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Non-Destructive Condition Assessment of Concrete

Méthodes non-destructives d'évaluation de l'état du béton

Zerstörungsfreie Verfahren zur Zustandsbeurteilung von Beton

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SUMMARY
Under the auspices of the Swedish National Road Administration research on different non-destructive methods for condition assessment of concrete has been carried out comprising both laboratory and in situ tests on thermography, impulse radar, utrasonic testing, electropotential mapping and chloride content determination.

RESUME
La Direction Nationale des Routes de Suède a commandité des recherches portant sur différentes méthodes non destructives d'évaluation de l'état du béton. Les essais, en laboratoire et sur le terrain, ont fait appel à des techniques telles que la thermographie, le radar à impulsion, les tests ultrasoniques, les relevés potentiométriques et la détermination de la teneur en chlorure.

ZUSAMMENFASSUNG
Unter der Schirmherrschaft des Schwedisch Reichsamtes für Straßenwesen wurden ein Reihe von Forschungsprojekten im Hinblick auf zerstörungsfreie Verfahren zur Zustandsbeurteilung von Beton sowohl mit, Laborversuchen als auch entsprechenden Tests in situ, mit Thermographie, Impuls-Radar, Ultraschall, Elektropotential- Kartierung und Chloridgehalt-Bestimmung, durchgeführt.

1. BACKGROUND

Virtually all material is broken down with the passage of time, sooner or later, owing to the influence of the ambient environment or on account of wear, load etc. This is also true of concrete including reinforcement steel. Bearing structures of reinforced concrete therefore always have a limited service life, i.e. a time during which the bearing function of the structure is satisfactory. The service life can vary considerably, depending on design, material qualities, construction, protective treatment, environmental impact and loads. These matters are more comprehensively reviewed in [1].

Standards and other collections of codes include regulations in the respects that affect the structure as above. This knowledge, expression of which is given in the standards, is steadily increasing, and consequently structures designed and constructed in accordance with these standards acquire ever better durability. In many respects, however, our knowledge of resistance to environmental impact is fairly new and consequently older structures, even if they were perfectly made in accordance with the standards of their time, can be in very great need of maintenance and repair in order to "be kept alive".

As emphasized in the Swedish state-of-the-art report on operation and maintenance of bridges and other bearing structures [2], repair of concrete structures involves removing damaged concrete, and possibly also reinforcement bars, and replacing it with new material. Repairs of this nature involve three important tasks, namely:

- deciding which concrete is damaged and has to be removed

- removing damaged concrete with a suitable method, which leaves the remaining sound concrete and reinforcement undamaged and with a surface capable of bonding to the actual repair material

- supplying the repair material and possible new reinforcement in a manner giving a strong and lasting repair.

In the same way as stated in [3], criteria for removal of damaged concrete can be listed as follows. As a guideline the concrete must be removed if any of the following conditions are met:

- the concrete is found to be delaminated when sounding with a hammer or chain-drag

- the chloride ion content exceeds 0.3 per cent relative to the weight of the cement. To ensure the durability of the repair, every effort should be made to remove concrete containing more than 0.1 per cent chloride ions

- the concrete is not frost-resistant in pure water (this can be applied to a bridge deck slab from underneath through absorption of humidity, despite waterproofing on the upper side)

- the compressive strength upon testing of drilled-out cylinders is lower than is assumed in design, or the splitting strength is lower than seven per cent of the measured compressive strength

- microcracks are found on a chipped surface when it dries after-being blown clean and wetted

- the concrete is carbonated all the way into the reinforcement or so far that the residual service life is judged to be too short.

If the requirements of concrete removal listed above cannot be met, some other protective measure is necessary, such as the use of a proper coating or a cathodic protection system. Similar criteria as above are listed in [4]. These also include assessment and repair of structural effects on concrete of alkaline-silica reactions.

The criteria listed above can be looked upon as the basis for a proper condition assessment of concrete.

2. DESTRUCTIVE CONDITION ASSESSMENT OF CONCRETE

The methods used in inspection to assess the condition of a concrete structure may vary from simple visual inspection to sampling and measurement. This chapter is mainly concerned with various kinds of destructive methods.

The following investigations may enter the picture.

- Visual inspection of free and bared concrete surfaces.
- Carbonation check.
- Visual inspection of drilled-out specimens.
- Determination of chloride content.
- Determination of resistance to frost and salt.
- Strength testing.

2.1 <u>Visual inspection</u>

Visual inspection reveals obvious deterioration such as frost scaling, severe reinforcement corrosion, wide cracks etc. Hidden deterioration and that in course of development may also be revealed through colour changes, leaching of lime etc.

In the experience of the Swedish National Road Administration free or bared concrete can be more closely assessed by attacking it with a chisel and small sledge hammer, in which case the following conclusions may be drawn by observation of rupture surfaces:

- If both cement paste and aggregate appear as ruptural surfaces then the concrete is "sound" and the chloride content is probably less than about 0.1 per cent.

- If ruptural surfaces are formed between paste and aggregate the bond is poor, which may indicate that the chloride content is higher than 0.3 per cent. White sediments are also a sign of a high chloride content.

In addition to this, the inspector has to note the depth to which the concrete is deteriorated, if the reinforcement has started to rust etc.

2.2 Carbonation check

Carbonation should be looked for in the first instance on concrete surfaces that are exposed to air. The carbonation depth is easily examined by spraying an indicator fluid consisting of phenolphthalein dissolved in ethanol onto a dry, fresh ruptural surface through the concrete. This surface may either be a drilled-out core which has been split or a surface that has been produced in the concrete by chipping. If the pH is 9 or more, the concrete is coloured red, whereas uncoloured concrete is considered to be carbonated. When the carbonated area extends as far as the reinforcement this may begin to rust.

2.3 Drilled-out cores

Drilled-out cores can be examined in many ways. Visual inspection, keeping a watch-out for porosity, surface structure, delaminations, cracks, reinforcement, etc. should always be carried out as it affords an important complement to measurements and tests.

2.3.1 Chloride content

The chloride content is determined through chemical analysis of disks sawn from the drilled-out core. These are taken at different levels, enabling a chloride profile to be drawn. The chloride content commonly refers to the total content of free chloride ions in relation to the weight of the cement. A Swedish standard, SS 137235, is available for determination of chloride content. This is similar to British Standard BS 1881, Part 6.

2.3.2 Frost resistance

Frost resistance can be measured in various ways. A common method is for a disk sawn from a drilled-out core, moistened with or submersed in water or salt solution, to be exposed to repeated cycles of freezing and thawing. The loss in weight due to frost scaling as a function of the number of cycles is then a measure of the frost resistance. In order for different tests to be comparable a high level of standardization is essential with regard to salt content, pre-storage time, freezing velocity, duration of freezing cycles etc. See [5].

2.3.3 Strength

The strength can be determined by compressive or splitting tests (tensile strength) of drilled-out cores. International standards are available for both these tests, namely ISO 4012 and ISO 4108 respectively.

Rules for assessment of strength in a finished structure are given in [6]. The implication of these rules is that the compressive strength measured in the structure corresponds to roughly 0.8 times the cube strength in accordance with the standard test procedure. This matter has thoroughly been investigated. See, for example, [7] and [8].

In the experience of the Swedish National Road Administration the relation between splitting (tensile) and compression strength is an important indication of the condition of the concrete. The splitting strength thus appears to be reduced more quickly than the compression strength if the concrete has been deteriorated by frost and salt. A low splitting strength in relation to the compression strength can therefore be sign of deteriorated concrete, even if the compression strength is satisfactory.

2.3.4 Composition

In addition to the investigations mentioned above, the composition of the concrete and its other properties can be determined in detail on drilled-out cores by means of the thin section technique. This involves looking at a concrete section with a thickness of 0.02 mm made by sawing and gradual grinding down of an epoxy-impregnated concrete specimen. A fluorescent substance is added to the epoxy and by studying the sample in a microscope with fluorescent or polarized light information can be obtained on the following:

- cement type
- water cement ratio (W/C)
- mixing (varying W/C)
- air pore system (size, shape, distribution)
- recrystallization
- bond between cement paste and aggregate
- carbonation
- cracks (micro and macro)
- freezing (in the construction stage or later)
- concrete age
- shape of sand grains
- possible alkaline-silica or alkaline-carbonate reactions
- petrographic composition of aggregate.

3. NON-DESTRUCTIVE CONDITION ASSESSMENT OF CONCRETE

Beside indirect strength measurements, condition assessment of concrete by non-destructive methods such as determination of concrete cover and potential mapping is a very useful complement to the destructive assessment techniques dealt with in chapter 2. Under the auspices of the Swedish National Road Administration research on different non-destructive methods for condition assessment of concrete has been carried out in collaboration with the Royal Institute of Technology, the Swedish National Testing Institue, the Lund University of Technology and the Swedish Cement and Concrete Research Institute. Results gained from both laboratory and in situ tests on thermography, impulse radar, ultrasonic testing, electropotential mapping and chloride content determination are so far promising. When using each of these techniques in its proper context, detection of frost scaling, severe reinforcement corrosion, wide cracks, voids, laminations and evaluation of strength is possible.

3.1 Indirect strength determination

Indirect, more or less non-destructive methods can be used to determine strength. In this case compressive strength is not measured and attention is instead concentrated on tensile strength, modulus of elasticity, hardness or some other property which is assumed to have a certain relationship to the compressive strength. These relationships are never unambiguous and consequently the methods will be more or less unreliable in comparison with direct pressure testing of drilled-out cores. In this context it should nevertheless be remembered that the standardized testing of cubes is not particularly reliable either when it comes to the strength of the finished structure. According to [9], different testing methods can be ranked in the following manner in view of accuracy, the figure in brackets indicating the standard deviation in MPa:

1. Testing of drilled-out cylinders	(1.6)
2. Pull-out testing	(3.3)
3. Combined NDT measurement	(3.9)
4. Rebound hammer measurement	(4.5)
5. Testing of standardized cubes	(5.7)
6. Ultrasonic measurement	(8.0)

3.1.1 Pull-out testing

Pull-out testing according to [10] and [11] implies that a cone is pulled out of the concrete by means of an embedded (Lok-test) or subsequently drilled-in bolt (Capo-test), whereupon the pull-out force largely depends on the tensile and indirectly the compressive strength of the concrete.

3.1.2 Combined NDT measurement

Combined NDT measurement (Non-Destructive Testing), usually implies a combination of ultrasonic measurement and rebound hammer testing. See paragraphs 3.1.3 and 3.1.4 below.

3.1.3 Rebound hammer testing

Rebound hammer testing according to [12] involves measuring the rebound of a weight which is thrown against the concrete surface with a certain energy. The rebound is a measure of the surface hardness of the concrete. The results may, however, be difficult to interpret since the rebound value will be too high if the concrete is deeply carbonated or if aggregate close to the surface is struck. See [13].

When determining a relationship between the rebound value and the strength of the concrete in question calibration is essential, either against cast test cubes or against the structure at a point where cylinders are drilled out for compression testing. This method is described in Swedish standard SS 137250.

3.1.4 Ultrasonic testing

Ultrasonic testing involves measurement of the velocity of sound propagation in the concrete, which in turn depends on the modulus of elasticity. See [14] and [15]. In combination with rebound hammer testing according to [9] reasonable accuracy can be obtained. For estimates of the compressive strength on the basis of rebound value and sound velocity a Swedish standard, SS 137252, is available. Concerning detection of deteriorated concrete by ultrasonic testing, see sub-chapter 3.7 below.

3.1.5 Other methods

Other methods for indirect determination of strength exist, such as the American Windsor probe, and the Norwegian TNS method. See [16] and [17], respectively.

3.2 Concrete cover determination

Covering concrete layer can be determined in a non-destructive manner with the aid of electro-magnetic detectors of which several different kinds are available on the market. These devices are known as pachometers. For location of reinforcement bars a simple metal detector will often suffice.

The pachometers do not always give satisfactory results in rather heavily reinforced members, such as bridges, as the effect of deeper steel cannot be eliminated. According to [18] parallell bars also influence the meter reading if their spacing is less than two or three times the depth of cover .

3.3 Potential mapping

When steel corrodes in concrete, a potential difference exists between the anodic half-cell areas and the cathodic half-cell areas on the steel. The potential of the corrosion half-cells can be measured by comparison with a standard reference cell, which has a known, constant value. A copper-copper sulphate cell (CSE) is normally used in field work because it is rugged, inexpensive, and reliable. The potential difference between the steel reinforcement and the reference cell is compared by connecting the two through a high-impedance voltmeter.

This is done by connecting one lead of the voltmeter to the reinforcing steel. The other lead is connected to the reference cell, enabling electrode potentials to be measured at any desired location by moving the half-cell over the concrete surface in an orderly manner. The cell can be used vertically downwards, horizontally, or vertically upwards provided that the copper sulphate solution is in contact with the porous plug and the copper rod in the cell at all times.

A full description of the equipment and test procedures has been published by the American Society for Testing and Materials (ASTM C 876). The interpretation of the potential measurements has been as follows:

- less negative than -0.20 V (CSE): greater than 90 % probability of no corrosion
- between -0.20 and -0.35 V (CSE): corrosion activity is uncertain
- more negative than -0.35 V (CSE): greater than 90 % probability that corrosion is occurring.

Measurements in both the field and in the laboratory have indicated that corrosion can occur at a potential of about -0.2 V (CSE).

An alternative approach to interpreting the data is to examine the potential gradients on a structure. While criteria have not been established, it is generally agreed that differences in potential of more than 50 mV are significant and differences of 100 mV are indicative of active corrosion.

It should be recognized, especially when working on prestressed structures, that if surface measurements are made, it is the potential of the mild reinforcement which is measured. If the potential of pretensioning strand is required, wells must be drilled so that the half-cell can be placed in close proximity to the strand.

Potential measurements cannot be made through post-tensioning ducts. If the potential of posttensioning steel is to be measured, the duct must be opened and the cell placed on the grout adjacent to the post-tensioning steel.

Results obtained in Sweden from performed potential mapping of bridge piers in a marine environment show, according to [19], that there seems to be an almost straight-linear relationship between the measured chloride ion content and the half-cell potential observed. See Fig. 1. The conclusion may perhaps be that potential mapping can be used as a method to determine the chloride ion content in situ. See sub-chapter 3.4 below.

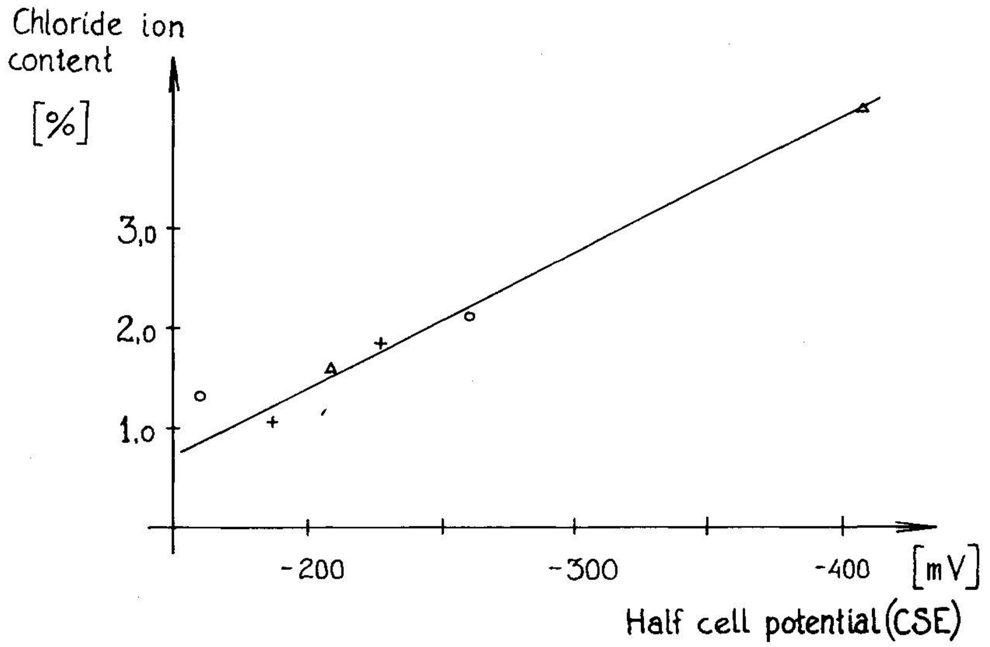


Fig.1 Observed half-cell potential as a function of the actual chloride ion content [19].

3.4 Chloride ion content tests

The chloride-ion content of concrete is usually measured in the laboratory using a wet chemical method of analysis. See paragraph 2.3.1 above. However, the method of sampling affects in situ operations. On behalf of the Swedish National Road Administration a literature survey has been done at the Swedish Cement and Concrete Research Institute [20]. This survey deals mainly with the possibilities of making chloride ion content determinations in situ. From this it can be concluded that there are two promising methods for this purpose. One is based on the concrete surface being sprayed with different salts, among them silver nitrate and potassium chromate. If there are no chloride ions present the brown silver chromate will be the result. The Danish "RCT Rapid Chloride Test" is based on this principle. The other promising method is based on a portable X-ray analyser for fluorescence measurements. Equipment named ASFX, developed on the basis of the latter technique mentioned, is now available in Sweden. The next research step of the Swedish National Road Administration will be to use both the RCT Rapid Chloride Test and the ASFX equipment in parallel for chloride content measurements in salt-contaminated bridges. In Finland there is also X-ray equipment called X-Met 840, which is similar to the ASFX equipment.

3.5 Impulse Radar

Investigations into the use of ground-penetrating radar for detecting deterioration in pavements and concrete bridge decks began in the United States and Canada in the mid 1970s. See [21] and [22]. The pulses are of extremely short duration, approximately one nanosecond, which is the technique known as impulse radar.

An impulse radar equipment normally consists of a monostatic antenna, transmitter, receiver and oscilloscope. Pulses of radio frequency energy are directed into the concrete, a portion is reflected from any interface, and the output is displayed on an oscilloscope. An interface is any discontinuity or differing dielectric, such as air to asphalt, asphalt to concrete, or cracks in concrete. See [23].

A number of American and Canadian studies have been carried out on both bare concrete and asphalt-covered bridge decks, see for instance [24] and [25]. In all cases the radar was found to be capable of identifying anomalous areas on the concrete surface. The practical problem was analyzing the large amount of data that were collected and relating the different radar signatures to physical distress. The use of impulse radar therefore has considerable potential for the automatic processing of the output signal to produce a site plan of a structure identifying the extent and type of deterioration. An important advantage of radar is that it is almost independent of weather conditions. The only environmental influence is that radar does not work effectively if the concrete surface is wet or if there is significant moisture in a bituminous or other surfacing because of attenuation of the signal.

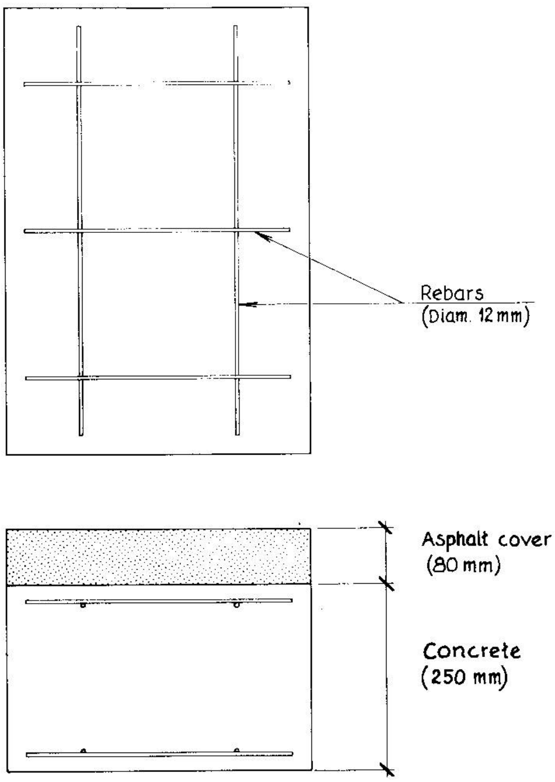


Fig.2 Test specimen with different chloride ion contents 0, 0.3, 0.6 and 1.2 %, respectively [26].

The research efforts on impulse radar in Sweden has been focussed on the detection of whether the concrete bridge deck underneath the asphalt cover is salt-contaminated or not causing different dielectric properties. On behalf of the Swedish National Road Administration tests have been carried out [26] on specimens, shown in Fig.2, with different salt contents. These tests showed that there was a significantly increased attenuation with increasing chloride content. The laboratory investigation was followed by in situ tests on two bridges, which confirmed that salt-contaminated concrete can be detected using the reflectivity of an impulse radar signal as a parameter.

3.6 Thermography

According to [27] and [28] infrared thermography has been found to be capable of detecting delaminations in concrete. The method works on the principle that as the concrete heats and cools, there is a substantial thermal gradient within the concrete because concrete is a poor conductor of heat. Any discontinuity, such as a delamination parallel to the surface, interrupts the heat transfer through the concrete. The differences in surface temperature can be measured using sensitive infrared detection systems. The essential components of such a system are an infrared scanner, control unit, battery pack and display screen.

The images can be recorded on photographic plates or videotape. Either colour or black-and-white images can be used. Ideal conditions are summer sun with no cloud or wind as the temperature differential is reduced by wind, cloud cover and high humidity.

The test specimens used at the impulse radar tests [26], which are shown in Fig.2 above, were also investigated on behalf of the Swedish National Road Administration by using thermography at the Swedish National Testing Institute [29]. It was then discovered that the different chloride contents could be recognized by the thermography technique when the temperature of the surrounding air dropped. This result shows that salt contamination causes a different emissivity of the concrete.

3.7 Ultrasonic Technique

3.7.1 State-of-the-art

Studies of literature dealing with ultrasonic technique reveal that testing of concrete has hitherto mostly been performed on the basis of determination of the time it takes for a sound pulse to pass through the material in direct or semidirect transmission. The various types of equipment available on the market are also designed in the first instance for this application. The transit time is commonly used to calculate the sound velocity in the concrete, as described in paragraph 3.1.4 above.

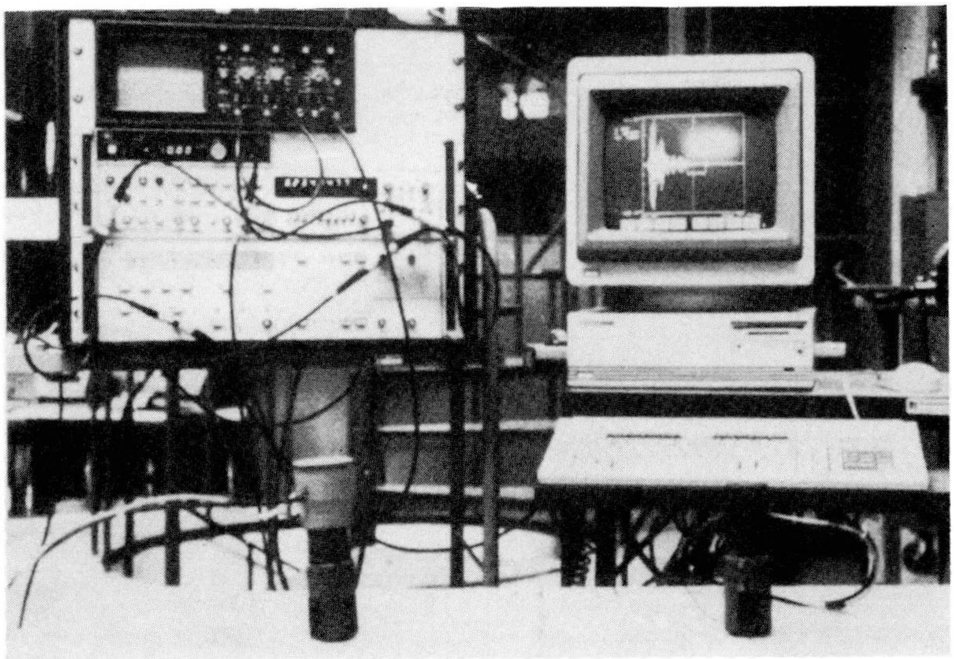
Applications for surveying of cracking and deterioration of concrete are also often described in user descriptions for different equipment and articles. On indirect transmission measurement along different distances, a difference in velocity can reveal the depth of a surface crack in the way of the pulse through purely mathematical calculations. Similarly, the thickness of a layer of poor concrete on sound concrete can be determined theoretically. These applications, in which only the transit time is considered, presuppose similar conditions throughout the entire measurement distance and thus give an average strength over the transit distance. Measurements of this type will also be influenced by embedded reinforcement bars if the pulse is permitted to pass in a direction parallel to a bar within the zone where the steel exerts effect. A correction factor must then be added to the measured sound velocity, as proposed in [30]. Measurement perpendicular to the reinforcement will also be influenced to some extent and consequently the velocity will also have to be slightly adjusted.

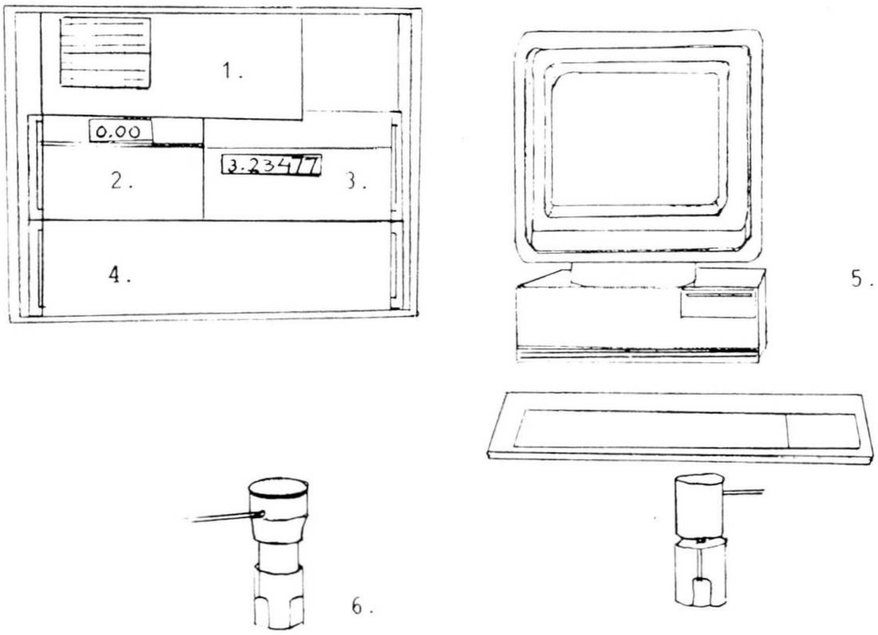
In recent years, new types of applications of ultrasonic testing of concrete have been studied and the findings presented in research reports. At the University of Braunschweig a doctoral thesis [31] has been presented, which deals with the possibilities of developing the thechnology in terms of both new measuring methods, such as intensity measurements, impulse echo measurements and ultrasonic spectroscopy and as regards the development of measuring equipment. At the University of London a thesis has been presented [32], in which the attenuation of the sound signal has been studied, in addition to velocity measurement, as a parameter for determination of strength.

It should be noted that measurements of pulse velocity through concrete are affected by the smoothness of the concrete surface, concrete temperature, moisture content, mix proportion, age of the concrete, and presence of reinforcing steel. Temperatures within the range of 5 to 30°C do not significantly affect pulse-velocity measurements. Outside this range, corrections can be applied according to [33].

3.7.2 Research and development

At the Royal Institute of Techology, Dep. of Structural Engineering, in Stockholm, Sweden, a research project was started in 1986, which is planned to be completed in 1988. This project is intended to further investigate and develop the ultrasonic technology in order to extend the possibilities of detecting deterioration of concrete. The ultrasonic technique will be used to detect damage due to frost attacks, such as laminations, cracks, etc. by determining not only the sound velocity but also





1. OSCILLOSCOPE - continuously displaying signals
2. FUNCTION GENERATER - generating various types of input signals
3. COUNTER - measuring transit time
4. AD-CONVERTER - digitizing received signal
5. COMPUTER - controlling and analysing measurements
6. PROBES - transmitting and receiving signals

Fig.3 The ultrasonic equipment used at the Royal Institute of Technology in Stockholm.

the attenuation of the signal. By exploiting modern digital technology, excellent opportunities are afforded for analysis of the received signal. In this research project the newly designed equipment shown in Fig.3 will be used.

As the goal is to establish relations between measured ultrasonic velocity and loss of energy, respectively, and the properties of the concrete being examined (strength, extent of damage etc.), certain fundamental parameters for the materials included in the concrete must be determined. The ultrasonic velocities and the energy absorptions of the constituent materials and their influence on the sound wave as reflecting and dispersing surfaces will be examined.

With the aim of determining the fundamental relations governing how ultrasonic velocity and attenuation are influenced by combined deterioration due to environmetal and functional effects, tests are performed on salt and frost damaged concrete cylinders. These experiments based on direct transmission are subsequently intended to be used to evaluate experiments with direct and indirect transmission on specimens of severely frost-damaged concrete.

The possibility of detecting laminations in concrete will be investigated by scanning of a boundary surface parallel and perpendicular to the detector surfaces of the transducers for different lamination thicknesses.

4. CONCLUDING REMARKS

In order to assess the condition of concrete structures, several methods are available, both destructive and non-destructive. Each of them have both advantages and disadvantages, as reviewed above in chapters 2 and 3. They are, however, complementary rather than competitive options, which by judicious selection offer rather good condition assessment opportunities for concrete structures.

REFERENCES

1. Durability of concrete structures. CEB-Rilem International Workshop, 18-20 May 1983, Department of Structural Engineering, Technical University of Denmark, Copenhagen.

2. INGVARSSON H., WESTERBERG B., 1985, Operation and Maintenance of Bridges and Other Bearing Structures. Publ. No. 42 from the Swedish Transport Research Board, Stockholm, Sweden, ISSN 0282-8022.

3. Swedish National Road Administration, 1985, Repair of Concrete Bridges. Publ. No. TB 151. (English version), Borlänge, Sweden.

4. Department of Transport, 1986, The Investigation and Repair of Concrete Highway Structures. Departmental Advice Note BA 23/86, London.

5. RILEM, 1977, Method of Carrying out and Reporting Freeze/thaw Tests of Concrete. Materials and Structures No 10.

6. National Swedish Committee on Concrete, 1979, Swedish Regulations for Concrete Structures (BBK 79), Svensk Byggtjänst, Stockholm.

7. LEWANDOWSKI R., 1971, Beurteilung von Bauwerksfestigkeiten an hand von Betongütewürfeln und Betonbohrproben, Schriftenreihe der Institut für Konstruktiven Ingenieurbau der TU Braunschweig, Heft 3, WernerVerlag, Düsseldorf.

8. PETERSONS N., 1973, Bedömning av betongs kvalitet i färdiga konstruktioner - några praktiska fall. The Swedish Cement and Concrete Research Institute (CBI), Utredningar nr 10, Stockholm.

9. BELLANDER U., 1977, Hållfasthet i färdig konstruktion. Del 3. Oförstörande metoder. Laboratorie- och fältförsök. The Swedish Cement and Concrete Research Institute (CBI), Forskning/research 3:77, Stockholm.

10. KRENCHEL H., 1970, Lokstyrkeprøvning af betong. Structural Research Laboratory. Technical University of Denmark, Sagsrapport nr S 3/69, 21 pp. Copenhagen.

11. KIERKEGAARD-HANSEN P., 1975, Lokstrength. Nordisk Betong no. 1975:3, pp 19-28. (Journal of the Nordic Concrete Federation).

12. GAEDE K. & SCHMIDT E., 1964, Rückprallprüfung von Beton mit dichten Gefüge. Deutscher Ausschuss für Stahlbeton, Heft 158, Berlin.

13. INGVARSSON H., 1979, Concrete Strength of a Slipform Concreted Structure, Contribution to the RILEM Symposium on Quality Control of Concrete Structures, Stockholm, June 17-21, 1979. Preprints Vol. 1, p 55-62.

14. EVANS E., 1960, The Effects of Curing Conditions on the Physical Properties of Concrete. PhD Thesis. University of London.

15. HANSEN T., 1960, Creep and Stress Relaxation of Concrete. Swedish Cement and Concrete Research Institute (CBI). Proceedings No. 31, Stockholm.

16. MALHOTRA V.M., 1970, Preliminary Evaluation of Windsor Probe Equipment for Estimating the Compressive Strength of Concrete. Mines Branch investigation report 1 R 71-1, 33 pp.

17. JOHANSEN R., 1977, En praktisk prøvningsmetod for in situ bestemmelse av byggverksfasthet. Nordisk Betong 1977:4. (Journal of the Nordic Concrete Federation).

18. MALHOTRA V.M., 1976, Testing Hardened Concrete - Nondestructive Methods, American Concrete Institute, Monograph No. 9, 188 pp.

19. INGVARSSON H., 1986, Svenska Vägverkets brotekniska forskning och utveckling rörande tillståndsbedömning, reparation och underhåll. Proc. from VTT Symposium 66 on Repair of Concrete Structures, 1986, Espoo, Finland.

20. ROMBEN L., 1986, Bestämning av klorid i betong med fältmetoder (Interimsrapport 1986-04-15), Swedish Cement and Concrete Research Institute (CBI), Stockholm.

21. CANTOR T. & KNEETER C., 1978, Radar and Acoustic Emission Applied to Study of Bridge Decks, Suspension Cables and Masonry Tunnel, Transportation Research Record No. 676, pp 27-32.

22. STEINWAY W.J., ECHARD J.D., LUKE C.M., 1981, Locating Voids Beneath Pavement Using Pulsed Electromagnetic Waves, NCHRP Report 237, Washington.

23. ALONGI A.V., CANTOR T.R., KNEETER C.P., ALONGI A. Jr., 1982, Concrete Evaluation by Radar, Theoretical Analysis, Transportation Research Record 853, pp 31-37.

24. MANNING D.G., HOLT F.B., 1983, Detecting Deterioration in Asphalt-Covered Bridge Decks, Transportation Research Record No. 899, pp 10-20.

25. CLEMENA G.G., 1983, Nondestructive Inspection of Overlaid Bridge Decks With Ground Penetrating Radar, Transportation Research Record No. 899, pp 21-32.

26. ULRIKSEN P., 1982, Application of Impulse Radar to Civil Engineering, Dep. of Engineering Geology, Lund University of Technology (Doctoral Thesis), Lund, Sweden.

27. CLEMENA G.G., McKEEL W.T. Jr., 1977, The Application of Infrared Thermography in the Detection of Delamination in Bridge Decks, Rep. No. VFHTRC-78-R27, Virginia Highway and Transportation Research Council, 35 pp.

28. MANNING D.G., HOLT F.B., 1980, Detecting Delamination in Concrete Bridge Decks, Concrete International, Vol.2, No. 11, pp 34-41.

29. BLOMQUIST N., NILSSON I., 1983, Användning av värmekamera för detektering av saltbemängd betong. Statens Provningsanstalt, laboratoriet för byggnadsfysik, rapport 8311:203 (Swedish National Testing Institute), Borås, Sweden.

30. CHUNG H.W., 1978, Effects of embedded steel bars upon ultrasonic testing of concrete. Magazine of concrete research, Vol 30, No. 102, March 1978.

31. HILLGER W., 1983, Verbesserungen und Erweiteriungen von Ultraschallpruferverfahren zur zerstörungsfreien Fehlstelle- und Qualitätskontrolle von Betongbauteilen. Dissertation TU Braunschweig.

32. CHEUNG L.C.F., 1977, Examination of Concrete by Ultrasonic pulse Attenuation and Velocity Measurements, Thesis, University of London.

33. JONES R., FACAOARU I., 1969, Recommendations for Testing Concrete by the Ultrasonic Pulse Method, Materials and Structures/Research and Testing, Vol. 2, No. 10, pp 275-284, Paris.

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