SINTEF REPORT

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TITLE

COIN P1 Advanced cementing materials
SP 1.3 F Reduced cracking

Influence of fibers on cracking due to plastic and drying shrinkage

State of the art

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ABSTRACT

A literature review showed that non-metallic fibers added to concrete in general has considerably reducing effect on the early-age cracking. When the effect of non-metallic fiber is compared with ordinary mesh reinforcement, the fiber reinforcement shows the best results. It is also found that longer fibers have better effect than shorter fibers, probably due to better bond strength between concrete and fiber. The optimum fiber length is found to be somewhat larger than the maximum aggregate size.

Non-metallic fiber added to concrete at fiber dosages of 0.5vol% can eliminate the problem with plastic shrinkage cracking, without reducing the workability considerably.

Adding steel fibers are also described in the literature to prevent plastic shrinkage. In general steel fiber is found to be less effective than non-metallic fiber.

The best way to prevent plastic shrinkage may be to combine steel and non-metallic fiber. Even though non-metallic fiber is more effective than steel fiber, the workability restricts the maximum content of non-metallic fiber. Adding steel fiber on top of the maximum content of non-metallic fiber may give the best results.

It is recommended to focus further research on water saturated cellulose fibers in order to elucidate the potential combination of internal curing and fiber reinforcement to mitigate shrinkage cracking in hardening phase.

KEYWORDS	ENGLISH	NORWEGIAN
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GROUP 2	Concrete	Betong
SELECTED BY AUTHOR	Shrinkage	Svinn
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Foreword

COIN - Concrete Innovation Centre - is one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfill this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology - NTNU (research partner) and industry partners, 15 - 20 PhD-students, 5 - 10 MSc-students every year and a number of international guest researchers, work on presently 5 projects:

- Advanced cementing materials and admixtures
- Improved construction techniques
- Innovative construction concepts
- Operational service life design
- Energy efficiency and comfort of concrete structures

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %). The present industrial partners are:

Aker Kværner Engineering and Technology, Borregaard LignoTech, maxitGroup, Norcem A.S, Norwegian Public Roads Administration, Rescon Mapei AS, Spenncon AS, Unicon AS and Veidekke ASA.

For more information, see www.sintef.no/coin

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1 Introduction

Fibers may work to distribute cracks and to reduce total cracking. This action may work both in the plastic phase and in the hardening (and hardened) phase. Both the mechanisms behind cracking and the favorable fiber properties are however somewhat different in the two phases.

The plastic phase lasts from casting to around final setting. The most important mechanism behind cracking is the early contraction occurring when fresh horizontal concrete surfaces dries out causing water menisci between the solid particle and capillary tension in the concrete pore water. This leads to contraction of the concrete, so-called plastic shrinkage, and the result is often plastic shrinkage cracking. Subsequently, the bleeding capacity of the concrete and the evaporation rate from its surface are key parameter as well as the pore fineness of the concrete which determines the magnitude of the pore water pressure and hence the magnitude of plastic shrinkage. Settlement as well as early autogenous shrinkage (in low w/b-concretes) may also contribute and will then add to the deformations caused by plastic shrinkage, but plastic shrinkage is generally the major contributor. Since the concrete in this phase are plastic, and the plastic shrinkage may decrease with the depth of the surface, the fiber distribution is probably more important in crack reduction than its stiffness and strength. This probably explains why high amounts of short non-metallic fibers are found to be more effective than steel fibers added in lower numbers (but the same volume).

Hardening (and hardened) phase: The concrete in hardening phase has significant stiffness and the driving forces to cracking are temperature, drying shrinkage and autogenous shrinkage due to self-desiccation. The fiber bond length, stiffness and strength are now favorable properties in crack limitation, explaining why long/strong/stiff steel fibers are more effective than short/soft/week non-metallic fibers. The idea of "internal curing" action of adding moist non-metallic fibers is to make the fibers work as internal water reservoirs during hydration in order to mitigate self-desiccation/autogenous shrinkage. For low w/b-concretes (w/b<0.45) it is found that autogenous shrinkage often constitutes 20-40% of the total contraction during the hardening phase [1], hence mitigating autogenous shrinkage with internal curing has potentially a very favorable effect, at least on one of the three driving forces listed above.

Regarding reduced cracking by fibers, there have been carried out experimental programs mainly on two types of cracking; cracking under loading conditions and cracking under volume changes. Volume changes are caused by plastic shrinkage, drying shrinkage, autogenous shrinkage or thermal deformation.

It is well known from the literature that high elastic modulus steel fiber enhance the flexural toughness and ductility of concrete. While the contribution of high elastic modulus steel fiber is mainly observed after cracking (reducing crack widths and crack spacing), non-metallic fiber primarily reduce the early-age cracking. Because of the lower stiffness of non-metallic fiber, for instance polypropylene fiber, the strain is higher at a given stress level compared to steel fiber. This result in larger crack widths for concrete reinforced with non-metallic fiber compared with steel fiber reinforced concrete (SFRC) under the assumption that both fiber types have the same bond strength to concrete.

To fully understand how fiber can prevent plastic shrinkage cracking, it is important to know the mechanism that controls plastic shrinkage. These mechanisms are not presented in this report, but for instance Bjøntegaard [2] have presented these mechanisms.

2 Objective

This report is state-of-the art report (STAR) no. 2 in task 1.3f within COIN, which have the overall objective to make concrete with crack free surfaces, or at least making them “invisible” by distribution.

This report mainly deals with the plastic phase, but also the hardening phase is in smaller extent reviewed. Both metallic fibers and non-metallic fibers effect are evaluated.

3 Literature review

A comprehensive investigation on plastic shrinkage cracking of concretes without fiber is reported in [3]. In this investigation the effect of w/b-ratio, paste volume, cement type, sand/stone-ratio and super-plasticizer are analyzed.

Many experimental investigations have been carried out on the use of fiber reinforcement to prevent plastic shrinkage cracking. The concrete mixture proportions and environment conditions defines the concretes potential for plastic shrinkage. Most of the experimental investigations are carried out on concretes with relatively high water/binder ratios (w/c+s > 0.6) and relatively high amount of fine aggregate to provoke plastic shrinkage.

3.1 Ambient conditions

Most of the experiments are carried out under ambient conditions that give high evaporation rate. The evaporation of water from the concrete surface is the predominant cause of plastic shrinkage. Air temperature, concrete temperature, air humidity and wind velocity are the factors that control the evaporation rate.

At NTNU/SINTEF the standard ambient conditions to measure plastic shrinkage cracking are an air temperature of 20±1°C, relative humidity (RH) of 40±1% and a wind velocity of 4.5 m/s [2]. Under these conditions, both steel fiber reinforced concrete and non-metallic fiber reinforced concrete prevent plastic shrinkage cracking [4, 5, 7 and 8].

In other research institutes similar ambient conditions are used. The NTNU/SINTEF-testing involve somewhat lower air temperature, higher relatively humidity and lower wind velocity. Higher air temperature, lower relatively humidity and higher wind velocity all gives higher evaporation rate, and therefore higher plastic shrinkage [2].

3.2 Effect of different types of fibers

3.2.1 Non-metallic fibers

SINTEF has made several experiments regarding to non-metallic fiber in concrete. Hammer [4] found that adding fibers to concrete in general had considerably reducing effect on the early-age cracking. Fiber reinforcement had also considerably better effect than ordinary mesh reinforcement. At the same fraction by volume, non-metallic fiber had better effect than steel fiber. At a fiber dosage of 0.1vol% the crack widths were reduced by 67-85%, while a fiber dosage of 0.3-0.5% gave almost crack-free concrete.

Dahl [5] made an experimental program to investigate the effect of polypropylene on plastic shrinkage cracking tendency. The polypropylene fibers were 10mm long fibers from Sika, 15mm long fibers from Sika, and 12mm long Krenit “coarse special”. The fiber dosages were rather small (0.1vol%). The results from this project indicated that the fiber had no noticeable influence on the concretes workability. The cracking widths, on the other hand, were reduced to between 14-26% of the reference. A relative comparison with the results found by Banthia and Gupta [6] indicated that the longest fiber had the greatest effect.

Dahl [7] discussed the influence of fiber length based on the results from an investigation on the influence of 8 types of Krenit fiber on the plastic shrinkage cracking. From these experiments the optimum fiber length seems to be somewhat larger than the maximum aggregate size (16mm). The positive effect of fibers on reducing shrinkage cracking found in this investigation corresponded well with the results from other investigations.

When the shopping center City Syd in Trondheim was built in 1988, a field experiment was performed [8]. Of a total of approximate 5000 m^2, 300 m^2 of the overlay was cast with fiber reinforced concrete, approximately 75 m^2 for each fiber type. The rest was placed with ordinary concrete and mesh reinforcement. The non-metallic fibers used were 0.1vol% Harbourite 300 and 0.1vol% Krenit standard. The results from this field experiment indicate that the overlay with non-metallic fibers as reinforcement had smaller cracking widths (maximum 0.50mm) than the overlay with mesh reinforcement (maximum 0.75mm). It should be noted that in the field experiment reported in [8] the shrinkage mechanism probably is a combination of plastic- and drying shrinkage. This indicates that such fibers improve cracking resistance in the drying shrinkage phase too.

3.2.2 Steel fibers

SINTEF has also made several experiments regarding steel fiber in concrete. In general steel fiber is found to be less effective than non-metallic fiber in order to control plastic shrinkage cracking. Hammer [4] reported a reduction in crack widths of approximate 80% for steel fiber reinforced concrete with a fiber dosage of 0.5vol% (while only 0.1vol% of non-metallic fiber was needed to give 67-85 % reduction in crack widths, see chapter 3.2.1).

The field experiment performed under constructing City Syd also included steel fiber [8]. Dramix (0.75vol%) and EE fibers (0.75vol%) were tested as reinforcement. While ordinary mesh reinforcement and non-metallic fibers gave maximum crack widths of 0.75mm and 0.50mm, respectively, the steel fiber reinforced concrete overlay had a maximum crack width of 0.15mm. It can not be concluded from this field experiment that steel fiber is more effective in reducing crack widths than non-metallic fiber because the fraction by volume was considerably higher (0.75 vs. 0.1vol%). Again, the shrinkage mechanism in this study probably is a combination of plastic- and drying shrinkage.

Banthia et al. [9] have made a novel experimental technique to assess the cracking potential of cement-based materials when used as bonded overlay. In their experiment, an overlay was cast on a substrate that was given an enhanced roughness by manually placing 20mm aggregate on the surface such that approximate half the aggregate size remained exposed. A 100mm deep layer of the overlay material to be investigated was then placed on the substrate, and he whole assembly were transported to an environmental chamber. The ambient conditions under hardening created more evaporation than the NTNU/SINTEF-standard. An air temperature of 38°C and a relative humidity of 5% were chosen. Measurements were made every 30 minutes in the initial two hours and then every 4 hours afterwards. All measurements were terminated 48 hours after casting. In this experiment it was found that steel fiber not only reduced the maximum crack widths but also caused multiple cracking in the composite up to a fiber dosage of 0.5%. At 1vol% fiber, only minimal cracking was observed.

3.2.3 Non-metallic fibers and steel fibers acting together

Sivakumar and Santhanam [10] studied how to control plastic shrinkage cracking in concrete by adding fiber reinforcement up to 0.5vol%. The concrete was placed in a slab mould of dimension 500x250x75mm.The slab was provided with a stress riser of 55mm height at the center and two base restraints of 35mm height at 35mm from both ends, along the transverse direction. In addition to this, a bolt and nut arrangement was provided at the ends to restrict longitudinal movement of the concrete slab from the edges and to provide additional restraint, increasing the potential of cracking at the notch. The slabs were exposed to a constant temperature of 35±1°C, a relative humidity of 40±1% and a wind velocity of 6m/s. An increase in non-metallic fiber dosage resulted in a clear crack width reduction, but it also caused a decrease in workability. According to the study by Sivakumar and Santhanam [10] this decrease in workability restricts the maximum dosage of polypropylene and polyester fibers to an optimal level of 0.25 vol% based on the workability range of 50-75mm. In the case of glass fibers, a dosage up to 0.38 vol% did not affect the workability. The main results from this study were:

- The plastic shrinkage cracking was reduced significantly by fiber addition (50-99% compared to plain concrete without fibers)
- Hybrid fibers were more effective in crack reduction compared to individual steel fiber
- Steel-polyester was the best fiber combination to reduce cracks
- In order to maintain good workability the maximum content of non-metallic fiber was 0.25 vol%.

3.3 The effect of ambient conditions on experimental results

Almost all experimental studies regarding plastic shrinkage cracking available in the literature have ambient conditions which accelerate the evaporation of water from the concrete surface. The key factors regarding the evaporation rate are high air temperature, low relative air humidity and high wind velocity.

According to Bjøntegaard [2] autogenous shrinkage is believed to contribute to what seems to be plastic shrinkage cracking. In some cases, the concrete surface cracks even if evaporation of water is prevented; it means it can not be plastic shrinkage cracking. In the hardening phase autogenous shrinkage can contribute to considerable tensile stresses and cracking risk. Bjøntegaard [11] analyzed experimentally the effect of 0.4 vol% fibers (60mm long Dramix fibers) on self-induced restrained stresses that will develop during hardening phase of the concrete due to early age self-induced strains (thermal dilation and autogenous shrinkage). The results from these tests showed that fiber addition (0.4-1.0vol%) had no significant effect on the self-induced strains and drying shrinkage, nor had it any affect at the corresponding restraint stress, time of failure and failure load.

Self-induced strains (thermal dilation + autogenous shrinkage) develop due to hydration heat and self-desiccation. The self-induced strains act over the whole concrete thickness and tend to generate a uniaxial tensile stress state in a structure subjected to a high degree of restraint. Steel fiber reinforced concrete has showed to have high flexural toughness, and when the situation is dominated by drying shrinkage (evaporation of water from the concrete surface) the high flexural toughness will reduce the cracking tendency because high evaporation rate creates a flexural condition [11].

4 Future research

Autogenous shrinkage is one of the mechanisms that can give problems with surface cracking [2]. The reason that autogenous shrinkage occur, is self-desiccation or lack of water inside the concrete. The idea of water saturated additives to the concrete to prevent self-desiccation (i.e. internal curing) is evaluated in state-of-the art report no. 3 in task 1.3f within COIN. One possibility is that water saturated cellulose fiber can act as water reservoir and as a fiber at the same time. In this way the water reservoir may reduce shrinkage in hardening phase, and the fiber itself may reduce cracking in plastic phase. This potential combined effect is recommended for further investigations.

5 Conclusion

A literature review showed that non-metallic fibers added to concrete in general has considerably reducing effect on the early-age cracking. When the effect of non-metallic fiber is compared with ordinary mesh reinforcement, the fiber reinforcement shows the best results. It is also found that longer fibers have better effect than shorter fibers, probably due to better bond strength between concrete and fiber. The optimum fiber length is found to be somewhat larger than the maximum aggregate size.

To summarize the effect of non-metallic fiber, the literature shows that non-metallic fiber added to concrete at fiber dosages of 0.5vol% can eliminate the problem with plastic shrinkage cracking, without reducing the workability considerably. At lower fiber dosage (as low as 0.1vol%), the problem with plastic shrinkage cracking is found to be reduced, but not necessarily eliminated.

Adding steel fibers are also described in the literature to prevent plastic shrinkage cracking. In general steel fiber is found to be less effective than non-metallic fiber. The main reason for this may be the number of fibers. Non-metallic fibers are thinner than metallic fiber, thus a certain volume non-metallic fiber contain a higher number fiber than the same volume metallic fiber.

Results indicate that the best way to prevent plastic shrinkage cracking may be to combine steel and non-metallic fiber. Even though non-metallic fiber is more effective than steel fiber, the workability restricts the maximum content of non-metallic fiber. Adding steel fiber on top of the maximum content of non-metallic fiber may give the best results.

6 References

[1] Bjøntegaard Ø.:" Thermal Dilation and Autogenous Deformation as Driving Forces to Self-Induced Stresses in High Performance Concrete", doctoral theses, NTNU, 1999.

[2] Ø. Bjøntegaard, UM13 Volumendring og risstendens i betong, emne i NTNU fag TKT 4215 Betongteknologi 1, 2004 (in Norwegian).

[3] Bjøntegaard Ø, Hammer T.A. and Sellevold E.J.: "Cracking in High Performance Concrete before Setting", Proceedings: Int. Symposium on High-Performance and Reagtive Powder Concretes, Sherbrooke.

[4] T.A. Hammer: "Fiberarmert Mørtel og Betong. Delprosjekt nr 1-Materialegenskaper. Risstendens for fiberarmert betong ved plastisk svinn", SINTEF rapport STF65 A87023, 1987-10-02, 17 pp. (in Norwegian).

[5] P.A. Dahl: "Risstendens ved plastisk svinn for betong tilsatt Polycrete fiber", SINTEF rapport STF65 A88036, 1988-02-25, 13 pp. (in Norwegian).

[6] N. Banthia and R. Gupta: "Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete". Cement and Concrete Research, Vol. 36, 2006, pp. 1263-1267.

[7] P.A. Dahl: "Cracking tendency of Krenit fiber reinforced concrete exposed to plastic shrinkage", SINTEF report STF65 A88033, 1988-06-21, (in English).

[8] T.A. Hammer: "Fiberarmert mørtel og betong. Delprosjekt 1 Materialegenskaper. Feltforsøk med fiberarmert påstøp", SINTEF rapport STF65 A88063, 1988-09-22, 10 pp. (in Norwegian).

[9] N. Banthia, C. Yan and S. Mindess: "Restrained shrinkage cracking in fiber reinforced concrete: A novel test technique", Cement and Concrete Research, Vol. 26, No. 1, 1996, pp. 9-14.

[10] A. Sivakumar and M. Santhanam: "A quantitative study on the plastic shrinkage cracking in high strength hybrid reinforced concrete", Cement and Concrete Composites, Vol. 29, 2007, pp. 575-581.

[11] Øyvind Bjøntegaard: "Material properties of hardening fiber reinforced concrete relevant for design". Proceedings of the workshop Design Rules for Steel Fiber Reinforced Concrete Structures, Oslo, 6th October 2003, the Nordic Concrete Federation, p. 75.