SYNTHESIS REPORT

FOR PUBLICATION

CONTRACT No: **BREU -CT 91-0490**

PROJECT No.: **BE -4300**

TITLE: **Image Analysis of Building Materials**

PROJECT CO-ORDINATOR: **Belgian Building Research Institute**
WTCB - CSTC

PARTNERS:
Dansk Beton Teknik A/S

Centre Scientifique et Technique du Bâtiment

Kontron Elektronik GmbH

STARTING DATE :01.12.1991 **DURATION :48 Months**

PROJECT FUNDED BY THE EUROPEAN COMMISSION UNDER THE BRITE/EURAM PROGRAMME

DATE :31,07.1996

TABLE OF CONTENTS

Image Analysis of Building Materials

1. Research and Partners

The following researchers have contributed substantially to this research report :

Belgian Building Research Institute
WTCB - CSTC
Violetstraat21 -23
B -1000 BRUSSELS
Jan ELSEN, Ph.D. Mineralogy
Nicole LENS, Civil Engineer

Dansk Beton Teknik A/S
Hellerupland Allé, 21
DK -2900 HELLERUP
Tine AARRE, Ph. D. Engineer

Centre Scientifique et Technique du Bâtiment
Rue Joseph Fourier, 24
F -38400 SAINT MARTIN D'HERES
Daniel QUENARD, Ph. D. Engineer

Kontron Elektronik GmbH
Oskar-von-Miller Strasse 1
D -85385 ECHING/MUNICH
Vito SMOLEJ, Dr. Material Science

2. Abstract

The general aim of this project was the development and the introduction of automated image analysis techniques into the petrographic analysis methods for monitoring and assessing quality of concrete constructions and cementitious building materials.

Petrographic analyses on thin sections have already been used in concrete technology for more than 10 years in Europe and has proved to be a very important method for the quality control of recently cast concrete, for the inspection of the concrete structures and for the investigation of concrete deterioration. .

But a traditional petrographic analysis mainly consists in a qualitative and subjective assessment of a number of relevant parameters for the durability of concrete which is a serious limitation of this method.

Several of those parameters can be quantified by image analysis methods, which replace traditional time consuming point counting techniques.

Automated image analysis methods have been developed to quantify the W/C ratio and the homogeneity of the cement paste. Measurements on cement paste samples and on concrete samples confirmed the direct relationship between the W/C ratio and the mean grey value measured on thin sections. Measurements on samples with different amounts of different types of sand indicate that the effective W/C ratio of concrete is strongly influenced by the specific surface of the sand. Two new homogeneity coefficients, one describing local (multifractal concept) and the other one describing global homogeneity (statistical analysis) have been defined. A comparison between the measurements of these coefficients and an expert classification gave satisfactory results.

A procedure has been established to investigate quantitatively the cement microstructure using polished sections and SEM-techniques. To improve the quantitative aspect, more methods have to be developed using thresholding techniques and new concepts have to be introduced to describe the disorder of the microstructure. The results indicate that the fractal dimensions range from 1.44 to 1.71, but although the specimens have different compositions, the shapes of their structure are characterised by similar fractal dimensions. The fractal dimension is therefore not useful as a means of differentiating pore structure from BSE images of cement based materials.

New procedures have been developed to characterise the air void system using automated image analysis techniques. The different measurement procedures have been evaluated on concrete samples covering a wide range of air content and specific surface. In parallel the air void structure has been evaluated by traditional point count methods as described in ASTM C457 on thin sections. The results indicate that air void analyses on thin sections do not provide sufficiently accurate results. First of all, the measured air content is apparently too low. Secondly, the area provided by two thin sections yields a higher scatter of the measured parameters than if one plane section is measured.

Image analysis procedures have been developed to characterise quantitatively the presence and the morphology of cracks and to recognise and to quantify crack patterns. Therefore, a sample catalogue in four copies of thin sections illustrating different types of cracks in concrete has been prepared.

The grain size distribution of aggregates in hardened concrete has been determined using automated image analysis techniques

3. Introduction, background of research

In the Technical Annex of the project the state-of-the-art of this research programrne was presented as follows:

As a consequence of the widespread and increasing deterioration in concrete structures in the EC, research in durability of concrete has been conducted at a high priority level for the last 10 to 15 years. However, this research does not seem to have been conducted in parallel to the research in high performance concrete.

As a result, severe deterioration may be observed in most concrete structures exposed to environmental conditions which could be harmful to concrete not absolutely durable. The main deterioration mechanisms are :

- frost/thaw action
- alkali aggregate reactions
- corrosion of reinforcement

Petrographic analyses have already been used in concrete technology for more than 10 years in Europe and has proved to be a very important method for the quality control of recently cast concrete, for the inspection of the concrete structures and for the investigation of concrete deterioration.

But in a traditional petrographic analysis, the eye is used as a measuring instrument for the identification of the different components and for the recognition of structure phenomena of the material, The human visual system is extremely powerful in extracting interesting detail from an image but has limited capability in measuring quantitatively. As a consequence, a number of relevant parameters for the durability is determined qualitatively. This means that a traditional petrographic analysis mainly consists in a subjective assessment of these important parameters, which is a serious limitation of this method.

However, several of those parameters can be quantified by image analysis methods, which replace traditional time consuming point counting techniques.

4. Objectives

The ultimate target of this project was the development and the introduction of automated image analysis techniques into the petrographic analysis methods for monitoring and assessing quality of concrete constructions and cementitious building materials.

This project had the objective :

- to prepare guide-lines, rules and a sample catalogue for the petrographical assessment of the durability parameters in order to assure the use of uniform procedures and evaluations and to contribute to the pre-normative work in the EC;

- to develop, evaluate and standardise methods in order to measure and quantify the following parameters which until now are described qualitatively by petrographical means:

  - Determination of the W/C ratio and its homogeneity by image analysis techniques.
  - Introduction of a fractal approach to characterise the microstructure of the cement paste to provide a mean for assessing the quality of a cement paste.
  - Determination of the air void content, pore size distribution and pore shape morphology by image analysis techniques.
  - Quantitative characterisation of the presence and of the morphology of cracks and the development of methods in order to recognise, to describe and to quantify complex crack patterns with the aid of mathematical morphology and fractal theory.
  - Determination of the granulometry and the shape of aggregates by image analysis techniques.

- to develop the necessary procedures for an automated image analysis system to measure and to evaluate all the aforementioned parameters and methods.

5. Results

TASK 1: W/C ratio

The main objective of this research task was the development of an automated image analysis procedure to determine the W/C ratio optically from fluorescent dye impregnated thin sections of concrete.

The W/C ratio (or the capillary porosity) and the homogeneity of cement paste can be examined exposing a fluorescent epoxy impregnated thin section of the concrete to UV-light in a fluorescence microscope. Traditionally, determination of W/C ratio and homogeneity has been carried out by visual petrographical analysis. However, the result of such procedure will always be submitted to the subjectivity and the competence of the operator. To assure a uniform and comparable fabrication of fluorescent impregnated thin sections between laboratories, a standard procedure for the preparation technique has been prepared. The aim of this standard procedure is to enable a comparable interpretation of the information provided by thin sections prepared at different laboratories. To enable a reproducible and reliable estimation of W/C ratio and homogeneity, a set of guidelines has been prepared. The guidelines contain general recommendations that are valid for both visual analysis and for Automated Image analysis of thin sections.

A number of series of reference samples have been produced with well defined W/C ratio : pure cement paste samples with different cement types, mortar samples with half and full sand content and different concrete samples. Thin sections prepared out of these reference samples have been used in a first phase of the research project to develop the automated image analysis procedures.

Three different methods have been tried out to measure the W/C ratio by Image analysis techniques : an interactive method, a semi-automatic method and a fully automatic method. Both the interactive and the semi-automatic method gave reliable results but the semi-automatic one is preferred for its higher objectivity and its much higher speed. The fully automatic method has been rejected because it seems to be impossible to measure a thin section automatically with its complete grey level distribution and to pick out afterwards the cement phase grey level distribution without losing the important unhydrated cement particles.

Concrete mixes with unknown W/C ratio have been prepared in a second phase of the project to investigate the precision of the method.

The measurements on the pure cement paste samples confirm the direct relationship between the W/C ratio of the samples and the mean grey value measured on thin sections. Both transmitted and incident illumination can be used for this measurement, but the transmitted illumination is more sensitive to differences in thickness of the thin section. Concrete made with CEM III-type cement is much more sensible to maturity then concrete made with CEM-I type cement.

The results of the measurements on the thin sections prepared out of the reference concrete series also indicate a clear relationship between the W/C ratio and the mean grey value but these measurements indicate that the effective W/C ratio measured is influenced by other parameters related to the aggregate fraction present in the concrete. The measurements on concrete samples with similar aggregate composition and unknown W/C samples indicate that the mean difference between calculated W/C ratio (using regression fitted values) and intended W/C ratio values is 0.023 (max. of 0.031). Concrete samples with an intended W/C ratio higher than 0.60 are difficult to prepare because of bleeding.

Several series of different concrete and mortar samples have been prepared in a third phase of the project to investigate the influence of the cement type and of the hydration on the measurements and to investigate the influence of the amount, type and specific surface of the aggregates on the effective W/C ratio of the cement paste in concrete.

The following conclusions can be drawn from the measurements on these different concrete and mortar samples :

- The automated image analysis method is valid for Quality Control of concrete made with CEM-I and CEM -III type cements with well-known composition and maturity. If the maturity is not known the method is only valid for CEM-I-type cements. The method is very promising for research purposes for example to determine the influence of the specific surface of the sand on the effective W/C ratio of the concrete, or to study the influence of the interracial zone between aggregate and cement paste. For damage diagnosis this method must be used with great care especially for concrete samples prepared with other than CEM-I type cement and for samples with less-known aggregate types.

- Results of automated measurement techniques are not influenced by reflection from air voids.

- The effective W/C ratio decreases as the amount of sand increases.

- Varying the maturity between 7 and 28 days does not have any significant influence on the estimated effective W/C ratio (CEM-I-type cements).

- The effective W/C ratio is reversibly related to the sand/cement ratio.

- The effective W/C ratio is reversibly related to the fineness of the sand.

The last two findings indicate that the effective W/C ratio of concrete and mortar is strongly influenced by the specific surface of the aggregate. The surface area of aggregate per unit volume of mortar can be varied, as demonstrated in the experimental investigations here, by changing, e.g., the sand/cement ratio, or the grading of the sand.

The correlation between W/C_{eff} and the specific surface of aggregate is supposedly caused by the increased porosities in the interracial zone between paste and aggregate. (As the specific surface of aggregate increases, more water will be trapped in the interracial zones and less free water will be present in the bulk paste.)

An image analysis procedure has been developed to measure the homogeneity of the cement paste in hardened concrete. The measurement results in two homogeneity coefficients. The first one gives an indication of the homogeneity of the cement paste on a local scale and its measurement is based on multifractal theory. The second one estimates the homogeneity of the cement paste on a global scale and its measurement is based on a statistical approach.

A comparison between the measurements of this newly defined homogeneity coefficients on a series of thin sections and the expert classification on a visual basis, has given satisfactory results.

TASK 2 : **Cement Microstructure**

The main objective for this task was to introduce new techniques to analyse the microstructure of the cement paste. These techniques, based on stereology, mathematical morphology and fractal geometry have been developed in other fields of research such as metallography, medical image analysis and disordered systems. The characterisation of the microstructure is expected to provide a mean for assessing the “quality” of a cement paste.

To reach this main objective the task was split up in the following subtasks.
- preparation of cement paste and mortar samples.
- preparation of highly polished samples.
- measurement by SEM.
- development of image analysis procedures.

Several cement paste and mortar samples were made with a set of formulations in order to get various microstructure types. The Water/Cement ratio was changed and several different admixtures were used (air entrainer, silica fume, . . .). The size of the samples was always 16x 16 x 4 cm. Small sections of 10 x 10 x 2 mm were cut from these samples for impregnation.

These sections were impregnated with an epoxy or acrylic resin and were polished using SiC-grains and diamond pastes. The SEM was used in backscattered mode in order to produce grey images in which phases with distinct average atomic numbers are differentiated by their grey-value.

Several algorithms were developed in order to :

- enhance the contrast between the four phases : anhydrous grains, pores, hydrated products (CSH) and Calcium Hydroxide (CH)
- estimate the fractal dimension of the porosity and of the interface pore-structure.

We can state that a procedure is well established to investigate quantitatively the cement microstructure using polished sections and SEM-techniques. To improve the quantitative aspect, more methods have to be developed using thresholding techniques and new concepts such as multifractal analysis have to be introduced to describe the disorder of the microstructure.

The results indicate that the fractal dimensions range from 1.44 to 1.71. It means that the interfaces voids-solid are more or less rough, but although the specimens have different compositions, the shapes of their structure are characterised by similar fractal dimensions.

Conclusions :

- The fractal dimension is not useful as a means of differentiating pore structure from 13SE images of cement based materials.
- The scaling behaviour of the pore (and crack) shape is independent of structured differences and the fractal dimension may be useful as a "universal value" for modelling.

TASK 3: Air void system

The main objective of this task was to determine by automated Image Analysis techniques the air void content, spacing factor and specific surface following ASTM C457-82.

As a first subtask the results of three different measuring techniques for measuring air void analyses have been compared. This work was carried out in association with the work performed in the BRITE/EURAM Project QA/QC, BE-CT90-0358.

The three techniques applied are; the DBT air void analyser, polished plane sections analysed according to ASTM C457 and thin sections analysed according to ASTM C457. Furthermore, the advantages and the possible errors related to different techniques have been evaluated.

Ten different concretes have been prepared under conditions that reflect full scale mixing, placing and compaction techniques of cementitious materials. During preparation of these 10 concrete samples, the **true** air void distribution has been measured by the DBT Air Void Analyser. By means of this technique, the amount of air and the diameter of the individual air voids of the fresh concrete are being recorded. From these results, the spacing factor, the specific surface and the air content has been calculated.

To establish a reference value for the air void structure, polished plane sections from each of the 10 concretes have been analysed in accordance to the Linear Traverse Method as described in ASTM C457, Standard Practice for Microscopical Determination of Air Void system in Hardened concrete. The analysis is carried out on contrast enhanced, polished plane sections using equipment designed for automatic registration of chord number and length.

For each of the above mentioned concretes a number of thin sections have been produced. The air void structure of the concrete in the thin sections has been evaluated by petrographic analyses by point counting as described in ASTM C457, sections 11-15, modified point counting method. On basis of the results of this analysis, it is assessed whether the analysis area traditionally being applied when measuring the air void structure on thin sections is sufficient to provide reliable and reproducible results.

Comparing the results of the air void analyses of thin sections with the corresponding results of plane sections, the following comments can be made :

- the air content measured on thin sections is approximately 15% lower than the air content measured on plane sections.
- the specific surface and the spacing factor measured on thin sections is not systematically different from those measured on plane sections.
- the standard deviation of the air void parameters measured on thin sections is significantly higher than the standard deviation of the air void parameters measured on plane sections.

Generally, the results indicate that air void analyses on thin sections do not provide sufficiently accurate results. First of all, the measured air content is apparently too low. Secondly, the area provided by two thin sections yields a higher scatter of the measured parameters than if one plane section is measured.

A second subtask consisted in developing new procedures to characterise the air void system using automated Image Analysis techniques.

1) Elaboration of a fast and accurate method for an automated air void analyser for polished concrete specimen following the specifications of ASTM C457-82 very strictly.

   In a first step the linear traverse method according to ASTM C457 has been implemented on a digital image processing system by the BBRI. Using this procedure only one parameter, the selection of the discrimination interval, has to be selected by the operator. DBT and BBRI have for this research part established a co-operation to ensure that the measurements obtained after this implementation were on a comparative level. To this extent an exchange of specimens has taken place, the measurements on these samples gave very satisfactory results.

2) Development of new methods and procedures to characterise the air void structure in hardened concrete on polished specimen and on thin sections using more advanced stereological methods and image analysis techniques.

The introduction of image analysis techniques offers the possibility to use new concepts in describing the air void characteristics of hardened concrete, which is related to its frost resistance. One of the objectives of this subtask was to establish the possibility of measuring under the same conditions and on the same sample and a traditional air void analysis and a more advanced analysis using new and powerful image analysis methods.

The different IA techniques have been evaluated by comparing the measured results of 6 concrete samples from 6 concrete mixes. The concrete mixes covered a wide range of air content and specific surface. Furthermore, the same samples have been remeasured by the automated measurement system of the laboratory of DBT to enable a comparison of the results of the measurements between the two laboratories.

Two different procedures have been developed using the entire surface of the polished or thin sections. The first one measures very rapidly the two most important parameters : the total air content and the specific surface. A disadvantage of this method is that a continuous field has to be examined. A second method with an ad random sampling has been developed in order to obtain a three-dimensional distribution of the air voids. Different methods to reconstruct the air void sections being intersected by the image frame edge have been deveIoped and evaluated. A distribution of air void sections is obtained by combining the total air content with the number of air void sections. Finally the three-dimensional distribution can be calculated using existing stereological methods.

TASK 4: Cracks

The main objective of this task was to characterise quantitatively the presence and the morphology of cracks and to develop methods that recognise, describe and quantify crack patterns by image analysis techniques.

A sample catalogue of thin sections illustrating different types of cracks in concrete has been prepared. The catalogue has been produced in four copies.

A number of images of typical crack patterns, selected by DBT and the BBRI, have been analysed by CSTB and Kontron using their image analysis equipment.

Image Analysis procedures for crack analysis have been developed. They are based on a quantitative image analysis of polished sections of hardened concrete samples. The information available therefore is two-dimensional. To obtain information of the three-dimensional character statistical-geometrical relationships have been applied provided by stereology. The classical methods in stereology proposed by Saltykov are based on a coverage of the sample by a line-grid. The basic idea is to count the number of intersections between the crack network and the template. It is possible to derive from these measurements the following characteristic parameters for the crack network : total crack length per unit sample area, degree of orientation, specific surface area, mean free path...

TASK 5: Granulometry

The main objective of this task was to determine for a set of mortar and concrete samples by Image Analysis techniques the granulometry and shape of aggregates.

The granulometry of aggregates as determined by image analysis techniques has been evaluated by a comparison with the results obtained by a mechanical method being used traditionally.

The granulometry of 10 different sand types has been determined of the pure sand and of the same sand obtained after chemical treatment and grinding of the hardened mortars. Thin sections of these mortars have been prepared and have been analysed by image analysis techniques, A traditional petrographic analysis of seven different concretes and five mortars has been assessed on thin sections and on plane polished sections.

6. conclusions

A summary for the assessment of the results is given below:

Task 1:	***W/C ratio - Cement Paste:***	*Very satisfying* - Research ideas confirmed.
	W/C ratio - Concrete:	*Satisfying for OPC-concrete* - Limited for concrete with slag cement. Further research is needed for different cement replacing materials
	Homogeneity:	*Satisfying* - Needs further research
Task 2:	***Cement microstructure:***	*Failed* Method shows promise to quantify the different components of the cement phase
Task 3:	***Air void analysis:***	*Very satisfying* - Methods ready for standardisation.
Task 4:	***Crack analysis:***	*Satisfying* - Production of a sample catalogue - Successful discrimination of the different crack types by IA techniques. - Needs further research
Task 5:	***Granulometry :***	*Satisfying* - Development of a general method unsuccessful

7. *Acknowledgements*

This research has been carried out with funding from the European Community under the BRITE-EURAM Programme.

Image Analysis of Building Materials
- Project Number: BE-4300
- Contract Number : BREU-CT91 -0490

The project team would, further, like to express their thanks to the Project Officer Ms. Adele Lydon of the European Commission for excellent co-operation and support during the research period. **We also** want to thank the Project Technical Auditor, Mr Steen Rostam, COWI Consult, for his contribution.