HETEK

Laboratory Tests of Vibration

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Preface

This report has been made as an examination project at the Department of Applied Civil and Environmental Engineering, DTU. In addition to this main report the thesis project includes an Enclosure Report and a Phase 1 Report. Both reports are available at the library at the Department of Applied Civil and Environmental Engineering, the FYM passage.

The report primarily applies to persons with a building technology background.

We want to thank our supervisors Lecturer, B.Sc.Ing. Torsten Thorsen, DTU/IABM and B.Sc.Ing. Jens Frandsen, 4K-BETON A/S who has assisted and inspired us during the whole project.

During our testings in the laboratory of 4K-BETON in Ejby we have got great help from Janusz Jackowski, 4K-BETON A/S and the laboratory staff and would like to use this opportunity to thank them.

Besides, we would like to thank Peter Laugesen, Dansk Beton Teknik A/S for the execution of thin section, plan section and air void analyses. We both thank Anders Henrichsen and Peter Laugesen from Dansk Beton Teknik A/S for inspiring conversations.

Finally, we would like to thank NPL-BYG for lending us their vibrating table and Fundia Østykke A/S for the supply of handles for the tile moulds.

Summary

This project has three purposes:

1. To demonstrate a connection between the air content and density in fresh and hardened concrete by making a number of test where the vibrating intensity of specimens is varied. A proposal for revision of DS423.15 and DS423.21 is made: "Determination of Air Content in Fresh Concrete" and "Casting of Cylinders" respectively.
2. To examine how fast air bubbles move up along the mould side. Is it possible to obtain a nice surface without air bubbles and without destroying the air-void structure in the concrete?
3. To examine a new measure of workability by measuring the discharge time from a workability funnel.

In the project it is demonstrated that the number of casting layers has no influence on the density and the air content in specimens of fresh and hardened concrete. Neither does it has any influence when vibrating during casting of specimens.

The type of vibrating table has very little influence on the density and the air content as long as the vibration level is normal. High levels (accelerations) have not been tested.

The conclusion is drawn that it is not expedient to vibrate specimens with a poker. The poker destroys the micro structure of the concrete as the specimen moulds are to small for the poker.

Tamping with a steel bar can be applied for casting of concrete specimens if the slump is set higher than 100 mm. The method can be applied for concrete testing on building sites where no vibrating table is available.

It should be considered whether the air content of the concrete can be indirectly determined by the density so that it is only necessary to perform a density determination by concrete control.

A proposal for revision of DS423.15 and DS423.21: "Determination of Air Content in Fresh Concrete" and "Casting of Cylinders" respectively is included in chapter 14.

The movement of air bubbles up along the mould side has been examined by casting a number of tiles standing upright where one of the mould sides is made of transparent Plexiglas (acrylic) so that the movement of the air bubbles along the mould side can be studied. Approx. 300 air bubbles in the fresh concrete have been studied. The casting of tiles proves that the formation of air bubbles is the same at the Plexiglas mould (the front of the tile) as at the usual mould surface (the rear of the tile). The formation of bubbles depends on the applied form oil. The method might be developed for use during testing of the suitability of form oil.

If the velocity of bubbles bigger than 5 mm is valued and if vibrating is performed for 25-50 seconds with a mould vibrator, a 300 mm layer in a wall will obtain a surface partly free of bubbles. If the mould vibrator is mounted at right angles to the surface, which is normal practise, it is probably possible to avoid bubbles bigger than 5 mm.

If concrete with a slump bigger than 120 mm is applied and vibration is performed

with a poker for 20 seconds, it is possible to obtain a surface in a 300 mm thick layer with bubbles no bigger than 5 mm. By a vibrating time shorter than 20 seconds, which is often preferable in order not to destroy the air void structure or by stiffer concrete than slump 120 mm, air bubbles in the surface can be expected. The results from the tests can not be directly compared to the practise as vibration is performed differently on building sites.

The workability funnel as a measure of workability has not been studied intensively.

The funnel that has been examined in this report can be applied as a measure of workability for concrete with slumps between 70 and 130 mm and for concrete that has a d_{max} = 32 mm.

The discharge time should be compared with the slump or the flow and other measures of workability like e.g. two-point tests based on Bingham material as it is not a good idea to develop a new measure of workability if the measure does not describe the workability in a better way than the slump.

Table of Contents

1 Introduction

Our interest for concrete was aroused in connection with the material lessons at DTU-IABM and during a trainee period at NPL-BYG's in Sydhavnsgade, Copenhagen.

The background for the project is the tendered project HETEK (Hojkvalitetesbeton Entreprenorens Teknologi) from the Danish Road Directorate, where this project covers part 5c:

Laboratory tests of vibrations.

The project was made in co-operation with 4K-BETON A/S and Dansk Beton Teknik A/S.

By way of introduction to this thesis project we made a Phase 1 Report [30]. The purpose of the report was to examine various vibrating tables as to oscillations, amplitudes, accelerations and frequency with and without load in order to find an optimum adjustment, if any, of the vibrating tables during vibration of specimens. The results from the examination can be studied further in the Phase 1 Report.

The purpose of the present report is to demonstrate a connection between the air content and the density in fresh and hardened concrete by making a number of tests where the vibrating intensity of specimens is varied. A proposal is made for revision of DS423.15 and DS423.21: "Determination of Air Content in Fresh Concrete" and "Casting of Cylinders" respectively.

Besides, it is also examined how fast air bubbles move up along the mould side. Is it possible to obtain a nice surface without air bubbles and without destroying the air void structure in the concrete? A number of tiles standing upright where one of the mould sides is made of transparent Plexiglas (acrylic) are cast so that the movement of the air bubbles along the mould side can be studied. A video is taken of the movements so that the bubble size and the velocity can be registered afterwards.

In addition, a new measure of workability is tested by funnel tests.

The project is very test-oriented but does also include a theory dealing with the study of literature about vibration as well as the theory behind oscillations, the workability of concrete and the air void structure of concrete.

The test program has been planned and implemented in co-operation with Jens Frandsen and Janusz Jackowski, 4K-BETON A/S.

The main report is divided into three parts:

- Theory
- Test Planning
- Results, Treatment and Conclusion

The text refers to enclosures that can be found in the Enclosure Report. References are stated as "enclosure X".

The figures in the report are referred to according to chapters/sections by "figure Y.Y-number", where the number states the succession of the figures in the chapter starting by 1. The list of figures starts on page 97. A bibliography is placed at the end of the report which is referred to by [Z].

All photos have been taken by Anne Kirstine Gjaldbæk and Pernille Konner. The negative numbers are stated e.g. ("F1, negative No. 1).

2 Description

In this thesis project tests have been made in order to try to find an answer to the following questions:

- Is it possible to work out a revision for DS423.15 Determination of Air Content in Fresh Concrete and DS423.21 Casting of Cylinders?
- Is there a connection between the air content in the concrete and the applied vibration method?
- Is there a connection between the density in fresh and hardened concrete and the applied vibration method?

Furthermore, answers will be given to the following questions:

- Is it possible to vibrate so that a nice surface without air bubbles is obtained without destroying the air void structure?
- Is it possible to use the discharge time from a workability funnel as measure of workability?

In order to examine the above a number of tests are made in the laboratory of 4K-BETON A/S in Ejby.

3 Symbols and Definitions

Symbol	Meaning/definition	Unit
x(t)	Oscillation at the time t	[mm]
A	Amplitude, peak value	[mm]
v	Velocity, oscillation change per time unit	[m/s]
a	Acceleration, changes in the velocity per time unit	[m/s^2]
f	Frequency, number of oscillations per second	[Hz] [s^{-1}]
ω	Angular velocity, angular frequency	[radians/sec]
r	Radian, unit for angle $\left(\frac{\pi}{180°}\right)$	
T	Vibration time, one cycle	[seconds]
n	Revolutions per minute	[min-1]
φ	The phase shift of the oscillation	
v	Viscosity, the flow of the concrete	
κ	Cohesion, description of the inner cohesion of the concrete	
φ	Friction, the ability of the aggregate grains of sliding into the right position between each other	
α	Specific bubble surface per volume of the bubbles	
	Specific surface = $\frac{0_{bubbles}(mm^2)}{V_{bubbles}(mm^3)}$	[mm-1]
$\bar{L}$	Power's distance factor	[mm]

PART 1
Theory

This main section illustrates the theory that forms the basis of the tests and the examinations that have been performed in connection with this project.

First, a study of literature about vibrator types and other varying parameters in connection with vibration has been written, after which a brief description of the theory behind oscillations follows in chapter 5.

Chapter 6 and 7 deal with the concept workability and a valuation of the inner structure in hardened concrete.

4 Study of Literature

There are several ways of compacting concrete. The most usual and the one that this report will mainly cover is vibration.

Compaction of concrete by vibration can easily be described as divided into two phases. First, the concrete is consolidated and the afterwards entrapped air is driven out/removed.

The vibration should be of such duration that the entrapped air is reduced so that the concrete has obtained the density that gives the strength and density that is defined. [11].

Various types of air bubbles can be seen in the concrete, the entrapped air and the entrained air. It is important to distinguish between these types of air bubbles as their influence on the qualities of the concrete is different.

Entrapped air

Are often irregular big air bubbles that are differently distributed in the concrete. The air bubbles have formed when placing the concrete in the mould as a result of lacking or insufficient consolidating of the concrete or as a result of an inexpedient mix design. Entrapped air in greater volumes than 1 - 2 vol. % is regarded as detrimental as it contributes a considerable reduction of the strength and the density of the concrete.

Entrapped air is also described as naturally entrained air.

Entrained air

Are small, equally distributed air bubbles (5-200 μm) formed in the concrete by an air-entraining medium. The entrained quantity of air typically ranges from 2-6 vol. % (approx. 20-60 l/m3 concrete), and the entrained air bubbles will, typically as a result of the homogeneous distribution in the concrete, improve the resistance of the concrete to frost. Air-entraining improves the workability of fresh concrete. The air reduces the density and the strength of the concrete a little. [29].

4.1 Vibrator Types

Various types of vibrators are available. Generally, they can be divided into two groups: the internal and the external types. The vibrators are generally characterised by the following parameters:

1. The acceleration of the vibrator
2. The frequency of the vibrator
3. The amplitude of the vibrator

The internal vibrator is called a poker. The poker works directly on the concrete as the vibrator is inserted in the fresh concrete.

There are electrical, hydraulic and pneumatically operated pokers in many sizes and with various frequencies.

The most common used poker within the contractors' line of business is the electrical poker with a frequency of 200 Hz (12000 revolutions per minute). [11].

The external vibrator can be divided into two groups:

1. The vertical vibrators - form vibrators
2. Horizontal vibrators - beam vibrators and vibrating tables

This report will mainly deal with vibration on vibrating tables.
There are many different types of vibrating tables which can generally be divided into:

1. Electric motors mounted on eccentric masses
2. Electromagnetic vibrators
3. Shock tables

Electric motors mounted on eccentric masses. The eccentric masses are mounted on an axis which, when the system is rotating, generates an eccentric moment that is led to the mould and the concrete (cf. Figure 4.1-1). Either by moving one or more of the eccentric masses or by turning them 120 degrees, it is possible to change the oscillation amplitude and centrifugal force. For this vibrator type one can speak of harmonic oscillations.

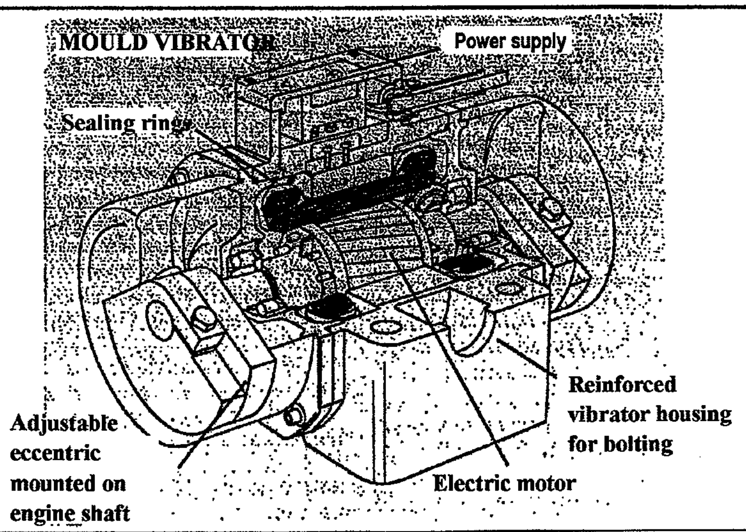

Figure 4.1-1: Electric motor

The electromagnetic vibrator works in that way that an armature, a foundation plate and trimming masses are bolted together and accelerated in a certain direction. This movement is transferred to the housing through the spring bolts. The spring system then accelerates the housing in the reversed direction. The housing is bolted to the table plate (cf. Figure 4.1-2).

This vibrator type works with a magnet as motive power. For this vibrator type one can not speak of harmonic oscillations.

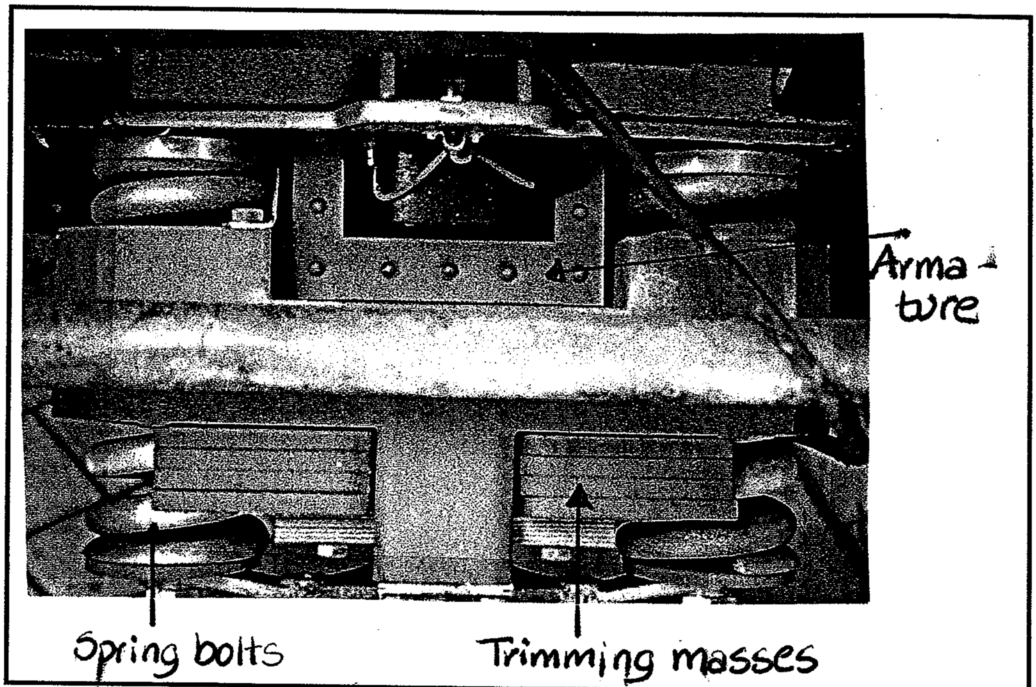

Figure 4.1-2: Electromagnetic vibrator

The shock table works that way that the mould is lifted 3 or 13 mm and then released so that it falls down and then strikes a fixed system. This collision makes the concrete be "pounded" together to a dense mass. The frequencies range from 150 to 250 impacts per min or 2.5 to 4 Hz. [12].

The simplest way to compact concrete in a test specimen is by tamping with a bar.

A detailed description of the different vibrating tables and the poker that have been applied during the tests described in Part 2 can be found in appendix A.

4.2 Vibration Factors Stated in the Literature

The literature recommends a number of values for frequency, amplitude, acceleration, number of casting layers and vibrating time. In the following some of those values are presented in figure 4.2.-1. Frequency, amplitude and acceleration are described further in chapter 5.

The dividing line between a high and a low frequency is 100 Hz.
The dividing line between a high and a low amplitude is 0.13 mm. [12].

Poker

If the poker gets closer than 2 or 3 times the dimension of the poker, the air void structure is destroyed (cf. Chapter 7). This means that neither cylinders nor a press-ur-meter container can be vibrated with a poker without destroying the void structure. [13].

It is recommended that the vibrating time at poker vibration at 200 Hz, depending on the workability of the concrete, ranges between 5 and 25 sec. [14].

Vibrating tables

Figure 4.2-1 states the requirements for vibrating tables in laboratories.

Reference	12	15	16	17	18	19	20	21
Frequency (Hz)	min 60	50-100	50	50	40	50	40	40
Amplitude (mm)	0.025 - 0.050	0.05	0.5[1)]	0.5[1)]	0.2-1.0[1)]	0.5[1)]	none	none
Acceleration (m/s^2)	30-50	50-100[1)] 10-30[2)]	none	none	none	none	none	none

Figure 4.2-1: Requirements for the values frequency, amplitude and acceleration for vibrating tables.
1) Without load. 2) Loaded with mould and concrete.

Amplitude

At a frequency of 50 Hz, the amplitude should at least be 0.15 mm.

Acceleration

There is a good connection between consolidating of the concrete and the acceleration. The resulting influence is increased linearly from 1-4g. [15].
The acceleration must be bigger than 1.5g. [22].

Vibrating time

No specific vibrating times are stated in the literature, but the vibrating time depends on a visual valuation. For press-ur-meters "each layer is to be vibrated until the concrete surface has become plane, bright and coherent". [17]. Or "each layer is to be vibrated until the concrete surface has become relatively bright and has a glossy look." [20].

As to cylinders vibration of each layer is to be performed for such long time "that a thin layer of cement mortar covers all big aggregate grains and big air bubbles no longer are released from the concrete surfaces. Overvibration should be avoided." [19]. "Vibration of each layer should be performed for at least such long time as necessary for optimum consolidating of the concrete." [21].

Casting layers

Values for number of casting layers in a specimen are presented in figure 4.2-2.

Reference	14	17	18	20	21
Poker	min. 2	2	2 or 3	3	free
Vibrating table	min. 2	2	2 or 3	3	free
Bar	min. 2	3	2 or 3	3	free

Figure 4.2-2: Casting layers in a specimen.

In the literature there is no agreement whether the best results are obtained with a lose or a fixed specimen mould.

As to compaction of the concrete specimens, a lose specimen mould gives a little better result than a fixed one. The advantage of the fixed mould is a lower noise level. [12].

4.3 Measuring Instruments

More or less advanced instruments exist for measuring vibrations.

Oriented measuring for determination of oscillations, acceleration and frequency is performed with a rather simple equipment. In the following the measuring instruments and the measuring methods are described.

Accelerometer

Measuring of accelerations requires a more advanced measuring instrument. For the preliminary tests an Integrating Vibrating Meter, type 2513 from Brüel & Kjær has been used.

Type 2513 states maximum values and RMS values (those values are described further in chapter 5) as well as vibration acceleration or vibration velocity. The measure range is from 1 to 1000 m/s^2 or 0.1 to 100 mm/s.

The sensor of the accelerometer is equipped with a magnet which is fastened on the vibrating table.

The acceleration is read directly from the display by means of light-emitting diodes.

Frequency meter No. 1

The frequency can be determined by using a tachometer. It is a small "box" with resonance beams. The tachometer is fastened on the vibrating table during vibration. Number of revolutions per minute can be read from the instrument by viewing which resonance beams are active.

Frequency meter No. 2

The frequency can also be measured with a vibrating indicator (the pen type). This method is also based on resonance. The instrument is fastened on the vibrating table. Number of revolutions per minute are read from the instrument by maximum oscillation. [12].

Stroboscope

A stroboscope is a lamp that can flash with adjustable frequency. It looks like the vibrating specimen stands still if the stroboscope flashes with the same frequency as the frequency of the specimen. If slight adjustments are made of the frequency either on the stroboscope or the vibrating specimen, it will look like the specimen is moving slowly. A more detailed study of the vibration is possible if a video camera is connected to the system.

Amplitude

Usually, the amplitude is measured within one oscillation period (peak to peak value). The oscillation can be visually valued on a label as shown in figure 4.3-1 where the amplitude appears as a dark area starting at the point 0 mm.

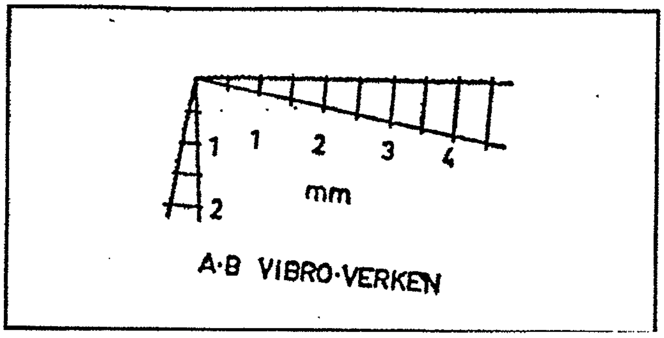

Figure 4.3-1: *Simple oscillating meter.*

Mechanical oscillating meter
The mechanical oscillating meter is a cylinder with a ratchet that is able to follow the oscillation. The oscillating meter is fastened on the vibrating table during vibration and the oscillation can be read on the scale that magnifies the oscillations ten times.

Oscilloscope
The oscilloscope displays the movement of the acceleration on a screen. A storage oscilloscope is an oscilloscope that can store an oscillation on the screen.
The vibrating time and the acceleration can be read directly from the screen. The acceleration is read as the amplitude of the oscillation and the vibrating time is read directly.

5 Oscillations

As to concrete where there are requirements for strength and density, there are usually requirements for compaction by vibration. It is important that the compaction is performed in such a way that the qualities of the concrete are not deteriorated. The usual way of compacting concrete is by vibration. [1].

Vibration means an oscillating movement out from a position of equilibrium. The mathematics behind a vibrating system can be very complicated. In the theory the description of an oscillation is often idealised by describing it as a harmonic oscillation or a sine oscillation as shown in figure 5.0-1.

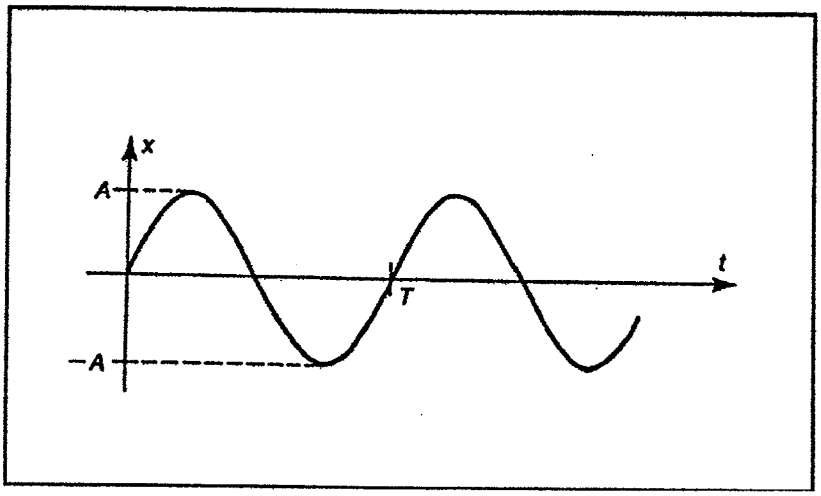

Figure 5.0-1: Graphical representation of a harmonic oscillation. [4].

The vibrating mass is moving from its position of equilibrium to an extreme position on the other side, back to the position of equilibrium and then on to a symmetric extreme position on the other side after which the oscillating movement is repeated. This can e.g. be a plumb oscillating up and down in a spring, cf. Figure 5.0-2. [2].

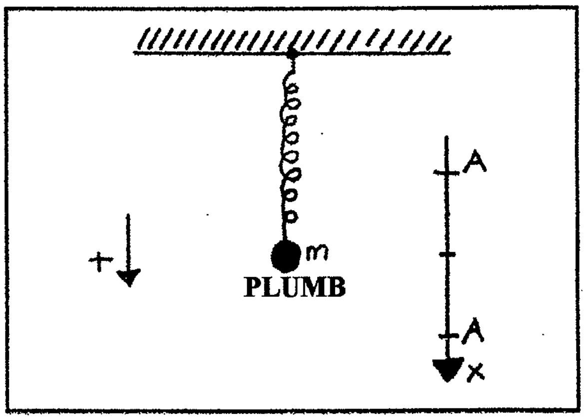

Figure 5.0-2: Plumb oscillating in a spring.

If the oscillation x(t) is zero at the time zero, the oscillation can be described according to the formula:

$$x(t) = A \cdot \sin(\omega \cdot t)$$

where

- A is the **amplitude** of the movement, i.e. the biggest oscillation from the position of equilibrium [meter]
- The swing width is the double amplitude, i.e. 2 · the amplitude
- ω is the **angular velocity** or the angular frequency of the movement [radians/second]
- t is the time [seconds]
- T is the time for a whole oscillation period. T is called the **vibrating time** or the **vibrating period** [seconds]
- f is the **frequency** of the oscillation, i.e. the number of whole oscillations or revolutions per second [Hz]

$$f = \frac{1}{T} = \frac{n}{60}$$

where:

- n is the **number of revolutions** [revolutions per minute]

From the time 0 to the time T the angle grows $\omega \cdot t$ from 0 to $2 \cdot \pi$, i.e.

$$\omega \cdot T = 2 \cdot \pi$$

The angular velocity ω can therefore be described according to the formula

$$\omega = \frac{2 \cdot n}{T} = 2 \cdot \pi \cdot f$$

The velocity v indicates the change of the oscillation per unit of time [m/s]. The velocity is determined by differentiation of the oscillation x(t) = $A \cdot \sin(\omega \cdot t)$

$$v(t) = x'(t) = \omega \cdot A \cdot \cos(\omega \cdot t)$$

The acceleration a states the change of the velocity per unit of time [m/s²]. The acceleration is determined by differentiation of the velocity v(t):

$$a(t) = v'(t) = -\omega^2 \cdot A \cdot \sin(\omega \cdot t)$$

The oscillating picture as to most vibrator types can be characterised as a sine oscillation. However, there are vibrating tables that do not oscillate harmonically but only periodically as the oscillation is repeating itself. Although the oscillation is not harmonic it is, however, possible to describe the oscillation in a harmonic way. This is possible by dividing the measured oscillation into a sum of harmonic oscillations. [5]. If the oscillation is e.g. the sum of 2 oscillations (cf. Figure 5.0-3) the **acceleration** is written in the formula

$$a(t) = A_1 \cos(\omega_1 \cdot t) + A_2 \cos(\omega_2 \cdot t \cdot \varphi)$$

where
φ is the **phase shift.** φ is a constant.

The velocity v is the integral of a(t)

$$v(t) = \int a(t)dt = A_1 \frac{1}{\omega_1} \cdot \sin(\omega_1 \cdot t) + A_2 \frac{1}{\omega_2} \cdot \sin(\omega_2 \cdot t + \varphi)$$

The oscillation x(t) is the integral of v(t)

$$x(t) = \int v(t)dt = A_1 \frac{-1}{\omega_1^2} \cdot \cos(\omega_1 \cdot t) + A_2 \frac{-1}{\omega_2^2} \cdot \cos(\omega_2 \cdot t + \varphi)$$

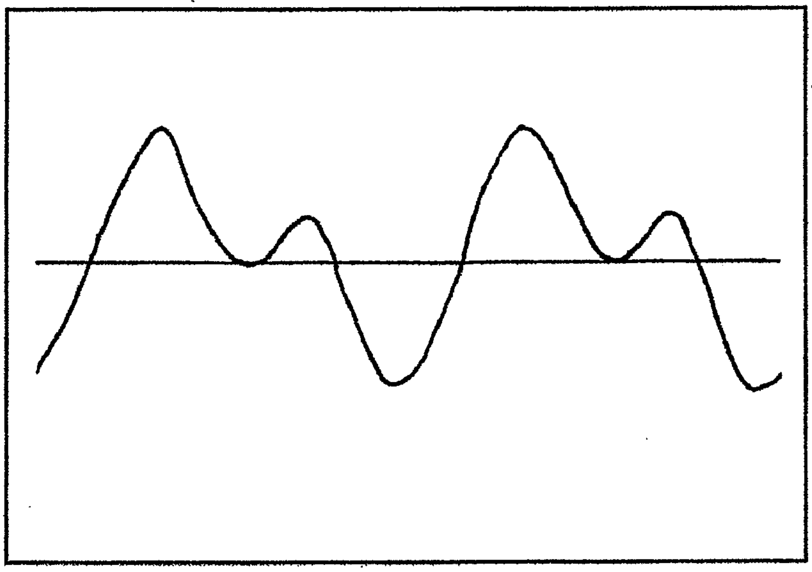

Figure 5.0-3: Non-harmonic oscillation.

The theoretical connection between acceleration, frequency and amplitude for a harmonic oscillation appears in figure 5.0-4.

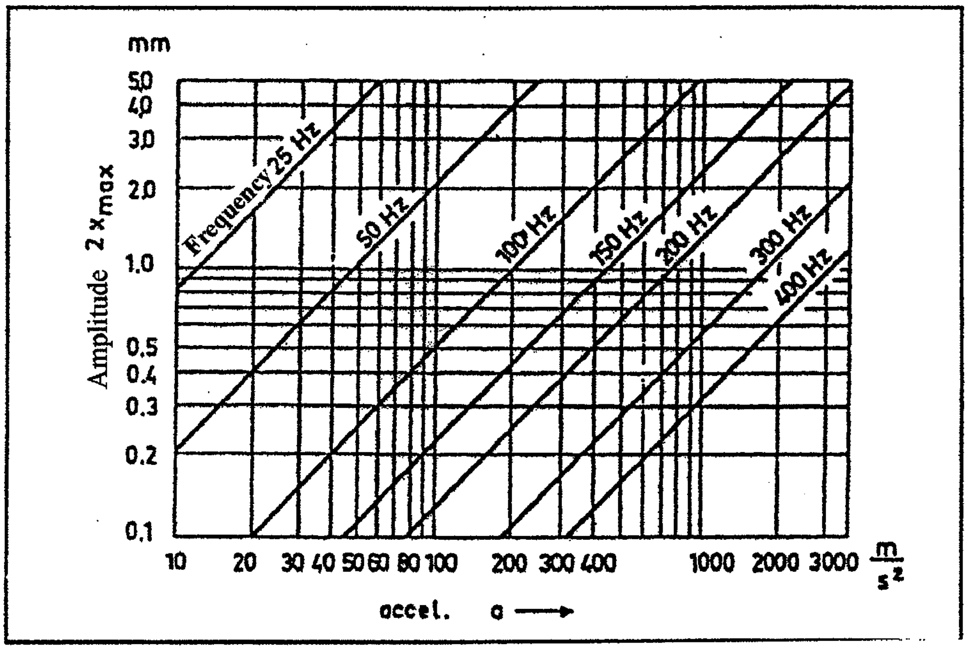

Figure 5.0-4: Theoretical connection between acceleration, frequency and amplitude. [3].

The figure is used to compare the measured results and the theory in the Phase 1 Report. [30].

RMS, peak and peak-peak values

The amplitude A indicates as mentioned earlier the maximum amplitude of an oscillation. By measuring the oscillation (oscillation, velocity and acceleration) an average value, X_{RMS}, is often used which gives a more real picture of the oscillation as it calculates the average value of the area under the frequency curve. This is especially expedient when measuring over a short period of time.

The amplitude function is integrated from 0 to the time T and the average value is calculated, giving:

$$x_{RMS} = \sqrt{\frac{1}{T}\int_0^T x^2(t)dt}$$

For a clean sine-shaped oscillation as shown in figure 5.0-5, the following formula applies:

$$x_{RMS} = \frac{1}{\sqrt{2}} \cdot x_{peak} = 0{,}71 \cdot x_{peak}$$

The amplitude A is here indicated as X_{peak}.
The swing width is the double amplitude, i.e. $2 \cdot X_{peak} = X_{peak\text{-}peak}$
The same applies for the velocity and the acceleration.

$$v_{RMS} = \frac{1}{\sqrt{2}} \cdot v_{peak} = 0{,}71 \cdot v_{peak}$$

$$a_{RMS} = \frac{1}{\sqrt{2}} \cdot a_{peak} = 0{,}71 \cdot a_{peak}$$

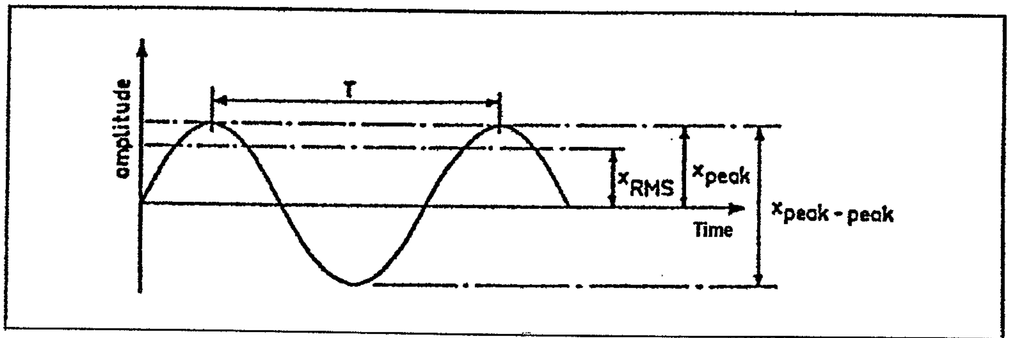

Figure 5.0-5: Relative quantities for x_{RMS} and x_{peak} as shown for a sine-shaped oscillation. [3].

6 The Workability of Fresh Concrete

Usual concrete without retards and accelerations is characterised as "fresh" concrete in approx. 1 - 2 hours of maturity after adding of water. The same moment as cement grains and water get in contact which each other, the new physical and chemical transformations start which as a whole is designated the hydration process.

The concrete gradually becomes stiffer as a result of the beginning hydrating of the cement and the forming of cement gel.

The hydration process will start after this period which means that the strength is increased. After 4-5 hours the concrete will be mould stable and the setting ends. The concrete is in the following period called hardening concrete. The hydration process continues for several years but with decreasing velocity. [1].

The workability of fresh concrete can be described by the quantity of energy that must be added in order to be able to cast the concrete in a mould. I.e. concrete with a good workability requires less energy during casting than concrete with a bad workability.

The word workability is used as a synonym to the word consistency which is typically measured by methods like air content, slump and flow (cf. Section 6.1). Regarding the workability as a synonym to its consistency it is however misleading as none of the three mentioned methods describes the practical workability of the concrete precisely. [7].

The following 4 items briefly describes what is understood by a good workability in practice on a building site. [2].

1. It should be possible to mix, transport and place the concrete where there is use for it.
2. The concrete should be able to float out in each corner of a mould and in between the reinforcements without separating or bleeding. Bleeding is when water separates from the cement paste.
3. It should be able to vibrate the concrete so that the entrapped air can be driven out from the fresh concrete. Thereby it is possible to obtain a maximum of strength and density.
4. The concrete surface should look nice when the mould is removed.

These criteria of application can briefly be described with the words:

1. Stability
2. Compactability
3. Mobility

The **stability** of the concrete means that this remains homogeneous by outside influence. If the concrete is not stable, it will lead to a separation of the materials. Separation can be unequally distribution of cement paste and aggregate grains, separation of water on the surface and under the aggregate grains (bleeding) and agglutination of air bubbles (agglomeration). [6].

The **compactability** of the concrete is the ability of the concrete to obtain compactness. [1]. The compactability is an important part in the concrete production as an optimum concrete as to strength requires a good compaction. When the compaction is optimum, most of the entrapped air will be removed and the materials will consolidate between each other contributing to higher strength and density.

The **mobility** of the concrete or the flow is its ability to fill out a mould and float in between the reinforced rods. The workability of the fresh concrete is here characterised by the reological parameters:

1. The viscosity v that describes the ability of the concrete to float.
2. The cohesion k that describes the inner connection i.e. the resistance of the fresh concrete to separating.
3. The friction φ that describes the ability of the aggregate grains of sliding into position between each other.

The ability of the aggregate grains of floating in between each other depends on the **viscosity** of the cement paste. A big viscosity of the cement paste contributes increased mobility of the aggregate grains in the concrete.

The **cohesion** are the forces that work between the aggregate grains and the cement paste. These forces are surface forces that hold the particles together. A high cohesion contributes good workability. The cohesion will be reduced by low sand percentages as the inner surface area becomes smaller which entails less tension between the aggregate grains. A big sand percentage gives a big surface tension which can be seen as viscosity in the concrete. Concrete with high cohesion between the particles will have a good workability and the particles will easily slide around each other. [7].

The optimum sand percentage, seen in relation to a good workability, is obtained when the mortar is just able to wrap all the aggregate grains and fill out the air spaces so that they can easily slide around each other. In this situation a lower viscosity and cohesion is obtained. The cohesion can even get so low that it entails separation from the concrete mixture. (Bleeding).

During mixing, transport and compacting of concrete the individual parts of the mixture will move in relation to each other which generates **friction**. [6].

By low sand percentages there will not be sufficient mortar to cover the surface of the stone particles. This leads to a direct contact between the particles and thereby an increased inner friction that reduces the workability. The inner friction of the concrete also depends on the shape of the different aggregate grains. I.e. their grain shape, angularity, surface character (texture) and particle size distribution. As to aggregate grains that are very angular and with uneven surfaces, great inner tension will be generated in the shape of friction and thus the workability will be reduced.

The distribution of grain sizes and the consolidating are factors that have an essential influence on the workability. A grading gap in the combined distribution of grain sizes will contribute to an increased workability. On the other hand, excess of one fraction, particle interference, will increase the inner friction and thereby reduce the workability. [8].

6.1 Methods of Measurement

The amount of energy that is added to the concrete at a given deformation is the measure of workability that can be determined by different experimental tests.

Most methods used to determine the workability of concrete are empirical i.e. they are based on experience, tests and personal valuations. [9].
This also applies for the methods of measurement that will be described in this section, namely the slump, the flow, the air content and the transformation figure.

Drawbacks of the empirical methods of measurement:

1. All the empirical methods of measurement are 1-point measurements i.e. that in each test only one parameter is measured and thus the result is given by one single figure.
2. The same result can be obtained for two concretes that might react differently when using them on the building-site.
3. All methods depend on the applied equipment.
4. All methods depend on who performs them.
5. None of the methods can measure the workability exactly.

Slump

The most common method to measure the workability of concrete is the slump. This method is applied in almost all the world [2] and is standardised in the The Danish Standard: DS 423.12. With given materials the slump is a simple indication of the water content in the concrete and thus the workability of the concrete. [6]. Concrete types with a large workability are difficult to compare by slumps as the concrete cones will collapse and therefore it is difficult to make precise measurements.

According to the Betonbogen [1] the method is only valid for concrete with a slump between approx. 10 and 150 mm.

The slumps can be grouped with designations of the flow of the concrete, cf. Figure 6.1-1.

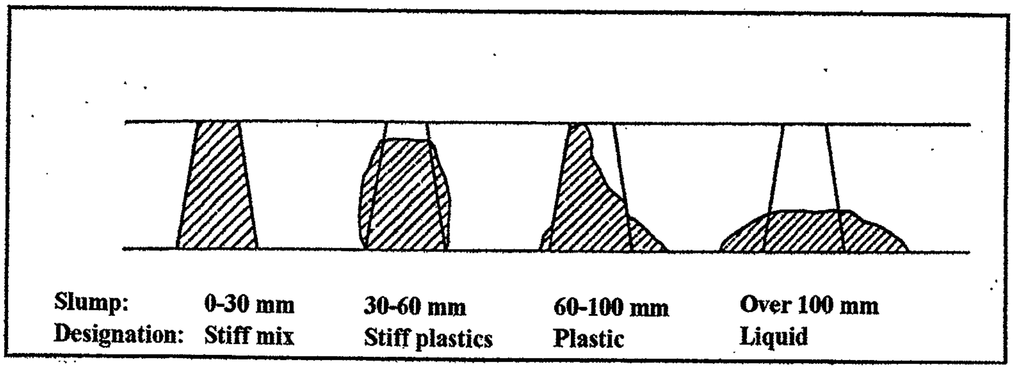

Figure 6.1-1: The size of the slumps including designation of the flow of the concrete. [1] and [2].

Flow

The determination of flow is standardised in DS 423.14.

The method is of German origin and concurrently with the application of plasticizers and other chemical additives it has become popular in Denmark as well. The flow can not be applied for dry concrete as the concrete cone often overturns during the first impacts. [6]. The test for determination of the flow shows the ability of the concrete to float which tells something about the viscosity of the cement paste and thus the mobility of the concrete. [2].

The method is valid for concrete with a flow between approx. 350 mm and approx. 650 mm. [1].

In figure 6.1-2 the connection between slumps and flow is shown for plastic and liquid concrete (slump 30 - 210 mm). From the figure it appears that there is a linear relation between the slump and the flow meaning that no further information can be found about the workability of the concrete by measuring the flow as well. [32].

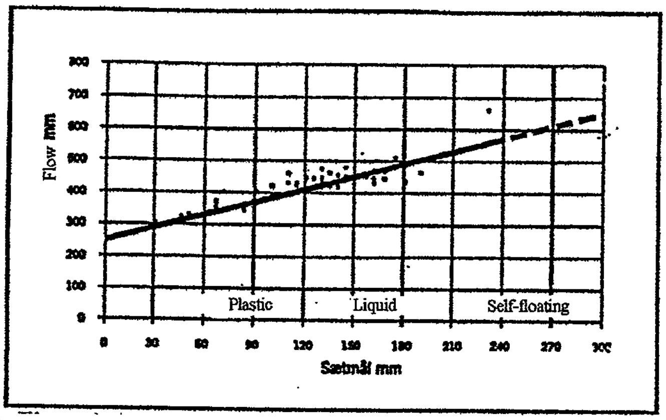

Figure 6.1.-2: *The connection between slump, and toughness. [32].*

Vebe

The vebe of the concrete is indicated by seconds, rounded off to the closest integer. The less vebe the better is the workability of the concrete. The vebe test is only expedient if the vebe lies between 5 and 30. [1].

The vebe test is standardised in DS 423.13. The test is telling something about the deformation ability of the concrete by admitting a certain energy.

Vebe is used for very dry concrete normally with zero slump.

Transformation figure

The ability of the concrete of being compacted can be valued by the transformation figure. The test can be compared with practical circumstances where concrete is to be cast in moulds and usually forced in between the reinforced rods and formwork. The transformation figure is measured from the energy that is necessary in order to give the concrete a new shape. In this connection the concrete is transformed from a cone into a cylindrical shape. A bad workability entails a higher transformation figure than a good workability. [6].

7 Valuation of the Inner Structure in Hardened Concrete

The inner structure of the hardened concrete depends on the physical and the chemical structure of the concrete.
The physical and the chemical structure of the concrete means:
The character and the quantity ratio of the constituent materials.

1. The void structure, i.e. the void quantity, the void size, distribution and void shape.
2. The composition of the concrete.
3. The structure of the concrete, i.e. the porosity, adherence, bleeding and cracks.

These parameters can be measured and described by a number of methods. In this project air void and petrographic analysis have been performed on impregnating plan section and thin section. The methods are destructive as they require that a piece of concrete is taken out of the constructions in order to be able to perform the measurements/tests.

7.1 Petrographic Analyses

The petrographic analyses are performed on cast concrete cylinders or bored concrete cores and cover a qualitative and semi-quantitative analysis of the macro and micro structure on impregnated plan section and thin section.

The structure analyses on impregnated plan section are made to get an overview of the porosity, crack distribution and the distribution of the different components of the concrete.

There is no standardised method of performing an impregnated plan section.

The plan sections in this report have been made at Dansk Beton Teknik A/S and have therefore been made according to the method that is applied there and which complies with the requirements from Oresundskonsortiet.

Thin section is performed at Dansk Beton Teknik A/S as well.

Impregnated plan section
The concrete surface is ground plane and impregnated with epoxy plastics which is often mixed into a fluorescent tracer. The epoxy plastics penetrates all cracks and the detached air voids. When the epoxy plastics are hardened they are ground to the concrete surface. The surface is valued by means of an ultra-violet lamp that makes the filled in cracks and air voids lighten up by means of the fluorescent tracer. When the valuation has been registered, 1 mm is cut of the surface and another valuation and registration are made. Once more 1 mm is cut of the surface and a final valuation and registration are made. Photos of this registration can be found in Enclosure 1.

Thin section
The structure analyses on thin section performed by fluoroscopic microscope (TI-B 5)

are used to describe the composition, the mixture, the compaction and the void structure of the concrete.

Thin section is a 20 μm thick 40 x 30 mm slice of the concrete to be examined. The slice is impregnated with epoxy plastics and glued on a glass plate to keep the specimen together during and after grinding. Also here a fluorescent tracer is used.
In order to value the registrations from the structure analyses, BBB [27] has the following requirements.

By structure analyses the following must not be found:

1. Inhomogeneity in the paste due to dosing or mixing faults
2. Unequal distribution of stones and sand
3. Strong bleeding around the aggregate grains
4. Rough cracks
5. Many cement paste cracks
6. Many adhesion cracks or adhesion defects
7. Many or big air void accumulations

7.2 Air Void Structure

Air void structure analyses are performed on special made plan sections in order to describe the air void structure, i.e. void quantity, void size, distribution and void shape. Air voids mean open or closed holes in the concrete.

The void structure has influence on strength, stiffness and resistance to frost.

If the concrete has an air content of 5%, there may be a big difference in the way the void structure looks. One extreme consists of a lot of equally distributed small air bubbles, cf. figure 7.2-1. The other extreme consists of a few big air bubbles, cf. figure 7.2-2. The most usual is that the air void structures lies somewhere in between the two extremes.

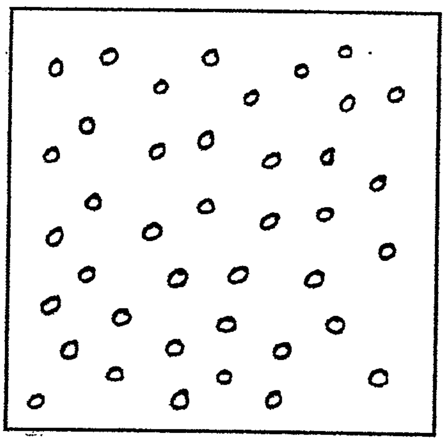

Figure 7.2-1: Many small air bubbles

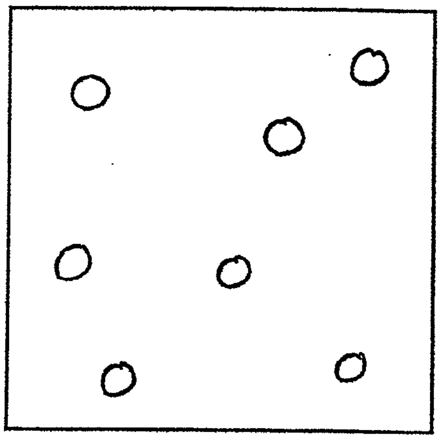

Figure 7.2-2: A few big air bubbles

The best distribution of air voids is a lot of equally distributed small air bubbles that can absorb the hydraulic pressure in the voids that is generated by e.g. effects of frost. The application of thawing salts makes the damages caused by freezing with clean water worse. The presence of the brine in the cement paste increases the osmotic pressure that works together with the pressure of the ice.

The voids in the cement paste and concrete cover several different dimensions. According to size the voids are divided into gelatine voids (<2 nm), capillary voids (2 nm - 5μm) and macro voids (> 5μm).

Air bubbles with a diameter bigger than 2 mm are called rough air. [26].

Requirements for air content in the hardened concrete according to BBB. [27]:

- Min. air in the putty mass (cement paste and air) 10%
- The specific surface must at least be 25 mm-1

In order to examine the air void structure in a plan section or a thin section in the hardened concrete, an air void structure analysis can be made.

7.3 The Linear Traverse Method

A ground concrete flat of 10 x 10 cm is coloured dark and the voids are marked by filling in with white zinc paste. Afterwards it is enlarged 50 times under a microscope. A base line is selected. Along this line the number and lengths of the chords of air bubbles are measured which are cut off by the base line, c.f. figure 7.3-1. The measuring spot is 2 µm in diameter. 40 lines with a distance of 2 mm or a total of 4 m are measured. A real picture of the air void structure is secured by a length between gauge points of min. 3 m. [26].

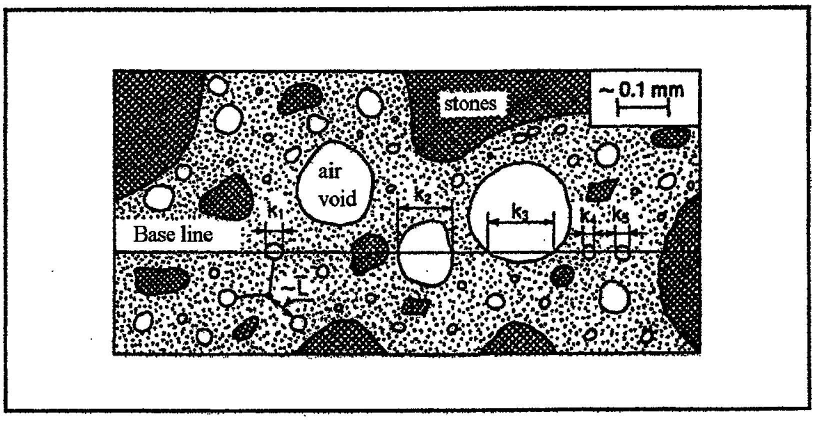

Figure 7.3-1: Ground concrete flat with base line for measurement of air void distribution. [1].

The air content A (percent by volume) can be calculated by:

$$A = (l_k / l_{tot}) \cdot 100\%$$

where l_k is the total measured chord length (mm) and l_{tot} is the total length between the gauge points (mm).

The void system is characterised by the specific bubble surface per volume unit of the bubbles $\alpha(mm^{-1})$ and by Power's distance factor $\bar{L}$.
The specific bubble surface per volume unit of the bubbles is calculated as follows:

$$\alpha = \frac{4n}{l_k}(mm^{-1})$$

where n is the total number of chords. [1].

The specific surface can also be calculated as follows:

$$\alpha = \frac{O_{averageairvoid}}{V_{averageairvoid}}\left(mm^{-1}\right)$$

where O is the surface area of the average air void, and v is the volume of the average air void. [26].
The specific surface is designated as follows:

- smaller than 25 mm^{-1} , rough
- bigger than 35 mm^{-1} , fine

If the specific surface is bigger then 25 , the distribution of air voids consists of many small air voids.
The distance factor $\bar{L}$, which is also known as Power's distance factor, is a fictive quantity. A concrete body is according to Power resistant to frost if the distance factor is less or equal to a critical distance factor that expresses that the mean distance from an arbitrary point in the cement paste to the closest air bubble must be less or equal to $\bar{L}$ critical (cf. Figure 7.3-2). The theoretic condition of Power for calculation of distance factors is that the entrained air bubbles must be the same size and homogeneously distributed in a simple cubic pattern in the paste (cf. Figure 7.3-2.).
The distance factor is calculated as follows:

$$\bar{L}=\frac{P}{\alpha \cdot A}(mm) \qquad \text{if } \frac{P}{A}\langle 4,342$$

$$\bar{L}=\frac{3}{\alpha}\left(1,4\left(\frac{P}{A}+1\right)^{1/3}-1)\right)\text{(mm)} \qquad \text{if} \frac{P}{A}\geq 4,342$$

where P is the volume of the cement paste without voids in % of the concrete volume. [1].

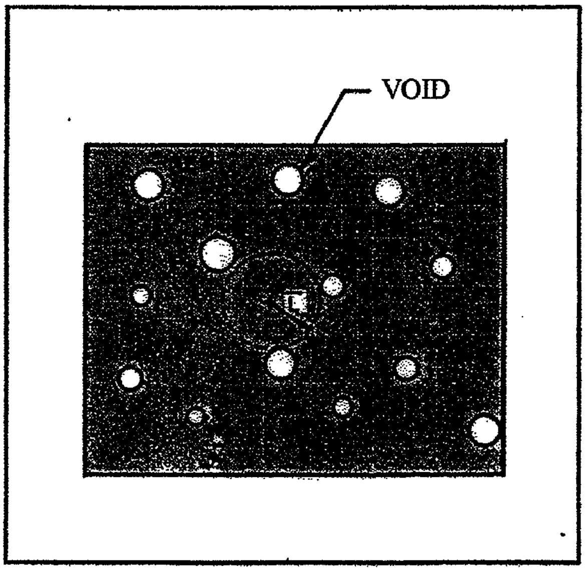

Figure 7.3-2: Definition of distance factor. [31].

PART 2

Test Planning

The test planning was at first meant to include 9 test days with measurements of 3 different concrete types; each with 3 different slumps. The concrete types were selected on the basis of the tendered material from the HETEK project.

All test are made in the laboratory of 4K-BETON in Ejby.

The tests were currently revised in order to obtain optimum results. Since the preliminary tests with vibrating tables were more time-consuming than expected the number of tests was reduced to 7. The tests are referred to as test No. 1, 2, 3 etc. up to test No. 7.

The tests can generally be divided into 3 fields:

1. A number of press-ur-meters and cylinders are cast being subject to different influences in order to provide a practical basis to work out a proposal for revision of DS423.15 and DS423.21: Determination of Air Content in Fresh Concrete and Casting of Cylinders respectively.
2. Movements of air bubbles up along a mould side are studied by casting tiles standing upright where one of the sides is made of Plexiglas (acrylic). The movements of the bubbles are recorded on a video so that the bubble size and velocity can be registered. The tiles are referred to as tile No. 1, 2, 3 etc. up to tile No. 46.
3. The possibility for application of the discharge time from a funnel as measure of workability is examined. The tests are referred to as test No. A, B, C etc. up to funnel test No. K.

In order to get an overview of the tests performed, a test plan is made as shown in figure 8.0-1

Test No.		Date	Activity	Concrete mix design	Target slumps (mm)
A, B, C, D		28.08.96 to 20.09.96	Preliminary funnel tests	2035, 1420 1835, 6011	120, 150, 100, 90
1	E	26.09.96	Air, density, funnel and tiles	2035	90
2	F	01.10.96	Air, density, funnel and tiles	1425	60
3	G	08.10.96	Air, density, funnel and tiles	6021	120
4	H	22.10.96	Air, density, funnel and tiles	2035	120
5	I	29.10.96	Air, density, funnel and tiles	4361	80
6	J	05.11.96	Air, density, funnel and tiles	4361	30
7	K	14.11.96	Air, density, funnel and tiles	4361	150

Figure 8.0-1: *Test plan. The concrete mix designs are described further in section 8.1.*

8 Test Parameters

In order to perform a test as adequate as possible, it is important to define exactly the parameters that may have influence on the result. Since it is impossible to examine all parameters that may influence the air content, the density and the workability, a number of test parameters have been selected for this project, which are varied during the tests. The following parameters are varied during the casting of specimen and tiles:

- Vibrator type, external/internal
- Frequency, amplitude and acceleration of vibrating tables
- Vibrating time
- Number of cast layers in concrete cylinders or press-ur-metre
- Continuos vibration during filling of press-ur-metres and cylinders
- Application of different concrete types including variations in the properties of the fresh concrete
- The age of the concrete at casting
- Slump
- Form oil in tile mould

The workability funnel is varied as to size of discharge spout and placement of vibrator. The reason why none of the other parameters are varied is primarily that the funnel tests are intended as a pilot project.

8.1 Concrete Types

The main data for the 4 concrete types according to the concrete form at slump 100 mm, used during test Nos. 1 to 7, appear from figure 8.1-1. Concrete mix designs from all tests including funnel test Nos. A to K, are collected in enclosure 2.

Mix design	Concrete Type	Strength (Mpa)	w/c	Water (l/m³)	Slump (mm)	Air (%)
2035	4K Standard concrete A according to BBB	35	0.41	129	100	6.2
1425	4K Standard concrete P according to BBB	25	0.73	152	100	2.6
6021	HETEK concrete, environment class SB	40	0.39	130	100	5.6
4361	Environment class A according to BBB	35	0.41	127	100	6.2

Figure 8.1-1 *Concrete types according to concrete form at slump 100 mm. The concrete forms are enclosed in Enclosure 3.*

Visual examination of fresh concrete

A photograph is made of all the concretes both before and after the tests. The photos of the concrete prior to the test are shown in chapter 9. The other photos are available in enclosure 4.

The size of the cylinders

The concrete is cast in cylinders for strength and density determination. Big standard cylinders according to DS423.20 with a diameter of 150 mm and a height of 300 mm are used for this purpose.

Demoulding

The cylinders are demoulded the day after, marked, water cured and hardened in water bath at 20°C for 28 days.

Tests with hardened concrete

After 28 days in water bath the density of all cylinders is determined according to DS 423.27. Some of the cylinders are weighed both before and after the water curing in order to test whether the density changes considerably during the water curing.

At least 3 cylinders from each test are subject to compression test. The results appear from chapter 11. As to petrographic analysis and air void analysis selected cylinders are sent to Dansk Beton Teknik A/S. These results appear from section 11.8.

8.2 Vibrating Tables

By way of introduction in phase 1, 6 different vibrating tables are tested after which 3 vibrating tables are selected for the real tests.

The vibrating tables are tested by measuring the frequency, acceleration and amplitude.

The vibrations of the tables are measured by a storage oscilloscope. A photograph is taken of the frequency picture showing the oscillations.

The test can be studied further in [30].

On basis of the tests in the phase 1 report, it is not possible to optimise the adjustments of the vibrating tables. Therefore the vibrating tables are adjusted according to "Study of Literature" in chapter 4.

For the test in this project the following vibrator types are selected:

Table 1: Building site table from NPL-Byg A/S in Sydhavnsgade
Table 2: Stationary vibrating table in the laboratory of 4K-Beton in Ejby
Table 3: New vibrating table from SKAKO A/S with adjustable frequency.
Poker from the laboratory of 4K-Beton in Ejby. The diameter of the vibrator head is 28 mm.

The selected vibrating tables are chosen because they represent a wide range of the vibrating tables that have been tested and of the vibrating tables that are available on the Danish market. The vibrating tables are applied in different fields.

- The building site table is used for concrete samples on the building sites of NPL-Byg A/S. A similar vibrating table is also used in the laboratory of Dansk Betonteknik in Gladsaxe.
- The stationary vibrating table is used for daily concrete control in the laboratory of 4K-Beton A/S in Ejby.
- The new vibrating table from SKAKO A/S is selected as it is possible to adjust the frequency from 0 - 180 Hz. This makes it possible to examine what happens to the concrete when vibrating at other frequencies than 50 Hz, which is the normal for vibrating tables.
- The poker is chosen as it is used on building sites and is recommended as a standard method of vibrating specimens in the European and Danish standards, the frequency is 200 Hz.

The selected vibrator types are described further in appendix A.
As it appears from the study of literature in section 4.2 the vibration is normally performed at an acceleration of 30 m/s² (figure 4.2-1).
In order to compare the results of the vibrating tables, they are adjusted to vibrate at the same acceleration.

To obtain this the tables are adjusted as follows:

Tables 1:	No adjustments possible. Without load the table vibrates at an acceleration of 30 m/s² in the middle of the table. [30] Frequency 50 Hz.
Table 2:	50% impact force which without load gives an acceleration in the middle of the table of 30 m/s². [30]. Frequency 50 Hz.
Table 3:	Frequency 50 Hz corresponding to an acceleration of 10 m/s² and frequency 100 Hz corresponding to an acceleration of 27 m/s². [30]. Both measurements have been performed in the middle of the vibrating table.
Poker:	No adjustments possible. The frequency of the vibrator head is 200 Hz.

8.3 Vibration Method for Cylinders and Press-ur-meter

During test Nos. 1-7 different vibration methods have been applied where the number of casting layers and vibration time have been varied. The different vibration methods are described in this section. The vibration methods are named methods A-O.

Method A: 2 layers.
Vibration time 30 seconds per layer; total 60 seconds.
Vibration is not performed during filling of specimens.

Method B: 1 layer.
Vibration time 60 seconds.
Vibration is not performed during filling of specimens.

Method A and B are applied on vibrating table Nos. 1, 2 and 3.

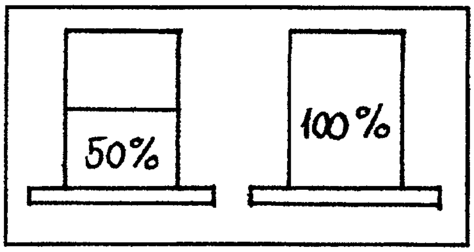

Figure 8.3-1a: Method A.

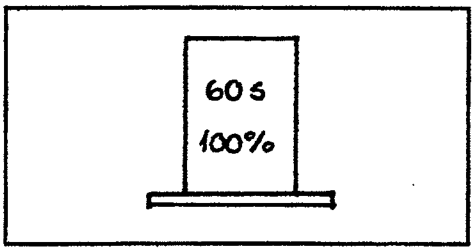

Figure 8.3-1b: Method B.

Method C: Approx. 5 layers
The container is filled approx. 20%. The vibrating table is started. The container is filled during vibration so that each shovelful has been levelled before the next shovelful is placed.
The time from start of the vibrating table to levelling of the topmost layer is registered.

Method C is applied on vibrating table Nos. 1, 2 and 3.

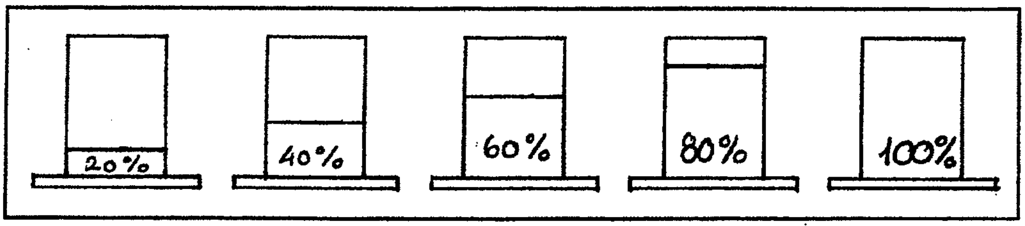

Figure 8.3-2: Method C.

Method D: Tamping with steel bar according to DS423.15.
The container is filled with concrete in 3 layers. Each layer is worked with 25 impacts by the steel bar. The impacts are to be equally spread over the surface of each layer.

Method E, F, G:	Vibration with poker. 2 layers. The poker is inserted vertically into the concrete. The vibrator is started just as the poker gets in contact with the concrete. Vibration is not performed during filling of specimens.
Method E: Method F: Method G: Method H, I, J:	Vibration time 5 seconds per layer; total 10 seconds. Vibration time 10 seconds per layer; total 20 seconds. Vibration time 25 seconds per layer; total 50 seconds. Vibration on vibrating table No. 3. Frequency 50 Hz. 2 layers.
Method K, L, M:	Vibration on vibrating table No. 3. Frequency 100 Hz. 2 layers.
Method H, K: Method I, L: Method J, M:	Vibration time 10 seconds per layer, total 20 seconds. Vibration time 20 seconds per layer, total 40 seconds. Vibration time 50 seconds per layer, total 100 seconds. Vibration is not performed during filling of specimens.
Method N: Method O:	Vibration on vibrating table No. 3. Frequency 50 Hz. Vibration on vibrating table No. 3. Frequency 100 Hz.
Method N, O:	The container is filled approx. 20%. The vibrating table is started. The container is filled during vibration so that each shovelful has been levelled in the container before the next shovelful is placed. Total 5 layers. The time from start of the vibrating table to levelling of the topmost layer is registered.

8.4 Tiles

The tile moulds are cast to examine how fast air bubbles move up along the mould side. Is it possible to obtain a "nice" concrete surface at the same time as the entrapped air is vibrated out without destroying the air void structure of the concrete?

The quality of the surface
The vibration work is classified by the visual quality of the demoulded surfaces.

The quality of the surface depends traditionally of the number of defects in the surface. The following defects in the surface relates to the vibration of the concrete

- honeycombing
- sand stripes
- number of air bubbles (blow holes)

Honeycombing and sand stripes should not be accepted as they are a given sign of separation. It is quite different with the air bubbles which are very difficult to remove from the surface.

In this project the quality of the surface is classified on basis of the number of air bubbles in the surface.

In the studied literature there are no available tests of the inner structure of the concrete and the air void system compared with vibration methods and air bubbles in the surface. Sources [13] and [14] show that the structure and the resistance to frost are destroyed if the vibration is performed too close to the mould.

If the need for vibration is valued solely from the look of the surface, there is a great risk that the concrete is overvibrated in order to remove the air bubbles from the surface. At the same time it will lead to a bad structure in the inner concrete. [28]

During the testing

4-10 tiles are cast per test. The tiles are vibrated on vibrating table Nos. 1, 2 and 3 for 120 seconds and with poker for 30 seconds.

During the vibration there is a vertical movement of air bubbles moving towards the surface of the concrete. Usually, it is not possible to register those movements in usual moulds. Therefore a mould has been produced where one of the sides is made of transparent Plexiglas (acrylic), cf. figure 8.4-1. Acrylic is easy to wet with fresh concrete and there are no visible air bubbles when casting against a raw acrylic plate. When the acrylic plate is treated with form oil, air bubbles will form.

The Plexiglas plate makes it possible to view the bubble movements, which can be registered on a video.

To find out whether air bubbles at the acrylic surface are representative for all mould surfaces, the air bubbles at the acrylic surface for each tile are compared with the air bubbles at the usual mould surface. The Plexiglas is referred to as the front of the tile.

The usual mould side is referred to as the rear of the tile.

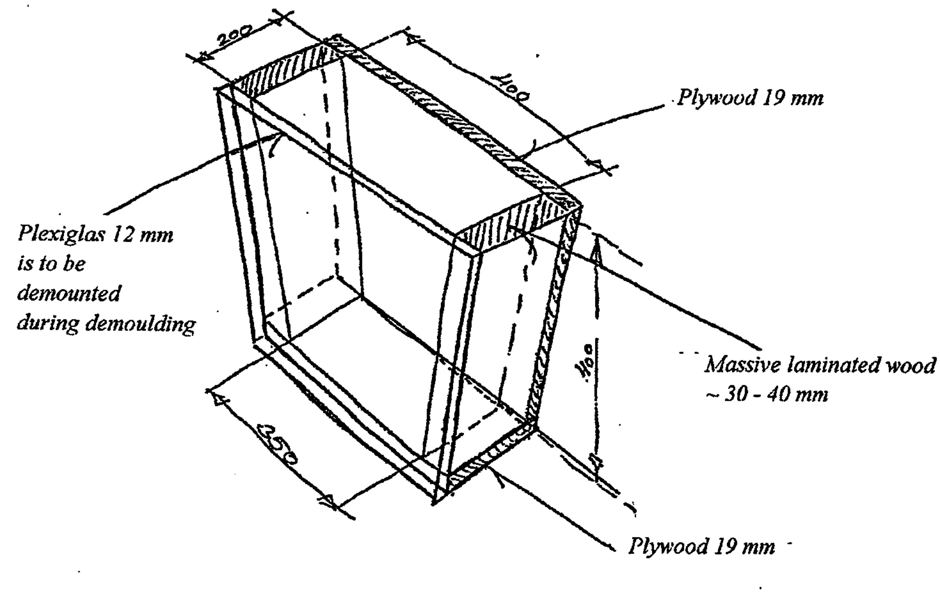

Figure 8.4-1: Sketch of tile mould.

The casting of tiles is performed with the same concrete as in test Nos. 1-7. All tiles are filled with concrete at one time. Vibration is not performed during filling of concrete. The tile moulds are lubricated with different form oils to observe whether the oil has any influence on the number of bubbles and the size of the bubbles. The applied form oils are listed in figure 8.4-2 below.

Test No.	Vibrating table	Tile No.	Form Oil
1-3	1, 2, 3	1-9, 11-19, 21-29	Sunflower oil from
	Poker	10. 20. 30	the laboratory in Ejby
4	1, 2, 3	31, 32, 33	Lasol M100
	Poker	34	from NBK Rødekro
5	1, 2, 3	35, 36, 37	WEGANO W-2
	Poker	38	from NBK Rødekro
6	1, 2, 3	39, 40, 41	FORMLEN 10
	Poker	42	from Statoil
7	1, 2, 3	43, 44, 45	FORMOL 5
	Pole vibrator	46	from Statoil

Figure 8.4-2: Tiles and form oils.

After the testing
The tiles are demoulded the day after the test.

The "concrete skin" is brushed of the surface of the hardened concrete. Then the air bubbles of the concrete surface are counted on the front and the rear of the tile. During counting the tiles are divided into 3 sections of equal size as shown in figure 8.4-3.

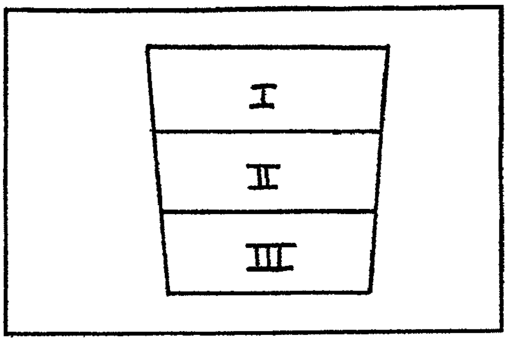

Figure 8.4-3: Division of tile

The air bubbles are grouped into 3 sizes:

1. Bubbles between 2 - 5 mm
2. Bubbles between 5 - 10 mm
3. Bubbles bigger than 10 mm

After the counting of air bubbles the air content of the front and the rear of the tile is calculated. Within each group of air bubbles an average area is calculated where the average diameter is used:

$$A_{2-5mm} = \frac{(3{,}5mm)^2}{4} \cdot \pi = 9{,}6mm^2$$

$$A_{5-10mm} = \frac{(7{,}5mm)^2}{4} \cdot \pi = 44{,}2mm^2$$

For air bubbles bigger than 10 mm the area of the air bubble is calculated individually:

$$\text{Air content at front and rear} = \frac{x_1 \cdot A_{2-5mm} + x_2 \cdot A_{5-10mm} + \sum x_3 \cdot A_{biggerthan10mm}}{A_{tile,frontorrear}}$$

where:

x_1 is the number of air bubbles of size 2 - 5 mm
x_2 is the number of air bubbles of size 5 - 10 mm
x_3 is one air bubble bigger than 10 mm

Selected tiles are cut in two to examine the entrapped air voids. The examination is performed at Dansk Beton Teknik A/S.

The video of the bubble movements has been processed by a computer program Win/TV which makes it possible to freeze pictures and print them out.

The movement of selected air bubbles are drawn on the printed pictures and on the basis of these it is possible to determine the velocity of the individual air bubbles. The air bubbles are grouped according to the same principle as by the manual counting.

By means of frequency analysis diagrams it is tested whether the velocity for each group is normally distributed (cf. chapter 12). Afterwards the average value and the standard deviation is calculated.

8.5 Workability Funnel

The workability funnel is examined in order to evaluate whether it can be used as a measure of workability.

Conditions for development of the funnel

The funnel is to be developed as an alternative to the now-existing workability methods, as slumps and flow.

In this report it will be compared with slumps.

The funnel is to be developed so that it is easy to use both in the laboratory and on the building sites.

It should be easy to carry out measurements, no more than 5 - 10 min., which will be referred to as discharge time.

It must be possible to use the funnel for floating concrete of "all age levels", and to compare the discharge time with the slump.

The funnel has the following dimensions:

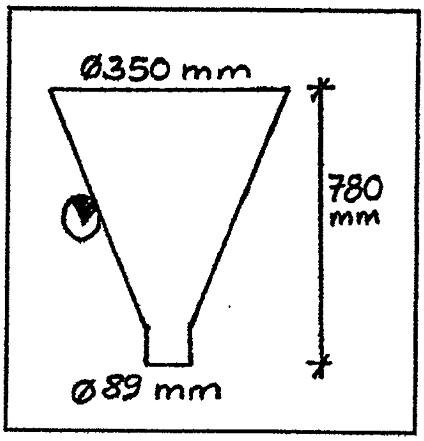

Figure 8.5-1a: Workability funnel before moving of the vibrator

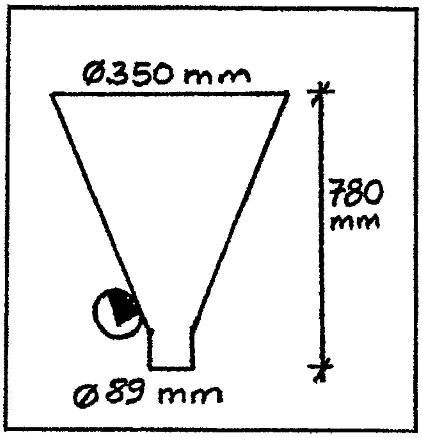

Figure 8.5-1b: Workability funnel after moving of the vibrator

The present development of the funnel makes it necessary to mount a vibrator in order that concrete with a maximum stone size of 32 mm can be discharged. After test No. 3 the vibrator is moved (cf. figure 8.5-1.a and b). The vibrator is an electrical motor with eccentric masses.

During the testing
For the funnel tests Nos. A-K 7 different concretes are used. Figure 8.0-1 (page 28) shows a list of the test days and the concrete types that are used during the tests.

During the tests, funnel tests are made where the discharge time, temperature, time and slump are registered.

Test method
The funnel is filled 2/3 with concrete after which the vibrator is started at the same time as the opening at the bottom of the funnel is opened. The opening is closed when a 15 x 30 cm standard cylinder has been filled corresponding to a volume of 0.005 m^3 or approx. 12 kg concrete.

After the testing
The discharge time is compared with the slump.

9 Implementation of the Tests

For each subsection a simplified diagram of the test process has been completed. Tests Nos. 1 - 4 are performed within 3 periods of time: 10 minutes, 60 minutes and 120 minutes after mixing of the concrete.

Cylinders and press-ur-meters

As it will appear from this section, the tests were revised and changed currently.

The varying parameters for casting of cylinders and press-ur-meters for the tests are as follows:

For test Nos. 1 - 4

- Concrete type and slump
- The age of the concrete at casting
- Number of cast layers
- The frequency of the vibrating table
- Vibration times

For test Nos. 5 - 7

- Slump
- Vibration method
- External and internal vibration of cylinders and tiles
- Number of cast layers
- The frequency, amplitude and acceleration of the vibrating tables
- Vibration times

Tiles

In order to study the movement of air bubbles along a mould side the following was cast:

For test Nos. 1 - 3

10 tiles per test. One tile per period per vibrating table vibrated for 120 seconds and one tile vibrated for 30 seconds with a poker.

For test No. 4

4 tiles for a period of 60 minutes. One tile per vibrating table vibrated for 120 seconds and one tile vibrated for 30 seconds with a poker.

For tests Nos. 5 - 7

4 tiles per test. One tile per vibrating table vibrated for 120 seconds and one tile vibrated for 30 seconds with a poker.

All tiles are filled at one time and are not vibrated during filling.

The workability of the concrete is determined prior to, during and after the test by slumps according to DS 423.12 and by discharge time from funnel.

The values for slumps and air are target values right after mixing.

Test No. 1

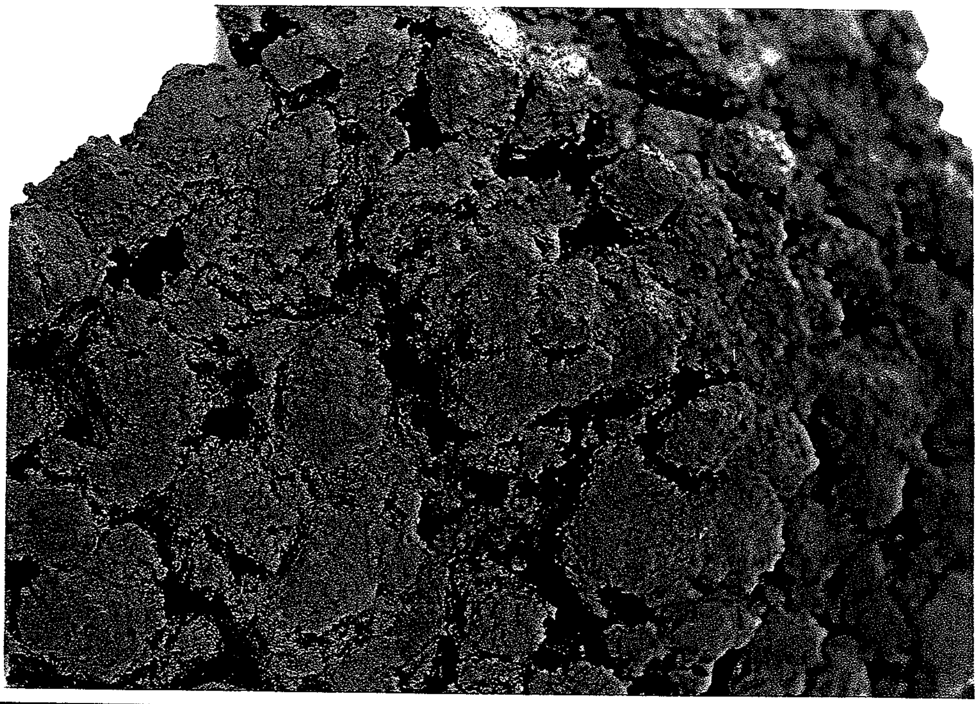

Photo 9.0-1: Concrete type used at test No. 1 (F2, negative No. 2)

Concrete type: 4K standard concrete A according to BBB, mix design 2035			Methods: A and B
Air content: 6.2%	w/c: 0.45	Slump: 90 mm	Strength: 35 MPa

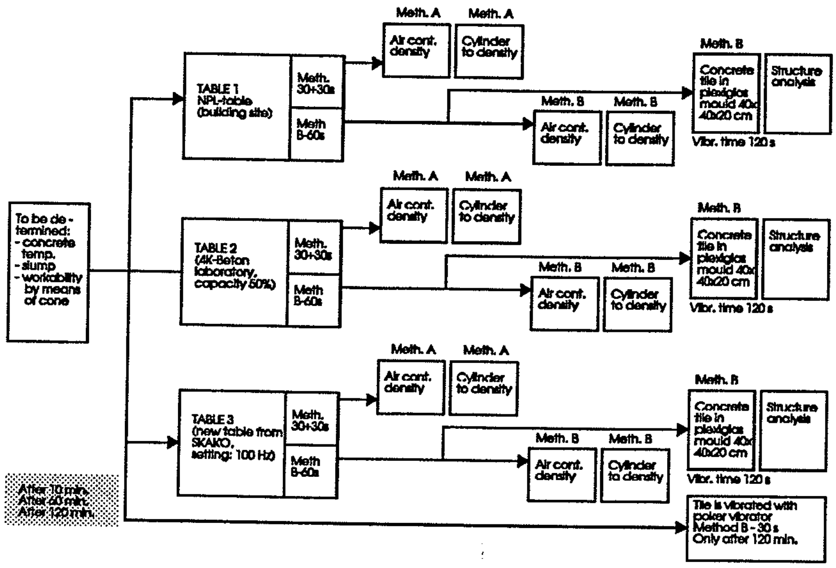

Figure 9.0-1: Program for test No. 1

Test No. 2 has the same program as test No. 1

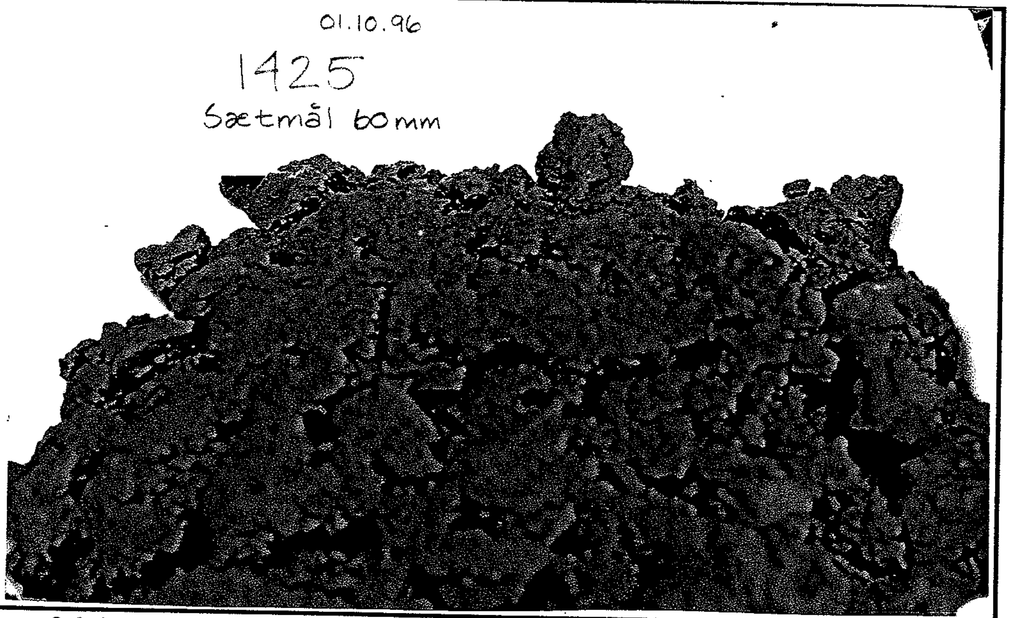

Photo 9.0-2: Concrete type used at test No. 2 (F2, negative No. 18)

Concrete type: 4K standard concrete P, mix design 1425			Methods: A and B
Air content: 2.6%	w/c: 0.73	Slump: 60 mm	Strength: 25 MPa

Test No. 3 has the same program as test No. 1 and 2.

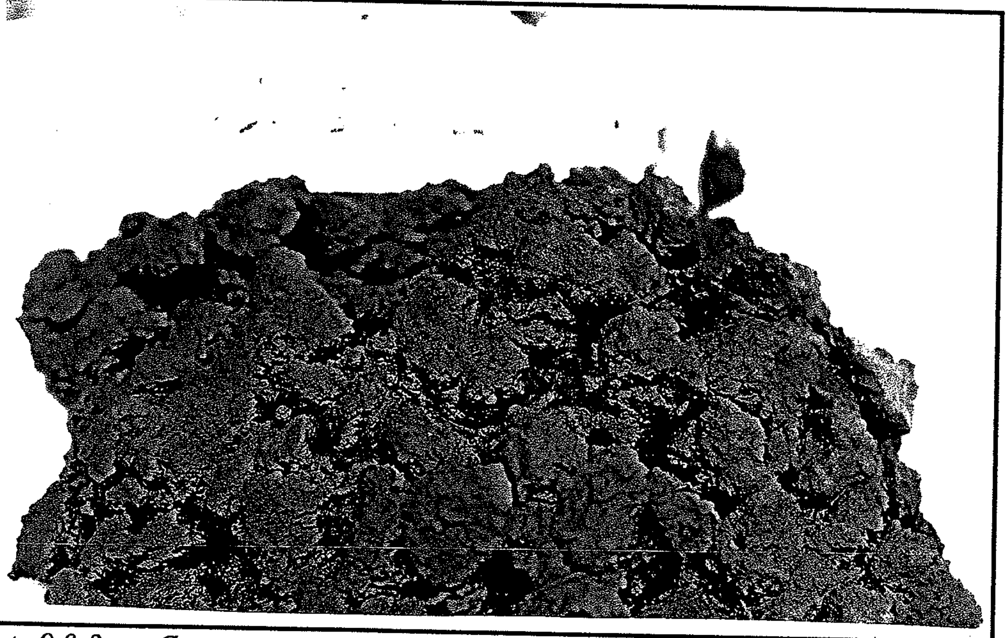

Photo 9.0-3: Concrete type used at test No. 3. (F3 negative No. 27)

Concrete type: HETEK concrete, environment class SB, mix design 6021			Methods: A and B
Air content: 5.6%	w/c: 0.39	Slump: 120 mm	Strength: 35 MPa

Test No. 4

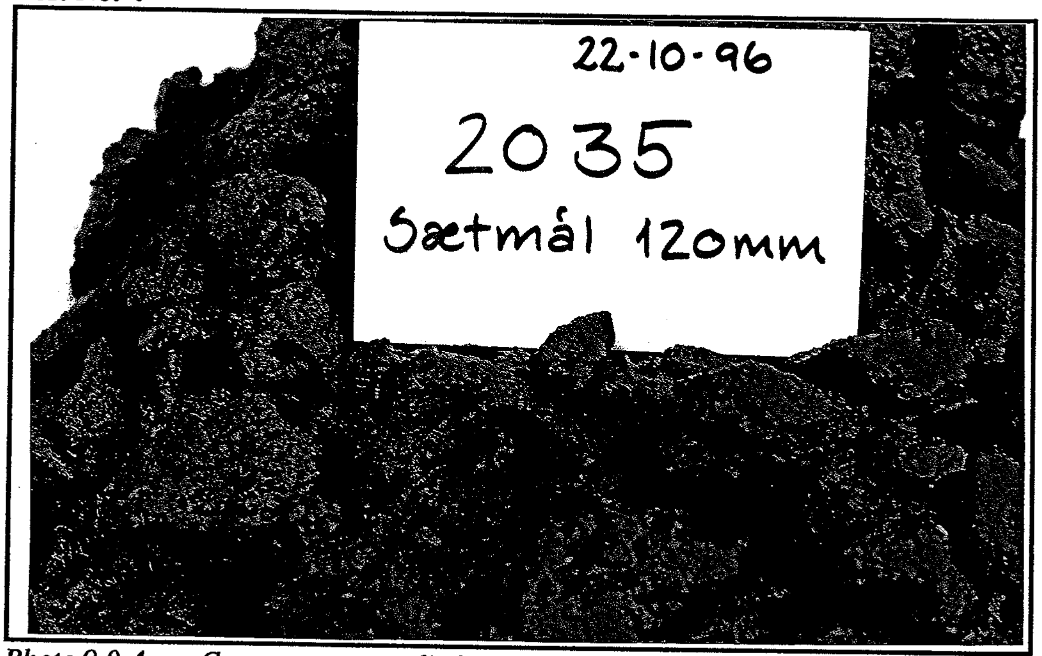

Photo 9.0-4: Concrete type applied at test No. 4. (F5, negative No. 1).

Concrete type: 4K standard concrete, according to BBB, mix design 2035			Methods: A and B
Air content: 6.2%	w/c: 0.45	Slump: 120 mm	Strength: 35 MPa

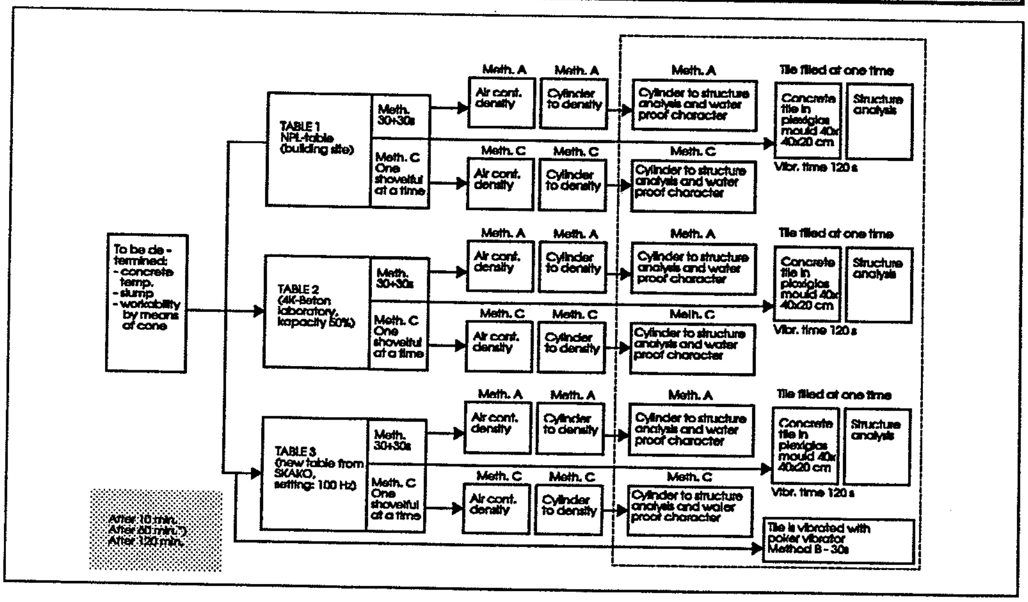

Figure 9.0-2: Program for test No. 4

At 60 min. 4 tiles and 6 additional cylinders are cast.

Test No. 5

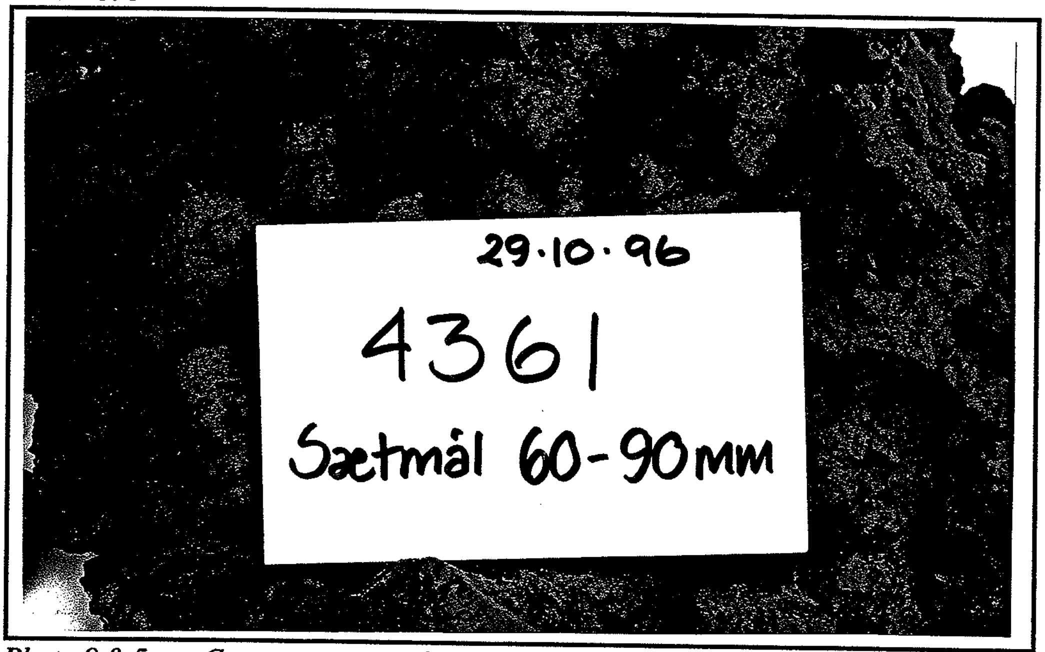

Photo 9.0-5: Concrete type applied at test No. 5. (F5, negative No. 9).

Concrete type: Environment class A according to BBB, mix design 4361			Methods:D,E,F,G, H, I,J,K,L,M,N,O
Air content: 6.2%	w/c: 0.41	Slump: 120 mm	Strength: 35 MPa

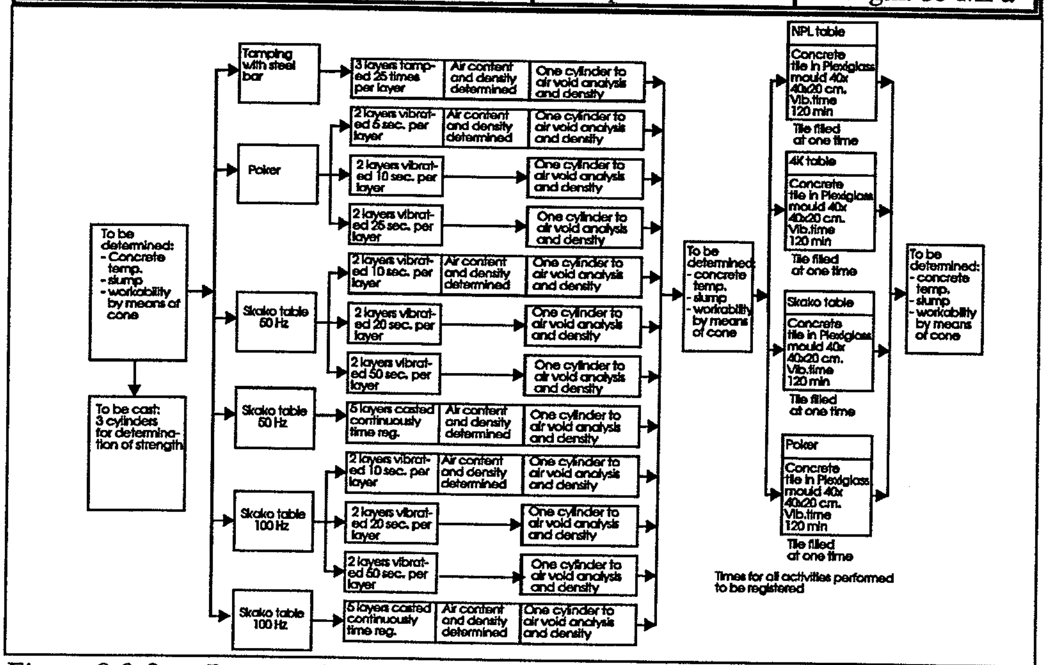

Figure 9.0-3: Program for test No. 5.

Test No. 6 has the same program as test No. 5

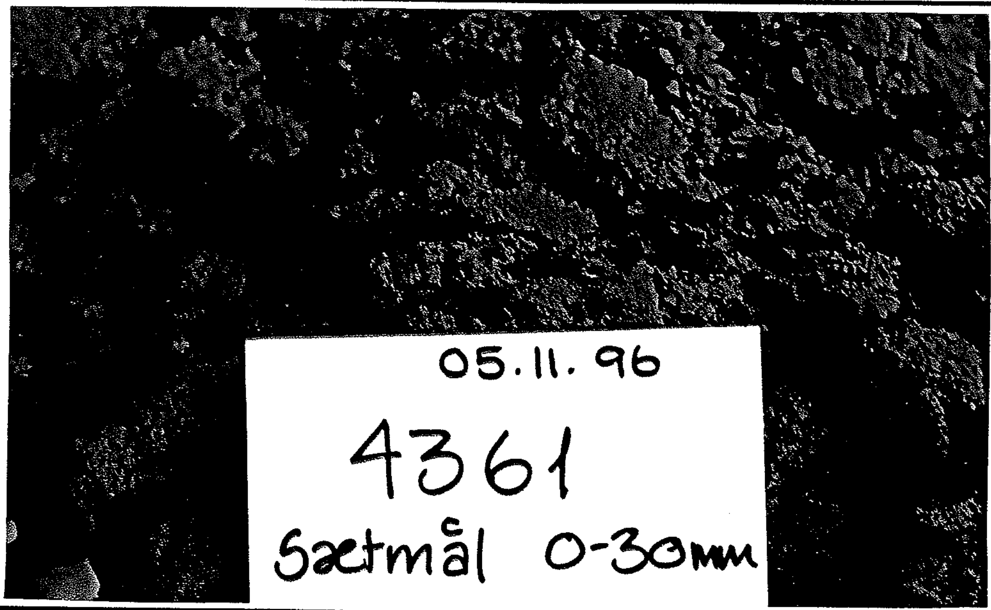

Photo 9.0-6: Concrete type applied at test No. 6. (F5, negative No. 16)

Concrete type: Environment class A according to BBB, mix design 4361			Methods:D,E,F,G, H, I,J,K,L,M,N,O
Air content: 6.2%	w/c: 0.41	Slump: 30 mm	Strength: 35 MPa

Test No. 7 has the same program as test No. 5 and 6.

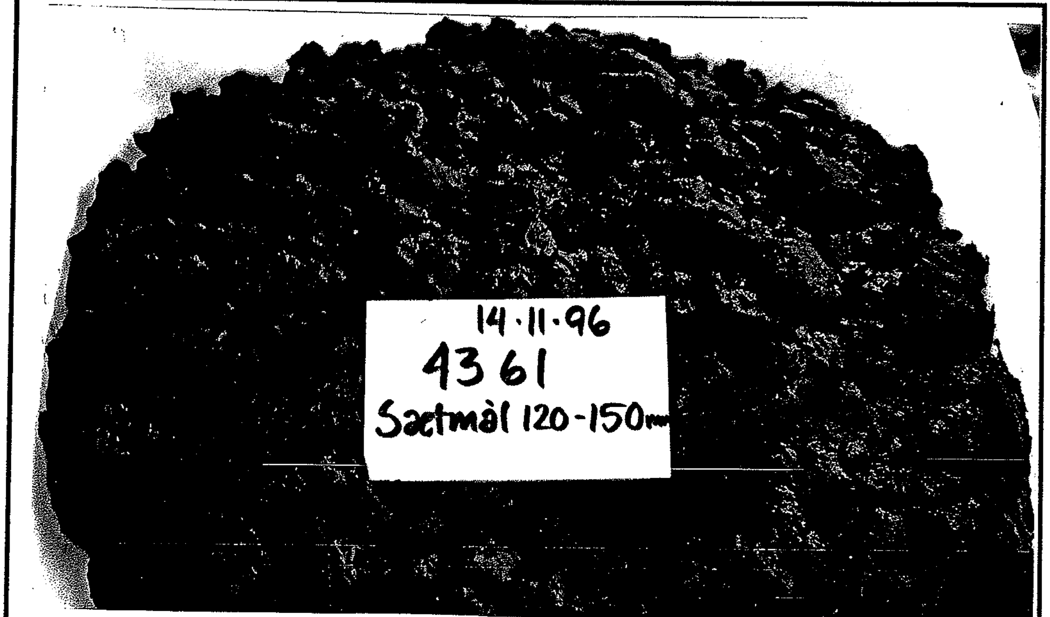

Photo 9.0-7: Concrete type applied at test No. 7. (F5, negative No. 25).

Concrete type: Environment class A according to BBB, mix design 4361			Methods:D,E,F,G, H, I,J,K,L,M,N,O
Air content: 6.2%	w/c: 0.41	Slump: 150 mm	Strength: 35 MPa

10 Measuring Uncertainty

In order to value the results from a test, the uncertainty that arises during casting of specimens from the method of measurement, the dependency on the person and the measuring equipment must be considered.

The uncertainty will be valued for the press-ur-meter and the cylinder as the results from those measurements are relatively close, and the uncertainty will play an important part.

10.1 Mathematical Terms

During testing it is not possible to predict the result as there are several possible outcomes. The result is said to be an uncertain quantity or a stochastic variable. [23].

Mathematical functions

There is a number of different distribution functions: rectangular, triangular and gauss distribution. The gauss distribution is the most applied distribution by description of test results. This distribution is called the normal distribution.

The normal distribution

Pleasant to work with as it is completely determined only by two parameters; the mean value E(X) and the distribution D(X).

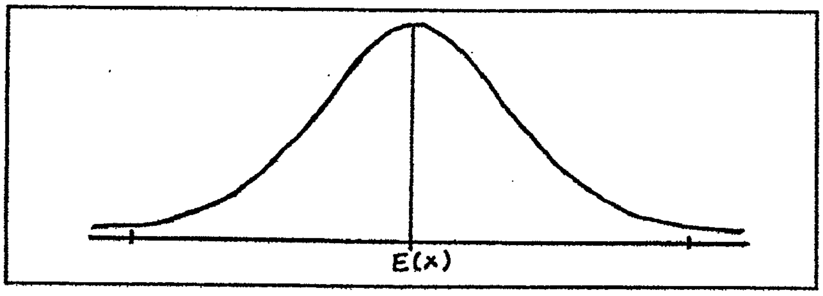

Figure 10.1-1: Distribution curve for normal distribution

The mean value E(X) for a stochastic variable X partly characterizes the present distribution of probability as E(X) can be said to be the number around which the values of the variable groups - a kind of centre of gravity. [24].

Distribution D(X)

The values may lie closely distributed around E(X) or they may lie with big deviation to each side. The distribution is a measure for how close the values are lying around E(X). [24].

The variance Var(X)
A value for the moment of inertia around a line through the point of gravity at right angles to the numeral axis.

$$D(X)^2 = Var(X)$$

The variation coefficient V_x
A value for the relation of the distribution to the mean value.

$$V_x = \frac{D(X)}{E(X)}$$

10.2 Press-ur-meter - Air Content

The basic designations and values in the valuation of the uncertainty of measurements with a press-ur-meter are from the manual: Calibration of measuring equipment in the production of concrete elements, concrete products and manufacturing concrete. [25]. In the manual the valuations are based on Boyle-Mariottes's law ($p \times V$ = constant when T is kept constant, p is the pressure, V the volume and T the absolute temperature).

In order to value the uncertainty by measuring with a press-ur-meter it is essential to know the theory behind the measuring process.

The press-ur-meter works by establishing a known pressure in a known volume, the pressure chamber. The concrete, of which the air content is to be determined, is filled in a container that is connected to the pressure chamber. The known pressure from the pressure chamber equalizes the pressure from the unknown air content in the concrete. The loss of pressure can be recalculated into a known air content for the concrete.

In order to value the uncertainty it is expedient to divide the press-ur-meter into its components:

- V_T Volume of the pressure chamber
- P_{ta} The absolute pressure in the pressure chamber
- V_0 The total volume of the container
- V_L The part of air hereof
- P_{La} The absolute pressure in the container

Other symbols:

- P_m The effective, measured pressure after opening of the valve
- P_T The effective, established pressure in the pressure chamber prior to opening of the valve

During casting of specimens there is a number of parameters that may influence the uncertainty (U±%) for the press-ur-meter:

1. The uncertainty of calibration (internal) on the press-ur-meter, F
2. The reading uncertainty of P_T
3. The repeatability P_T
4. The process is not completely isotherm P_T
5. The reading uncertainty of P_m
6. The process is not completely isotherm P_M
7. The repeatability P_M
8. Display errors - non-linear P_M
9. Invisible leakage P_M
10. Pollution, dew in the pressure chamber V_T
11. Temperature and mechanical extension V_T
12. Pollution in the container V_0
13. Temperature and mechanical extension V_0
14. Construction error/underfilling V_0
15. Temperature dependent of the manometer P_T
16. Temperature dependent of the manometer P_M

The uncertainty components from the Calibration Manual [25] is stated by ± the uncertainty $U_{parameter}$, of each of the parameters:

Ad.:	1	2	3	4	5	6	7	8
$U_{parameter\ \%}$	0.127	0.017	0.00	0.032	0.031	0.091	0.098	0.05
Ad.	9	10	11	12	13	14	15	16
$U_{parameter\ \%}$	0.031	0.019	0.00	0.005	0.00	0.002	0.002	0.002

The total uncertainty is the individual parameters, by casting of specimens (u) is calculated by adding the uncertainty parameters geometrically:

$$(u = \sqrt{\sum U^2_{parameter}}).$$

The total uncertainty makes u = ±0.2%.

The uncertainty is defined as U = k · u where k normally is set to 2. This will give a confidence level of 95% meaning that the uncertainty will lie within the stated limit in 95% of the cases. This applies if the uncertainty components are normally distributed (the real distribution is unknown).

Measuring uncertainty U = ± 0.4% (k=2). [25].

This means that if the air content is measured to 5.0% the air content with 95% certainty lies between 4.6% and 5.4%.

10.3 Press-ur-meter - Density

The Calibration Manual does not state a value for the uncertainty of measuring the density with a press-ur-meter container. The uncertainty of the density is therefore valued out from the filling height of the press-ur-meter container. It is valued that the height of the concrete can vary by max. ±1 mm.

The press-ur-meter container has a diameter of 21.5 cm and a height of 22 cm. This makes: a maximum volume, vol_{max} of:

$$\frac{\pi}{4}(21{,}5)^2 \cdot (22{,}1) = 8023cm^3$$

a minimum volume, vol_{min} of:

$$\frac{\pi}{4}(21{,}5)^2 \cdot (21{,}9) = 7950cm^3$$

and a normal volume, vol_{nom} of:

$$\frac{\pi}{4}(21{,}5)^2 \cdot (22) = 7987cm^3$$

The maximum deflection of the results = $\dfrac{vol_{max} - vol_{min}}{vol_{nom}} = \dfrac{8023 - 7950}{7987} = 0{,}009$

This gives a maximum uncertainty of the measurement of ±0.45% meaning that a density of 2350 kg/m³ and densities between 2339 kg/m³ and 2361 kg/m³ are valued in the same way.

The uncertainty factor of weighing of press-ur-meters is extremely small compared to the uncertainty of the filling height. Therefore this factor is disregarded.

10.4 Cylinders

In the calibration norm no uncertainty is stated for cylinders. Therefore the cylinders are valued out from the expansion requirements from the given calibration norms.

A cylinder may according to DS423.20 expand ±1% in the height and the width i.e. a standard cylinder with the dimensions 15-30 cm can have a maximum volume, vol_{max} of:

$$\frac{\pi}{4}(1{,}01 \cdot 15)^2 \cdot (1{,}01 \cdot 30) = 5462cm^3$$

a minimum volume vol_{min} of:

$$\frac{\pi}{4}(0{,}09 \cdot 15)^2 \cdot (0{,}09 \cdot 30) = 5144cm^3$$

and a normal volume vol_{nom} of:

$$\frac{\pi}{4}(15)^2 \cdot (30) = 5301cm^3$$

The maximum deflection of the results is the total possible expansion in relation to the nominal volume:

$$\text{The maximum deflection of the results} = \frac{vol_{max} - vol_{min}}{vol_{nom}} = \frac{5462 - 5144}{5301} = 0{,}06$$

This means that a maximum uncertainty of the measurements of ±3%. I.e. that a density of 2350 kg/m³ and densities between 2280 kg/m³ and 2421 kg/m³ are valued the same way.

The uncertainty factor of the weighing of cylinders is extremely small compared to the uncertainty factor of expansion of the cylinder. Therefore this factor is disregarded.

PART 3

Results, Treatment and Conclusion

The tests are, as mentioned in part 2, divided into 3 different fields. The treatment of the results and the conclusions are divided into 3 sections as well:

- 11.0 Air - Density
- 12.0 Tiles
- 13.0 Workability funnel

Furthermore Part 3 includes

- chapter 14 Recommendation for Vibration of Specimens

11 Air - Density

In this chapter the density and the air content from the tests are valued.
The tests with casting of cylinders and press-ur-meter specimens are performed to document the influence from the following parameters:

- Vibrator type, external/internal
- The frequency, amplitude and acceleration of the vibrating tables
- Vibrating times
- Number of cast layers
- The age of the concrete at casting
- The slump of the concrete

The air content and the density are measured on the fresh concrete with a press-ur-meter and the density of the hardened concrete is measured on cylinders. On selected cylinders the air content is measured of the hardened concrete by air void analysis.
The test results are registered in tables in appendix B. The results from each test are studied intensively in the following sections.
In tests 2-7 the calculated density from the factory is shown, which is calculated out from the batch report for the concrete. The calculated density is shown with the degree of accuracy of ±3% which is stated in the calibration norm.
The compression strengths from the test are as expected. In figure 11.0-1 the average compression strengths are shown. The compression strengths will not be treated further in this report.

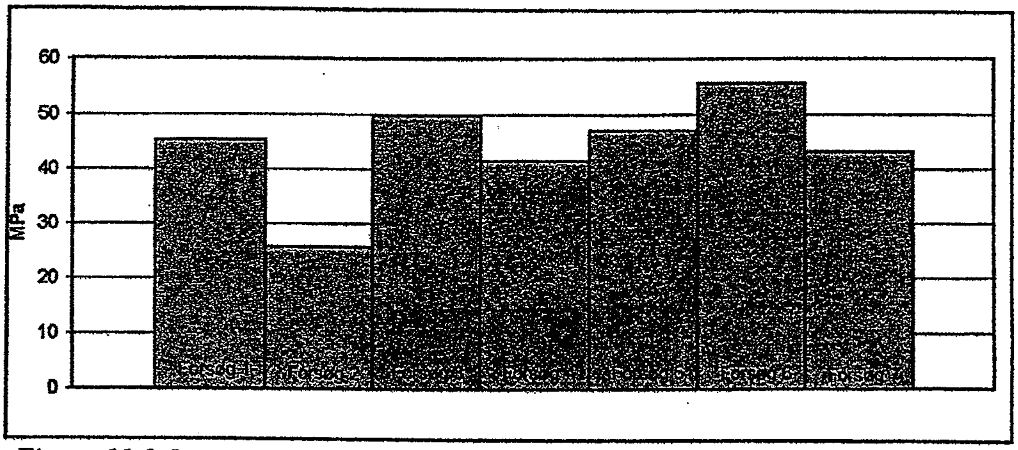

Figure 11.0-1: *Compression strengths for tests Nos. 1 - 7*

The press-ur-meter container and the cylinders were not fastened during the tests. The importance of this parameter will not be analysed further in this report.

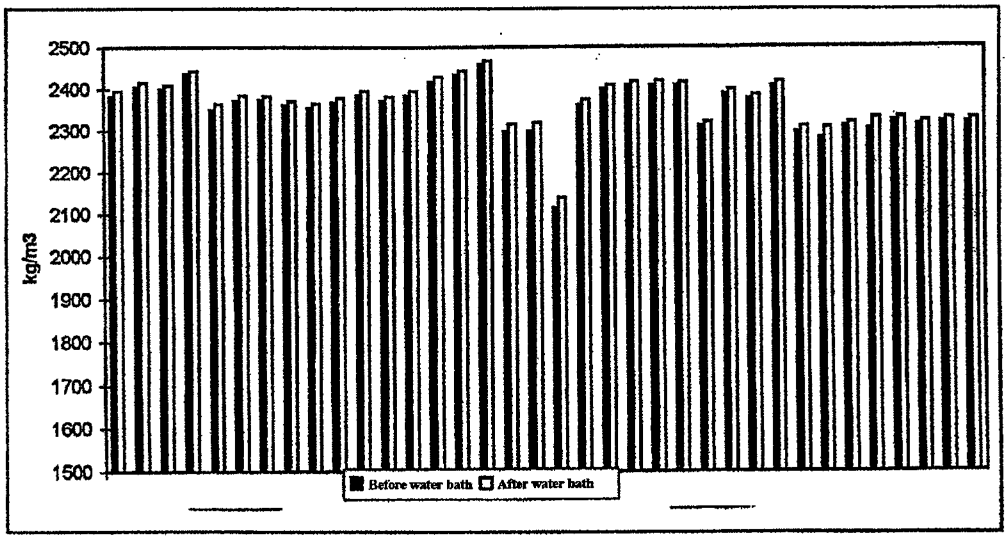

Figure 11.0-2: Densities before and after storage in water bath.

As it appears from figure 11.0-2 the densities measured before the water curing and the densities measured after the water curing are of the same size. For concrete with a slump of more than 70 mm there is a difference of 9-12 kg/m³ and for concrete with a slump of less than 70 mm there is a difference of 10-25 kg/m³. It is not of essential importance for the soft concrete whether the cylinders are weighed before of after the water curing, but it may be of importance as to dry concrete.

11.1 Air Content and Density for Test No. 1

Concrete for aggressive environment.
Slump 90 mm falls to 25 mm after 180 min.
Vibrating tables Nos. 1,2 and 3.
Vibration methods A and B

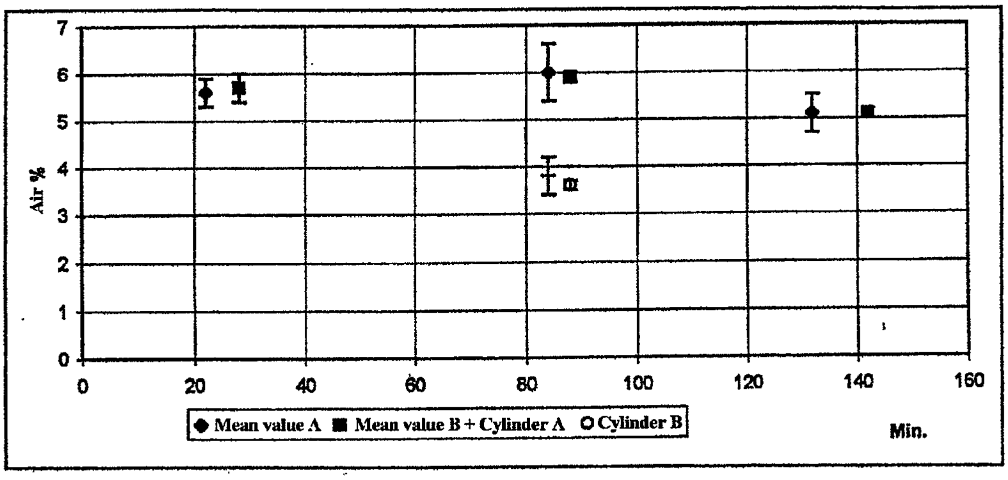

Figure 11.1-1: Air content for test No. 1.

Figure 11.1.-1 shows the mean value and standard deviation of the air content for the 3 vibrating tables.

This has been chosen as the difference between the results is so little that the influence from the vibrating tables can not be documented.

The air content is remarkably constant between 5 and 6 % during the whole period from mixing to 140 min. after mixing.

The air content in the hardened concrete in the cylinders is 2% lower than the air content in the fresh concrete from the press-ur-meter.

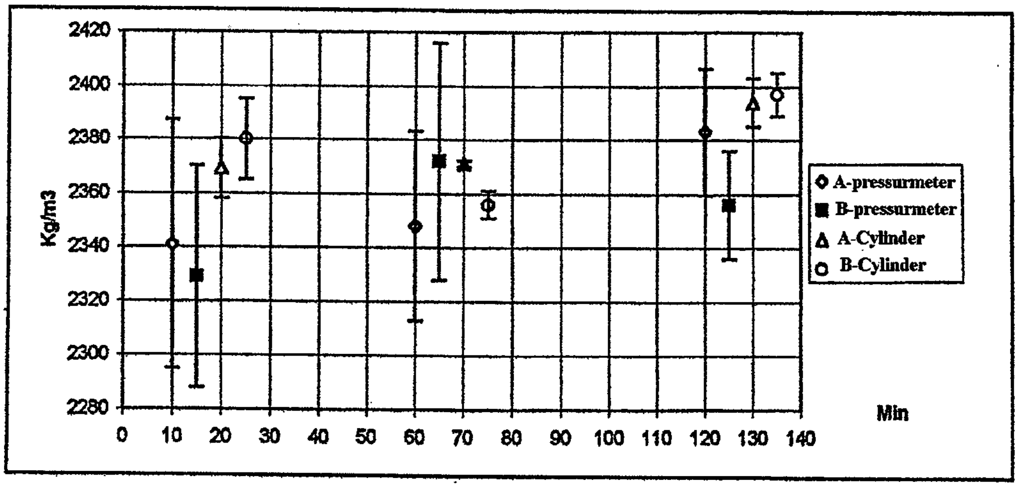

Figure 11.1-2: The densities for test No. 1.

Figure 11.1-2 shows the densities, also as mean values and standard deviation of the 3 vibrating table.

The standard deviation of densities measured on cylinders is remarkably small compared to both the densities from the press-ur-meter and what might be expected. The standard deviation is in all cases less than 15 kg/m³.

The densities determined by the press-ur-meter varies more than expected. The standard deviation is three times as big as the distribution on the cylinders. It suggests that the press-ur-meter containers have not been sufficiently cleaned on the outside.

The low air content in the cylinders does not as expected recur as higher density in the cylinders cast at the same time. This might be due to the fact that the air void analysis of the cylinder is not representative for the number of air voids bigger than 2 mm due to the small area that is examined.

Generally, test No. 1 shows that the vibration methods A and B and the 3 vibrating tables do not have any significant influence on the density and the air content of the concrete.

11.2 Air Content and Density for Test No. 2

A concrete for passive environment class (25 Mpa) with a small dose of air mixture was applied.
The slump 50 mm falls to 15 mm after 160 min.
Vibrating tables 1, 2 and 3.
Vibration methods A and B.

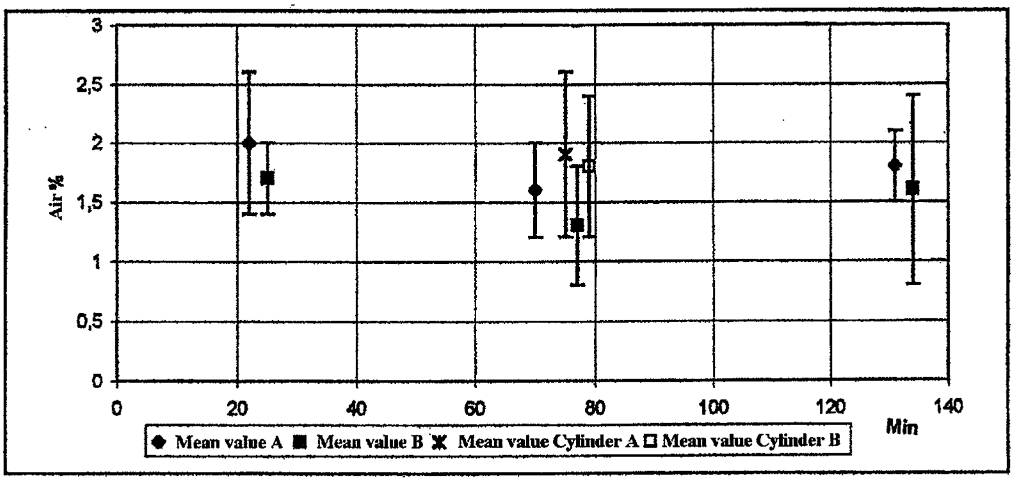

Figure 11.2-1: Air content for test No. 2

Figure 11.2-1 shows the mean value and standard deviation of the air content like for test No. 1.

The air content is constant in the period from mixing to 130 min. after mixing.

The mean values are the same for the press-ur-meter test and the cylinders, both as to the fresh concrete and to the hardened concrete.

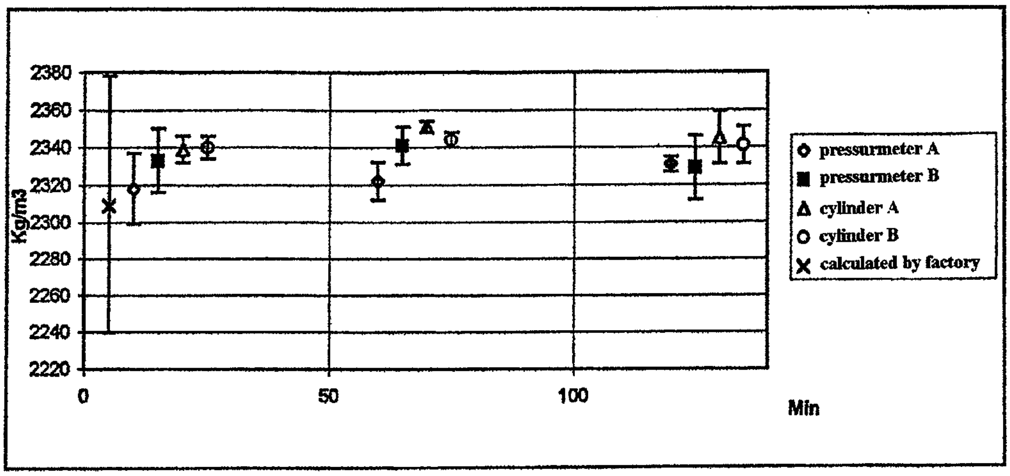

Figure 11.2-2: The densities for test No. 2.

Figure 11.2-2 shows the mean value and standard deviation like for test No. 1.
The densities for the press-ur-meter and the cylinders are remarkably similar with a very small standard deviation..
The densities are 30 kg/m³ higher than the factory calculated. This corresponds to approx. 1% lower air content.
Test No. 2 shows like test No. 1 that the vibration methods A and B and the 3 vibrating tables have no significant influence on the density and the air content of the concrete.

11.3 Air Content and Density for Test No. 3.

Concrete for especially aggressive environments, w/c < 0.40 (HETEK - concrete). The slump 90 mm falls to 0 mm after 60 min.
Vibrating table 1, 2 and 3.
Vibration methods A and B.

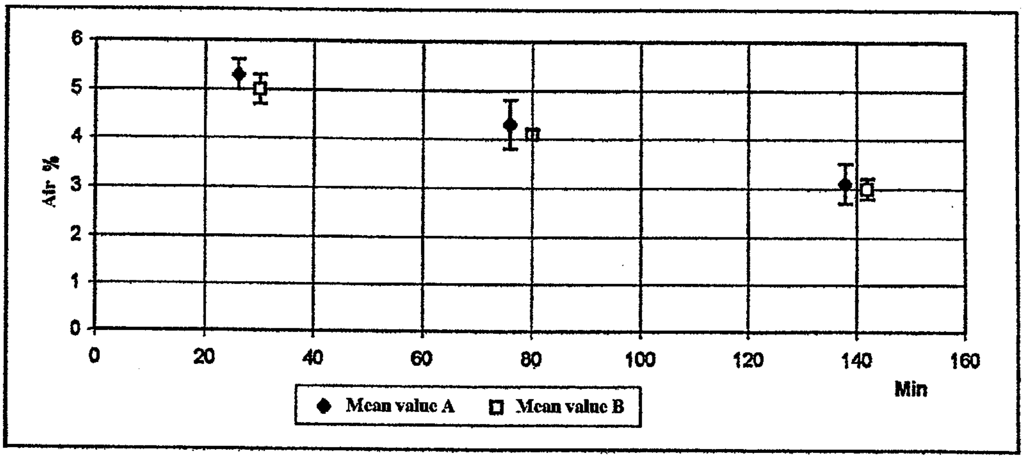

Figure 11.3-1: Air content for test No. 3.

Figure 11.3-1 shows the mean value and standard deviation of the air content as with tests Nos. 1 and 2. The air content of the hardened concrete is not measured.
The air content falls approx. 2% from the mixing to 140 min. after mixing of the concrete.
The mean values for method A and B are the same and the distribution is very small.

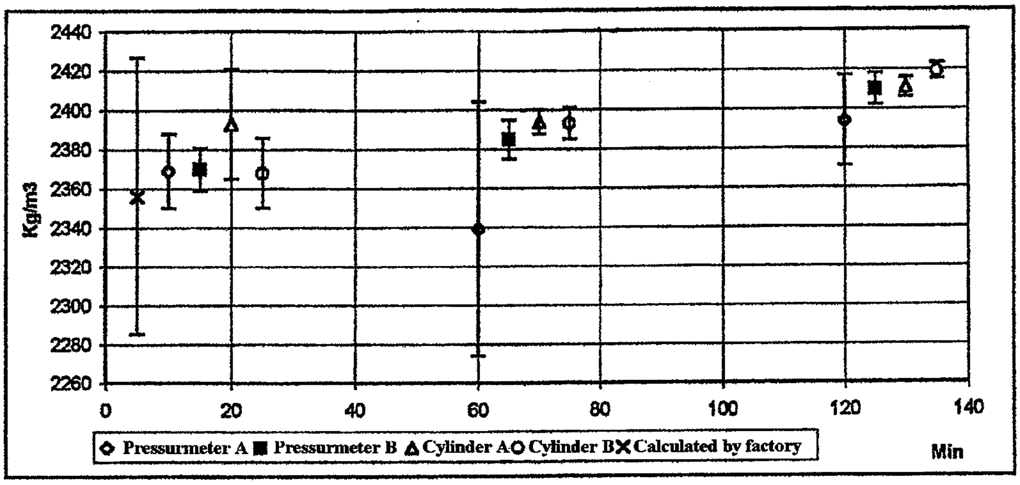

Figure 11.3-2: The densities for test No. 3.

Figure 11.3-2 shows the mean value and the standard deviation as with test No. 1 and No. 2.

The densities from the press-ur-meter A varies after 60 min. They have a considerably bigger standard deviation than the remaining densities. Apart from the density measured with press-ur-meter after 60 min, the remaining densities are the same and have for all the methods a small standard deviation. The density increases by the time corresponding to the loss of air.

Generally, test No. 3 shows like test No. 1 and No. 2 that the vibration methods A nd B and the 3 vibrating tables have no significant influence on the density and the air content of the concrete.

11.4 Air Content and Density for Test No. 4

Same concrete as at test No. 1.
The slump 110 mm falls to 30 mm after 150 minutes after mixing.
Vibrating tables 1, 2 and 3.
Methods A and C.

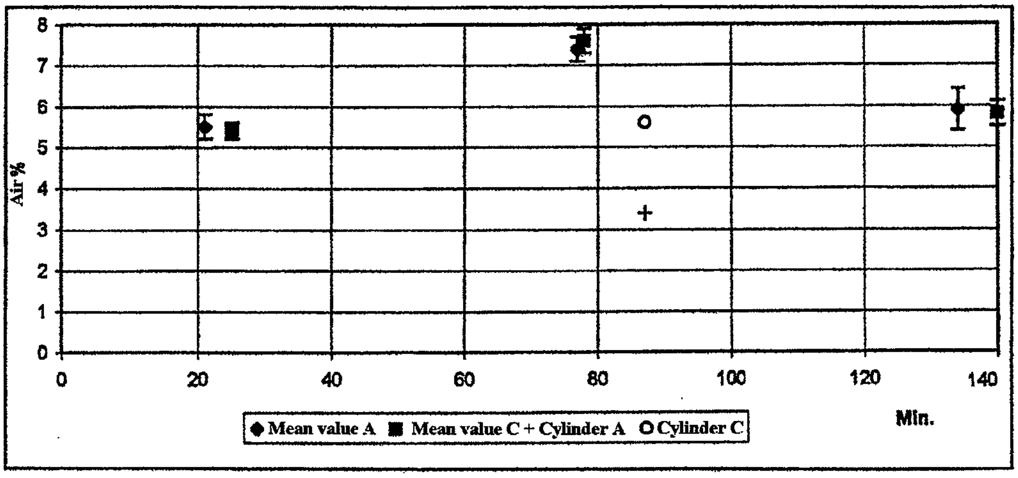

Figure 11.4-1: Air content for test No. 4

Figure 11.4-1 shows the mean value and standard deviation of the air content in the same way as the previous tests. The air content increased approx. 2% in the period 20 min. to 80 min. and falls 1.5% from 80 min. to 140 min.

The mean value for the air content for the press-ur-meter tests are the same for methods A and C.

The air content in the cylinders of the hardened concrete is for method A 4% and for method C 2% lower than the air content of the fresh concrete from the press-ur-meter. This difference can not be explained, and since these values stand alone, the result of the air void analysis might be a coincidence.

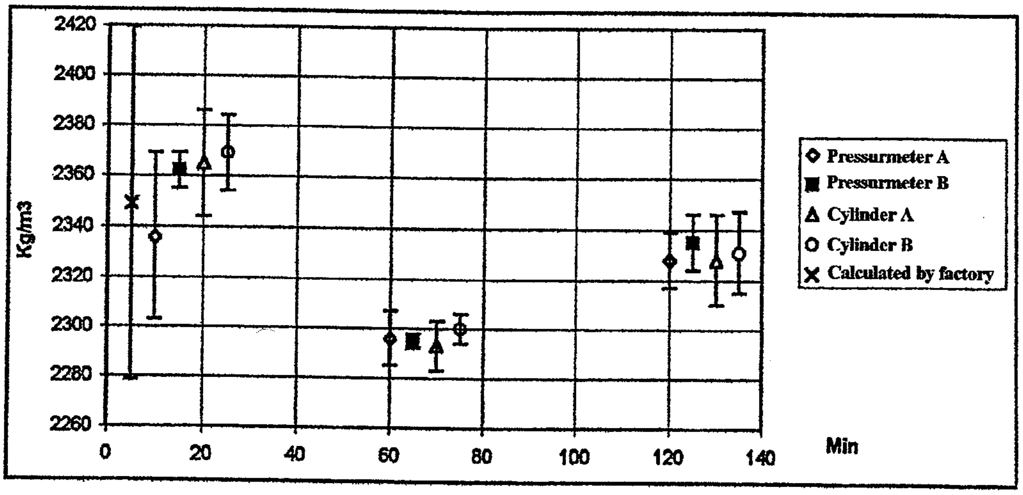

Figure 11.4-2 The densities for test No. 4

Figure 11.4-2 shows the mean values and standard deviation of the densities as like by the previous tests.

The densities from the press-ur-meters and the densities from the cylinders are the same and a small standard deviation is the case for all methods.

The two lower air contents in the cylinders do not recur as corresponding higher densities for cylinders cast at the same time.

Test No. 4 does like tests Nos. 1, 2 and 3 generally show that the vibration methods A and C and the 3 vibrating tables have no significant influence on the density and the air content of the concrete.

11.5 Air Content and Density for Test No. 5

Concrete for aggressive environment class.

The slump 100 mm is falling to 70 mm after 70 min.

Tamping by a steel bar and vibration with poker for comparison with the vibrating tables.

The vibration times are changed by the application of new vibration methods.

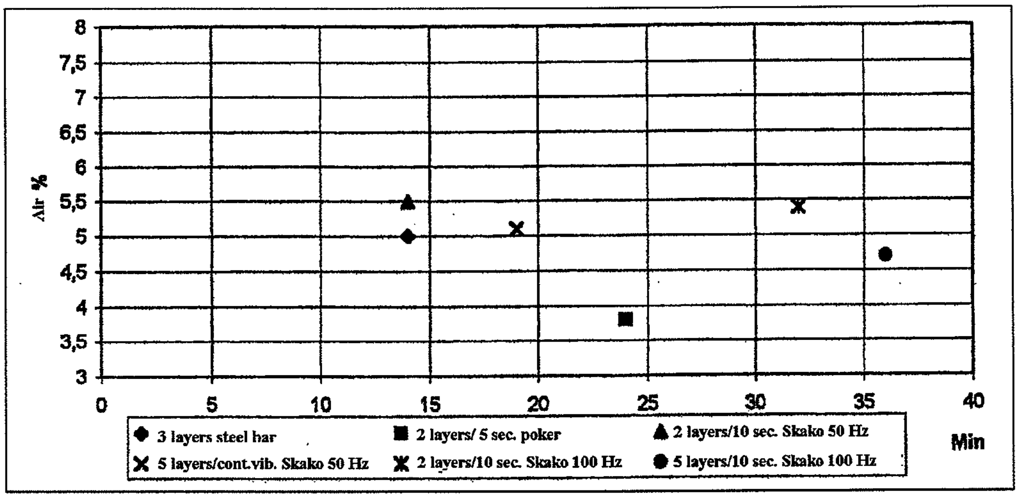

Figure 11.5-1: Air content in the fresh concrete for test No. 5.

Figure 11.5-1 shows the air content measured by press-ur-meter as individual results by the different vibration methods.

The vibrating tables show the same results between 4.5% and 5.5%. Tamping with a steel bar lies on 5% corresponding to the average of the vibrating tables. The result from the poker lies considerably lower than the other results with 3.8%.

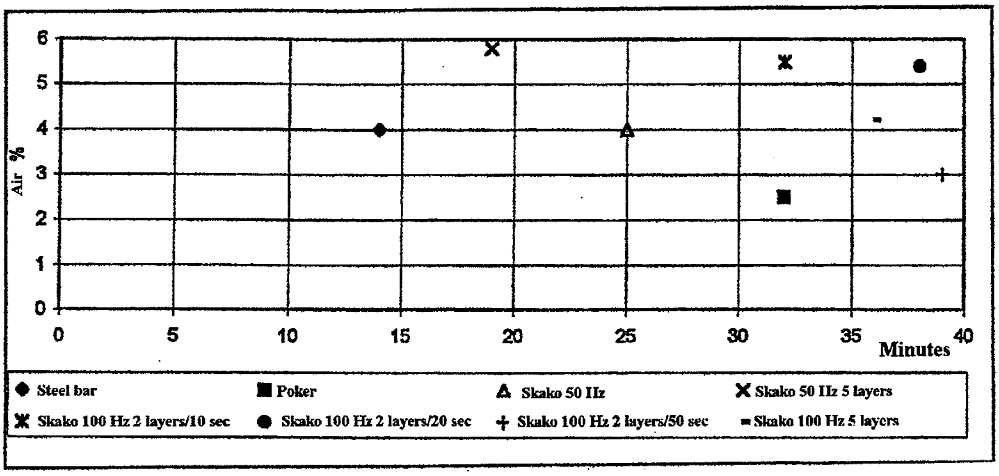

Figure 11.5-2: Air content in the hardened concrete for test No. 5.

Figure 11.5-2 shows the air content measured on the hardened concrete from the cylinders. The air content on the vibrating tables ranges between 4% and 6% except vibration for 2 x 50 sec. at 100 Hz on the Skako table which gives an air content of approx. 3%. Tamping with a steel bar has an air content of 4% at the low end compared to the vibrating tables.

Vibration with a poker for 2 x 10 sec. makes 2.5% which is considerably lower than the other air contents.

	Press-ur-meter kg/m³	Cylinder kg/m³
Tamping with steel bar	2358	2384
Poker	2395	2414
Skako 50 Hz	2365	2366
Skako 50 Hz	2370	2361
Skako 100 Hz	2353	2370
Skako 100 Hz	2378	2370
Mean value all types	2370	2381
Standard deviation	15	24
Mean value for vibrating tables	2367	2368
Standard deviation	11	4
Calculated by factory	2368	

Figure 11.5-3: The densities for test No. 5.

Figure 11.5-3 shows a table of the densities for the press-ur-meter and the cylinder from test No. 5. The mean values are very equal and the standard deviation very small. In figure 11.5-4 the densities from test No. 5 and the theoretical uncertainty of the measurements are shown in the next picture.

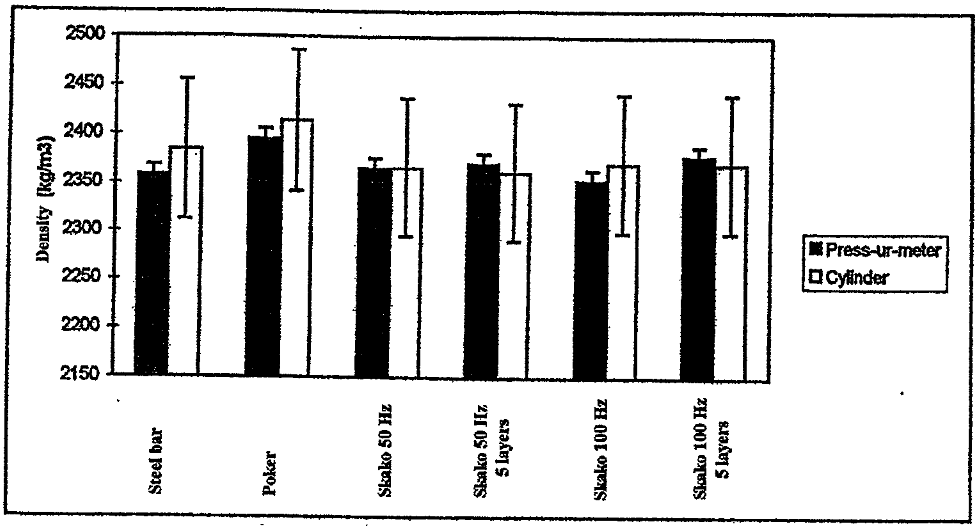

Figure 11.5-4: The densities for test No. 5.

11.6 Air Content and Density for Test No. 6

For test No. 6 the same concrete as for test No. 5 is used but with a considerably lower slump. The slump is at mixing 30 mm and falls to 0 mm after 45 min. after mixing.

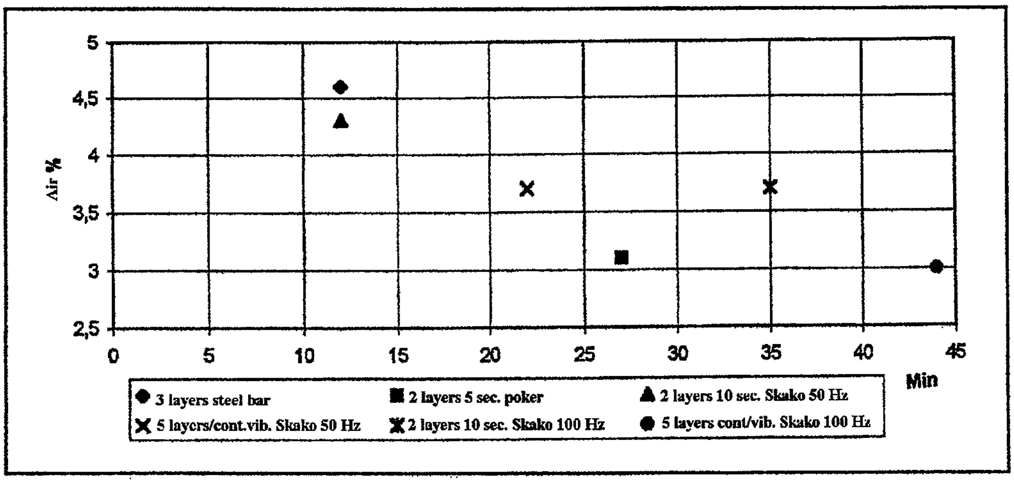

Figure 11.6-1: Air content in the fresh concrete for test No. 6

Figure 11.6-1 shows the air content measured in the fresh concrete with a press-ur-meter as individual values for the methods.

All the measured air contents lie between 3% and 4.6%. The results show the influence by the low slump. The two previous measurements after 12 min. give a relatively high air content 4.3% and 4.6% where the air content after 45 min. has fallen to 3%.

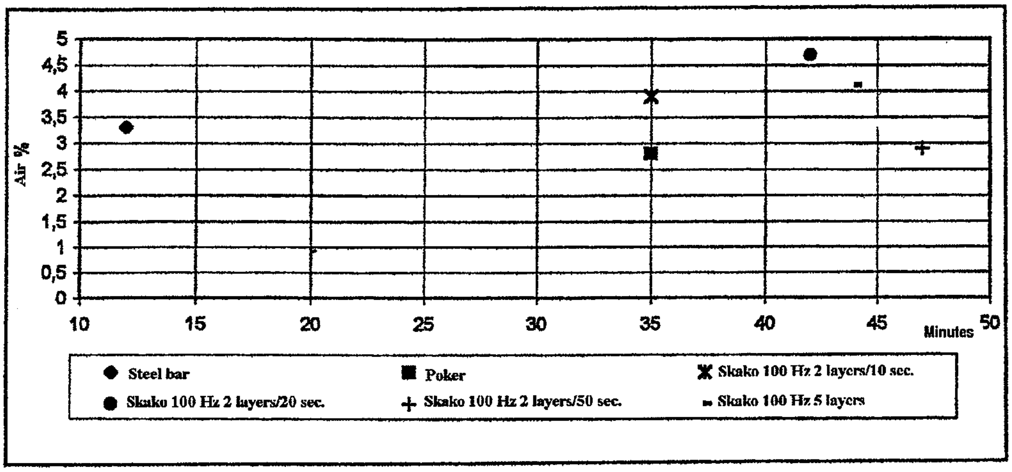

Figure 11.6-2: Air content in the hardened concrete for test No. 6.

Figure 11.6-2 shows the air content measured on the hardened concrete from the cylinders.

The results from the cylinders are contrary to the press-ur-meter. The air content seems to rise by the age of the concrete. These results can lead to the conclusion that:

Compaction with tamping is possible as long as the concrete has a slump over 20 mm. The poker can compact the concrete even if the slump is zero after 35 min.

The vibrating tables have difficulties in compacting the concrete at slump zero.

	Press-ur-meter kg/m³	Cylinder kg/m³
Tamping with steel bar	2385	2386
Poker	2413	2437
Skako 50 Hz	2391	2300
Skako 50 Hz	2411	2361
Skako 100 Hz	2423	2405
Skako 100 Hz	2456	2408
Mean value all types	2413	2389
Standard deviation	25	51
Mean value for vibrating tables	2420	2369
Standard deviation	26	51
Calculated by factory	2395	

Figure: 11.6-3: The densities for test No. 6

Figure 11.6-3 shows a table with the densities for the press-ur-meter and the cylinder from test No. 6. The results indicate that it is much more difficult to compact the dry concrete than to compact the plastic concrete in test No. 5. In figure 11.6-4 the densities from test No. 6 and the theoretical uncertainty of the measurements are shown in a picture.

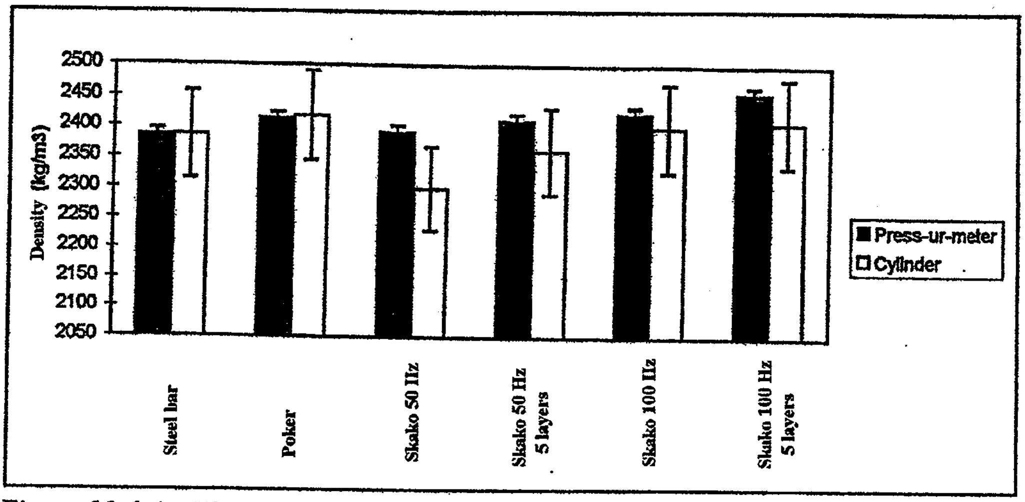

Figure 11.6-4: The densities for test No. 6.

The density of the fresh concrete from the press-ur-meter is generally higher than the density on the hardened concrete from the cylinders.

The density for Skako 50 Hz/2 layers/5 sec. has been disregarded as the acceleration of the table is too low for the dry concrete as the density is approx. 200 kg/m³ lower than the remaining measurements, both prior to and after water curing.

11.7 Air Content and Density for Test No. 7

For test No. 7 the same concrete as was applied as for tests Nos. 5 and 6, but with a considerably higher slump. The slump is at mixing 160 mm and falls to 110 mm after 70 min.

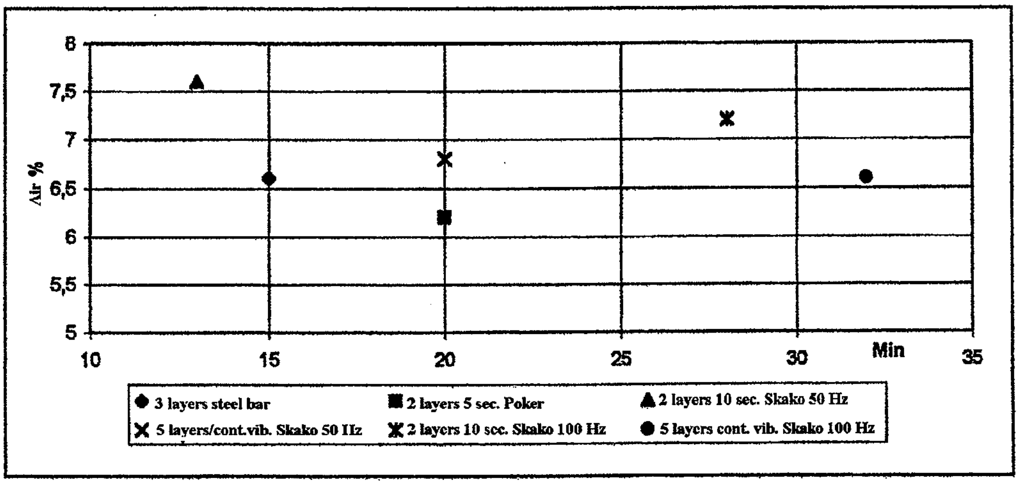

Figure 11.7-1: Air content in the fresh concrete for test No. 7.

Figure 11.7-1 shows the air content of the fresh concrete measured with press-ur-meter as individual values for the methods.

The air content for the vibrating tables ranges between 6.6% and 7.6%. Tamping with a steel bar is with an air content of 6.6% at the low end compared to the vibrating tables.

The poker again has the lowest air content.

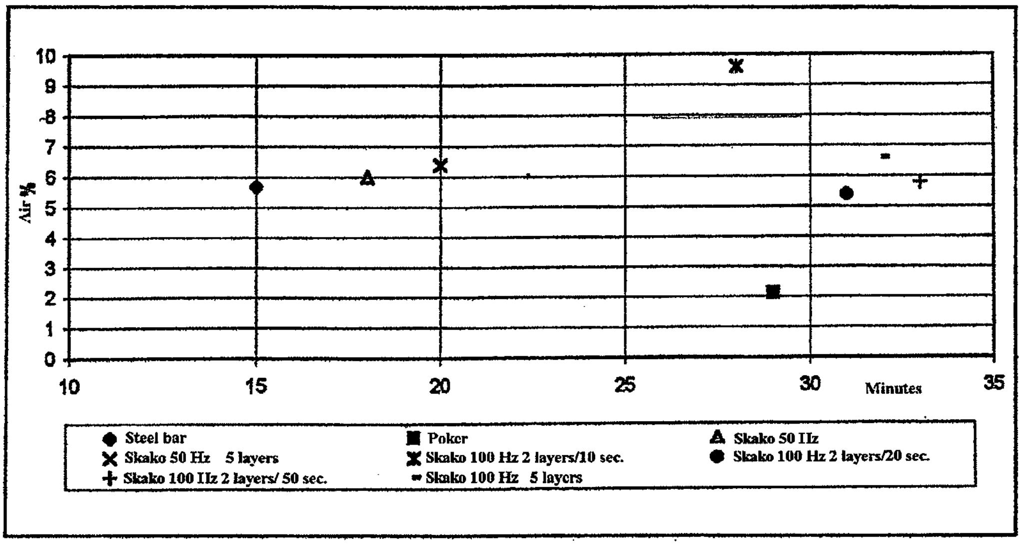

Figure 11.7-2: Air content in the hardened concrete for test No. 7.

Figure 11.7-2 shows the air content measured on the hardened concrete from the cylinders.

The air content from the vibrating tables ranges between 5% and 7% except one result of 9.6%. This air content will be disregarded as the density for the cylinder is at the same level as the other densities.

Tamping with a steel bar gives an air content at the low end compared to the vibrating tables.

Vibration with a poker gives again a considerably lower air content than the other measurements.

	Press-ur-meter kg/m³	Cylinder kg/m³
Tamping with steel bar	2314	2312
Poker	2337	2390
Skako 50 Hz	2294	2296
Skako 50 Hz	2314	2305
Skako 100 Hz	2313	2319
Skako 100 Hz	2324	2320
Mean value all types	2316	2330
Standard deviation	39	39
Mean value for vibrating tables	2311	2310
Standard deviation	13	12
Calculated by factory	2250	

Figure 11.7-3: The densities for test No. 7.

Figure 11.7-3 shows a table of the densities for the press-ur-meter and the cylinder from test No. 7. The mean values are very equal and the standard deviation very small. In figure 11.7-4 the densities from test No. 7 and the uncertainty of the measurements are shown in a picture.

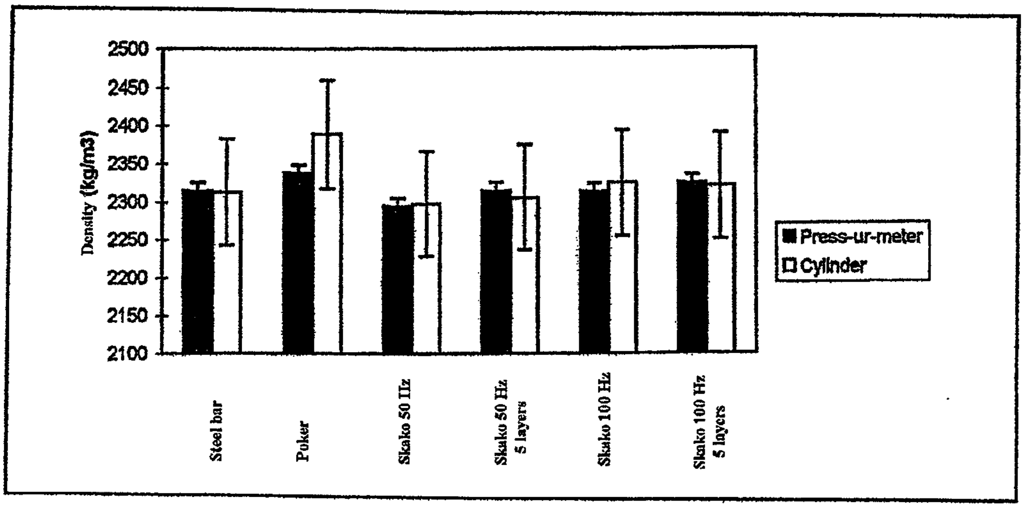

Figure 11.7-4: The densities for test No. 7.

The density of the fresh concrete from the press-ur-meter and the density of the hardened concrete from the cylinders are approx. the same.

11.8 Valuation of Plan Section

Plan section has been performed on selected cylinders from all tests except test No. 3.

The plan sections are documented with photos of the 3 surfaces that appear during the plan section: raw flat, 1 mm down and 2 mm down (cf. enclosure 1).

The method of plan section is described further in section 7.1.

The plan sections are valued in co-operation with Jens Frandsen, 4K-BETON based on the documentation photos.

The valuation is made based on the following:

A - there is a good **stone distribution** or there are areas without stones.
B - there is much **entrapped** air.
C - there are **big air bubbles** over 10 mm.
D - there is **paste separation.**
E - there are many **cracks.**

Each of the items are valued according to a character scale from 1-3, where:

1 is good
2 is OK
3 is bad

The different vibration methods are summed up mutually to get a joint valuation of the vibration method where the lowest number is the best one. This valuation gives, however, no total characteristic of the vibration method as the high characters are not of the same risk. A high number of air bubbles is not as risky as a high paste separation.

	A	B	C	D	E	TOTAL
Test 1 after 60 minutes. (Aggressive concrete)						
NPL A	1	1	2	1	1	6
NPL B	2	1	1	1	1	6
4K A	1	2	2	1	1	7
4K B	2	2	2	2	1	9
Skako A	1	2	1	1	1	6
Skako B	1	2	2	1	1	7
Test 2 after 60 minutes. (Passive concrete)						
NPL A	1	2	2	1	1	7
NPL B	1	2	3	1	1	8
4K A	1	2	3	1	1	8
4K B	1	2	3	1	1	8
Skako A	1	3	3	2	2	11
Skako B	1	3	3	2	2	11
Test 4 after 60 minutes. (Same concrete as test 1)						
Skako A	1	2	2	2	2	9
Skako C	2	2	2	2	2	10
Test 5. (Modified aggressive concrete)						
Steel bar	2	1	1	1	1	6
Poker	1	1	1	1	2	6
Skako 50 Hz 50 sec.	1	3	3	2	1	10
Skako 50 Hz 5 layers	1	2	2	2	1	8
Skako 100 Hz 10 sec.	1	3	2	2	1	9
Skako 100 Hz 20 sec.	1	2	2	2	1	8
Skako 100 Hz 50 sec.	1	3	3	2	1	10
Skako 100 Hz 5 layers	1	2	1	2	1	7
Test 6. (Modified aggressive concrete)						
Steel bar	1	3	2	1	1	8
Poker	3	2	1	1	1	8
Skako 100 Hz. 10 sec.	1	2	3	2	1	9
Skako 100 Hz. 20 sec.	1	3	3	2	1	10
Skako 100 Hz. 50 sec.	1	3	2	2	1	9
Skako 100 Hz. 5 layers	1	3	2	2	1	9
Test 7. (Modified aggressive concrete)						
Steel bar	1	1	1	1	1	5
Poker	3	1	1	2	1	8
Skako 50 Hz. 50 sec.	2	1	1	2	1	6
Skako 50 Hz. 5 layers	1	2	1	1	1	6
Skako 100 Hz. 10 sec.	1	2	2	1	1	7
Skako 100 Hz. 20 sec.	1	2	1	1	1	6
Skako 100 Hz. 50 sec.	1	1	2	1	1	6
Skako 100 Hz. 5 layers	1	2	2	1	1	7

Figure 11.8-1: Valuation of plan section.

General valuation of the plan sections

A: The stone distribution.

- The stone distribution is more stable in the passive concrete (test No. 2) than in the aggressive concrete.
- The poker destroys the stone distribution by making "marks" in the concrete after vibration.

B : Entrapped air

- There is most entrapped air in the passive concrete.
- There is more entrapped air by vibration with vibrating tables than by tamping with a steel bar.

C : Big air bubbles over 10 mm.

- The biggest amount of big air bubbles is found in the passive concrete.
- There are fewest big air bubbles in the aggressive concrete with a high slump.

D : Paste separation

- Most paste separations are found in the modified aggressive concrete at a low and mean slump and fewest in the same concrete at a high slump.

E : Cracks

- There are most cracks by vibration of the passive concrete with a poker.

If the character of the vibrations methods are compared, the distribution looks as follows:

Character	Vibration method (test number)
5	Tamping (7)
6	NPL A and B, Skako A (1); Tamping, Poker (5); Skako 50 Hz/50 sec. and C, Skako 100 Hz/20 sec. and 50 sec. (7)
7	4K A, Skako B (1); NPL A (2); Skako C (5); Skako 100 Hz/10 sec. and C (7)
8	NPL B, 4K (2); Skako 50 Hz C, Skako 100 Hz/20 sec. (5); Tamping, Poker (6); Poker (7)
9	4K B (1); Skako A (4); Skako 100 Hz/10 sec. (5); Skako 100 Hz (6)
10	Skako C (4); Skako 100 Hz/50 sec. (5); Skako 100 Hz/20 sec. (6)
11	Skako A and B (2)

The main part of the vibration methods lies between the characters 6 and 8. The best character obtained is by tamping with a steel bar at a high slump. The worst character obtained is by Skako A and B in the passive concrete.

The new Skako vibrating table with adjustable frequency is not as efficient as the other more simple vibrating tables.

11.9 Conclusion of the Air Content and the Density in Test Nos. 1-7

The test and the changes of the tests are described in chapter 9.

Generally, the tests Nos. 1 - 7 show that as to densities and air content for the methods there is only a small variation. The valuation of the air void structure is generally the same by the same table type for the different methods.

The densities and the air content for the methods A, B and C are mutually the same. From this the conclusion can be drawn that the number of casting layers has no influence on the density and the air content. Neither has it any influence whether vibration is performed during casting of specimens (method C).

It is not very clear which influence the type of vibrating table has on the air void structure. The Skako table, however, especially at 100 Hz tends to deteriorate the air void structure more than the other vibrating tables.

The type of vibrating table is at the daily concrete control of very little importance for the density and the air content.

The 7 tests have shown that it is possible for concrete with a slump higher than 100 mm to obtain the same density in cylinders and press-ur-meters by vibrating on vibrating tables. The vibrating tables are set to an acceleration of 30 m/s^2 based on the study of literature. It is not possible to exclude that if the vibrating tables had been set to a higher acceleration, a correspondingly better compaction would have been obtained without destroying the air void structure.

For dry concrete with a slump below 30 mm the acceleration of 30 m/s^2 is not sufficient.

DS423.15, DS423.21 and the European standard (4848 and 6276) recommend to cast specimens with a poker.

It must be concluded from the tests that it is not expedient to vibrate a press-ur-meter container and cylinder with a poker. It is practically not possible to vibrate the concrete in the specimen the same way as in structures as the specimen mould is to small for the poker.

The poker therefore destroys the air void structure in the concrete. If vibration with a poker should be applied for casting of specimens, this requires that the dimensions of the specimen moulds are increased. However, this would not be expedient as it will not be possible to handle bigger specimens in laboratories and test machines.

DS423.15, DS423.21 and the European standard (4848 and 6276) recommend to compact specimens by tamping with a steel bar. The conclusion must be drawn that tamping with a steel bar can be applied for casting of specimens if the slump is bigger than 100 mm. However, it will not be possible to compare the air void structure with the cast concrete constructions as the concrete has been worked quite differently.

The method can be applied for concrete testing on building sites where no vibrating table is available. It would, however, not be expedient to perform the method in a laboratory.

The densities during the 7 tests have had a considerably small standard deviation and therefore it should be considered whether the air content of the concrete can be indirectly determined by the determination of the density.

The density at different air contents could be stated on the concrete form of BBB (enclosure 3) so that it is only necessary to carry out the density determination during control of concrete.

E.g. the densities could be stated in a table that shows the air content as well, as shown below:

Air content %	Density kg/m^3
0	2500
2	2450
4	2400
6	2350

If the requirement for the air content is 5% the corresponding density will be 2375 kg/m^3. This density could thus be the requirement for the air content in question.

12 Tiles

This sections differentiates between air bubbles in the fresh concrete, air bubbles in the surface of the hardened concrete (blow holes) and air voids in the inner concrete e.g. in tiles that are cut in two.

The casting of tiles is performed in order to determine how fast air bubbles move up along the mould side.

12.1 The Velocities of the Air Bubbles in Fresh Concrete

It is difficult to see and measure bubbles through a Plexiglas plate. Bubbles appear and disappear into the concrete so that the measuring time is short. When concrete has been filled into the mould, the transparent Plexiglas surface is like a mirror and it is difficult to see what happens and even more difficult to record the movements of the bubbles on a video. As it will appear from section 12.2 and 12.3 there is no characteristic difference in the number of air bubbles on the front and the rear of the tiles. Therefore it makes sense to observe the bubbles through a Plexiglas plate.

The video films of the movements of the air bubbles were processed by means of the computer program Win/TV. After approx. 15 seconds of vibrating a representative number of bubbles were selected. The size and velocity of altogether 225 bubbles from the 7 tests are measured. The measurements are performed on hard copies from the computer program as shown in figure 12.1-1. The movement is measured on the hard copy and the time is given by the video. Simultaneous measurements and hard copies are enclosed in enclosure 5.

The air bubbles are grouped into 3 sizes when counting as with the hardened concrete:

1. Bubbles between 2 and 5 mm
2. Bubbles between 5 and 10 mm
3. Bubbles bigger than 10 mm

Furthermore (before the Win/TV was available) the velocity of 79 bubbles from tests Nos. 1, 2 and 3 was measured at the time "60 minutes after mixing" by drawing from a television screen. These bubbles are not grouped as to size. The measurements are also enclosed in enclosure 5.

In test No. 2 the video recording was so bad that all the registrations of bubbles on the 4K vibrating table and the Skako table at the time "60 minutes after mixing" were not possible.

At test No. 3 the registration of bubbles on the 4K table at the time "60 minutes after mixing" was not possible due to bad video recording.

At test No. 5 the applied form oil, WEGANOL W-2 from NBK Rødekro, prevented bubbles on the glass plate. After demoulding and removal of the cement skin the number of air bubbles was, however, the same as by counting of the remaining tiles, cf. enclosure 7.

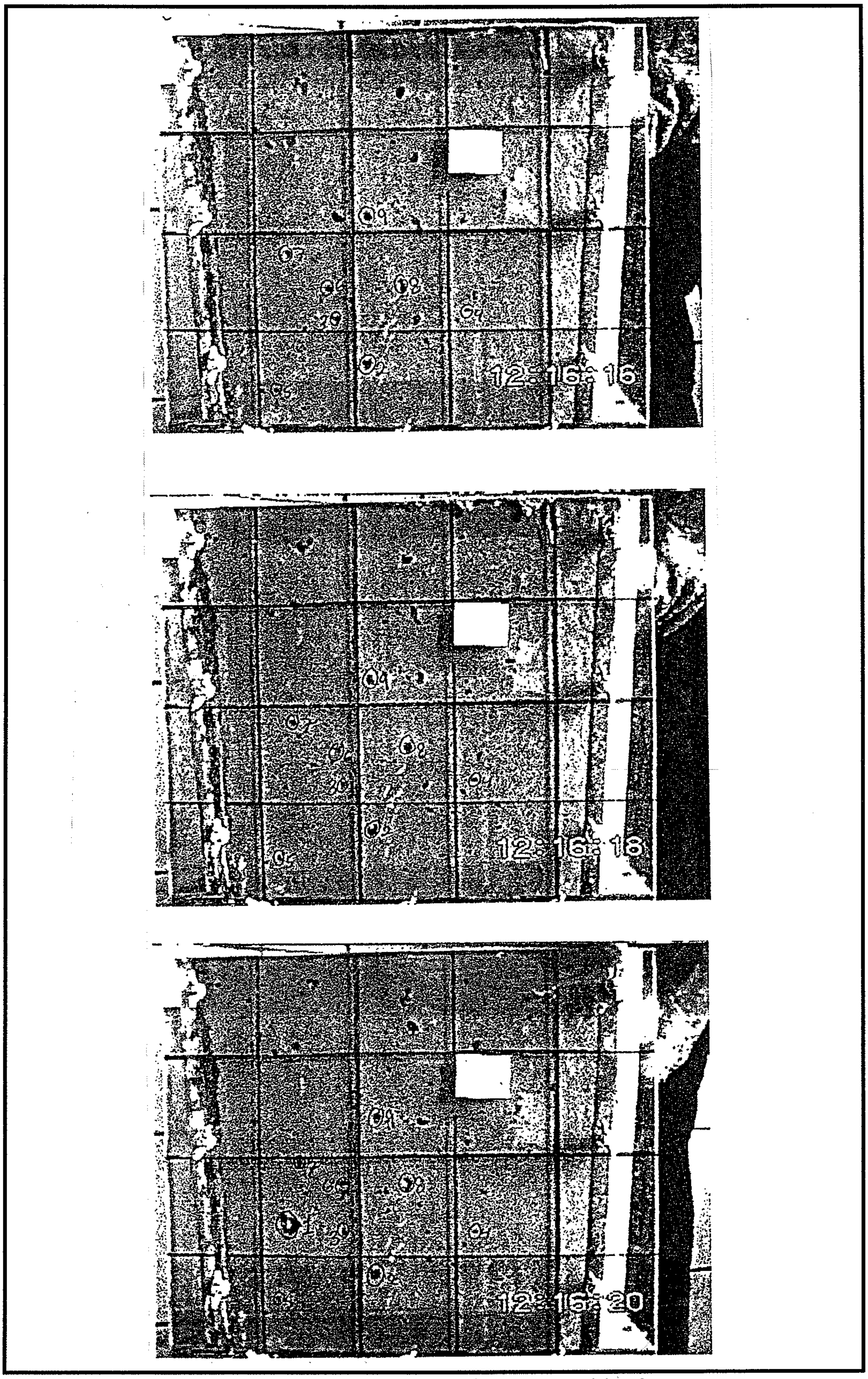

Figure 12.1-1: The movement of air bubbles along a mould side.

The distribution of the results have been examined graphically by plotting them in frequency analysis diagrams (normal distribution). The results are normally distributed if the distribution is rectilinear in the frequency analysis diagram and thus it makes sense to calculate the standard deviation.

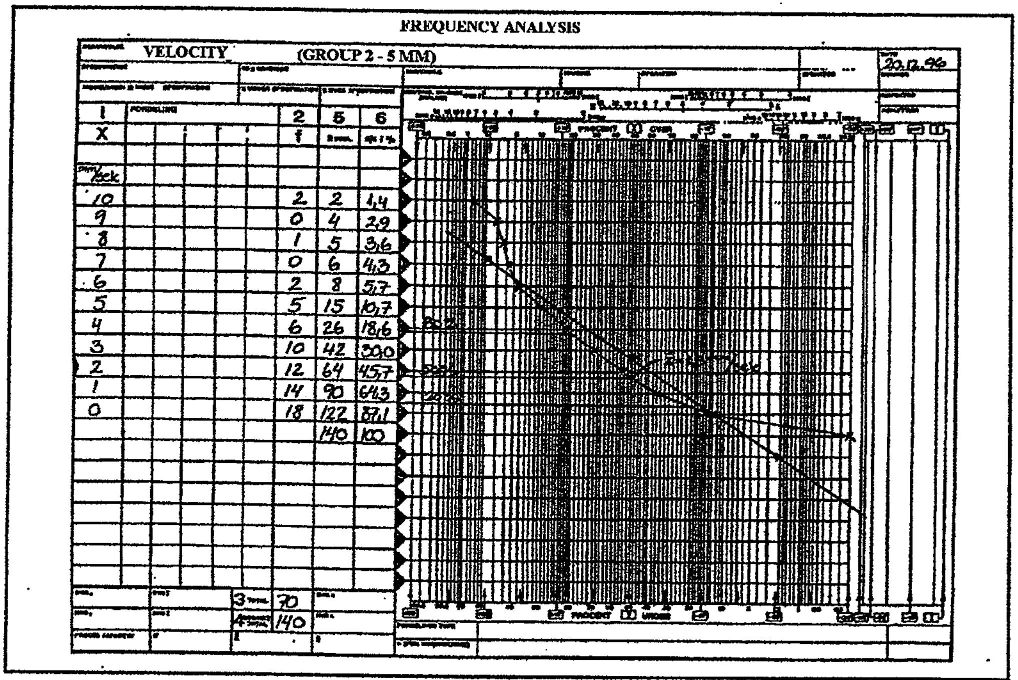

Figure 12.1-2: *Frequency analysis diagram for velocities of bubbles of the size 2 - 5 mm.*

The results for air bubbles of the size 2 - 5 mm (figure 12.1-2) are not rectilinear but considering the distribution between the 90% and 10% fractile alone, the normal distribution may be accepted to be valid.

The right line in the frequency analysis diagram goes through the calculated mean value for all vibrating tables. The calculated mean value and the standard deviation are shown in a table on page 75.

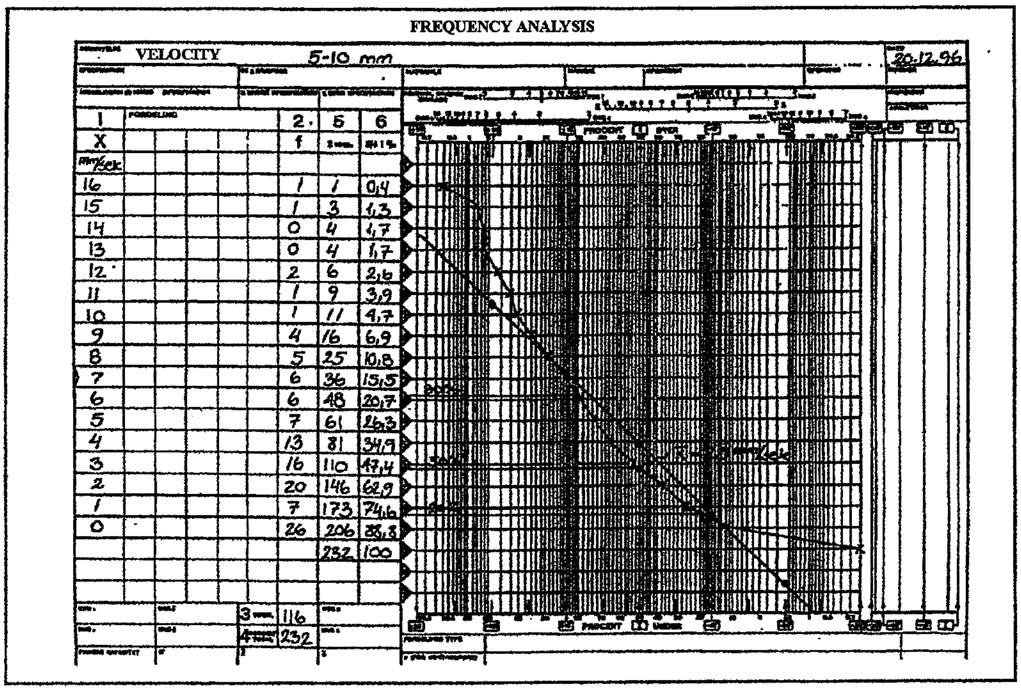

Figure 12.1-3: *Frequency analysis diagram for velocities of bubbles of the size 5 - 10 mm.*

As to air bubbles of the size 5 - 10 mm the results may reasonably be supposed to be normally distributed between the 95% and 20% fractile (figure12.1-3).

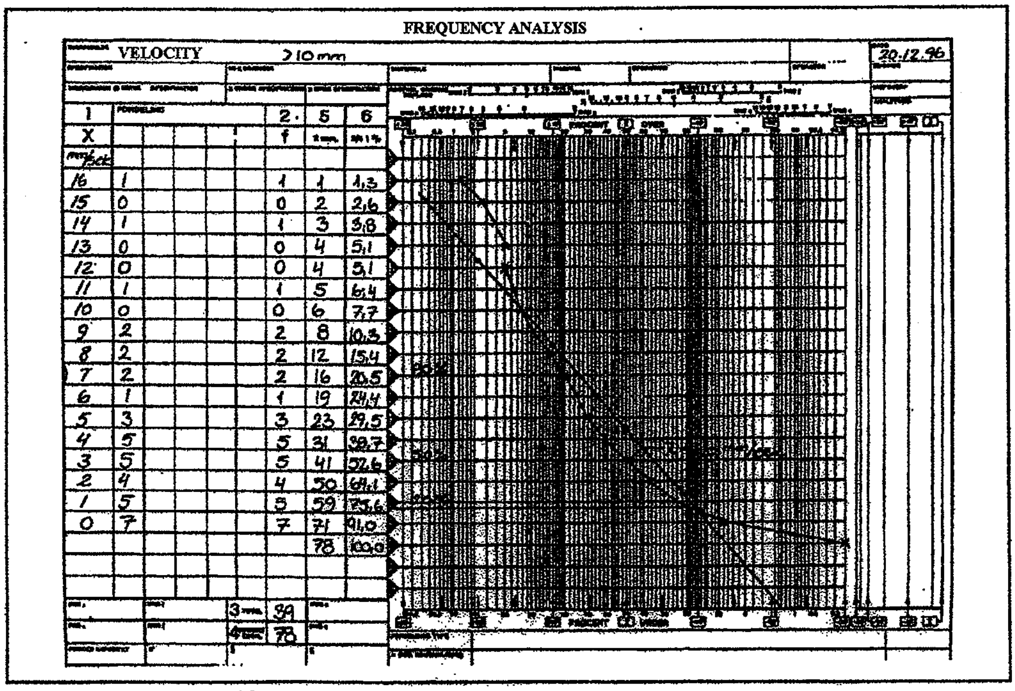

Figure 12.1-4: Frequency diagram for the velocity of bubbles bigger than 10 mm.

The results for bubbles bigger than 10 mm (figure 12.1-4) are not rectilinear but considering the distribution between the 90% and 10% fractile alone, the normal distribution may reasonably be accepted to be valid.

The mean velocities are determined within each group for all tests.

In the table below the calculated mean velocities for bubbles on all vibrating tables are stated as well as standard deviations and variation coefficients. Furthermore the read mean values from the frequency analysis diagrams in figures 12.1-2, 12.1-3 and 12.1-4 are stated.

	Bubble size		
Calculated values	2 - 5 mm	5 - 10 mm	> 10 mm
Mean velocity for all vibrating tables (mm/sec)	2.6	3.9	4.5
Standard deviation (mm/sec)	2.3	3.3	3.9
Variation coefficient (%)	85	85	85
Read values from figure 12.1-2, 12.1-3, 12.1-4	2 - 5 mm	5 - 10 mm	> 10 mm
Mean velocity for all vibrating tables (mm/sec)	1.8	2.9	3

The standard deviations are generally very high as expected, as different concrete types with different slumps have been applied. The read mean velocities are lower than the calculated mean value.

The results for bubbles at the time "60 minutes after mixing" are, as shown in figure 12.1-5, rectilinear between the 95% and 20% fractile and therefore standard deviations have been calculated. The curve tends to be S-shaped meaning that it may be combined of two normal distributions.

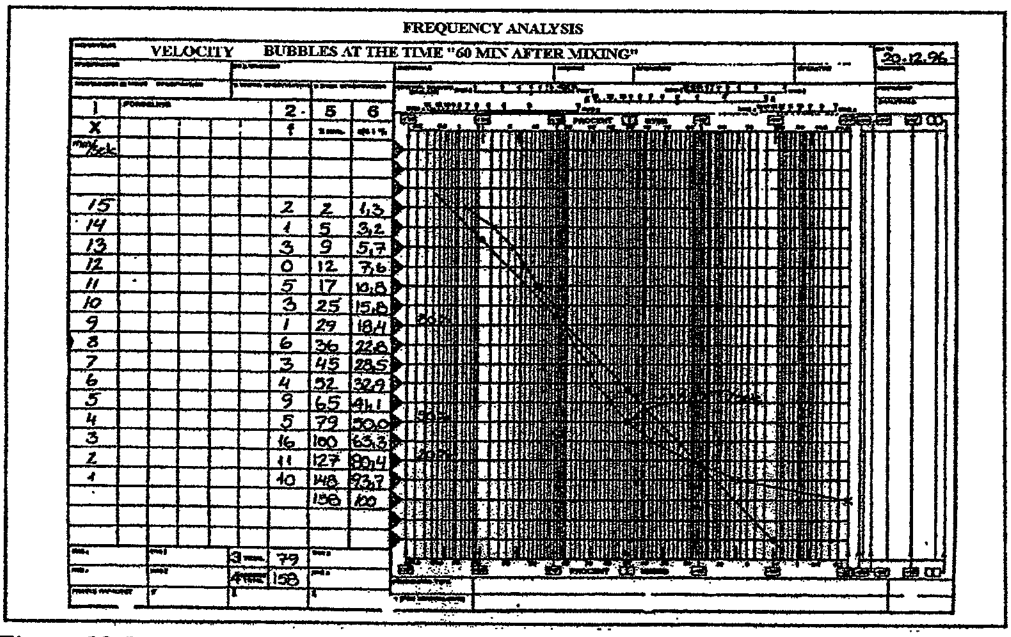

Figure 12.1-5: Frequency analysis diagram for velocities of bubbles at the time "60 minutes after mixing".

In the table below the calculated mean velocities for bubbles at the time "60 minutes after mixing" are stated as well as standard deviation and variation coefficient. Furthermore the read mean velocity from the frequency analysis diagram in figure 12.1-5 is stated.

Time "60 minutes after mixing", calculated values	
Mean velocity for all vibrating tables (mm/sec)	5.7
Standard deviation (mm/sec)	3.8
Variation coefficient (%)	67
Read value	
Mean value for all vibrating tables (mm/sec)	4

The distribution of the results from tests Nos. 1, 2 and 3 at the time "60 minutes after mixing" is approx. 10% lower than the distribution of the other tests. This might be due to the fact that all bubbles were drawn recorded from a television screen during the whole process after approx. 15 seconds of vibration whereas during the other tests only a representative number of bubbles in a period of approx. 20 seconds was counted and measured.

The mean velocities for all counted bubbles are stated in enclosure 6.

In the frequency analysis diagrams (figure 12.1-2, 12.1-3 and 12.1-4) the distribution of the velocities is read for bubbles of the size 2 - 5 mm, 5 - 10 mm and bigger than 10 mm.

The values appear from the table below. E.g. 20% of the bubbles of the size 2 - 5 mm move at a velocity of less than 0.5 mm/sec. 50% of the bubbles of the same size move at a velocity of less than 1.8 mm/sec. and 80% are moving at a velocity of less than 3.8 mm/sec.

	Bubble size		
	2 - 5 mm	5 - 10 mm	> 10 mm
20%	0.5 mm/sec	0.7 mm/sec	0.8 mm/sec
50%	1.8 mm/sec	2.9 mm/sec	3.0 mm/sec
80%	3.8 mm/sec	6.1 mm/sec	7.0 mm/sec

In the frequency analysis diagram figure 12.1-5) the distribution of the velocities is read for air bubbles at the time "60 minutes after mixing". 20% of the bubbles move at a velocity of less than 2 mm/sec. 50% of the bubbles move at a velocity less than 4 mm/sec and 80% move at a velocity of less than 9 mm/sec.

In figure 12.1-6 the mean velocities for the 3 different groups of bubbles from the 3 vibrating tables and the poker are plotted as a function of the slump.

From the figure it is not possible to decide which size of bubbles move at the largest velocity as the mean velocities are rather spread. Especially as to the 4K vibrating table and the poker. Generally, the values for bubbles between 2 and 5 mm lie lower than values for bubbles bigger than 5 mm. Besides, the velocity of all bubbles tends to increase the more flowable the concrete is.

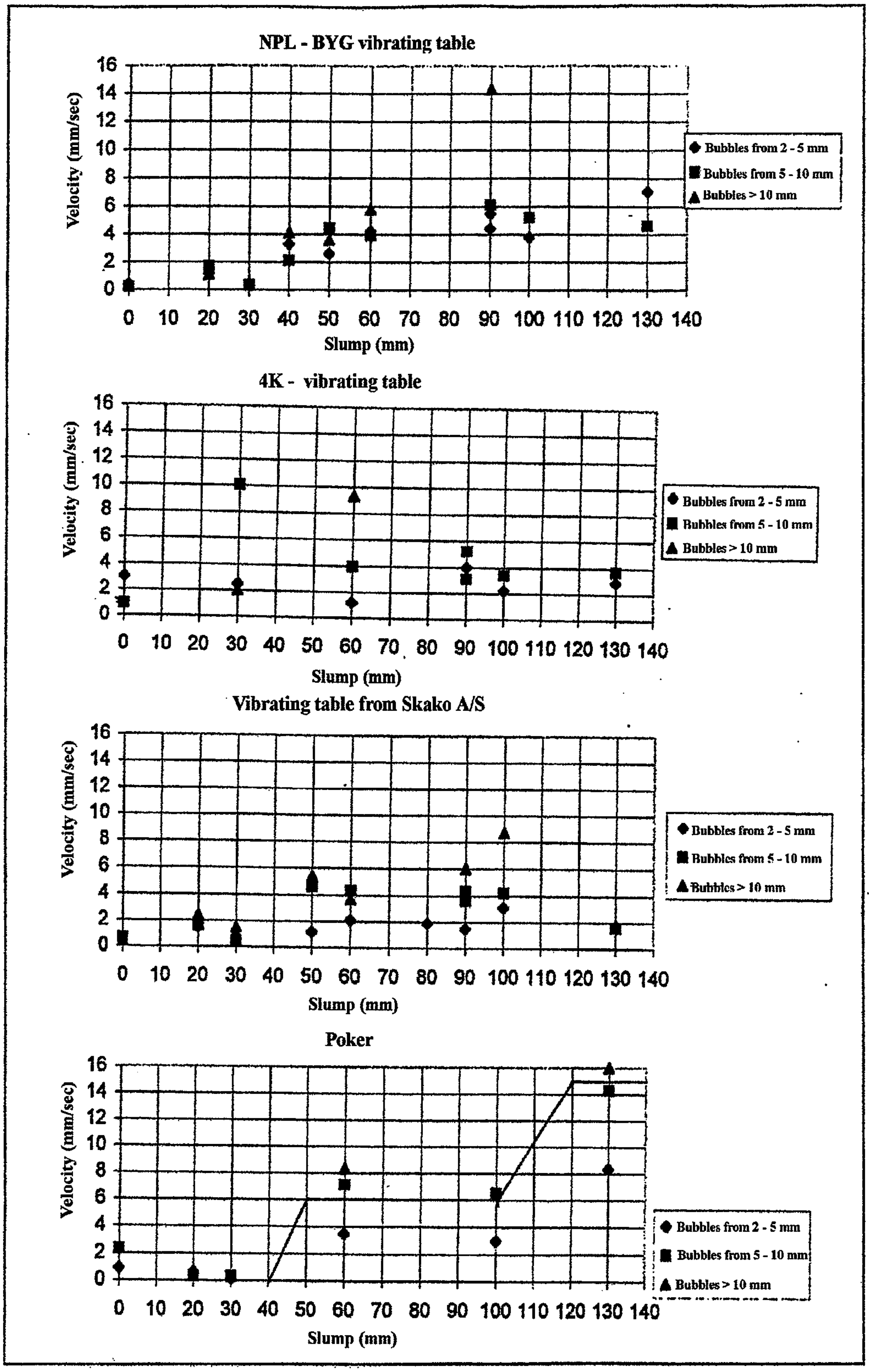

Figure 12.1-6: The mean velocities of air bubbles on different vibrating tables.

For concrete with a slump of less than or equal to 30 mm the velocities generally range from 0 - 3 mm/sec. Most bubbles have a velocity of 0 - 1 mm/sec.

The velocity of bubbles in concrete with a slump higher than 30 mm generally ranges between 2 and 6 mm/sec.

The results from vibrating tables are not representative for practice and can not directly be compared to practice on building sites. E.g. when a wall is to be cast, a horizontal form vibrator that is fastened to the wall is applied or a poker is used. During the testing the tiles are vibrated vertically as they are vibrated on a vibrating table, c.f. figure 12.1-7.

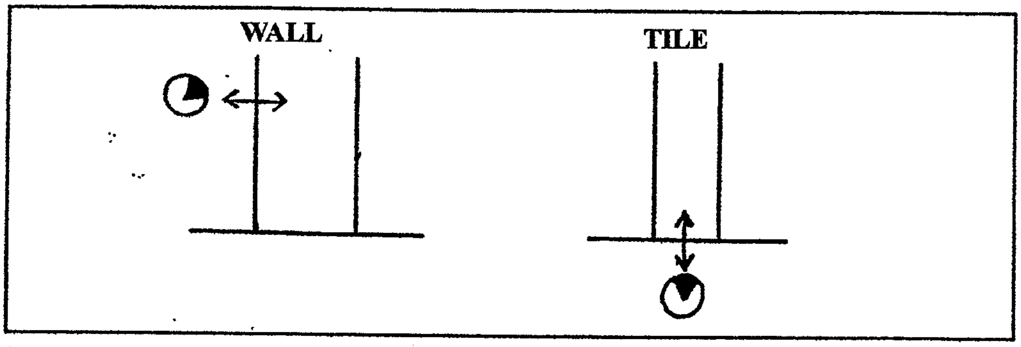

Figure 12.1-7: Horizontal and vertical vibration of a wall and a tile.

The results from the poker shown in figure 12.1-6 is the method that is closest to practical vibration of walls.

From the figure the following result for vibration with a poker is obtained for bubbles bigger than 5 mm:

Vibration with a poker	
Slump	Velocity of bubbles
0 - 40 mm	0 mm/sec
50 - 100 mm	6 mm/sec
> 120 mm	15 mm/sec

In the table below the distance moved by the bubbles is states as a function of the vibrating time and the velocity. An air bubble with the velocity 2 mm/sec, moves only 10 mm during a vibrating time of 5 seconds. Air bubbles with a velocity of 15 mm/sec (poker at a high slump), on the other hand, move 75 mm at 5 seconds of vibrating.

Vibrating time (sec)	The velocity of the air bubbles 2 mm/sec	4 mm/sec	6 mm/sec	8 mm/sec	15 mm/sec
5	10 mm	20 mm	30 mm	40 mm	75 mm
10	20 mm	40 mm	60 mm	80 mm	150 mm
15	30 mm	60 mm	90 mm	120 mm	225 mm
20	40 mm	80 mm	120 mm	160 mm	300 mm
25	50 mm	100 mm	150 mm	200 mm	375 mm
50	100 mm	200 mm	300 mm	400 mm	750 mm

Normal cast layers in walls are 300 mm thick. From the above table the conclusion can be drawn that the entrapped air cannot be driven completely out of the concrete by vibrating times of 5 - 25 seconds per layer.

During form vibration a longer vibrating time is applied than by vibration with a poker. A vibrating time of 25 - 50 seconds is the normal. If the velocity of bubbles bigger than 5 mm is valued to range between 4 and 6 mm/sec., they will move between 100 and 300 mm. This will give a 300 mm layer a surface partly free of bubbles. If the form vibrator is mounted so that it vibrates at right angles to the surface, which is normal practice (cf. figure 12.1-7), bubbles of the size over 5 mm can probably be avoided.

As to vibration with a poker, the vibrating times applied range from 5 to 25 seconds. [14]. If the velocity of the bubbles from figure 12.1-6 for bubbles bigger than 5 mm is valued to be 6 mm/sec for slump 50 - 100 mm, and to be 15 mm/sec for slumps bigger than 120 mm, the following result is reached:

Slump	Distance covered by vibration for 20 seconds.
50 - 100 mm	120 mm
> 120 mm	300 mm

It seems possible to obtain a surface in a 300 mm layer without bubbles bigger than 5 mm if a concrete with a slump bigger than 120 mm is applied, and if vibration is performed for approx. 20 seconds with a poker. At a lower vibrating time than 20 seconds, which is often preferred to secure the air void structure (resistance to frost), or at a stiffer concrete than slump 120 mm, air bubbles in the surface may be expected.

12.2 Air Bubbles in the Hardened Concrete

All tiles were hardened for a minimum of 5 days before the air bubbles at the front and the rear were counted, except from the tiles from tests Nos. 3 and 4, which were counted 2-3 days after casting.

On the tiles from test No. 5 (tiles Nos. 35, 36, 37 and 38) no air bubbles could be seen in the surface after demoulding and before the removal of the cement skin. This is as mentioned in section 12.1 due to the applied form oil, WEGANOL. After demoulding and removal of the cement skin, the number of air bubbles was, however, the same size as when counting the remaining tiles.

During counting of air bubbles in the surface of the tiles, the air bubbles were grouped as to size as during measuring of velocities.

In the table below the total number of air bubbles at the front and the rear is stated.

Bubble size	Front(numbers)	Rear(numbers)
2 - 5 mm	4020	4376
5 - 10 mm	1059	1209
> 10 mm	324	349

As it appears from the table, there is no remarkable difference in the number of air bubbles at the front and the rear.

The air content was after the counting determined out from the average area within the 3 groups. The calculation of the air content is described further in section 8.4.

The number of air bubbles at the front and the rear and the calculated air content can be found in enclosure 7.

During recording of the frequency analysis diagrams (normal distribution) the distribution of the air content has been examined graphically.

The results of the distribution as to the air content of the front and the rear are not rectilinear (cf. figure 12.2-1 and 12.2-2), but considering the distribution between the fractile 95% and 5% alone, the normal distribution can reasonably be accepted as valid.

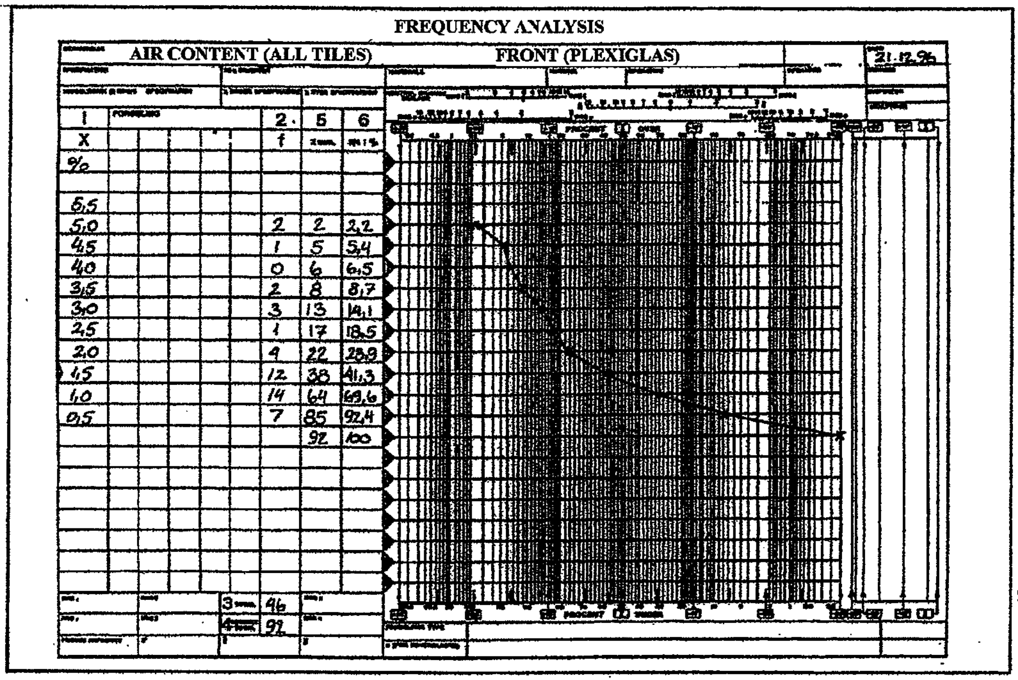

Figure 12.2-1: Frequency analysis diagram for air content at the front of the tiles.

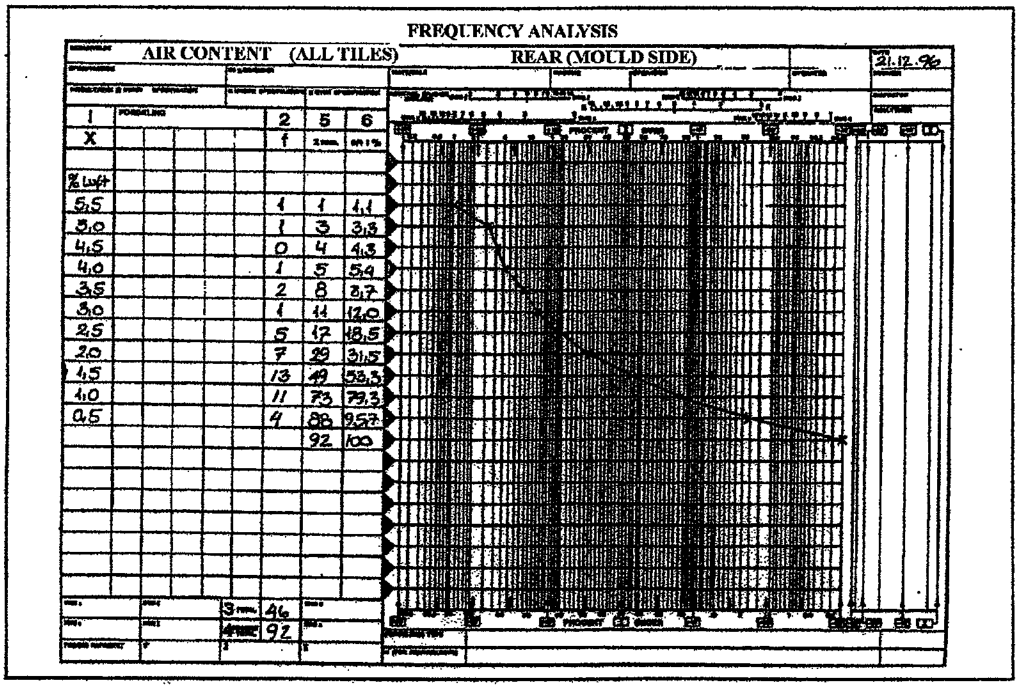

Figure 12.2-2: Frequency analysis diagram for air content at the rear of the tiles.

The average air content at the front and the rear and the number of air bubbles are stated in the table below. Furthermore the standard deviation and the variation coefficients are stated.

Air bubbles in the surface	Aircontent (%)		2 - 5 mm (number)		5 - 10 mm (number)		> 10 mm (number)	
	F	R	F	R	F	R	F	R
Mean value	1.9	2	87	95	23	26	7	8
Standard deviation	1.1	1.1	21.7	30.7	12.3	13.4	6.9	5
Variation coefficient (%)	60	54	25	32	53	51	98	67

From the table the conclusion can be drawn that there is no difference in the number of air bubbles and the air content at the front and at the rear of the tiles.

The variation coefficients show a big distribution of the air content and the number of air bubbles on the surface. The big distribution of the results might be due to the fact that during the testing different concrete types with different slumps (0 - 130 mm) were applied.

Tiles cast with the very dry concrete from test No. 6 (target slump 30 mm; slump at casting of tiles not measurable) had many big and deep air bubbles in the surface, especially tile No. 39 vibrated on the NPL vibrating table (5.0 - 5.5% air). This means that the tiles have not been sufficiently compacted.

In the table below the air content is stated per tile and per m^2.

	Number of air bubbles	
Bubble size	Per tile	Per m^2
2 - 5 mm	95	633
5 - 10 mm	26	173
> 10 mm	8	53

Average area of tile = 0,375 x 0,400 m^2 = 0,15 m^2.

The General Specification of the Danish Road Directorate (AAB) prescribes that as a maximum there may be 5 air bubbles of the size 5 - 10 mm per m^2 and no air bubbles bigger than 10 mm. Air bubbles smaller than 5 mm can be accepted. [11]. This is not in correspondence with the results from the vibrated tiles. However, the results can not be used directly as a wall will never be vibrated in the same way as the tiles as mentioned in section 12.1 about the velocities of bubbles.

Nevertheless, the AAB is unrealistic and should be revised on this requirement.

12.3 Internal Air Bubbles in Tiles

Selected tiles were sent to Dansk Beton Teknik A/S where the content of entrapped air bigger than 2 mm was determined by cutting the tiles in two and counting the air voids on the inner surface in the same way as during the counting of air bubbles at the front and the rear of the hardened tiles and during measuring of velocities.

The following tiles were examined by Dansk Beton Teknik A/S:

- Tiles Nos. 4, 5, 6 and 10 from test No. 1
- Tiles Nos. 24, 25, 26 and 30 from test No. 3
- Tiles Nos. 31, 32, 33 and 34 from test No. 4.
- Tile No. 37 from test No. 5
- Tile No. 41 from test No. 6
- Tile No. 45 from test No. 7

The reports from Dansk Beton Teknik A/S can be found in enclosure 8.

The area percentage of the entrapped air in the tiles is compared with the area percentage of air bubbles at the front and the rear of the hardened tiles. This is illustrated in figure 12.3-1.

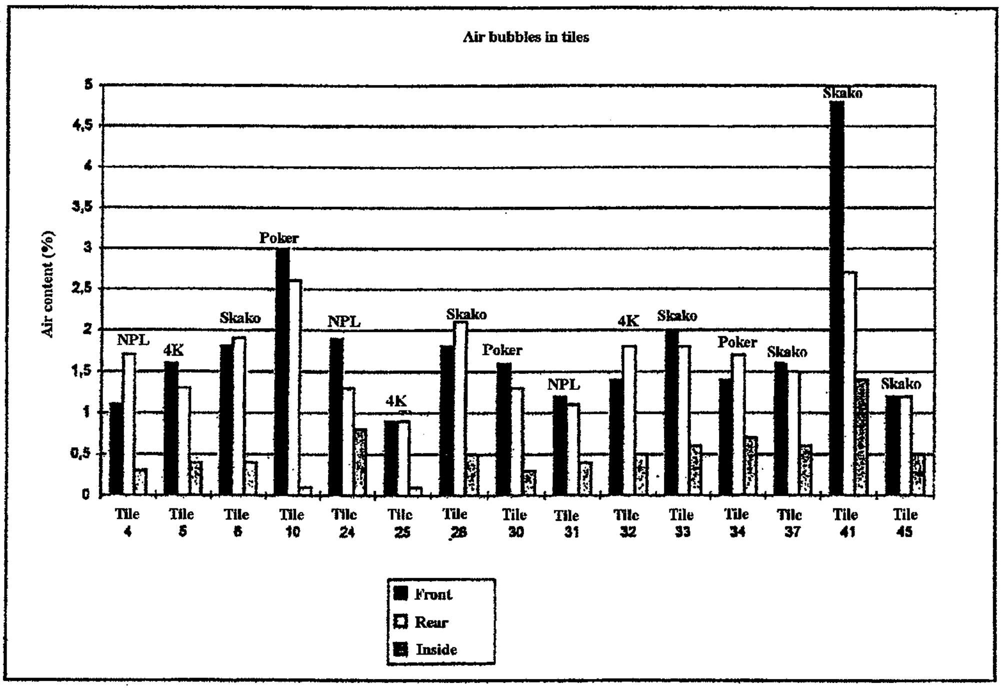

Figure 12.3-1: Air voids inside the tiles compared to air bubbles at the front and the rear. The front of the tiles is made of Plexiglas (acrylic).

The air content inside the tiles is, as it appears from the figure, much lower than the air content at the front and the rear. This illustrates that the concrete has been well compacted (or over-compacted) in the tiles but that the surfaces have not been optimum influenced by the vibrating table (vibration should not be parallel to the surface).

The high air content in tile No. 41 is due to the fact that during the testing a very dry concrete with a non measurable slump was applied.

On the assumptions that are usually applied at Dansk Beton Teknik A/S' the following result is achieved:

- Air content > 2% is an insufficiently compacted concrete
- Air content 1 - 2% is a reasonably compacted concrete
- Air content < 2% is a well vibrated/over-vibrated concrete. [26].

All the examined tiles have been over-vibrated except tiles Nos. 33 and 37 from tests Nos. 4 and 5 that have been well vibrated.

All the tiles have an equally distributed air content but generally the tiles tend to have a low stone content on the topmost 30 mm. In tiles Nos. 26 and 34 the concentration of entrapped air is higher than in the middle of the tile, whereas the highest concentration of entrapped air is to be found in the topmost part of tile No. 41.

In tile No. 31 from test No. 4 there are no stones on the topmost 40 mm which is a sign of over-vibration.

In tile No. 45 where a concrete with slump 130 mm was applied during casting of the tiles, the air bubbles have formed strings of pearls around the stones which might be a sign of bleeding.

Tile No. 10 and No. 30 that are vibrated with a poker both have a clear mark of where the poker has been as there are no stones in the middle of the tiles. The tiles are cast with concrete with a slump of 60 mm and 30 mm respectively. In tile No. 10 there is a slurry layer in the topmost 5 - 10 mm. Tile No. 34 is also vibrated with a poker. There are no stones in the topmost 50 mm. In the topmost 50 - 80 mm there is a low content of stones.

The registration of air bubbles on the tile surface was made to examine whether the formation of bubbles was different at the Plexiglas mould than at the usual mould side. The examination documents that the formation of bubbles is the same at the two surface but that it is dependant of the applied form oil. The method might be developed for use during testing of the suitability of the form oil.

Conclusion

The movement of air bubbles up along the mould side has been examined by casting a number of tiles standing upright. The casting of tiles documents that the formation of bubbles is the same at the Plexiglas mould (the front of the tile) and at the usual mould surface (the rear of the tile), but that it is dependant of the applied form oil.

The method might be developed for use during testing of the suitability of the form oil.

13 Workability Funnel

The workability funnel is valued by comparing the discharge time with the slump.
By the measurements an uncertainty of ±2 sec. as a result of the reaction time has been valued.
In order to compare the results the valuation of the results have been divided into the preliminary tests and tests Nos. 1 - 3, test No. 4 and tests Nos. 5 - 7.
After test No. 3 the form vibrator was moved to the funnel outlet.
Test No. 4 did not give any linear connection between the discharge time and the slump.
Tests Nos. 5 - 7 are performed with the same concrete.
The preliminary tests and the first 3 tests did not give any good relation between the discharge time and the slump, cf. figure 13.0-1.

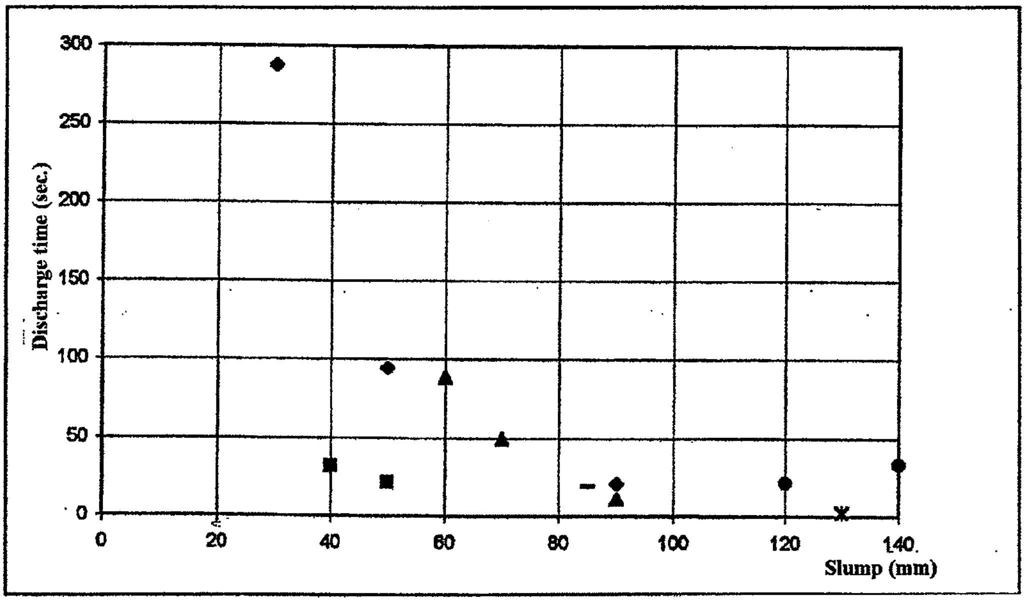

Figure 13.0-1: Discharge time as a function of the slump for tests Nos. 1 - 3.

This might be due to the fact that the vibrator that is welded on the funnel was placed in the middle and concrete with different d_{max} were applied.
However, the funnel should be developed so that it can be applied for all concrete types. The problem with the different d_{max} can be set right by developing a system where it is possible to mount outlets of different sizes.

Test No. 4, which did not give any linear connection between the discharge time and the slump, is illustrated in figure 13.0-2.

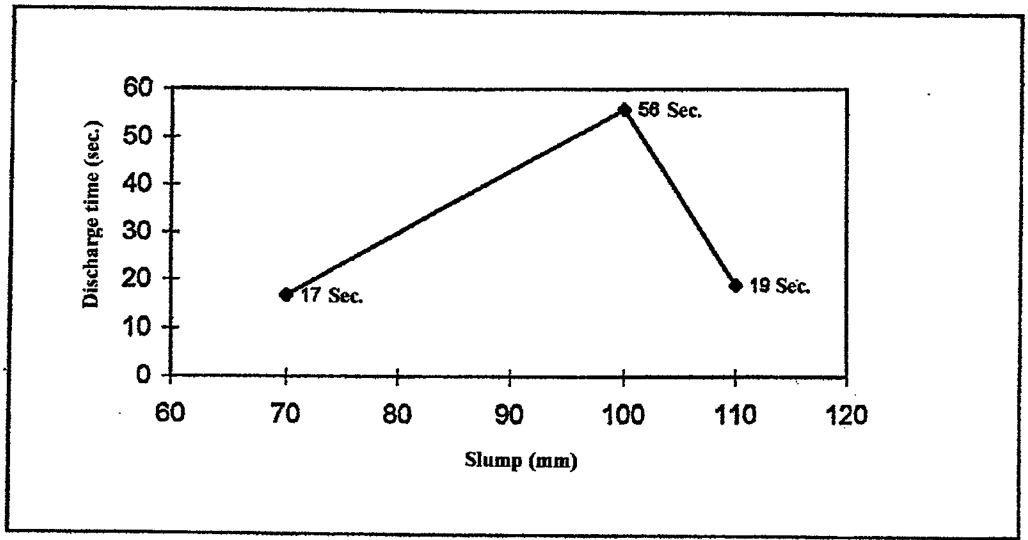

Figure 13.0-2: Discharge time as a function of the slump for test No. 4.

This may be due to the separation of the concrete at the high slump or an error may have occurred during measuring of the other outlet. The measurements were not double checked and therefore the results can not be verified.

Tests Nos. 5 - 7 have been performed with the same concrete (mix design 4361, d_{max} = 32 mm), with different slumps.

The illustration of the discharge time as a function of the slump is shown in figure 13.0-3. The exponential connection has been drawn in as well as the uncertainty of the measurements of the discharge time as a result of the reaction time.
The illustration gives an approximately exponential dependency with a correlation coefficient R=0.95.

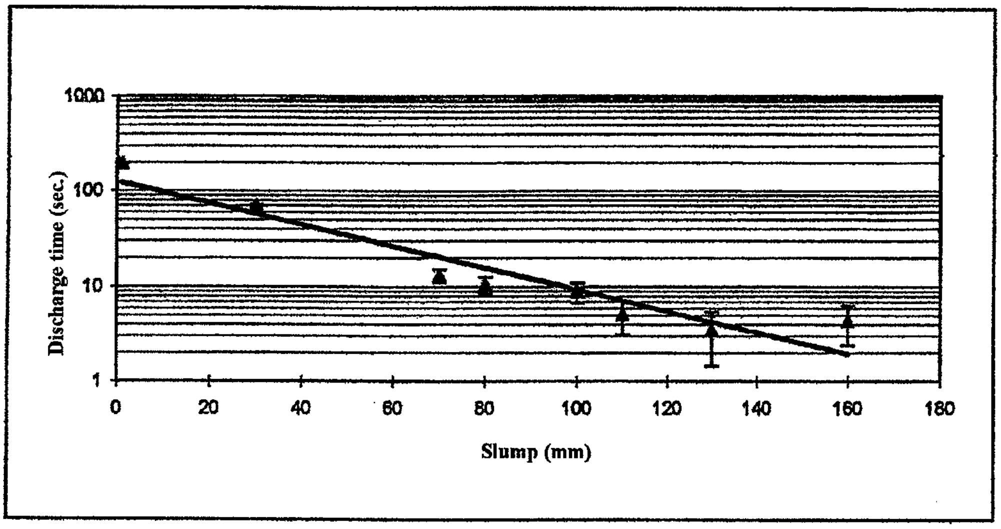

Figure 13.0-3: Discharge time as a function of the slump for tests Nos. 5 - 7.

Under the condition that the workability funnel is used only for concrete with a slump between 70 and 130 mm and for concrete with a d_{max} = 32 mm, the illustration of the discharge time as a function of the slump is a linear dependency of the correlation coefficient of R=0.98 as shown in figure 13.0-4. In the figure the uncertainty of the measurements of the discharge time as result of the reaction time is shown.

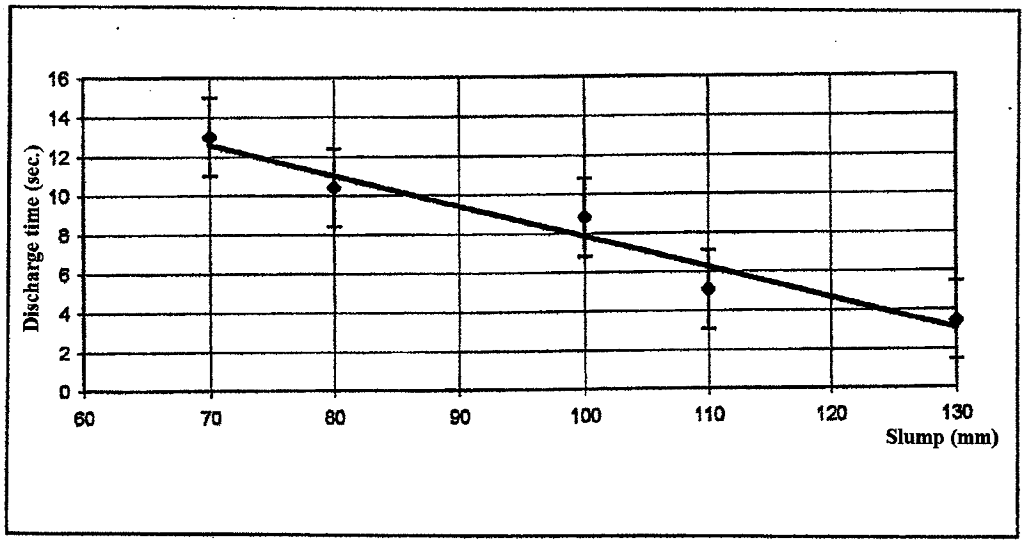

Figure 13.0-4: Discharge time as a function of slumps between 70 and 130 mm.

Conclusion

The workability funnel as a general measure of workability has not been examined thoroughly. The funnel that is examined in this report can be used as a measure of workability for concrete with a slump between 70 and 130 mm and for a concrete with a d_{max} = 32 mm.

The workability funnel might become a good measure of workability, but this requires that is developed so that the outlet of the funnel can be adjusted according to d_{max}. More tests should be made where among others the design of the funnel should be changed, i.e. the size of the funnel, the size and the design of the outlet, the inclination of the sides, treatment of the inside (formoil/water) and the size and the placement of the vibrator.

The discharge time should be compared with slumps or flow and other measures of workability such as two-point tests based on Bingham material, [2], as it is not a good idea to develop a new measure of workability if the measure does not describe the workability in a better way than the slump.

When a new measure of workability is to be introduced, it is important that it is developed expediently so that a good handling of the equipment is achieved for the daily use. If the new method is difficult to use, it will not be used in an optimum way.

One of the problems at present as to the workability funnel is that the emptying afterwards requires two persons to lift the funnel. This can be avoided by constructing a smaller funnel so that the discharge time becomes the time it takes to empty the funnel instead of the time it takes to fill a known volume.

14 Recommendation for Vibration of Specimens

Equipment

1) Vibrating table for compaction of concrete with slumps higher than 50 mm.

Frequency	Acceleration (m/s^2) (*1)		Swing width (mm) (*2)	
	Minimum	Maximum	Minimum	Maximum
50 Hz	20	50	0.4	1
100 Hz	20	50	0.1	0.2

(*1) The accelerations are as RMS. values, the corresponding maximum values are obtained by multiplying by 1.41.

(*2) The swing width is 2 × the amplitude.

Control of vibrating tables:

The safest way of controlling a vibrating table is by measuring the acceleration with an accelerometer. Sufficient control is achieved by measuring the swing width.

2) Steel bar of the length approx. 600 mm, diameter approx. 16 mm with rounded ends.

Procedure

The container is filled approx. 20% with concrete. The vibrating table is started. Hereafter the container is filled so that each shovelful is levelled before the next shovelful is placed.

The vibrating time is the time from when the vibrating table is started until the topmost layer is levelled. The vibrating time should not exceed the vibrating times in the table as over-vibration may cause separation of the concrete and loss of air voids.

Slump	Maximum vibrating time
150 mm	20 sec.
120 mm	30 sec.
90 mm	40 sec.
60 mm	50 sec.

If the slump is bigger than 100 mm, tamping with a steel bar can be applied for casting of concrete specimens.

The method of tamping is based on DS423.15 where:
The container is filled in three layers of approx. the same thickness which are worked with 25 impacts by the steel bar each. The impacts must be equally distributed over the surface of each layer.

The bottom layer is worked by impacting through the whole layer. The second and the topmost layer are worked so that the steel bar just penetrates into the underlying layer. The topmost layer is filled with a top before the working. If this results in a sinking of the concrete surface under the top side of the container, refilling without tamping is performed. The surface is levelled with a sawing movement with the steel bar.

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APPENDIX

APPENDIX A: Description of vibrating tables applied during testing

Building Site Table from NPL-Byg A/S

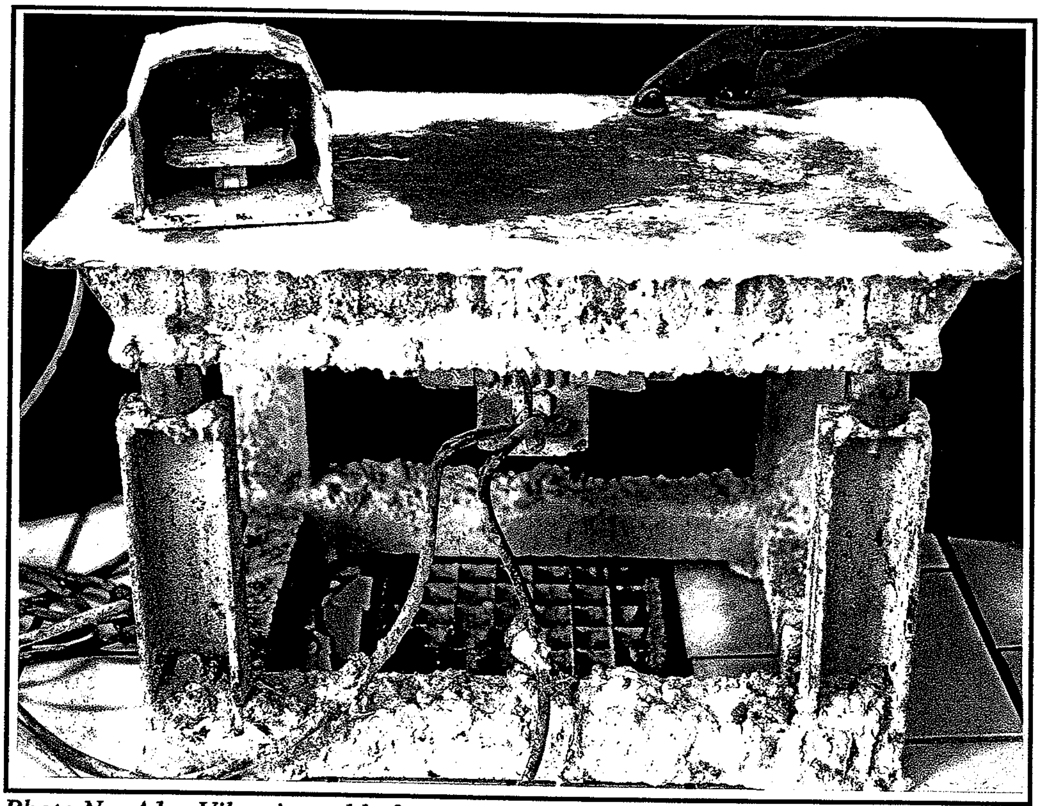


Photo No. A1: Vibrating table from NPL-Byg A/S, (f2, negative No. 26)

Description
Dimensions: 400x600 mm

The table is equipped with 1 vibrator that is constructed like a form vibrator, which is a vibrator that transfers the vibrations to the concrete through the mould material.

The form vibrator is an electric motor with eccentric masses mounted on an axis (cf. figure 4.1-1, section 4.1). The eccentric masses on this vibrator consist of 2 mm thick disks that can be locked on the axis in the same direction or at an angle of 120 degrees proportionally to each other. This makes it possible to make different adjustments of the centrifugal force.

1. By removing some of disks
2. By turning some of the disks

For this type of vibrator one can speak of harmonic oscillations. This is illustrated in photo No. A2 and A3 from an oscilloscope.

The impact force is not adjustable during vibration.

Measured values on vibrating table from NPL-Byg A/S										
Acceleration RMS. values(m/s^2)			Swing width (mm)			Frequency 1		Frequency 2		Annotations
side	centre	side	side	centre	side	(r/m)	(Hz)	(r/m)	(Hz)	
	30			1		3000	50	2800	50	No load
30	20	28	0.6	0.6	0.6	3000	50	2800	50	Load - 1 cyl.
20 - 30			0.4 - 0.6				50		50	Theory, figure 5.0-4, chapter 5.

The cylinder weighs approx. 25 kg.

It appears that the measurements are in good correspondence with the theory.

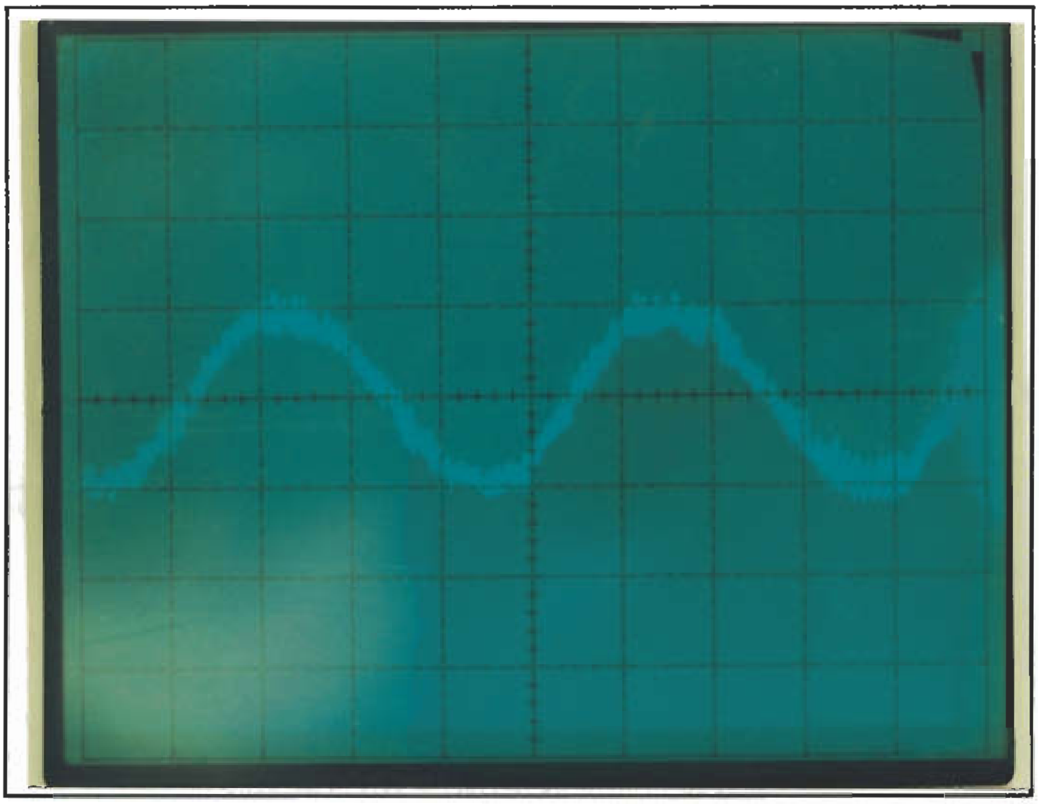


Photo No. A2: Frequency picture from oscilloscope, vibrating table loaded with 60 kg.(F2, negative No. 35).

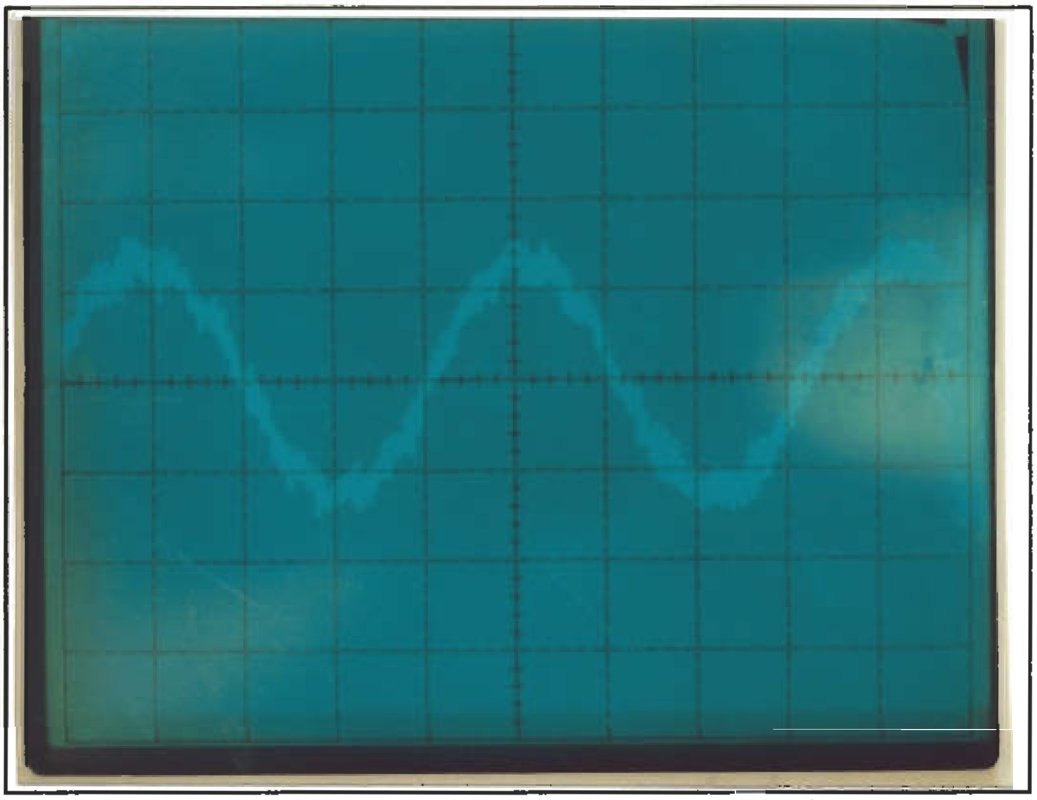


Photo No. A3: Frequency picture from oscilloscope, vibrating table without load. (F2, negative No. 33).

Stationary Vibrating Table from the Laboratory of 4K-BETON in Ejby

Photo No. A4: Stationary vibrating table from the laboratory of 4K-BETON in Ejby. (F2, negative No. 30).

Description

Dimensions: 360 mm x 900 mm

Type 50D, No. 50 67 07

Description: The vibrating table is equipped with an electromagnetic vibrator.

The impact force can be adjusted from 0 - 100% by turning a button. The impact force can be changed during vibration.

Vibrator type

The electromagnetic vibrator works that way that an armature, a foundation plate and trimming masses are bolted together and accelerated in a certain direction. This movement is transferred to the housing through the spring bolts. The spring system then accelerates the housing in the reversed direction. (cf. Figure 4.1-2, section 4.1).

This vibrator type works with a magnet as motive power.

The vibrations are not simple harmonic waves, cf. oscilloscope pictures, photos Nos. A5 and A6.

The frequency is constantly 50 Hz.

Lose materials, e.g. fresh concrete only works slightly attenuating on the swing width.

Measured values on a stationary vibrating table in the laboratory of 4K-BETON in Ejby									
Impact force (%)	Accelerations RMS. values(m/s²)		Swing width (mm)		Frequency 1 (r/m)		Frequency 2 (r/m)		Annotations
	centre	side	centre	side	centre	side	centre	side	
25	12	13	0.3	0.3	3000	3000	2800	2800	No load
40	24	24	0.6	0.6	3050	3050	2900	2900	
50	30	32	0.7	0.8	3050	3050	2900	2900	
60	34	36	0.8	0.8	3050	3050	3000	3000	
70	37	40	1.0	1.1	3050	3050	3000	3000	
80	42	45	1.1	1.3	3050	3050	3000	3000	
100	47	50	1.2	1.3	3050	3050	3000	3000	

Measured values on a stationary vibrating table in the laboratory of 4K-BETON in Ejby									
Impact force (%)	Accelerations RMS. values(m/s²)			Swing width (mm)			Frequency (r/m)		Annotations
	centre	side	cyl.	side	centre	cyl.	No. 1	No. 2	
25	12	11	11	0.4	0.3	0.4	3000	2900	Load:
40	24	21	22	0.7	0.7	0.7	3000	2900	1 cylinder
50	30	27	28	0.8	0.8	0.8	3000	2900	weight
60	35	32	34	0.9	0.9	0.9	3000	2900	approx
70	40	36	37	1	1	1	3000	2900	25 kg
80	42	40	42	1.2	1.1	1.1	3000	2900	
100	50	45	47	1.3	1.3	1.3	3000	2900	

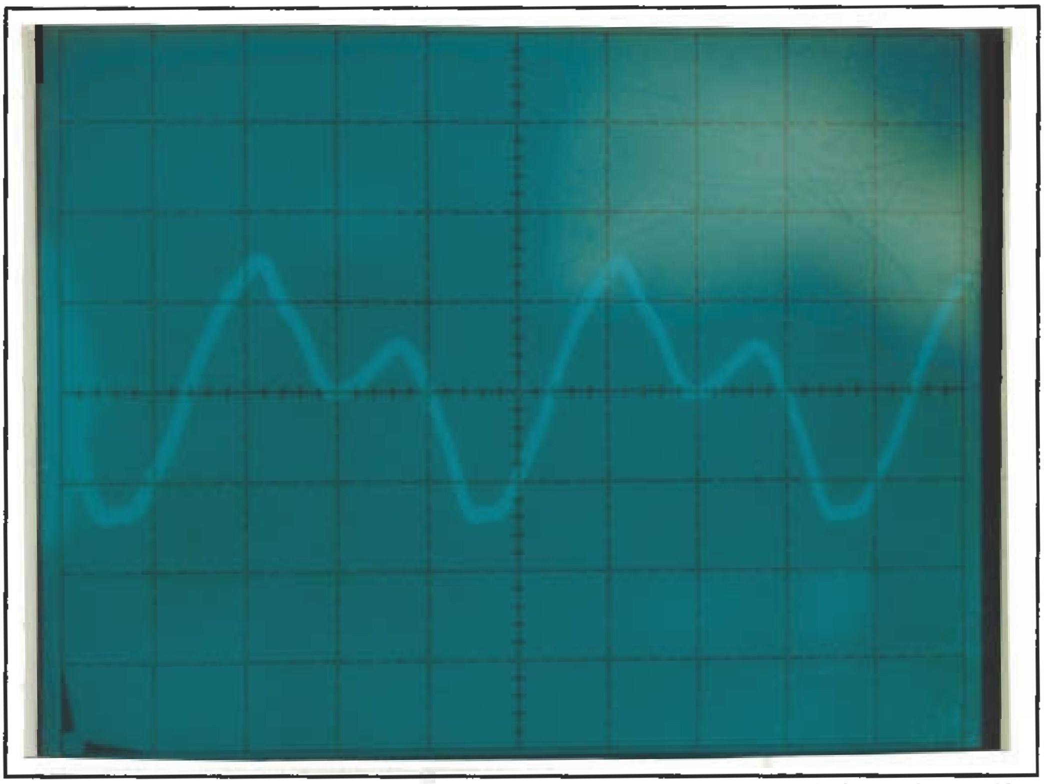


Photo No. A5: Frequency picture from oscilloscope, vibrating table loaded with 60 kg, 50% impact force, (F3, negative No. 6)

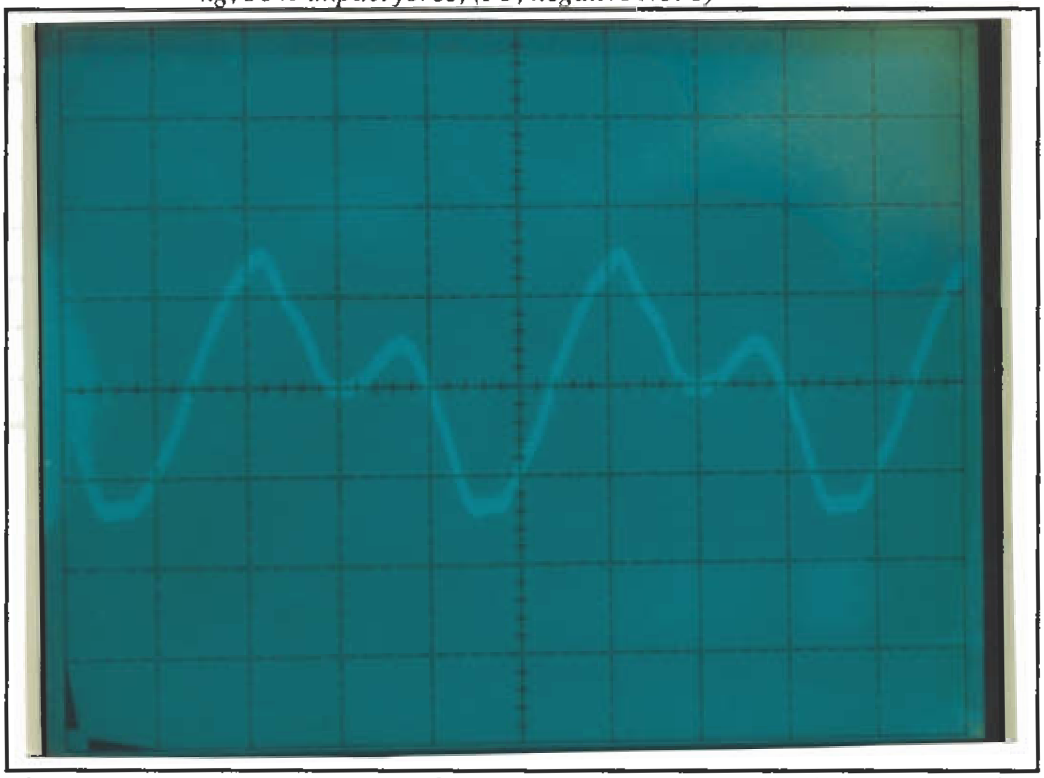


Photo No. A6: Frequency picture from oscilloscope, vibrating table, no load, 50% impact force (F3, negative No. 5)

Vibrating table from SKAKO A/S

Photo No. A7: Vibrating table from SKAKO A/S. (F2, negative No. 24)

Description
The vibrating table from SKAKO A/S is of the type TSU 40/050 and has the No. 360096 (52953) with table plate W x L = 400 x 500 mm, the height of the table is 370 mm.

The table is equipped with a vibrator that is constructed like a form vibrator (cf. description of vibrating table from NPL-Byg A/S). For this type of vibrator one can speak of harmonic oscillations. This is illustrated in photos Nos. 8 and 9 from an oscilloscope.

Specifications for the vibrator:

Type:	AR 44/9/042 - 120 kW
Force:	40 volt - 150 Hz
	14 ampere
	IP65

The vibrating table is controlled by an electronic frequency converter, built-in in a cabinet with a density degree of IP65. The frequency can be adjusted from 0 - 180 Hz.

It is possible to adjust the time of vibration on a clock from 0 - 15 minutes. The vibration can be controlled manually as well.

Measured values on vibrating table from SKAKO A/S				
Adjustment of masses on vibrator	Frequency (Hz)read	Acceleration RMS. values (m/s^2) centre	Swing width (mm) centre	Annotations
2.1 Centrifugal force 2.65 kN	25.07	3.25	3.25	Loaded with 85 kg
	50.35	6.7	0.2	
	75.02	12	0.2	
	100.5	26	0.2	
	124.9	32	0.2	
	150	47	0.2	
	180	70	0.2	

Measured values on vibrating table from SKAKO A/S				
Adjustment of masses on vibrator	Frequency (Hz)read	Acceleration RMS. values (m/s^2) centre	Swing width (mm) centre	Annotations
2.1 Centrifugal force 2.65 kN	25.07	3.25	0.4	No load
	50.35	10	0.2	
	75.02	15	0.2	
	100.5	27	0.2	
	125	35	0.2	
	150	50	0.2	
	180	70	0.2	

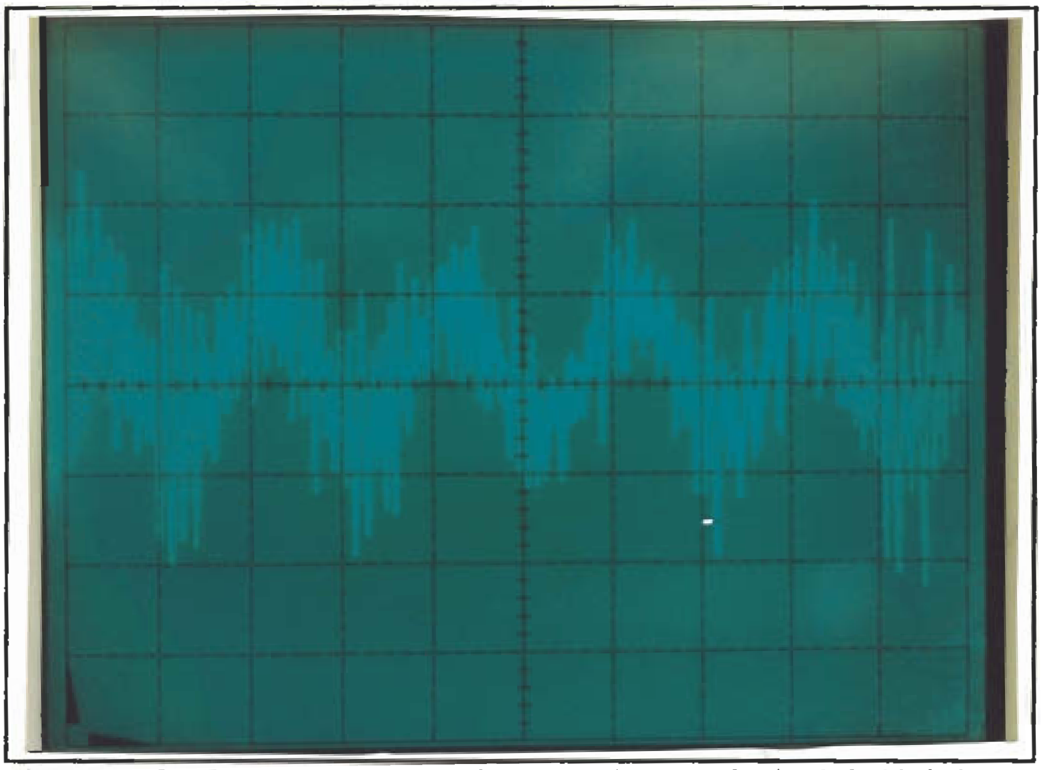


Photo No. A8: Frequency picture oscilloscope, vibrating table loaded with 60 kg. 100 Hz. (F3, negative No. 10)

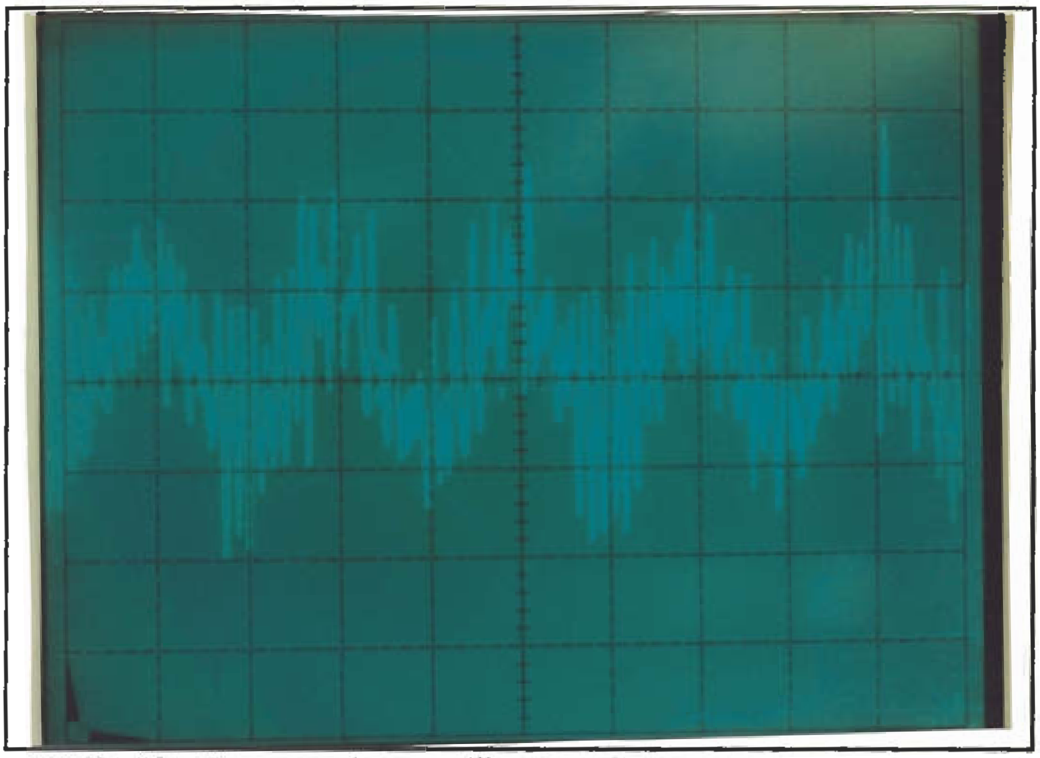


Photo No. A9: Frequency picture oscilloscope, vibrating table, no load, 100 Hz. (F3, negative No. 8)

Poker from 4K-BETON in Ejby

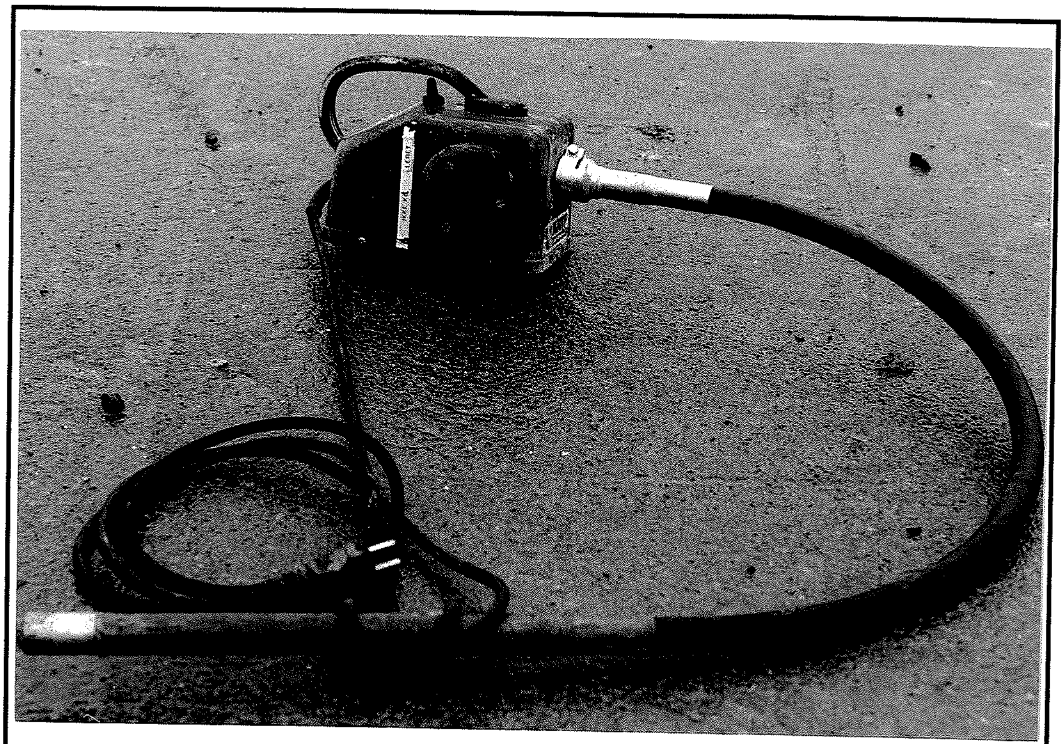


Photo No.A10: Poker from the laboratory of 4K-BETON in Ejby. (F2, negative No. 13).

Description

The poker is a minivip P14 from the Byggefagenes værktøj ApS.

The poker consists of an engine housing formed as a hand grip. The engine housing is connected to the vibrator head with a vibrator hose.

Specifications of the poker

Diameter	Weight	Frequency	Frequency r/m	Centrifugal force	Amplitude
28 mm	2.0 kg	200 Hz	12000	2500 N	0.8 mm

The poker should be connected to a power supply of 50 Hz

APPENDIX B: Test results from the tests Nos. 1 - 7

The test results are presented in tables.
The below table is model where the meaning of each column is explained.

Test No. and date of test

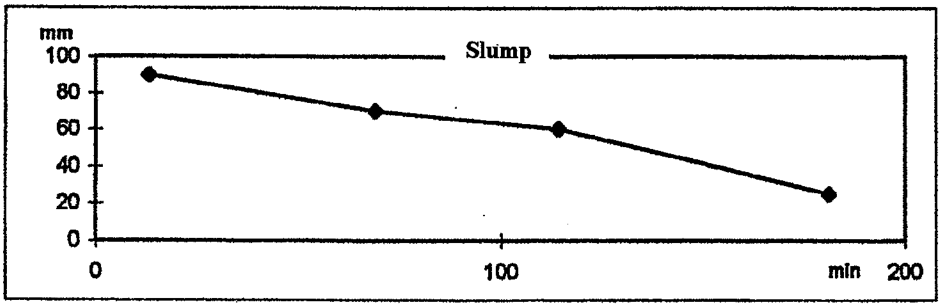
Mix design: 4K's description of goods
Concrete type: Description of the concrete
Mixing time: The time at which the concrete is mixed.

				Press-ur-meter						Cylinders			
Time (min)	Table No.	Concr. age min		Air (%)		Weight kg		Density kg/m³		Density kg/m³		DBT air total %	
		A	B	A	B	A	B	A	B	A	B	A	B
Divided into fixed period of times	Table type used during casting of specimens	Concrete age for casting of method A	Concrete age for casting of method B	Air content for method A	Air content for method B	Weight of press-ur-meter container used for method A	Weight of press-ur-meter container used for method B	Density measured with press-ur-meter container for method A	Density measured with press-ur-meter container for method B	Density measured on cylinder cast by method A	Density measured on cylinder cast by method B	Air content measured at air void analysis on cylinder from method A	Air content measured at air void analysis on cylinder from method B
Mean value+A2													
Standard deviation													
Variation coefficient (%)													

Test No. 1, Thursday, September 26th, 1996

Mix design: 2035
Concrete type: 4K Standard concrete A, slump 90 mm, d_{max} = 32 mm
Mixing time: 10.21

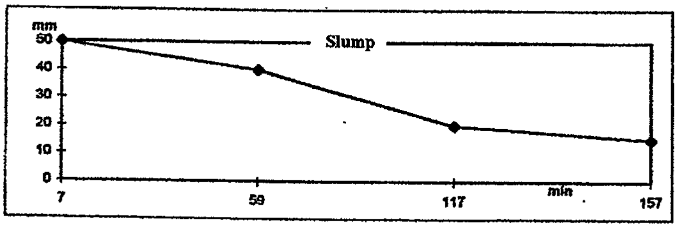
				Press-ur-meter						Cylinders			
Time (min)	Table No.	Concr. age min		Air (%)		Weight kg		Density kg/m³		Density kg/m³		DBT air total %	
		A	B	A	B	A	B	A	B	A	B	A	B
10	1. (NPL table)	9	9	6	6	18	19	2348	2365	2369	2369		
	2. (4K table)	23	29	6	6	18	19	2292	2336	2380	2397		
	3. (Skako A/S)	34	47	5.3	6	19	18	2383	2285	2359	2375		
Mean value				6	5.7	18.4	18.6	2341	2329	2369	2380		
Standard deviation				0	0	0.3	46	41	11	11	15		
Variation coefficient (%)				5	2	1.9	1.9	1.7	0.4	0.6	0.6		
60	1. (NPL table)	73	76	5.9	5.8	18.6	19.4	2365	2423	2372	2357	3	4
	2. (4K table)	84	84	7	6.0	18.1	18.8	2307	2344	2371	2360	4	4
	3. (Skako A/S)	94	104	5.4	6	19	18.8	2371	2350	2371	2351	4	4
Mean value				6	5.9	18.4	19	2348	2372	2371	2356	3.8	3.6
Standard deviation				0.6	0.1	0.28	0.35	35	44	1	5	0.4	0
Variation coefficient (%)				11	2	1.5	1.8	1.5	1.8	0	0.2	11	3
120	1. (NPL table)	122	129	5.3	5.1	18.6	18.7	2366	2334	2405	2399		
	2. (4K table)	134	144	5.3	5.1	18.6	18.9	2372	2364	2390	2403		
	3. (Skako A/S)	139	152	4.6	5.0	18.9	19.0	2409	2371	2388	2388		
Mean value				5	5.1	18.7	18.9	2383	2356	2394	2397		
Standard deviation				0.4	0.1	0.2	0.2	23.4	19.8	9	8		
Variation coefficient (%)				8.0	1.1	1.0	0.8	1.0	0.8	0.4	0.3		



Test No. 2, Tuesday, October 1st, 1996

Mix design: 1425
Concrete type: 4K Standard concrete Passive, slump 60 mm, d_{max} = 25 mm
Mixing time: 12.18

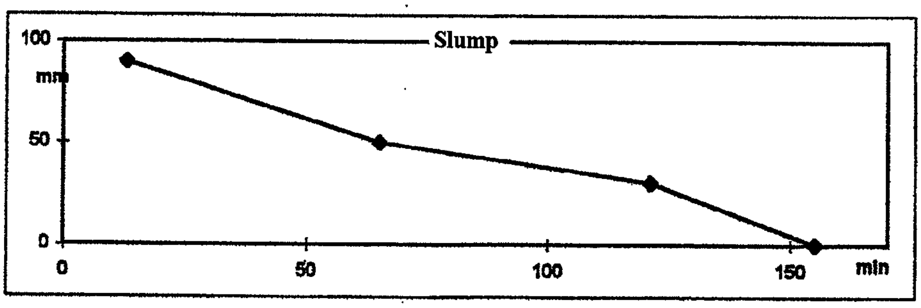
				Press-ur-meter						Cylinders					
Time (min)	Table No.	Concr. age min		Air (%)		Weight kg		Density kg/m³		Density kg/m³		DBT air total %	
		A	B	A	B	A	B	A	B	A	B	A	B
10	1. (NPL table)	13	23	2.5	1.6	18.1	18.6	2305	2318	2344	2333		
	2. (4K table)	22	14	1.4	1.4	18.4	18.8	2341	2351	2341	2344		
	3. (Skako A/S)	32	38	2.1	2.0	18.1	18.6	2310	2329	2331	2342		
Mean value				2	1.7	18,2	18.7	2318	2333	2339	2340		
Standard deviation				1	0	0.2	0.1	19	17	7	6		
Variation coefficient (%)				28	18	0.8	0.7	0.8	0.7	0.3	0.3		
60	1. (NPL table)	62	67	2.0	1.0	18	19	2315	2346	2350	2341	2	1
	2. (4K table)	74	78	1.2	1.0	18.3	18.8	2333	2346	2354	2344	1	2
	3. (Skako A/S)	84	86	1.7	1.8	18.2	18.7	2318	2330	2348	2348	2.5	3
Mean value				2	1.3	18.2	18.7	2322	2341	2351	2344	1.9	1.8
Standard deviation				0	0.5	0.1	0.1	10	9	3	4	0.7	0.6
Variation coefficient (%)				25	36	0.4	0.4	0.4	0.4	0.1	0.1	38	32
120	1. (NPL table)	119	125	2.1	1	18.3	18.8	2329	2344	2354	2352		
	2. (4K table)	132	135	1.6	1.2	18.3	18.7	2329	2334	2351	2336		
	3. (Skako A/S)	142	149	1.8	2.5	18	19	2335	2310	2329	2335		
Mean value				2	1.6	18.3	18.6	2331	2329	2345	2341		
Standard deviation				0	0.8	0.0	0.1	4	17	14	10		
Variation coefficient (%)				14	52	0.2	0.7	0.2	0.7	0.6	0.4		



Test No. 3 Tuesday, October 8th, 1996

Mix design: 6021
Concrete type: HETEK concrete, slump 120 mm, d_{max} = 32 mm
Mixing time: 10.12

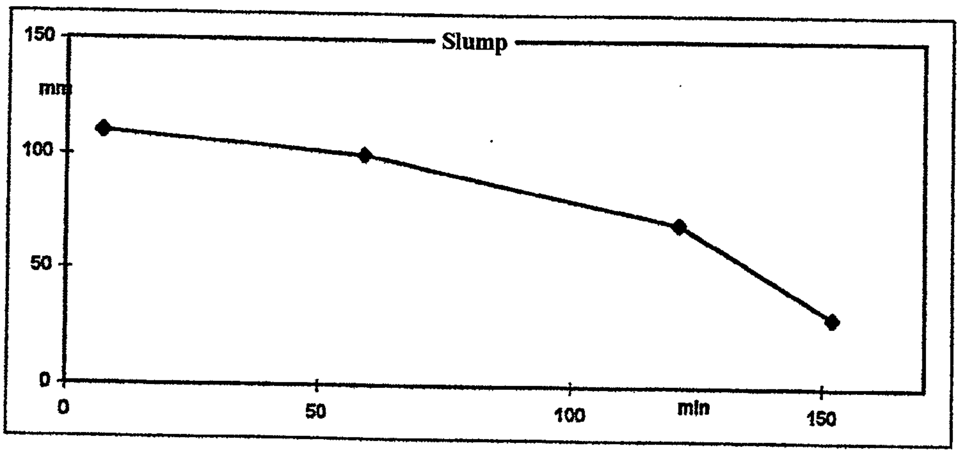
Time (min)	Table No.	Concr. age min		Press-ur-meter Air (%)		Weight kg		Density kg/m³		Cylinders Density kg/m³	
		A	B	A	B	A	B	A	B	A	B
10	1. (NPL table)	21	13	5.0	5.0	18.7	19.0	2375	2378	2393	2367
	2. (4K table)	28	33	5.4	4.7	18.7	19.0	2385	2375	2420	2350
	3. (Skako A/S)	38	43	5.6	5.3	18.4	18.9	2348	2358	2365	2386
Mean value				5.3	5.0	18.6	19.0	2369	2370	2393	2368
Standard deviation				0.3	0.3	0.1	0.1	19	11	28	18
Variation coefficient (%)				5.7	6.0	0.8	0.5	0.8	0.5	1.1	0.8
60	1. (NPL table)	67	73	4.8	4.2	17.8	19.0	2264	2378	2395	2384
	2. (4K table)	76	80	3.8	4.1	18.7	19.1	2381	2380	2399	2397
	3. (Skako A/S)	86	88	4.3	4.0	18.6	19.2	2372	2396	2388	2399
Mean value				4.3	4.1	18.4	19.1	2339	2385	2394	2393
Standard deviation				0.5	0.1	0.5	0.1	65	10	6	8
Variation coefficient (%)				11.6	2.4	2.8	0.4	2.8	0.4	0.2	0.3
120	1. (NPL table)	128	133	3.5	2.8	18.9	19.3	2408	2414	2416	2422
	2. (4K table)	138	140	3.1	3.2	18.9	19.2	2407	2401	2408	2408
	3. (Skako A/S)	148	153	2.8	2.9	18.6	19.3	2367	2415	2408	2427
Mean value				3.1	3.0	18.8	19.3	2394	2410	2411	2419
Standard deviation				0.4	0.2	0.2	0.1	23	8	5	10
Variation coefficient (%)				11.2	7.0	1.0	0.3	1.0	0.3	0.2	0.4



Test No. 4 Tuesday, October 22nd, 1996

Mix design: 2035
Concrete type: 2035, slump 120 mm, d_{max} = 25 mm
Mixing time: 10.28

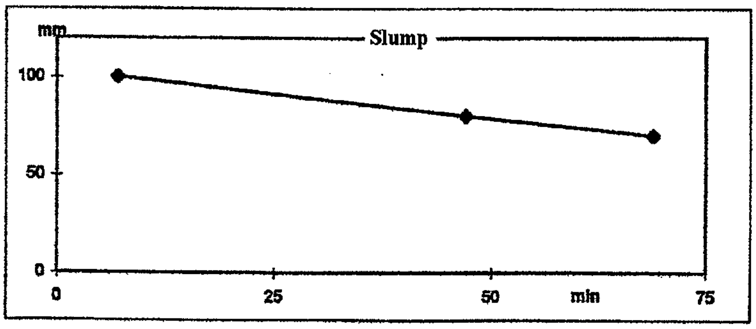
Time (min)	Table No.	Concr. A	Concr. C	Press-ur-meter Air A	Press-ur-meter Air C	Press-ur-meter C	Press-ur-meter Weight A	Press-ur-meter Weight C	Press-ur-meter Density A	Press-ur-meter Density C	Cylinders Density A	Cylinders Density C	Cylinders DBT A	Cylinders DBT C
10	1. (NPL table)	12	17	5.2	5.4	30	18.1	18.9	2298	2358	2341	2369		
	2. (4K table)	22	27	5.7	5.5	35	18.5	18.9	2349	2358	2382	2354		
	3. (Skako A/S)	29	32	5.7	5.2	50	18.5	19.0	2361	2370	2371	2384		
Mean value				5.5	5.4	38.3	18.3	18.9	2336	2362	2365	2369		
Standard deviation				0.3	0.2	10.4	0.3	0.1	33	7	21	15		
Variation coefficient (%)				5.2	2.8	27.2	1.4	0.3	1.4	0.3	0.9	0.6		
60	1. (NPL table)	67	67	7.4	7.6	35	18.0	18.4	2293	2293	2297	2307		
										2nd cylinder	2303	2297		
	2. (4K table)	77	79	7.5	7.8	45	18.1	18.4	2307	2293	2293	2301		
										2nd cylinder	2278	2293		
	3. (Skako A/S)	87	89	7.3	7.3	60	18.0	18.4	2292	2301	2303	2308	3	5.6
										2nd cylinder	2284	2295		
Mean value				7.4	7.6	46.7	18.0	18.4	2293	2295	2293	2300		
Standard deviation				0.1	0.3	12.6	0.1	0.0	11	3	10	6		
Variation coefficient (%)				1.4	3.3	27.0	0.4	0.2	0.5	0.2	0.4	0.3		
120	1. (NPL table)	127	127	6.0	6.4	40	18.2	18.6	2316	2323	2310	2314		
	2. (4K table)	142	134	5.8	5.9	60	18.4	18.7	2339	2336	2327	2346		
	3. (Skako A/S)	152	142	5.5	5.5	80	18.3	18.8	2328	2345	2346	2333		
Mean value				5.8	5.9	60.0	18.3	18.7	2328	2335	2328	2331		
Standard deviation				0.3	0.5	20.0	0.1	0.1	11	11	18	16		
Variation coefficient (%)				4.4	7.6	33.3	0.5	0.5	0.5	0.5	0.8	0.7		



Test No. 5 Tuesday, October 29th, 1996

Mix design: 4361
Concrete type: Pihl & Søn A/S, environment class AB
slump 80 mm, d_{max} = 32 mm
Mixing time: 10.21

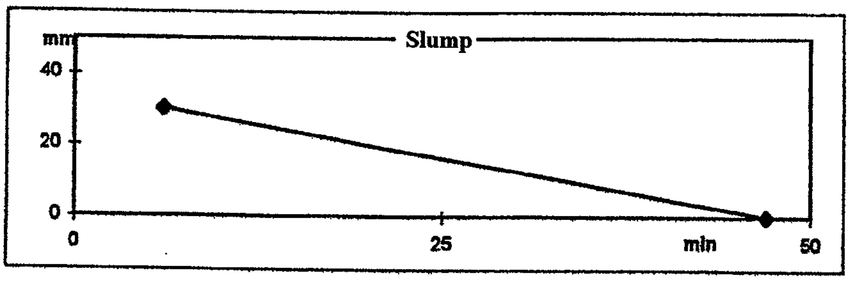
				Press-ur-meter			Cylinders	
Table	Method	Concr. age min	Vibrating time sec	Air %	Weight kg	Density kg/m³	Density before water-bath	DBT air content total %
Tamping with steel bar	3 layers 25 times	14		5	18.5	2358	2384	4.0
Poker	2 layers5 sec per layer	24		3.8	18.8	2395	2405	
	2 layers10 sec per layer	32					2399	2.5
	2 layers 25 sec per layer	34					2437	
Skako table 50 Hz	2 layers 10 sec per layer	14		5.5	18.9	2365	2350	
	2 layers 20 sec per layer	21					2373	
	2 layers 50 sec per layer	25					2374	4.0
Vibrating time on Skako table at 50 Hz	5 layers method C continuos vibration	19	Press 105 Cyl. 60	5.1	19	2370	2361	5.8
Skako table 100 Hz	2 layers 10 sec per layer	32		5.4	18.8	2353	2356	5.5
	2 layers 20 sec per layer	38					2369	5.4
	2 layers 50 sec per layer	39					2386	3
Vibrating time on Skako table at 100 Hz	5 layers method C continuos vibration	36	Press 40 Cyl. 40	4.7	19	2378	2373	4.2
Mean value				4.9		2370	2381	4.3
Standard deviation				0.6		15	24	1.2
Variation coefficient %				13		0.6	1	28



Test No. 6 Tuesday, November 5th, 1996

Mix design: 4361
Concrete type: Pihl & Søn A/S, environment class AB
slump 61 mm, d_{max} = 32 mm
(target slump 30 mm)
Mixing time: 12.28

Table	Method	Concr. age min	Vibrating time sec	Press-ur-meter: Air %	Press-ur-meter: Weight kg	Press-ur-meter: Density kg/m³	Cylinders: Density before water-bath	Cylinders: DBT air content total %
Tamping with steel bar	3 layers 25 times	12		4.8	18.7	2385	2386	3.3
Poker	2 layers 5 sec per layer	27		3.1	19	2413	2418	
	2 layers 10 sec per layer	35					2435	2.8
	2 layers 25 sec per layer	37					2459	
Skako table 50 Hz	2 layers 10 sec per layer	12		4.3	19.1	2391	2299	
	2 layers 20 sec per layer	17					2301	
	2 layers 50 sec per layer	26					2116**	
Vibrating time on Skako table at 50 Hz	5 layers method C continuos vibration	22	P: 120 Cyl. 180	3.7	19.3	2411	2361	
Skako table 100 Hz	2 layers 10 sec per layer	35	3.7	19	2411	2361	2399	3.9
	2 layers 20 sec per layer	42					2408	4.7
	2 layers 50 sec per layer	47					2408	2.9
Vibrating time on Skako table at 100 Hz	5 layers method C continuos vibration	44	P: 135 Cyl. 90	3.0	19.7	2456	2408	4.1
Mean value				3.7		2413	2389	3.6
Standard deviation				0.6		25	51	0.74
Variation coefficient %				17		1	2	21



Test No. 7 Tuesday, November 14th, 1996

Mix design: 4361
Concrete type: Pihl & Søn A/S, environment class AB
slump 150 mm, d_{max} = 32 mm
Mixing time: 11.42

Table	Method	Concr. age min	Vibrating time sec	Press-ur-meter Air %	Press-ur-meter Weight kg	Press-ur-meter Density kg/m³	Cylinders Density before water-bath	Cylinders DBT air content total %
Tamping with steel bar	3 layers 25 times	15		6.6	18.2	2314	2312	5.7
Poker	2 layers 5 sec per layer	20		6.2	18.4	2337	2388	
	2 layers 10 sec per layer	29					2376	2.1
	2 layers 25 sec per layer	32					2407	
Skako table 50 Hz	2 layers 10 sec per layer	13		7.3	18.4	2294	2297	
	2 layers 20 sec per layer	15					2282	
	2 layers 50 sec per layer	18					2310	6
Vibrating time on Skako table at 50 Hz	5 layers method C continuos vibration	20	Press 90 Cyl. 60	6.8	18.5	2314	2305	6.4
Skako table 100 Hz	2 layers 10 sec per layer	28		7.2	18.5	2313	2324	9.6
	2 layers 20 sec per layer	31					2314	5.4
	2 layers 50 sec per layer	33					2320	5.8
Vibrating time on Skako table at 100 Hz	5 layers method C continuos vibration	32	Press 45 Cyl. 30	6.6	18.6	2324	2320	6.6
Mean value				6.8		2316	2330	6
Standard deviation				0.5		14	39	2
Variation coefficient %				7.3		1	2	34