

# SYNTHESIS REPORT

## FOR PUBLICATION

CONTRACT N<sup>o</sup>: BREU-CT90-0358

PROJECT N<sup>o</sup>: BE-3376

TITLE:

QUALITY ASSURANCE OF CONCRETE BASED ON TESTING OF THE FRESH, STILL PLASTIC MATERIAL

PROJECT  
COORDINATOR           DANSK BETON TEKNIK A/S

PARTNERS           CUR  
Büchnerweg 3  
NL-2800 AK Gouda  
The Netherlands

INTRON  
Dr. Nolenslaan 126  
NL-61 30 PD Sittard  
The Netherlands

FORCE Institutes  
Park Allé 345  
DK-2605 Brøndby  
Denmark

CSTC  
Avenue P. Holoffe 21  
B-1342 Limelette  
Belgium

Dansk Beton Teknik A/S  
Helleruplund Alle 21  
DK-2900 Hellerup  
Denmark

STARTING DATE : 01/03-1991

DURATION :48 MONTHS



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

---

DATE: 31 December, 1996

## I N D E X

1. List of researchers and authors
2. Abstract
3. Introduction, background of the research
4. Technical Description
5. Results and Conclusions
6. Acknowledgements

## 1. RESEARCHERS AND AUTHORS

During the research period the following key personnel have made substantial contributions to the research:

### DANSK BETON TEKNIK A/S

Helleruplund Allé 21, DK-2900 Hellerup, Denmark

Anders Henrichsen, Professor h.c., M.Sc., Civil Engineering

Bent Jensen, Bachelor of Engineering

### FORCE INSTITUTES

Park Allé 345, DK-2605 Brøndby, Denmark

Allan Northeved, M.SC., Electrical Engineering

Dr. Oskar Klinghoffer, M. Sc., Civil Engineering

### CUR

Centre for Civil Engineering Research, Codes and Specifications

Búchnerweg 3, NL-2800 AK Gouda, The Netherlands

Aad Fuchs, Bachelor of Engineering

### INTRON BV

Dr. Nolenslaan 126, NL-6130 PD Sittard, The Netherlands

Dr. Gert van der Wegen, M.SC., Chemistry

Gerard Bosmans, B.Sc., Physics

### CSTC,

Centre Scientifique de Technique de la Construction

Avenue P. Holoffe 21, B-1342 Limelette, Belgium

Johan Paul Vyncke, M .Sc., Civil Engineering

## 2. ABSTRACT

The aim of the research has been to develop and document a series of innovative test methods and procedures for use in Pre-testing and Quality-Assurance of concrete in general and particularly of High Performance Concrete.

This goal was transformed into the following task-objectives:

- \* Development of a method for determination of the water/cement-ratio of a given concrete at the concrete production plant.
- \* Further development of this method for on-site Quality Assurance of variations in w/c-ratio of the concrete.
- \* Development of a fast and reliable method for assessment of the air void structure of fresh concrete at the concrete production plant.
- \* Further development of this method for use on-site. Quality Assurance, Quality Control and Monitoring of the air void structure of the placed and compacted concrete.
- \* Development of a method for determination of the degree of compaction of concrete.
- \* Development of a method for detection of defects in placed and compacted but still, plastic concrete.
- \* Development of a method for prediction of the chloride diffusivity of the fully matured concrete material.

An assessment of the results is given below:

Objective	Assessment of Results			
	I	II	III	IV
W/c-ratio, concrete plant	+			
W/c-ratio, structures		+		
Air-voids, laboratory	+			
Air-voids, structure	+			
Degree of compaction			+	
Defects in structures				+
Prediction of diffusivity	+			

The assessment classes are as follows:

- I) Very satisfying, Commercially feasible;
- II) Satisfying but needs further research or documentation;
- III) Research ideas confirmed, but further research is needed;
- IV) Failed.

For the group I research; Very satisfying results with immediate commercial values, a number of prototypes of the testing equipment were constructed.

These prototypes have been tested in full scale on large civil engineering, High Performance Structures.

During this practical test phase it has been documented that the research did meet an industrial need and it is already proved that some of the methods already at this premature stage have contributed to reduction of construction costs and to improvements in Quality Assurance Management.

For these tests, test method statements have been prepared.

### 3. INTRODUCTION, BACKGROUND OF THE RESEARCH

#### 3.1 Background, State-of-the-art

In the Technical Annex of July 1990 the background of the research was presented as follows:

Quality Assurance and Quality Control of concrete are today in its advanced form carried out in separate stages:

i) Quality verification of the concrete components, i.e. cement, water, aggregates and additives. By this process it is assured that the materials going into the concrete mix are of the specified quality. It is, hereby assured that harmful alkali-aggregate reactions cannot appear. It is, further, assured that the alkali- and the chloride content of the materials are below the specified level.

ii) During batching and mixing it is assured that the composition of concrete is in accordance with the specification, i.e. that the aggregates are batched by their correct quantities and that the average water/cement-ratio is correct for the batch.

The air void content of the concrete may also be determined.

The testing methods for the determination of these properties are well known and described in Standards of Practice (Sieving, determination of water content, air content determination by pressure-meter method etc. )

Based on this information an accurate forecast of the ultimate strength of the concrete can be given.

iii) Strength testing of laboratory produced specimens. Hereby, the strength properties of the concrete are verified normally after 28 days.

iv) Petrographic analysis of hardened concrete.

Hardened concrete bears inherent evidence of the materials used, the methods of work, factors influencing the concrete both during the hardening process and later, chemical transformations and of any damages.

Analyses of the concrete's structure and its components, using suitable methods and combination of methods, makes it possible to describe the composition of the concrete, account for its origin and determine events which occurred in the concrete during and after its hardening. On the basis hereof the durability can be predicted through comparison with an idealized model and with existing empirical information. It is, thus, easy to determine factors directly influencing the durability of the concrete such as air-void size and distribution, w/c-ratio and its variation in the concrete, formation of cracks or the appearance of other types of flaws.

Generally it can be stated that the above mentioned methods and procedures are excellent for the **control** of the hardened concrete and for the **documentation** of the properties achieved as to durability as well as strength performance.

The methods are also excellent to assure that harmful alkali-aggregate reactions will not appear in the concrete structure.

At present, however, there are hardly any methods available for predicting the properties described in iv) of the hardened concrete. Based on present knowledge and methods it does not seem possible (by testing with the freshly mixed concrete or the compacted in-place, but still plastic concrete) **to assure the** quality of the concrete with regard to the following properties;

- \* density of the cement paste;
- \* uniformity of the cement paste;
- \* size and distribution of the air-voids;
- \* permeability and diffusivity of the concrete;
- \* homogeneity of the concrete, i.e. by detection of cracks, honeycombs and other types of flaw.

### 3.2 **OBJECTIVES OF THE PROJECT**

It has been the objective of the research to develop a system for Quality Assurance of Concrete and to test and verify this system based on petrographical analyses in combination with testing of permeability and diffusivity of the hardened concrete using traditional testing methods.

It was the goal of the project that the R&D would result in the following new test methods:

Determination of w/c-ratio of fresh concrete and the homogeneity of the cement paste. The accuracy of the test method should be within  $\pm 0.05$  of the equivalent w/c-ratio. This accuracy requirement was, further, strengthened during the research to  $\pm 5\%$  on the water content or  $\pm 0.03$  on the w/c-ratio.

Determination of air-void structure (quantity of air with diameter  $< 0.5$  mm, size and distribution) in the fresh concrete. The accuracy of the test method is expected to be within  $\pm 10\%$  on single tests and  $\pm 5\%$  on series of 3 as compared with results of testing in accordance with ASTM C457 on the hardened concrete.

Determination of the consolidation of the in-place, still plastic concrete and the homogeneity of the material. Relevant measures to describe the uniformity of the concrete will be developed during the research.

Determination of maturity, permeability and diffusivity:

Determination of maturity. The accuracy of the method is expected to be within  $\pm 5\%$  (mature concrete = 100%).

Determination of permeability and diffusivity. The aim of the test method is as a minimum to classify the resistance towards ingress of chloride in a scale with five classes, the span of diffusion coefficients from the lowest to the highest being one order of magnitude.

## 4. TECHNICAL DESCRIPTION

### 4.1 Introduction

The research approach was described in a work programme which combined a number of tasks.

During the research this work plan has been slightly changed or rephrased. The objectives were not modified during these revisions and the final version of the technical description does, indeed, still reflect the original objectives.

The last revision is dated September 1993 and was a result of the Midterm Assessment. The document contained the following index of research topics:

- 1.1 *W/c-ratio determined by the relative specific weight of the cement mortar.*
- 1.2 *W/c-ratio determined by electromagnetic absorption or damping.*
- 1.3. *Water content determined by radar techniques.*
- 2.1 *Determination of Air Void Structures before compaction of concrete.*
- 2.2 *Determination of Air Void Structures before compaction of concrete.*
- 3.1 *Assessment of prevailing flaws in present state-of-the-art concrete structures.*
- 3.2 *Description of ultra sound and nuclear principles applied in the research.*
- 3.3 *Radar, impact-echo and infrared thermography.*
- 4.1 *Macro homogeneity and consolidation by radar principles.*
- 4.2 *Determination of consolidation by ultra-sound principles.*
- 4.3 *Degree of consolidation based on impact-echo principles.*
- 5.1 *Detection of severe compaction defects and honeycombing.*
- 5.2 *Detection of cracks based on ultra-sound measurements.*
- 6.1 *Determination of setting time by radar principles.*
- 6.2 *Determination of moist curing of concrete.*
- 7.1 *Determination of diffusivity based on resistivity measurements of the young concrete.*
- 7.2 *Determination of diffusivity based on resistivity measurements of hardening concrete.*

All these research tasks have been concluded with a report which has been approved by the Steering Committee of the project and annexed to either the annual reports or this final report.

### 4.2 Description of the Research

#### **Determination of water/cement-ratio of fresh concrete.**

Three principles were tested during the research in task 1:

determination of w/c by assessment of the relative specific weight of a mortar sample;

w/c-ratio determined by electromagnetic absorption or dumping;

w/c-ratio determined by radar techniques.

During the research it was demonstrated that the **relative specific weight** of a mortar sample was a precise measure for the paste density (w/c-ratio) conditioned that the air content and volume of the sample were known.

This requirement matched very well with the techniques and objective of task 2; *Determination of air void qualities.*

In task 2 a sample of 20 ccm is used for determination of the air void structure. Research in task 1 demonstrated that the precision of sampling this volume of cement mortar was not acceptable for meeting the requirement to precision in determination of the w/c-ratio within  $\pm 5\%$  ( $\pm 0.025$  on the ratio).

However, during the research in task 2 it was investigated whether the sampled mortar for air structure testing did, in fact, represent a homogeneous mixture of aggregates (below 6 mm), cement, water and air.

In order to address this issue, a series of tests were conducted on samples collected with the technique described in task 2.

The samples were weighed on a precision balance and, consequently, dried in a micro-wave oven for 5 minutes. The result of these tests was to determine the water content of the samples very accurately, allowing a determination of the w/c-ratio with an accuracy in the order of 0.02 if the batched sand/cement mix proportions are known.

Research carried out by FORCE Institutes revealed that the **electromagnetic absorption technique** rather determined the air content in a sample than the w/c-ratio. This was a very disappointing finding as it, for quite a while, was believed that this technology would turn out to be the most feasible.

Having recognized that the interpretation of the early test results was erroneous, research using this technique was terminated.

**Radar techniques** turned out to be a good option for determination of w/c-ratios. The test method developed by M-on determines the water content in a mortar or concrete sample with an inaccuracy of max. 5 % which meets the acceptance criteria.

### **Determination of the quality of air void structures in fresh concrete.**

Though, it may be claimed that the mechanism of saturation, freezing and deterioration is still not fully understood and certainly not yet assessable for modelling, it is today accepted that air entrainment of concrete exposed to severe weathering results in a much improved frost resistance. It is also well-known that such systems of entrained air should consist of a certain volume of air bubbles and that the diameter of these should be small. Air voids with diameters larger than 0.5 mm are not contributing to the durability of the material.

It is, thus, obvious that it is not the volume of air in a given concrete which is of importance but the number of very small bubbles. This quality is often described by the co-called spacing factor which is mathematically derived from the measurement on hardened concrete of air content and the specific surface hereof.

Usually the quality of the air void structure is assured by testing the air content of the fresh concrete by use of the pressure-meter method. This is, in consequence, of the above statements, clearly insufficient as a QA measure.

The objective was to gather necessary data to prove that the results obtained by testing the fresh concrete, according to a new technique called the Fresh Concrete Air Void Analyzer Technique (FCAA), are reliable and correlate well, irrespective of the type of concrete with the results obtained by analyzing the same concrete after hardening in accordance with the generally accepted ASTM C457 standard practise.

The results prove that for determination of the specific surface and the spacing factor the suggested new technology works very well.

Almost all individual measurements of the FCAA fall within the 95% confidence interval.

In relation to determination of total air content in the concrete the method is not sufficiently accurate.

This result is not surprising as analyses are based on samples of 20 ccm.

This size is too small for the required provision. If the total air content is of importance in the Quality Assurance process the use of traditional pressure-meter should be recommended.

It is concluded that the research is successfully completed and the technology is already in the commercial phase based on the obtained documentation,

### **Determination of macro homogeneity and degree of consolidation by radar principles.**

It was the objective of the present task to detect inhomogeneities in the fresh, already placed and compacted concrete.

The inhomogeneities which were examined were:

- \* large bleeding phenomena
- \* segregation of aggregates
- \* erroneous placing of different types of concrete in the same structure.

The technique applied was the radar technique which had proven valid in task 1 of the project.

This technique was applied on three types of structures; A concrete pavement, a power plant and a precast concrete element.

This field testing of the radar technique revealed that the positive results found at the laboratory are difficult to reproduce at a construction site. This is due to a number of practical problems. The use of an antenna with a lower frequency can solve the problem experienced with insufficient penetration depth. In that case attention has to be paid to the resolution. When measurements are conducted through wooden moulds, attention has to be paid to the detection of the reflection of interest. Special steel bars to strengthen the mould can disturb the electro magnetic waves.

In general a calibration line (the relationship between dielectric constant and water content of the concrete of interest) should be determined in the laboratory, Too many parameters influence the dielectric constant of the fresh concrete, meaning that the dielectric constant cannot be calculated.

It is believed that after solving the practical problems, the radar technique can be successfully used at construction sites to determine the water contents of concrete and, consequently, the uniformity of a casting.

Especially, the application of the radar technique in pre-cast concrete plants can be of great value.

### **Determination of degree of consolidation of ultra-sound principles.**

It was the objective of the present task to monitor the degree of compaction or rather the development of this parameter during actual work based on ultra-sound measurements.

The risk of failure in this task was considered to be high as the method of assuring ultra-sound contact between transducers and concrete must be established through the simple contact between concrete and the transducer while this is moved along with the vibrator or a rod close to the vibrator.

Initial test results looked very promising. However, the researchers did not manage to reproduce these results.

The research must, therefore, be considered unsuccessful.

### **Determination of degree of consolidation based on impact-echo principles.**

It was the objective of this task to investigate whether it was possible to transfer the existing impact-echo technique for detection of cracks and honeycombs in hardened concrete to application on concrete which was still plastic. Early in the research it became clear that the problems which were recorded in using the impact-echo equipment on fresh concrete were so severe that a successful completion was questioned.

Nevertheless, it was decided to continue the research until a justified assessment could be given.

Several approaches were made but the researchers seemed unable to control the process.

The final conclusion was that impact echo is working well on hardened concrete but the scatter and 'noise' which were recorded when applied on fresh concrete indicated that the method was not feasible for the intended purpose.

### **Detection of defects in fresh concrete.**

Prevailing flaws in modern concrete structures were initially described. These studies identified the most serious defect areas as systems of oriented cracks and interconnected zones with increased capillary porosity probably due to overvibration or lack of micro stability of the concrete.

Radar-, ultra-sound and impact echo techniques were tested. However, it was concluded that the phenomena were not detectable with the techniques which were available.

### **Determination of diffusivity based on resistivity measurements of different hardening materials.**

The objective of this research was to develop a method which would enable the researcher in a concrete pre-testing phase to predict the final diffusivity of a concrete composition based on measurements of electrical resistivity in the early stage of hardening,

In order to determine the final diffusivity of the samples it was necessary to document the development of conductivity as a function of time and maturity of the concrete.

Depending on concrete composition the conductivity changes with different rate. This rate of conductivity changes were determined for different types of concrete. The results were compared with measurements of chloride diffusivity for the same concretes at a fully matured age.

The conclusions of the research were:

- i) Measurements of electrical conductivity may be used for prediction of chloride diffusivity at full maturity.
- ii) In order to predict the diffusivity measurements of both conductivity of the concrete and its pore water are required.
- iii) Prediction of diffusivity by means of conductivity measurements of concrete younger than 28 days makes it possible to apply this technique in pretesting-procedures provided the correlation between resistivity and conductivity for this type of concrete (i.e. OPC concrete, BFSC-concrete etc.) has been previously established.

## 5. RESULTS AND CONCLUSIONS

### 5.1 Results

The following test methods have been developed during the research:

#### 1. Prediction of the paste density

The water cement ratio of a concrete with known theoretical composition can be determined with an accuracy of  $\pm 0.02$  corresponding to determination of the water content with an accuracy of  $\pm 5 \text{ kg/m}^3$ .

Two principles proved feasible:

- Sampling of mortar, drying out and fast chemical testing;
- Radar detection;

#### 2. Prediction of the quality of an entrained air void system.

Based on principles of separation of air voids from paste and succeeding recording of their size and number through buoyancy recordings an intensive documentation of the accuracy of the method has been carried out.

The outcome has been that the specific surface and the spacing factor of a given air void structure may be determined with an accuracy of  $\pm 10\%$  assuming that an average of 5 measurements of the same properties performed according to ASTM C457 represents the 'true' air void structure.

#### 3. Prediction of the permeability and diffusivity of concrete.

The research has resulted in a test procedure which in the pre-testing phase enables the researcher to predict essential properties of the concrete. Under normal circumstances it may take up to one year to produce the same results.

The following conclusions may be drawn:

- \* Measurements of electrical conductivity can be used for determination of concrete diffusivity, e.g. chloride which rate influences time to initiation of reinforcement corrosion.
- \* In order to determine concrete diffusivity both conductivities of concrete and its pore water must be determined.
- \* The diffusivity of a specific concrete mix can be calculated if the conductivity measured in early stage of hardening is corrected to the values which will be developed in fully matured material. This correction is done by means of empirical determined correlation factors.
- \* Results obtained in this work correlate well with similar data published in the literature.

- \* Determination of diffusivity by means of conductivity measurements performed in the early stage of concrete maturity makes it possible to apply this technique in the quality control procedures, while the traditional methods require at least double as much time before the test results are available.

In the following field the research did not yield fully operational test method statements; However, in this area it is expected that further research or documentation will lead to test methods and equipment which will be industrially feasible.

#### **4. Determination of degree of consolidation by ultrasound.**

During the research it was recorded that the degree of consolidation could be monitored by ultrasound measurements. The industrial potential for such tests is enormous and studies of the accuracy of the test were concluded. These proved that at present the scatter is too big.

The research seems, however, to be so promising that a continuation of the research is foreseen.

## **5.2 Conclusions**

The research aimed at developing a complete Quality Assurance System for modern concrete structures.

This objective has not been achieved 100%.

However, the results obtained represent significant breakthroughs and extensions in the state-of-the-art which allow the partners to exploit the results commercially within a short time horizon.

## 6. ACKNOWLEDGEMENTS

This research has been carried out with funding from the European Community under the Brite EuRam Programme.

The contract and project number were:

BREU-CT90-0358/BE-3376; *Quality Assw-ante of Concrete based on Testing of the Fresh, Still Plastic Material.*

The authors and researchers want to express their gratitude for the support.

The project team would, further, like to express their thanks to Ms. Adele Lydon of the European Commission for excellent cooperation and support during the research period.

We also want to thank the Project Technical Auditor, Mr. Michael Quigley, ESB International Limited for his contribution.