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Sammendrag

Rapporten inneholder følgende innlegg til RILEM TC 119's Internasjonale symposium "Thermal Cracking in Concrete at Early Ages":

Reidar Kompen:	High Performance Concrete: Field Observations of Cracking Tendency at Early Age.
Erik J. Sellevold et al:	High Performance Concrete: Early Volume Change and Cracking Tendency.

Artiklene oppsummerer den viten og erfaringen en har pr. våren 1994 om årsaken til opprissing av brubetong i fersk fase, og hvordan slik opprissing kan unngås.

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Seksjon: *45 Betong*
Saksbehandler: *Reidar Kompen* */KØ*
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Statens vegvesen, Vegdirektoratet
Veglaboratoriet
Postboks 8142 Dep, 0033 Oslo
Telefon: 22 07 39 00 Telefax: 22 07 34 44

HIGH PERFORMANCE CONCRETE: FIELD OBSERVATIONS OF CRACKING TENDENCY AT EARLY AGE.

R. KOMPEN
Norwegian Road Research Laboratory, Oslo, Norway.

Abstract

Horizontal surfaces of concrete having a water/binder-ratio of 0,40 or less have shown an annoying tendency for cracking in the early plastic stage. This paper summarizes the field observations and the qualitative field experience as to the occurrence of the cracking phenomenon. Recommendations based on field trials are given for concrete mix design and for execution, on how to minimize cracking.

1 Introduction

Since concrete with a water/binder- ratio of 0,40 came into regular use for bridges in Norway, free (unformed) surfaces, especially bridge decks, have shown an annoying tendency for cracking in the early plastic stage. This paper will summarize the field observations and the qualitative field experience from the bridge construction projects through the years 1989 - 1993, where efforts have been made to overcome the cracking problem.

2 Specification for bridge concrete

Several cases of early deterioriation of bridges in marine climate have called for improvements of the concrete quality of bridges. In 1988 the Norwegian Public Road Directorate put forward a new specification for bridge concrete:

- a mass ratio $m = w/(c+2 \cdot s)$ less or equal to 0,40.
- silica fume content (s) 2-5% by weight of Portland cement (c).
- air content 5 ± 1,5% measured in fresh concrete
- strength class C45 or higher
- consistency max 12 cm slump for superstructures, max. 16 cm for other structural members.

Due to experiences gained the slump limits are no longer valid. Slump is typically 18-20 cm, and an air content of 4,0-4,5% is normally aimed at. In several projects strength class C55 and C65 have been specified, and mass ratios down to 0,32 have been applied.

3 Types of field problems experienced

In addition to the early age cracking problem, several other and possibly interrelated field problems, have been observed in practical use of concrete with low w/b-ratios. These include the following:

1. To obtain proper workability.
2. To retain workability for a reasonable period of time.
3. Trowelling of free concrete surfaces.
4. Frequently an abnormal drop in strength when the air content exceeded a certain limit, usually 5,0-5,5% for m=0,40.
5. Testing often showed that water-impermeability was not achieved.

Compared to "ordinary concrete", low w/b-ratio concretes were very cohesive and sticky. Poker vibrators often showed poor effiency, despite high slump due to the use of superplasticizers at rather high dosages. Because the fresh concrete looks "wet", experienced concrete workers misinterpret the need for compaction.

The rapid loss of workability often experienced consists of two phenomena:

A. Ordinary slump loss as with "ordinary concrete".
B. Some kind of coagulation taking place when the concrete moves slowly or stands still due to its thixotropic character.

The extent of the field problems varied considerably from site to site and also at each site, due to both identified and unidentified parameters.

4 The cracking phenomenon

The majority of the sites using concrete with a mass ratio of 0,40 experienced cracking of free surfaces while the concrete was still in the plastic stage. The extent of cracking, both number of cracks and crack-widths, increased with reductions in the mass ratio. At a mass ratio of 0,45 only one case of plastic cracking has been observed.

The cracking occured from 15 minutes up to 6-8 hours after striking off the surface, depending on the concrete temperature, mass ratio, weather conditions and the degree of retardation. Early cracking gave generally wider cracks.

The pattern of cracking varied, mainly within three variants:

1. A large number of wide (1-2 mm) and short (10-30 cm) cracks in all directions, possibly with a main orientation at 45° with the reinforecement. This pattern is similar to ordinary plastic shrinkage cracking.
2. A small number of wide (1-3 mm) and very long (2-5 m), almost straight cracks, mainly parallel to the edges of the cast section. The cracks often coincide with discontinuities in the soffit of the slab.
3. An enormous number of fine, parallel haircracks of approx. 1,0-1,5 m length and 10-30 mm distance, mainly at 45° with the reinforcement.

An example of extreme cracking is shown in fig 1.

The depth of the cracks varied, but where wide cracks were found, the depth was often 80-120 mm, that is down to and beyond the reinforcement. Drilled cores from the cracks often showed an odd shape, their width increasing with distance from the surface, see fig. 2.

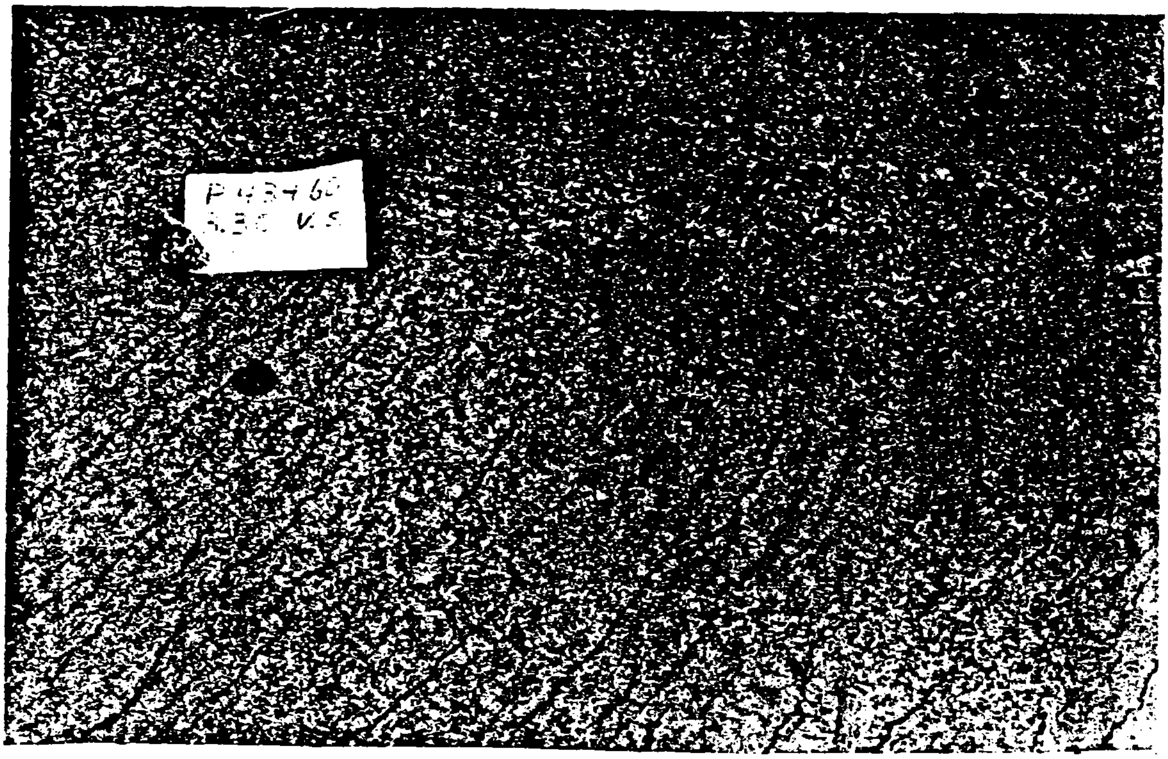

Fig. 1 An extreme case of cracking for a bridge deck.

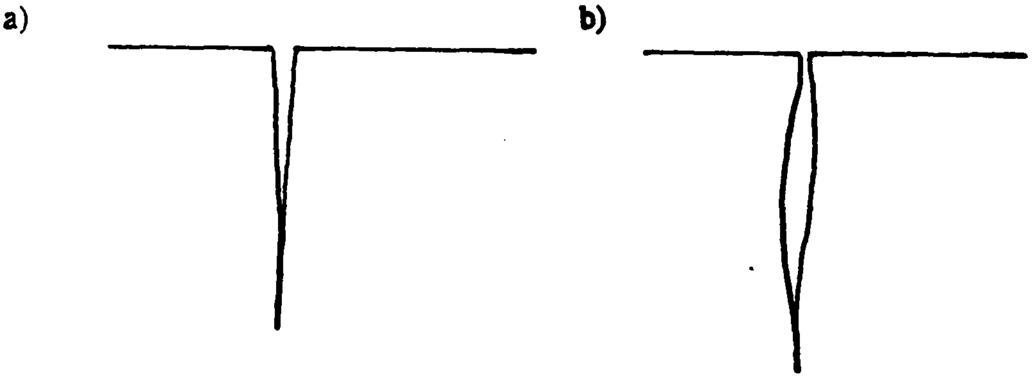

Fig. 2 Shape of cracks experienced from drill-cores.
a) Ordinary plastic shrinkage cracks.
b) Plastic cracks in low w/b-ratio concrete.

It was also generally experienced that bridge decks which looked to have only modest cracking turned out to have more pronounced cracking and wider cracks when they were sandblasted.

It has to be pointed out that the cracking occured irrespective of the curing procedure. Of course increased cracking occurs if the curing procedure is poor or starts late, but neither the application of a thick layer of curing membrane nor casting in rainy weather can eliminate the cracking, if the concrete "feels for cracking".

It should also be pointed out that the cracking phenomenon has not been consistently observed, except at mass-ratios well below 0,40. At a mass-ratio of 0,40 the problem often appears and then disappears, without any easily explainable reason.

5 Conditions influencing cracking

A number of observations have been made as to which circumstances increase cracking and which measures can be taken to reduce cracking.

5.1 Weather conditions

Particularly windy weather promotes cracking, no matter if it is in combination with sunshine, overcast or rain. Dry winds are of course the worst.

High temperatures also promote cracking, but not to the same degree as wind. Sunshine also has some effect, but remarkably little compared to wind and temperature if good curing procedures are followed.

On hot and windy days casting of bridge decks should be postponed until late evening or night.

5.2 Structural design

Thick slabs have shown to have a far greater tendency for cracking than thin ones. Bridge decks having a thick core and slender wings always show more pronounced surface cracking above the thick section. Hollow core box girders with haunches also show more cracking above the haunches, see fig. 3

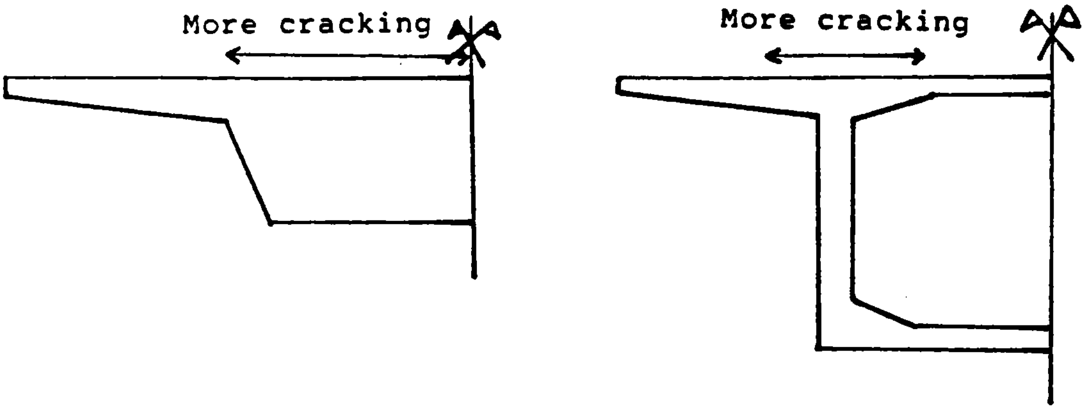

Fig.3 Areas of a bridge deck with more pronounced cracking.

There is also a marked tendency that bridge decks with a large inclination show more cracking than horizontal ones.

5.3 Casting procedure

From the "old days" there is a well established rule that deep concrete sections should be cast in layers, and that the top layer should not exceed 100-150 mm to avoid plastic settlement cracking. When the new cracking phenomenon showed up, all the "good old rules" were followed strictly. This gave no improvement, on the contrary.

Experience has shown that cracking is reduced significantly if the thickness of the top layer is increased to 250-300 mm. This is especially the case for thicker slabs. For thin slabs it implies that the whole depth of the slab should be cast in one operation.

Experience has also shown that the final striking off with vibratory screeds should proceed at a very low speed, to reduce cracking. Too rapid movement of the screed is expected to leave the fresh concrete surface in a state of tensile stress.

5.4 Curing procedure

Good curing procedures carried out very conscientiously are important to reduce cracking, but are no guarantee of avoiding cracking.

A curing membrane must be applied immediately after striking off. Every minute the curing membrane is delayed will increase cracking. The dosage of curing membrane should be 0,4-0,5 l/m^2 to achieve full coverage, which is well above the 0,15-0,20 l/m^2 recommended by the manufacturers. Comparative tests in the field have shown that different products have different protecting abilities, but the best ones in the field are not the ones showing best results in laboratory testing. Both wax-based and acrylic-based curing membranes are found among the most effective ones in the field.

As to the curing practice after membrane application, experiences differ. Some contractors have experienced that covering with a plastic sheet as soon as it is possible, will make the best result. It is the experience of the author that plastic sheet does not work, but that gentle sprinkling with small amounts of water (fog-curing) makes a great difference. Fog-curing should start as soon as the membrane has created a continous film or the concrete shows a loss in consistency, and should proceed until ordinary water curing can be applied.

5.5 Concrete mix design

It is a widespread opinion that cracking problems in concrete will be reduced by reducing the cement content or the cement paste content. However, field experience has shown very clearly that when facing this special early cracking problem, the opposite of that theory is true.

It has been observed that the quicker workability is lost, whatever might be the reason, the more pronounced cracking will be the result. Consequently a normal and slow loss of workability must be a primary goal for the mix design.

It has been experienced that if workability is to be retained, the water content (or the binder paste volume, if one prefers, since the w/b-ratio is fixed), has to exceed a critical limit, which is dependent on the aggregate source and the mixing procedure. This limit is quite sharp, 2-3 liters of water may decide if the workability is retained or is lost in less than 10 minutes. If the water content is below this limit, the consumption of superplasticizer will increase enormously, with no benefit as far as the cracking is concerned.

The dosage of water-reducing admixtures can be taken as a direct measure of how "stressed" the mix design is. The general experience is that dosages up to 6-8 kg/m^3 are acceptable, but that dosages above 8-10 kg/m^3 do more harm than good. This applies both for workability and cracking. Because the response of a concrete to plasticizers depends both on the cement and the aggregate characteristics, the total dosage of plasticizers does not, by itself, give an unambiguous measure of cracking tendency.

Use of constituent materials resulting in low water demand for the mix is favourable and should be aimed at. Reducing the water demand by increasing the proportion of coarse aggregate is not, however, as efficient as theory predicts. Plasticizers have a larger effect in mixes with a higher proportion of sand.

It is well known from the period where silica fume came into regular use that silica fume will promote plastic shrinkage cracking. Experience with early age cracking, however, indicates that the silica fume does not make any difference as long as the dosage is within the 5% limit, and the efficiency factor of 2,0 relative to Portland cement is applied.

From some field cases it can be inferred that long storage of the cement before use, or blowing the cement in moist weather may reduce the cracking tendency of the concrete.

The type of water reducing admixture used is found to have a significant effect. Limiting the lignosulphonate dosage to a maximum of 3,5 kg/m^3 reduces the thixotropic tendency. Use of highly efficient superplasticizers with a long duration period also reduces the necessary dosage and the rate of workability loss.

Concrete with a slump of 10-30 mm and a mass-ratio of 0,40 seems to be free from the cracking described. There is also some indication that 230-240 mm slump concrete has far less tendency for cracking than 140-200 mm slump concrete.

6 Understanding of the cracking phenomenon on the macro level

In full scale field work a number of cracking mechanisms are acting simultaneously. The reason behind the cracking experienced for low w/b-ratio concretes is believed to be a combination of one or more of the following effects:

A) Conventional cracking mechanisms; i.e.:
  - plastic shrinkage due to external drying
  - plastic settlement taking place after compaction
  - thermal gradients created by surface cooling and/or internal heat of hydration
  - lateral movement on inclined surfaces
  - deformations and vibrations in the scaffolding

and a "new" phenomenon:

B) Early volume contraction of the binder paste
  - overall volume reduction
  - differental plastic shrinkage due to internal suction of water between volumes of concrete.

It has been shown in two different field trials, where all the conventional cracking mechanisms were eliminated, that the early volume contraction of the binder paste might be large enough to create cracking.

In field work strains due to different cracking mechanisms are superimposed, and the crack pattern might correspond to the last single mechanism making the tensile strain capacity exeeded.

From field work it looks as if the early age cracking may be a result either from an increase in internal volume contraction with reductions in the w/b-ratio, or some incongruity between the rate of volume contraction and the rate of plasticity loss or the straicapacity for the binder.

Temperature effects play undoubtedly a role in the cracking phenomenon. It seems, however, that cooling of the surface is far more risky than temperature rise in the core. Even more important it is to be aware of the strain due to the internal volume contraction of the concrete when establishing criterias for allowable temperature gradients.

7 Recommendation for reduction of plastic cracking for low w/b-ratio concretes

7.1 Concrete mix design

1. If there are possibilities for choosing constituent materials, choose materials having the lowest possible water demand.
2. Choose a lignosulphonate dosage of maximum 0,9% by cement weight with P30 cement, maximum 0,6% by HS65 cement.
3. Choose a superplasticizer product among the ones having the greatest efficiency and the longest duration time. In combination with air-entraining agents, melamine-based superplasticizers normally give the best results. If high silica fume dosages are used, naphtalene-based superplasticizer should be used to reduce the cohesiveness.
4. In hot weather and/or with long transports, use a dosage of retarder minimum 0,8 kg/m^3, preferably 1,0-1,5 kg/m^3, to improve workability and reduce thixotrophy.
5. Choose an aggregate combination giving 41-44% passing the 4 mm sieve.
6. Choose binder and water content (binder paster volume) so high that the total dosage of water-reducing admixtures (admixtures for retempering included) can be kept below approx 8 kg/m^3.
7. Be aware that a stable mixing procedure is necessary to produce a constant product. The mixing procedure, especially the order of entering the constituents into the mixer, is also decisive for the mixing efficiency and the resulting water demand of the mix. Cement should be wetted by water before coming into contact with admixtures.

8. If the fresh concrete loses workability quickly, it will also have a great tendency for cracking. The reasons for quick loss of workability might be:
   - too low water content (point 6)
   - cement wetted by admixture (point7)
   - too high lignosulphonate dosage (point 2)
   - superplasticizer with short duration time (point 3)
   - high concrete temperature or aggregates with high water suction

7.2. Execution of work

1. During transport (in particular long transports) the automixer drum should be kept at a very low rotation speed, to reduce heat generation by friction in the concrete mass.
2. Upon arrival at the construction site the automixer drum should be run at maximum rotation speed for approx. 3 minutes, to eliminate coagulation. If retempering is necessary,(which should be considered normal if the transport time is 20 minutes or more),this remixing will take place automatically as a part of the retempering.
3. If the deck is thick enough to be cast in succeeding layers, the top layer should be of 25-30 cm thickness.
4. Striking off with vibratory screeds should be excecuted at a very low speed.
5. A curing membrane is to be sprayed on at a dosage of 0,4-0,5 l/m^2 immediately after striking off. For bridge decks which are to receive a waterproof membrane and an asphalt wearing course a non-wax based curing membrane is recommended.
6. As soon as the concrete has lost some of its workability , gentle water spraying (sweet water only) or preferably fog spraying should start and continue until ordinary water sprinkling can be started.
7. At temperatures below freezing point, where water cannot be supplied, the surface has to be covered by insulating sheets to avoid frost damage and/orexcssive thermal gradients.

8. Consequenses of the plastic cracking phenomenon

The plastic cracking phenomenon is regarded the most serious problem met in using low w/b-ratio concrete. There are serious worries that this phenomenon will jeopardize the quality improvements intended by the use of low w/b concretes.

By observations in the field and fullscale field trials a lot of experience has been gained on how to reduce cracking to a more acceptable level. Understanding of the mechanisms involved has, however, not reached such a level that this cracking can be completely avoided in everyday construction work. Consequenly it is strongly recommended that research should continue on the early age cracking problem, to develop both basic understanding and practical measures.

HIGH PERFORMANCE CONCRETE: EARLY VOLUME CHANGE AND CRACKING TENDENCY

E.J. SELLEVOLD, Norwegian Inst. of Technology, Division of Concrete,
Trondheim, Norway
Ø. BJØNTEGAARD , Norwegian Inst. of Technology, Division of Concrete,
Trondheim, Norway
H. JUSTNES, SINTEF Structures and Concrete, Trondheim, Norway
P.A DAHL, SINTEF Structures and Concrete, Trondheim, Norway

Abstract
A variety of experimental techniques concerning early volume change and crack sensivity have been applied to HPC and equivalent binder phases.

It appears from the results that the low w/b-ratios lead to more pronounced volume reductions at early ages, earlier build-up of internal tensile stresses and greater sensitivity to early cracking under conditions of strong evaporation from the concrete surface. Field experience has shown that cracking may occur even when great efforts have been made to avoid evaporation. We believe that chemical shrinkage and the consequent self-desiccation play a major role in the crack sensivity of HPC.

1 Introduction

High Performance Concrete (HPC) here denotes concrete with water-to-binder ratio of 0.40 or less. Such concrete is used more and more frequently in Norway today, in order to obtain increased durability of concrete structures in aggressive environments. However, a new problem has appeared with widespread use of HPC, particularly on horisontal surfaces such as bridge decks, which have shown great sensitivity to cracking at early ages, most often less than about 12 hours after casting. Field observations and experiences with the problem are described in detail by Kompen (1994) at this conference. The present paper describes a number of experiments using different techniques carried out over the last two years, in order to obtain a better understanding of the phenomenon of early cracking in HPC. The work was initiated and partly sponsored by the Norwegian Road Research Lab., Oslo.

Plastic shrinkage cracking is a well known phenomenon, associated with evaporation from the surface of newly placed concrete. A laboratory equipment to measure the sensitivity of concrete to this type of cracking has been developed and used a number of years at NTH/SINTEF, Johansen et al (1993). The technique was employed extensively in this work, in spite of the fact that in field situations cracking may well occur even though every possible precaution is taken to prevent evaporation from the surface. The technique was used for lack of a more relevant "macromethod", and with the hope that a meaningful rating of the factors influencing crack sensitivity could be obtained, also for situations when surface evaporation is not the main driving force.

The other methods used here were of a "microtype", focusing on measures of early volume change; "total chemical shrinkage" (le Chatlier shrinkage) and "external chemical shrinkage" (bulk volume shrinkage of cement paste isolated from the environment by a thin rubber membrane). Measurements of early relative humidity (RH) development in the pore system, and the development of pore water pressure both before and after final set of cement paste were also carried out.

The choice of these methods was based on the consideration that chemical shrinkage and self-desiccation becomes more important as the w/c-ratio is reduced, as is the case for HPC binders.

The purpose of these microtype experiments was to gain a better understanding of the early age behavior of the binder phase in HPC, and, if possible, to identify important driving forces to cracking. Several researchers and students have been engaged in this work; this article will only give brief summaries of the experimental work done so far, and should be seen as a report on work-in-progress on a very complex problem.

Note that cracking induced by thermal effects have not been mentioned so far, because these are not considered to be major effects in this particular problem, and that intensive work on the thermal problem is currently going on at several research centers.

2 Micro methods

2.1 Relative Humidity Measurements

One way to detect the presence of capillary tension in the pore water due to selfdesiccation is to measure the RH-development during isolated and isothermal hydration. Fig. 1 shows an example of such a measurement on a cement paste with a water-binder ratio of 0.30, and containing 8% silica fume. This low ratio was chosen since such a mixture is known to experience significant self-desiccation at very short times, and therefore tell us if it is possible to detect RH-effects within the first 12 hours. The Rotronic measuring system with Hygrolyt sensor was used. Fig. 1 demonstrates, as expected, very significant RH-decreases during the first two weeks, but no significant change during the first 12 hours.

It is useful to consider the relationship (Kelvin-Laplace equation) beetween RH and capillary tension (ΔP):

$$\Delta P = +133 \cdot \ln(RH)$$, where ΔP(MPa) is positive for tension.

A very small lowering of RH results in a very large tension in the pore water. F.inst., RH=0.99 gives ΔP=1.3 MPa, while RH=0.90 results in ΔP=14 MPa tension. RH=0.9 is achived in the pore system after about 200 hrs hydration (Fig. 1), thus clearly chemical shrinkage effects must be quite important in shrinkage of HPC. However, RH-measurements used to detect the much smaller effects present during the first 12 hours is not practical with the present accuracy of RH-measurements, which is expected to be no better than ±2% RH in this high range. In addition it must be taken into account that RH of the pore water is influenced by dissolved ions as well as by capillary effects. The effect may be several %RH, Hedenblad (1993). Thus RH-measurements may be useful for longer time measurements, but at short times a more sensitive technique appears to be to measure pore water pressure directly.

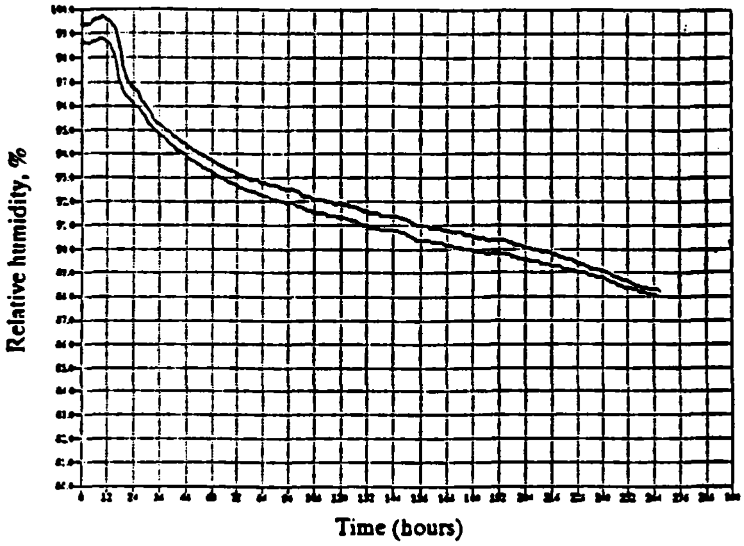

Fig. 1 Relative humidity development during sealed, isothermal hydration of cement paste with w/b=0.30 and 8% silica fume.

2.2 Pore Water Pressure Measurements

A very sensitive method to measure pore water pressure directly has recently been developed and applied extensively by Radocea (1990). The system consists of a water filled syringe connected to a very sensitive pressure transducer. Measuring on cement paste, the syringe is inserted to a certain depth in the paste, fixed in position, and the pressure recorded over time. The paste surface may be sealed or allowed to dry according to choice. Fig. 2 shows typical results for 3 norwegian cements at w/c=0.40, sealed condition, carried out by Radocea in Trondheim. The pressure is in units of mm water, and 0 indicates pure hydrostatic water pressure, i.e. the initial value of 30 mm in fig. 2 shows that for this paste with a fresh density of about 2.0, the syringe tip is inserted 30 mm vertically into the paste. The initial pressure decrease for the 3 pastes indicates the transition from a fluid paste to the establishment of a solid self-supporting skeleton. This transition involves both settlement and growth of hydration products on the cement surface. In fig. 2 the process is complete after 40-60 minutes, depending on the cement type, i.e. both on fineness and chemical composition. The length of the dormant period also varies with cement type (2-4 hrs), succeeded by further reduction in pore water pressure, which is taken to be a result of cement hydration and the consequent chemical shrinkage. It is unclear to what extent the reduced pressure is a pure "vacuum effect", created by the formation of contraction pores, or a capillary meniscus effect.

The pressure reduction has been reported by many researchers, however, values below absolute vacuum have not been reported, which we believe reflects a limitation in the measuring system. In any case we find the importance of the lower portion of fig. 2 to be that less than 0 mm water pressure indicates a situation where the solid skeleton in the paste is sufficiently strong to allow partly empty contraction pores to form. Before this point the total chemical shrinkage simply leads to "collapse" of the paste volume, i.e. the external chemical shrinkage is equal to the total chemical shrinkage.

The experimental system of Radocea is very simple, and to our mind yields very

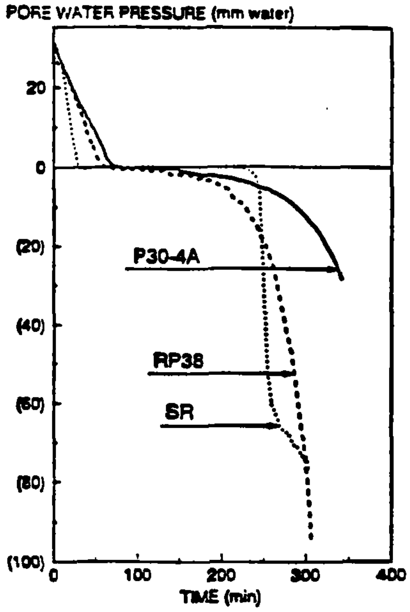

Fig. 2 Changes in pore water pressure due to sedimentation and cement hydration.

important information on early age behaviour of cement paste quite relevant regarding crack sensivity; it is probable that the transition from a semiliquid state to a solid skeleton represents a very sensitive period in that the skeleton initially is very weak with a low strain capacity and thus vulnerable to any external influence, that will add to the already existing internal stresses caused by vacuum/capillary effects.

2.3 Total- and External Chemical Shrinkage

The transition of the paste from a semiliquid to a solid with a coherent skeleton can also be recorded using the two techniques discussed here. Total chemical shrinkage is the easiest to measure accurately. In the present case a 10 mm layer of cement paste was placed in a small bottle, with water on top extending up in a capillary tube. The total chemical shrinkage is simply recorded as the level change in the tube. Knudsen and Geiker in RILEM (1982) have pioneered a variety of applications for the method since the early 1980's. For example the total chemical shrinkage is a direct measure of the degree of hydration for a given cement. To measure the external chemical shrinkage is, however, much more difficult and the litterature contains differing results; see a number of papers in the proceedings from RILEM "Concrete of early ages" (1982), and Setter and Roy (1978). Very careful linear measurements have recently been reported in combination with RH-measurements by Jensen (1993), however, only from the time of final set.

In priciple, the total and the external chemical shrinkage are identical as long as the paste is fluid and continually "collapse" as the hydration reduces the volume. When a self-supporting skeleton is formed, the external chemical shrinkage rate is of course much reduced, and the two curves will deviate. Fig. 3 illustrates this behaviour. Total chemical shrinkage measurements are usually given in terms of ml pr. 100 gram cement, and have been found to vary little with w/c-ratio the first day.

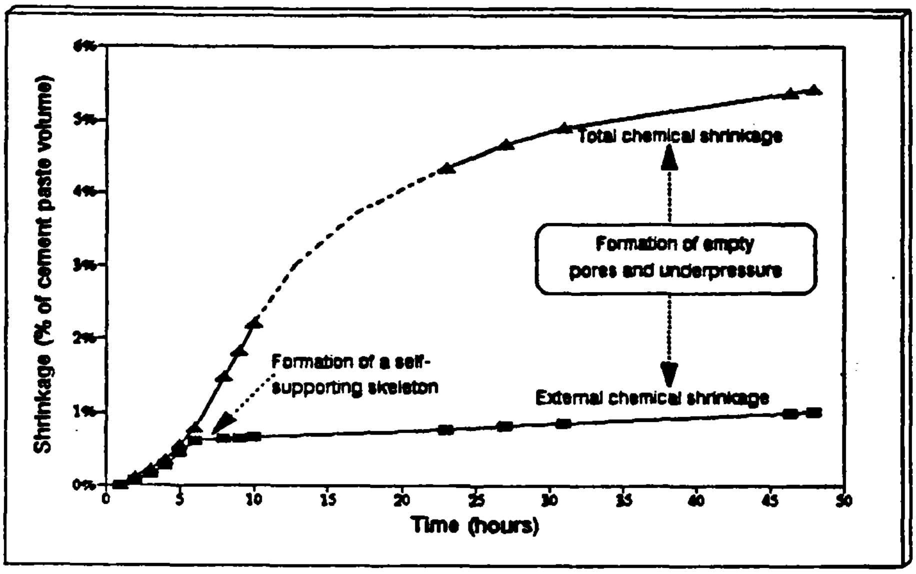

Fig. 3 Total- and External Chemical Shrinkage for cement paste with w/c=0.40.

When expressed as volume % of the binder (fig. 3), however, decreasing w/c-ratio means increasing volume change, probably contributing to the greater cracking sensivity of HPC.

The measurements of external chemical shrinkage are made with the cement paste contained in a rubber membrane (condom) which is immersed in a water bath at constant temperature. The volume change is recorded as a change in the buoyancy. The major problem with the method is an extreme sensitivity to bleeding. With bleeding, the water collects on the top, and when a skeleton is formed this excess water is gradually sucked into the pores and therefore erroneously recorded as an external volume change. To avoid the bleeding problem a system was made where the paste is rotated under water until final set. The extreme influence of bleeding is shown in fig. 4, Verboven and van Gemert (1994). In fig. 4a the w/c-ratio appears to have a very large influence on the external chemical shrinkage, however, fig. 4b demonstrates clearly that the main effect of the w/c-ratio is on the bleeding characteristics, and not, somewhat surprisingly, on the time and the neccessary degree of hydration to form a self-supporting skeleton.

The external chemical shrinkage behavior of course depends on cement type, admixture type and dosage and additions such as pozzolans.

Presently, there exist a fairly large number of experimental results on these factors which are in the process of being analyzed. We believe that the early volume change in the binder phase is related to the early cracking sensivity, but no model explaining the relationship to a "macro"-method which directly rates the cracking sensivity of a concrete exists now. One such a macro method is discussed in the following, the "Plastic Shrinkage Rig".

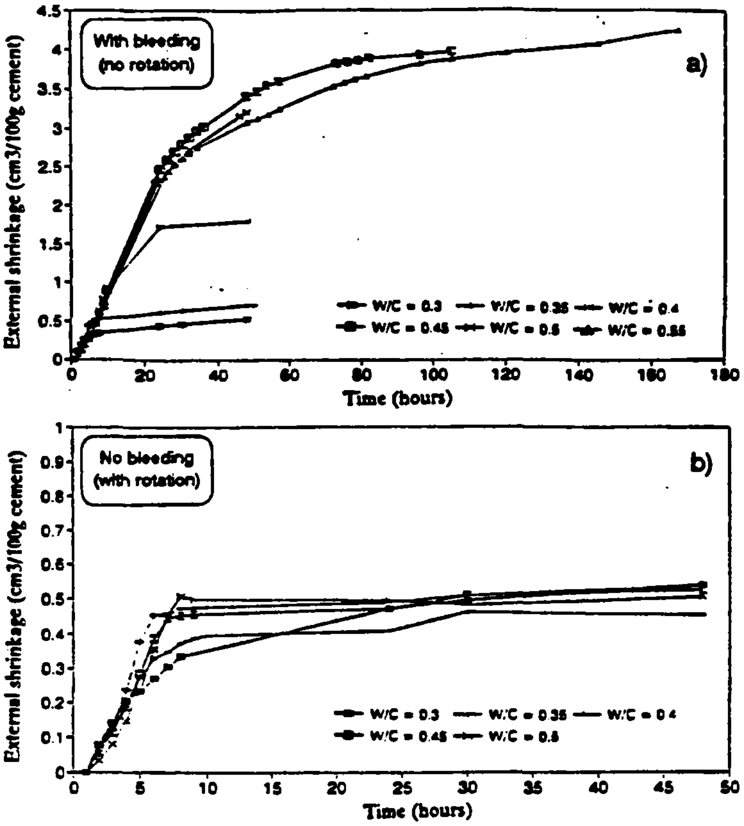

Fig. 4 External chemical shrinkage of cement paste with different w/c-ratios. Principle illustration, a) and b) are not from the same cement. Verboven and van Gemert (1994).

3 Macro methods: The Plastic Shrinkage Rig

The Rig is shown in fig. 5. Fresh concrete is contained between two rigid steel rings. The concrete surface is exposed to a laminar air stream with speed of 4.5 m/sec. The resulting evaporation activates plastic shrinkage and possibly cracking, because of the restraint provided by the stiff steel rings. Crack sensivity is characterized by the Crack index (C_i) measured as the average accumulated crack width around two concentric circles on the concrete surface (fig. 5).

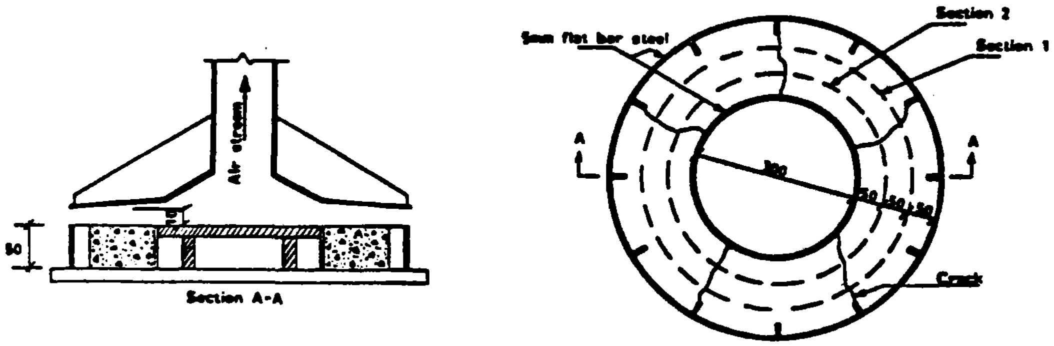

Fig. 5 The Plastic Shrinkage Rig.

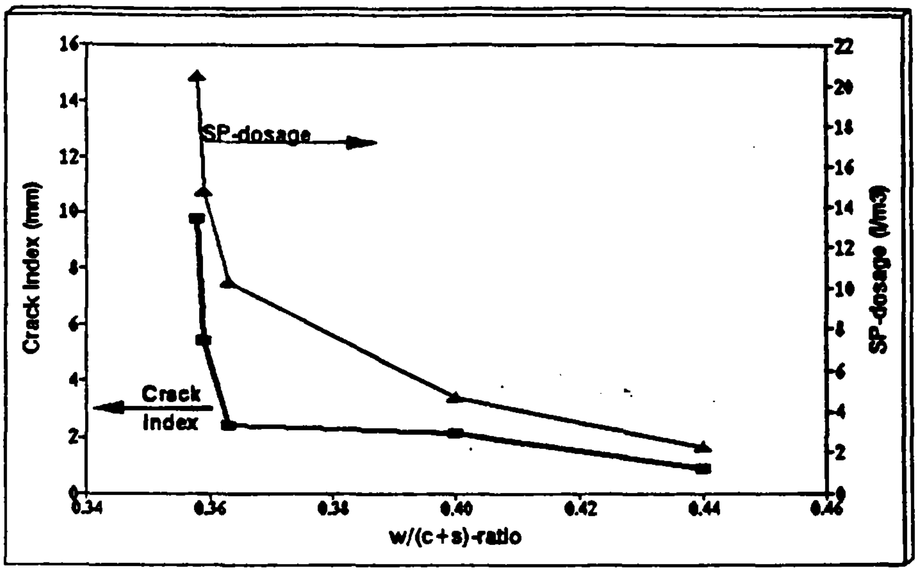

Fig. 6 Crack sensitivity (C_i) in the Plastic Shrinkage Rig as a function of w/b-ratio. SP (superplastisizer) dosage required for 18 cm slump is also given.

The apparatus has been utilized and improved continuously over the past decade, Johansen et al (1993), and is able to give at least a rough relative rating of crack sensivity. However, the C_i has a relatively high standard deviation, and is extremely sensitive to the initial slump of the concrete. Thus, careful control is necessary to obtain systematic results, and, in order to rate f.ex. a certain cement/admixture combination tests have to be carried out at several w/b-ratios, Bjøntegaard (1993).

Fig. 6 shows clearly the very large effect a reduction in water-binder ratio below a critical value has on the crack sensivity, Bjøntegaard (1992). Other cement types give different critical values, opening the possibility to rate binder compositions in terms of critical w/b-ratios; the lower value indicating smallest crack sensivity. Note however, in fig. 6 that the critical value could be assigned to the dosage of SP-admixture as well as to the w/b-ratio. Considering also the great influence that the initial slump of the concrete has on C_i, it is obvious that the situation is very complex, and modesty is called for when drawing conclusions. However, fig. 6 very clearly indicates that the problem of cracking would be expected to increase strongly at low w/b-ratios; excactly what is found in practice with HPC.

4 Concluding remarks

A variety of experimental techniques have been applied to HPC and to equivalent binder phases.

It appears from the results that the low w/b-ratios lead to more pronounced volume reductions at early ages, earlier build-up of internal tensile stresses and greater sensitivity to early cracking under conditions of strong evaporation from the concrete surface. Field experience has shown that cracking may occur even when great efforts have been made to avoid evaporation. It is indicated that more realistic test methods must be applied to map out the main factors affecting early crack sensivity of HPC under close to isotermal conditions. We believe the best possibility is to continue work on the principles pioneered in München (f.ex. Springenschmid and Breitenbücher 1990) and used by Paillere et al (1989) and Bloom and Bentur (1993). Such a restrained shrinkage rig is presently being made at NTH/SINTEF, and the testing will focus on the relationship between the tensile strength development and the corresponding self-induced tensile stress in HPC as a measure of crack sensivity.

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