closely spaced air bubbles provide sites for water to migrate and for ice crystals to grow, without the imposition of stresses. Accordingly, the central function of entrained air is to provide very many small, closely spaced, empty escape places for the excess water when freezing occurs. If no spot in the paste is farther than the critical distance from such an escape place, disruptive pressures cannot be generated, and the paste will be durable to freezing. When the stresses generated, due to freezing, exceed the tensile strength of concrete, the concrete cracks [29].

Admixture: Air-Entraining Mechanics

An understanding of the basic principles of how air-entrainment agents work should help to simplify the mechanics of controlling and production of air-entrained concrete and facilitate the selection of air-entraining admixtures.

Air-entraining admixtures are mostly hydrophobic, surface-active compounds. Most surface-active molecules consist of a non-polar hydrocarbon chain or some other hydrophobic group joined to a polar or hydrophilic group such as $-COO^-$, $-SO_4^{--}$, or $-NH_3^+$ (Figure 17) [1]. The polar group makes the molecule soluble in water at an appropriate temperature while the non-polar group tends to be expelled from the water. As a result of this two opposing tendencies, surface-active molecules are positively adsorbed at interfaces between different phases. At air-water interfaces the majority of the polar groups are oriented towards the water phase and the majority of the non-polar groups are oriented towards the air phase. This phenomenon, known as non-specific



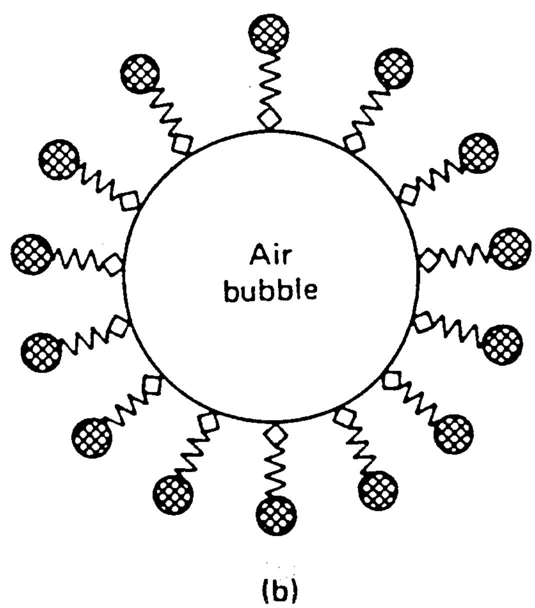


Figure 17. Schematic Representation of Air Entrainment by Surface Active Molecules: (a) Surface-Active; (b) Stabilized Air Bubble. [1]

adsorption, lowers the surface tension of water, promotes bubble formation, and counteracts the tendency for dispersed bubbles to coalesce [17].

At solid-water interfaces, when special directive forces exist on the solid surface, surface-active molecules are specifically adsorbed with the polar groups bound to the solid and the non-polar groups orient towards the water. This phenomenon makes the solid surface-hydrophobic so that air may displace water from it and, as a consequence, air bubbles may adhere to the solid.

Surface active agents may be classified according to the type of polar group in their molecules [17]:

(a) Anionic agents, e.g. sodium alkyl sulphates $RSO_4^-Na^+$ where R is an alkyl group or sodium abietate $C_{19}H_{30}COO^-Na^+$ where the non-polar group is a series of hydrocarbon rings.

(b) Cationic agents, E.g. alkylamine hydrochlorides $RNH_3^+Cl^-$ and alkyl trimethyl ammonium bromides $RN(CH_3)_3^+ Br^-$ where r is an alkyl group.

(c) Non-ionic agents, e.g. polyethenoxy agents $R(CH_2CH_2O)_nCH_2CH_2OH$.

(d) Miscellaneous agents which do not fit into any of the above groups, e.g. saponin which is a complex glycoside occurring in plants, gums, and synthetic polymers.

The Formation and Retention of Air Bubbles in Cement Pastes

The air contents produced in cement pastes by various types of surface-active agents, used over a concentrated range, vary widely. The relative air-entraining capacities of surface-active agents in concretes are governed to a large extent by the physical and chemical interactions between the agents and the paste material. The anionic agents, sodium dodecyl sulphate, sodium abietate and neutralized "Vinsol" resin, and the cationic agent tatradecyl trimethyl ammonium bromide are highly efficient air-entraining agents while the non-ionic agents, "Triton NE" and "Lissapol N 300^{+}" entrain practically no air even when used at high concentrations. Saponin, when used at low concentrations, is a poor air-entraining agent, at high concentrations however, it entrains large amounts of air.

No general correlation exists between the air-entraining capacities of surface-active agents and their foam capacities and foam stabilities in water, their tolerance to precipitation by the electrolytes present in cement paste, or the foam capacities and foam stabilities of filtrates obtained from cement pastes containing these agents [17]. For example, the non-ionic agents are powerful foaming agents in water, are not precipitated by electrolytes, and filtrates from pastes containing the non-ionic agents posses quite high foam capacities and stabilities, yet these agents are poor air-entraining agents. Conversely, the anionic agents are all precipitated by calcium ions and remain in solution as sparingly soluble calcium salts. Furthermore, filtrates from pastes containing these agents posses very low foam capacities and stabilities yet the anionic agents are efficient air-entraining agents.

The reasons for the different air-entraining behavior of various agents become apparent from studies of the flotation characteristics of cement in the presence of the various agents. The amounts of cement floated to the surface, attached to bubbles, indicate the degree of hydrophobic character conferred on the cement particle surface by the specific adsorption of the various agents and the resulting tendency for bubbles to adhere to such surfaces. It was noted that the efficient air-entraining agents floated cement to the surface while the poor air-entraining agents failed to float cement.

The formation of stable, air-entrained cement pastes therefore appears to depend on two major factors [17]. Firstly, after any precipitation or adsorption, the concentration of the surface-active agent remaining in the mixing water need not be great but should be sufficient to generate air bubbles when the paste is stirred. Secondly, the surface-active agent should be specifically adsorbed on the cement particles, making them hydrophobic so that the generated air bubbles will adhere to them. This process stabilizes bubbles of low stability, fixes bubbles in position in the paste preventing their coalescence, and allows the air content of the paste to build up as mixing progresses. When mixing ceases, bubbles are retained in the paste by attachment to cement particles which weigh them and prevent their escape. In addition, the attachment of bubbles to cement particles binds the particles together and reduces paste segregation.

For various reasons it is generally more advantageous to obtain the given air-entrainment by using smaller quantities of a more productive air-entraining admixture than larger quantities of a less productive admixture [18]. A too large quantity of surface-active compounds may hamper the process of cement hydration and thereby cause a reduction in strength and also a deterioration in other properties of the concrete.

Air Void System

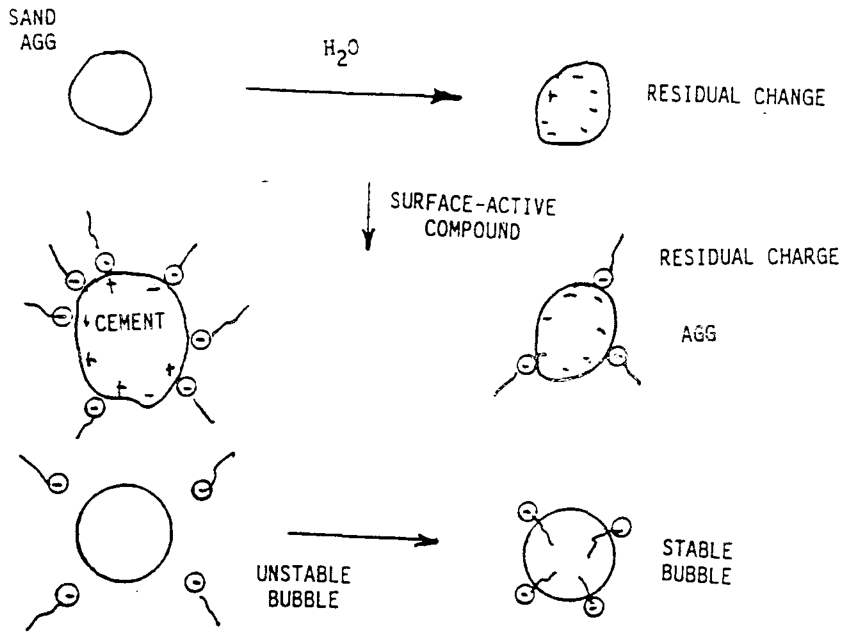
Air present in voids in the cement paste of unhardened concrete is derived from several sources.

1. Air originally present in intergranular spaces in the cement and aggregate,
2. Air originally present within the particles of cement and aggregate but expelled from the particles before hardening of the concrete by inward movement of water under hydraulic and capillary potential,
3. Air originally dissolved in the mixing water, and
4. Air which is in-folded and mechanically enveloped within the concrete during mixing and placing.

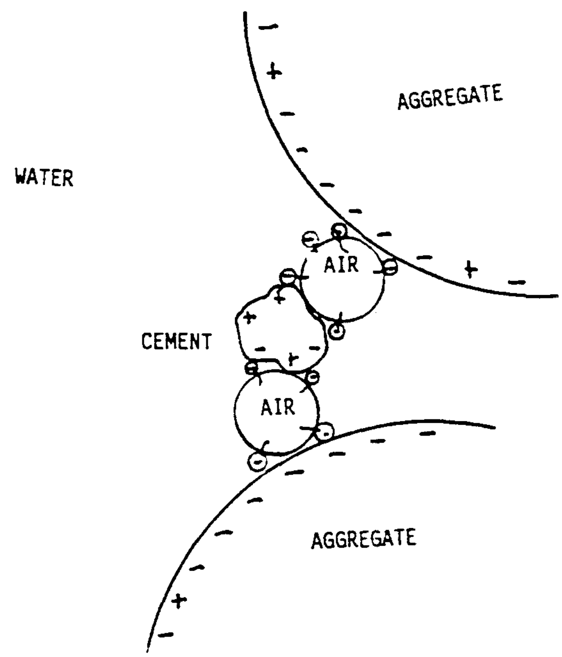
A large portion of the air bubbles generated by the mixing and placing operations remains within the concrete because the bubbles are enmeshed within the packed aggregate and because they may adhere to particles of cement or, less commonly, to particles of aggregate. (Figure 18)

Air voids escape from the granular structure of the concrete only by moving between intergranular spaces under the force of buoyancy as the aggregate particles are shifted with respect to one another during placing and compaction of the concrete.

Air voids in concrete range in their relationship to the granular structure of concrete between two extremes. One extreme relates to bodies of air entirely enclosed among particles of aggregate may be under pressure approaching that imposed only by the overlying water. The other extreme relates bubbles enclosed by a paste composed of aggregate fines and cement that are under pressure approaching that imposed by the



(a) Dissociation and Orientation at the Solid/Air Bubble Interface



(b) Net Adsorption/Stabilization Effect

Figure 18. Basic Mechanism of Air Bubble Formation. [9,10]

entirety of the overlying concrete [20].

The air entirely enclosed among particles is commonly said to be "natural" or "entrapped". These voids characteristically are 0.26 inches or more in diameter and are irregular in shape because the periphery of the void follows the contour of the surrounding aggregate particles. The second type of air voids - "entrained" air voids are retained in the concrete as a result of entrapment among the aggregate, adherence by surface-chemical forces to particles of cement and aggregate, and the viscosity of the cement paste. These voids typically are between 10 and 100 microns in diameter (Figure 19) and are spherical or nearly so because of the hydrostatic pressure to which they are subjected by the surrounding paste of the cement, water and aggregate fines. Entrained air bubbles effectively improve workability in the unhardened concrete because they increase the spacing of solids in the mass and thus decrease dilitancy and, by bearing short time loads, they facilitate movement of aggregate particles past one another [24].

There is no secure way to establish a size range distinctive between the entrapped and entrained air. Even if a critical size were established, the true diameter of a void is not perceivable on random section. Additionally, measurement of air in practice is commonly is made as a check against total air, as determined by pressure meter in the fresh concrete. The air indicated by the pressuremeter is the summation of all the void space. The pressuremeter does not distinguish between entrapped and entrained air. Compliance with a specified volume of entrained air is presently impossible for fresh concrete, and requires both microscopic analysis and a clear definition of the distinction

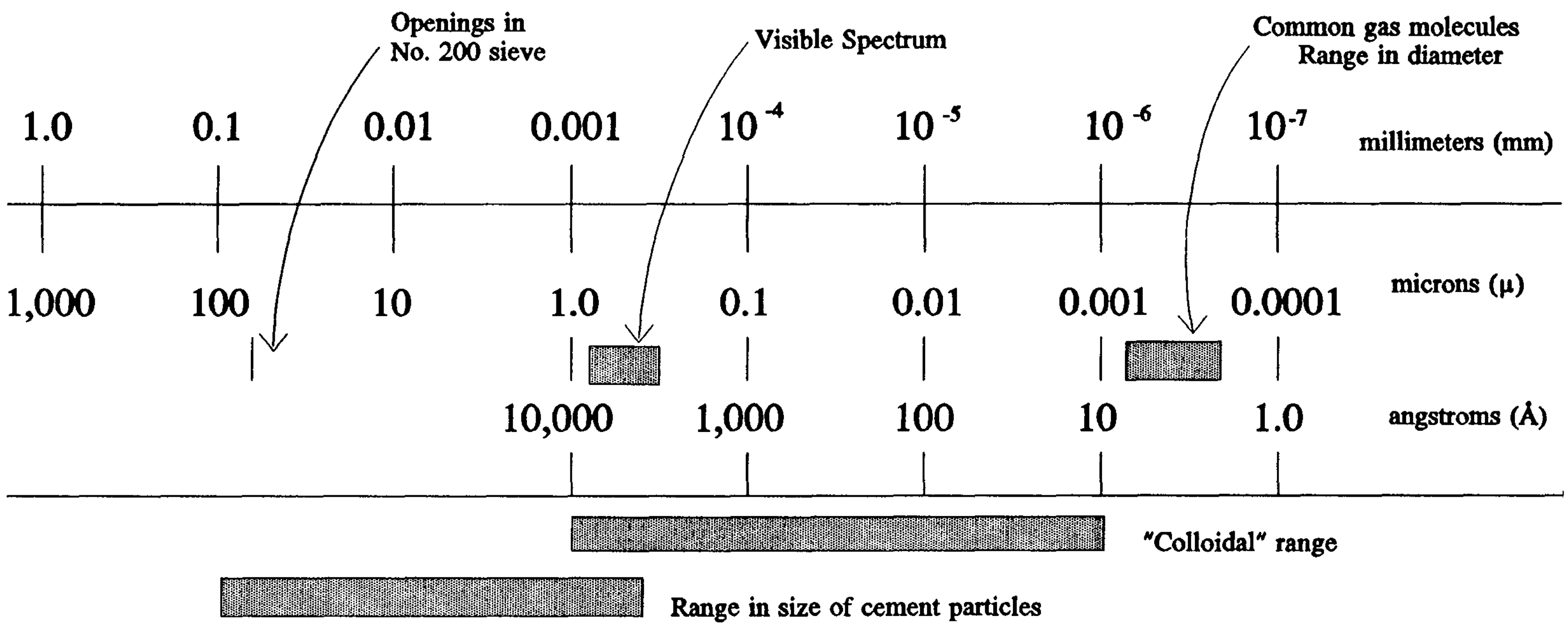


Figure 19. Small-dimension relationships [3].

between entrapped air and entrained air for hardened concrete [25]. Some of this discussion may change depending on results which may be obtained from such devices as the Air Voids Analyzer referred to later in Chapter 4.

Air entraining agents are positively adsorbed at water interfaces and reduce the surface tension possibly by 4.25 dynes per cm or more when used in ordinary concentrations. The film of the air entraining agent can cause changes in the air bubbles in a liquid or slurry because coalescence of bubbles and rate of dissolution of the air in the bubbles are reduced. The reduction in the rate of dissolution depends upon the concentration and properties of the film forming substance. Films formed by adsorption on the surface of the particles will reduce the hydrophobic quality of the surface and may render it hydrophobic. In this event, air bubbles will tend to cling to the cement particles with a force determined by the interfacial tension and the contact angle. The greater the contact angle measured in the liquid, the greater the adhesive force. (Figure 20) [20].

Air enclosed in bubbles in unhardened cement paste in concrete is under greater than atmospheric pressure because of:

1) The hydrostatic pressure of the overlying concrete, or a portion thereof, and any other load imposed on the concrete, and
2) The curvature of the air-water interface.

Hydrostatic pressure resulting from weight of the overlying concrete may range from virtually nil to several pounds per square inch, the increase being at the rate of about 1 psi per foot of concrete depth. The pressure resulting from surface tension at the water interface is

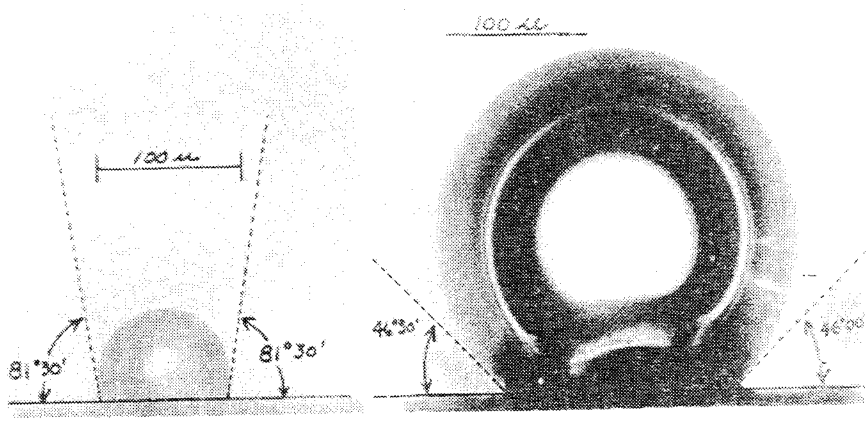
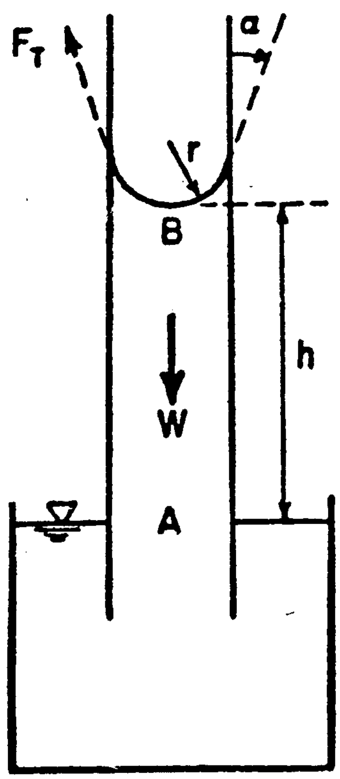


Figure 20. Contact Angle Measured in the Liquid. [23]



$W = F_T \cos \alpha$ (Equilibrium of water column)

Figure 21. Height of Rise in a Capillary Tube. [30]

controlled by the relationship and given in Figure 21.

$$P - \frac{2\gamma}{D} \tag{2}$$

where

P = excess pressure resulting from surface tension at the air-water interface in plastic concrete

γ = surface tension of the water phase in plastic concrete and

d = diameter of the air bubble

The pressure within the an air bubble in water increases rapidly as the diameter of the bubble decreases in the range less than 100 microns (Figure 22) [20].

From the fundamentals of Henry's law relationship, (pank) pressure can be equated to the product of the mole fraction of gas (n) dissolved in water because of the excess pressure and Henry's constant (k) where p = pressure in the bubble. The increase is extremely rapid in the range below 10 microns. Consequently, while concrete is fresh, the air in very small bubbles is being dissolved far more rapidly than the air in large bubbles. It is improbable that a bubble originally less than 10 microns will be preserved because of the rapid dissolution of air. Bubbles originally larger than 10 microns will produce voids less than 10 microns in diameter in the hardened concrete because the cement paste hardens during the dissolution of air.

As the air in the small bubble dissolves, the water soon becomes

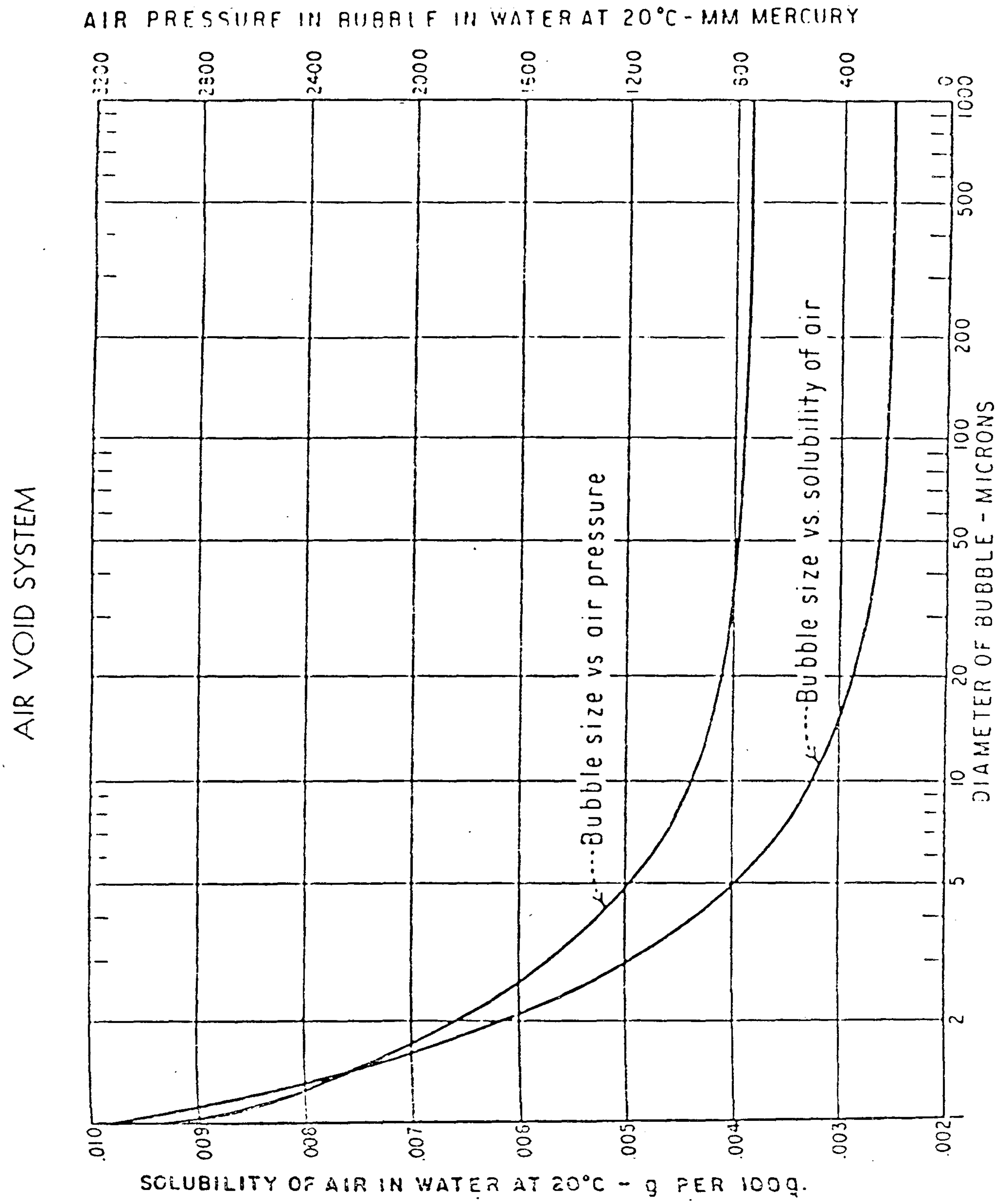


Figure 22. Relationship of solubility of air and internal pressure to the size of an air bubble in water at 20 C. [23]

saturated with the dissolved air with respect to the atmosphere above the concrete. From this point in time until the cement paste becomes sufficiently rigid to produce a relatively stable structure, air in bubbles smaller than the average dissolves and bubbles larger than the average increase in size because of release of the air from the water. As a result of the dissolution of air from small bubbles and its release into large bubbles, the air content of the concrete will increase unless the gain so produced is offset by escape of air into the air from the exposed surfaces of the concrete. Increase in air content is ordinarily to be expected following the completion of placing operation. For instance, air entrained in bubbles of 20 microns in diameter on completion of placing of the concrete will occupy about 2/3 more volume when transmitted to voids 1 mm in diameter.

The rate of interchange from small bubbles to large bubbles is directly proportional to the area of the air-water interface, the pressure differential established between bubbles losing air and those gaining air, the solubility of air in water, and the rate of diffusion of air through the water. It is inversely proportional to the distance through which the diffusion occurs. The rate of interchange between the bubble of diameter d_1 and a large bubble of diameter d_2 at any time when the mass of air transmitted is B is given by:

$$\frac{dB}{dt} \alpha \frac{aD\gamma}{T} \left[\frac{1}{d_1} - \frac{1}{d_2}\right] \tag{3}$$

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 which increases with the solubility of air in the water, the rate of diffusion of molecules of the gas through the water, and the permeability of the adsorbed film at the air-water interface.

For a system of entrained air bubbles, the effective surface area through which the transmission takes place depends upon the size distribution of the bubbles and varies directly with the specific surface "a", and the distance between the surface of the bubbles varies directly with the spacing factor L.

The size distribution, frequency of air voids, spacing factors and freezing and thawing restance, are influenced by many factors. Among the most important are the kind and the amount of air entraining agent. The average size of the air voids and the computed spacing factor tend to decrease with increasing proportion of air entrainment agent at constant water-cement ratio. The spacing factor decreases with decreasing water-cement ratio within the range of workable mixtures at constant air content [21].

Other factors are related to the water-cement ratio and the intensity of the compaction. Water-cement ratio influences the size distribution of air voids because the viscosity of the water phase and the air content of the cement paste are altered. As the water-cement ratio decreases, the viscosity of the water phase increases and the air content of the cement paste decreases. The rate of diffusion of dissolved air tends to decrease with in increased viscosity of the water phase and the amount of air diffused from small bubbles to large bubbles decreases with the increase in the distance between the bubbles [22].

The method and extent of compaction used to place concrete exert fundamental influence on the air voids. Air content is reduced by the process of compaction, primarily because the air bubbles tend to move towards the surface and the escape from the surfaces of the concrete as facilitated by vibration. Also because some of the larger bubbles are broken into smaller bubbles in which the air content is more compressed by capillary action. The increased period of vibration is found to increase the specific surface of the concrete.

CHAPTER 3

ANALYSIS, LABORATORY, AND FIELD RESULTS

Air Measurement Methods

Three methods employed by the Texas DOT for determining the air content in freshly mixed concrete are,

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

There is also a fourth method, Chase Air Indicator method which provides only an approximate air content of freshly mixed concrete. All the above methods measure the insitu volume of air.

Pressure Method

This is a standard test method for determining the air content of freshly mixed concrete. This method is suitable for all kinds of concrete except those made with highly porous and light aggregates. Another advantage of this method is that this can be used effectively in the field.

The air content of the freshly mixed concrete is determined by the apparatus pressure meter on the principles of Boyle's law (Figure 23). The air content is determined by standard procedure ASTM C231. The pumped pressure replaces the air voids in the concrete, thus giving the volume count of the air voids in the fresh concrete.

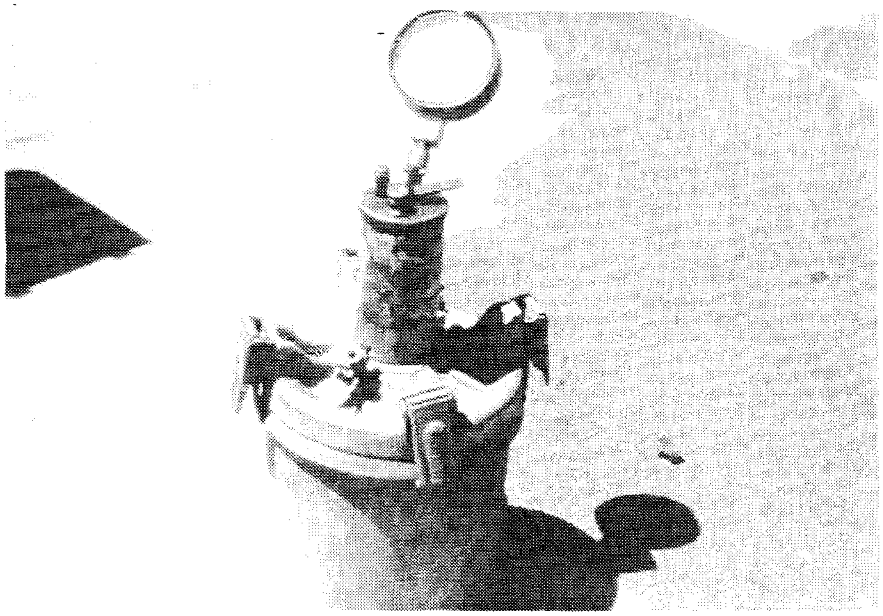


Figure 23. Pressure Meter.

Volumetric Method

Volumetric method involves the use of a volume type meter indetermining the air content of the freshly mixed concrete according to ASTM C173 (Figure 24). This method is useful for field testing all concretes, but is more effective for the concretes made with light weight and porous aggregates [26]. The air in the voids is replaced by the water mixed in the roll-a-meter giving the count of the air voids in the concrete.

Gravimetric method

The air content of the freshly mixed concrete is determined by comparing the theoretical unit weight of air free concrete with the measured weight of the entrained air concrete. This method requires the

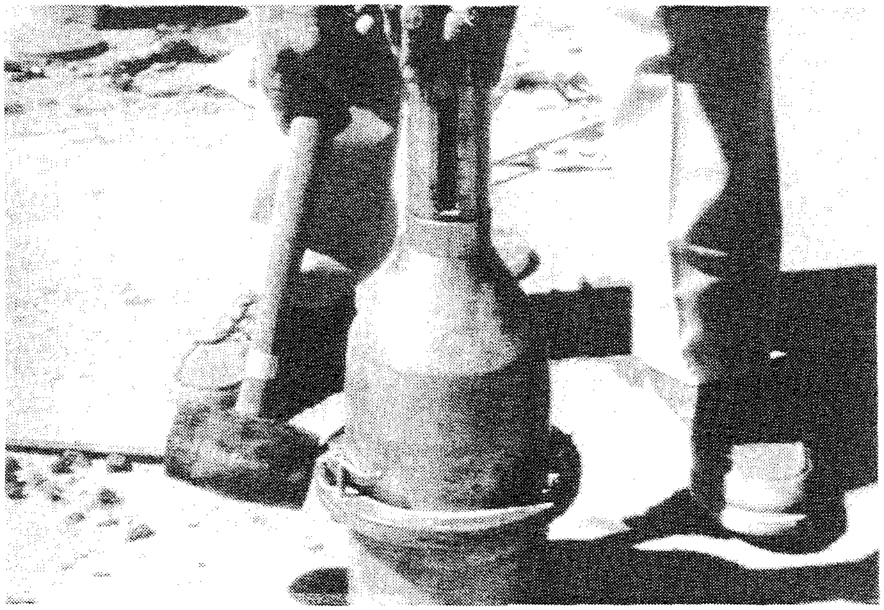


Figure 24. Roll-a-meter.

material's specific gravities and absolute volumes of concrete ingredients. This method is impractical for a field test but can be used satisfactorily in laboratory [26].

Linear Traverse Method

The current method of determining the air content of hardened concrete is Linear Traverse Method. The air content is determined by means of microscopic method. The air-void content, spacing factor is determined by standard procedure ASTM C457. Microscopic analysis is only an accurate measure of the air content when performed correctly as it measures the bubbles of all sizes, where as it is quite unlikely the bubbles of less than 50 microns are read in pressure meter method.

New Developments in Air Measurement

A new fiber-optic device for assessment of air-entrained concrete has been developed by SHRP-sponsored researcher. This fibre-optic system will provide detailed information on air void quantity, size, and distribution (Figure 25). In addition to quick measurement of air voids, other specific advantages of the new device, as compared with existing practice, include:

1. Insitu measurement capability at any point in the mixing, transportation, pouring, and casting of concrete.
2. Ability to rapidly sample air entrainment at different locations or depths in a strip of pavement, considerably improving existing quality control procedures.
3. The air content measurements are direct, and not effected by the type and amount of aggregates, cementitious components, and admixtures.[27]

Initial reports indicate the sensitivity of this device is somewhat lacking.

Laboratory Investigations

Work was done in the laboratory to determine the air content by both the pressuremeter method and volumetric method for one type of aggregate. The basic idea of conducting lab experiments was to measure the air content of fresh concrete with both pressuremeter and roll-a-meter (volumetric) methods to examine the sensitivity of these methods to the variation in measured air. The local available aggregates in the laboratory were used in the mix. An analysis of aggregates was done in the laboratory and the tests of air content were reported for both a gap graded and a well graded mix. The well graded mix seemed to have a lower

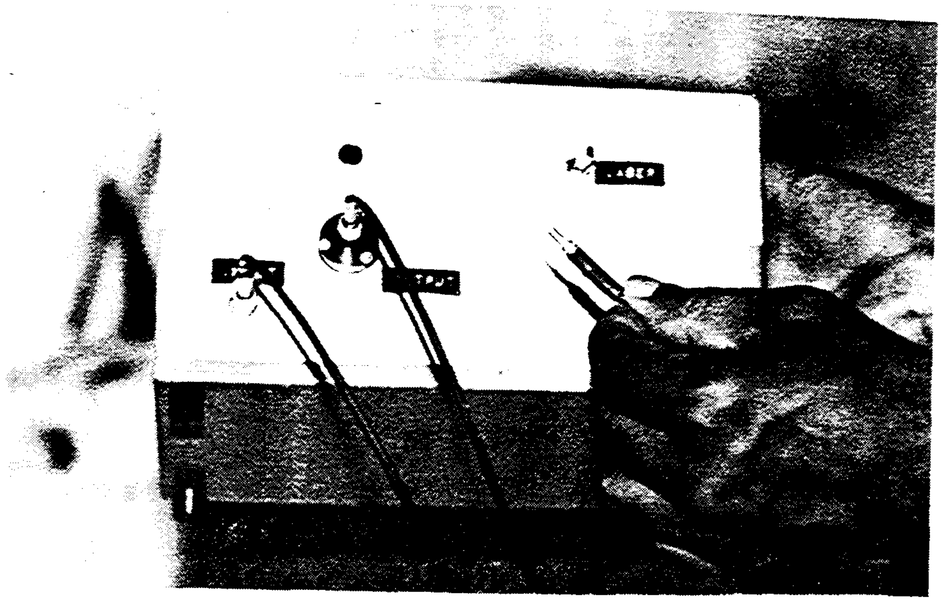


Figure 25. Fiber-Optic Device. [27]

percentage of loss of air.

A laboratory procedure was developed in this project to simulate the pressure histogram the concrete pump undergoes (55 to 110 bars). The pumping of concrete was simulated in the laboratory by applying a calculated amount of hydraulic pressure on the cement concrete in a specially designed cylinder (Figure 26). The concrete was placed in the cylinder and a calculated amount of pressure is applied, which is same as the pressure applied on the concrete during pumping, for approximately 3 minutes, which is more or less the same time for which pressure is applied on the concrete in the pump. The tests were repeated for different mix designs in order to find the effect of the mix design on the air entrainment in cement concrete.

Air content was measured by both pressuremeter method and volumetric method immediately after the concrete was removed from the mixer and then the calculated amount of pressure was applied. The air content was

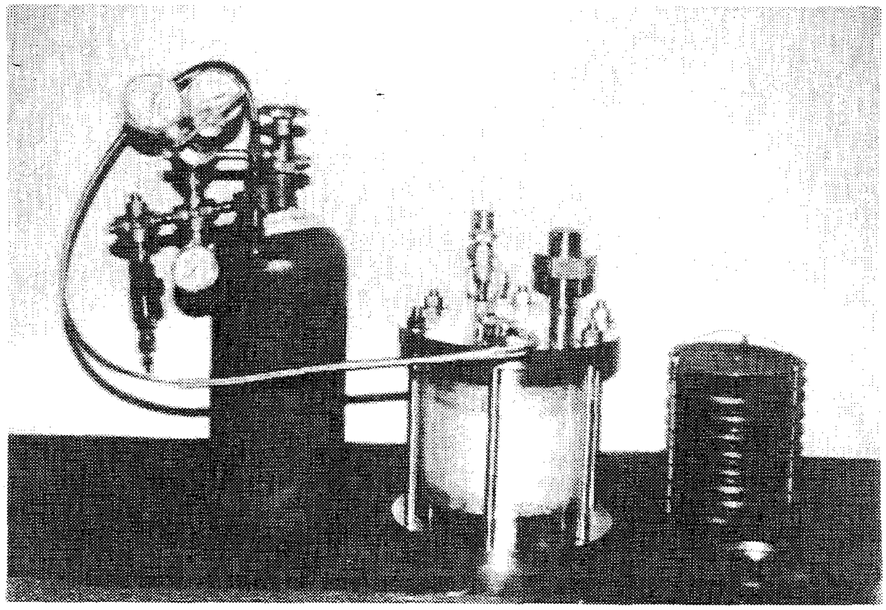


Figure 26. Hydraulic Cylinder.

measured again after pressure was removed from the concrete. The results are listed in the Table 4 and Table 5. However, the air content tests were not conducted for the inplaced concrete since only a small amount of concrete was mixed in the laboratory and it was not possible to conduct additional tests. However, the concrete was allowed to set for 30 minutes, and then the air content tests were repeated by both the methods. The setting time was provided in order to allow the dissolution process to take place. Although, the air void system is expected to change after the concrete is pumped, the results shown in these tables tend to inclusive. Further work will be necessary to use this test procedure to investigate the dissolution time of the bubble based on equation 3. (The dissolution time is referred to as the time of travel of a small bubble to a larger bubble.)

Effforts were initiated to examine the air void system of concrete and the evolution of the air-void system after pressure is applied

Table 4. Air Content of Cement Concrete in the Laboratory when Pressure is Applied.

Time	CAF = 0.6				CAF = 0.7			
	Unpumped		Pumped		Unpumped		Pumped	
	R.M.	Type "B"	R.M.	Type "B"	R.M.	Type "B"	R.M.	Type "B"
Fresh	4.7%	7.2%	4.7%	--	4.0%	5.3%	--	--
After Pumping	--	6.5%	4.0%	--	5.2%	5.0%	--	--
After 30 mins	--	6.2%	3.8%	--	4.8%	5.0%	--	--
After 65 mins	--	--	--	--	3.8%	5.0%	--	--

Table 5. Air Content of Cement Concrete in the Laboratory

	Pressuremeter "B"
At the Truck	5.5%
After Pumped	4.0%
After Placement	4.3%

through the use of an advanced image processing method. The concrete was mixed in the laboratory and an attempt was made to capture the void system pictographically by using a sophisticated video camera with a microscopic lens. By following this process, the image can be used to find the change in air void system over time and due to the pressure applied, and to calculate the average size of the bubble and the bubble spacing both before and after concrete pressurization. This technique is some what limited due the reflection of the light caused on the wet surface of the fresh concrete. However, it was possible to capture bubbles after the surface of the fresh concrete has dried for approximately 20 minutes. Work will be continued to characterize the bubble distribution in the later stages hydration prior to final set.

Field Investigations

Various investigations were conducted during this phase of the study to examine, under field conditions, the process by which air loss and recovery occurs during and after pumping operations. In this phase, the focus was to test concrete pumped by equipment which was in reasonably good condition. It was recognized that the condition of the equipment may have a bearing on the measured results however, it was of interest to minimize the number of variables under consideration in the field. In each instance referred to in this section, the pumping equipment appeared to be relatively new and in good operating condition.

Field tests were conducted on a pumping job site in Bryan where a local construction company was placing a foundation slab with the normal dosage of air entraining agent. The tests were conducted in an effort to verify the problem noted in District 24. It was found that there was a certain amount of air loss during the pumping operation and most of which was regained after the placement operation as shown in Table 6. The mix used for this pumping job was a well graded mix with a coarse aggregate factor (CAF) of about 0.58.

Field tests were conducted at field test site in College Station/Bryan where the concrete was pumped without an air entraining agent for a slab. There was not much difference in the air content between the initial and discharge end of the pump, except for a loss of about a maximum of half to one percent (Table 7).

Table 6. Air Content of Cement Concrete at a Local Site in College Station with CAF-0.58.

	Volumetric Method	Pressuremeter "B"
Fresh Concrete	4.7%	7.2%
After a pressure of 350 psi Applied for 3 mins	4.0%	--
After 15 minutes	3.8%	6.5%
After 30 minutes	--	6.2%

Table 7. Air Content at a Field Test in College Station/Bryan Without an AEA

	Pressure "B"	Volume M	Slump
Before Pumping	2% 3%	2% 2%	6½" 6"
After Pumping	2% 1.8%	2% 2%	
Second Set			
Before Pumping	4.2%	4.2%	5¼"
After Pumping	4.0%	3.5%	4¾"

Tests were also conducted on a deck bridge at field test site on the Houston Ship Channel in Houston, Texas. There was a considerable amount of air loss in the cement concrete between the truck end and discharge end of the pump (Table 8). However, consideration of the effect of the boom configuration of the pump on the concrete air entrainment was limited because the boom configuration remained constant throughout the day. This was possible because the concrete was conveyed through a conveyor belt across the width of the bridge deck thus keeping the configuration the same throughout the job work. The mix design for this project is listed below:

CAF:	0.693	Cement:	366 lbs.
CF:	6.0	Fly Ash:	155 lbs.
WF:	4.3	CA:	1924 lbs.
AF:	6.0	FA:	1174 lbs.
		Water:	25.8 gal/CY

Research work is also concentrated on the different variables involved in equation 3 as discussed previously. The variables of primary interest are surface tension and the pressure loss in the pipe. Surface tension tests were conducted on various different state approved air entraining admixture in order to calculate the effect on the pressure. The rate of transmission of air from small bubbles to large is directly proportional to the surface tension at the air-water interface. Surface tension of the different state approved admixtures was determined by the capillary rise method. The results are enclosed in the Table 9.

Table 8. Air Content & Slump on a Bridge on Houston Ship Channel.

Truck No.	Slump (inches)		Air Content			30 Min. After Placement
	Before	After	Before	After		
			PM	PM	VM	
1	3"	3.5"	4%	3.2%	2.5%	
4	3"	4"	4.5%	3.2%	3.5%	
6	2"		5.5%			
7	4.5"	4"	5.5%	3.4%	3.7%	
11	5.5"		5.5%			
14	2.75"	2"	4.5%	3.2%	5%	
17	3.5"		5%			
21	2.5"	2"	4.5%	3.2%	4.5%	
24	4"		4.75%			
26	2.5"		4.25%			
29	3.5"	3"	5%	3.3%	4%	
32	4.5"	3.5"	5.4%	3.5%	6%	
37	3.5"		4.5%	2.9%	6.2%	
41	4"		4.4%	3%		3.9%

Note: PM = Pressure meter
VM = Volumetric meter

Table 9. Surface Tension of State Approved Admixtues

PRODUCER	PRODUCT	SPECIFIC GRAVITY (γ)	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 AIR 30	1.02	2.05	26.366
	SEPTAIR	1.04	2.50	36.484
SIKA-CORP	SIKA-AER	1.048	2.35	34.567

CHAPTER 4

PRELIMINARY CONCLUSIONS AND RESEARCH DIRECTION

Several activities have been undertaken to investigate the nature of air content measurements in fresh concrete. These activities have ranged from literature reviews, laboratory tests and experiments to full scale field tests and air content measurements on actual project sites. As a result of these investigations, some preliminary observations and conclusions can be made.

These observations and conclusions center on a theoretical model describing the behavior of entrained air within the fresh concrete matrix (Equation 3). This model can serve as a key to relate material properties, test results, and mix characteristics to the variations in ares around air contents.

The concrete mixes consisting of high CAF's (>0.70) are typically more difficult to pump and the loss of air content during pumping is higher as compared to the amount of air loss in mixes with low CAF's (~0.62). It has been observed that more pressure is required to pump mixes with the higher CAF's in which the increased pressure on the concrete may increase the number of smaller bubbles which move into large bubbles (in comparison to unpumped concrete), thus causing a considerable change in the measured air content.

It is expected that the type of aggregate plays an important role in the loss of air with the amount of aggregate affecting the friction characteristics of the mix. More study is required on the types of aggregates and their role in the pumping of concrete. A method is being considered to relate the aggregate shape and surface texture to the friction characteristics of the mix. This characterization is based upon fractal dimension concepts.

Field experiments have indicated that a greater percentage of air is lost when an air entraining agent is used than when no air entraining agent was used in the concrete mix. This can be attributed to the change in the air void system caused in the fresh concrete due to the use of an air entraining agent. The type of air entraining agent may also affect the air void system. Consequently, the effort is being focused on the effect of different Tex DOT approved admixtures with respect to the surface tension at the air-water interface. The surface tension of the agent serves to hold the bubble in position and to prevent the transfer of air pressure from one bubble to another bubble limiting the collapse of the bubbles and thus the variation of the air void distribution.

More study is required to examine the bubble distribution of fresh concrete which may be possible by use of a new device known as the Air Voids Analyzer. This equipment is available, although somewhat costly, from Dr. Carolyn M. Hansson at Queens University, Kingston, Ontario, Canada. The determination of air content and bubble distribution of hardened concrete is done by means of Linear Traverse Method.

Research Direction

Future efforts will be concentrated on the affects of types of aggregate on the air void system and pumping of the concrete. Budget constraints may limit the number of aggregates which can actually be tested. Fractal dimension measurements are expected to play a very useful role in this process.

Concrete mix proportioning is also an important part of our study. The study will consider recent technology to modify present mix design procedures by use of an intermediate filler material and by changing the percentage of coarse aggregate, which relates to the effect of CAF.

For the measurement of head loss in the pump pipeline, short segments of pipe have been instrument to measure head loss. The segments consist of two pipes to fit both 5 inch ID and 4 inch ID cast iron pipe. Head loss is measured by two pressure transducers which are powered by a 10 volt source. The difference in the pressure is directly related to the difference in the voltage measured by a voltmeter. The difference in the voltage is directly proportional to the difference in the pressure. However, due to the rapid amount of pressure changes during pumping operation, a Bascom Turner Data Acquisition System was integrated into the testing system. A test program, described later, is being developed using a portable concrete pump to investigate the effect of boom configurations, pump pressure, and type of admixture.

Efforts are also underway to examine further the amount of air in hardened samples taken from the test bridge at El Paso, Texas. They are being rechecked by the Linear Traverse Method to examine a possible correlation between the boom configuration and the final amount of air. Cores have been collected from the test bridge at El Paso, Texas. Cores have also been collected from a project in La Porte, Texas, where field experiments were conducted to measure the air content when the concrete was pumped 140 feet vertically to the bridge deck. The air content of the hardened concrete will be correlated with the air content of the fresh concrete at different times.

Experimental Procedure for Pumping Tests

As referred to previously, experimental work is underway to determine the affect of various factors effecting air entrainment in cement concrete. Experiments will be conducted on 13 mix and pumping conditions selected to formulate a fractional factorial design (FFD). Factorals are selected on the basis of factors involved in the study, such as CAF, mix characterization, admixture, boom angle, and the pipe diameter. The concrete mix and pumping conditions factorals are designed for two extremes of the range associated with the above mentioned factors. The proposed mix designs to be tested will consist of high and low CAF (0.63 being the separating point), with and with out intermediate aggregates (for mix characterization), and admixtures with high and low surface tension characteristics. The range in pipe diameter to be included is from 4 to 5 inches while the range in boom configuration is from an acute angle to the boom being as horizontal as possible. In each boom configuration, the concrete will be allowed to free fall through the flexible hose at the end of the boom. Prior to pumping the concrete characteristics such as size of the pump, maximum pressure that can be exerted by the pump on the cement concrete, the boom length, and the pipe diameter are noted. Figure 27 illustrates the test program to be followed. Tests for slump and air content will be conducted before the concrete is pumped. The non-pumped concrete is also allowed to set for 30 minutes in order to check the effect of the dissolution process without the application of pump pressure. It is anticipated that only

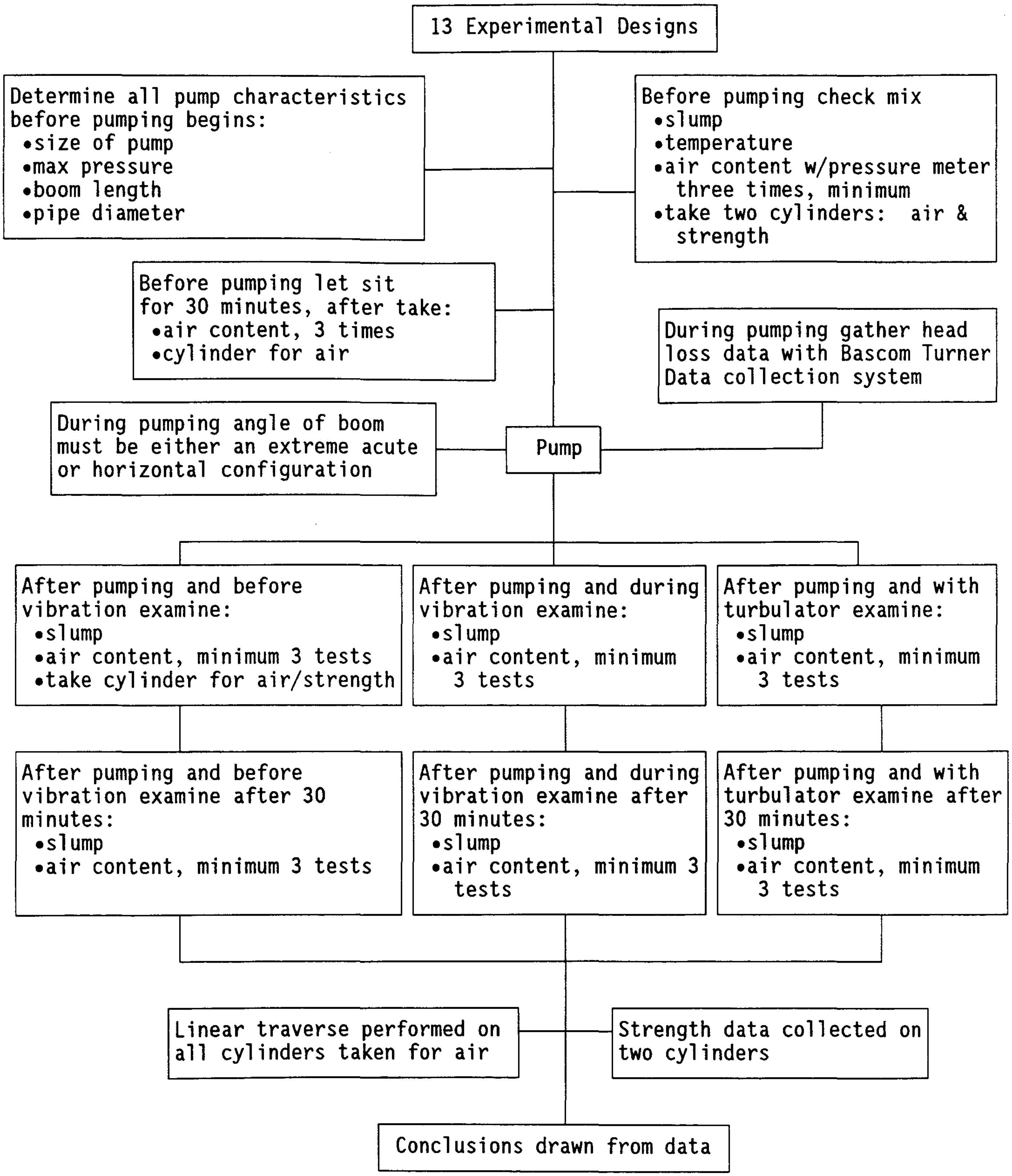


Figure 27. Experimental Procedure for Pumping Tests.

one type of pumping equipment will be tested in this factorial.

Slump and air tests will be conducted immediately after the concrete is pumped. Air tests are also scheduled after the placement operations are simulated by means of vibrating the concrete sample. Air content tests are also to be conducted for the concrete pumped by using a turbulator. The air content tests are repeated after 30 minutes of settlement for all of the above tests. At least two air content readings will be taken at every step inorder to minimize the error due to the readings.

Laboratory Investigations:

Tests will be continued in the laboratory for different CAF's to calculate its affect on the air void system and the role CAF may play in the dissolution process. Type of aggregate will also be related to head loss incurred during the pumping process (based on the pumping tests described above). These results will be contrasted with field tests conducted with different aggregates in order to study the affect on the air content of the concrete when placed by pumping. This will then be compared with the air content of cement concrete when no pressure is applied on it.

The field tests will also include the above factors to develop improved mixes with the possibility of using lower coarse aggregate factors in design.

Tests will also be conducted for the various boom angles of the pump, such as for free fall and when negative pressure is developed. This tests will be helpful in determining the determination of effect of the angle on the pumping and the loss of air. It may be possible to relate this to mix characteristics and the design CAF.

Investigation of different air entraining agents will be conducted depending on the basis of surface tension at the air-water interface to study the effect of different air entraining agents on the air void system of cement concrete. By this process it may also be possible to account for interaction affects caused by other admixtures used in the concrete.

We anticipate analyzing these effects (using image processing) while the concrete is in the fresh state and while the air void system evolutes to its final condition.

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