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DETERMINATION OF AIR CONTENT
OF HARDENED CONCRETE
USING IMAGE ANALYSIS

A THESIS

Submitted to the Faculty of Graduate Studies
through the Department of Civil Engineering
in Partial Fulfillment of the Requirements for the
Degree of Master of Applied Science
at the University of Windsor

By

Leo P. H. Meyer
B.A. Sc., University of Windsor, 1978

Windsor, Ontario, Canada
1983

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ABSTRACT

It was the intent of this work to develop a "hands off" procedure for utilizing image analysis equipment to determine total air content and other air void parameters in a hardened concrete sample.

Lemont Scientific Image Analysis equipment was used and an appropriate procedure was developed. Samples required 30 minutes of actual preparation with an overnight drying in a desiccating oven to allow masking. The actual analysis took 10 minutes.

Three batches of concrete of approximately 3.0%, 6.0% and 9.0% air content by volume were prepared. Air content for each batch was evaluated using the pressure test and hardened concrete samples from each batch were used for a standard Rosiwal linear traverse and the image analysis evaluation.

The results of the three test methods were comparable. The degree of reproducibility of the Image Analysis procedure (approximately ± .5% with 95% confidence for typical air contents) was similar to results of researchers using either standard linear traverse or image analysis procedures.

DEDICATED TO MY WIFE

DEBORAH

FOR HER CONSTANT

SUPPORT AND ENCOURAGEMENT

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

Since concrete is a very important building material, much work has been carried out to both understand and improve its properties. Naturally, durability is a large factor in the acceptability of concrete as an externally used material. When it was noticed in the late 1930's(1) that some concrete roadways gave good service while other comparable concrete roadways in the same area were subject to extensive spalling due to frost damage, an effort was made to find out why some concrete was seemingly protected and to learn how to achieve this protection in all external concrete. It was eventually recognized(44) that the grinding aid used in the manufacture of the cement was responsible for the entrainment of small air bubbles in the concrete which in turn was the reason for the protection against spalling. There is still not full agreement as to how the protection mechanisms actually work, but it is generally accepted that an entrained air content of 9% in the mortar portion of concrete will protect against frost damage in most cases.

Many procedures to determine the air content of concrete have been formulated. The methods used for air content measurement of fresh concrete only yield information as to total air content, which, while adequate for field quality inspection, does not provide a complete picture. The size and spacing of the air voids are also important parameters to know and these can currently only be established by microscopic examination of the hardened concrete. The procedures which have been developed such as linear traverse and modified point count are characterized by high cost, tedious work and inaccuracies due to human error.

The relatively new technology of image analysis makes it possible to replace the human operator in a conventional linear traverse by changing the sample preparation somewhat. It is the intent of this study to develop a "hands off" air void analysis procedure for hardened concrete analysis using image analysis and to demonstrate that this new procedure can provide air void information with at least the same reliability as standard linear traverse with a savings in time and manpower.

CHAPTER 2

AIR ENTRAINMENT OF CONCRETE

2.A General

Air entrained concrete is simply concrete in which air has been incorporated in the form of numerous discrete air bubbles, usually ranging in size between 10 and 1000 microns in diameter.(25) This entrained air is in addition to entrapped air which is usually present in all concrete. Entrapped air voids are usually larger in diameter and irregular in shape due to their having been moulded against adjacent particles. Usually, these entrapped air voids are caused by bubbles that were in the process of escaping from the concrete when initial set of the concrete began. Together, entrapped air and entrained air comprise the total air content of the concrete. Some authorities report that due to the rapid rate at which air voids of small size dissolve in the mixing water before hardening of the cement paste, air voids less than 7 microns in diameter are essentially non-existent.(26) However, recent work(21) indicates that air voids of 0.1 micron and larger are present and may be responsible for a large part of the resistance of air entrained concrete resistance to frost damage.

Air entrainment was discovered in 1938 when it was noted that concretes made from cements produced with resin and tallow grinding aids were more durable. It was found that these grinding aids produced foaming compounds during the concrete mixing process,(31) which resulted in a system of small stable air bubbles. The air bubbles protected the concrete against frost damage but to date, there is not full agreement as to the important mechanisms involved. Various theories are discussed in Section 2.C.

The first intentionally air entrained concrete was placed in a test section of a highway in the State of New York in 1938. Thereafter, complete highway projects were built with air entrained concrete and the durability carefully monitored in the following years. One study(1) showed that ten to fourteen years after construction, in fourteen separate projects located in the northwestern United States, there was no scaling or D-cracking on any sections using air-entrained portland cement. With such good results the use of air entrainment in exterior concrete surfaces spread rapidly.

Many kinds of air entraining agents have been formulated. The main types are shown in Table 2.B1. While they work in various manners they all rapidly produce a system of fine and stable foam. The air bubbles that make up the foam resist coalescence and the foam does not have any harmful chemical effect on the concrete.

A	animal and vegetable fats and oils and their fatty acids (beef tallow being an example of this group)
B	natural wood resins, which react with lime in the cement to form a soluble resinate. The resin may be pre-neutralized with NaOH so that a water-soluble soap of a resin acid is obtained (e.g. Vinsol resin)
C	wetting agents such as alkali salts of sulphated and suphonated organic compounds (e.g. Darex)

TABLE 2.A1 THREE MAJOR CLASSES OF AIR ENTRAINING AGENTS

2.B Effects of Air Entrainment on Concrete

The most important and best known effect of air entrainment in concrete is the increased frost resistance it renders.(8) However, there are additional benefits that in some cases are even more important. The increased workability is of prime importance in mass concrete, as the lowered water/cement ratio results in less shrinkage.(29) Air entraining agents also render less entrapped air and less bleeding of the finished concrete. (See Figure 2.B1 for effect of air entrainment on durability)

There is a theoretical disadvantage to air entrainment in that due to the added porosity of the concrete, for a given water/cement ratio, the strength decreases approximately 5.5%(29) for every 1% of air entrained. However with the increased workability of the air entrained concrete, the water/cement ratio can be decreased to maintain slump, thereby increasing strength. For a lean mix, this addition in strength compensates for the loss due to porosity completely, and in some cases, a net increase in strength may be realized. For rich mixes there may not be such a large strength increase since workability is not as greatly improved by air entrainment. However, strength loss will be much less than 5.5% per 1% air entrainment.

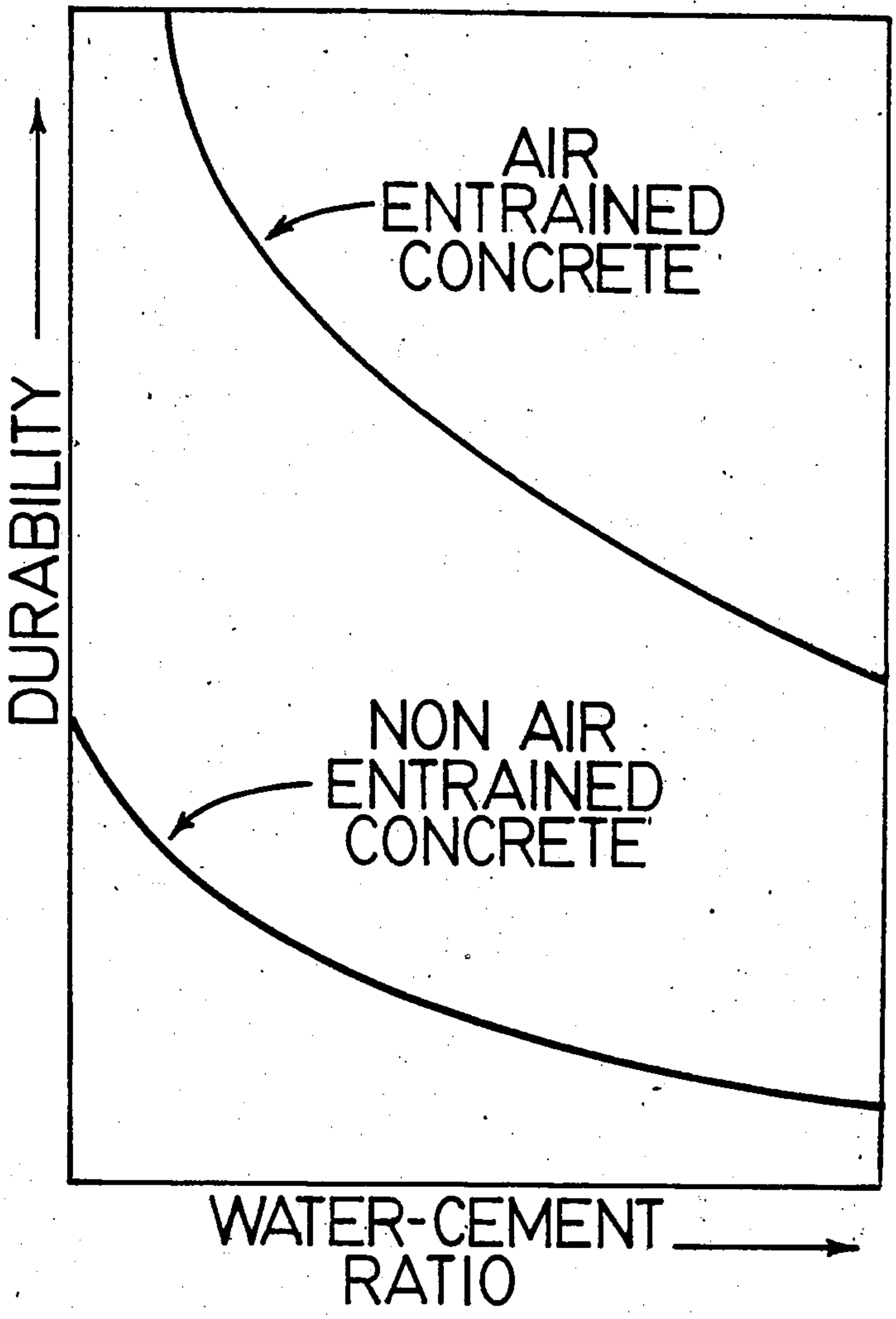


FIGURE 2.B1 WATER CEMENT RATIO VS. DURABILITY - COMPARISON OF NON AIR ENTRAINED AND AIR ENTRAINED CONCRETE (FROM POWERS (30))

2.C Theoretical Considerations

While it is generally accepted that entraining air into concrete increases frost resistance, it is not universally agreed upon as to by which mechanism this protection occurs.(45)

One popular theory put forward by T.C. Powers in his early papers,(34) postulates that during freezing, water, in voids even smaller than those caused by air entrainment, is able to migrate a small distance through the cement paste to an air void and thus relieve the hydraulic pressure due to the freezing of water in the capillary voids, that, were there no air voids, would build up until frost damage occurred. While some still hold this theory, Powers himself now discards it.

Powers and Helmuth in later research,(35) found that water moves towards, not away, from freezing sites during the freezing of cement paste. With this in mind, they developed a hypothesis involving osmotic pressure. The water in cement paste is a weak alkali solution. As freezing occurs in the cement paste, ice crystals form in the larger capillaries, thereby increasing the alkali content of the unfrozen water. The success of the air bubbles in this competition depends on the distance the nearest air bubble is to the unfrozen water.

Litvan, a noted concrete researcher, presented another theory as to the mechanism of frost action in concrete.(22) He felt that the water absorbed on the surface and contained in the pores, in instances where it cannot freeze, becomes supercooled during the freezing of the cement paste. This supercooled liquid would have a greater vapour pressure than the bulk ice in the regions where the water could freeze; therefore, there would be a migration of the supercooled liquid to the regions where it could also freeze. Damage occurs where this migration is restrained by too much water, lack of time available or lack of entrained air bubbles resulting in a long migration path. In situ freezing (semi-amorphous solid) results in great stresses.

It is to be noted that while these theories differ in some respect, each bases the protection of air entrainment in terms of shortening the flow paths of water through the concrete paste. Hence, the benefits of air entrainment do not derive directly from total air content of concrete, but rather from the size and spacing of the air bubbles in the system. Each void can protect a small volume around it. (See Figure 2.C1) Theoretically, this limit is the distance the water can migrate through the cement paste during freezing. For concrete to be fully protected, those areas enclosed by a dotted line should overlap. Powers derived a parameter, "spacing factor ($\bar{L}$)" which is based on the average distance any point in the cement paste is from the nearest air void. Generally, every point should be no more than 75 microns from an air void.

Durability is related to the spacing of the air bubbles in the concrete. (See Figure 2.C2). For a given air content,

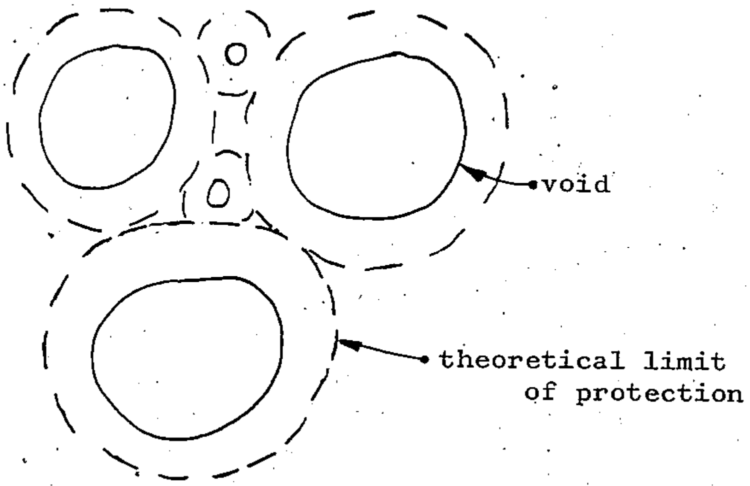

void
theoretical limit
of protection

FIGURE 2.C1 SPACING FACTOR

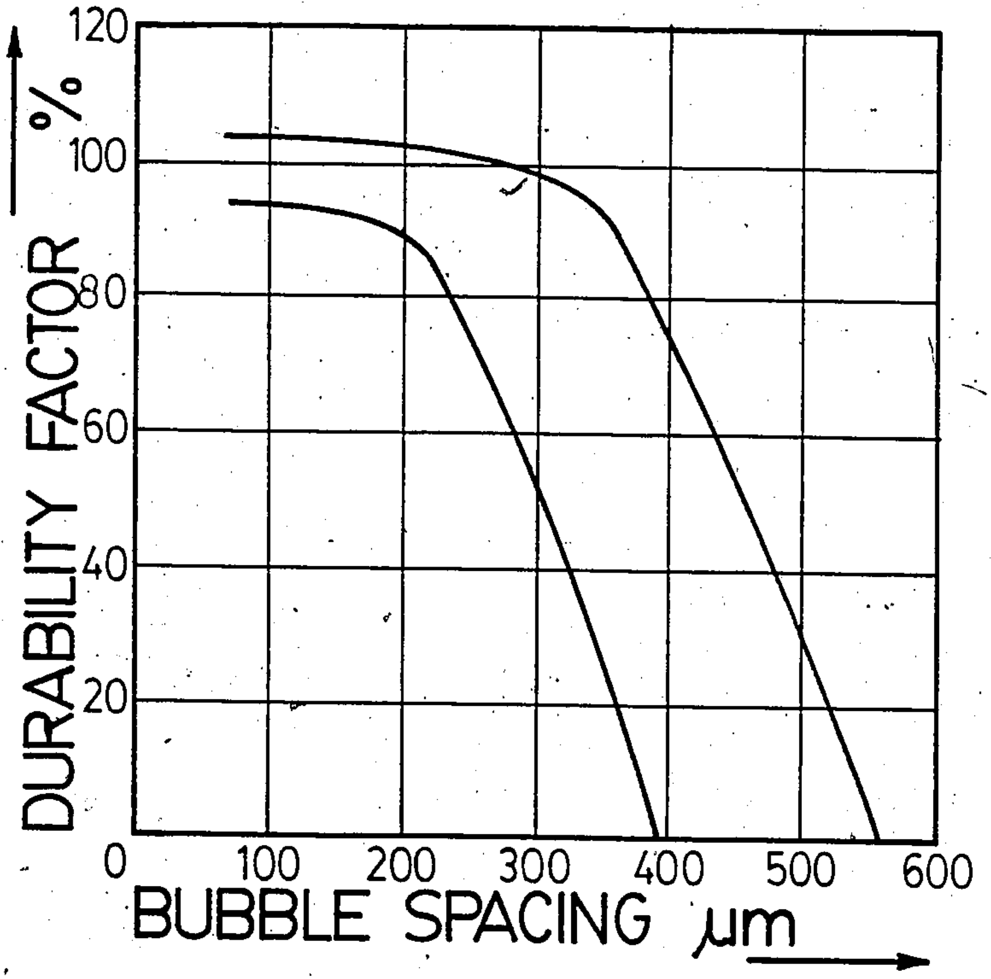


FIGURE 2.C2 BUBBLE SPACING VS. DURABILITY FOR GIVEN AIR CONTENT (FROM POWERS (30))

durability increases as the spacing of the air bubbles decreases.

However, Mielenz(27) was not able to find a general correlation between durability and spacing which was calculated based on measurement of voids 10 microns in diameter or greater. Each air entraining agent produced a different relationship between the two parameters. Litvan's(22) hypothesis was that durability is related directly to air voids with diameters in the 0.1 to 2 micron range, which are not measured in any air void parameter evaluation of hardened concrete. Since different air entraining agents cause different relationships between the amount and size distribution of pores with diameters in the 0.1 to 2 micron range and amount and size distribution of pores with diameters in the 10 to 1,000 micron range, the indirect relationship between durability and spacing based on voids with diameters in the 10 to 1,000 micron range would be different for each air entraining agent.

Another parameter of spacing and size of air bubbles is "specific surface" ($\propto$), which is simply the ratio of total surface of air bubbles to the volume of concrete in which the air bubbles are located. (Common units are square millimeters per cubic millimeter and square inches per cubic inch.)

CHAPTER 3

MEASUREMENT OF AIR CONTENT OF CONCRETE

3.A General

Shortly after the beneficial effects of air content in concrete were discovered, it became apparent that the degree of benefit varied with the percentage of air present in the concrete. It was also realized that the quantity of air entrained was due to many different influences so that air entraining cements could not be relied on to give consistent air contents based simply on amounts used. Therefore, it became necessary to somehow test the concrete for air content to ensure that sufficient, but not too large an amount of air was present.

J.C. Pearson(52) did much early work in developing a test for air content by which the volume of air is measured directly by removing it from the concrete. This work formed the basis on which the A.S.T.M. issued their "Tentative Method of Test for Air Content (Volumetric) of Freshly Mixed Concrete (C173-42T)" in 1942.(49) In 1944, the A.S.T.M. adapted the "Standard Method of Test for Yield of Concrete (C138-39)" to calculate the air content of concrete and retitled it as "Standard Method of Test for Weight per Cubic Foot, Yield and Air Content (Gravimetric) of Concrete (C138-44)".(48)

While these two tests became standards, researchers were continually looking for ways to make testing for air content more exact and more convenient. The Indiana Method,(28) the Rolling Method and the modified Rolling Method(24) are all variations of the Volumetric test procedure. The Chace "vest pocket" air content tester is a variation of the Volumetric test procedure which measures the air content of a thimbleful of mortar and while it only yields a rough estimate of the air content of concrete, it is very convenient.

An indirect method of measuring the volume of air in a concrete sample by the change in volume when a known pressure is applied was first proposed by W.H. Klein and developed by Klein and Stanton Walker.(16)

All of the above tests are performed in conjunction with fresh concrete samples. While the amount of air present in fresh concrete is generally very close to what is found in the same concrete after placing and hardening, this is not always true. It is possible, for example, to over vibrate the concrete to the extent that a significant amount of the entrained air is lost. Therefore, it is desirable to test for air content in hardened concrete samples. In a test based on the same principle as the Pressure Test, a hardened concrete sample is immersed in water at atmospheric pressure so as to be brought to an equilibrium moisture content, then placed in water in a high pressure air meter and subjected to approximately 5000 psi. The quantity of water forced into the specimen under the applied pressure is measured and Boyle's Law is applied to estimate the original air content. This test was originally proposed by Lindsay,(19) and was described in detail by R.P. Vellines and T. Ason.(42)

The High Pressure Air Meter like fresh concrete test procedures yields only total air content of concrete, the sum of the entrapped air and entrained air. As discussed in Chapter 2, the durability of concrete is related to the air bubble size and spacing. Durability is being related empirically to total air content on the basis of past experience with the air entraining agent used and the assumption that for a given total air content, the amount of entrapped air and the size distribution of the entrapped air bubbles will be the same for each mix. However, this assumption is not always valid as there are many factors affecting air bubble size and spacing such as air-entraining agent, organic contamination, handling and placing of the concrete, mixer efficiency and aggregate proportioning. Therefore, two mixes of similar total air content might have very different bubble size and spacing characteristics and therefore, a very different durability. A test that directly yields void data such as air bubble size and spacing would give the most reliable indication of durability.

Air void data can be obtained from a microscopic analysis of a finely ground plane concrete surface. The first work in this area was done by G.J. Verbeck(41) who applied a procedure used by W.J. Sollas(40) in 1889 to determine the composition of granites. Verbeck prepared plane concrete samples using polishing techniques similar to those used in petrographic evaluations. With a camera lucida attachment on a microscope, he was able to draw and, using a planimeter, to measure air voids and aggregate in a specified area on each sample. With that information and by counting the number of air voids in the specified area, the air content, the average void area and void concentration can be calculated for the observed area.

A technique presented in 1898 by A. Rosiwal(39) for determining the mineral composition of rocks was adapted to measuring air voids in concrete. Rosiwal showed that the ratio of the volume of a constituent of a solid to the volume of the solid is the same as the ratio of the sum of the chord intercepts of the constituent, measured along a random line through the solid, to a total length of the random line. Rexford(37) used the "Rosiwal" traverse on a Wentworth Intergrator which allowed about a 1"x 1" specimen to measure the percentage of air in the cement paste and to calculate the percentage of air in the concrete. L.S Brown and C.U. Pierson(3) built an apparatus to allow a large scale linear traverse, for example, a 6"x10" plane surface sample, and to measure the air content of the concrete sample directly. Specific surface can be calculated from the traverse results. Power's spacing factor (L) can also be calculated if the paste content of the sample is known. F. Chayes(6,7) described a procedure similar to that of a linear traverse where the sample surface is sampled at equidistant points along a random line and it is noted what constituent of the solid is encountered at each point. Applying this method to determining air content of a concrete surface, it can be shown that the ratio of points that occur over an air void to the total number of points will be the same as the ratio of total chord intercepts to total traverse, that is the result of the linear traverse method.

The popularity of the Rosiwal or Linear Traverse is due mainly to the lack of better methods. The procedure is time consuming, tedious and results have been shown to differ significantly from operator to operator for a given sample.(2,25a) Since many of the drawbacks relate in fact to the necessity of a human operator, the possibility of replacing the operator with a computer employing image analysis would make the new procedure very attractive. Preliminary work in this area was done by S. Chatterji and H. Gudmundsson.(5) They demonstrated good correlation between concrete air content evaluated by accepted methods and that by image analysis. However, the method was still somewhat manual as an operator was required to focus and adjust image analysis equipment as the sample was analyzed.

It is the purpose of this study to further automate the image analysis procedure to, in effect, make the analysis of the sample a "hands off procedure".

The details of the most widely accepted methods of determining air content of concrete are presented in the following sections because the quality of the results obtained with this new image analysis method will be compared with those found by researchers using some of the present standard methods.

Mercury intrusion porosimetry is a relatively new technique of evaluating hardened mortar specimens for air void size distributions. G.G. Litvan(21) found evidence, using the procedure, that air voids with diameters ranging from 0.3 to 2 microns play an important role in improved frost damage resistance. He suggests a test based on measurement of the air void content in the 0.3 to 2 micron pore diameter range could be developed and used to assess frost damage resistance. An appropriate sampling procedure would have to be devised to assure representativeness in concrete.

3.B Gravimetric Methods

The gravimetric method is outlined in A.S.T.M. standard test method C138-81.(48) This method was first proposed as a tentative procedure in 1938. However, it was not until 1944 that the measurement of air content was formally recognized as being possible using the gravimetric procedure.

To determine air content, the sum of the absolute volumes of the ingredients in a known volume of concrete is calculated and subtracted from the known volume.

The procedure requires a balance accurate to within 0.3% of the test load at any point within the range of use, generally sensitive to about 0.01 pound, a tamping rod, a strike off plate, an internal vibrator and a measure which is a cylindrical container of minimum capacity of 0.2 cubic feet for an aggregate size of one inch.

Briefly, the container is filled with concrete, in three layers rodded twenty-five times each for measures smaller than 0.4 cubic feet, a slump greater than three inches or in two layers each in three locations for slumps less than three inches. Care is taken to release all entrapped air and in the case of vibration, to not overvibrate, potentially losing entrained air. The container is then struck off so as to make it level and obtain a smooth finished surface. The container is then weighed ensuring the exterior is clear of excess concrete.

The air content is calculated as

$$A=[(T-W)/T]x100$$

OR

$$A=[(Y-V)/Y]x100$$

where:

A = air content (percentage of voids) in the concrete

T = theoretical weight of concrete computed as an airfree basis (lb/ft3)

W = unit weight of concrete (lb/ft3)

V = total absolute volume of the component ingredients in the batch (ft3)

The theoretical weight per cubic foot is usually determined in the laboratory and assumed to be the same for all batches of identical components and proportions. It is calculated by

$$T=W_1/V$$

where:

W_1 = total weight of all materials batched

The absolute volume of each ingredient in cubic feet is equal to the quotient of the weight of that ingredient divided by the product of its specific gravity times 62.4. For aggregate components, the bulk specific gravity and weight are based on the saturated surface dry condition. The specific gravity of cement is determined by A.S.T.M. method. Accuracy depends primarily on accurate determination of specific gravities of the materials and mix proportions, and especially the water-cement ratio.

The advantages of this method are that the equipment is simple and inexpensive, the measurements required are also required for batch purposes in any case, and the calculations are simple.

There are several disadvantages. The small variations in the specific gravity of aggregates can result in large errors in the computed air content. The moisture content of aggregate needs to be determined for each test. It is not possible to test ready mixed concrete. The early shrinkage of cement-water mixture introduces undetermined error. It is necessary for the volume to be exact (for the 0.5ft^3 container the volume should be known to within 0.001 cubic feet where the measure of unit weight is reproducible to 0.3 pounds per cubic foot for ± accuracy of 0.2%) and therefore, strike off will often introduce an unacceptable error; the required scale (sensitive to about 0.01 pounds) is difficult to transport and maintain in the field.

3.C Volumetric Method

The A.S.T.M. originally published the "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method" in 1942 as C173-42.(49) The method resulted primarily from the work of J.C. Pearson(52). In his original method, a cylindrical pycnometer with the approximate size of four litres was filled with a concrete of known unit weight and weighed. The volume of the sample was then calculated and by subtraction, the volume of water required to fill the pycnometer was arrived at. A portion of this water was added and the pycnometer was agitated in order to free the air held in the concrete. A larger volume of water was necessary to fill the pycnometer than was first calculated due to a loss of air and the additional volume necessary was the volume of air entrained in the concrete. The original method proved too cumbersome because of the accurate weighings involved and the test was modified to become a direct volumetric procedure and this is the standard today.

The apparatus for the test consists of a bottom bowl of about 0.1 cubic foot capacity and a top section of volume at least 1.2 times that of the base, equipped with a flexible gasket and an attachment method to allow top and bottom sections to be joined with a watertight seal. The top must have a transparent neck graduated in increments of 0.5% or less from 0% at the top to 9% or more, of the volume at the bowl. (See Figure 3.C1) The upper end of the neck has a threaded cap with a gasket to allow

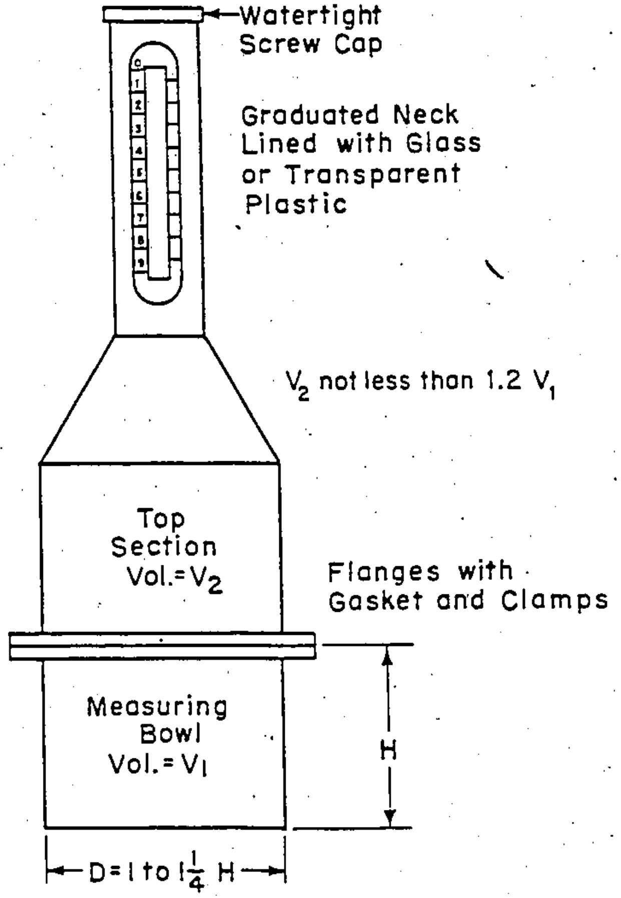

Watertight Screw Cap
Graduated Neck Lined with Glass or Transparent Plastic
0
1
2
3
4
5
6
7
8
9
V_2 not less than 1.2 V_1
Top Section Vol.= V_2
Flanges with Gasket and Clamps
Measuring Bowl Vol.= V_1
H
D = 1 to $1\frac{1}{4}$ H

Figure 3.C.1 APPARATUS FOR MEASURING AIR CONTENT OF FRESH CONCRETE BY VOLUMETRIC METHOD (FROM ASTM C-173-78 (49))

a watertight seal. Also required for the method is a funnel of shape such that it can be inserted in the neck with the spout just above the concrete level in the bottom bowl so that water can be added without disturbing the concrete, a tamping rod, a strike off bar, a measuring cup of capacity 1.03 ± 0.4% of the volume of the bottom bowl, a syringe of capacity or larger than the measuring cup, and a supply of isopropyl alcohol (7% by volume).

The method basically involves filling the bottom bowl with concrete in three layers, each rolled twenty-five times and striking off the excess. The top section is then added to the bottom ensuring a water tight seal. Using the funnel sufficient water is added to the apparatus. Care should be taken not to disturb the concrete until the top section is almost filled. The funnel is removed and a small amount of water is added to bring the level of water in the transparent neck up to the zero mark. The watertight cap is then screwed on and the entire apparatus is agitated, rolling and rocking it to mix the water into the concrete and free the entrained air. Then the apparatus is set upright and the level of water in the neck is noted. This is repeated until further agitation does not result in a drop of the water level in the neck. The cap is then removed and sufficient isopropyl alcohol, in one cup increments, is added to dissipate the foam on the surface of the water. The fluid level in the neck is then read directly.

The air content of the concrete is calculated as the value read on the graduated transparent neck plus the amount of isopropyl alcohol added, since each cup of isopropyl alcohol was 1.03 ± .04% of the original concrete volume and after mixing the water and isopropyl alcohol, each cupful will displace 1% of the volume.

The precision of this method is not yet officially established by the A.S.T.M. It has been reported that reproducibility depends mainly on the degree of reproducibility of concrete in the container.

Advantages of the method are that the equipment is simple and inexpensive and that the method is independent of variations in property and proportions of the ingredients in the concrete.

Disadvantages of the method are that the method requires substantial time to complete and uncertainty exists as to how completely air removal can be achieved.

3.D Pressure Method

The pressure method, designated C231-81,(50) by the A.S.T.M. is a practical simple application of Boyle's Law. Where temperature is constant, the product of pressure on a gas and its volume is constant. By taking a known quantity of concrete and subjecting it to a known pressure, the air content, which is the only compressible component, will decrease in volume. The amount the volume decreases is directly related to the total air content.

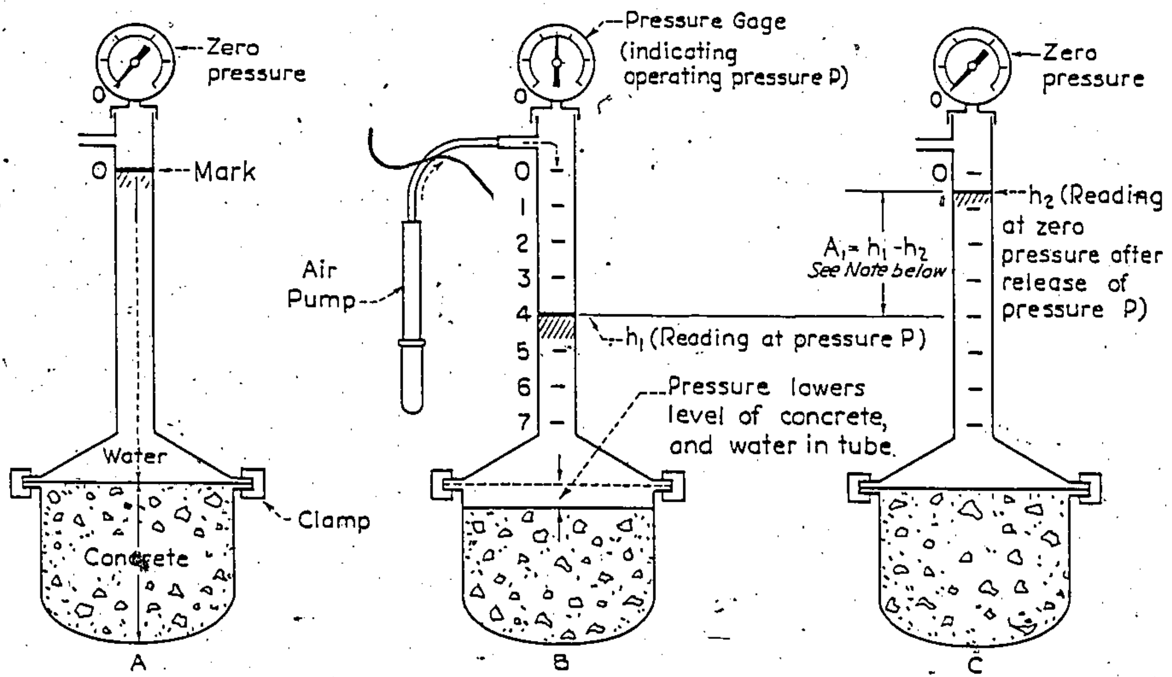
There are two main types of air meters utilizing this relationship to determine air content. A.S.T.M. designates these as type A and type B. Both types use a cylindrical measuring bowl having a capacity of at least 0.2ft3 with a flange provided to allow a pressure tight connection to the cover. The cover is contoured to provide an air space above the surface of the concrete when placed in the measuring bowl. Both measuring bowl and covering assembly have to be sufficiently rigid to limit expansion of internal volume under pressure to 0.1% of the air content as shown on the calibrated scale.

In a type A meter, (See Figure 3.D1) the top is fitted with a transparent neck with a pressure input and meter at the top so that the water can be placed to a given height above the concrete sample and a known pressure applied above the water. The volume of air in the concrete decreases with a comparable drop of the water level in the transparent neck which is calibrated to show air content of the given concrete volume.

A type B meter, (See Figure 3.D2) measures air by allowing a known volume of air at a known pressure in the sealed air chamber to be cross connected with a given known volume of concrete to be tested. A pressure gauge measures the pressure drop due to the pressurization of any air existing in the concrete. The more air in the concrete, the greater the pressure drop will be and therefore the pressure gauge can be calibrated in terms of the air content of the concrete sample.

For both types of meters, the placement of the concrete is the same. The measuring bowl is filled with three layers, each rodded twenty-five times or optionally where concrete slump is not over three inches, in two layers, each vibrated by three insertions of a vibrator spaced over the cross section. The measuring bowl is struck off flat and the cover is wetted and attached ensuring a clean pressure tight seal between the cover and the bowl. Water is added to fill the concave space between the cover and the struck off concrete up to the mark near the top of the neck in an A type meter. The measuring bowl is then tapped to release any air bubbles entrapped above the concrete sample. For type B meters, the given pressure and air volume is applied and the air content is read directly. For an A type meter, the given pressure is applied, the value of the water level noted and the pressure released back to atmospheric and the value of the water level noted against. The air content is the difference between these two values.

This method has the advantage of utilizing very durable equipment which is well suited to the field environment. The test is easy to perform, requiring minimal operator training. Calibration of the equipment is easy, quick and inexpensive requiring only water in addition to the equipment. A disadvantage to the procedure is that it measures the air content of the fresh concrete rather than the finished hardened concrete. While there is usually good correlation between the air contents of the two, there can be discrepancies due to such things as overvibration of the concrete which greatly reduces air content. A.S.T.M. has not yet officially established the precision of this method.


Zero pressure
0
O
Mark
Water
Concrete
Clamp
A
Pressure Gage (indicating operating pressure P)
Air Pump
0
1
2
3
4
5
6
7
h_1 (Reading at pressure P)
Pressure lowers level of concrete, and water in tube.
B
Zero pressure
$A_1 = h_1 - h_2$
See Note below
h_2 (Reading at zero pressure after release of pressure P)
C

Note: $A_1 = h_1 - h_2$ when bowl contains concrete as shown in this figure; when bowl contains only aggregate and water, $h_1 - h_2 = G$ (aggregate correction factor). $A_1 - G = A$ (entrained air content of concrete)

FIGURE 3.D1 TYPE A PRESSURE METER (FROM ASTM C231-78 (50))

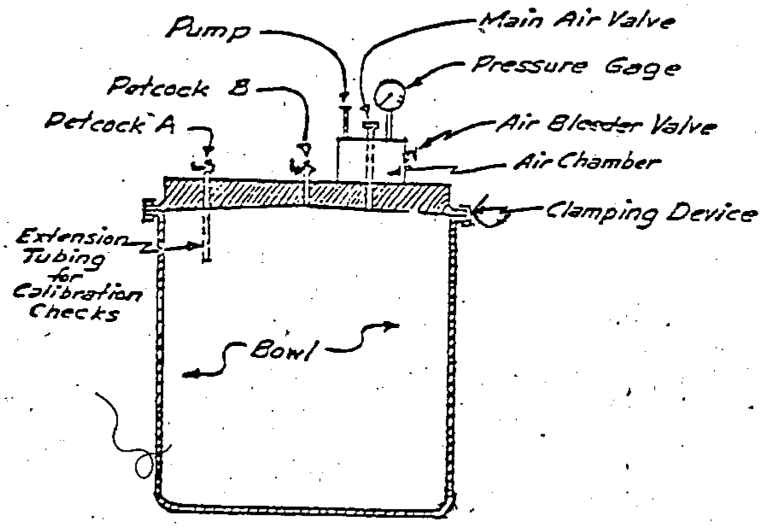

Pump
Main Air Valve
Pressure Gage
Petcock B
Petcock A
Air ~~Bleeder~~ Valve
Air Chamber
Clamping Device
Extension Tubing for Calibration Checks
Bowl

FIGURE 3.D2 TYPE B PRESSURE METER (FROM ASTM C231-78 (50))

3.E Linear Traverse (Rosiwal) Method

This procedure designated A.S.T.M. C457-80(51), "Standard Practice for Microscopical Determination of Air Void Content and Parameters of the Air Void System in Hardened Concrete" was originally published in 1960. There are two methods described in the procedure, the linear traverse or Rosiwal method (based on work done by L.S. Brown and C.V. Pierson(3) and the Modified Point Count method (based on work by F. Chayes)(6). The linear traverse method is the more popular of the two and will be briefly detailed in this section.

The procedure requires the hardened concrete sample to have a surface prepared using standard petrographic procedures. The minimum area of finished surface required for a given aggregate size is given in Table 3.E1. The plane of the surface should be perpendicular to the layers in which the concrete was placed.

The apparatus required for the linear traverse must have a stage which moves in two perpendicular directions under a binocular microscope of at least 40x magnification (provided with a crosshair). The binocular microscope allows the operator to perceive depth, differentiating the voids from the plane surface they lie in. There should be two mechanisms for moving the stage in one direction, with a separate measurement of distance moved for each mechanism. A means for measurement of distance moved in the perpendicular direction must also be provided. Measurement of these distances should be accurate to at least three microns.

The distance of travel in both directions should be sufficient to allow the required area to be traversed. A counter for tallying the number of voids intersected should be provided.

The prepared hardened concrete sample is placed with the plane polished surface up on the stage of the linear traverse apparatus. The prepared surface of the sample is made plane to the surface of the stage (using a level and four pieces of modelling clay under the four corners of the sample). A light source is placed so that the beam of light strikes the sample surface at a very low angle so as to shadow the leading edges of the air void (to aid in identification). Beginning in the upper right hand corner of the sample, the microscope is focused on the sample surface with the crosshair clearly visible. All counters are set to zero. The stage is moved slowly past the microscope, the first counter measuring the distance being traversed. When the crosshair reaches the edge of an air void, the tally counter is advanced one to start the count of the number of air voids traversed; the other mechanism of moving the stage is employed until the crosshair reaches the far edge of the air void, the second counter measuring the distance traversed across the air void (or chord length). At that point, the stage is again moved by the first mechanism until the next air void is encountered. Therefore, the first counter measures the total distance of non-air void traversed, the second counter measures the total distance of air void traversed (or the sum of all chords across the air voids) and the tally counter measures the total number of air voids intercepted.

The traverse continues until the far edge of the prepared surface is encountered. The first traverse length is calculated (first counter plus second counter) and the number of traverses across the samples is calculated by dividing the total traverse required (as shown in Table 3.E2) by the first traverse length. The length of the prepared surface perpendicular to the direction of traverse is divided by the number of traverses required to get the perpendicular distance between traverses. The stage is then moved the distance perpendicular to the direction of the traverse using the perpendicular mechanism. The traverse is then continued in the opposite direction as before. When all the traverses have been performed, the values appearing on the two distance counters and the tally counter are tabulated.

The final results of the test can then be calculated. The air content is calculated as

$$A = \frac{\Sigma l}{T}$$

where:

A = air content (proportional volume of air voids in concrete expressed as volume percent of the hardened concrete)

Σl = the sum of all chord intercepts of the air voids (value of second counter) (inches)

T = total length traversed (value of first counter plus value of second counter) (inches)

The average chord intercept can be calculated as

$$\bar{l} = \frac{\Sigma l}{N}$$

where:

$\bar{l}$ = average chord intercept of the air voids (inches)

N = total number of air voids intersected during total traverse (value of tally counter)

The specific surface can be calculated as:

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

where:

α = specific surface (surface area of air voids in hardened concrete) (in.^{2}/in.^{3})

The spacing factor can be calculated if the paste content of the concrete is known:

$$\bar{L} = \frac{pT}{400N} \qquad \text{(if } \frac{P}{A} \text{ is less than 4.33)}$$

or

$$\bar{L} = \frac{3}{\alpha}\left[1.4\left(\frac{P}{A} + 1\right)^{\frac{1}{3}} - 1\right] \quad \text{(if } \frac{P}{A} \text{ is greater than 4.33)}$$

where:

$\bar{L}$ = spacing factor (maximum distance of any point in the cement paste from the edge of the air void) (inches)

p = paste content (volume percentage of concrete)

The linear traverse method is most often used to calculate the air content of hardened concrete due to lack of better alternatives. It has been demonstrated that there will be a variance in results from operator to operator (2,25a) and the procedure is expensive as it is tedious work requiring an experienced operator four to eight hours to complete 100" of traverse.

Nominal or Observed Maximum Size of Aggregate in the Concrete, in. (mm)	Total Area to be Traversed for Determination of α or $\bar{L}^a$, min, in.^{2} (cm^2) Based on Direct Measurement of:	
	Total Air Content, A^b	Paste-Air Ratio, p/A
6 (150)	250 (1613)	100 (645)
3 (75)	65 (419)	30 (194)
1½ (37.5)	24 (155)	15 (97)
1 (25)	12 (77)	12 (77)
¾ (19.0)	11 (71)	11 (71)
½ (12.5)	10 (65)	10 (65)
⅜ (9.5)	9 (58)	9 (58)
3⁄16 (4.8)	7 (45)	7 (45)

[a] See Section 2 for the interpretation of symbols employed.

[b] The indicated values refer to reasonably homogeneous, well-compacted concrete. The microscopical measurement should be made on proportionately larger area of sections if the concrete is markedly heterogeneous in distribution of aggregate or large air voids. If more than one finished surface is taken from a single portion of the concrete, the finished surfaces shall be separated by a distance greater than one half of the nominal or observed maximum size of aggregate.

Table 3.E1 MINIMUM AREA OF FINISHED SURFACE FOR MICROSCOPICAL MEASUREMENT (FROM ASTM C457-71 (51))

Nominal or Observed Maximum Size of Aggregate in the Concrete, in. (mm)	Length of Traverse for Determination of A, α, or $\bar{L}$, min, in. (mm)[a]
6 (150)	160 (4064)
3 (75)	120 (3048)
1½ (37.5)	100 (2540)
1 (25.0)	95 (2413)
¾ (19.0)	90 (2286)
½ (12.5)	80 (2032)
⅜ (9.5)	75 (1905)
3⁄16 (4.8)	55 (1397)

[a] The limits of uncertainty of results obtained for air-void content depend upon the length of traverse and the air-void content of the concrete. Based on experience, the recommended minimum length of traverse shown in this table should produce limits of uncertainty such that up to 3 percent air-void content the standard deviation is not greater than 0.5 percent, which at 3 percent air-void content corresponds to a coefficient of variation of 17 percent. For traverse lengths greater than 55 in. (1397 mm) and air-void contents greater than 3 percent the coefficient of variation is correspondingly reduced. The data obtained can be analyzed by statistical methods to determine the limits of uncertainty to be applied.

Table 3.E2 MINIMUM LENGTH OF TRAVERSE FOR THE LINEAR TRAVERSE METHOD (FROM ASTM C457-71 (51))

CHAPTER 4

IMAGE ANALYSIS

4.A General

Image analysis is only one aspect of the relatively new technology of image processing. An image is converted into an electronic form that can be manipulated, generally, in one of two ways. The image may be enhanced by the processing, with the improved image being the final result. An example of this is the pictures received from satellites and spacecraft which are computer enhanced to yield better clarity or colour effects are added to aid human evaluation of the image. More commonly, the image is analyzed with information such as feature identification and measurement being derived.

Most of the original image analysis equipment was hardwired, which made analysis not very flexible. The modern approach to image analysis is software control so that an operator can be very flexible in tailoring the actual analysis of the particular image dealt with in order to yield optimum test parameters.

With the increasing interest in applications of image analysis, several firms now make image analysis equipment. Imanco, Bausch and Lomb, and Lietz market an image analysis system based on a conventional fixed rapid scanning of a television camera, which limits the flexibility of the operator.

Tracor Northern Inc. and Lemont Scientific offer very flexible systems which utilize an image dissector camera controlled by computer and software oriented controls, which allow sophisticated image analysis on line without expensive data collection required by off line analysis.

4.B Theory

The first step in image analysis is to convert the image into an electronic form to be analyzed. A standard television camera does this by scanning across the image and converting the optical image into an equivalent electrical signal image on the basis of grey scale of the optical image corresponding to the level of the electrical signal. Each scan line (raster line) gives a cross section of grey levels in the image at that point. A given number of raster lines describes the image completely. This is an analogue signal.

It is possible to take this analogue signal and sample it at given intervals (usually at the spacing of the raster lines) to yield a matrix of picture points (ie. the grey level is now sampled at the matrix points of the image).

Each picture point grey level is then considered representative of the small square area of which it is the centre. In this way, a black and white image can be thought of as a matrix of small squares, each of a varying grey level. The more small squares the image is divided up into, the greater the resolution of the image.

There are generally two different ways to proceed with the image analysis. It is possible to "digitize" the matrix of small squares by letting each grey level be a number from 0 (white) to 255 (black) depending on the light intensity of the small square (which in turn is the level of the analogue signal). In this way, the entire image is described digitally. This information can then be stored in a computer memory and the entire image can be manipulated by the operator. Limitations of this approach lie in the large amount of data storage required to get an image of good resolution totally described. However, with the data in storage, very sophisticated manipulation is possible. (Examples are grey level histogram equalization, thresholding, image addition and subtraction, gradient, low pass, high pass and band pass filtering.).

A more common method of image analysis uses an analogue comparator to test the signal at each picture point for a threshold level and then binary codes the results (ie. 0 for on feature, 1 for off feature). This requires that the features of the image that you are analyzing are of a sufficiently different grey level from the background of the image. In this way, a new image is derived, a binary image which is composed of feature and non feature areas. These binary images are frequently displayed in black versus white and offer a striking visual effect of having isolated the features that are to be analyzed. This binary data occupies much less computer memory. However, possible manipulation of this data is rather restricted since so much information has been lost. There is sufficient information to analyze the features, usually for geometrical data (ie. feature shape, dimension, number).

Even less computer memory is required if, instead of storing the binary image in its entirety, the image is analyzed directly and only the required feature information retained.

Many image analysis systems use television Camera Imaging where the image is focused by the optics onto a silicon target (Videcon) (See Figure 4.B1). This target is discharged by the impact of electrons. The video signal is arrived at by monitoring the discharge process of the target. The charge on the target increases with time (See Figure 4.B2a), so that for Television Camera Imaging, sweep speed cannot be made variable. The practical maximum resolution is 512 x 512 pixels.

An image dissector camera tube (See Figure 4.B3) has no storage capacity on the target (See Figure 4.B2b) and therefore, lower sweep speeds can be used. In the image dissector tube camera, the image to be analyzed is projected on the face plate of the tube. In the tube itself, a quantity of photoelectrons proportional to the light input is emitted and accelerated toward the back plane by an electrostatic field. An electromagnetic field is used to focus the electron image (converted from original light image) on the back plane. An externally controlled (usually by computer) electromagnetic deflection field scans across a small aperture located in the middle of the back plane. Photoelectrons which pass through the aperture excite an electron multiplier, thus generating a video signal. The resolution is based on the size of the aperture since the aperture is essentially equivalent to the spot size with which the image is scanned. As the size of the aperture decreases, the signal to noise ratio decreases and possible resolution increases.

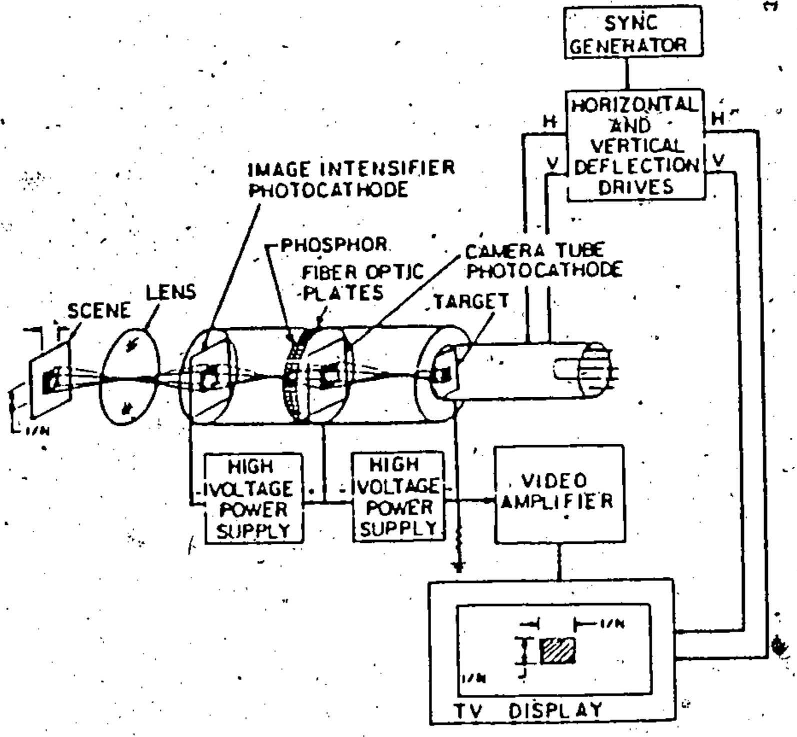
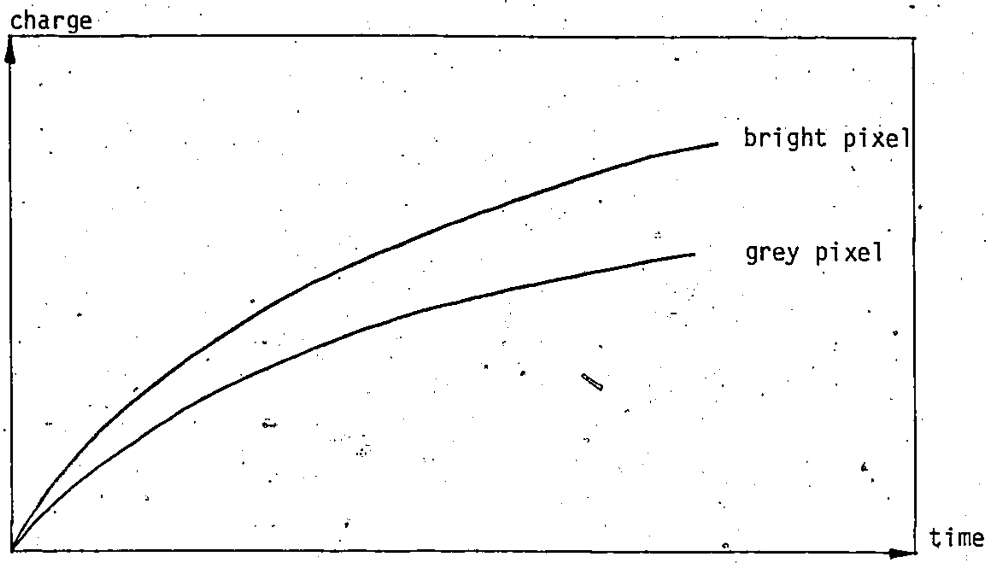
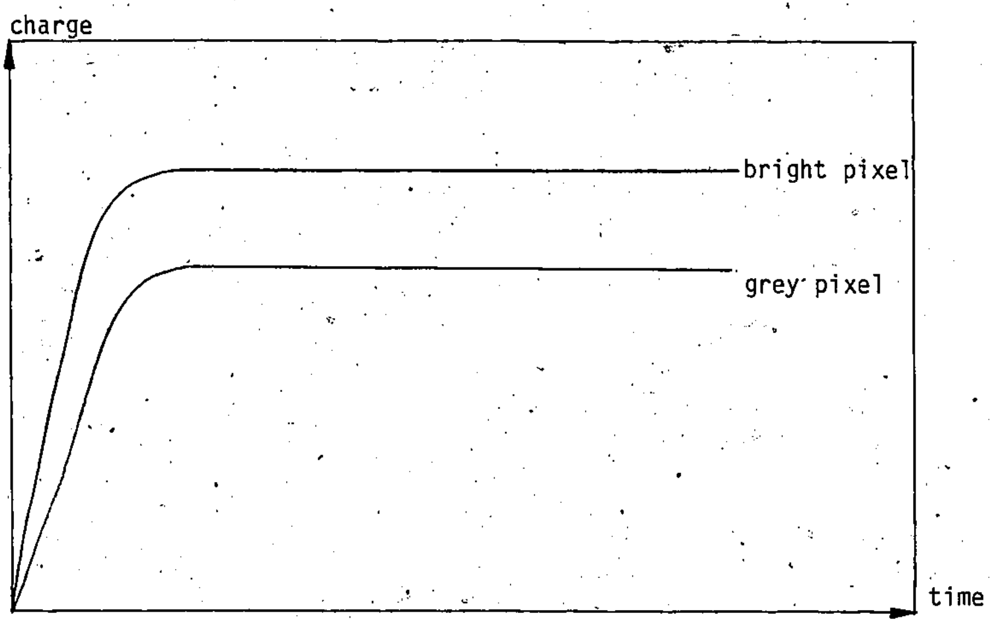

SYNC GENERATOR
HORIZONTAL AND VERTICAL DEFLECTION DRIVES
H
V
H
V
IMAGE INTENSIFIER PHOTOCATHODE
PHOSPHOR
FIBER OPTIC PLATES
CAMERA TUBE PHOTOCATHODE
TARGET
LENS
SCENE
1/N
HIGH VOLTAGE POWER SUPPLY
HIGH VOLTAGE POWER SUPPLY
VIDEO AMPLIFIER
1/N
1/N
TV DISPLAY

FIGURE 4.B1 TELEVISION CAMERA TUBE



(a) Television Camera Tube



(b) Image Dissector Tube

FIGURE 4.B2 CHARGE VS. TIME FOR A) TELEVISION CAMERA TUBE
B) IMAGE DISSECTOR TUBE

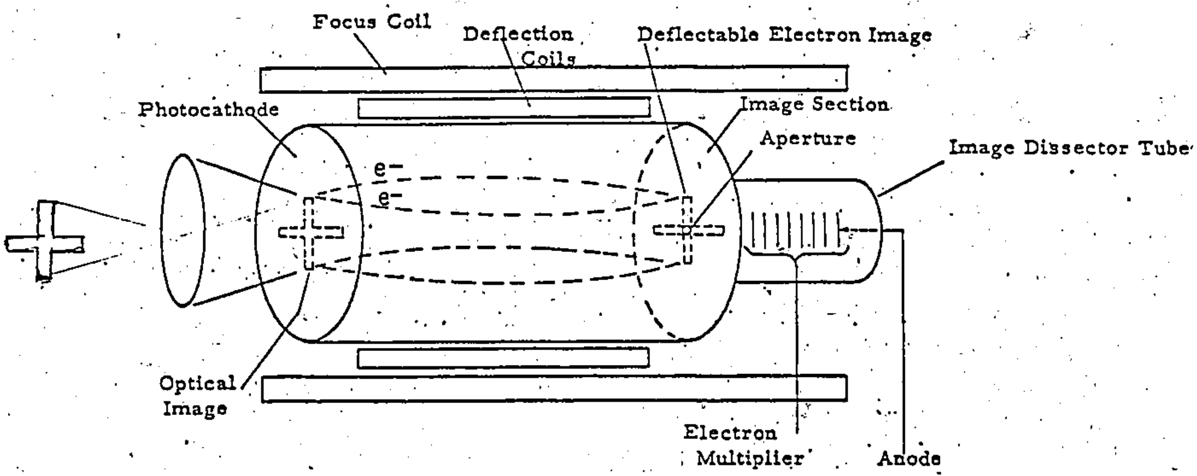

Focus Coil
Deflection Coils
Deflectable Electron Image
Photocathode
Image Section
Aperture
Image Dissector Tube
e-
e-
Optical Image
Electron Multiplier
Anode

FIGURE 4.B3 IMAGE DISSECTOR CAMERA TUBE

An image dissector camera tube can be controlled by a computer which allows absolute freedom in beam position, and the ability to dwell at any location of the image. Therefore it is possible to search for features at one point density and analyze features at a greater point density, so that a full scan of the entire image at the greater point density required for image analysis is not necessary.

4.C Lemont Scientific Hardware

The Lemont Scientific B-10 Image Analysis System is a computer based system which utilizes either an image dissector tube (which receives an image through a direct macro optic system or through a light microscope) or a Scanning Electron Microscope (S.E.M.) in order to perform physical and/or chemical characterization of microscopic features. (See Figure 4.C1)

For this study, only the central unit (See Figure 4.C2) (computer, digital scan generator, threshold selector, image selector), the line monitor, the Image Dissector Camera (See Figure 4.C3), the direct macro optic system, the automatic stage control, the CRT, the high speed printer and the dual floppy disk storage unit are required.

The computer contained in the system is an Interdata 6/16 with 64 kilobytes of main memory. Since the Lemont Image Analysis is largely software based, the computer controls many functions usually run by special purpose hardware. The camera used is an Image Dissector Camera OID1. It offers electronic magnification of 1X, 2X or 4X. A shading correction is provided. Variance in background lighting level can be corrected electronically either vertically or horizontally (See Figure 4.C4). The Analogue Comparator provides a width, level and gain for the incoming signal. With the threshold established, increasing or decreasing the level defines the grey level of the threshold. The gain allows the signal to be stretched to allow better setting of

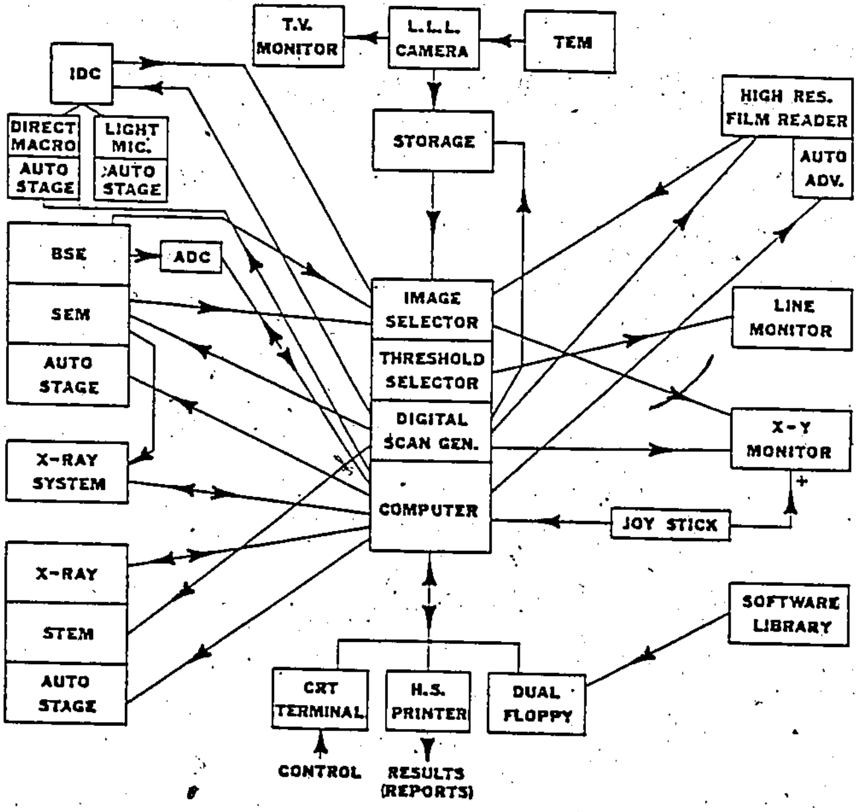

T.V. MONITOR
L.L.L. CAMERA
TEM
IDC
DIRECT MACRO
AUTO STAGE
LIGHT MIC.
AUTO STAGE
STORAGE
HIGH RES. FILM READER
AUTO ADV.
BSE
ADC
SEM
AUTO STAGE
IMAGE SELECTOR
THRESHOLD SELECTOR
DIGITAL SCAN GEN.
COMPUTER
LINE MONITOR
X-Y MONITOR
+
X-RAY SYSTEM
JOY STICK
X-RAY
STEM
AUTO STAGE
SOFTWARE LIBRARY
CRT TERMINAL
H.S. PRINTER
DUAL FLOPPY
CONTROL
RESULTS (REPORTS)

FIGURE 4.C1 B-10 SYSTEM CONFIGURATION

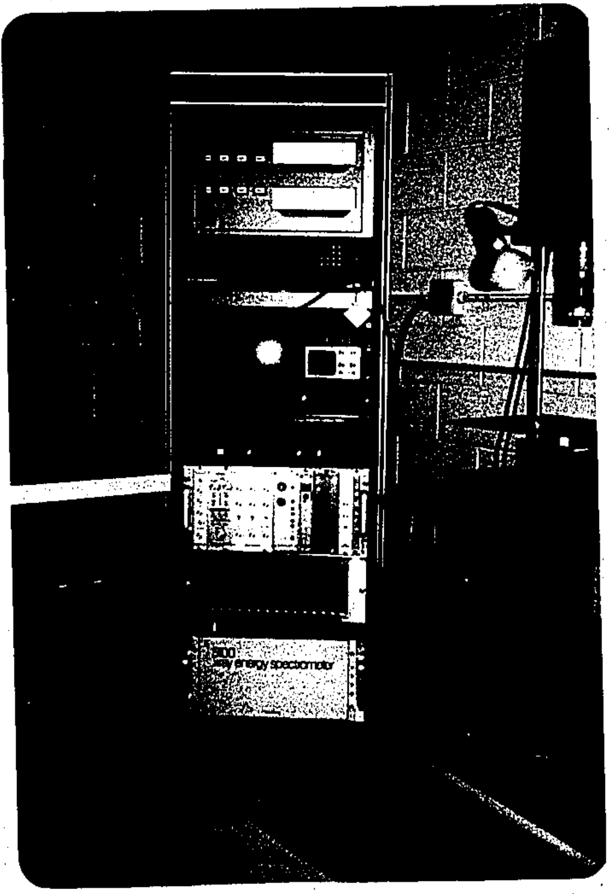

800
x-ray energy spectrometer

FIGURE 4.C2 CENTRAL UNIT (COMPUTER, DIGITAL SCAN GENERATOR THRESHOLD SELECTOR, IMAGE SELECTOR, DUAL FLOPPY DISK STORAGE UNIT)

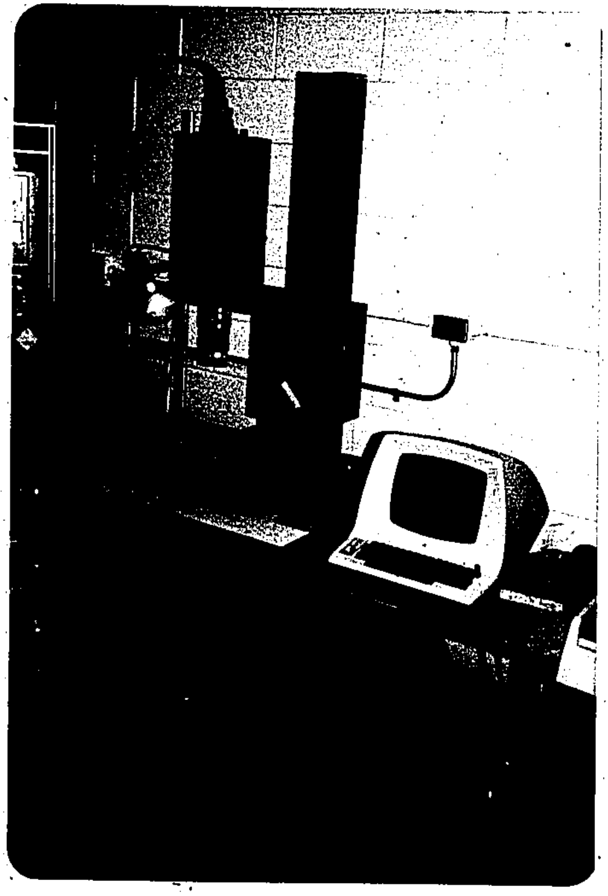
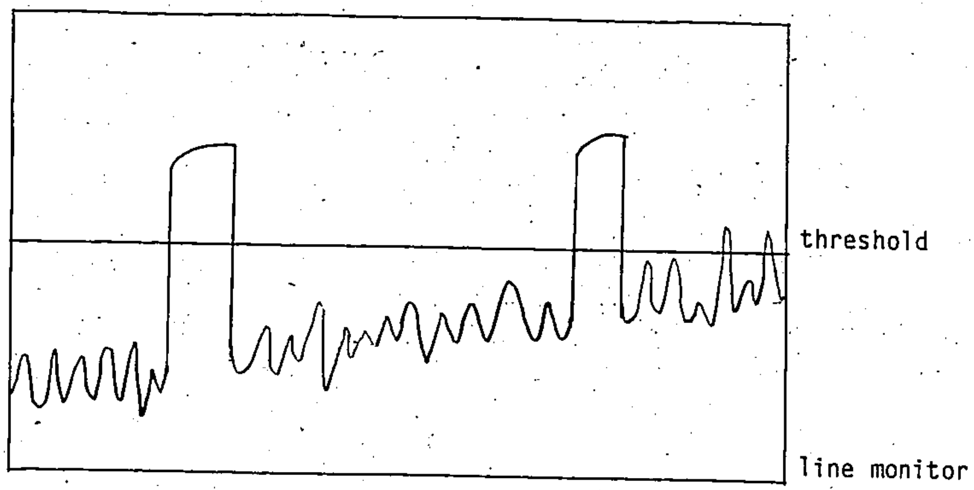
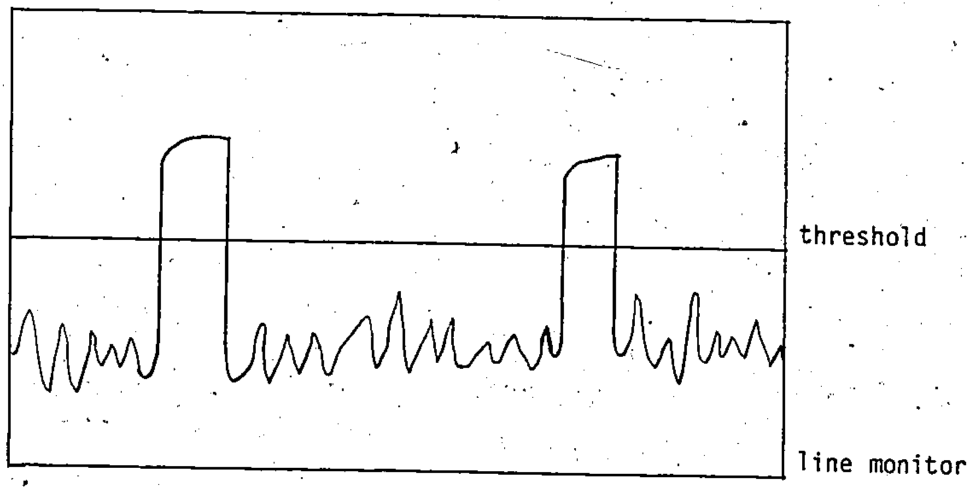


FIGURE 4.C3 IMAGE DISSECTOR CAMERA, DIRECT MACRO OPTIC SYSTEM, AUTOMATIC STAGE CONTROL, CRT



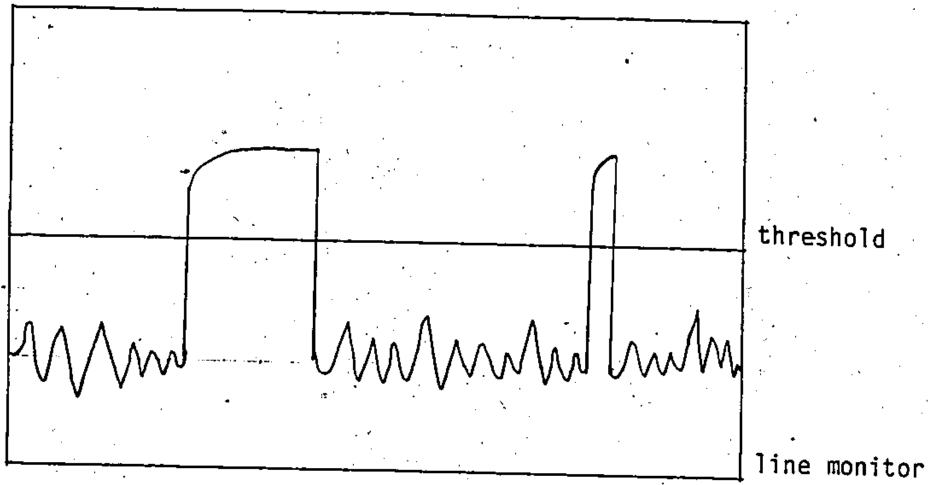
(a) before correction



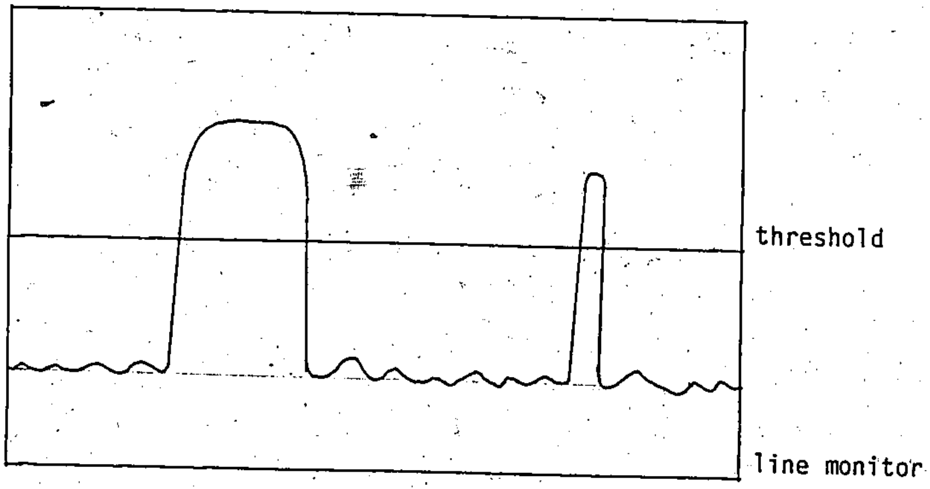
(b) after correction

FIGURE 4.C4 SHADING CORRECTION

the threshold. A switch allows inversion of the signal (allows on feature to be higher or lower grey level than threshold. A Low Pass filter is provided to improve the signal to noise ratio by averaging the signal over user defined intervals. The noise is averaged out of the signal. This has the effect of slightly reducing the sharpness of the boundaries of features. (See Figure 4.C5) The Image Selector allows choice of Image (from S.E.M. Light Microscope or Auxiliary System) An inversion switch is also provided.


threshold
line monitor

a) low pass filter not used


threshold
line monitor

b) low pass filter used

FIGURE 4.C5 EFFECT OF LOW PASS FILTER

4.D Lemont Scientific Software

4.D1 Lineal Analysis

The Cross Section Chord Length Analysis (Version P-02E) program yields a quantitative analysis of features within a solid. This program makes the assumption that the cross sectional area of the analyzed image is representative of the solid.

The program performs an analysis of an image by traversing a user defined number of lines across the image and sampling the grey scale of the image at user defined intervals along each line. Each "pixel" or "picture point unit" is considered to have the width of spacing between individual picture points and is centered on the individual picture point. (See Figure 4.D1) An "on picture point unit" would be a picture point unit where the individual picture point at the centre has a grey level above the threshold set in the analogue comparator and is therefore "on feature". (See Figure 4.D2) The chord length of a feature would be the number of "on picture point units" found consecutively.

The input parameter for this program are points/line, lines/frame, sweep speed, scan option and magnification. The points/line input has a large effect on the results of the program. A maximum of 4096 points/line can be sampled. However, the maximum chord length allowed is 512 picture point units. If an oversized chord is encountered (chord length) 512 on point units), the operator is warned by the program and must either reduce the magnification or reduce the number of points/line.

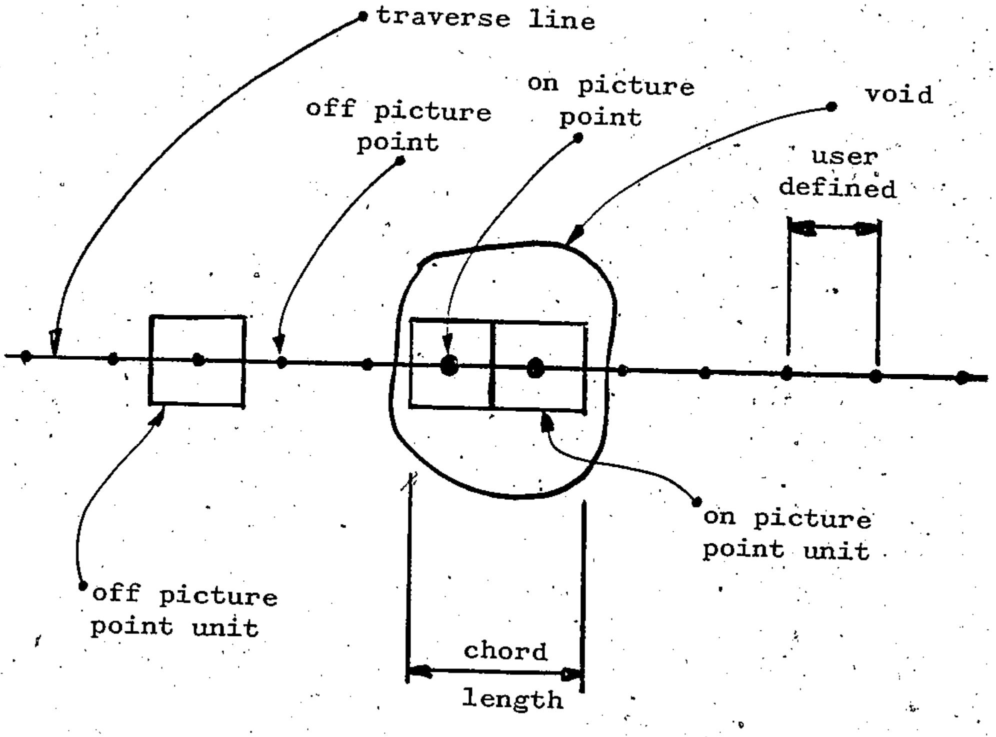

traverse line
off picture point
on picture point
void
user defined
off picture point unit
chord length
on picture point unit

FIGURE 4.01 LINEAL ANALYSIS TRAVERSE

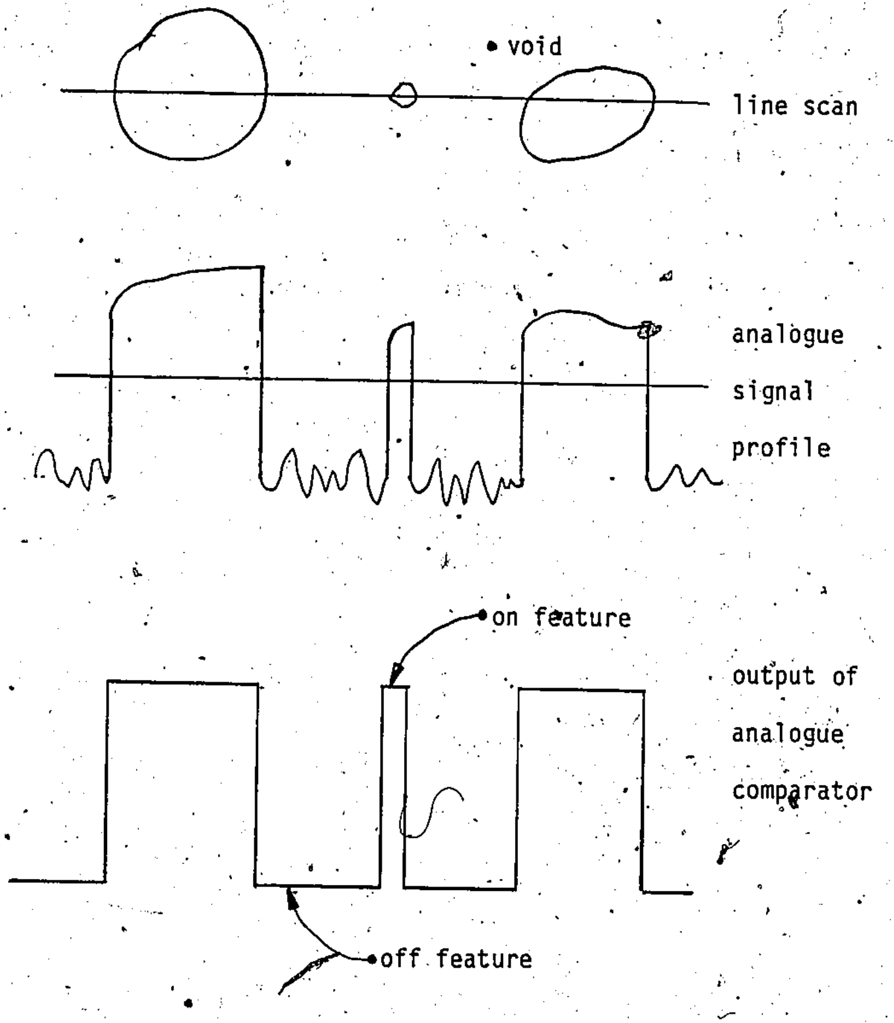
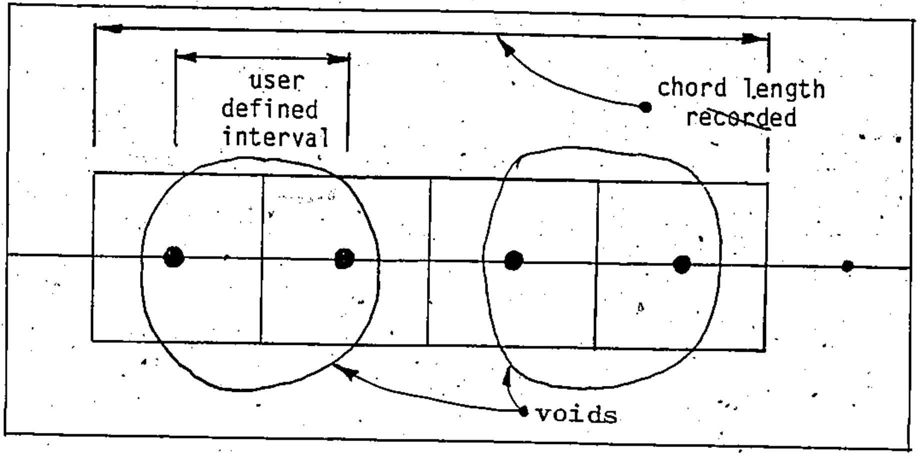

void
line scan
analogue
signal
profile
on feature
output of
analogue
comparator
off feature

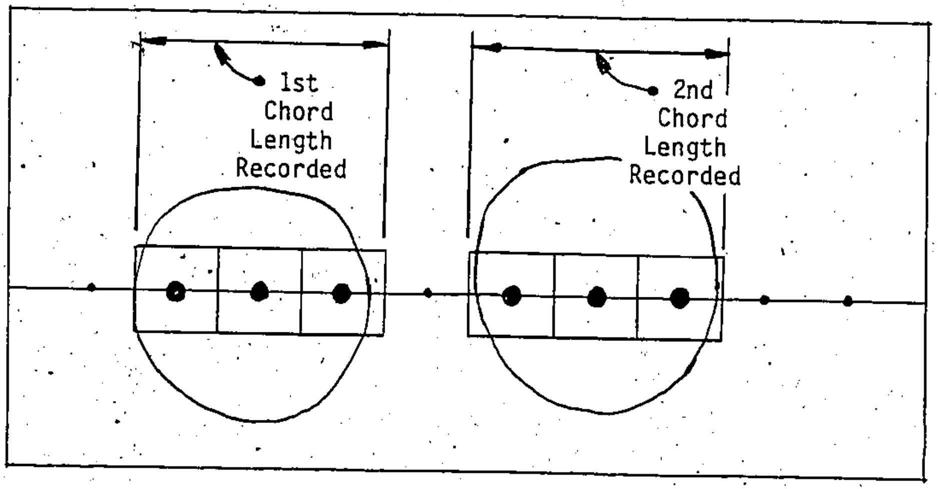
FIGURE 4.D2 OPERATION OF ANALOGUE COMPARATOR

In the case of image analysis of features of widely varying size ranges (ie. image analysis of air voids in hardened concrete samples where entrained air voids range from 10 microns to 1200 microns), it is best to use a maximum number of 512 points/line so that where a feature completely fills the frame, an oversized chord length will not be encountered because frame edge to frame edge is 512 "on picture points". The greater the number of points/frame, the slower the analysis runs. The number of points/line should not be so small as to lump the chord lengths of two adjacent features into a single chord length. (See Figure 4.D3) A large number of points/line will also increase the accuracy of the chord length recorded for a feature. The interval between picture points should be sufficiently small to detect the smallest feature of interest. The point to point spacing for a given magnification and number of points/line can be found in Figure 4.D3.

The number of lines/frame is user definable. The program will not allow 1 line/frame. Up to 4096 lines per frame are allowed. Having more than one line pass through the smallest feature of interest is not efficient use of program type. Features of widely varying size distort the number of features calculation since it is likely a traverse line will encounter the same feature more than once. The optimum would be to have only one traverse line encounter any given feature. Sufficient lines should be scanned so


user
defined
interval
chord length
recorded
voids

(a) insufficient number of points/line


1st
Chord
Length
Recorded
2nd
Chord
Length
Recorded

(b) sufficient number of points/line

FIGURE 4.D3 CORRECT CHOICE OF POINTS/LINE

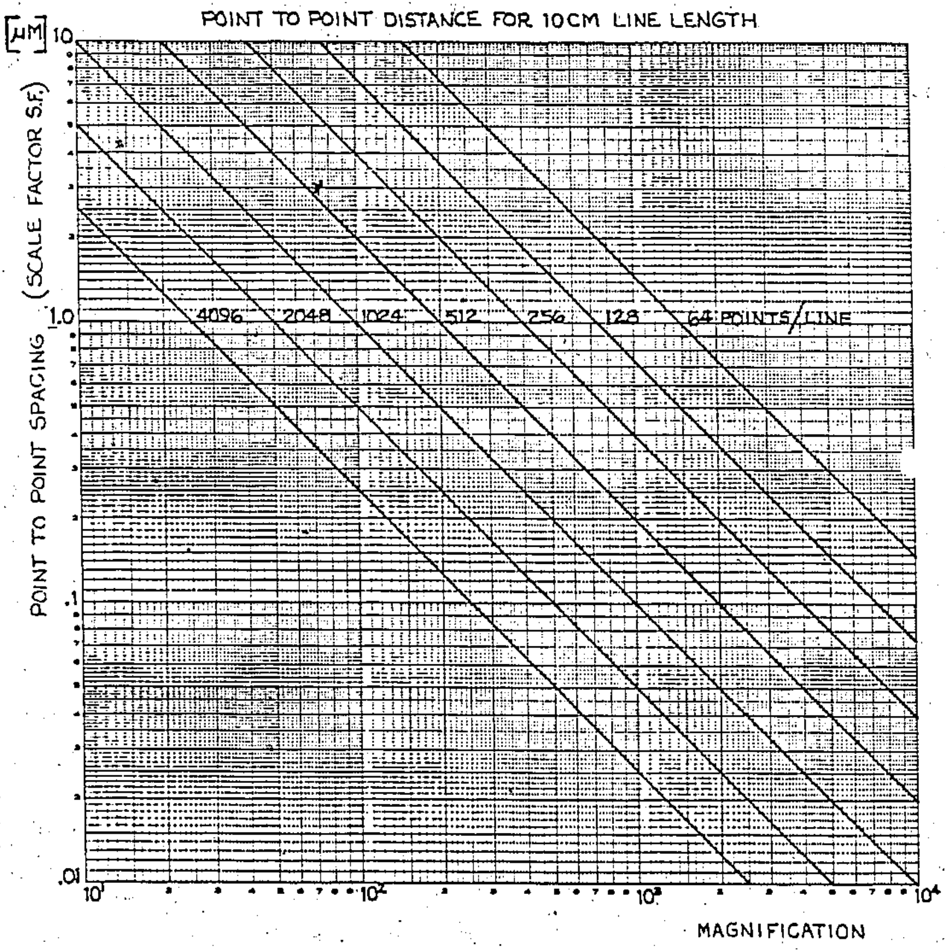


FIGURE 4.D4 POINT TO POINT SPACING FOR MAG. AND # POINTS/LINE (FROM LEMONT)

that the total line is scanned for all frames is sufficient to yield the required accuracy for the analysis of the material of the sample.

Sweep speed is the rate at which the line is scanned (amount of time that the beam remains at an "off" or "on" point before moving to the next point). A slower sweep speed should achieve a more accurate measurement while increasing the time of analysis. If the low pass filter is used, the sweep speed must be slower than the filter.

The scan option chosen defines the location of frames analyzed on the sample surface. Three options are available as discussed in Section 4.D3, the total coverage, Z Pattern and spaced frame pattern.

The magnification entered should be derived by testing a known feature using the optic system and the 1X, 2X or 4X electronic magnification that would be used for the analysis (it was found experimentally that the magnification for a given optical lens system with the electronic magnification at 4X does not equal exactly 4 times the magnification for the same optical lens system with the electronic magnification at 1X).

The results of the Lineal Analysis program are calculated as below:

$$\text{Pp} = \frac{\text{number of "on" point counts}}{\text{no. of "on" points \& no. of "off" points}} = \frac{\text{"on" point count}}{\text{total count}}$$

where:

Pp = point fraction of a phase

$$\therefore Pp = Ll = Aa = Vv \quad \text{(due to the relationship assumed)}$$

where:

Ll = line fraction

Aa = area fraction

Vv = volume fraction (% of picture points actually within the volume of a feature, taken over the total volume searched)

$$Vv\% = Pp \times 100\%$$

$$C = \frac{10^{(5)}\,(\text{um/point})}{(\text{Magnification})(\text{number of points/line})}$$

where:

C = point to point spacing (the real distance between adjacent horizontal picture points on the specimen for the 10cm x 10cm CRT screen, and the required parameters in um

$$\bar{L} = \frac{\text{"on" point count}}{(\text{Total number of chords}) \times c}\ (\text{um})$$

where:

$\bar{L}$ = average chord length (mean length of chords (intercepts) for all frames)

$$N_L = \frac{\text{number of chords}}{(\text{"on" points and "off" points}) \times C}\ (\text{um}^{-1})$$

where:

N_L = number of features (number of chords per unit length)

$$= \frac{1 - V_v}{N_L} \quad (\mathrm{um})$$

where:

= edge to edge mean free path (average edge to edge spacing between features)

$$S_p = \frac{1}{N_L} \quad (\mathrm{um})$$

where:

S_p = average centre to centre spacing of the features

$$S_v = 4N_L \quad (V_v < 1)$$

where:

S_v = surface to volume ratio (surface area to unit volume ratio for features randomly interspersed within the solid ($V_v \cong 1$)

$$S_v = 2N_L$$

where:

S_v = surface to volume ratio (used in boundary applications where feature edges touch ($V_v = 1$)

$$\mathrm{TPTS} = \frac{\text{no. of points}}{\text{line}} \times \frac{\text{no. of lines}}{\text{frame}} \times \text{no. of frames}$$

where:

TPTS = total number of picture points

TLEN = TPTS x C

where:

TLEN = total test line (sum of lengths of lines crossing the sample for all the frames.

A chord length distribution histogram is available for print out. It displays the number of chords found for each class, class limits determined by chord lengths encountered. Typical program output can be seen in Appendix A.

4.D2 Diameter Analysis

Version V4.1 of the Lemont Diameter Analysis was used as it runs faster than the alternative program for Diameter Analysis, Version V5.1, which is a version V4.1 modified for particles of width to length ratios of less than 0.33. Since the voids analyzed in this study are usually approximately spherical, Version V4.1 is sufficient.

In the Diameter Analysis program, a dual picture point density is used to separate the analysis into a "search" mode and an "analysis" mode. The image is scanned (signal level sampled) at user set intervals (off point density) and at each sample point, the signal level (grey scale) is compared to the threshold value set in the analogue comparator to determine whether the point is on feature or off feature. If off feature, the scan continues. If on feature the interval between sample points is decreased (to a user set on point density) in order to get a high on feature resolution. (see Figure 4.D5) The program locates the centre of the feature (along the line of scan) by backstepping to the boundary and then forwardstepping to the far boundary and finding the middle of that horizontal diameter. Then a second horizontal is done at the centre of the vertical diameter. Using the centre of the second horizontal, a check of features previously analyzed is carried out to ensure that the feature has been encountered for the first time (large features may be "found" many times depending on the off point density). If the

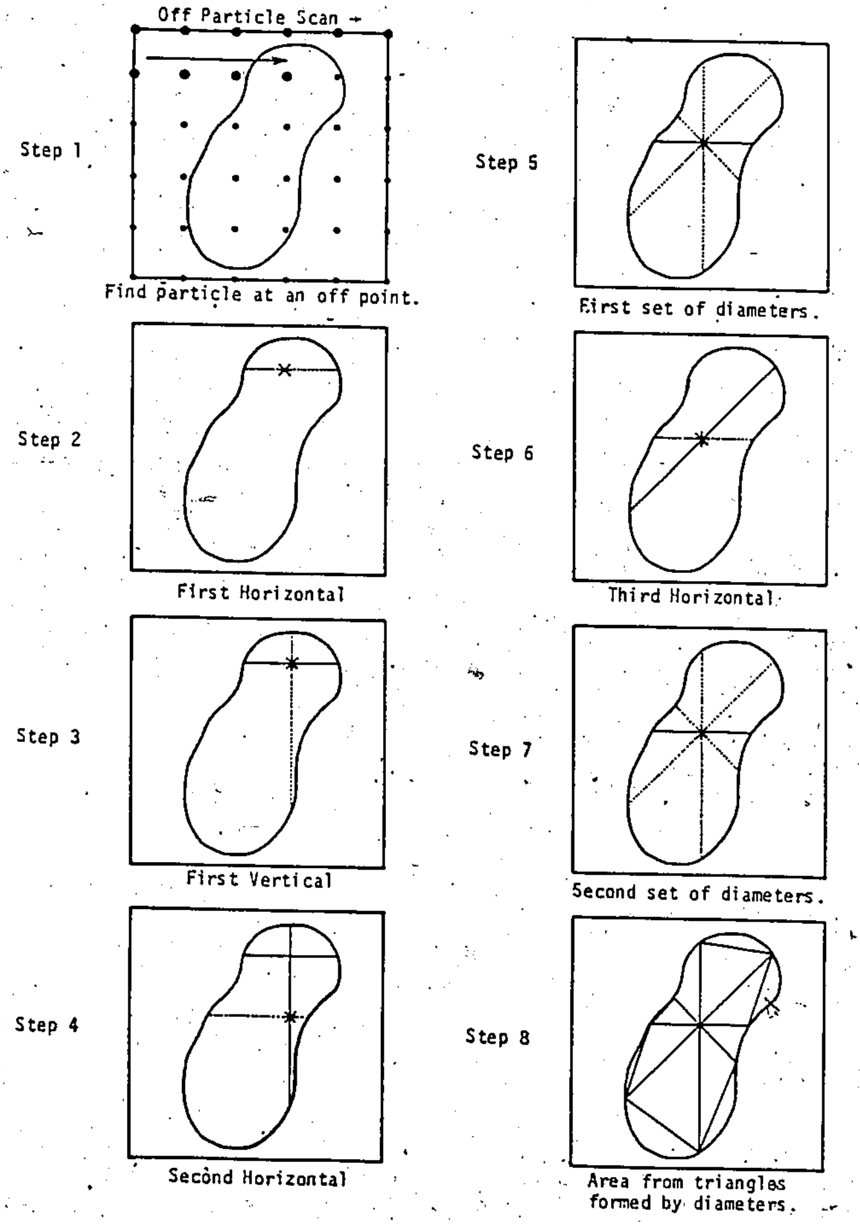

Step 1
Off Particle Scan →
Find particle at an off point.
Step 2
First Horizontal
Step 3
First Vertical
Step 4
Second Horizontal
Step 5
First set of diameters.
Step 6
Third Horizontal
Step 7
Second set of diameters.
Step 8
Area from triangles formed by diameters.

FIGURE 4.D5 DIAMETER ANALYSIS FOR A PARTICLE OF A REGULAR SHAPE (FROM LEMONT)

feature has been analyzed the program reverts to off point density and continues the search for particles at the boundary of the feature on the original scan line. If the feature is new, the program constructs a set of 4 or 8 diameters (depending on user input) from the centre of the second horizontal. The program then does a third horizontal from the centre of the maximum diameter. Using the centre of the third horizontal, the program again checks to see if the feature has been encountered before. If it has, the program reverts to search mode. If not, a second set of diameters is constructed from the centre of third horizontal. The intersection of each diagonal with the feature boundary is joined by chords to the adjacent intersections and the sum of the areas of the resulting triangles is the approximate area of the feature. Eight diagonals result in a closer approximation of the actual area. The feature parameters (maximum and minimum axis, aspect ratios) are calculated. The program compares the feature parameters against discriminators and if it passes, particle count is incremented and the feature parameters are classified for distribution plots.

The basic input requirements for this program are off point density, on point density, sweep speed, magnification and guard ring size. The off-point density should be set high enough to be sure that at least one picture point will fall on the smallest feature of interest. Recommended on point density would result in 5 to 10 on points across the minimum axis of the smallest feature of interest. Sweep speed must be slow enough to yield desired accuracy and has to be slower than the low pass filter if used. Magnification used should be appropriate to the smallest feature being analyzed. Guard ring size should be one tenth the frame size (guard ring eliminates features lying only partially on screen from analysis).

Output for this program is number of particles analyzed, minimum diameter found, maximum diameter found, total length of test line scanned, the mean and standard deviation of particles/frame, the mean and standard deviation of the average particle diameter, the mean and standard deviation of the aspect ratio (minimum/maximum diameter for a given particle) and volume percentage of particles and the surface/volume ratio. Histogram distributions are available for average diameter and minimum/maximum diameter. Typical printout for this program can be found in Appendix B.

4.D3 Software Modification Required

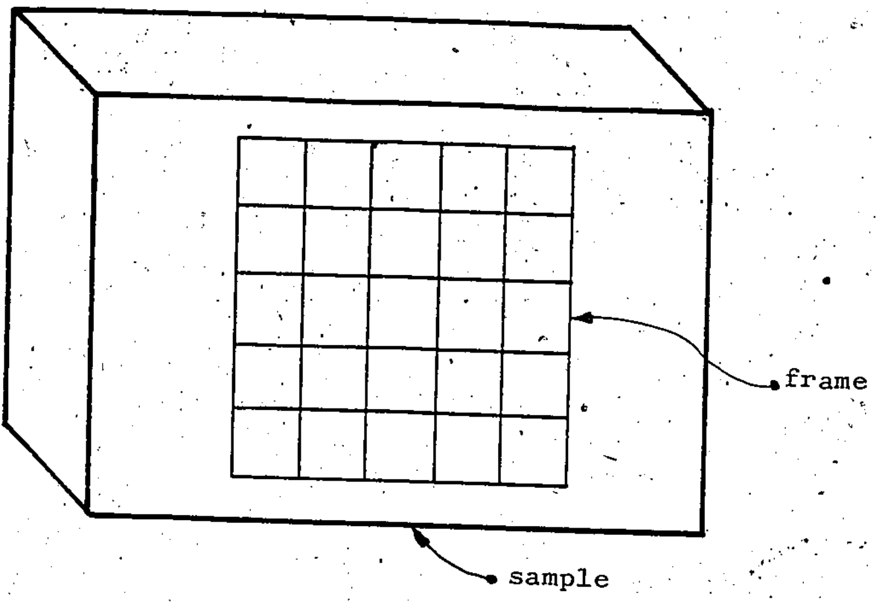
Both Lemont Software programs (the Diameter Analysis and the Lineal Analysis) required modification for use in the evaluation of air content.

Both programs allow two options for automatic stage control. Analysis of a given area of sample can be done by dividing the entire area into frames or by analyzing a Z pattern of frames over the area. (See Figure 4.D6) Unfortunately, neither of these options is desirable because to analyze the entire sample is time consuming and concrete is not sufficiently homogeneous to allow a Z pattern (ie. a piece of aggregate could lie along diagonal).

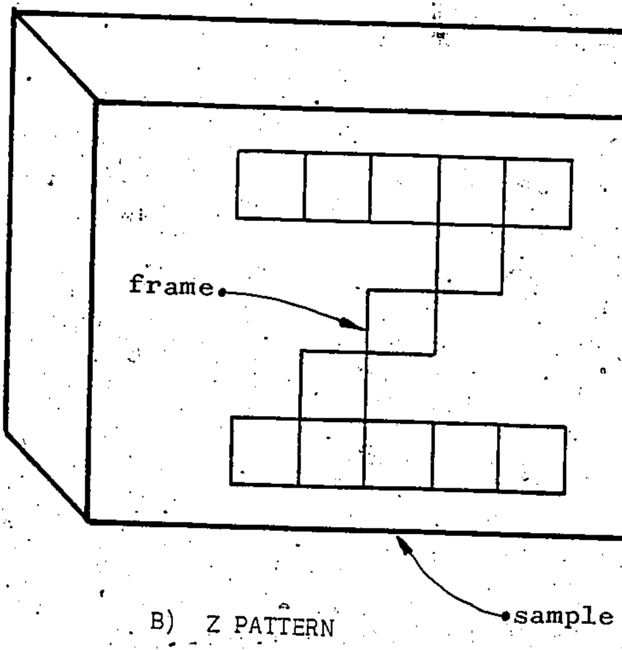
The problem was solved by programming a third option where a "checkerboard" of frames analyzed would be possible, with the interval between frames being user set in both X and Y directions. (See Figure 4.D7)

The optical lens system used to supply an image to the image dissector camera allows many possible actual magnifications. These were checked experimently to two decimal places using a test sample with a precisely measured reamed hole. Both programs allowed only a whole number magnification to be entered into the calculations. This was modified to allow two place decimal magnifications to be used in the calculations.

The automatic stage control automatically returned the stage to an initial position prior to analysis. This caused the sample to move completely out of view necessitating relocation of sample prior to analysis. This procedure was also time consuming. The


frame
sample

A) TOTAL COVERAGE


frame
sample

B) Z PATTERN

FIGURE 4.D6 POSSIBLE FRAME PATTERNS

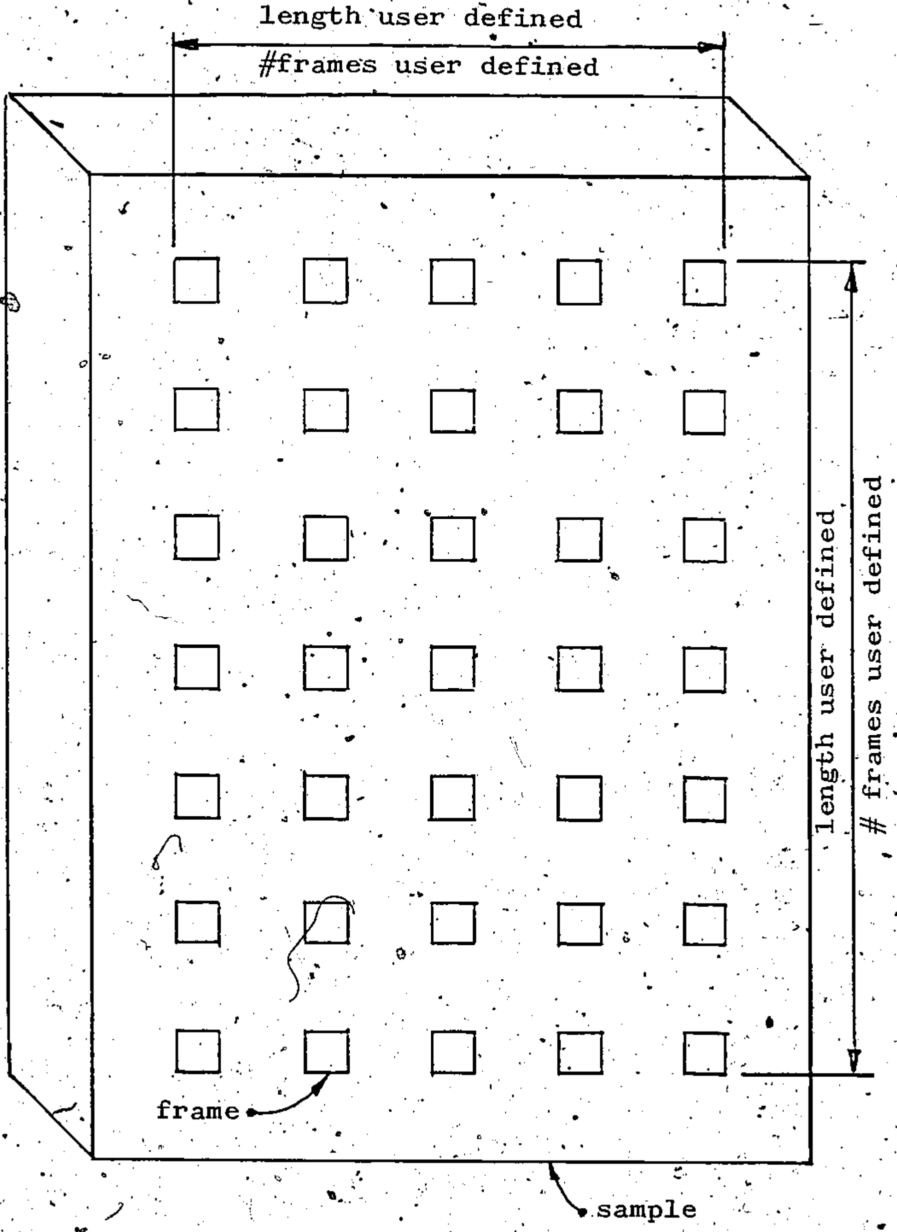

length user defined
#frames user defined
length user defined
# frames user defined
frame
sample

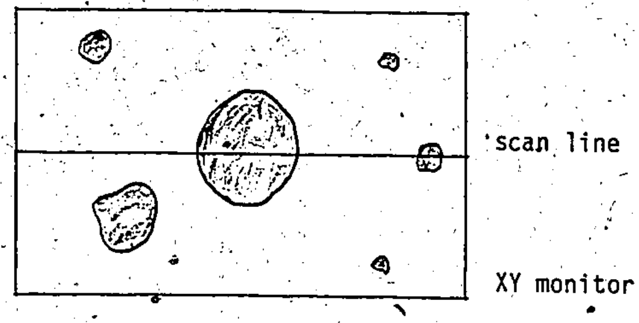
FIGURE 4.D7 "SPACED STAGE CONTROL SCAN PATTERN" programs were both corrected to allow a user option of eliminating the initialization.

4.E Use and Control of Lemont Scientific Hardware

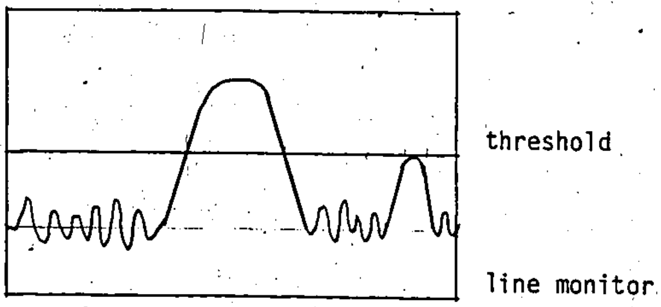
A quality image is required for good image analysis results. To ensure a quality image, care should be taken to optimize three important parameters, which are focus, light level and threshold level.

Focussing is accomplished by first establishing a rough focus of an image by moving the camera lens to a distance from the sample surface appropriate to the lens. The image is allowed to be scanned in the XY monitor until the scan line crosses a large feature. That scan line is held by switching the Scan Generator to Hold. By observing the analogue signal displayed on the Line Monitor, it is possible to focus the camera to an optimum condition. (See Figure 4.E1). The small knob on top of the image dissector camera is used to fine focus the camera until the boundaries of the void are shown to be as distinct as possible (most abrupt change in grey level).

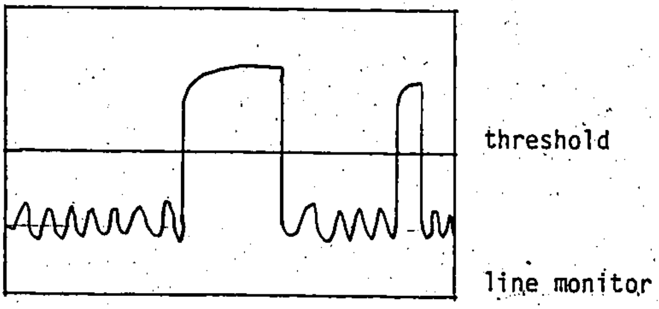
Optimum light level is that just below a level which causes saturation of the signal. This results in best possible contrast. Saturation occurs when the camera can no longer detect any increase in light level. On the basis of 256 grey levels, if two areas of white are only a few grey levels apart, increasing the light level is only productive until the grey level for one area becomes 0. Further increase of light level will result in the grey level of the second area becoming 0, eliminating any contrast between the areas. (See Figure 4.E2).


scan line
XY monitor

a) Scan Line

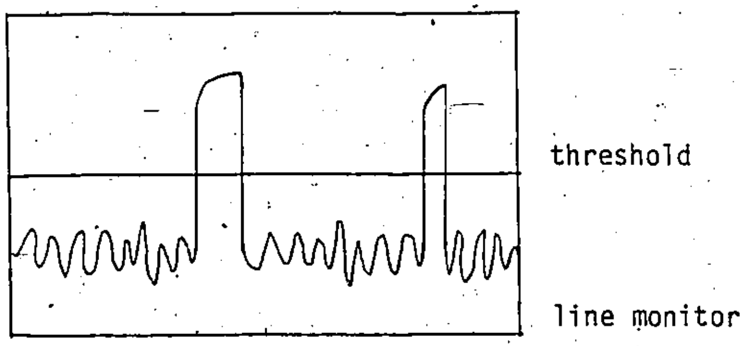


b) Out of Focus

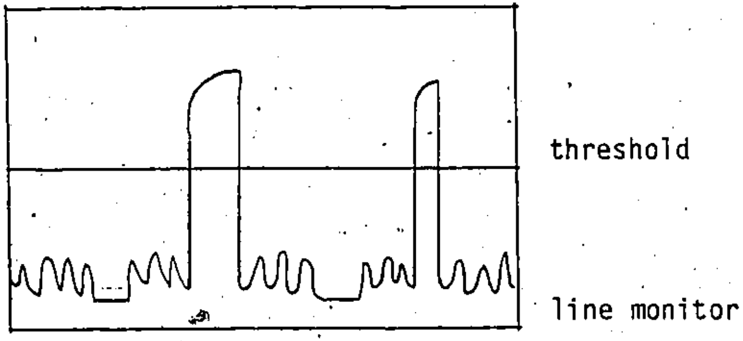


c) Focused

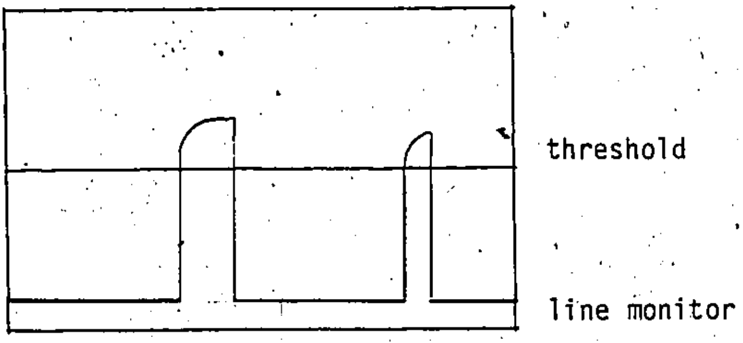
FIGURE 4.E1 FOCUSING OF IMAGE DISSECTOR CAMERA


threshold
line monitor

a) Before Saturation


threshold
line monitor

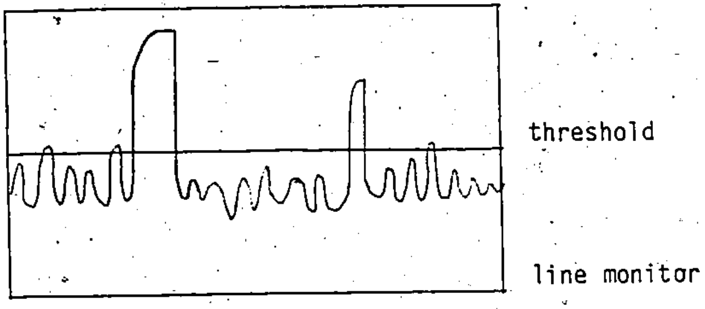
b) Saturation of Few Background Areas


threshold
line monitor

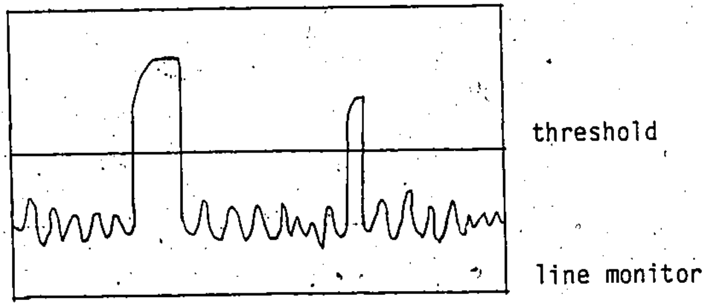
c) Majority of Background Saturated

FIGURE 4.E2 OPTIMUM LIGHT LEVEL

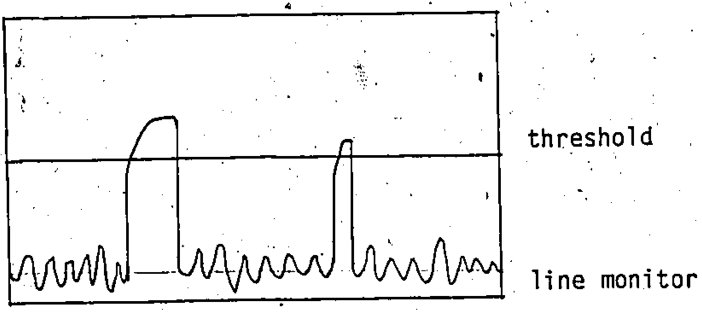
Threshold level should be set to differentiate between the grey level of the features to be analyzed and the background. In the case of black pores on a white background, the threshold should be set just above the level of the noise, but not so high as to lose the smaller voids. (See Figure 4.E3).


threshold
line monitor

a) threshold set too high


threshold
line monitor

b) optimum setting


threshold
line monitor

c) threshold set too low

FIGURE 4.E3 THRESHOLD LEVEL

CHAPTER 5

EXPERIMENTAL PROGRAM

5.A General

The object of the experiment was to use an image analysis apparatus to replace the human operators in a procedure similar to the standard linear traverse (Rosiwal) method of determining air-void content and the parameters of the air-void system in hardened concrete as detailed in the A.S.T.M. standard C457-80. It was decided to employ an image analysis apparatus manufactured by Lemont Scientific of State College, Pennsylvania. Three batches of concrete of various air contents were prepared and tested for air content by the pressure method (A.S.T.M. C231-81) and the linear traverse method (C457-80) as these are the most widely used methods in the industry, and therefore, are a good reference with which to compare the results of the new procedure. A standard procedure for using the image analysis equipment to determine air content was carefully developed. This procedure was used to measure the air content of specimens from each of the three concretes, and the results compared with those for the pressure and the standard linear traverse methods of air content measurement.

5.B Sample Preparation

5.B1 Casting

A standard concrete mix was designed having a water-cement ratio of 0.49 and a maximum size aggregate of $^3/_4$". The design strength of the mix was 4500 psi (with no air entraining agent added). (See Table 5.B1 for exact mix proportions). Six separate batches of concrete were prepared. The first three batches were used to estimate the amount of air entrained by the air entraining agent, Darex, for the design mix. Darex is an alkali salt of a sulphonated organic compound. Batch No. 4 was prepared with 19 ml. of Darex added to the water (to yield an estimated 9% air content). Batch No. 5 was prepared with 10 ml. of Darex (to yield approximately 6% air content) and Batch No. 6 was prepared with 6 ml. of Darex (to yield approximately 3% air content).

Each batch was sufficient to allow two pressure tests for air content of fresh concrete to be performed, one slump test to be performed and one cyclinder cast.

A slump test was performed on to each batch and Batches 4, 5 and 6 had slumps ranging from 4" to 6".

A standard 6" diameter by 12" high cylinder was cast for each batch of concrete in accordance with A.S.T.M. C192-76. These cylinders were stripped after twenty-four hours and water cured for twenty-eight days. Each cylinder was then cut into eight 6" x 4" x 1" samples using a diamond bladed block saw, the

COMPONENT	WEIGHT (LB)	% BY WEIGHT
PORTLAND CEMENT	25#	15.4%
WATER	12#	7.4%
FINE AGGREGATE	49#	30.2%
COARSE AGGREGATE (3/4" MAXIMUM)	76#	47.0%
	162#	100%

TABLE 5.B1 PROPORTIONS OF MIX COMPONENTS

6" x 4" surface to be finished being perpendicular to the finished surface and across the layers in which the fresh concrete was deposited (See Fig. 5.B1). Samples from the first three batches were retained for use in developing the polishing and masking procedures. Samples from Batches 4,5 and 6 were retained for use in the experiment once optimum polishing and masking procedures were developed.

FIGURE 5.B1 SAMPLE BEING CUT FROM CYLINDER

5.B2 Polishing

Each sample was polished on a twelve inch rotating grooved cast iron wheel, using a free grit system. (See Figure 5.B2). A #80 coarse grit is used to remove cutting marks from the sample face and then successive polishing steps followed using #220, #320 and #600 grits. It was originally attempted to use a system of grit coated papers of similar grit sizes, glued to smooth the cast iron wheel. This system was discarded due to the greater speed of free grit polishing (which is fifteen minutes for one sample), the expense of preparing one sample at a time since discs are nonreuseable after being removed and the rigidity of being unable to repeat a polishing at a coarser grit once polishing at the next grit size begins. (See Figure 5.B3) A problem inherent in using the free grit system to polish concrete possessing air voids is the accumulation of a grit "muck" in the sample pores. This causes problems during polishing since when polishing at finer grades of grit, coarse grit left in the pores from previous polishing can fall out and scratch the surface, necessitating repolishing at a coarser grit. As well, some pores remain filled throughout the polishing, a conditon that might cause those pores to be eliminated from the pore counting and sizing process. Attempts to clean the "muck" out of the pores with strong jets of water, brushing with a fine brush, blasting the surface with compressed air and a "water pik" used to clean crevices between teeth were unsuccessful. Fortunately, it was

FIGURE 5.B2 GRINDING APPARATUS

FIGURE 5.B3 POLISHING SYSTEMS

found that by suspending a sample for 5 minutes in an ultrasonic cleaning unit filled with warm water, the grit "muck" was adequately removed from the pores. (See Figure 5.B4)

A final polishing on a sheet of plate glass using a slurry of water and #1000 silicon carbide grit (see Figure 5.B5) and a final cleaning in the ultrasonic cleaning unit concluded the polishing of the samples.

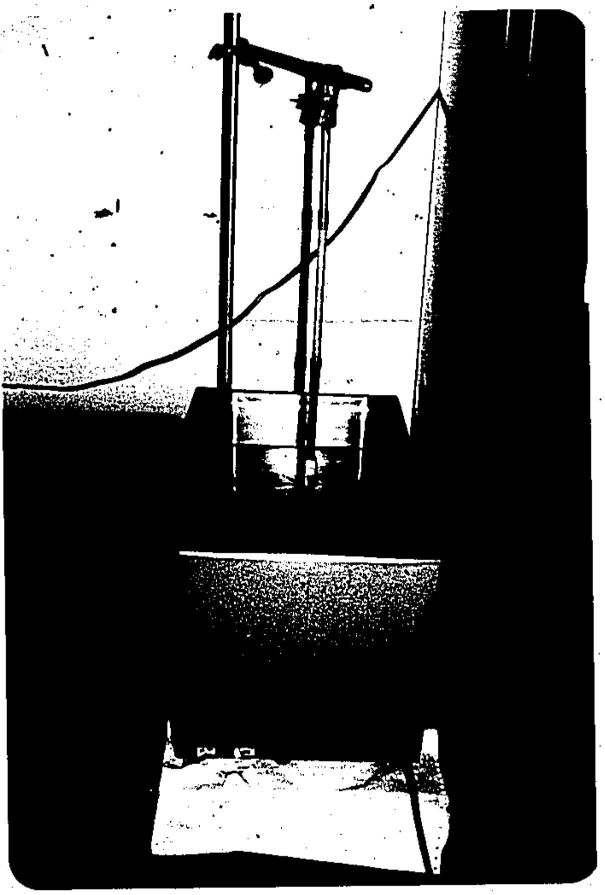


FIGURE 5.B4 ULTRASONIC CLEANING UNIT

FIGURE 5.B5 FINAL POLISH #1000 GRIT ON PLATE GLASS

5.B3 Masking

Since image analysis is based on recognition of given features differentiated by grey scale, it is necessary to give the pores a grey level adequately different from any grey level found in the matrix around the pores. By shining a light on the polished surface at an oblique angle, (See Figure 5.B6) the pores appear black due to shadowing. However, there are many shades of black aggregate visible in the concrete matrix of comparable grey level to the pores, making it impossible for the image analysis system to differentiate between the pores and the darker aggregate. Because of this, the matrix must be treated so as to eliminate any black. This "masking" may be done in a variety of ways. The Danish researchers, referred to earlier, masked their samples by blacking the sample surface with ink, heating the surface and placing a half vaseline and half zinc oxide (white paint base) into the pores, scraping the excess off with a straight edge. A final dusting with gypsum yielded a black matrix with white pores. It was felt by this researcher that this was a cumbersome method and as well, some number of smaller pores could perhaps be filled with black ink. An alternative method therefore appeared desirable. It was decided to try masking the surface of the test sample with aluminum, utilizing vacuum deposition methods. This would yield an aluminum coloured surface, fairly white, with pores darkened by oblique lighting. (See Figure 5.B7 for contrast between masked and unmasked sample).

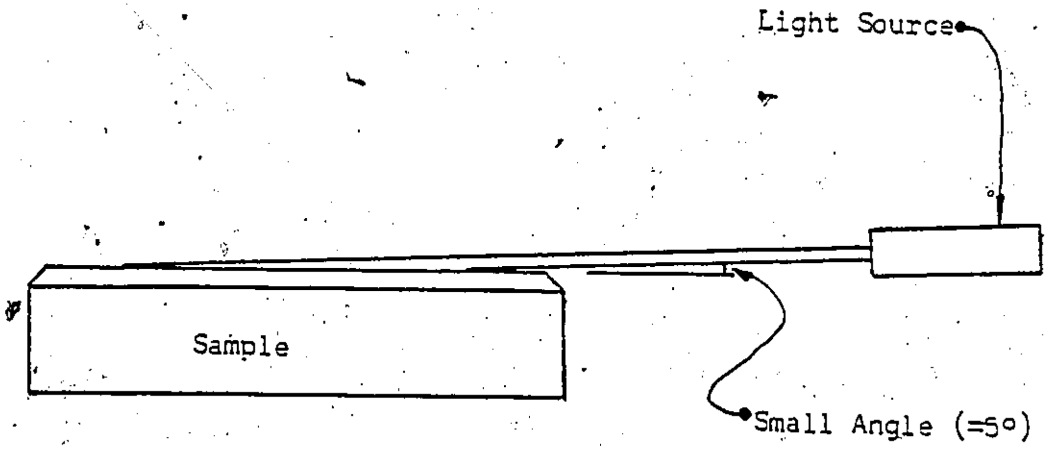

Light Source
Sample
Small Angle (=5°)

FIGURE 5.B6 OBLIQUE LIGHTING

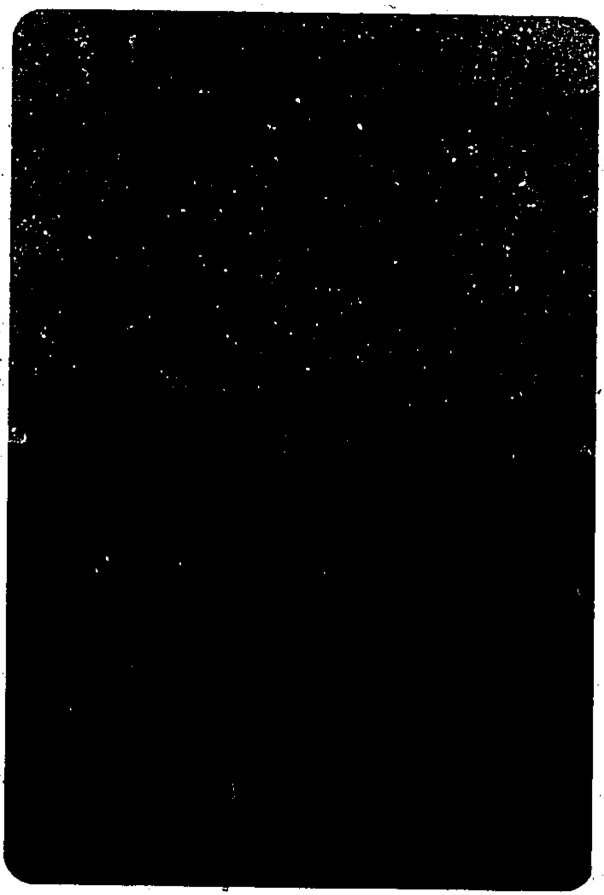


FIGURE 5.B7 CONTRAST BETWEEN MASKED AND UNMASKED SAMPLES

The aluminum was applied to the sample surface with a vacuum deposition apparatus manufactured by Balzers. (See Figure 5.B8).

The procedure for coating samples is fairly straight forward. Air is admitted to the bell jar (stored at vacuum) to atmospheric pressure and the bell jar is raised electrically. The sample is placed on a ring clamp, (See Figure 5.B9) and the surface is to be coated downwards positioned above a tungsten crucible. The crucible, held between two electrodes, is charged with several small pieces of 99.9% pure aluminum. A check is performed to ensure the seal is absolutely clean and the bell jar is lowered. Primary vacuum is obtained by the use of a rough pump. A diffusion pump further evacuates the bell jar down to about 10^{-6} torr. A large current is passed through the electrodes vaporizing the aluminum which is deposited on the sample in a uniform thin film. Film thickness is monitored by measuring the change in resonance in a quartz crystal that receives the same film thickness as the sample.

A problem encountered in early attempts to coat samples was the length of time required for "pump down" the bell jar to an acceptable vacuum. This was somewhere on the order of two days due to the outgassing of the concrete sample. However, overnight drying in a desiccating oven was found to eliminate this problem allowing "pump down" times of less than one hour. The concrete sample should be dried at no higher than 105 degrees centigrade since greater temperatures cause the aggregate to

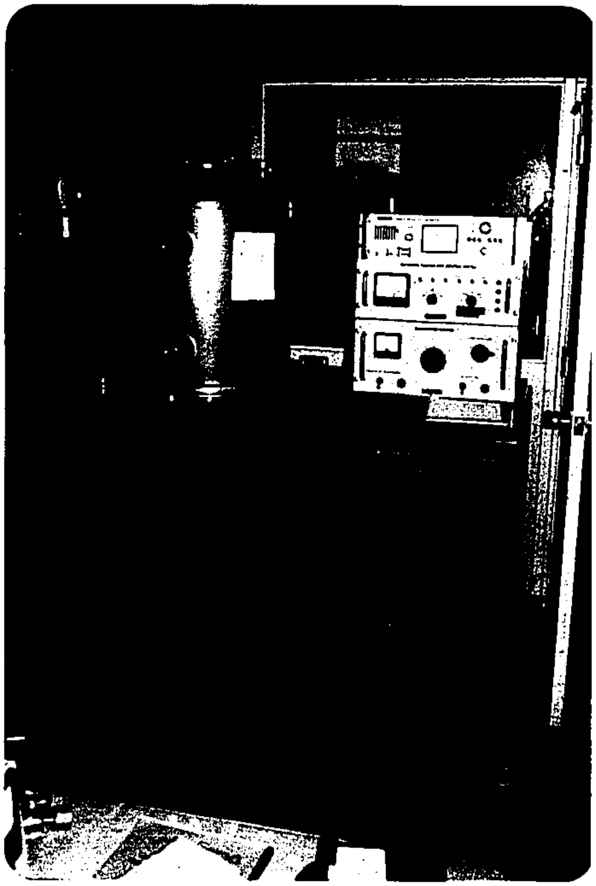


FIGURE 5.B8 VACUUM DEPOSITION APPARATUS

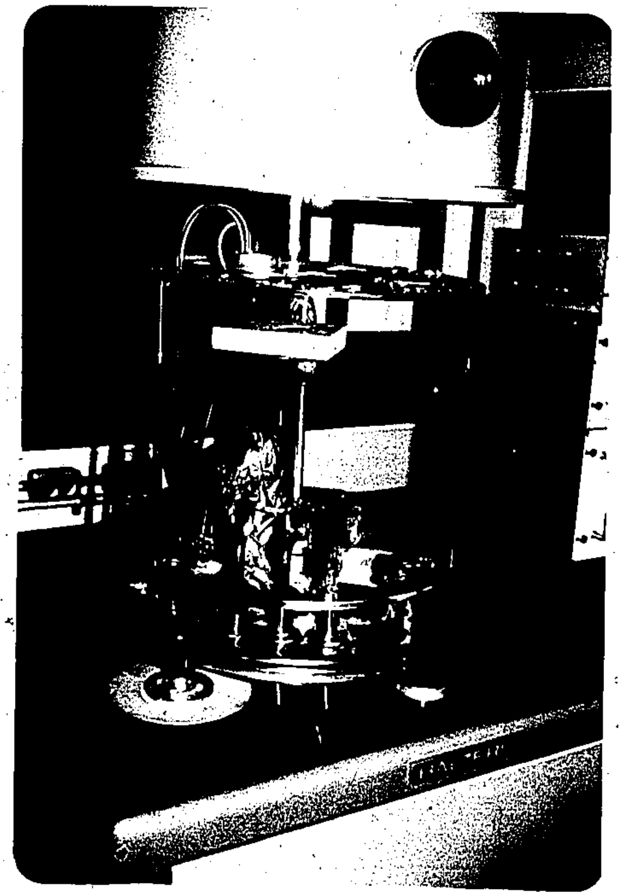


FIGURE 5.B9 INTERIOR OF BELL JAR

"break out" of the cement matrix due to differential expansions leaving a badly cracked and unusable sample.

Other metals such as zinc were used as films to try to determine which would give the whitest coating. Aluminum was found to be the best.

Originally, a thin film of 300A was applied to the surface. However, when a fixed paper light shield in contact with the sample surface which moves during the image analysis was added to the testing apparatus, this thin film soon wore through. It was attempted to put a clear thin hard coating on top of the aluminum by vacuum depositing pure silica onto the sample. Unfortunately, this resulted in a colourful diffraction pattern rather than a clear coating. Increasing the thickness of the aluminum film to 2000A which is still a very thin film, was found to give satisfactory abrasion resistance.

It was also discovered that for optimum test procedures, the oblique lighting system was not adequate to blacken the pores. Therefore the pores were filled with a black pigment which was rubbed gently into the pores with a fingertip. (See Figure 5.B10). Excess pigment was removed with a solvent moistened lint-free cloth. (See Figure 5.B11). This procedure also blackened the surface somewhat, but the contrast (the difference between the grey levels of the pores and that of the surface) was increased. (See Figure 5.B12).

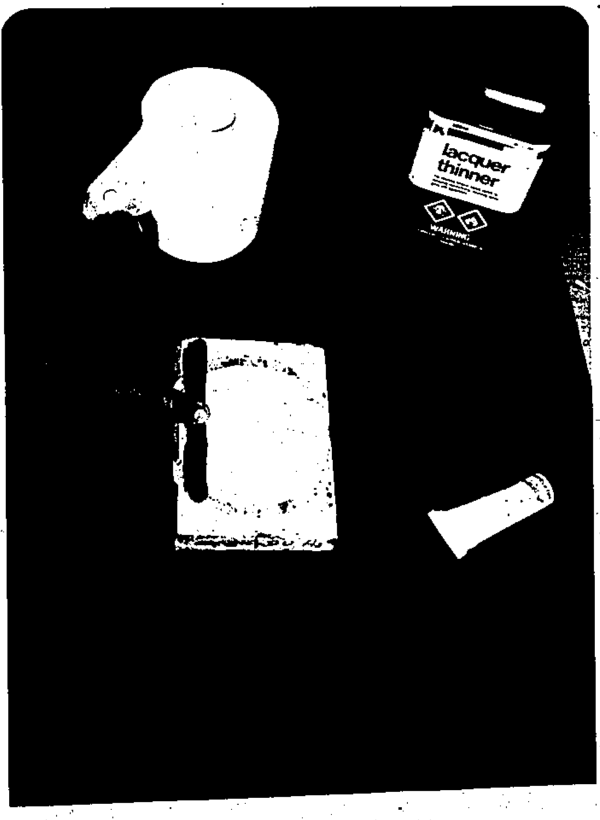

lacquer thinner
WARNING

FIGURE 5.B10 APPLYING PIGMENT

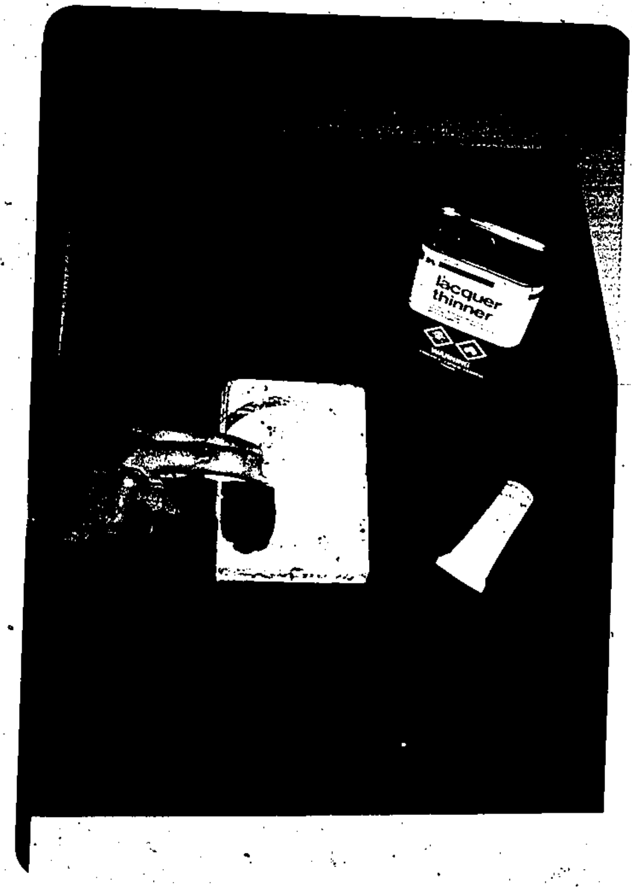

lacquer thinner

FIGURE 5.B11 REMOVING EXCESS PIGMENT

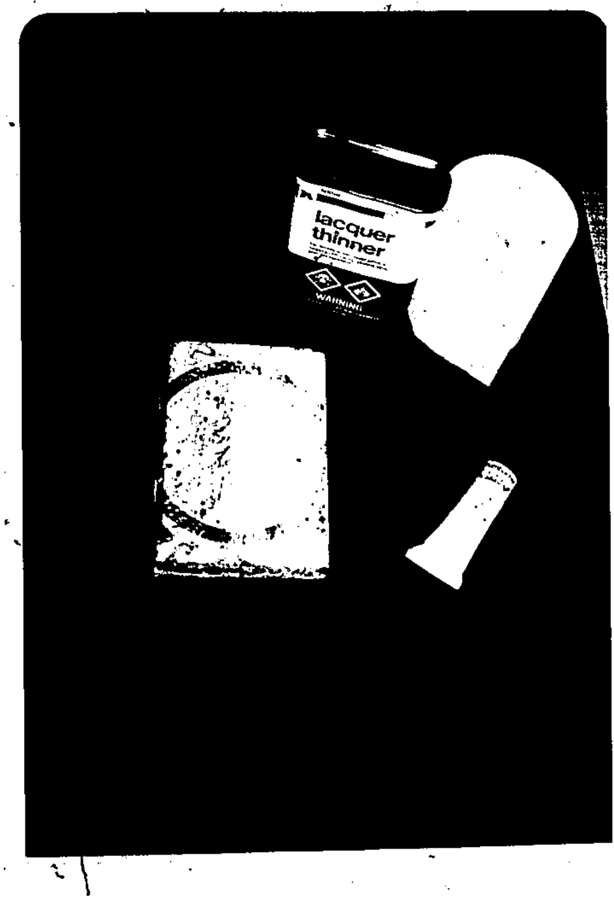

lacquer thinner
WARNING

FIGURE 5.B12 CONTRAST BETWEEN SAMPLES WITH AND WITHOUT PIGMENT

5.C Pressure Test

The pressure test for determining air content of fresh concrete was performed utilizing a Techkote White Air Meter (Type B Apparatus having a capacity of 0.25 cubic foot) Serial No. 2478, manufactured by the Techkote Co (See Figure 5.C1). The apparatus was calibrated using water in accordance with the manufacturer's instructions and was found to be in perfect working order. Sufficient concrete was taken from each batch of concrete to perform the test twice. The procedure (C231-81) was conducted as outlined in Section 3.D. The tests were carried out before casting the cylinders as varying results would have necessitated a third test. This was not necessary as the results were comparable. The results were averaged to arrive at a value for comparison with other test methods. Results are tabulated in Table 5.C1.

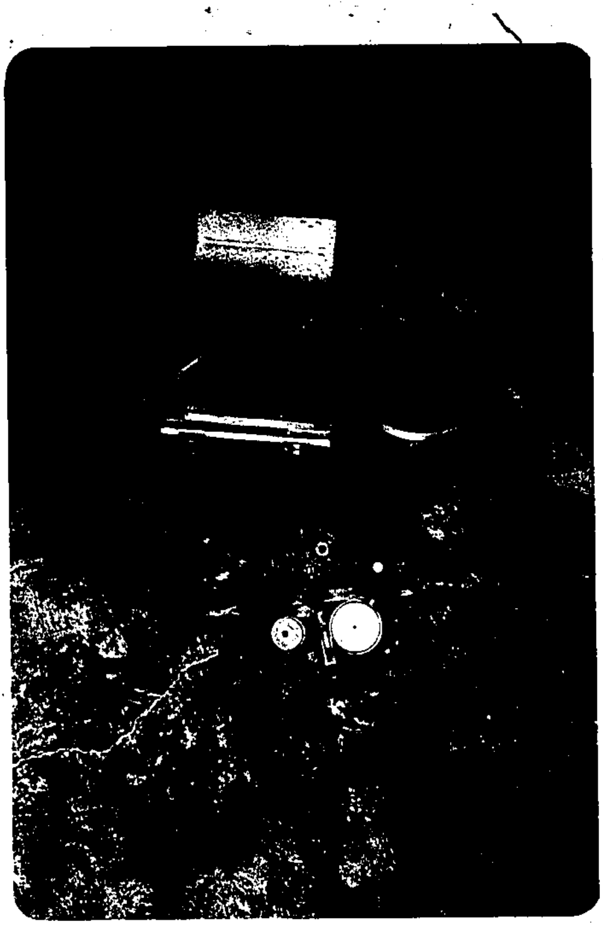


FIGURE 5.C1 PRESSURE TEST APPARATUS USED (TYPE B)

MIX NO.	TEST NO. 1 % Air Content	TEST NO. 2 % Air Content	AVERAGE % Air Content
4	9.3	9.5	9.4
5	6.1	6.0	6.1
6	2.9	2.9	2.9

TABLE 5.C1 RESULTS OF PRESSURE TEST

5.D Linear Traverse of Hardened Samples

As $^3/_4$" aggregate was used in the mix, ASTM C457 requires at least 11 square inches of prepared surface to be traversed and a minimum total traverse of 90". Since the samples used in this experiment had a prepared plane surface of about $5^1/_2$" x $3^1/_2$" it was determined to perform twenty traverses of about 5" spaced .15" apart, which resulted in a total traverse length of 90" to 100".

The equipment used to perform the traverse was constructed by the Central Research Shop at the University of Windsor, in accordance with ASTM C457 specifications. (See Figure 5.D1)

The procedure (C457-71) was conducted as outlined in Section 3.E on one sample from each of Batch # 4,5 and 6. The linear traverse was performed twice on each sample and the results averaged. These results are tabulated in Table 5.D1.

The linear traverse apparatus used was found to be quite difficult to use accurately due to several inherent design deficiencies. Possible modifications would be the elimination of the play in the binocular microscope mount, positive damping of the stage travel to eliminate run on, and revision of the binocular microscope location to eliminate having to lean over the apparatus during use and elimination of stage travel while operating the clutch to shift from on feature traverse to off feature traverse.

SAMPLE NO.		1ST TRAVERSE	2ND TRAVERSE	AVERAGE
4	A(%)	7.93	8.55	8.2
	$\bar{l}$(um)	120.05	115.38	117.72
	α(mm-1)	33.33	34.69	34.00
	L(mm)	0.15	0.13	0.14
5	A(%)	5.17	5.61	5.4
	l(um)	108.84	100.59	104.72
	α(mm-1)	36.74	39.77	38.26
	$\bar{L}$(mm)	0.15	0.14	0.14
6	A(%)	2.61	2.37	2.5
	l(um)	124.30	115.65	119.98
	α(mm-1)	32.18	34.59	33.38
	L(mm)	0.24	0.23	0.23

TABLE 5.D1 RESULTS OF LINEAR TRAVERSE

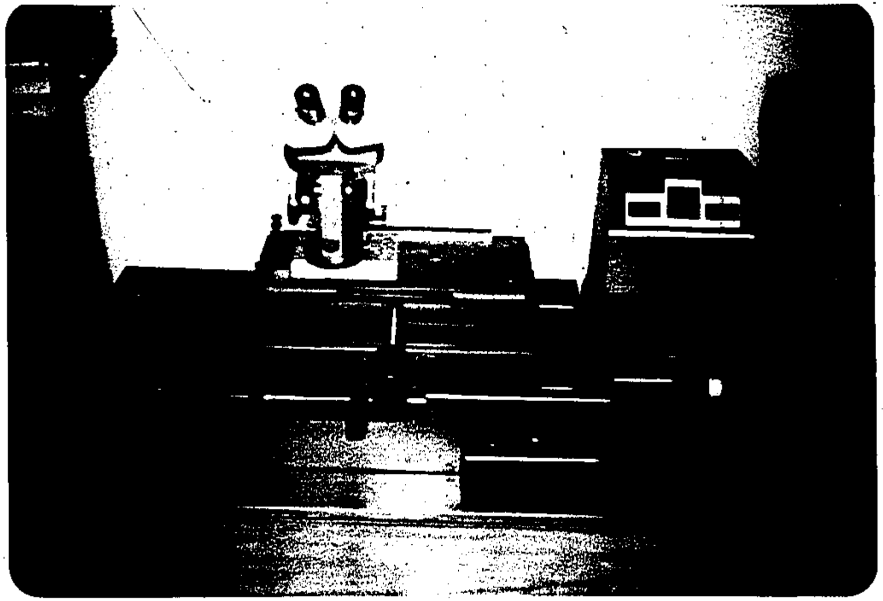


FIGURE 5.D1 LINEAR TRAVERSE APPARATUS

5.E Development of Image Analysis Procedure

5.E1 Preliminary Work

The ability of the Lemont Scientific image analysis equipment to determine air content of hardened concrete was established in preliminary work done by the author.(24a) The samples used for this work were cast, polished and aluminized as described in Sections 5A, 5B and 5C. The samples to be analyzed were placed upon the computer driven stage and made plane to the stage surface (utilizing a calipher micrometer and a small amount of modelling clay under each of the sample four corners). (See Figure 5.E1) Care must be taken in this step since with the magnifications and the lens used, depth of field is very small and the sample may become out of focus due to the movement of the sample during analysis. The pores of the sample were made to appear black by shining light from a single 150W reflector type bulb at a very low angle of incidence to the sample surface so as to cast the pores into shadow. (The lettering was removed from the face of the bulb to provide as uniform a light as possible). Sufficient contrast was achieved between the shadowed pores and the brightly lit aluminized surface. (See Figure 5.B7) This simple set up (See Figure 5.E2) required the use of the shadowing correction to balance the background light level across the sample (due to the single light source). A 50 mm Canon lens was used in conjunction with an adapter ring with an electronic magnification factor of 4X to yield a magnification of 12.2X as measured by using a test sample of known dimensions. A

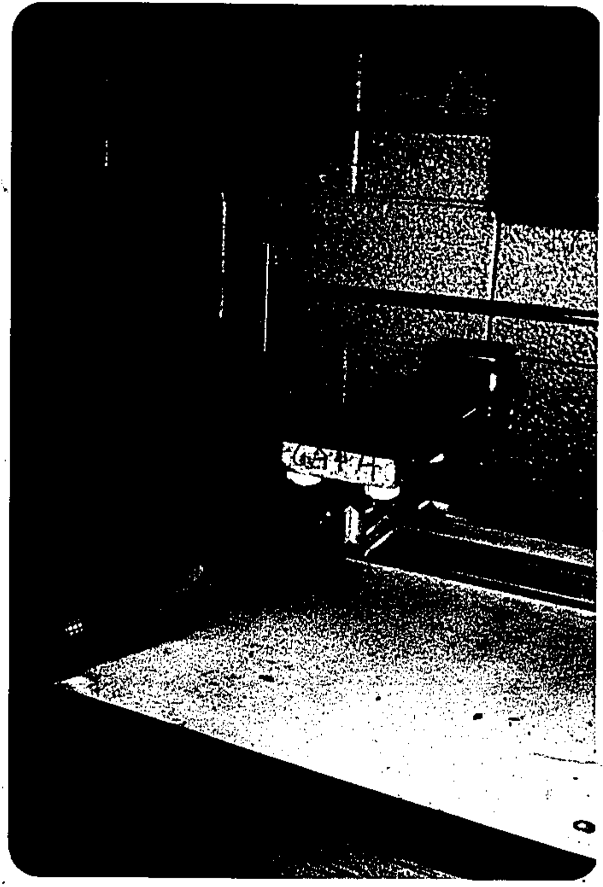


FIGURE 5.E1 LEVELLING THE SAMPLE

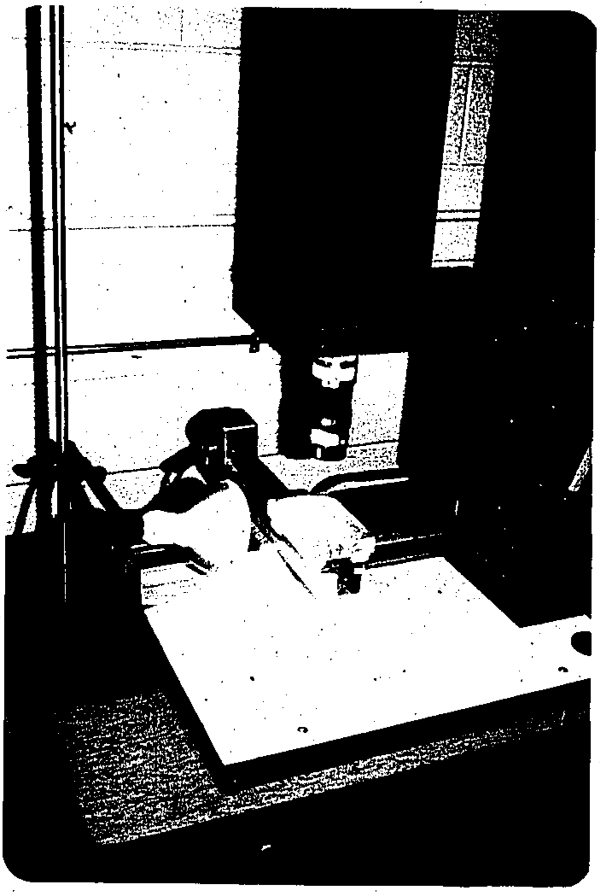
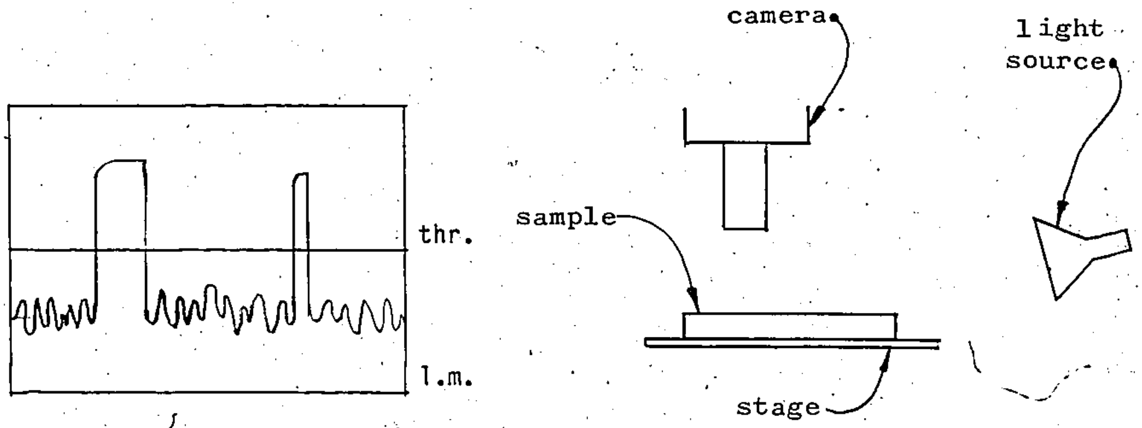


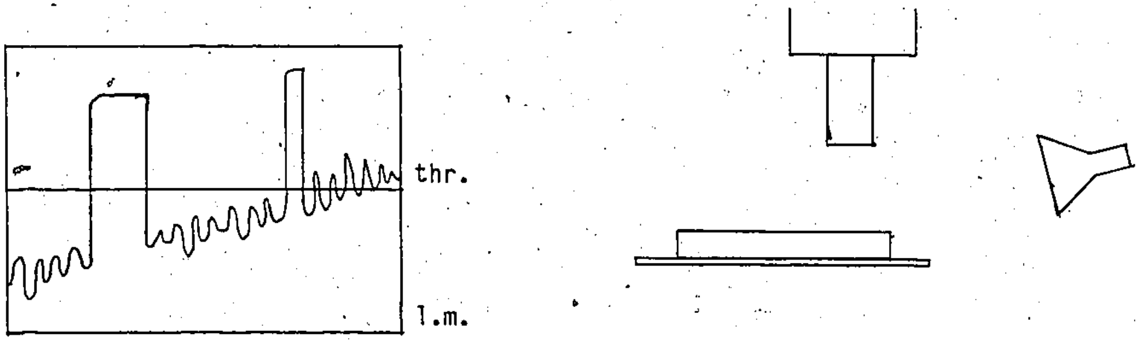
FIGURE 5.E2 PRELIMINARY SET UP

magnification of 12X was used because at that time the program would only accept whole numbers for magnification. The program used for the analysis was the Diameter Analysis Version V4.1. Input parameters were an off point density of 500 x 512 and a point density of 500 x 500. Off point density was set much higher than recommended to determine the particle size distribution yielded in a more complete search. Sweep speed was set to 200 µS/point. Guard ring was not used. Sixteen frames were analyzed for each sample with option two (Z Pattern) used for computer stage control. It was necessary to stop the analysis before each frame and readjust the lighting level, threshold control and shading correction for optimum analysis of that particluar frame. Time of analysis was approximately 40 minutes per sample. Results obtained were comparable to those obtained from pressure and linear traverse procedures. Insufficient work was done to determine reproducibility, efficiency of analysis and test procedure was still extremely cumbersome since a skilled operator was required to intervene regularly in the procedure.

The necessity for intervention before every analysis was due to the fluctuation of lighting levels because of the movement of the sample by the computer controlled stage. As the sample moved, the light level across the area of analysis changed due to changing reflectivities of the areas surrounding the area of analysis. (See Figure 5.E3) Correct shading, level and threshold adjustments for one frame may place the background level far


camera
light source
thr.
sample
l.m.
stage

a) start of analysis



b) after movement

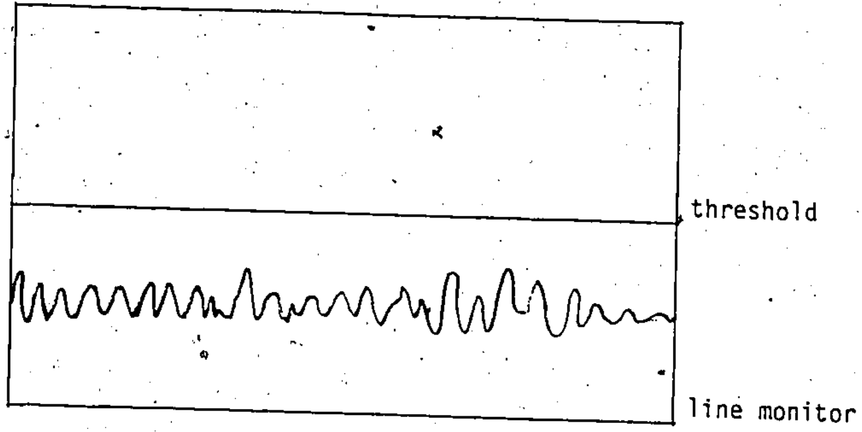
FIGURE 5.E3 EFFECT OF SAMPLE MOVEMENT OF LIGHT LEVELS

above threshold on all or part of another frame, invalidating the analysis.

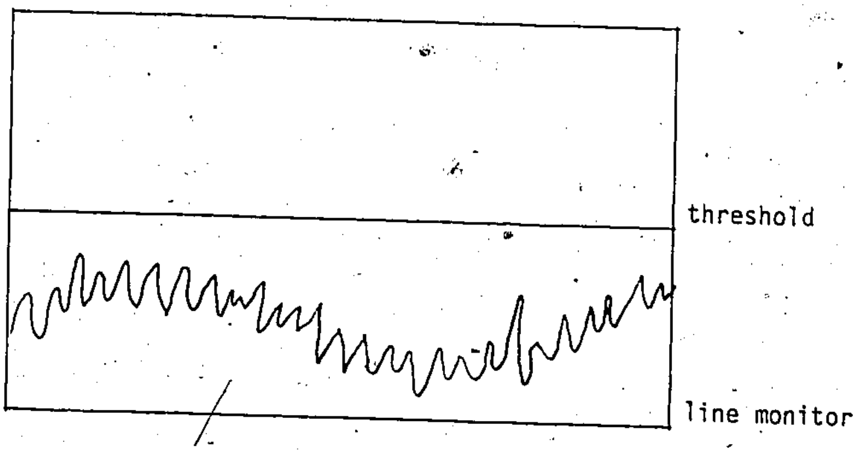
It was the purpose of this study to modify the procedure so as to allow a "hands off" analysis.

5.E2 Magnification of Lighting

It was first attempted to use a second identical light source to eliminate variation in lighting level. It was hoped that while the sample moved the amount of intensity lost from one source would be increased from the second source. The arrangement was not entirely satisfactory as there was still variation in the background light level of the frames as the stage moved. Four smaller high intensity lamps were used to try to get the light sources closer to the point of analysis and provide a uniform background light level. It was found that an A.C. light source contributed a slight cyclical variation in light output which affected the analysis. (See Figure 5.E4) Previously, this slight variation was negligible since each frame was being optimized. However it did cause problems from frame to frame, once light levels were already varying. Four small D.C. high intensity light sources were then used. This yielded an improvement but there was still too much variation in background light level. Four large 150W reflector type bulbs were then used in conjunction with milky plastic diffusers to place a large amount of diffuse light at the point of analysis so that the amount of variation due to reflectivity of surrounding surface would be negligible. The four large bulbs contributed insufficient light to accomplish this and the geometry of the set-up did not allow the lights to be moved closer. Therefore, four fresnel lens (of the type used in overhead projectors) were



(a) Analysis of White Paper Sheet using D.C. light source



(b) Analysis of White Paper Sheet using A.C. light source

FIGURE 5.E4 BACKGROUND LIGHT LEVEL FOR A.C. & D.C. LIGHT SOURCE

added to the lighting arrangement to "funnel" more light into the area of analysis. This was also not successful. Since reflectivity seemed to be the problem, it was attempted to completely darken the experimental set up and illuminate the small area of analysis with a red laser light suitably dispersed with a series of lenses. The background lighting level seemed to be fairly constant, but the amount of light supplied was insufficient for contrast between pore and non pore areas, the image dissector camera used by Lemont is not as sensitive to red light and there was much difficulty in keeping the laser focussed properly. Modification of lighting parameters was therefore not the solution.

5.E3 Use of Photography in the Procedure

Since the lighting for the sample was required to be at a low angle of incidence with the sample surface (to adequately shadow the pores), arrangement of lighting was severely limited. Using a high contrast film (Kodak Contrast Process Ortho) and a 4" by 6" negative size, a photograph (8" by 10") was made of the sample surface, correctly illuminated. A thin piece of steel, machined exactly 1 cm square was placed on the sample surface (at the edge) in order to control magnification. This photograph could then be lighted at any incident angle without affecting the darkness of the pores. (See Figure 5.E5) However, there still was a problem with reflected light causing variance in the background light level.

Since the photograph negative was approximately 1:1 in scale, an attempt was made to backlight the negative on a light table (which provided diffuse light) mounted on the computer driven stage. Because the light was transmitted through the image rather than reflected off it, it was hoped reflectivity would be less of a problem, since the background light could be increased easily. However, movement of the stage did result in a variation in the background light levels.

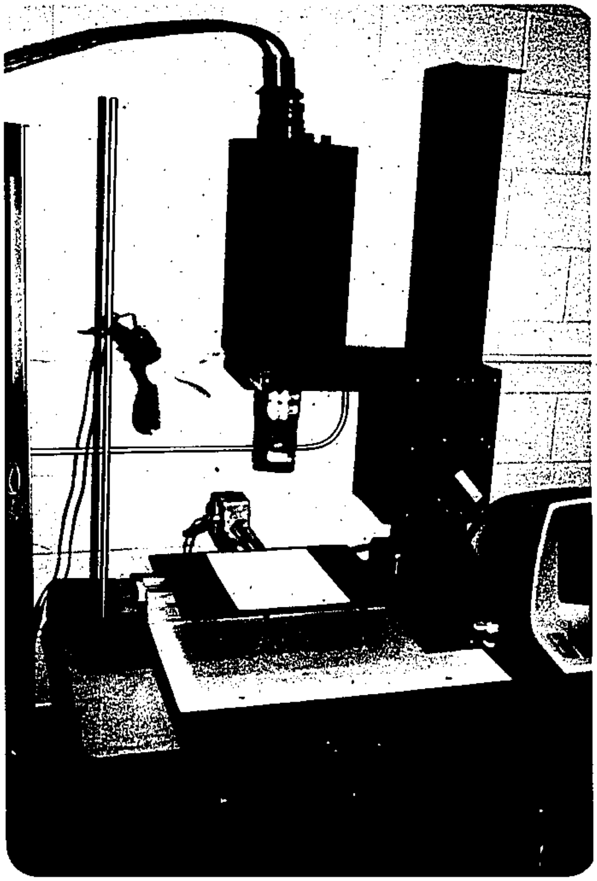


FIGURE 5.E5 ANALYSIS OF PHOTOGRAPH OF SAMPLE SURFACE

5.E4 Coverage of All Reflecting Surface

Since the main problem seemed to be with reflected light, an attempt was made to cover all reflecting surfaces. The set up area was draped with black velvet. The main problem reflecting areas were the portions of the computer controlled stage. A template was designed to cover the entire area except for a 1" diameter port hole through which the analysis could be conducted. (See Figure 5.E6) A black soft paper screen was used since the aluminum surface of the sample is both thin and soft, easily abraded. The only reflective surface, therefore, was the 1" diameter portion of the sample revealed by the port hole. Even though the sample was able to move under the cover, the reflective surface shown never changed location or size. The result of this was that once the light level was balanced for the first frame, the entire analysis could be conducted with the same values for, level, threshold and shading.

Unfortunately, due to the high level of light intensity required for the analysis, with the resultant high heat output of the four 150W reflectors, the paper mask caught fire. A new cover was fabricated out of heat resistant phenolic board. This cover had to be held off the surface of the sample since the plastic would have abraded the aluminum coating. The phenolic board warped due to the heat to the extent that it was unusable.

A single high intensity quartz light source (120V, 300W) was adopted to provide illumination for the procedure. The background light level was balanced electronically. Without the

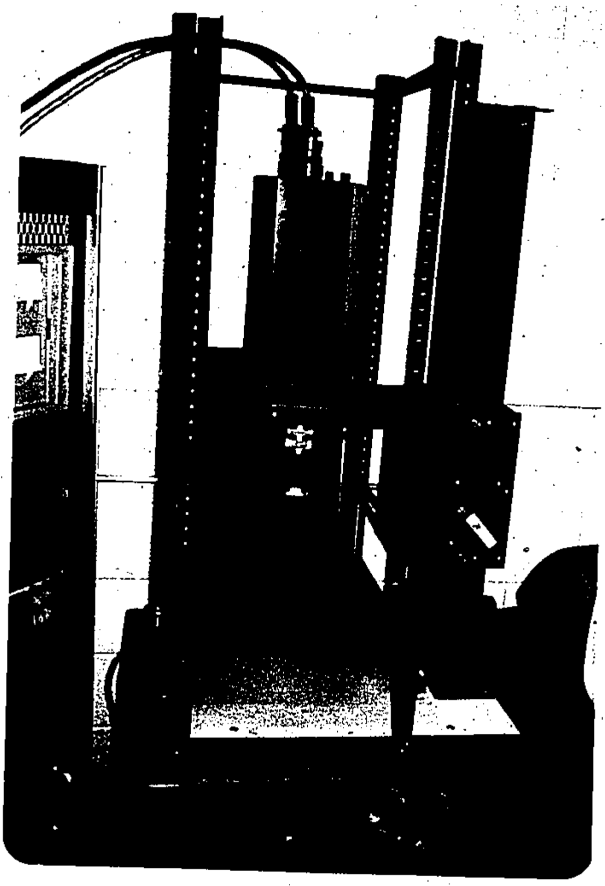
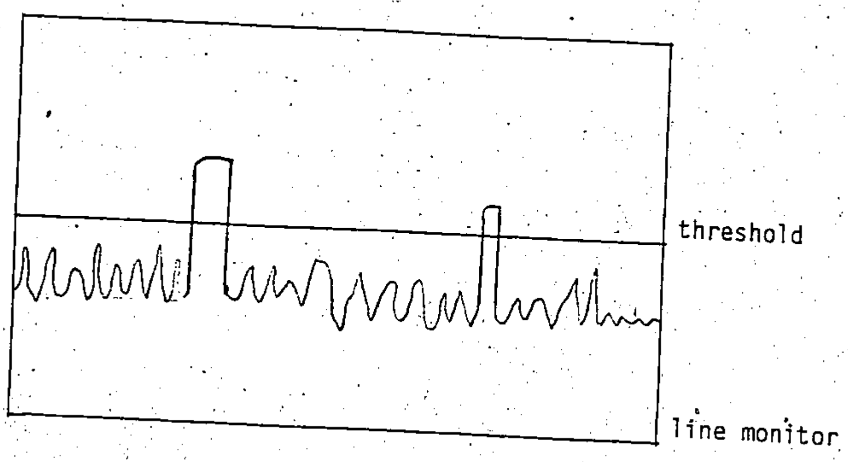


FIGURE 5.E6 SYSTEM FOR COVERAGE OF REFLECTING SURFACES

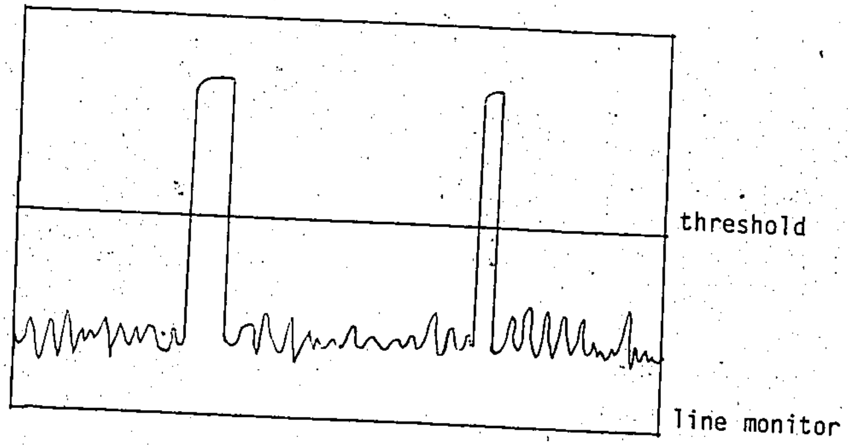
high heat levels of the four 150W reflector bulbs, the paper screen could be used. After being analyzed several times, the aluminum surface of the sample began to wear thin, so the masking procedure was revised to apply 3000A rather than 500A of aluminum to the sample surface.

5.E5 Pigmentation of Pores

The 300W bulb did not supply as much light intensity as the four 150W bulbs. This resulted in a decrease in the contrast between the pores and the background level, so that the signal to noise ratio became a problem. An attempt was made to darken the pores with various materials (carbon black, black pigment) and it was found that the black pigment worked best. (See Section 5.B3 for procedure) This greatly increased the signal to noise ratio, allowing unaided analysis of an entire sample. (See Figure 5.E6 for effect of pigmentation)


threshold
line monitor

(a) without pigmentation


threshold
line monitor

(b) with pigmentation

FIGURE 5.E7 EFFECT OF PORE PIGMENTATION OF SIGNAL TO NOISE RATIO

5.F Final Experimental Image Analysis Procedure

The samples were cast, polished, masked and pigmented as described in Sections 5.A1,2 and 3 (2000Å of aluminum was used to mask samples). The experimental set up was described in preceding sections. (See Figure 5.E8) The Program used for Analysis was Lineal Analysis. While Lineal Analysis does not provide as extensive information as Diameter Analysis V4.1. it runs much faster than the Diameter Analysis. The program provides Air Content by volume and sufficient information to calculate specific surface and Power's Spacing Factor (assuming paste content is known). The Diameter Analysis has a problem with the variation in pore diameter of two orders of magnitude (10 to 1000 microns) since off point density sufficient to detect most 10 micron pores will encounter larger voids thousands of times making the program very slow running. Many voids will lie on the boundary of a given frame, distorting the analysis.

Input parameters used were 512 points/line, 10 lines/frame with 100 frames analyzed. Each frame was 12 mm^2 (3.46mm x 3.46mm). Since there were 512 points/line, spacing between points was 6.766 microns. The smallest possible chord to be encountered would therefore be 6.766 microns. Sweep speed was 16 µs/pt. Stage control chosen was Option 3 (Spaced Stage Control Scan Pattern). Magnification used was 26X. A Nikon F4, 105mm Macrolens was used on the Image Dissector Camera. The sample from Batch No. 5 was analyzed 30 times. Samples from Batches No. 4 & 6 could only be analyzed 15 times because of degradation of the aluminum film. Time of analysis was 10 minutes.

An extended analysis of the sample from Batch No.5 was done to determine if results would vary from those found in the analysis used. A total test line of 177.2 meters was used as compared to a total test line of 3.462 meters used for the regular analysis. All other parameters remained the same. Time of analysis was 90 minutes.

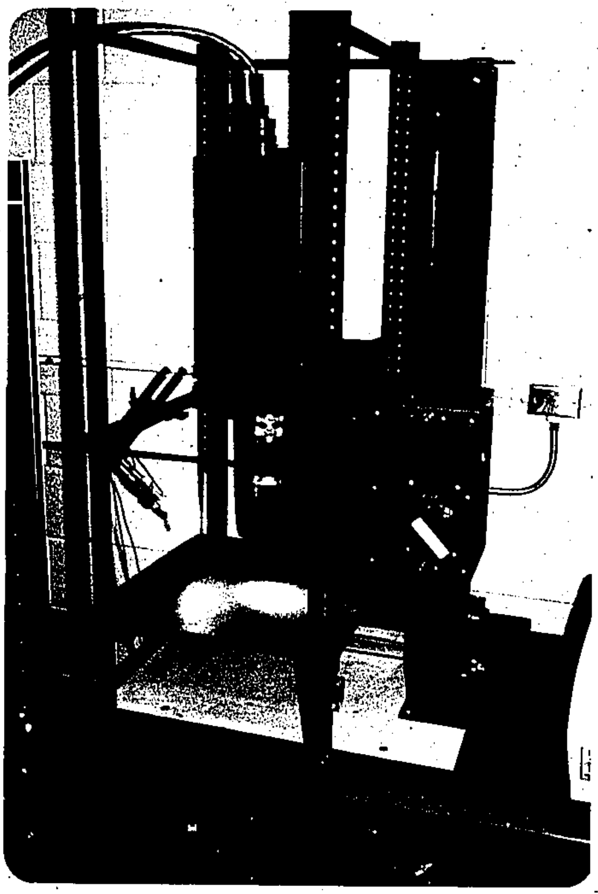


FIGURE 5.E8 FINAL EXPERIMENTAL SET UP

CHAPTER 6

RESULTS

6.A Experimental Results

Air Content (% Volume), Average Chord Length, Specific Surface and Spacing Factor for the thirty separate evaluations of the prepared concrete sample from Batch No. 5 may be found in Table 6.A1. Results of the fifteen evaluations of the prepared concrete sample from Batch No. 4 may be found in Table 6.A2 and the results from the fifteen evaluations of the prepared concrete sample from Batch No. 6 may be found in Table 6.A3

Results are based on a test line 3.462 meters long for each sample. An average of 4208 voids were encountered for the sample from Batch No. 4. During the analysis of the sample from Batch No. 5, an average of 2937 voids were encountered. The sample from Batch No. 6 had an average of 1582 voids encountered during analysis.

An extended analysis of the sample from Batch 5 yielded an air content of 6.193%, average chord length of 72.66 microns, specific surface of 55.05 mm^2/mm^3 and a spacing factor of 0.95mm. Results are based on 151057 chords discovered along a test line 177 meters long.

Evaluation No.	% Air Content	Av. Chord Length (um)	Specific Surface $(mm)^{-1}$	Spacing Factor (mm)
1)	5.907	72.59	55.10	0.10
2)	6.191	74.36	53.79	0.10
3)	6.032	72.99	54.80	0.10
4)	6.272	72.08	55.49	0.09
5)	5.969	73.51	54.41	0.10
6)	6.176	71.36	56.05	0.09
7)	6.219	73.54	54.39	0.10
8)	5.755	73.10	54.72	0.10
9)	5.856	72.16	55.43	0.09
10)	5.888	71.95	55.59	0.09
11)	5.955	72.05	55.52	0.09
12)	6.310	70.30	56.90	0.09
13)	6.358	70.03	57.12	0.09
14)	6.315	72.03	55.53	0.09
15)	6.389	71.25	56.14	0.09

TABLE 6.A1 RESULTS AIR CONTENT EVALUATION BY IMAGE ANALYSIS BATCH NO. 5

Evaluation No.	% Air Content	Av.Chord Length (um)	Specific Surface $(mm)^{-1}$	Spacing Factor (mm)
16)	6.320	70.71	56.57	0.09
17)	6.377	70.33	56.87	0.09
18)	6.271	69.53	57.53	0.09
19)	5.963	72.89	54.88	0.10
20)	5.911	72.65	55.06	0.10
21)	5.938	71.30	56.10	0.09
22)	6.135	72.33	55.30	0.09
23)	6.135	73.51	54.41	0.10
24)	6.121	72.51	55.16	0.10
25)	6.140	70.82	56.48	0.09
26)	5.978	72.12	55.46	0.09
27)	5.939	71.38	56.04	0.09
28)	5.950	71.39	56.03	0.09
29)	6.013	71.02	56.32	0.09
30)	6.195	71.41	56.01	0.09

TABLE 6.A1 RESULTS AIR CONTENT EVALUATION BY IMAGE ANALYSIS
BATCH NO. 5 (Continued)

Evaluation No.	% Air Content	Av. Chord Length (um)	Specific Surface $(mm)^{-1}$	Spacing Factor (mm)
1)	10.03	93.20	42.92	.09
2)	10.66	86.25	46.38	.07
3)	10.55	88.58	45.16	.08
4)	11.37	86.25	46.38	.07
5)	10.62	88.60	45.15	.08
6)	10.05	90.04	44.42	.08
7)	10.52	84.85	47.14	.08
8)	11.19	85.93	46.55	.07
9)	11.47	86.08	46.47	.07
10)	10.54	85.77	46.64	.08
11)	9.75	82.57	48.44	.08
12)	9.89	83.64	47.82	.08
13)	10.53	89.93	44.48	.08
14)	10.60	86.33	46.33	.08
15)	9.47	80.00	50.00	.08

TABLE 6.A2 RESULTS AIR CONTENT EVALUATION BY IMAGE ANALYSIS BATCH NO. 4

Evaluation No.	% Air Content	Av.Chord Length (um)	Specific Surface $(mm)^{-1}$	Spacing Factor (mm)
1)	4.22	86.75	46.11	.14
2)	4.17	82.13	48.70	.13
3)	3.43	83.36	47.98	.13
4)	3.94	87.29	45.82	.14
5)	3.67	85.42	46.83	.14
6)	4.06	87.45	45.74	.14
7)	4.23	85.51	46.78	.14
8)	4.04	86.48	46.25	.14
9)	3.87	82.12	48.71	.13
10)	4.27	91.88	43.54	.15
11)	3.82	87.25	45.83	.14
12)	3.64	83.99	47.62	.14
13)	3.63	81.17	49.28	.13
14)	4.22	94.63	42.27	.15
15)	4.154	93.62	46.28	.15

TABLE 6.A3 RESULTS AIR CONTENT EVALUATION BY IMAGE ANALYSIS BATCH NO. 6

6.B Statistical Analysis of Results

A mean ($\overline{x}$) and standard deviation(s) of the test parameters (air content, average chord length, specific surface, and spacing factor) were calculated for the series of analyses done on each sample. (See Table 6.Bi).

The image analysis procedure evaluated air content (% volume) to be 10.48% ± 1.14% for the sample from Batch No.4, 6.10% ± 0.36% for the sample from Batch No. 5, and 3.96% ± 0.53% for the sample from Batch No. 6, with a 95% confidence level in all cases. The analysis of a sample was not done using the exact same 100 frames for each analysis in the series. However, the frames were arranged in a uniformly spaced pattern over the sample surface so that a given frame would have been located in the same general area for each analysis (i.e. if a frame was superimposed over a piece of aggregate on the first analysis, it would have likely been over that piece of aggregate for the following analysis). There was some movement of the location of the frames on the sample surface from analysis to analysis as evidenced by the varying number of chords collected. The effect of this movement on air content would be increased as the air content of the paste portion of the concrete increases since movement of a frame off aggregate onto paste would result in increasingly more chords being evaluated. This effect could be diminished by using more frames in an analysis of concrete with high air content. The slightly greater variability of results

Batch Number	Air Content		Av. Chord Length (mm)		Specific Surface(mm)-1		Spacing Factor (mm)	
	$\overline{X}$	S	$\overline{X}$	S	$\overline{X}$	S	$\overline{X}$	S
4	10.48	0.58	86.60	4.08	46.29	1.74	0.08	0.0044
5	6.10	0.18	71.91	1.15	55.64	0.89	0.09	0.0017
6	3.96	0.27	85.87	2.77	46.28	2.12	0.14	0.0066

TABLE 6.B1 STATISTICAL ANALYSIS OF RESULTS

for the sample from Batch No. 6 could possibly be due to the greater scarcity of voids in the paste portion of the concrete. Again, more frames analyzed would decrease the variability of results. Use of this procedure to evaluate concrete of average air content (7%) would likely yield results with an accuracy of ±.5% with a confidence level of 95%.

Specific surface (mm^2/mm^3) was determined by the image analysis procedure to be 46.29 mm^{-1} ± 3.41 for the sample from Batch No. 4, 55.64 mm^{-1} ± 1.76 for the sample from Batch No. 5, and 46.28 mm^{-1} ± 4.16 for the sample from Batch No. 6, with a 95% confidence level in all cases. Variation of results was seen to increase for lower and higher than average total air contents. For analysis of samples with a low or high air content, more frames should be used.

Spacing factor (mm) was evaluated by the image analysis procedure to be 0.08 mm ± 0.009 for the sample from Batch No. 4, 0.09 mm ± 0.003 for the sample from Batch No. 5, and 0.14 mm ± 0.013 for the sample from Batch No. 6, within a 95% confidence level in all cases. Spacing factor for the sample from Batch #4 was calculated using the alternate formula since $p/a < 4.33$.

The sample from Batch No. 5 had an average chord length (71.91 microns) which was less than those found for the samples from Batch No. 4 and Batch No. 6 (85.87 microns and 86.60 microns, respectively). Since the same air entraining agent was used in all cases, it was expected that there would be a similar distribution of pore sizes, resulting in a common average chord length found during analysis. It was noted that the sample from Batch No. 5 had less entrapped air exposed on the surface analyzed than the other two samples, possibly due to a slightly greater vibration while casting the cylinder. This would account for both the lower average chord length encountered during the analysis of the sample from Batch No. 5 and the decreased variation of results for air content and void parameters since entrapped air would tend to distort results should a frame be superimposed on the boundary of an entrapped air pore and be moved slightly from analysis to analysis. A comparison of chord length distributions for the three samples show that far fewer chords larger than 316 microns were encountered during the analysis of the sample from Batch No. 5 than for the other two samples. (See Appendix C).

The results of the extended analysis for the sample from Batch No. 5 were not significantly different from those found from the standard analysis used in this study.

6.C Comparison of Results with Linear Traverse and Pressure Test

The results of the Image Analysis Procedure, while comparable to those given by the Pressure Method, are generally higher. (See Table 6.C1). This is likely due to large water filled voids in the plastic concrete which would be immeasureable by the Pressure Method. These voids would appear as "entrapped air voids" in the hardened concrete and would be measured by the Image Analysis Procedure. The hardened concrete sample from Batch No. 5 did not display many of these "entrapped air voids". This is consistent with the close agreement for the two test methods in the case of the sample from Batch No.5.

The Linear Traverse Method yielded air contents that while correlating with those of the Image Analysis Procedure, were considerably lower. This can likely be attributed to the relative inexperience of the operator and the poor design of the Linear Traverse equipment used. For all samples, the average chord length encountered was considerably higher for the Linear Traverse Method than that for the Image Analysis Procedure (i.e. for the sample from Batch No. 4, the average chord length found by the Linear Traverse method was 120.0 microns compared with 86.6 microns found by the Image Analysis Procedure and 0.638 voids/mm were encountered in the Linear Traverse while 1.215 voids/mm were encountered in the Image Analysis Procedure). This implies the operator missed many small voids during the Linear

Batch Number	Pressure Method (%)	Linear Traverse (%)	Image Analysis (%)
4	9.4	8.2	10.5
5	6.1	5.4	6.1
6	2.9	2.5	4.0

TABLE 6.C1 COMPARISON OF AIR CONTENT AS TESTED BY PRESSURE METHOD, LINEAR TRAVERSE AND IMAGE ANALYSIS

Traverse which were included in the results of the Image Analysis, thereby increasing the size of the average chord encountered.

A comparison of air void parameters (See Table 6.C2) is consistent with this possibility. The Specific Surface is, in every case, lower as calculated from the results of the Linear Traverse than that yielded from the results of the Image Analysis Procedure. Similarly, while both procedures show the Spacing Factor to be sufficient (less than 0.2[(33)]) to ensure protection against frost damage (Linear Traverse shows Batch No. 6 to be marginal), the Spacing Factors were consistently lower when calculated from data from the Image Analysis Procedure. Missing small voids in the Linear Traverse greatly affects the calculation of Specific Surface and Spacing Factor.

	Specific Surface $(mm)^{-1}$		Spacing Factor (mm)	
Batch Number	Linear Traverse	Image Analysis	Linear Traverse	Image Analysis
4	34.00	46.29	0.14	0.08
5	38.26	55.64	0.14	0.09
6	33.38	46.28	0.23	0.14

TABLE 6.C2 COMPARISON OF AIR VOID PARAMETERS AS TESTED BY LINEAR TRAVERSE AND IMAGE ANALYSIS

6.D Comparison Results to Those Obtained by Other Researchers

Amsler and Chamberlin(2) reported that, between 5 trained operators performing the Linear Traverse method on the same samples, there was a significant difference in their measure of air content. However, they concluded that a properly trained operator should be able to measure air content to within ± .6 percentage points of the true value with a 95% confidence level. In tests performed in a laboratory, they also attempted to correlate air content as measured by the Pressure method and the Linear Traverse method for a given batch of concrete. The results showed variations of as much as 2% (7% to 9%) in the results as measured by the Linear Traverse method for 3 batches of concrete that had all been measured as having an air content of 7% by the Pressure Method. For nearly all cases, the air contents measured by Linear Traverse tended to be higher than those measured by the Pressure Method. This is consistent with the results obtained in this study.

Mielenz and Wolkodoff(25A), comparing results for three operators performing Linear Traverse on the same samples, found that individual results varied as much as 9% from the average results (for a 6% air content, this would be ± 0.5%). However the average deviation found was only 2.3%. Since tests of trained operators seem to indicate significant operator to operator variation for air content as measured by Linear Traverse for a given sample, it is possible that variations between results of an Image Analysis Procedure and a ~~Linear~~ Traverse may likely be attributed to variation inherent in the Linear Traverse method.

Mather(23A) found that air contents of plastic concrete measured in the laboratory by the Pressure Method and micrometric (by Linear Traverse) air contents of specimens from the same batch show agreement in some cases and disagreement in others. This might be due to the problem of large water filled voids in the fresh concrete indicated in this study.

Chatterji and Gudmusson(5) found that in 7 analyses of a given hardened concrete sample by an Image Analysis procedure (320 frames of 1mm^2 analyzed each time), the results showed an air content of 7.34% ± 0.45% with a confidence level of 97.5% (would be 7.34% ± 0.39% with a confidence level of 95%). This is comparable to the reproducibility found in this study for a comparable air content (i.e. 6.10% ± 0.35% with a confidence level of 95%). Chatterji and Gudmusson also compared the air contents and void parameters of a given sample as measured by their Image Analysis with air contents and void parameters for the same sample as measured by the Linear Traverse Method. The two techniques compared quite favourably, with the Rosiwal giving slighty higher values for air content, Specific Surface and Spacing Factor. This correlation is likely due to a well conducted Linear Traverse on good equipment. The two researchers also compared air contents of fresh concrete batches as measured by the Pressure Method with air contents of hardened concrete samples from those batches as measured by their Image Analysis Procedure. They found a correlation coefficient of 0.92 with a linear regression equation of:

$$Y = 1.07\,X - 0.14$$

where Y is the air content in the fresh concrete and X that in hardened concrete. This indicates slightly lower values for air contents as measured by the Pressure method, which is at variance with this study and others. Possibly, care was taken to ensure no large water filled voids were present in the fresh concrete.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.A Conclusions

1. The Image Analysis Procedure developed in this study will yield Air Content and void parameters with a reproducibility comparable to other Image Analysis procedures (which required manual intervention) and to the Linear Traverse method (which is subject to operator error).

2. The accuracy of the results given by the Image Analysis Procedure is similar to that of other methods. Variance between results of other methods and the Image Analysis Procedure may be attributable to inaccuracies inherent in the other methods.

3. The Image Analysis Procedure used in this study is a very quick test (10 minutes) while providing results comparable to those of the Linear Traverse method. If additional reproducibility is required, it is possible to greatly increase the area analyzed in the Image Analysis procedure without a large expenditure of time (i.e. doubling the amount of analysis used in this study

in the Image Analysis procedure would require an additional 10 minutes of machine time while doubling the amount of analysis done by Linear Traverse would require an additional 8 hours of operator time).

4. The Image Analysis Procedure, with no additional time required, provides information about the pore size distribution not available from a standard Linear Traverse. This information could be used to calculate a durability parameter comparable to Power's Spacing Factor, but based only on those voids that are of a size to be effective in frost damage protection.

7.B Recommendations

1. Recent work(21) seems to indicate that durability of concrete is only empirically related to air content and size distribution of pores with diameters in the range of 10 to 1,000 microns. It seems durability may be directly related to the total volume of and size distribution of voids in the 0.1 micron to 2 micron range. If this is demonstrated, work should be done to determine if the Lemont Scientific Image Analysis equipment with an appropriate lens system and the Diameter Analysis software is capable of evaluating these parameters using a procedure similar to the one employed in this study. If not, a mercury intrusion porosimeter should be acquired and work done to develop a standard test to assess the frost damage resistance of hardened concrete by evaluating the total volume of and size distribution of pores with diameters in the 0.1 to 2 micron range.

2. If it is demonstrated that pores with diameters of 0.1 to 2 microns are responsible for the frost damage resistance of concrete, it is possible that salt crystalizing in and filling these small voids making them ineffective is the reason that application of salt to concrete road surfaces sometimes renders air content ineffective in protecting the concrete against frost

damage. It would be interesting to prove or disprove this hypothesis using samples taken from concrete bridge decks that were constructed with sufficient air content but, because of regular salt applications, suffered frost damage.

3. The Linear Traverse apparatus used in this study should be scrapped, as its design precludes any possibility of repair to an adequate level of operation.

4. It would be of interest to submit existing hardened concrete samples from this study to qualified laboratories for evaluation of air content and void parameters by the Linear Traverse method. These results could be averaged and compared with the results of the Image Analysis procedure. If the Linear Traverse equipment used is of the type that uses a microprocessor to retain all chord lengths encountered, these could be compared with those found by the Image Analysis Procedure since the Lineal Analysis program will retain and print out all chord lengths encountered during analysis, grouping them in size classifications if desired.

5. Work should be done to determine if use of a polarized light source and special filter for the camera could eliminate the need for the template used in this study to solve problems with reflected light.

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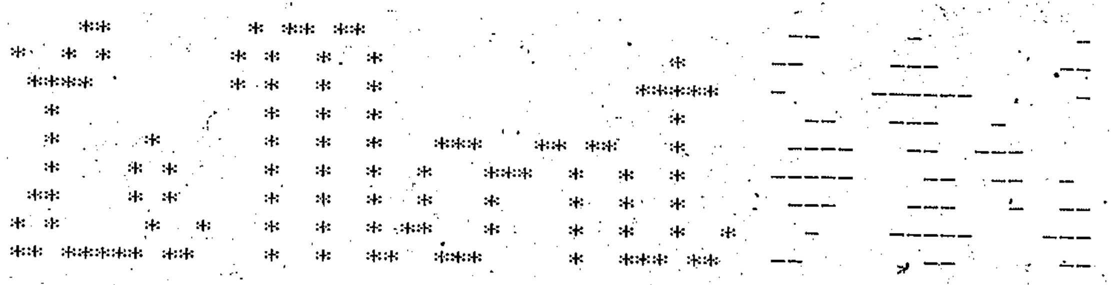
APPENDIX A

TYPICAL PRINTOUT
"LINEAL ANALYSIS"



```
  LEMONT SCIENTIFIC IMAGE ANALYSIS  PROGRAM  P-024E  V81A-UON
        CROSS-SECTION CHORD LENGTH ANALYSIS

 SAMPLE ID: 4A3 100F 10L/F 8                                       81/09/19

 TYPE 3 "SPACED" STAGE CONTROL SCAN PATTERN FOR   10 X   10 FRAMES
 LENGTH OFSTAGE TRAVEL = 7. 00E 01 X 7. 00E 01 MM
 TOTAL AREA TO BE ANALYZED= 1. 20E 03 MM

 RUN PARAMETERS:            CHORD DATA:             FRAME DATA:
 --------------------       --------------------    ----------------------
    512  PTS/LINE             4500.  TOTAL           1. 20E 03 AREA (SQMM)
     10  LINES/FRAME           367   MAX CHORD            100 FRAMES
  26. 00 MAG.

 CHORDS/FRAME:
 --------------------
   45. 08 MEAN
   34. 02 ST.  DEV.

  LINEAL ANALYSIS RESULTS:

  POINT TO POINT SPACING            6. 761E 00 UM
  VOLUME FRACTION                   1. 119E 01 %
  AVERAGE CHORD LENGTH              8. 593E 01 UM
  AVERAGE CENTER TO CENTER SPACING  7. 679E 02 UM
  SURFACE TO VOLUME RATIO           5. 209E-03/UM
  EDGE TO EDGE MEAN FREE PATH       6. 819E 02 UM
  TOTAL TEST LINE                   3. 462E 06 UM
  TOTAL NO. POINTS                  5. 120E 05
  NO. POINTS ON                     5. 730E 04
  NO. FEATURES                      1. 302E-03/UM
```

2

```
SAMPLE ID: 4A3 100F 10L/F 8                                                  81/09/19
CHORD LENGTH DISTRIBUTION (UM.)

----------- CLASS --------0             1             2             3             4
  LIMIT      COUNT      %  0-------------0-------------0-------------0-------------0
5.60E 00 0.00E 00    0.00[
1.00E 01 1.50E 03   33.27[*************************************************
1.78E 01 4.27E 02    9.47[**************
3.16E 01 2.38E 02    5.28[*******
5.60E 01 4.70E 02   10.43[***************
1.00E 02 6.05E 02   13.42[********************
1.78E 02 6.46E 02   14.33[*********************
3.16E 02 4.01E 02    8.90[*************
5.60E 02 1.58E 02    3.50[*****
1.00E 03 5.40E 01    1.20[*
1.78E 03 8.00E 00    0.18[
3.16E 03 1.00E 00    0.02[
```

APPENDIX B

TYPICAL PRINTOUT

"DIAMETER ANALYSIS"

U

LEMONT SCIENTIFIC IMAGE ANALYSIS

SAMPLE ID: 6A04 1/3/78

CROSS SECTION ANALYSIS

```
PARMS. FOR THIS RUN:
 OFF PT. DENSITY =  500 X  512
 ON PT. DENSITY =  500 X  500
 SWEEP SPEED =   200 US/PT.
 MAGNIFICATION =    12
 SCALE FACTOR =  15.0000 UM/PT
 SAMPLE-ID: 6A04                                  1/3/78

DATA COLLECTION FOR . 219 PARTICLES

MAX. DIAM. = 1777.676 UM   MIN. DIAM. =   15.000 UM
TOTAL LENGTH OF TEST LINE =  5.4729E 01 M

PARTICLES/FRAME:   MEAN=   13.688   STAND. DEV. =   6.867

 PART  CHEMICAL       AVERAGE DIAMETER   MIN/MAX      VOLUME  REL.   SURFACE/
 TYPE   NAME          ----------------   -----------    %     VOL.   VOLUME
                       MEAN    SIGMA     MEAN SIGMA             %    (1/UM)
                       (UM)    (UM)

       ALL TYPES      224.46   192.98   0.43 0.288    0.023   100.   0.000240
```

```
SAMPLE ID: 6A04                                        1/3/78

        FOR ALL TYPES

AVERAGE DIAMETER (UM) DISTRIBUTION
------------------------------------------------------------------------

CLASS               CLASS   0    1    2    3    4    5    6    7    8    9    10
LIMIT        NO.      %     -----0----0----0----0----0----0----0----0----0----0
    25.00     0     0.00 [
    40.00     1     0.46 [
    63.00    13     5.94 [***
   100.00    48    21.92 [***********
   160.00    41    18.72 [*********
   250.00    45    20.55 [**********
   400.00    42    19.18 [**********
   630.00    22    10.05 [*****
  1000.00     5     2.28 [*
  1600.00     2     0.91 [
SAMPLE ID: 6A04                                                1/3/78

          FOR ALL TYPES

MIN/MAX DIAMETER DISTRIBUTION
--------------------------------------------------------------

CLASS            CLASS   0    1    2    3    4    5    6    7    8    9    10
LIMIT      NO.     %     -----0-----0-----0-----0-----0-----0-----0-----0-----0-----0
   0.050    9    4.11   [**
   0.100   26   11.87   [******
   0.150   22   10.05   [*****
   0.200   12    5.48   [***
   0.250   19    8.68   [****
   0.300    9    4.11   [**
   0.350    6    2.74   [*
   0.400    1    0.46   [
   0.450   11    5.02   [***
   0.500    4    1.83   [*
   0.550    6    2.74   [*
   0.600    5    2.28   [*
   0.650   18    8.22   [****
   0.700    7    3.20   [**
   0.750   21    9.59   [*****
   0.800   21    9.59   [*****
   0.850   15    6.85   [***
   0.900    6    2.74   [*
   0.950    1    0.46   [



COMMENTS,
```

APPENDIX C

"COMPARISON OF CHORD LENGTH DISTRIBUTIONS FOR SAMPLES FROM BATCHES NO.4, No. 5 AND No. 6"

2

```
SAMPLE ID: 4A3 100F 10L/F 8                                             81/09/19
CHORD LENGTH DISTRIBUTION (UM.)

---------- CLASS --------0          1          2          3          4
  LIMIT     COUNT    %   0----------0----------0----------0----------0
5.60E 00 0.00E 00   0.00[
1.00E 01 1.50E 03  33.27[*************************************************
1.78E 01 4.27E 02   9.47[**************
3.16E 01 2.38E 02   5.28[*******
5.60E 01 4.70E 02  10.43[***************
1.00E 02 6.05E 02  13.42[********************
1.78E 02 6.46E 02  14.33[*********************
3.16E 02 4.01E 02   8.90[*************
5.60E 02 1.58E 02   3.50[*****
1.00E 03 5.40E 01   1.20[*
1.78E 03 8.00E 00   0.18[
3.16E 03 1.00E 00   0.02[
```

24

```
SAMPLE ID: 5B4 -8                                                       81/08/26
CHORD LENGTH DISTRIBUTION (UM.)

---------- CLASS --------0              1              2              3
  LIMIT     COUNT    %   0--------------0--------------0--------------0
5.60E 00 0.00E 00   0.00[
1.00E 01 5.37[illegible]E 02  19.71[***************************************
1.78E 01 2.59E 02   9.50[*******************
3.16E 01 3.16E 02  11.60[***********************
5.60E 01 5.64E 02  20.70[*****************************************
1.00E 02 4.96E 02  18.20[************************************
1.78E 02 3.33E 02  12.22[************************
3.16E 02 1.48E 02   5.43[**********
5.60E 02 4.80E 01   1.76[***
1.00E 03 1.80E 01   0.66[*
1.78E 03 4.00E 00   0.15[
3.16E 03 2.00E 00   0.07[
```

24

```
SAMPLE ID: 6A4 100F 10L/F 9                                             81/09/16
CHORD LENGTH DISTRIBUTION (UM.)

---------- CLASS --------0          1          2          3          4
  LIMIT     COUNT    %   0----------0----------0----------0----------0
5.60E 00 0.00E 00   0.00[
1.00E 01 5.31E 02  32.54[************************************************
1.78E 01 1.68E 02  10.29[***************
3.16E 01 1.23E 02   7.54[***********
5.60E 01 2.35E 02  14.40[*********************
1.00E 02 2.14E 02  13.11[*******************
1.78E 02 1.74E 02  10.66[***************
3.16E 02 1.01E 02   6.19[*********
5.60E 02 5.60E 01   3.43[*****
1.00E 03 2.20E 01   1.35[**
1.78E 03 8.00E 00   0.49[*
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VITA AUCTORIS

1955	Leo Pieter Meyer was born on June 27, 1955 in Windsor, Ontario.
1961	In September, 1961, he enrolled at Central Public School in Windsor and completed Grades 1 through 4.
1965	He completed his elementary school education at D. M. Eagle Public School in St. Clair Beach, Ontario.
1969	In September, 1969, he enrolled at Belle River District High School in Belle River, Ontario where he obtained his secondary school education.
1974	In September, 1974, he entered first year engineering at the University of Windsor, Windsor, Ontario.
1978	In May, 1978, he graduated with a Bachelor of Applied Science degree in Civil Engineering from the University of Windsor. In September, 1978, he enrolled at the University of Windsor in order to obtain the degree of Master of Applied Science in Civil Engineering.