

Björn Schouenborg
Jan Erik Lindqvist
Matz Sandström

Air and Air Void Structures in Concrete - General Overview and Picture Atlas

Nordtest project 1121-93

Abstract

Air and air void structures in concrete - General overview and picture atlas

This Nordtest project is a joint inter-Nordic project and forms part of a series of picture atlases on the common theme microscopical analysis of building materials, mainly concrete.

This contribution focuses on the air void structures in hardened concrete. The different analytical techniques are described together with a discussion of measurement uncertainty and causes for variations between different techniques.

Automatic computer aided image analysis is used more frequently. In order to reduce the risk of misinterpretations, a picture atlas is included in this report. It is essential to be familiar with the general appearance of different air void structures in different concrete structures and products in order to assess the result of the automatic analysis.

Information is also given about requirements for air void structures in the Nordic countries.

Key words: Air void structure, concrete, thin section, face ground sample, image analysis

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Postal Address:
Box 857
S-501 15 BORÅS
SWEDEN
Telephone +46 33 16 50 00
Telex 36 252 Testing S
Telefax +46 33 13 55 02

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Preface

This report is the result of a joint inter-Nordic project concerning air void structures in concrete.

The project was carried out in collaboration between the Swedish National Testing and Research Institute (SP), the Danish Technological Institute, for Building Technology (DTI) and the Norwegian Institute for Building Technology (NBI).

The project group was composed of the following persons:

DTI: Ingrid Brandt

NBI: Hans Christian Gran

SP: Björn Schouenborg (project leader)

Valuable contributions have been given by Jan Erik Lindqvist and Matz Sandström, both from SP.

Kristoffer Mårtensson is thanked for numerous measurements (chapter 6.5).

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Borås, Sweden April, 1995

Björn Schouenborg

1 Introduction

This volume is a part of a series of picture atlases produced in a series of Nordtest-projects. Earlier picture atlases prepared in similar Nordtest projects are:

- Microscopical determination of wct in concrete (SP-AR 1988:43) *
- Guidelines on petrographical micro-analysis of concrete (Nordtest-project No. 790-88)
- Guidelines for Petrographical Micro-Analysis of Aggregates for Concrete (Nordtest-Project no. 826-89).

* wct = water cement ratio

The air void structure is a critical parameter for several concrete properties such as resistance to freeze-thaw action, compressive strength and insulation properties of lightweight aggregate concrete etc.

Fully automatic computer aided image analysis has become more frequently used during the last couple of years, for the assessment of the air void structures. It is therefore crucial for the quality control to be able to make a qualitative estimation of the air void characteristics in order to assess the result from such air void analyses. In this context a picture atlas is of good use.

The report deals with general characteristics of air voids in concrete. Examples of good and poor air void structures are presented. The origin and effects of air voids in the most common concrete products are illustrated. General test methods are outlined and sources of differing test results are discussed.

The full scope of the subject is not to cover all materials or causes for the development of air in concrete. A good and updated bibliography on this matter can be found e. g. in the latest edition of the "Swedish Concrete Handbook, Material" from 1994.

Examples of concrete products illustrated in this report are "ordinary" concrete, concrete pipes, shotcrete and lightweight aggregate concrete.

2 Definitions and requirements

2.1 Definitions

The definitions have been compiled from NT BUILD 381 (Concrete, hardened: Air void structure and air content) and ASTM C 457 - Microscopical determination of air void content and parameters of the air void system in hardened concrete and prEN 480-11 - Admixtures for concrete, mortar and grout - Test methods - Determination of air void characteristics in hardened concrete.

Air void

A space enclosed by cement paste and filled with air or other gas prior to the setting of the paste. Obvious cracks are not included

Air void content

The proportion of the total volume of the concrete that is air voids expressed as a percentage by volume.

Specific surface

The total surface area of the air voids related to their volumes, in hardened concrete, expressed in reciprocal millimetres (mm^{-1}).

Spacing factor

A parameter related to the maximum distance in the cement paste from the periphery of an air void, expressed in millimetres.

Paste content

The proportion of the total volume of the concrete that is hardened cement paste, expressed as a percentage by volume.

Chord

The intercept length across an air void or an aggregate, expressed in millimetres.

Kitmasse

The total volume of the concrete less the volume of the aggregates.

Kitmasseluft

The air content in the kitmasse.

2.2 Requirements

2.2.1 Sweden

In Sweden the general requirements are for the total air content. The frost resistance is checked by freeze-thaw testing according to SS 13 72 44. The requirement for the total air content is connected to four different environmental classes. See also BBK 94 vol. 2.

B 1 Insignificantly aggressive environments: Structures in dry climate or in humid climates without the risk of frost action. This mainly concerns indoor structures and foundations at frost-free depths. There is no requirement for the air content in this class.

B 2 Slightly aggressive environment: Structures partly exposed to freeze-thaw action with a moderate moisture load but without chlorides. Examples are outdoor surfaces with an inclination steeper than 30 °, e.g. vertical facades.

B 3, Moderately aggressive environment: Structures in a moist or very moist environment, with no or negligible exposure to chlorides but with a risk of repeated freezing and thawing. It also concerns structures with access to chlorides but with a low moisture load and structures exposed to water on one side. Examples of structures are: outdoor surfaces with an inclination of less than 30 °, dam-, quay- and bridge-structures in sea water, parts of quay- and bridge-structures situated higher than 5 metres above the high water level in marine water or beneath in the lap- or splash zone.

B 4 Very aggressive environment: Structures in a moist or very moist environment with moderate or high exposure to chlorides and with a risk of repeated freezing and thawing. Examples of structures are marine structures in the lap- or splash zone, construction parts exposed to de-icing salts.

Concrete structures exposed to class B 2 environment do not have to have air entraining agents if the wct is less than or equal to 0.60.

The requirements for total air contents, valid for fresh concrete, are also connected to the maximum particle size of the aggregate. Generally a total air content of between 5.0 and 7.0 % is required for concrete use in classes B3 and B4. Lower air contents are allowed for if the frost resistance of the concrete can be verified according to the official freeze-thaw test method SS 13 72 44.

It is worth noting that the air content shall, in a factory production control, be tested three times a day.

There are no regulations in Sweden concerning the spacing factor or the specific surface. However, a spacing factor of about 0.20 - 0.25 mm is generally preferred. Normally the specific surface is about 30 mm⁻¹ or more.

2.2.2 Denmark

Environmental classes similar to those described above also exist in Denmark (see BBB, 1985). The requirements are connected to the spacing factor and to the air void content in the "paste plus air". This parameter is called *kitmasseluft* and is calculated as the total volume of the concrete less the volume of the aggregates. A passive environmental class P, with no requirement for the air void content is valid for generally dry concrete constructions.

Moderately aggressive environment, class M

A minimum air void content, in the kitmasse, of 15 % is required for fresh concrete intended for constructions possibly exposed to freezing in a moderately aggressive environments. This is valid for outdoor and indoor humid climates. However, there is no requirement for exposed facades. Analysis of the air void structure is required for hardened concrete and the air content shall be larger than 10 % of the kitmasse and the specific surface shall be larger than 0.25 mm⁻¹.

Aggressive environment, class A

A minimum air void content, in the kitmasse, of 15 % is required for fresh concrete intended for constructions possibly exposed to freezing in aggressive environments. This is valid for outdoor and indoor humid climates with possible exposure to chlorides. Hardened, air entrained concrete shall have an air void content larger than 10 % of the kitmasse and a specific surface larger than 0.25 mm^{-1} . Analysis of the air void structure is also required for such a concrete.

2.2.3 Norway

The Norwegian standard NS 3420 defines environmental classes similar to those described for Sweden and Denmark. The environment classes are as follows:

LA Insignificantly aggressive environment: Dry indoor environments without aggressiveness. The content of air is not specified.

NA Slightly aggressive environment: Comprises outdoor structures, indoor structures in moist environments and structures in contact with fresh water. Where air entraining agents are required due to expected freeze-thaw action in very wet or moist conditions, the cast concrete should have a final air content of 3 to 6 %. The air content should be adjusted according to conditions, casting procedure, amount of sand in the aggregate et cetera.

MA Moderately aggressive environment: Comprises structures exposed to salt water, aggressive gases, de-icing salts, other types of chemical attack and freezing and thawing in wet conditions. The "requirement" for the air content is the same as for class NA.

SA Very aggressive environment: Strong chemical attacks where special protective action is required. This may comprise extraordinarily composed concrete, coatings/-membranes and the like. No requirement for the air content is specified.

The air content is generally measured in fresh concrete. Analysis of the air void structure in hardened concrete is not a requirement in Norway.

3 The effects of air and air voids in concrete

A well designed air void structure with spherical pores of suitable sizes and distribution has a positive influence on a number of concrete properties. In severe climates with repeated freezing and thawing, a good air void structure may prevent frost damages. A good air void structure may also allow for secondary components, like salts, alkali-silica gel and ettringite to develop, to some degree, without primarily damaging the concrete construction.

A too high air content or a poorly developed air void structure in general may, on the other hand, have a bad influence on the concrete. The compressive strength decreases rapidly at too high air contents (above ca. 7 %). Far too high air contents may increase the chloride ion permeability and hence induce corrosion of the reinforcement. For this reason a high amount of small air voids should be preferred.

The choice of methods and equipment for mixing and compaction may cause differences and variations in the air void structure. A too long time for vibration often leads to segregation and unevenly shaped air voids and consequently poor adhesion between the aggregates and the cement paste.

These negative effects can, to some extent, be diminished if air entraining agents are used. The workability of the fresh concrete mix is often improved with a slightly increased air content. In addition, the process of bleeding is normally slowed down. The amount of water needed for the mixing is also less (about 4 kg/m³ per percent air) for the same consistency.

The time factor is in many cases crucial for the making of a good air void structure. Too long time between mixing and compaction may influence the air void structure and the possibilities to remove entrapped air. Too long and too short mixing times reduces the possibilities to achieve a good distribution of cement, aggregates, water and admixtures.

Air voids may also affect the thermal conductivity in concrete. The amount of air as well as the structure of the air voids are important factors. This can be exemplified with lightweight aggregate concrete blocks where the lambda value increases if the air voids are large enough to become interconnected.

4 The formation of air and air voids in concrete

4.1 General

As described above there are a number of reasons to produce a good air void structure and to hinder the development of a poor one.

Air (cavities and cracks) and air voids in concrete can be the result of a combination of many different factors during the mixing of the fresh concrete, during compaction and during the hardening processes.

4.2 Fresh concrete

An ordinary concrete contains up to 2 % air when not air entrained. However, the optimum air content for a frost resistant ordinary concrete is thought to be about 4.5 - 7 %. In order to produce a good air void structure, admixtures are mostly added to the concrete mix. The admixture is generally some kind of synthetic tenside or neutralised Vinsol Resin.

When different admixtures and/or additives are used in combination they may influence the properties aimed at negatively or positively. The grading of the aggregates will also have an effect on the air void content and consequently also the amount of air entraining agents needed. The finer the aggregate the more air entraining agents need to be added to produce the necessary air content.

The influence of additives such as microsilica and flyash is not yet fully investigated. Some experience indicates that it is easier to achieve a good air void structure when microsilica is used.

4.3 Changes in the air void structure

4.3.1 During compaction

Transportation may alter the air void structure considerably depending on the stability of the air voids combined with the time and means of transportation. Long distance transportation with a truck agitator often leads to a decrease in the total air content. Loss of air due to transportation is commonly in the region of 0.5 to 1 %. Loss of air due to vibration is generally greater, about 1.5 to 2 %. These are figures that vary with the kind of transportation, vibration and type of air entraining agent and if it is used in combination with another admixture. Unfavourable combinations of admixtures may lead to unstable air void structures.

The larger air voids will in general disappear first. This does not lead to any major change in the spacing factor and consequently not in the frost resistance of the concrete.

4.3.2 During the hardening process

Air voids (cavities) which arise during the hardening stage have in most cases a negative influence on the concrete. Intrinsic shrinkage and plastic deformation often form worm-like cavities and cracks. The same is observed for freezing at early ages. This can cause a significant decrease in strength and other mechanical properties.

Other types of air introduced to the system can be the result of volume unstable aggregates such as clay particles. This type of aggregate may be more or less saturated with water prior to or during mixing. Subsequent shrinkage occurs during drying when the concrete hydrates.

4.3.3 In hardened concrete

The most common change of the air void structure in hardened concrete is due to secondary reaction products that tend to entirely or partly fill the air voids. Secondary crystallisation and other types of reaction products are the result of several different processes. They mainly develop in concrete constructions exposed to moist environments and are sometimes also related to temperature.

Common examples of secondary reaction products are ettringite, $\text{Ca}(\text{OH})_2$ and alkali-silica gel. All of these components may complicate an automatic analysis of the air void structure.

Cracking can also occur in the hardened concrete, e.g. as a result of deformation due to excess load or expansion due to secondary reactions. Smaller cracks do not influence the air void analysis.

Similar to the above, volume unstable aggregates may cause expansion and cracking in hardened concrete when exposed to moisture. Example of this is dolomite and dolomitic limestone with contents of swelling clays.

As mentioned in the definitions, cracks shall not be included in the analysis of the air void structure. However, they may in cases, impose difficulties during the analysis.

5 Test specimens and test methods

5.1 Samples and sample preparation

5.1.1 Face ground samples - plane sections

The traditional method to prepare face ground samples is described in e.g. NT BUILD 381, ASTM C 457-90 and prEN 480-11. The principles are given below.

A plane surface is prepared by sawing and wet grinding. Useful silicon carbide abrasive powder have a grain size of 120, 60, 30, 16 and 12 μm . However, it has been found better to use grinding wheels of different surface fineness in order to avoid contamination by abrasive powder in the air voids. A properly prepared specimen surface shall have a matt sheen and sharp and well defined air void edges.

In order to enhance the contrast between air voids on the one side and cement paste and aggregates on the other, the surface is generally treated with ink from a stamp or roller. The specimen is thereafter stored in 50°C for 4 hours, covered with zinc and then refrigerated. Finally, gypsum is pressed into the air voids and the excess gypsum is scraped off. An example of the final surface is shown in figure 1.

An alternative method of enhancing the contrast is to impregnate the surface with fluorescent epoxy. The analysis is carried out by fluorescent microscopy with incident light. An example of such a surface is shown in figure 2.

5.1.2 Thin sections

The preparation of thin sections for fluorescent microscopy is, in principal, as follows: A piece (approximately 50x30x10 mm) of the test sample is glued onto a working glass. The sample is ground plane parallel with the glass and impregnated with fluorescent epoxy. The surplus epoxy is ground off the impregnated surface and a final object glass is glued onto the finely ground surface. The specimen is sawn closely (ca. 0.5 to 1 mm) to the object glass. The specimen is finally ground to a thickness of ca. 25 μm and protected with a cover glass. The preparation is also described in NT BUILD 381.

5.2 Methods

The air content can be measured in the freshly mixed concrete as well as in the hardened concrete.

There are two commonly used methods for fresh concrete - a volumetric method and a pressure method. The volumetric method is described in ASTM C 173. The principle is to measure the volume of the concrete mix before and after treatment with a chemical (e.g. isopropyl-alcohol) that destroys the air bubbles. The method can be used for all kinds of concrete and aggregates and preferably when the air content is very high.

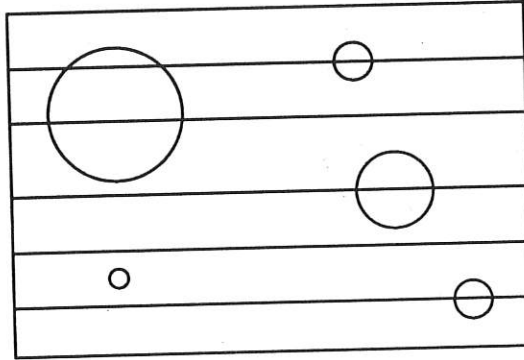
When using the pressure method, the concrete mix is exposed to an overpressure. The air is compressed and the total volume decrease is proportional to the air content as long as the temperature is held constant. See also national standards SS 13 71 24 and ASTM C 231. The method is recommended when relatively dense aggregates are used.

This report focuses on measurements on hardened concrete.

5.2.1 Linear traverse method

The measurement is carried out by registering the number and length of chords longer than 0.008 mm (NT BUILD 381) within air voids and aggregates along a set of test lines (traverses). The total length of the chords related to the total length of test lines determines the volume of air voids in the test sample.

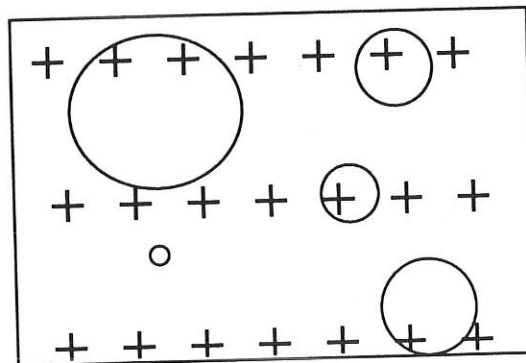
The illustration below is a principle sketch of how the test lines can be spaced over the analysis area. See also prEN 480-11.



5.2.2 Modified point count method

The measurement is carried out by measuring the total number of sections of air voids intersected along a line of traverse and the frequency with which regularly spaced points (index points), on the line of traverse are superimposed on the sections of air voids and aggregates.

This method does not provide the size distribution of the air voids. The illustration below is a principle sketch of how the index points can be spaced over the analysis area.



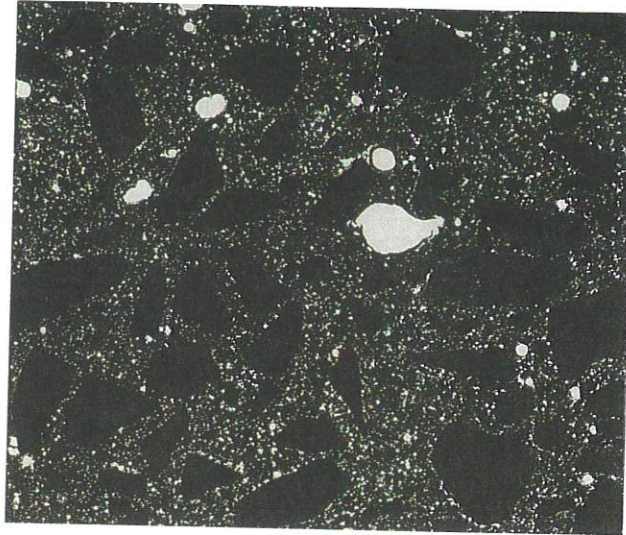


Figure 1. Photograph showing a face ground sample prepared with zinc paste and black ink.

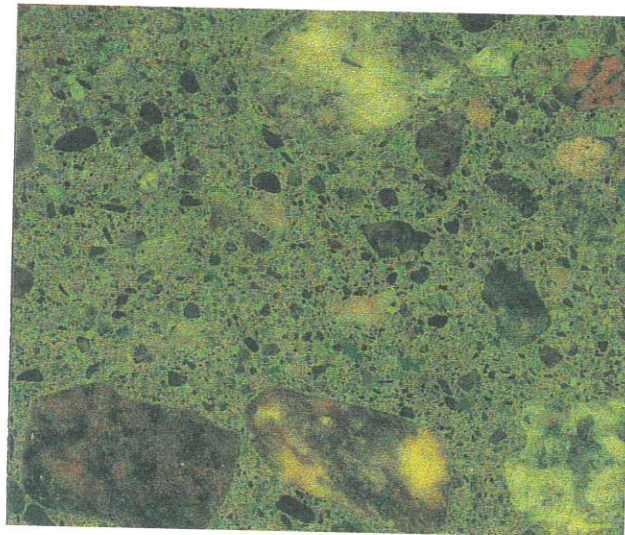


Figure 2. Photograph showing a face ground sample impregnated with fluorescent epoxy.

5.2.3 Calculations

The calculations of the air void content, specific surface and spacing factor are principally the same independently of which method that is used. The linear traverse method is a much slower method than the modified point count method but has advantage over the latter as the size distribution of the air voids can be determined. The determination is in most cases performed according to Lord's and Willis' method (see equation also in NT BUILD 240) of the cord intercept distribution. Other distributions, e.g. the maximum length (diameter) and area can also be used. These two are basically the same as the area is $\pi \cdot \text{length}^2/4$ for a sphere.

The basic formula for the calculation is shown below.

$$\Sigma N_{Ai} = N_{vj} * p_j * d_j \quad (1)$$

N_{Li} is the number per unit length of two-dimensional objects in size class i (size d_i - d_{i+1})

N_{Ai} is the number per unit area of two-dimensional objects in size class i (size d_i - d_{i+1})

N_{vj} is the number of air voids per unit volume of size class j (size d_j).

p_j is the probability that an air void of size class j (size d_j) reproduces as a two dimensional object of size d_i - d_{i+1} .

The probability distribution of cords is linear. The calculation of the three-dimensional (3D) distribution from the two-dimensional distribution can therefore be written according to the following formula

$$N_{vj} = \frac{2}{\pi} \left(\frac{N_{Li}}{a_i \cdot \Delta_i} - \frac{N_{Li+1}}{a_{i+1} \cdot \Delta_{i+1}} \right) \quad (2)$$

a_i is the middle of the class

Δ is the class interval (width of the class)

The probability distribution of diameters is non-linear. If the size classes are classified in a geometric series, the 3D distribution can be determined by solving the following system of equations

$$\begin{bmatrix} p_1 & 0 & 0 & 0 \\ p_2 & \ddots & 0 & 0 \\ \vdots & \ddots & \ddots & 0 \\ p_n & \cdots & p_2 & p_1 \end{bmatrix} \cdot \begin{bmatrix} d_1 \cdot N_{v1} \\ d_2 \cdot N_{v2} \\ \vdots \\ d_n \cdot N_{vn} \end{bmatrix} = \begin{bmatrix} N_{A1} \\ N_{A2} \\ \vdots \\ N_{An} \end{bmatrix}$$

5.2.4 Image analysis

In computerised image analysis applied to microscopy, a video camera is generally attached to the microscope. The images obtained by the camera are transferred to a computer equipped with a frame grabber which transforms the analogue signal to a digital image (see figure 3, 4 and 5). Each image is composed of a number of pixels usually between 512×512 and 1024×1024 . This gives 260 000 to 1 000 000 pixels. For each pixel the computer stores the XY co-ordinates in the image and the greyscale value. If it is a RGB colour system, the computer keeps track of a grey scale value for each colour plane. These three values define the colour in the three dimensional RGB space. It is then possible to identify objects using criteria given by the operator. An object can for example be an air void which is identified as a light area compared to the surrounding.

Quantification using image analysis gives a considerable amount of information about the measured objects. One measurement can give data concerning form, area, length, width, greyscale density, position and number of objects among other parameters.

The next step of development of the image analysis system is to use something called neurological networks, i.e. a kind of artificial intelligent computing. By use of this it is possible to train the computer to recognise different patterns, e.g. spherical air voids, and accordingly sort out unimportant information. This would minimise the amount of false results due to today's image analysis systems not always being able to differentiate between entrained air and entrapped air and air in cracks et cetera.

Image analysis applied thin sections using fluorescens technique

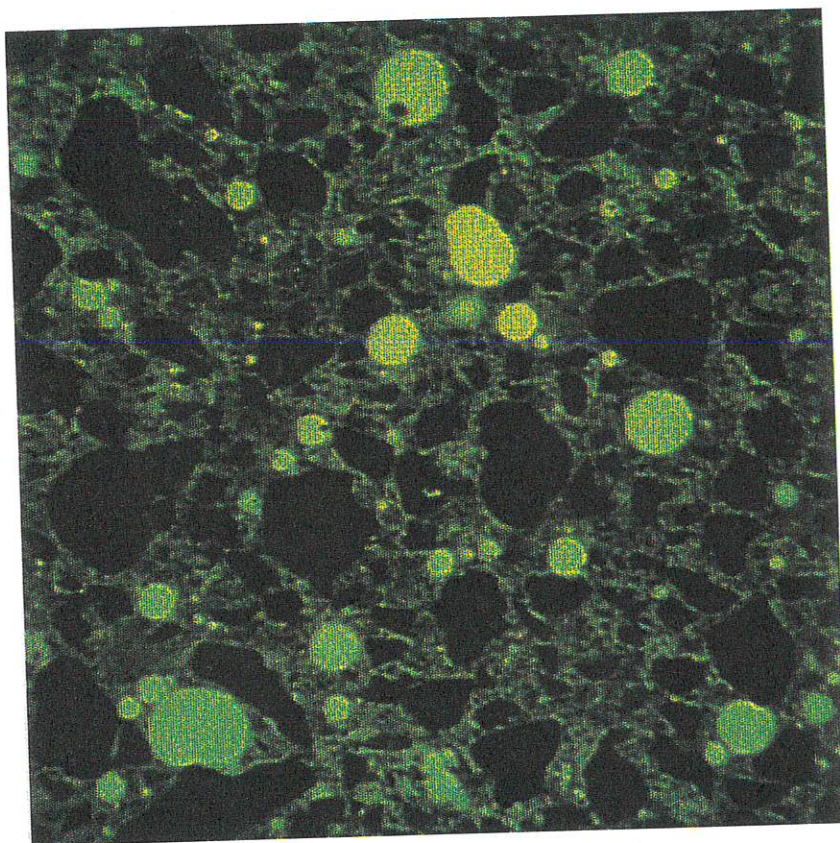


Figure 3. The primary RGB image. This image is stored in the computer as three grey scale images, one for each colour plane. These three colour planes define a three dimensional colour space.

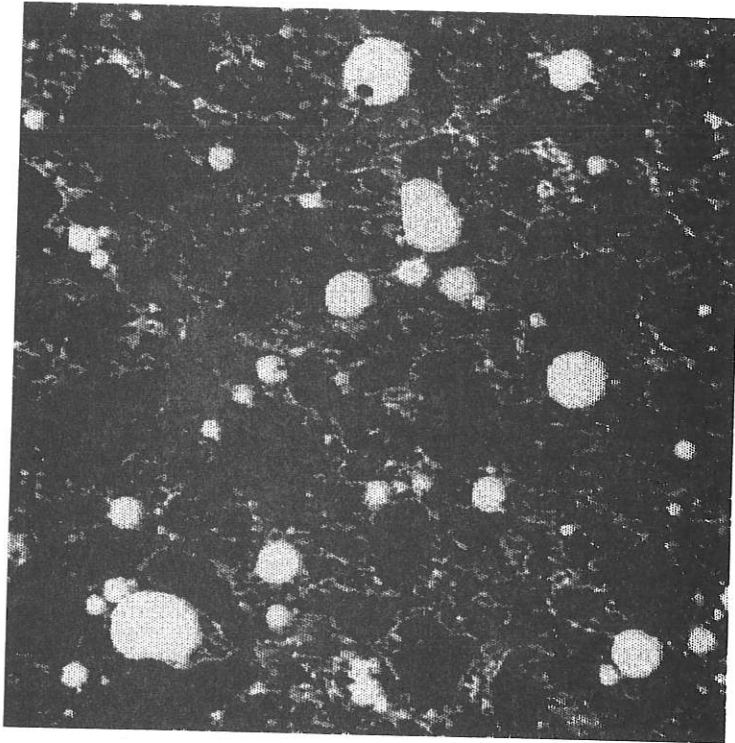


Figure 4. This greyscale image is obtained through filtering of the fluorescens image. In the filtering process, the colour of the air voids in the primary image is selected as white. The greyscale value is here determined by the distance in the RGB space from the colour of the air voids.

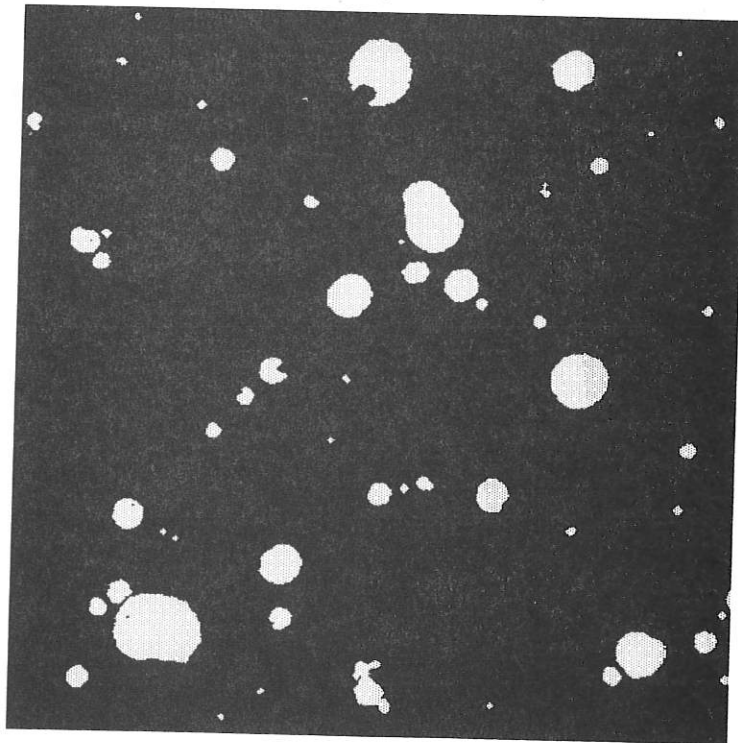


Figure 5. In this binary image, or object filtered image, the objects of interest (air voids) are white and the rest is black. The image has no greyscale. The image has been created through selecting a threshold value in the greyscale. Areas with values higher than the threshold have been marked as white and lower values as black.

6 Causes for variations in test results and misinterpretations

6.1 General

Variations in test results can have several different causes. Both sampling, preparation and test methods are likely to contribute to the overall testing error. In addition, the magnification and the procedure for choosing analytical parameters and computer settings, for image analysis, will also affect the test result.

A prerequisite for correct image analysis is high quality prepared test specimens where the air voids are recognised by having clearly defined sharp edges. Diffuse air void edges may be the result of poor preparation and the location of an air void in relation to the analysis surface. Cutting air voids in the centre results in sharp edges. On the other hand, cutting an air void off centre demands very high quality sample preparation.

Air void structure measurements are generally performed on face ground specimens. Making these measurements on thin sections instead enables determination of the cement paste content and the air void distribution in a single measurement. However, the analysed surfaces in thin sections are mostly smaller than those in face ground specimens, resulting in a poorer expected accuracy (see 6.3). Larger variations in the results are also expected when analysing inhomogeneous samples using the thin section technique compared to face ground specimens.

The sizes and distribution of the air voids will also depend on the location of the sample in the construction. The accuracy of the estimate is therefore depending on the deviation between the air void distribution in the samples, the air void distribution in the construction, and the accuracy of the test method. Depending on the sampling method, the estimate may also be influenced by the variation of the air void distribution within the samples.

6.2 Estimation of the sampling error

To estimate the accuracy of the test method and variation of the air void distribution in the sample, one concrete sample was taken from a concrete batch. The sample was filled in a mould (150 mm cubes) in two layers. Each layer was vibrated for 15 s. The sample was stored for 24 hours in the mould. It was thereafter de-moulded and stored for five days in water and 21 days at 20 °C and 50 % R.H. The air void content in the fresh concrete was measured to 6.15 %. The paste content was calculated to 30.1 %, from the mix proportions. A total of 19 thin sections, 28 x 45 mm², were taken from three vertical levels, (A, B, C) of the cube according to figure 6.

Each thin section was measured by use of modified point counting. The air void content, the cement paste and the number of intercepted air voids were measured on a total of 1192 points evenly distributed over an area of 375 mm². The air void content in the kitmasse, the specific surface and the spacing factor were calculated accordingly. The results are shown in figure 7. The upper figures in each square show the air void content in the top layer of the cube. The figures in the middle of each square show the air void content in the layer from the centre of the cube. The lower figures of each square show the air void content in the bottom layer of the cube.

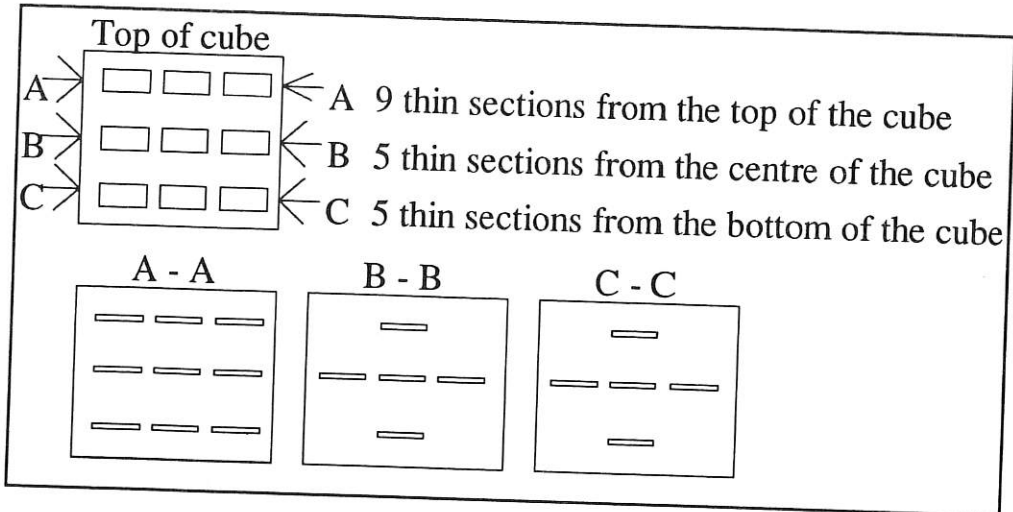


Figure 6. Sampling of thin sections from the concrete cube.

Total air void content (%)

11.6	6.0 9.7 4.0	7.2
11.4 10.7 6.1	7.9 5.5 4.5	8.0 9.6 4.5
11.4	8.3 6.7 5.8	7.4

Air void content in the kitmasse (%)

24.3	20.8 24.0 14.5	19.0
23.4 28.4 19.6	20.1 15.1 13.8	19.5 20.9 15.3
25.4	21.5 15.5 25.2	22.4

Figure 7a. Measured air void content. The figures in each square show the measured value in the three different vertical levels.

Specific surface of the air voids (mm^{-1})

25.3	29.7 29.4 52.4	35.0
27.8 21.1 30.3	29.9 39.8 45.9	32.9 29.7 33.7
23.7	32.9 39.4 25.1	29.5

Spacing factor (mm)

0.12	0.13 0.11 0.10	0.12
0.12 0.12 0.14	0.13 0.12 0.11	0.13 0.13 0.14
0.12	0.11 0.12 0.12	0.12

Figure 7b. Calculated specific surface and spacing factor. The figures in each square show the measured value in the three different vertical levels.

The figures in figure 7, indicate a systematic variation of the air void structure in the cube. The greater air voids seem to be concentrated in one side of the upper section. This means that the air void content and the mean size of the air voids decreases with the distance from the top of the cube. In spite of this the spacing factor is nearly constant.

That is because the calculation of the spacing factor is based on the measured value of the cement paste content instead of the cement paste content calculated from the mix proportions.

The mean values of the air void distribution parameters in the different layers are shown in table 1. The standard deviation between the different measurements are shown in table 2. In order to study the variation of the air void distribution, the mean values are calculated as the arithmetical mean of the measurements of the thin sections and not as traditionally where the measurements of all thin sections are considered to be the result from one measurement.

Table 1. Mean value of the air void distribution in the vertical direction of a concrete cube. Figures in brackets show the results of the thin sections from the centre of the cube.

Vertical level	Air void content (%)	Air void content in the kitmasse (%)	Cement paste content (%)	Specific surface (mm ² /mm ³)	Spacing factor (mm)
Top	8.8	21.8	31.2	29.6	0.12
Middle	8.4	20.8	32.3	31.9	0.12
Bottom	5.0	17.6	23.8	37.5	0.12
All levels	7.7 (6.0)	20.5 (16.3)	29.5 (30.1)	32.3 (38.5)	0.12 (0.12)
Fresh concrete	6.15	17.1	30.5		

Table 2. Standard deviation of the air void distribution in the vertical direction of a concrete cube. Figures in brackets show the results of the thin sections from the centre of the cube.

Vertical level	Air void content (%)	Air void content in the kitmasse (%)	Cement paste content (%)	Specific surface (mm ² /mm ³)	Spacing factor (mm)
Top	2.1	2.2	4.7	3.7	0.006
Middle	2.2	5.6	4.1	7.8	0.007
Bottom	0.9	4.8	4.0	11.3	0.018
All levels	2.5 (1.7)	4.2 (3.3)	5.4 (1.8)	7.7 (8.1)	0.01 (0.01)

6.3 Estimation of the accuracy of thin section analysis

In order to determine the minimum test area (number of measured thin sections) the sampling error must be estimated by the standard deviation between the samples (s_1), and the error of the measurement estimated by the standard deviation of the measurements (s_2). If the sampling error and the error of the measurement are considered to be independent observations of two different normal distributions, the relationship between those can be described by equation 3.

$$s = s_1 + s_2 / n \quad (3)$$

Where s is the observed standard deviation between the measurements. The variation in the air void distribution in the cube is systematic and not normally distributed. s could therefore be overestimated. In a construction with a variation in the air void distribution of this size, the estimate may still be valid.

The standard deviation of the measurements can be estimated by the standard deviation of the point counting measurement of one thin section according to equation 4.

$$s_2 = (p(100 - p) / N)^{1/2} \quad (\%) \quad (4)$$

Where p is the measured value and N is the total number of points.

The estimate of the standard deviation between the different thin sections are shown in table 3. The standard deviation of specific surface and spacing factor, within the samples, are estimated by use of logarithmic derivation. The figures in the table show that the deviation between the measurements (s) mostly depends on variation between the samples (s_1). The air void content in the kitmasse seems to be more accurate than the air void content. The measurement of the paste content in the thin sections gives a small variation of the spacing factor. The standard deviation within the samples depends mostly on the variation in the specific surface.

Table 3. Standard deviations of the measurements (rounded values).

Standard deviation	Air void content (%)	Air void content in the kitmasse (%)	Specific surface (mm^{-1})	Spacing factor (mm)
s_1	2.5	4.2	7.6	0.01
s_2	0.8	1.9	4	0.02
s	2.5	4.2	7.7	0.01

If the probability of accepting a batch of concrete with a good air void distribution is set to 95 % and the probability of accepting a batch of concrete with a bad air void distribution is set to 5 % the total test area must be at least 3000 mm^2 , which means 8 samples and a test area of 375 mm^2 on each sample, in order to achieve an accuracy of the same size as the standard deviation between the samples.

6.4 Comparison between analysis of thin sections and face ground samples

In a project carried out jointly by DTI, Denmark, SP, Sweden, VTT, Finland and NBI, Norway, air void measurements made on thin sections were compared with measurements made on face ground specimens (Sandström 1990). One thin section and one face ground specimen were prepared from the centre of three different concrete specimens, (150 mm cubes), according to figure 8.

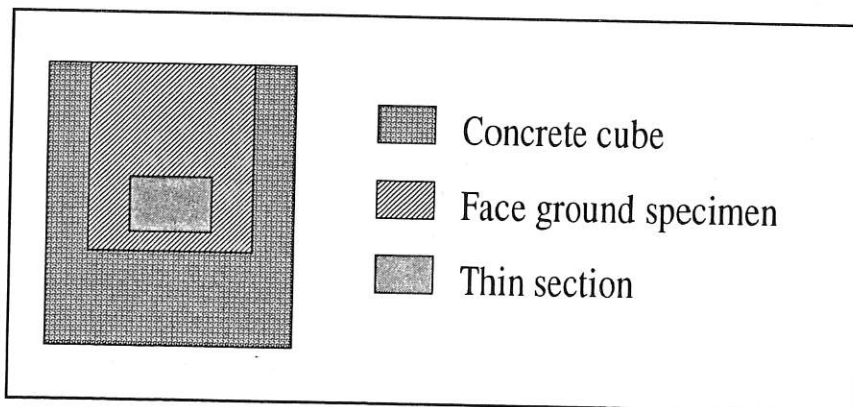


Figure 8. Sampling of thin sections and face ground specimens.

The air void distribution in the thin sections was measured by use of point counting according to ASTM C457-82, in applicable parts. The face ground specimens were measured according to NT Build 240. The results from the measurements are shown in figures 9, 10 and 11.

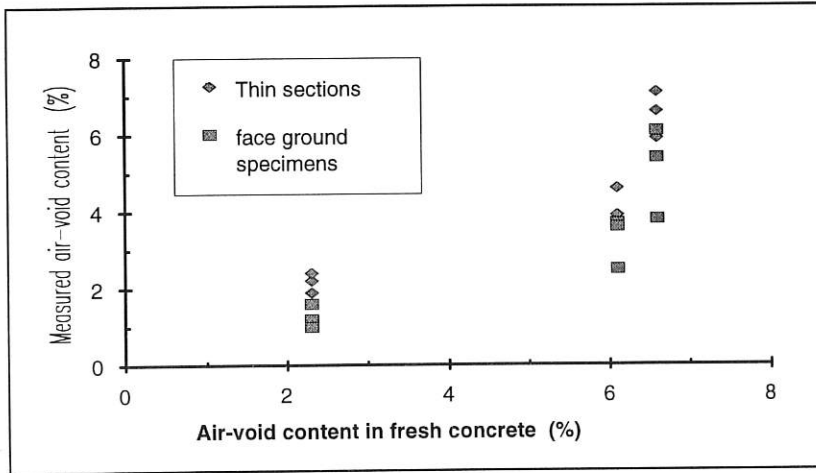


Figure 9 Air void content measured by use of point counting on thin sections and linear analysis (image analysis) on face ground specimens.

Linear analysis on face ground specimens gives according to this investigation approximately 25 % lower value than does point counting on thin sections. The coefficients of variation are in both cases lower than 25 %. Measurements on thin sections seem however to give a better correlation with the air content in the fresh concrete than measurements on face ground specimens.

Linear analysis of specific surface and spacing factor on face ground specimens gives according to this investigation a smaller standard deviation than point counting on thin sections. The specific surface measured on face ground specimens differs from the specific surface measured on thin sections probably depending on the difference in the measured area.

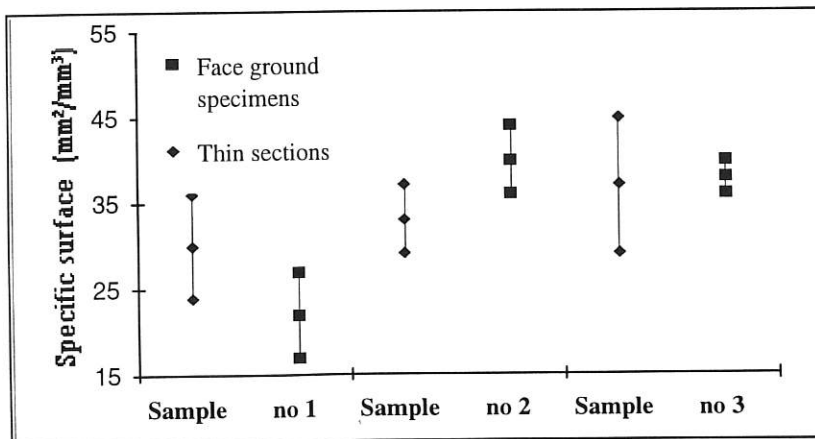


Figure 10 Specific surface (mean value \pm standard deviation) of three different concrete cubes, measured on thin sections and on face ground specimens.

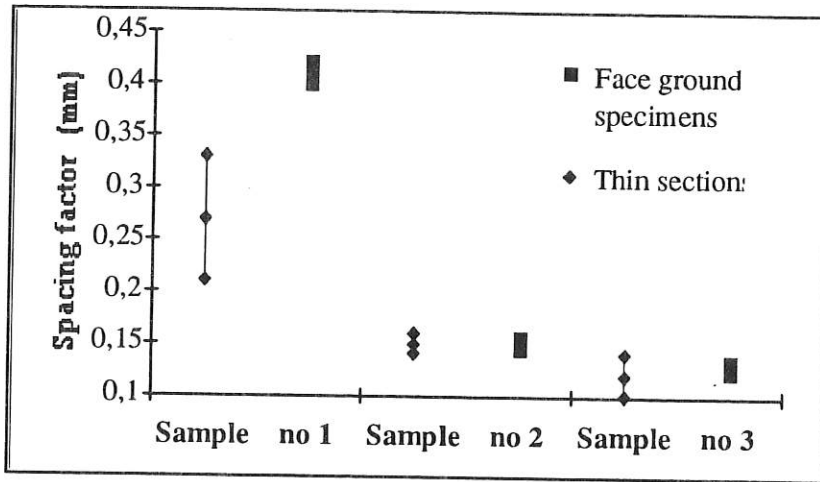


Figure 11. Spacing factor (mean value \pm standard deviation) of three different concrete cubes, measured on thin sections and on face ground specimens.

The difference, regarding the calculated spacing factor, is smaller at least for air entrained concrete. This is probably caused by the different methods used to estimate the paste content. In the thin section analysis, the spacing factor is calculated by use of the measured cement paste content on the same specimen. In the face ground analysis the cement paste content is calculated from the mix proportions.

Based on these findings a test method has been developed for testing of the air void distribution by use of point counting on thin sections. In order to achieve a good estimate with high repeatability and reproducibility, the measurements must be performed on an area of minimum 3000 mm². The number of analysed points must be at least 1500.

6.5 Image analysis procedures

There are several measuring parameters influencing the result. There is, among others, the magnification, and when using image analysis also the number of pixels in the erosion procedure. The instrumental magnifications 16, 25 and 50 times and pixel sizes 5.5, 3.5 and 1.8 μm were used in a study concerning the influence of these parameters on the spacing factor and the specific surface. Ten images from each sample were stored in the computer for each magnification. Measuring series with an opening of 1, 2 and 3 pixels in the erosion procedure were applied on each image.

It was demonstrated that the spacing factor and the specific surface were very sensitive to the parameters used in the measurement (figures 12 & 13). However, the expected increase in the measured air content with increasing magnification was less prominent.

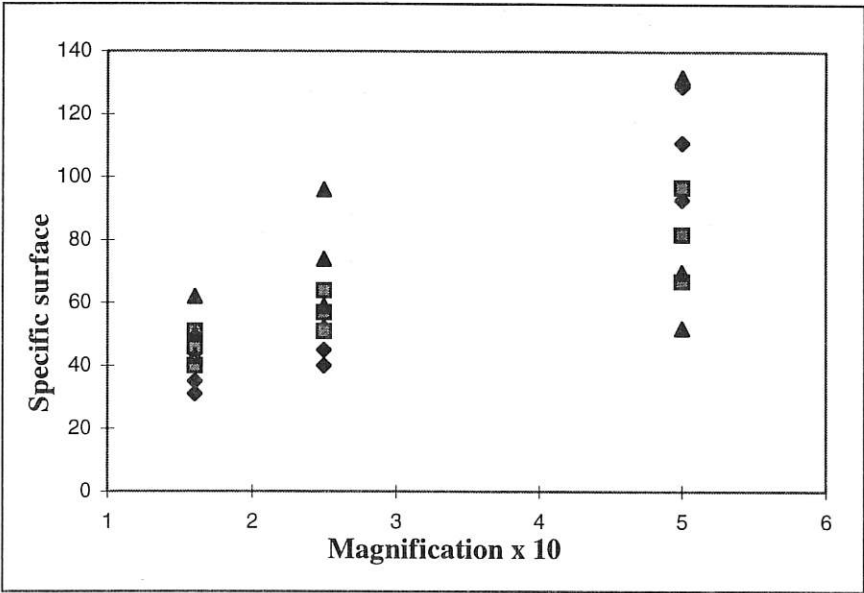


Figure 12. The influence of magnification on the measured value for specific surface.

The measured value for the spacing factor was also very sensitive to the measuring parameters. This is because the spacing factor is very dependent on the amount of fine air voids.

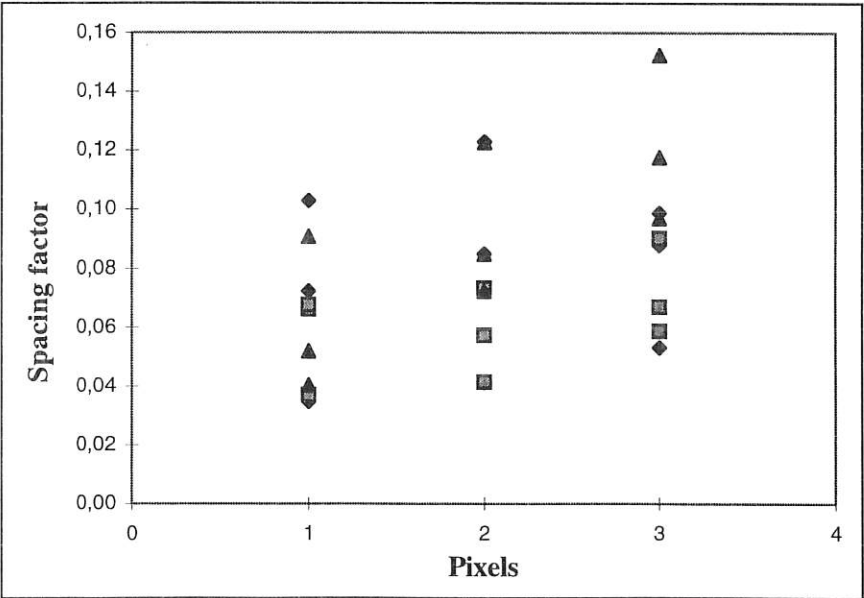


Figure 13. The influence of the number of pixels in the erosion process on the measured value for spacing factor.

6.6 Preparation techniques and variations in the air void structure in hardened concrete

The preparation techniques used today still have some weaknesses. It is, as mentioned earlier, very important for the possibility to achieve a correct test result that the edges of the air voids are sharp and that the air voids are separated in space.

Independent of whether thin sections or face ground specimens are used, the edge sharpness is better when an air void is cut in the middle compared to closer to the circumference.

In addition, when fluorescent impregnated face ground specimens are used there is a risk that the epoxy enters air voids beneath the surface and in the interfacial zone between the paste and the aggregate. Both these possibilities may lead to an erroneously high measured air content. On the other hand, when face ground specimens are prepared with zinc paste and ink, they have to be analysed within a certain amount of time due to shrinkage of the zinc paste. The edge sharpness is therefore best shortly after the preparation. The problem is greater with larger air voids than with smaller ones.

Other causes for poor edge sharpness is secondary reaction products of e.g. alkali-silica gel, ettringite and $\text{Ca}(\text{OH})_2$ in the air voids. Some of these are illustrated in the picture section.

When using computer aided image analysis, agglomeration of air voids may complicate separation of individual air voids. Methods exist to treat and compensate for this special problem, but a true picture of the air void structure may not be achieved.

There are also other potential risks of misinterpretations when a computer aided analysis is performed.

By use of poor equipment e.g. a rough and/or unbalanced saw or a too high drying temperature there is a risk of inducing cracks which may be wrongly interpreted during the analysis.

There may also be a risk of torn out aggregates e.g. if the grinding of a specimen is started too quick after the epoxy impregnation or if the concrete quality is very poor. It is therefore recommended to follow the procedures given in the various standards and methods very carefully if a measurement of the air void structure is performed.

Porous aggregates may also be mistaken for air voids, during a computer aided analysis, although they do not function as such.

7 Different types of material - photographs and descriptions

7.1 General

The picture sections are composed of a short introduction of the different types of material that are included and their characteristics. Where possible and relevant, the following information is given for most of the photographs. In some cases, all details have not been included in the original analysis.

Type of material:

General information (damage, other properties): Factory Production Control (FPC) or investigation of a damaged construction etc.

Total air content (vol. %):

Spacing factor (mm):

Specific surface (mm^{-1}):

Paste content (vol. %):

Kitmasseluft (air/(air+paste), vol. %):

Assessment of the air void structure for the specific material (good, poor etc.):

Type of filtration:

Enlargement of the photograph:

The first part of the picture section displays ordinary concrete with successively higher air contents, from 1 to about 10 % total air. The photographs show different concrete samples with different spacing factors and specific surfaces.

This part is followed by examples of other concrete products and typical air void structures. Possible causes for misinterpretations follow thereafter. Finally, alterations of the air void structure are displayed.

Computer aided image analysis of air void structures is generally performed in fluorescent light as shown in figure 3. However, most of the photographs in this report are taken in plane polarised light as this gives the viewer a better possibility to identify the different phases present.

In plane polarised light, air in the form of cracks, air voids etc. is shown in yellow. The cement paste (including aggregate fines) are shown in a dark almost black colour. The larger aggregates are mostly coloured white. Smaller variations in the colours may occur due to different magnification and porosity of the concrete.

7.2 Ordinary concrete

Ordinary concrete for outdoor purposes often contains air-entraining agents in order to withstand repeated freeze-thaw action. A total air content of approximately 4,5 - 7 % is therefore the target that is aimed at. This also depends on the spacing factor and specific surface. A spacing factor about less than 0.20 - 0.25 mm is generally preferred. Normally the specific surface is about 30 mm^{-1} and higher.

7.2.1 Ordinary concrete with a total air content of about 1 - 3 %, measured on thin sections.

DTI 4113-1

Type of material: **Ordinary concrete used in aggressive environment class A - tunnel road construction.**

General information: FPC

Total air content (vol. %): 2.30

Spacing factor (mm⁻¹): 39

Specific surface (mm): 0.17

Paste content (vol. %): 26.80

Kitmasseluft (vol. %): 8.00

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

86B3 46 11 (86-47)

Type of material: **Ordinary concrete.**

General information: Poor frost resistance and cracking.

Total air content (vol. %): 2.0

Spacing factor (mm⁻¹): 17

Specific surface (mm): 0.68

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

88 B3, 5632 (89-2)

Type of material: **Ordinary concrete.**

General information: Not frost resistant when exposed to chlorides.

Total air content (vol. %): 3.4

Spacing factor (mm⁻¹): 0.27

Specific surface (mm): 24

Type of photograph (filtration): Plane polarised light.

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

DTI 4281-5

Type of material: **Ordinary concrete used in aggressive environment class A.**

General information: FPC, Air-entraining agent "MICRO AIR"

Total air content (vol. %): 1.0

Spacing factor (mm⁻¹): 0.33

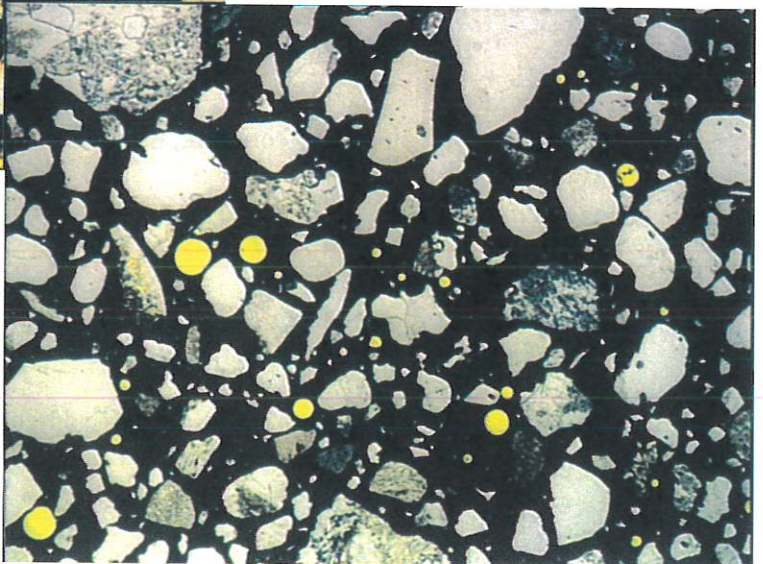
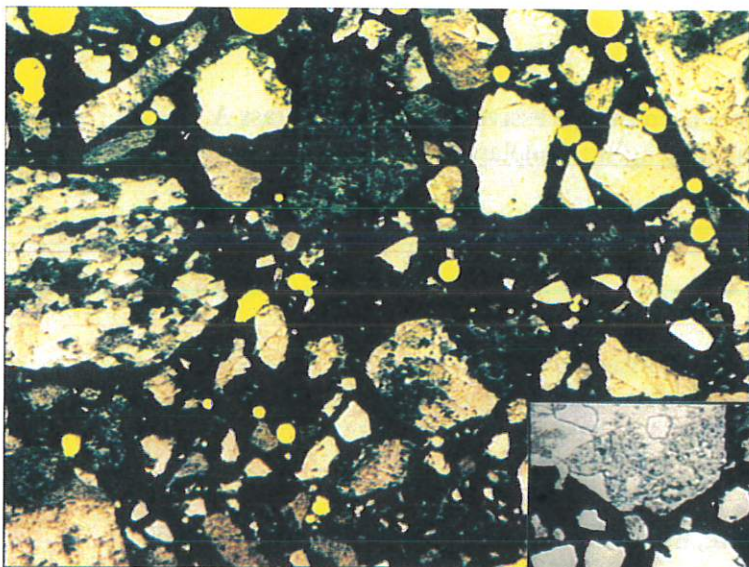
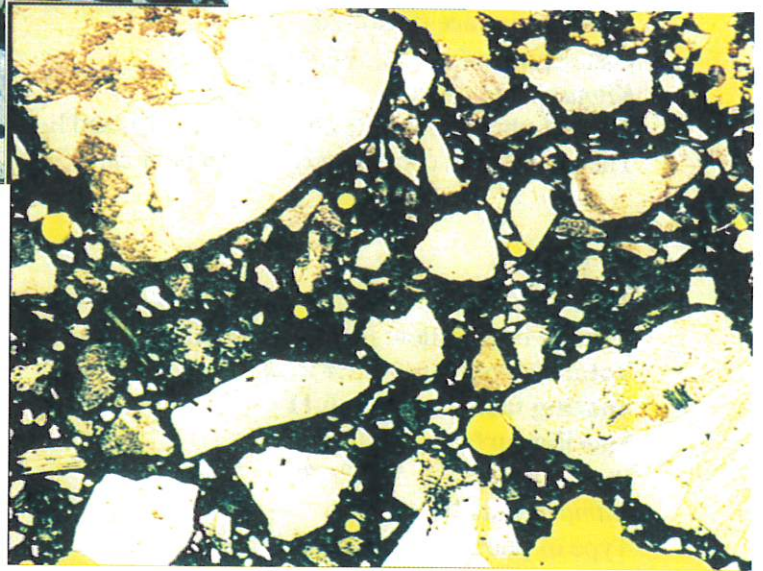
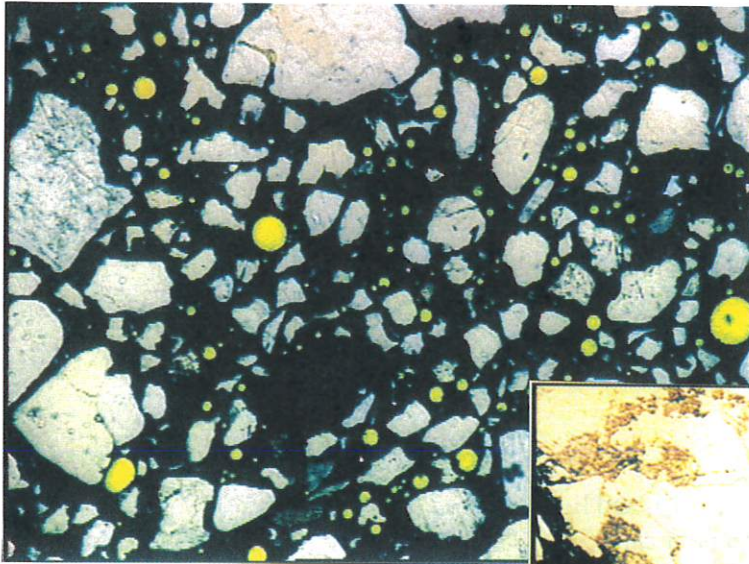
Specific surface (mm): 30

Paste content (vol. %): 28.7

Kitmasseluft: 3.2

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.



7.2.2 Ordinary concrete with a total air content of about 4 - 5 %, measured on thin sections.

DTI 4113-3

Type of material: **Ordinary concrete used in aggressive environment class A.**

General information: FPC, Air-entraining agent "MICRO AIR"

Total air content (vol. %): 4.50

Spacing factor (mm⁻¹): 0.25

Specific surface (mm): 20

Paste content (vol. %): 26.80

Kitmasseluft: 14.50

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

DTI 4123-6

Type of material: **Ordinary concrete used in aggressive environment class A.**

General information: FPC, Air-entraining agent: SikaAer-15

Total air content (vol. %): 4.60

Spacing factor (mm⁻¹): 0.11

Specific surface (mm): 45

Paste content (vol. %): 23.80

Kitmasseluft: 16.10

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

DTI 4120-2

Type of material: **Ordinary concrete used in aggressive environment class A.**

General information: FPC, Air-entraining agent: Conplast 316 AEA

Total air content (vol. %): 4.20

Spacing factor (mm⁻¹): 0.11

Specific surface (mm): 44

Paste content (vol. %): 24.90

Kitmasseluft: 14.50

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

DTI 4139-4

Type of material: **Ordinary concrete, used in moderately aggressive environment class M.**

General information: FPC, Air-entraining agent: Conplast 316 AEA

Total air content (vol. %): 4.7

Spacing factor (mm⁻¹): 0.26

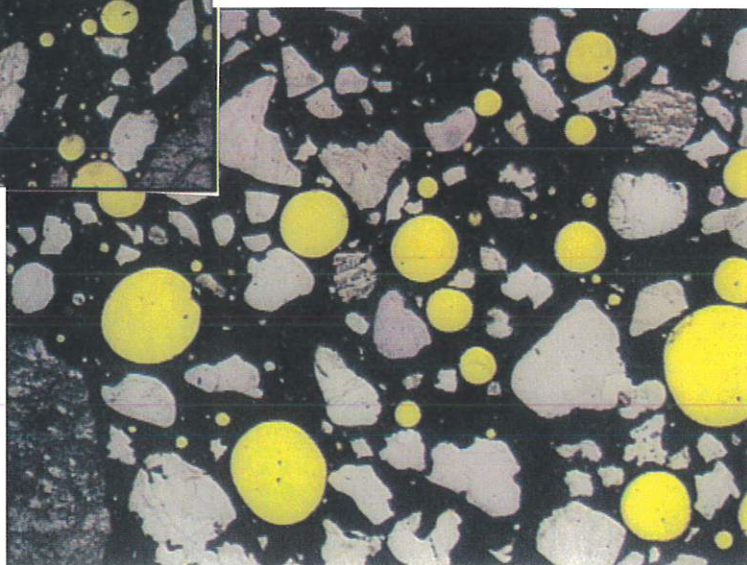
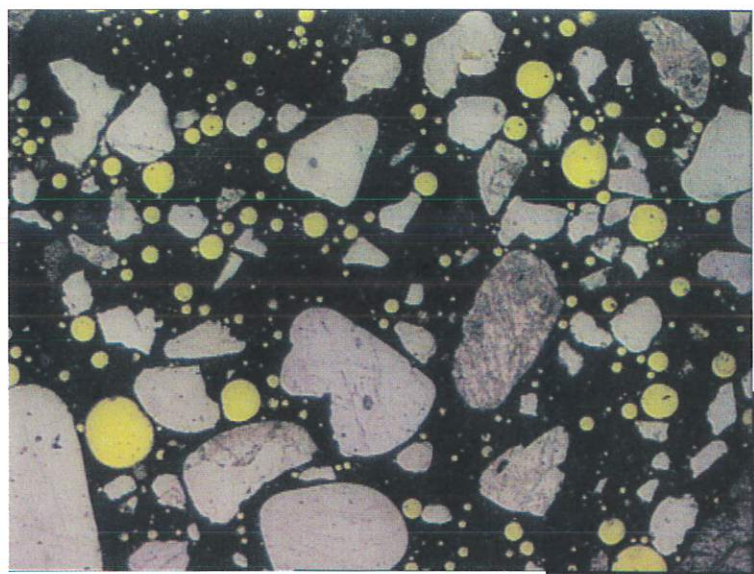
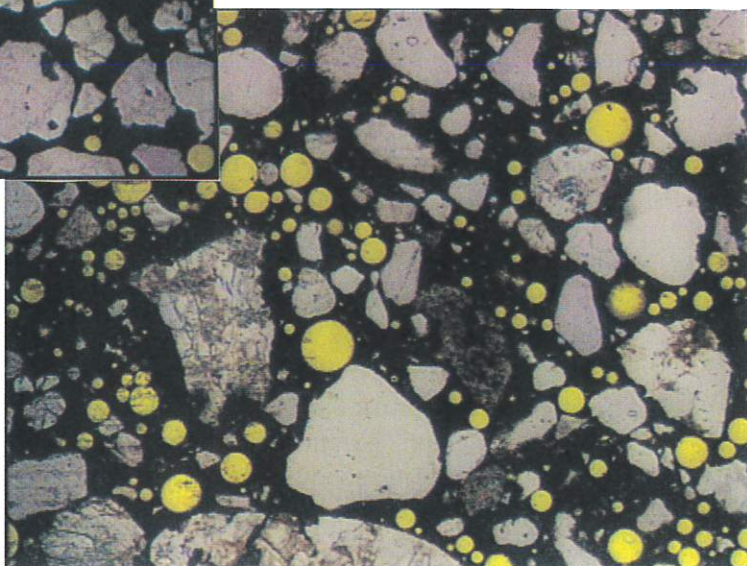
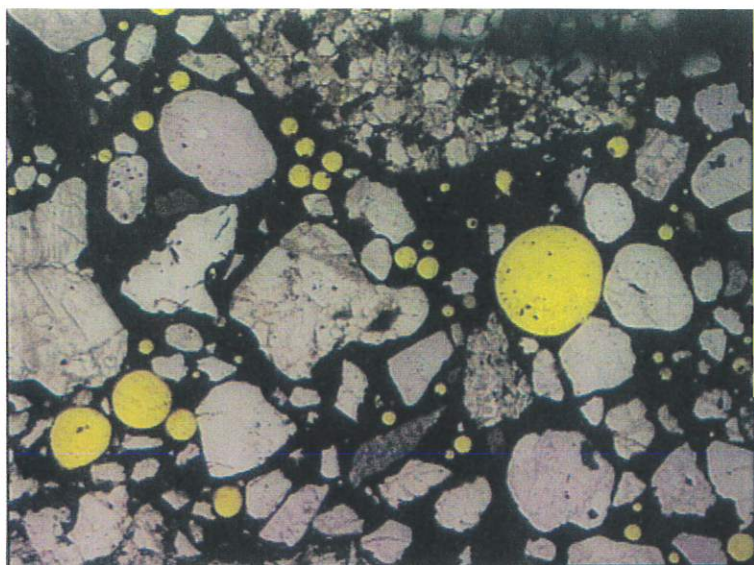
Specific surface (mm): 18

Paste content (vol. %): 24.6 (from recipe)

Kitmasseluft: 16.1

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.



7.2.3 Ordinary concrete with a total air content of about 8 - 10 %, measured on thin sections.

DTI 4455

Type of material: **Ordinary concrete used in aggressive environment class A.**

General information: FPC, Air-entraining agent: SikaAer 5-A

Total air content (vol. %): 8.5

Spacing factor (mm^{-1}): 0.07

Specific surface (mm): 38

Paste content (vol. %): 23.97 (from recipe)

Kitmasseluft: 26.1

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

86B3 4601 (85-205)

Type of material: **Ordinary concrete.**

Total air content (vol. %): 9.6

Spacing factor (mm^{-1}): 0.95

Specific surface (mm): 6.5

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

86B3, 4608 (86-20)

Type of material: **Ordinary concrete, stairs.**

General information: Poor frost resistance.

Total air content (vol. %): 10

Spacing factor (mm^{-1}): 0.58

Specific surface (mm): 10

Type of photograph (filtration): Plane polarised light.

The photograph corresponds to an area of ca. 9.0 x 6.7 mm.

92B3,2813 (92-51)

Type of material: **Ordinary concrete.**

General information: Frost resistant

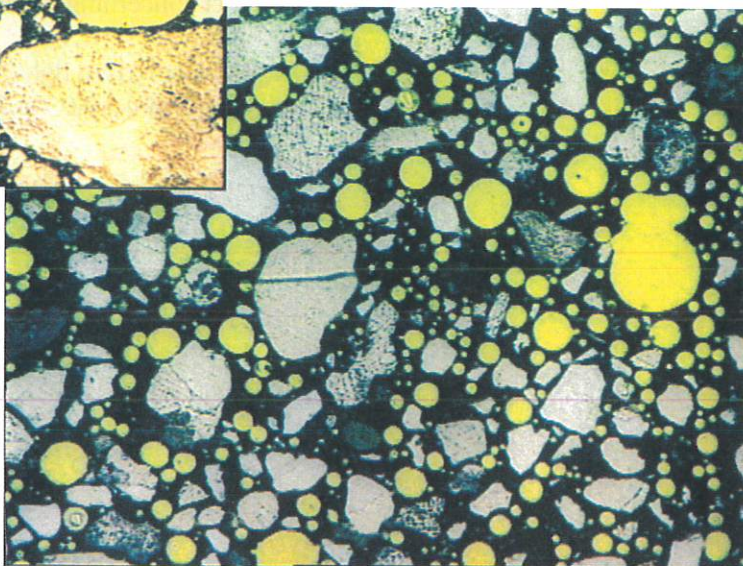
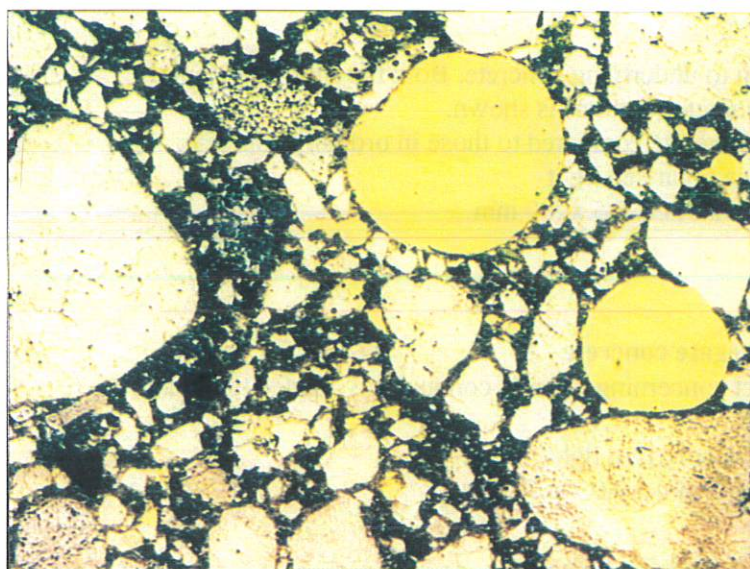
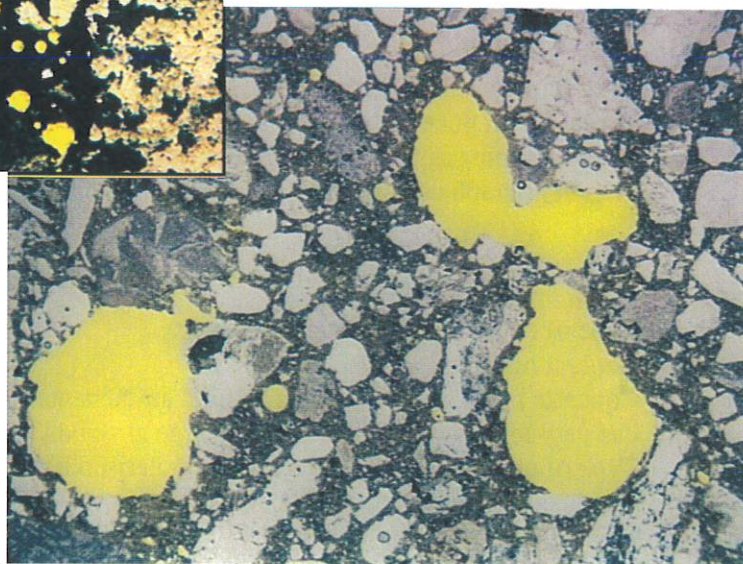
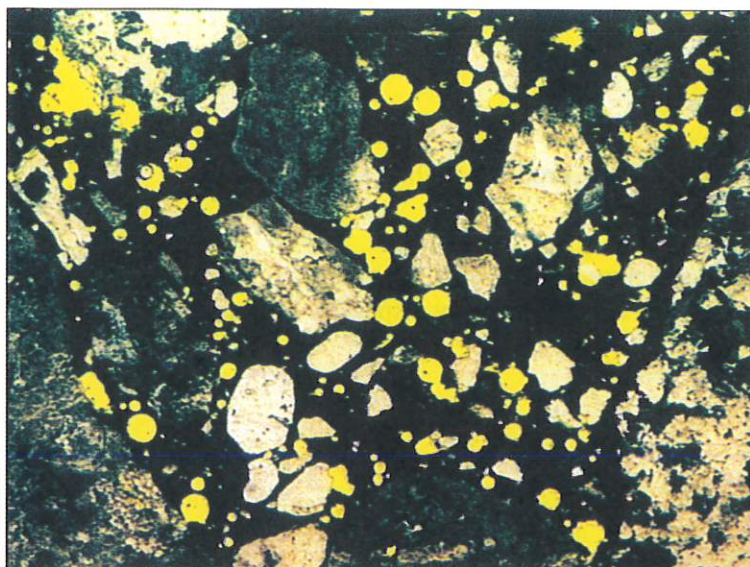
Total air content (vol. %): 9.6

Spacing factor (mm^{-1}): 0.10

Specific surface (mm): 26

Type of photograph (filtration): Plane polarised light.

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.



7.3 Other concrete products

Examples of typical air void structures in concrete products such as concrete pipes, shotcrete and paving products are shown below.

It is often difficult to design the air void structure of these concrete products. The air voids tend to become irregular and somewhat heterogeneously dispersed. The amount of air also varies greatly from case to case.

AM, SKRP

Type of material: **Concrete pipe**, Norway.

Typically irregular air voids.

Type of photograph (filtration): Plane polarise light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

88B3, 5613

Type of material: **Concrete pipe**, Sweden

General information: FPC

Concrete pipes generally contains high air contents with irregular air voids. This concrete has very high air content and rather large air voids.

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

93B3,2820 (93-7)

Type of material: **Shotcrete**

General information: Good adhesion to underlying concrete. Both the shotcrete (top of the photograph) and the ordinary concrete (bottom) is shown.

The air voids are often irregular in shotcrete compared to those in ordinary concrete.

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

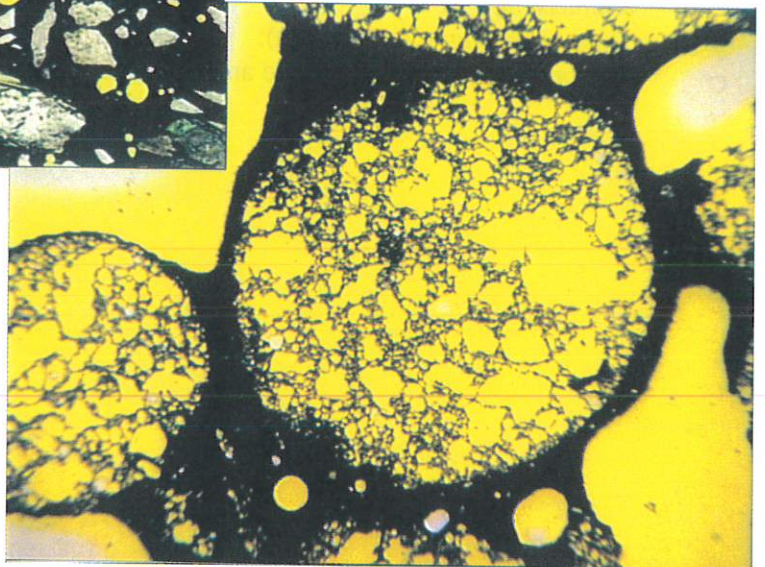
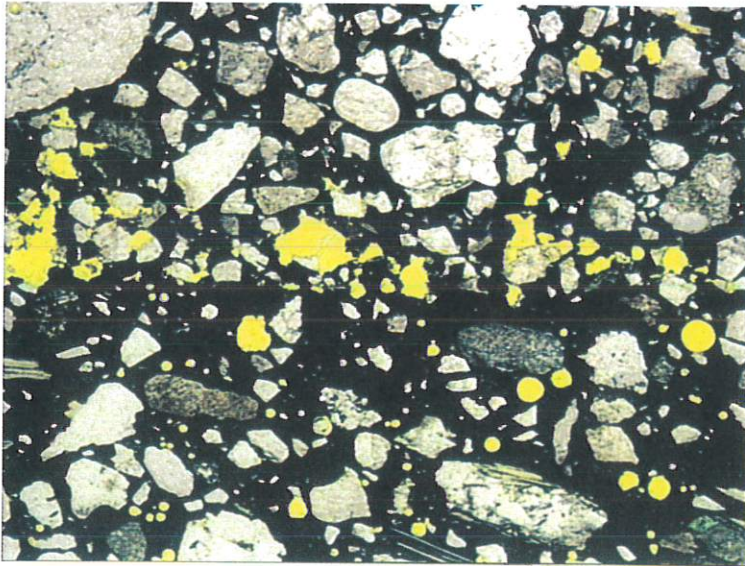
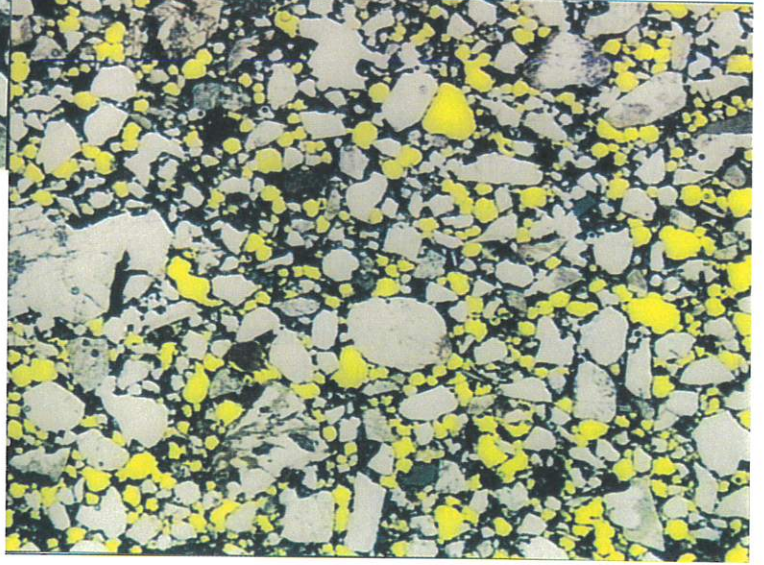
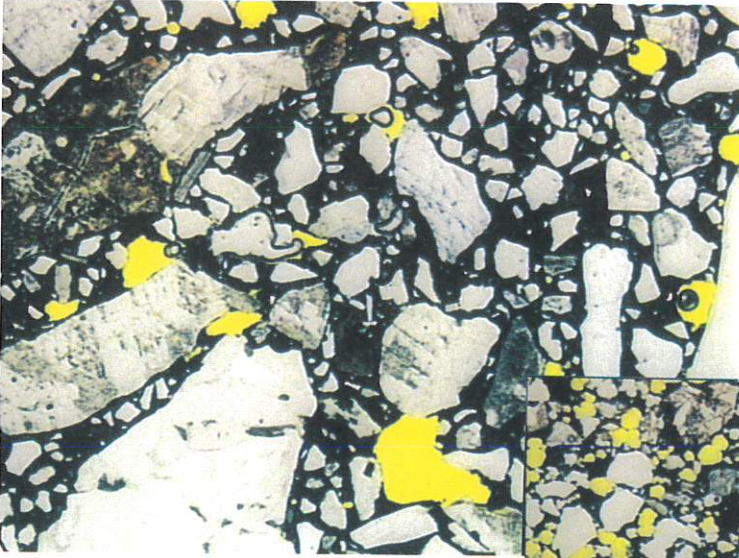
94B3,4088 (94-235)

Type of material: **Lightweight aggregate concrete**

The sample was taken from a project concerning thermal conductivity related to the air void structure.

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 9.0 x 6.7 mm.



95B3,3260 (95-60 A)

Type of material: **Concrete paver, Sweden**

Total air content (vol. %): 5,0

Spacing factor (mm^{-1}): 0,29

Specific surface (mm): 16

Paste content (vol. %): 25,0

Kitmasseluft: 17

Type of photograph (filtration):

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

95B3,3260 (95-61 B)

Type of material: **Concrete paver, Sweden**

Total air content (vol. %): 14,9

Spacing factor (mm^{-1}): 0,17

Specific surface (mm): 12

Paste content (vol. %): 31,4

Kitmasseluft: 32

Type of photograph (filtration):

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

95B3,3260 (95-62 C)

Type of material: **Concrete paver, Sweden**

Total air content (vol. %): 4,4

Spacing factor (mm^{-1}): 0,34

Specific surface (mm): 15

Paste content (vol. %): 29,8

Kitmasseluft: 13

Type of photograph (filtration):

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

95B3,3260 (95-63 D)

Type of material: **Concrete paver, Sweden**

Total air content (vol. %): 15,7

Spacing factor (mm^{-1}): 0,18

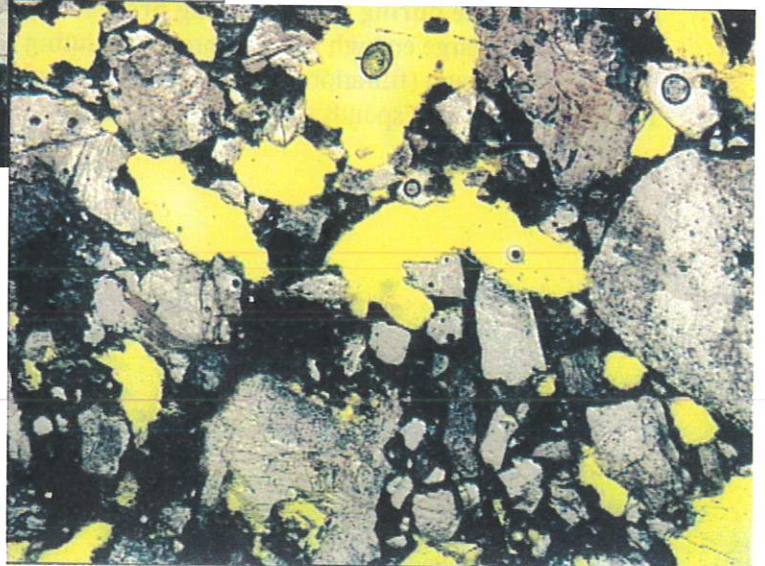
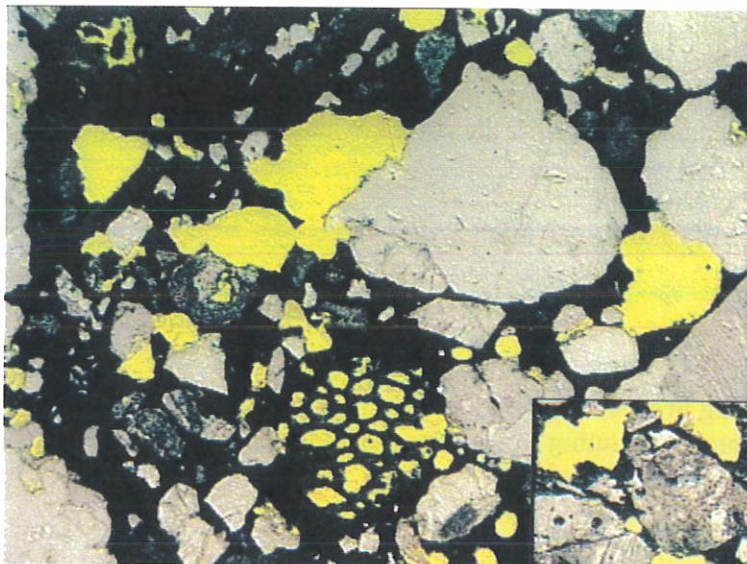
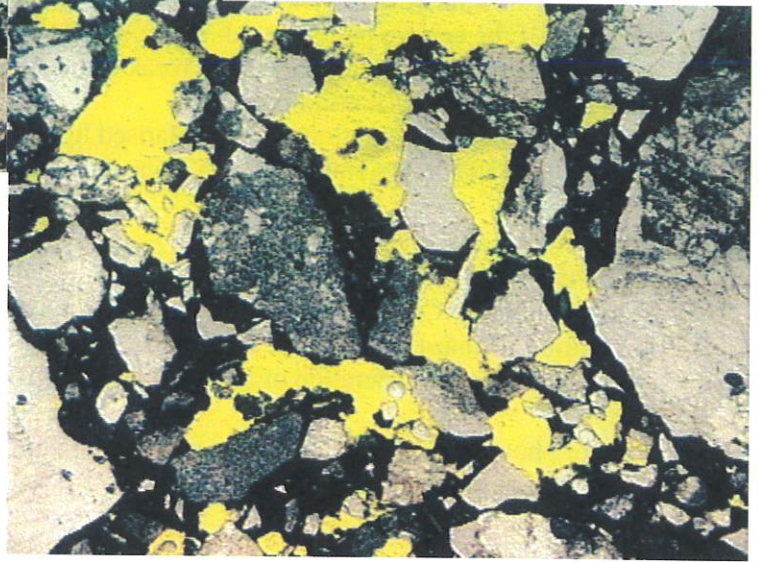
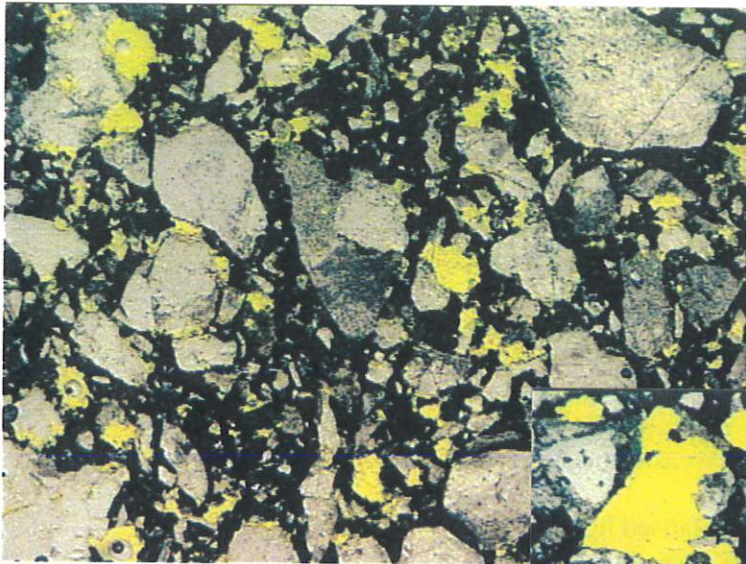
Specific surface (mm): 8

Paste content (vol. %): 22,7

Kitmasseluft: 41

Type of photograph (filtration):

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.



7.4 Causes for misinterpretations

Examples of air and air void structures that may lead to erroneous results if computer aided analysis techniques are used without a final qualitative check of the result.

94B4,4034 (94-109)

Type of material: **Ordinary concrete.**

The photograph shows **torn out aggregates** which can be mistaken for air voids in an analysis. This kind of fault generally occurs during too fast preparation of the thin section or if the cement paste is weak. One possible explanation is that the epoxy has not been given time enough for hardening. Weak cement pastes can be treated with nail hardener before the final grinding.

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

DTI 4459-5

Type of material: **Concrete used in "especially" aggressive environments.**

Formation of foam towards the reinforcement

Possibilities for agglomeration of air voids lead to difficulties during computer aided analysis.

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

92B3, 2816 (92-71)

Type of material: **Ordinary concrete.**

Two large **porous aggregate** particles occupy most of the photographed area. Porous aggregates can occasionally be mistaken for porous cement paste. The function of the porous aggregate varies very much depending on whether the pores are interconnected and have connections with the surrounding paste.

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

81B3, 5033

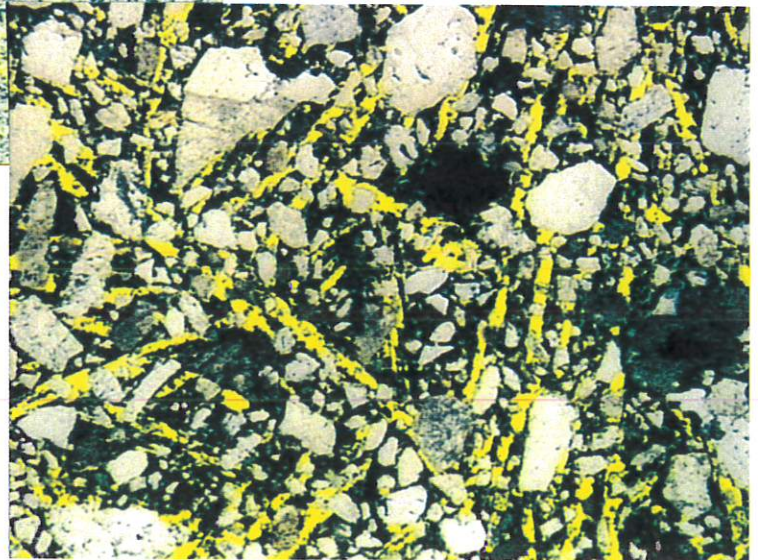
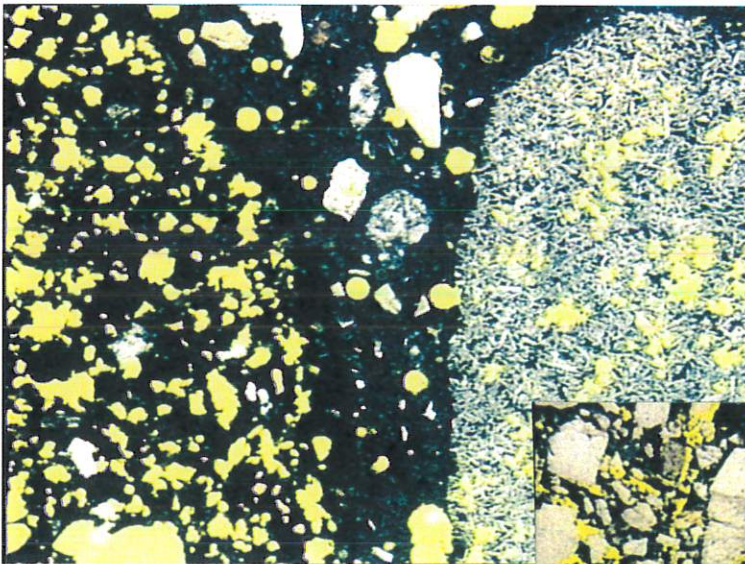
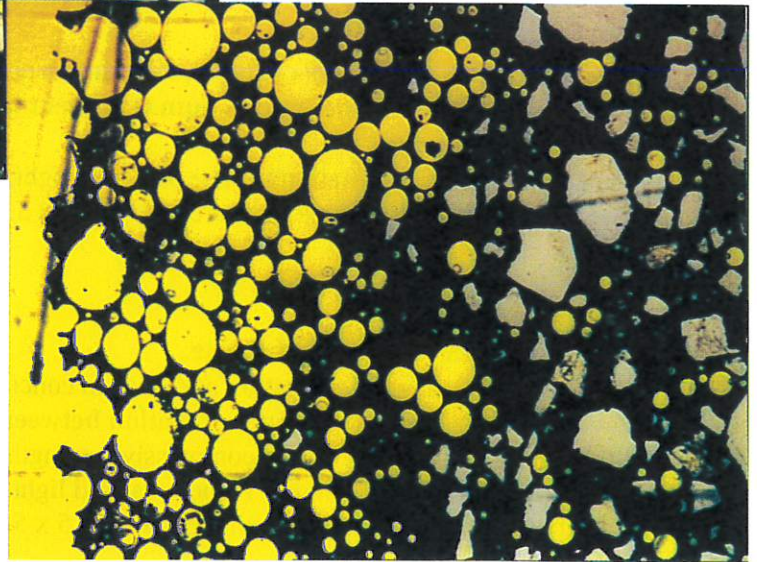
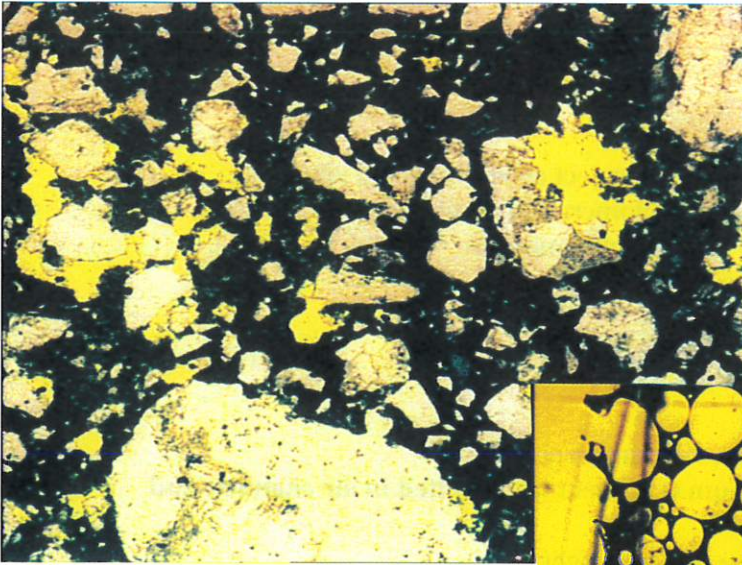
Type of material: **Ordinary concrete.**

Formation of ice during the hardening process has produced large amounts of air.

The cracks are large enough to cause problems during a computer aided image analysis.

Type of photograph (filtration): Plane polarised light

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.



8410,7615 (84-55)

Type of material: **Concrete prepared for a project concerning rod vibrators.**

Poor (too long) vibration has resulted in **agglomeration** of air voids. The resulting air void structure is not satisfactory and the concrete is not frost resistant.

Type of photograph (filtration): Plane polarised light.

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

89B3,5645 (90-01)

Type of material: **Ordinary concrete, vacuum treated.**

Poor compaction and too late vacuum treatment has resulted in air channels and entrapped air.

Type of photograph (filtration): Plane polarised light.

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

90B3,4838 (90-166)

Type of material: **Ordinary concrete.**

General information: Investigation of damaged concrete.

Poor vibration has resulted in segregation between aggregates and cement paste.

Higher permeability and poorer compressive strength may be the result.

Type of photograph (filtration): Plane polarised light.

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.

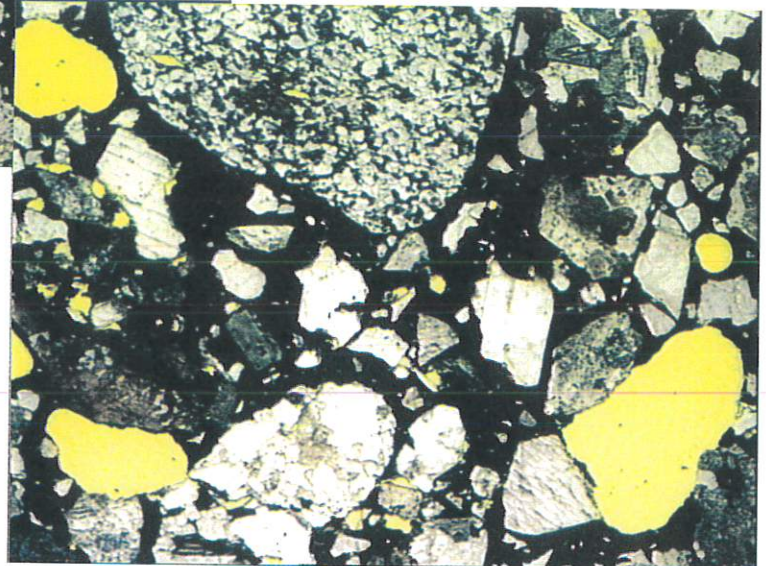
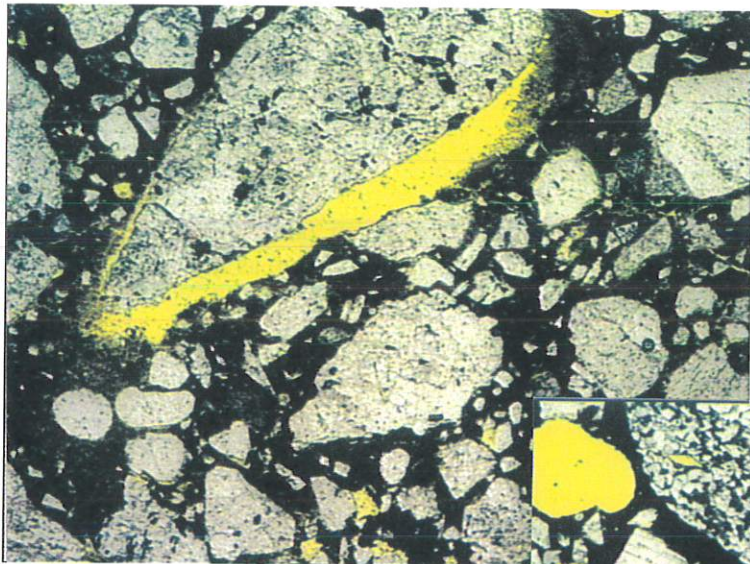
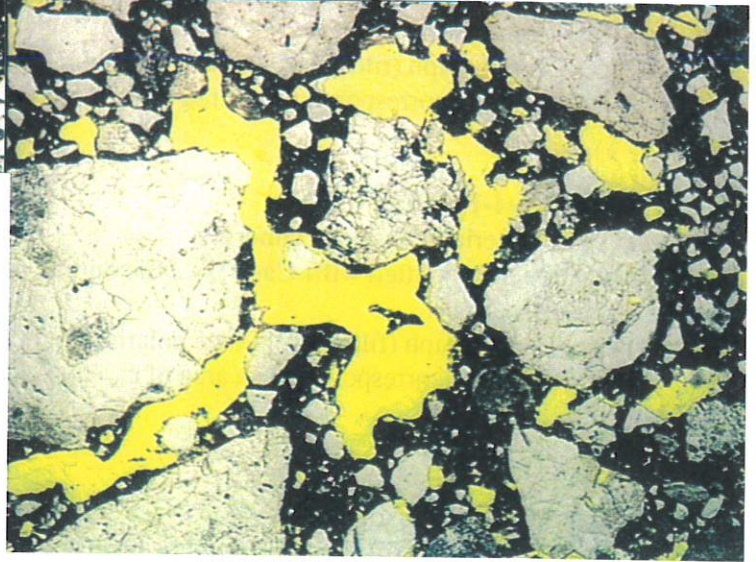
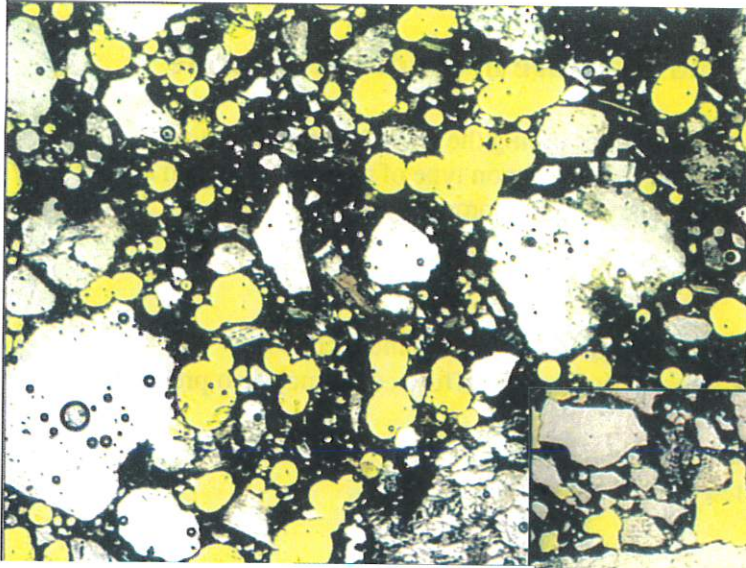
88B3,5003 (88-8)

Type of material: **Ordinary concrete.**

Air voids filled with water during mixing may later form large (mm-scale), rounded irregular voids.

Type of photograph (filtration): Plane polarised light.

The photograph corresponds to an area of ca. 6.5 x 5.0 mm.



7.5 Alterations of the air void structure in hardened concrete

Alterations can, in cases, be a cause for difficulties during the analytical procedure and may also give rise to misinterpretations. The most common type of alteration is when air voids are partly or entirely filled with secondary reaction products.

DTI 4403-5

Type of material: **Ordinary concrete** used in aggressive environment class A.

Hollow fly ash particles misinterpreted as air voids. The diffuse edges may also present difficulties to the analysis.

Type of photograph (filtration): Plane polarised light.

The photograph corresponds to an area of ca. 2.8 x 4.2 mm.

B4,6011 (94-193 015)

Type of material: **Ordinary concrete**

Air voids partly filled with $\text{Ca}(\text{OH})_2$. The outline of the air voids are irregular and difficult to define.

Type of photograph (filtration): Plane polarised light.

The photograph corresponds to an area of ca. 2.8 x 4.2 mm.

90-55 F3

Type of material: **Bridge concrete**

Ettringite crystals fill entire and parts of several air voids. Similar difficulties exist as mentioned above.

Type of photograph (filtration): Plane polarised light.

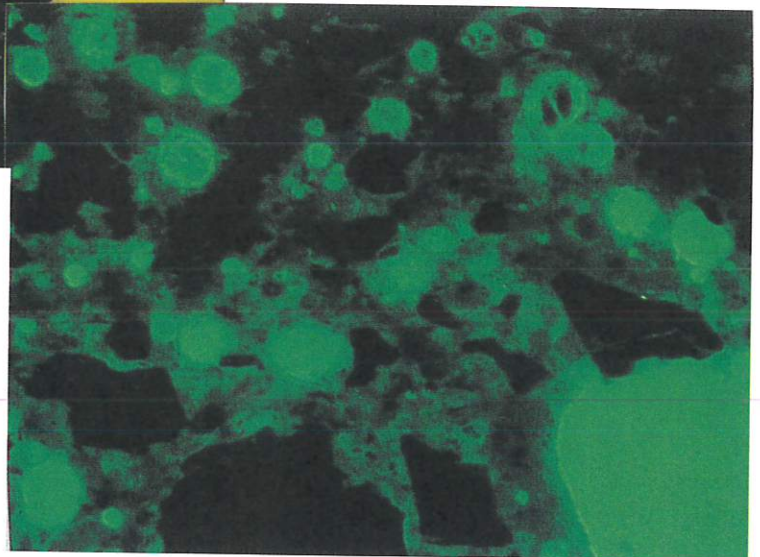
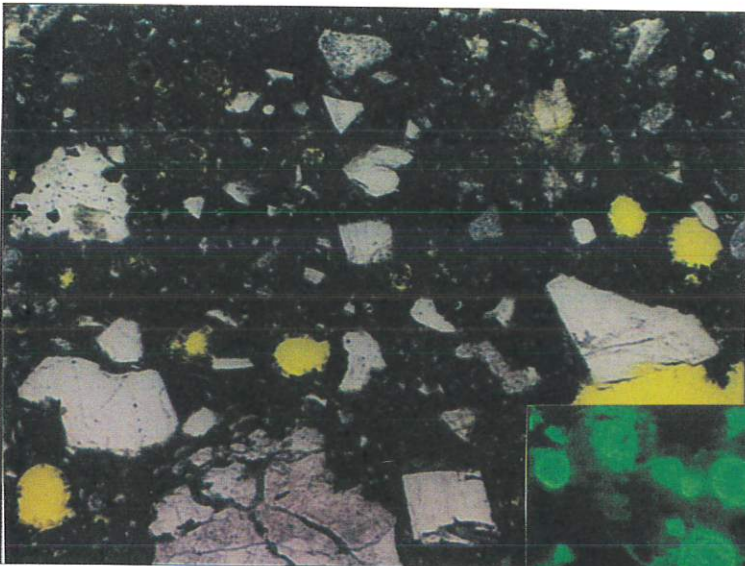
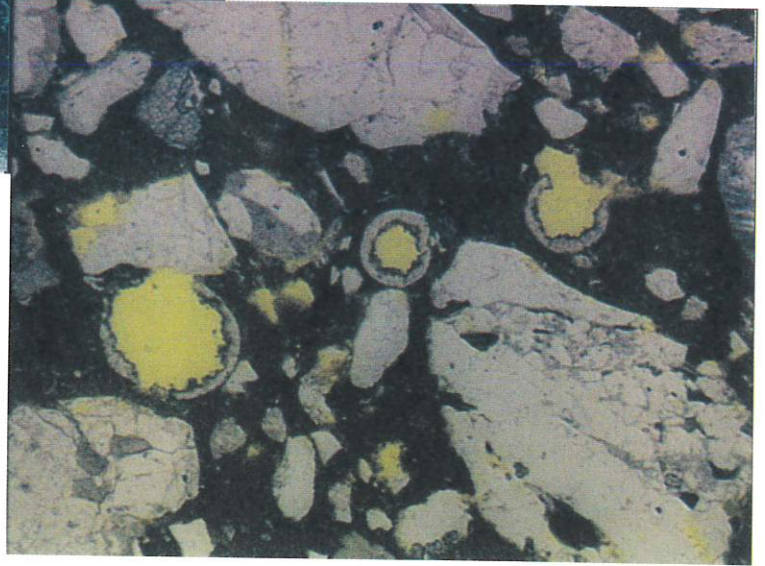
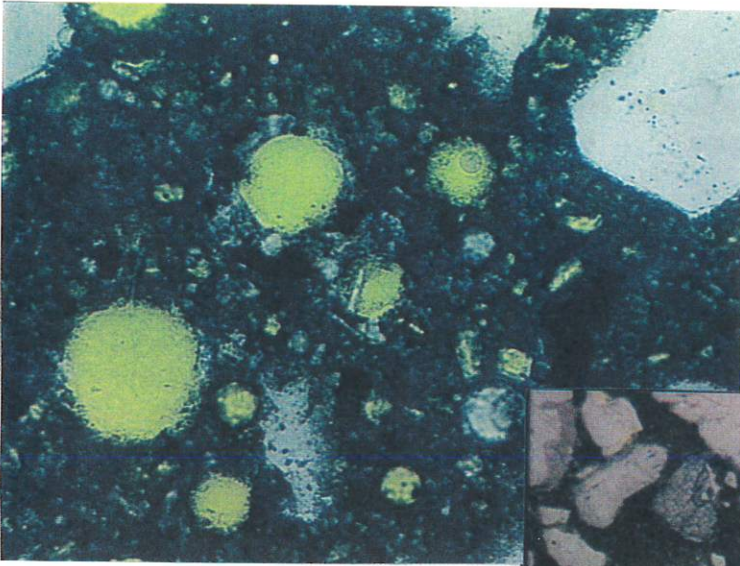
The photograph corresponds to an area of ca. 1.4 x 1.6 mm.

90-55 F3

Type of material: **Bridge concrete**, same sample as above

Type of photograph (filtration): Fluorescent light. Air voids light green, paste and aggregate dark green to black. Many light green spheres that do not function as air voids but will probably be interpreted as such during a computer aided analysis.

The photograph corresponds to an area of ca. 1.4 x 1.6 mm.



DTI 4450-3

Type of material: **Ordinary concrete** used in "especially" aggressive environment.

	Plane section	Thin section
Total air content (vol. %):	11.1	9.5
Air >350 µm:	6.4	4.2
Air < 350 µm:	4.7	5.3
Specific surface (mm):	16	26

Smaller air voids have been completely filled with Ca(OH)_2 . This has changed the performance of the concrete. The analysis of the air void structure in thin section includes the filled air voids while the analysis of plane sections do not. The concrete is young and was analysed as part of a quality control. It has to be determined which parameter and analysis that shall be compared with the requirements before any assessment.

Type of photograph (filtration): Plane polarised light.

The photograph corresponds to an area of ca. 2.8 x 4.2 mm.

DTI 4450-3

Type of material: **Ordinary concrete**, same sample as above taken with crossed polars.

Examples of Ca(OH)_2 - filled pores are indicated with arrows.

90-56 (F4)

Type of material: **Bridge concrete**.

The photograph shows a crack that penetrates the paste but not the aggregates. This indicates **early plastic shrinkage**. Smaller cracks tend to become removed/eroded during computer aided image analysis and do not normally cause any problem.

Type of photograph (filtration): Fluorescent light.

The photograph corresponds to an area of ca. 2.8 x 4.2 mm.

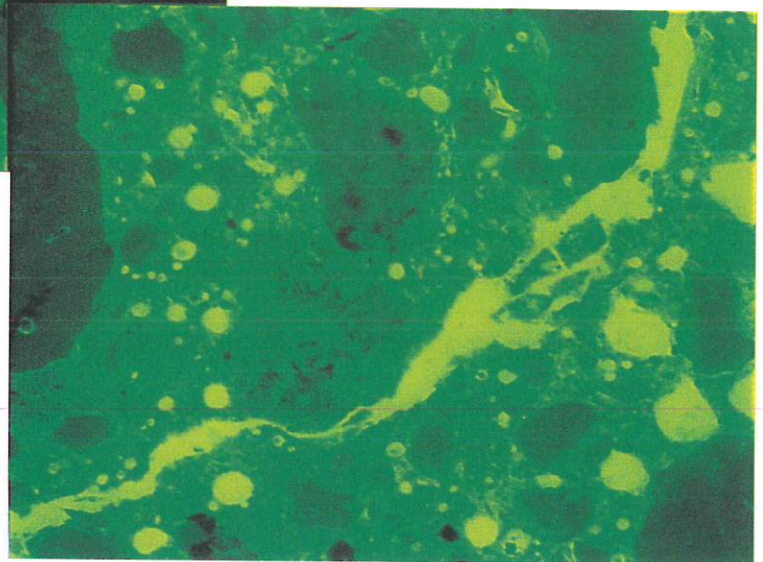
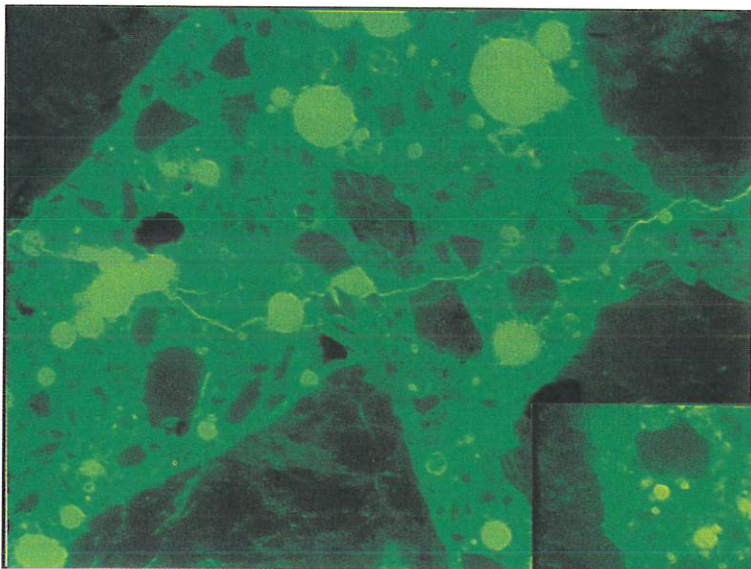
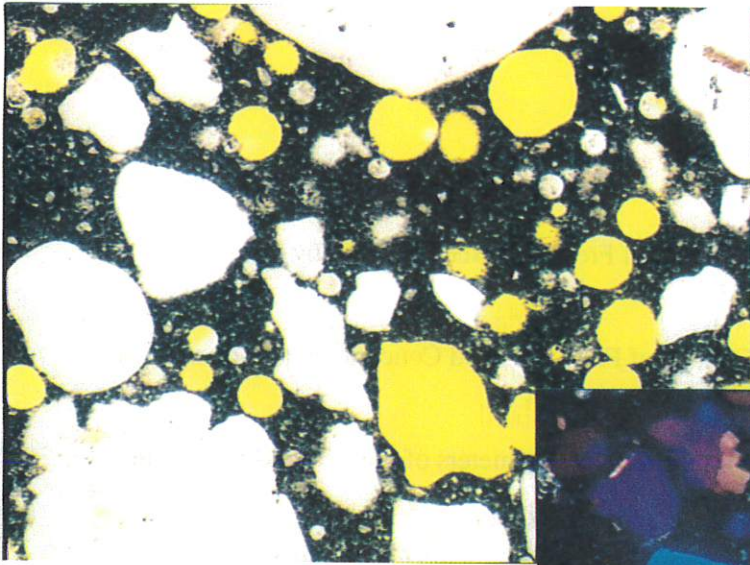
90-54 (F1)

Type of material: **Bridge concrete**.

The photograph shows a large crack that may cause problems during computer aided image analysis. The crack is much wider than the smallest air voids included in the analysis. An "erosion" of the crack would result in the disappearance of many smaller air voids, which in fact are most important for the interpretation of the concrete durability.

Type of photograph (filtration): Fluorescent light.

The photograph corresponds to an area of ca. 2.8 x 4.2 mm.



8 References

Standards, methods and regulations

ASTM C 173, Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method.

ASTM C 231 Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.

ASTM C 457-90, Microscopical Determination of Parameters of the Air void System in Hardened Concrete.

BBB 1986, Basisbetonbeskrivelse for Bygningskonstruktioner (includes the Danish regulations for ordinary concrete).

BBK 94 Betongkonstruktion, band 2 - Material, utförande och kontroll (Concrete constructions, vol. 2 - Material, handling and control).

Draft prEN 480-11: Admixtures for concrete, mortar and grout - Test methods - Determination of air void characteristics in hardened concrete.

ENV 206 Concrete - Performance, production, placing and compliance criteria.

NS 3420: Beskrivelse for bygg og anlegg. Tekniske bestemmelser, vol. 1, utg. 2, 1986. Norges Standardiseringsforbund.

NT BUILD 240, Concrete, hardened - air void structure and content (including calculations of the size distribution).

NT BUILD 381, Concrete, hardened - air void structure and content.

SS 13 71 15: Determination of air content in fresh concrete. Lufthalt enligt volumetrisk metod.

TI-B 4 Structural analysis of hardened concrete in connection with quality control.

TI-B 5 Analysis of air voids in hardened concrete.

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