SINTEF REPORT

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TITLE

COIN P2 Improved construction technology
SP 2.3 Quality and aesthetics

Quality of concrete surfaces

State of the art

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ABSTRACT

This state of the art report discusses parameters which influence quality and aesthetical impression of the concrete surface. The main focus has been on evenness of colour, occurrence of voids and pores and cracking due to drying shrinkage. Factors influencing the concrete surface such as material parameters, chemical admixtures, mix design, formwork, form releasing agents and production techniques are discussed. Test methods currently used for assessment of surface quality are listed.

The characteristics of self compacting concrete are finally compared with ordinary vibrated concrete.

The report is summarised with recommendations for further research. Beyond research, work is needed for the development of a Norwegian guideline covering concrete surface quality.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Materials technology	Materialteknologi
GROUP 2	Concrete	Betong
SELECTED BY AUTHOR	Surface quality	Overflatekvalitet
	Flaws	Feil
	Cracks	Riss

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

A major challenge of the concrete industry today is to control the concrete surface quality. Concrete may at times have a low public image caused by unappealing architecture and surface flaws such as cracks, discolouration, pores, etc. However, surface flaws might not solely be unappealing to the public eye. Finjab in Sweden was for instance caught by surprise as their survey disclosed that their single family house customers and potential customers would like to have walls of visible concrete in their houses. Pores and other "flaws" were, moreover, regarded as beautiful and something they wanted.

Concrete is clearly a versatile material which offers numerous choices of texture, colour and architectural solutions. This literature study, which is written for two projects namely SKBB (Self-compacting building concrete) and COIN (Concrete Innovation Centre), does not attempt to describe rules for good concrete architecture. The main focus is, however, on the material parameters which are of importance to obtain concrete surfaces of high quality and aesthetics. Some production techniques and methods for quality testing are also summarized.

2 Guidelines and methods for measurement of surface quality

There is currently no Norwegian guideline covering concrete surface quality. The Norwegian concrete association (Norsk Betongforening) distributes currently publication NB9 which has not been revised since 1981. NB9 covers demands for concrete surfaces, but none for design/projecting. The association calls attention to that this publication must be revised. Deutscher Beton- und Bautechnik-Verein (DBV) and Bundesverband der Deutschen Zementindustrie (BDZ) published in 2004 the third edition of Code of Practice for “Architectual Concrete”. The code is a good example of how a guideline can look like. It defines four concrete classes (SB1-SB4) which have different demands for

- texture (demand classes T1-T3)
- porosity (demand classes P1-P4)
- steadiness of shade (demand classes FT1-FT3)
- surface evenness (demand classes E1-E3)
- quality of formwork skin (demand classes SHK1-SHK3)
- quality of formwork joints (demand classes AF1-AF4)

The four classes are defined and described by Table 1 and Table 2 respectively, while the four porosity classes are given as an example in Table 3 (DBV 2004).

Table 1: Concrete classes according to DBV 2004

Classes of architectural concrete		Examples
Concrete with insignificant demands	SB1	Basement walls, areas with industrial use
Concrete with normal demands	SB2	Stairs, supporting walls
Concrete with high demands	SB3	Facades
Concrete with especially high demands	SB4	Representative components

Table 2: Classes of architectural concrete given by DBV in combination with the demands (Litzner and Goldammer 2005).

Concrete class	Texture	Porosity A[1]	Porosity Na[2]	Shade A[1]	Shade Na[2]	Evenness	Trial sample	Formwork skin	Formwork joints
SB1	T1	P1		FT1		E1	Optional	SHK1	AF1
SB2	T2	P2	P1	FT2			Recommended	SHK2	AF2
SB3		P3	P2			E2	Highly recommended		AF3
SB4	T3	P4	P3	FT2	FT3	E3	Imperative	SHK3	AF4

[1]A = Absorbing formwork, [2]Na = Not absorbing formwork

Table 3: Definition of porosity classes given by DBV (Litzner and Goldammer 2005).

Porosity class	P1	P2	P3	P4
Maximum pore units in mm^{2*}	Ca. 3000	Ca. 2250	Ca. 1500	Ca. 750*

*Pore units in mm^2 of pores with diameter within the limits of 2 mm and 15 mm. 750 mm^2 corresponds to 0.30 % of the test surface (500x500 mm)

Before casting the concrete, the skin and all other formwork components should be inspected. The value of a mock-up wall for the project as a whole should not be underestimated. It can be a separate entity or a less conspicuous part of the actual building. The construction of mock-up allows a better assessment to be made of the various design elements – ties, fixing cones, the formwork skin, its jointing etc.

The following methods can be used for assessment of surface quality:

- Surface hardness (measured by Rebound (Schmidt) hammer)
- Hardness
- Abrasion resistance
- Pore volume
- Water and air permeability
- Sorptivity
- Depth of carbonation
- Chloride and oxygen diffusivity
- Freeze-thaw resistance
- Visual assessment such as counting of blowholes and pores and evaluation of colour

Assessment of surface colour has proven to be somewhat problematic. According to report number 24 of the "International Council for Research and Innovation in Building and Construction" (CIB 1973) concrete surface measurements consists in simple visual comparison of the surface and a printed grey scale ranging from a very light grey (level 1) to a dark grey (level 7). Such a classification, although simple in principle, might be problematic due to the variability of the different printed scales of the standard, the subjectivity of the human eye, the different optical properties of concrete and paper, light conditions and a lack of information on homogeneity (Lemaire et al. 2005). GTM-Construction and LMDC have developed a new tool which allows an objective evaluation of grey levels of the surface and an accurate measurement of the area covered by surface bubbles. The GTM-LMDC process corrects pictures of concrete surfaces in order to obtain images having lightness levels that are independent of the ambient light and the camera used. The method is composed of two steps:

- An acquisition step followed by image correction
- A measurement step concerning lightness and bubble density.

3 Evenness of surface colour

3.1 Surface colour and discolouration

Variables found to be important in establishing the colour of concrete are the original colour of the cement, the water-cement ratio, and the extent and rate of hydration of the ferrite phase in the cement (Greening and Landgren 1966). Homogeneity of the binder resulting from the use of superplasticizers and the absorption properties of the mould have ,moreover, been found to have a major influence on tint homogeneity (Lallemant et al. 2000). Colour variations giving lighter shades can also be caused by use of light filler which prevents the formation of a dark, cementitious upper layer (Johansen 1999).

Surface discolouration may take the form of

- Gross colour changes in large areas of concrete caused by changes in the concrete mix
- Spotted or mottled discolouration where light or dark blotches appear on the surface
- Early discolouration by light patches of efflorescence.

These types of discolorations appear soon after placement and are due in the two latter cases to the procedures used to cast, finish and cure the slab.

Another surface blemish is the appearance of dark stains of irregular shape which are visible depending on the direction of light. These stains are originating from compacts of cement paste. They can be caused by the aggregation of coarse particles of cement which have hydrated only little in locations where the water/cement ratio is very low. It is the lack of hydration and the production of lime that leads to the dark colour. Such a segregation of coarse particles of cement can be caused by a filtering action of leaky formwork or of aggregate particles. With time, hydration may take place and the dark colour may disappear (Neville 1995).

3.2 Efflorescence

Building materials undergo a wide range of physical and chemical reactions in their service environment. Some of these reactions involve dissolution and physical migration of soluble salts with precipitation. When this occurs within pores in the solid matrix, the phenomenon is termed subflorescence. Subflorescence may on occasion be expansive with resulting physical disruption of the matrix.

Efflorescence is superficial deposits which look like a light, veiled or thick white crusts on the concrete surface. It may consist of different water soluble salts which precipitate as a crystalline layer on the concrete surface. These whitish deposits are aesthetically undesirable, but not normally expansive and do not deteriorate the wear resistance of the concrete (Dow and Glasser 2003).

Efflorescence can originate from the following materials:

- Carbonate for instance $CaCO_3$
- Sulphate for instance Na_2SO_4 and K_2SO_4
- Chloride for instance NaCl
- Nitrate for instance $Ca(NO_3)_2$
- Calcium hydroxide $Ca(OH)_2$
- Carbon dioxide CO_2

Lime is the main precipitant and will thus be discussed in the following.

Figure 1: Efflorescence

3.2.1 Lime precipitation

Primary lime precipitation looks like a light veil or as white, mostly spotty discolorations. This kind of precipitation originates from $Ca(OH)_2$ which is formed during cement hydration and which is in equilibrium with the pore water. $Ca(OH)_2$ precipitates on the concrete surface as the pore water reaches the surface. $Ca(OH)_2$ will then react with CO_2 from the air and form $CaCO_3$ (limestone). Primary precipitation occurs only for very young concrete.

Secondary lime precipitation is formed when water such as rainfall, accumulated water or condensed water penetrate the concrete from the outside. $Ca(OH)_2$ will in this case dissolve and be transported to the concrete surface. Solid lime will then precipitate in areas where the solute evaporates. Secondary lime precipitation can occur also for older concretes.

Lime scouring looks like partly white and yellow crusts which follow the direction of the water. Lime scouring is caused by continuous transport of water through fissures, grooves or other porous parts of the structure which dissolves $Ca(OH)_2$ and transports it to the surface. This solution precipitates lime in areas of evaporating solute.

The following factors favour lime precipitation:

- Insufficient compaction of the concrete and high permeability. The formation of efflorescence increases with shortened hydration times and increased water-cement ratios (Delair et al. 2007).
- Low temperatures since the solubility of $Ca(OH)_2$ and CO_2 increases markedly with decreasing temperatures. Figure 2 illustrates how the efflorescence formation reaches a maximum within a temperature range of 11-16 °C. Delayed concrete hardening will also be a contributing factor.
- Large temperature variations during the day (risk of condense formation). Figure 3 illustrates how efflorescence is influenced by climatic conditions. Samples exposed to fast drying from wind and/or sunshine precipitate for instance salts within the pores, subflorescence. Subflorescence may on occasion be expansive with resulting physical disruption to the physical coherence of the matrix. Precipitation of salts occurs, on the other hand, on the surface of the sample for slower drying rates such as for rainy weather and low temperatures. These deposits are normally not expansive.
- Piled concrete goods
- Water puddles
- Insufficient planning of water transport, continuous humidity fluctuations in the material.

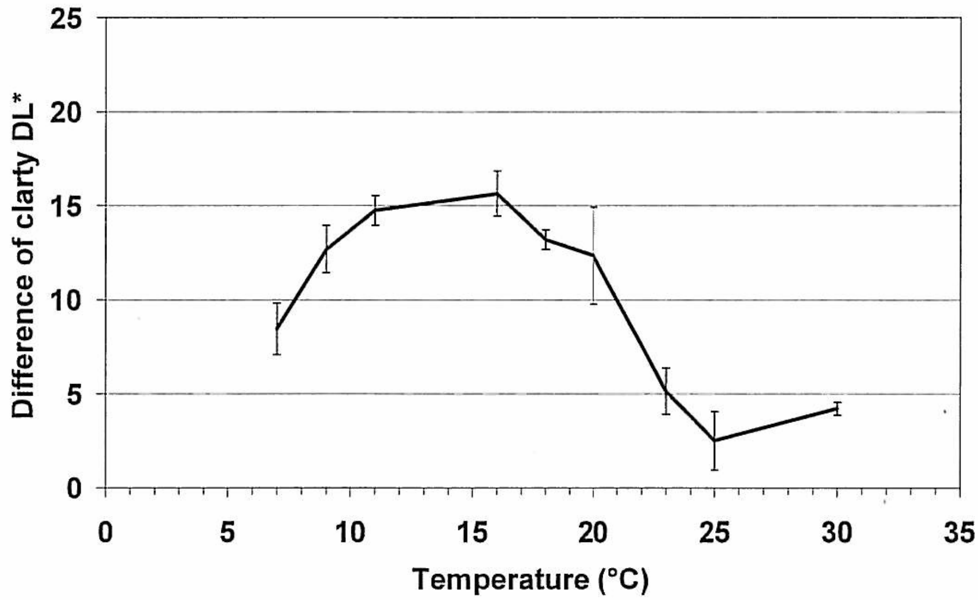

Figure 2: Influence of temperature on the formation of efflorescence (Delair et al. 2007)

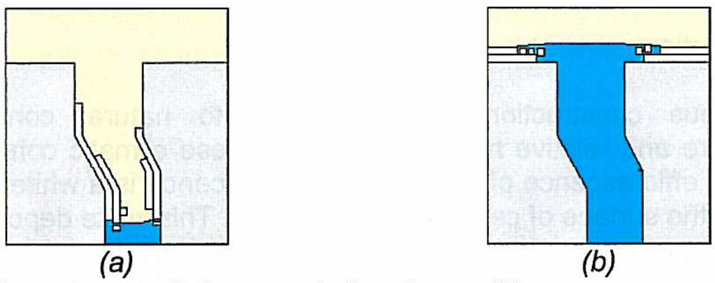

Figure 3: Influence of climatic conditions on salt precipitation. Image (a) shows precipitation within the pores as a consequence of fast drying, subflorescence. Image (b) shows precipitation of salts on top of the sample surface for slower drying rates, efflorescence (Delair et at. 2007)

The following measures can be taken to avoid lime precipitation:

- Use cement with granulated blast furnace slag, fly ash or another pozzolanic material which consume calcium hydroxide
- Use low-alkali cements. If alkalis cannot be avoided, sodium is preferred to potassium. Alkali contents need to be compared on a mole basis. (Dow and Glasser 2003).
- Produce joints as tight as possible
- Use of retarder and air entrainer
- Avoid evaporation inside the curing chamber
- Let the concrete dry quickly after it leaves the curing chamber
- Protect the concrete from direct rainfall and water
- Impregnate the concrete surface
- Cover gaps between formwork and concrete (protection against penetrating rainfall)
- Do not demould before or during strong rainfall
- Avoid to wash the surface with water after demoulding
- Prefabricated concrete should be stored with good ventilation (avoid too dense stacking of the goods)

3.2.2 Brown efflorescence

The colour of the so-called brown efflorescence can range from yellow to all shades of brown. Brown efflorescence has been linked to reduced compressive strength and increased porosity. The brown discoloration can develop both shortly after production as well as after longer periods of time. Brown efflorescence consists of calcium carbonate formed by carbonation of calcium hydroxide. The calcium carbonate crystals (calcite) are discoloured either wholly or partially to yellow-brown by soluble iron compounds present in the concrete. Sources of iron are cement clinker which has been burned under reducing conditions (iron (II) sulphate might be used as a chromate reducing agent during cement production), and stone chippings (aggregate) such as basalt. (Manns and Öttl 2002).

A method proposed for the investigation of efflorescence formation has been to cast cement paste samples of approximately 5 cm in diameter and 8 cm in height in plastic beakers. These are stripped after 24 hours and placed to a depth of 2 cm in a water bath with the finished surface facing upwards. The samples are then kept under observation for several weeks to determine any changes in colour (Manns and Öttl 2002). Another method is to apply controlled temperature and relative humidity to samples in a climatic chamber. The occurrence of efflorescenece can be evaluated visually or by spectrocolorimetry. The spectrocolorimeter gives values of clarity, L, which is scaled from 0 for black to 100 for white (Delair et al. 2007).

4 Surface discontinuities

4.1 Cold joints

Cold joints result from a delay in placement which is long enough to allow one concrete layer to harden before subsequent concrete is placed. Cold joints can be an aesthetical problem as illustrated by Figure 4 but can also cause other problems due to moisture penetration or loss of tensile strength of the concrete across the joint.

Figure 4: Cold joint illustrated by a sloping horizontal line (PCA IS536.01 2002)

4.2 Honeycombs

Honeycombs occur when mortar fails to fill the spaces between coarse aggregates. Congested reinforcement, segregation, and insufficient content of fine aggregates can contribute to honeycombing. Higher concrete slumps and vibration increase the concrete flowability and may, therefore, assist in preventing honeycombing.

Figure 5: Example of honeycombing (PCA IS536.01 2002)

4.3 Bugholes, pinholes and blowholes

One of the primary influences affecting the surface quality of concrete is blowholes. Bugholes, pinholes, blowholes, surface voids – they are recognized by various names, but all refer to the same phenomenon. Blowholes are small, regular or irregular cavities (over approx. 5 mm in size and usually not exceeding 15 mm) found at the surface and in the core of structural concrete.

These surface voids are primarily an aesthetic problem for exposed structural concrete. However, problems arise if the concrete surface is to be painted or if the voids reach a larger diameter (typically greater than 25 mm)

Blowholes result from the migration of entrapped air (and to a lesser extent water) to the fresh concrete-form interface during placement and consolidation. During consolidation, the densification and subsequent volume shrinkage of the fresh concrete forces entrapped air and excess water out of the cement matrix. The water will then tend to migrate upward due to its relatively low density and become bleed water. The air bubbles, however, seek the nearest route to reach pressure equilibrium. For a vertical form, the closest distance for the air bubbles' migration is to the interior form surface. Blowholes are, however, found more frequently in the upper portion of the concrete structure or at angled form surfaces as a result of additive accumulation of escaping air voids along the height of the structure (PCA, Linder 1992).

Figure 6: Blowholes

4.3.1 Parameters influencing blowhole formation

Mix design can be a significant contributor to blowhole formation. A sticky or stiff mixture that does not respond to consolidation can for instance be directly linked to increased surface void formation. Workable, flowing mixtures are easier to place and consolidate and reduce therefore the risk of blowhole formation. Concrete mixes that are richer in cement tend to show fewer blowholes than leaner mixes of the same workability. The effect of the cement content on a mix made with a well-graded aggregate appears, however, to be negligible (Thomson 1969). Silica fume and other pozzolanas such as granulated blastfurnace slag and fly ash have been shown to improve the concrete surface qualities as it reduces bleedwater in the concrete. As a result, voids caused by trapped bleed water are absent (Neville 1995).

Concretes made with lightweight aggregates having high water absorption present additional problems. If the aggregate is fairly dry when mixed, air within the aggregate particles can be displaced by water shortly after casting, causing more blowholes than would occur in concrete of the same workability made with fully saturated aggregate (Thomson 1969).

Improper vibration is perhaps the most influential cause of blowholes. Consolidation, usually through vibration, sets the air and water bubbles into motion. A proper amount of vibration sends both entrapped air and excess water to the free surface of the concrete – either vertically winding through the matrix or laterally in a direct route to the form wall. When impermeable forms are used, more vibration is necessary to move the air voids to the free surface of the concrete. The use of permeable forms can reduce blowholes significantly by allowing escaping air to move through the form to the ambient air.

Smooth, dense, wet, hard and rigid forming panels as well as water-repellent and thickly applied release agents result in more porous concrete surfaces than textured, porous, hygroscopic and soft facing materials onto which the emulsifying agents are thinly applied (Linder 1992). Impermeable forms (i.e. polymer impregnated wood and steel) and the use of form-releasing agents can restrict the movement of the air voids between the concrete-form interface that is necessary for blowhole reduction. It is, therefore, imperative that a given form-releasing agents is used with a suitable form material. Thomson (1969) reports on the other hand that the influence of formwork on the formation of blowholes is secondary provided that the shutters are clean and smooth and treated with a reliable form oil. An absorbent shutter lining will clearly reduce the size and number of holes and may completely remove them, but such linings can be expensive or impractical to use on large contracts. Thomson states, moreover, that the type of mould oil has little or no influence on the incidence of blowholes in concrete cast at normal temperatures. Some shutter materials and release agents may produce what is apparently a better finish by permitting a thin film of grout to conceal the blowholes, but this film may be easily broken and removed by weathering.

The temperature of a shutter can have a marked effect on the concrete finish. The casting of concrete of high or medium workability behind a thin shutter which is exposed to the cold can for instance result in the formation of small water-runs. The lower surface temperature delays the setting of the concrete and increases plastic settlement accompanying segregation of water from solids. The liquid water content increases also by water vapour present in the concrete which condenses in a higher degree on a colder surface. This effect might be avoided by insulating the shutters (Thomson 1969).

4.4 Water voids

Water voids, originating from bleeding, occur more frequently than air voids and in particular in the edge zones of concrete components. The shapes of small water voids may resemble the shapes of air voids. Water voids may also occur as narrow defects of longer length, with chain-like interlinked pores on perpendicular lateral faces. These run frequently perpendicular in streaks and are thus also referred to as water streaks. The number of water voids increases when release agents containing wetting agents are used, and in conjunction with soft facing materials that give during compaction. Excessive compaction, both in terms of duration and intensity will also increase the amount of formed water voids (Linder 1992).

4.5 Delaminations

Delaminations occur when air and bleed water become trapped under a prematurely closed mortar surface. The trapped air and bleed water separate the upper 3 to 6 mm layer of mortar from the underlying concrete. Delaminations are very difficult to detect during finishing and become apparent after the concrete surface has dried and the delaminated area is crushed. A smaller and more noticeable form of delamination is a blister that forms at the concrete surface from trapped air and bleed water.

The primary cause of delaminations is finishing the surface before bleeding is complete. Delaminations are more likely to occur when factors that extend the bleeding time of concrete are combined with factors that accelerate surface setting (PCA IS536.01 2002).

Figure 7: Delaminations and blisters (PCA IS536.01 2002)

4.6 Minimization of pores

Measures for minimizing pore formation during manufacture of concrete components are given in the following keywords (Linder 1992):

- Cement with little inclination to bleeding (e.g. most Portland cements with high fineness of grinding and cements containing pozzolanas,)
- Aggregate mix with sufficient ultrafine/sand contents, with a maximum particle size depending on the concrete cover and the type of reinforcement
- Utilization of plasticizers instead of a high water-cement ratio
- Uniform thin application of a suitable form release agent
- Thorough compaction, especially near edge zones and corners of components

5 Shrinkage

5.1 Definitions

Shrinkage can be grouped as follows:

- *Chemical Shrinkage* is the internal-microscopic volume reduction which is the result of the fact that the absolute volume of hydration products is smaller than that of the reacting constituents (cement and water). The main reason is the higher density of the chemically bound water compared to free water. Chemical shrinkage is roughly proportional to the degree of hydration beyond the very early stage. A consequence of chemical shrinkage is that concrete which is cured isolated without access to sufficient amounts of water will dry out internally in which the pores are not completely filled with water.
- *Autogenous Shrinkage* is the external-macroscopic (bulk) dimensional reduction of the cementitious system which occurs under isothermal conditions without exchange of moisture or any other substance with the surroundings (i.e. sealed curing). Autogenous shrinkage is usually driven by chemical shrinkage. This type of shrinkage is usually small for many normal compressive strength concretes and can usually be neglected. For concretes with water-cement ratios lower than 0.40, however, autogenous shrinkage may be a significant component of the total measured shrinkage (Tazawa 1999). The reader is referred to the State-of-the-art report written by Justnes (2004) for further information about autogenous shrinkage.
- *Drying shrinkage* of concrete is due to the evaporation of water from concrete which causes volume contraction. The measuring time for drying shrinkage is initiated 7 days after the sample has been immersed in water. A concrete specimen is typically exposed to an environment with low humidity and high temperature. Because drying shrinkage involves moisture movement through the material and moisture loss, drying shrinkage depends on the size and shape of the specimen.

5.2 Mechanisms of drying shrinkage

Although the mechanisms of drying shrinkage are not fully understood, the literature suggests that several mechanisms are dominant in different ranges of internal pore humidities. When considering concrete shrinkage in the 45-90 % relative humidity range, capillary stress appears to be the predominant mechanism. When pore water evaporates from capillary pores in hardened concrete during drying, tension in the liquid is transferred to the walls, resulting in shrinkage. For a given pore structure, the internal stress generated upon evaporation is proportional with the surface tension of the pore water solution and inverse proportional with the pore radius as described by the Kelvin-LaPlace equation for a circular meniscus:

$$P = \frac{2\gamma^{lg}}{R} = \frac{2\gamma^{lg}}{r\cos\Theta} \tag{1}$$

where
P is the capillary tension
R is the radii of the liquid meniscus
Θ is the liquid contact angle
r is the pore radius
γ^{lg} is the surface tension between the liquid (l) and gas phase (g)

5.3 Consequences of drying shrinkage

Since the moisture distribution in the concrete section is non-uniform and increases from the surface towards the centre, internal stresses develop. These are tensile stresses in the surface-near regions and compressive stresses in the interior parts. Quite frequently these tensile stresses lead to surface cracks.

Early age cracking spoils the concrete surface and may seriously affect the service life of structures, since they are pathways of H_2O, CO_2, O_2 and Cl^- which lower the durability due to hastening the corrosion of steel bars.

5.4 Factors influencing drying shrinkage

Drying shrinkage is larger the higher the w/c ratio because the latter determines the amount of evaporable water in the cement paste and the rate at which water can move towards the surface of the specimen.

The chemical composition of cement is not believed to affect shrinkage except that cements deficient in gypsum exhibit a greatly increased shrinkage. Shrinkage of concrete made with high-alumina cement is of the same magnitude as when Portland cement is used, but it takes place more rapidly. Finely ground cements result in greater shrinkage than coarser ground cements.

Type (restraining effect- shrinking/non-shrinking) and amount of aggregates is the most important factor in affecting the potential shrinkage of concrete as the aggregate restrains shrinkage of the cement paste. The size and grading of aggregate per se do not influence the magnitude of shrinkage, but a larger aggregate permits the use of a leaner mix and, hence, results in lower shrinkage. A rounder aggregate may result in a decreased paste content that will result in lower shrinkage. Care should be taken with aggregates containing clay minerals as these tend to increase the drying shrinkage due to their high water demands.

Differing results have been reported upon the effect of water reducing admixtures on drying shrinkage. Neville (1995) claims that water reducing admixtures probably cause a small increase in shrinkage. He states that their main effect is indirect in that the use of an admixture may result in a change in the water content and/or the cement content of the mix. Brooks (1989, 1999) states on the other hand that water reducing admixtures may increase shrinkage by 20 % at the same water content depending on composition.

Entrainment of air has been found to have no effect on shrinkage when the total content is less than 8 %.

Low humidity, wind and high temperature increase the rate of drying and lead thus to increased rates and magnitudes of drying shrinkage. Thick concrete members shrink at a slower rate than thin concrete members due to the slower rate of drying.

The shape of the specimen affects the distance moisture has to travel to the air. It also affects stress concentrations within the drying concrete obtained from nonuniform shrinkage occurring through the cross section of the specimen.

5.4.1 Effect of supplementary cementitious materials on drying shrinkage

Conflicting results are reported about the effect of supplementary cementitious materials on drying shrinkage. It is therefore likely that the reactivity is governed by the dosage, way of addition, particle size and reactivity of the material:

Addition of fly ash has been reported to increase shrinkage (Neville 1995) as well as having no influence (Brooks 1989, 1999). Ground granulated blast furnace slag has similarly been reported both to increase shrinkage (Neville 1995, Brooks 1989 and 1999) and reduce drying shrinkage (Jianyong and Yan 2001).

The presence of silica fume affects significantly the properties of fresh concrete. The mix is strongly cohesive and, in consequence, the bleeding tendency is reduced. Reduced bleeding can lead to plastic shrinkage cracking under drying conditions, unless preventive measures are taken. Silica fume is, moreover, believed to increase long-term shrinkage due to high pozzolanic reactivity and pore size refinement. Pore size refinement causes higher tension on the pore walls as described by equation (1) (Neville 1995, Rao 2001).

$$P = \frac{2\gamma^{\mathrm{lg}}}{r} \qquad (1)$$

Khatri and Sirivivatanon (1995) found that 10 % SF increased the early age drying shrinkage of the concrete. The long term drying shrinkage was, however, lower than the reference. The authors used variable plasticizer dosages for the mixes in order to keep a constant slump value for all mixes.

Alsayed (1998) found that *adding* 10 % (and thus reducing the the w/b ratio) to concrete reduced the 3 year drying shrinkage. Brooks (1989, 1999) found, on the other hand, decreased shrinkage when the *replacement* of cement with silica fume was less than 7.5 %.

5.5 Countermeasures of drying shrinkage

Some of the measures taken to reduce shrinkage cracking have been

- Appropriate reinforcement: The reinforcement does not reduce shrinkage, but distribute the deformation. A number of small cracks will thus occur instead of one big. The sum of deformation is, however, not changed
- Moist curing
- The use of high-range water reducers to attain low water-cement ratios
- The use of expansive admixture and shrinkage compensating cements
- Shrinkage reducing admixtures (SRAs)

5.5.1 Moist curing/watering

Extended periods of moist curing will usually reduce the amount of drying shrinkage in a concrete mixture by 10 to 20 %. This effect varies with different water-cement ratios. Perenchio (1997) showed that periods of curing greater than 4-8 days (96-192 h) and less than 35-50 days (840-1200 h) may increase the drying shrinkage. Heat and steam curing can significantly reduce drying shrinkage of concrete by as much as 30 %.

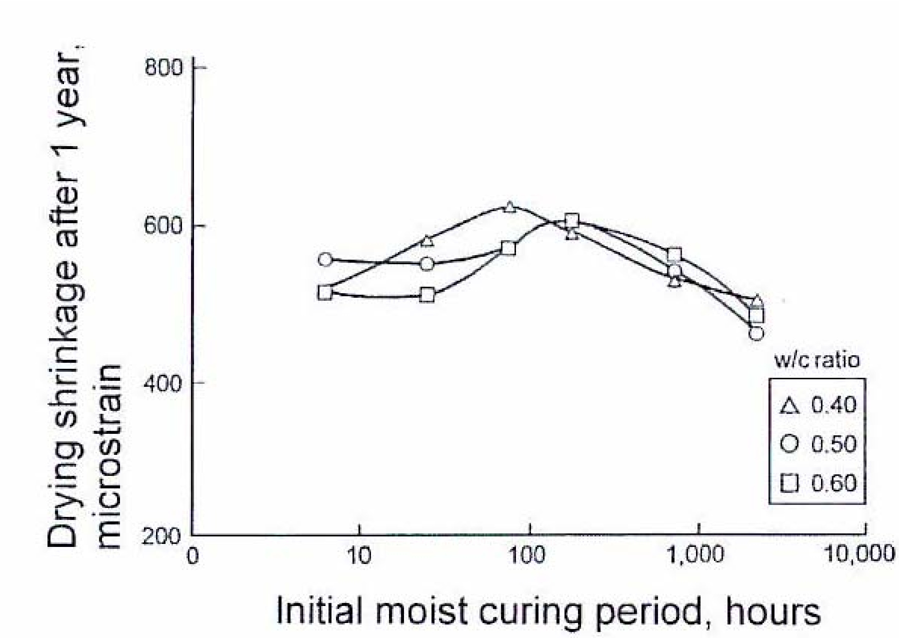

Figure 8: Effect of time of moist curing and water-cement ratio on drying shrinkage (Perenchio 1997)

5.5.2 Expansive agents

Many attempts have been made to develop a cement which on hydration will counteract the deformation induced by shrinkage. The use of expansive cements does not prevent the development of shrinkage: The shrinkage is merely balanced by restrained early expansion.

Usually, a small residual expansion is aimed at since shrinkage cracking will not develop as long as some compressive stress in concrete is retained.

The expansion of cement paste resulting from the formation of ettringite begins as soon as water has been added to the mix, but only restrained expansion is beneficial and no restraint is offered while concrete is in the plastic state or while it has negligible strength. Thus, prolonged mixing and delay before placing should be avoided. Delayed expansion in concrete in service may prove disruptive. It is therefore important that ettringite formation ceases after some days.

Because of the large amount of ettringite formation in the early hydration stage, proper early water curing and designed amount of restraint must be provided for concrete. Ettringite formation requires a large amount of water (32 water molecules per formula unit), wet curing is therefore necessary for full benefits of the use of such a cement.

Types of expansive agents

Expansive agents are special products which can increase the volume of concrete due to specific chemical reactions. There are several families of expansive agents. The most important are based on the formation of ettringite ($3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$) or calcium hydroxide ($Ca(OH)_2$) such as anhydrous sulfo-aluminate ($3CaO{\cdot}3Al_2O_3{\cdot}CaSO_4$ also known as Hauyne/Kleinite):

$$C_4A_3\overline{S} + 6C + 8CS + 96H \Rightarrow 3C_3A \cdot 3C\overline{S}H_{32} \tag{2}$$

$$\mathrm{C + H = CH} \tag{3}$$

The chemical reactions are written with the chemist short hand notation where

$A = Al_2O_3$
$C = CaO$
$\overline{S} = SO_3$
$S = SO_4$
$H = H_2O$

The expansion produced by lime and sulfo-aluminate must occur within a given period of time in a reinforced concrete, so that the restrained expansion produces a tensile stress in the reinforcement and a compressive stress in the concrete. This can occur only if the expansion process develops mainly after the concrete compressive strength starts to grow and consequently the steel-concrete bond starts to develop. From this point of view the ettringite formation depends on the reactants as illustrated by Figure 9. Figure 9 indicates that the process related to lime hydration occurs within 1-2 days, whereas that based on ettringite formation need about 5-7 days to completely develop its potential expansion. If these two expansion rates are compared with two typical strength developments (cement A and B) one can conclude that only ettringite formation agrees well with both concrete A and B. On the other hand, the expansion rate related to lime hydration agrees very well only with the early strength developments of A, whereas B does not develop an adequate strength level in the period of time (0-12 h) corresponding to the main part of the total expansion (Collepardi et al 2005).

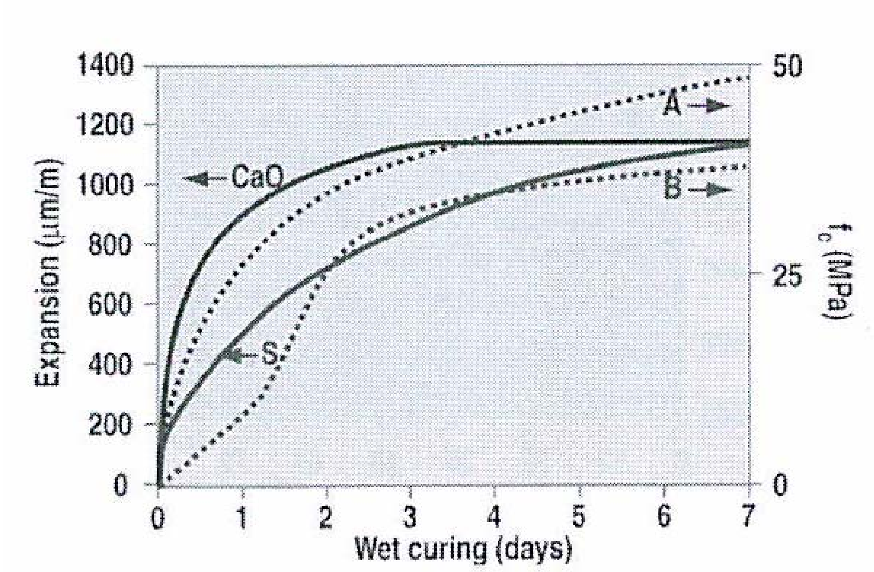

Figure 9: Restrained expansion and compressive strength (f_c) for concretes with CaO or sulfo-aluminate (S) (Collepardi et al 2005)

Three main types of expansive cements are produced. Each of the cements contains a source of reactive aluminate which combines with sulphates in Portland cement to form expansive ettringite:

- 1. Type K cement contains kleinite $C_4A_3\overline{S}$ and uncombined C
- 2. Type M cement contains calcium aluminates CA and $C_{12}A_7$
- 3. Type S cement contains C_3A in excess of the amount normally present in Portland cement. The cement has more limited application than the others because of the difficulty of steadily controlling the rate of formation of ettringite from C_3A
- Type O cement is produced in Japan and use specially processed calcium oxide to produce free-lime expansion

Another expansive agent is MgO (from Magnesite, $MgCO_3$, or Dolomite, $CaMg(CO_3)_2$) which reacts with water to form $Mg(OH)_2$ that causes a volume expansion of about 118 %. The dead burned MgO reacts very slowly with water which causes the expansion to take place after the solidification of cement. However, it is difficult to get cement with suitable content of MgO to obtain the required expansion rate and expansion ratio for various constructions. The expansion of pastes depends strongly on the production conditions (i.e burning temperature) and dosage of MgO-based expansive agents.

The use of shrinkage compensating cement has not been fully embraced by the concrete construction market. This lack of acceptance is due in part to the difficulty in understanding and harnessing the benefits of shrinkage compensating cement. For instance,

- Due to the abundance of ettringite formed during the early hydration stages, rapid slump loss is often observed and can be problematic.
- Since moisture is needed to trigger the expansive reaction proper moist-curing is essential.
- The amount of restraint provided within the concrete element (formwork, reinforcing steel etc.) must be accurately designed and incorporated into the structure to achieve the desired restrained expansion (Folliard and Berke 1997)

Shrinkage Reducing Admixture (SRA)

Shrinkage-reducing admixtures (SRA) alter the shrinkage mechanism chemically without expansion. SRAs are regarded as nonionic surface active agents. They are composed of two parts in their molecular structure, one is the hydrophobic (= water fearing) group and the other is a hydrophilic (= water loving) group. Surface active agents adsorb strongly and give a marked reduction in the surface tension even at low concentrations as illustrated by Figure 10. According to some reports, SRA can reduce plastic shrinkage, autogenous shrinkage and especially drying shrinkage (Engstrand 1997, Bentz et al 2001, Nmai et al 1998).

The mechanism of SRA is disputable, but some researchers (Folliard and Berke 1997, Bentz et al 2001) believe that SRA lowers the surface tension of water in the capillary pores. The driving force for water to evaporate is the lower surrounding humidity. As water filled pores in the size range 2.5-50 nm lose moisture, curved menisci are formed, and the surface tension of the water pulls the walls of the pores as described by equation (1). With the reduced surface tension of the water, the force pulling in on the walls of the pores is reduced. In addition to the decrease in free shrinkage, there could be a reduction in the volume of macropores in the hardened cement paste, the permeability of concrete and the crack widths in restrained concrete under drying conditions.

Other benefits that have been reported include

+ concrete mixture proportions remain relatively unchanged
+ reduced shrinkage strain
+ increased fluidity/workability of the fresh concrete (Berke et al. 1997)
+ decreased tensile creep
+ restrained shrinkage cracking
+ restrained chloride ingress in the hardened concrete (Berke et al. 1997)

On the other hand, some negative influences have also been attributed to the SRAs such as

- decreased compressive strength (Brooks and Jiang 1997, Gettu and Roncero 2005) (Folliard and Berke 1997)
- decreased tensile strengths (Brooks and Jiang 1997, Gettu and Roncero 2005)
- decreased modulus of elasticity
- negative effect on freeze/thaw resistance

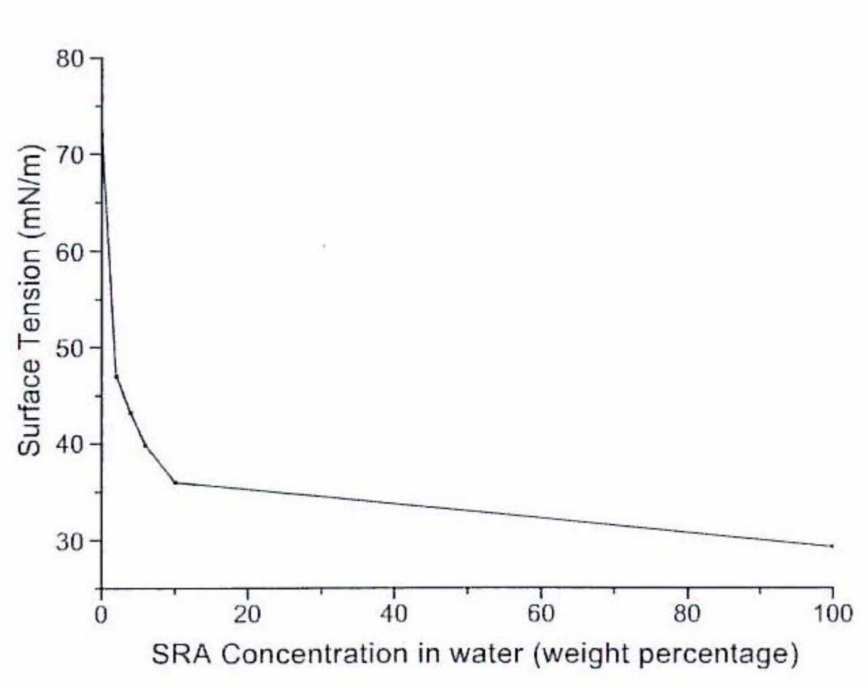

Figure 10: Effect of SRA on surface tension (Ronbing and Jian 2005)

Combined effect of SRA and expansive agent

Collepardi et al (2005) found a synergetic effect in the combined use of SRA and a CaO based expansive agent in terms of more effective expansion in the absence of wet curing. However, the effect was significantly reduced when a self-compacting concrete was used because of the prolonged fluid and plastic state of the mixture.

New generation plasticizer with shrinkage reducing component (SRC)

A plasticizer with a shrinkage reducing component composed of a diethylene glycol dipropylene glycol monobutyl ether has been developed that can reduce drying shrinkage and still keep the performances of the superplasticizer (Sugiyama et al. 1998, Yamada et al. 2004). The entrained air system is expected to be controlled successfully compared to traditional SRAs and so the degradation of the freeze/thaw resistance can be avoided (Sugiyama et al. 1998).

6 Influence of casting techniques, formwork and form releasing agents on the concrete surface

6.1 Influence of casting technique and temperature

The quality of a concrete surface depends generally on the way the concrete is cast. It is for instance imperative that the casting is continuous (Bilberg 1999). The concrete temperature should, moreover, be kept consistent. Concrete temperatures between 18 and 29 °C, have been reported to produce concrete uniform in colour. Concrete temperatures higher than 27°C may result in faster setting rate, visible flow lines, and cold joints if proper scheduling of concrete placement is not closely coordinated with the concrete producer. A high concrete (or ambient) temperature calls, thus, for a change in concrete mix proportions. Holding the temperature constant is especially difficult when the project extends over more than one season. If colour uniformity is critical, testing for variations of colour at different temperatures should be considered (ACI 303R-04).

There is a tendency for a lighter colour and an increase in amount of blowholes in concrete near the top of the placement lifts due to decreased form pressures, inadequate vibration, and an increase of w/cm at these locations. Attention should be given to properly consolidate the concrete in the upper layers of placement lifts to improve appearance (ACI 303R-04).

Figure 11: Flow line

6.2 Influence of form releasing agents on the concrete surface

Main parts of the following information about form releasing agents are taken from Waterloo (2003).

Hardened concrete will bond with any form surface, whether it is made of iron, steel, wood or other. Release agents, applied to the forms, are materials that permit, enhance or aid in the clean release of the partially hardened concrete from the casting form. The release agent is also expected to protect the form and contribute to the quality of the casting.

There are more than 400 different concrete form release agents offered in today's international market. Release agents fall into two primary categories: barrier and reactive. Barrier release agents create a physical barrier between the form and the concrete. The key to "reactive" release agents is the reaction of the fatty acid with the free lime on the surface of the concrete. This reaction causes the formation of metallic soaps, which are water insoluble and chemically inert. This metallic soap is what allows for the easy release of the product from the form and also allows the entrapped air on the vertical walls of the form to rise more easily to the fresh concrete surface during casting.

Chemically active release agents can be categorized as buffered reactive (partially reactive) and fully reactive types. Buffered form release agents tend to produce an improved soap film that not only helps remove entrapped air but may promote better flow of a thin skin of cement paste at the surface of the form. This may help explain why, in vertical castings, these release agents tend to minimize or eliminate the striped effect from vibrator insertions. Fully reactive form release agents can provide a good basic soap film that, depending on formulation, works well in most cases. Because buffered and fully reactive release agents are similar and proprietary, specifying absolute differences between them is difficult. Generally, the buffered release agents produce a slightly different type of soap film that, with some brands, assists in improving the visual impact (ACI 303R-4).

Chemically active release agents are the most common for architectural concrete surfaces. Soap formed by the reaction between fatty acids and basic constituents ($Ca(OH)_2$) in concrete is a better lubricant than oil for the removal of entrapped air in fresh concrete (ACI 303R-4).

Barrier release agents fall into six primary categories:

6.2.1 Plain petroleum oils

These are normally light bodied, low-viscosity petroleum oils that often contain paraffin. Straight diesel, fuel oil and kerosene fall into this category. Plain petroleum release agents are becoming less prevalent in the concrete industry because they require heavier application and often raise environmental and employee safety concerns. Straight petroleum oils will encapsulate air on the vertical sidewalls of the mould, causing voids, or blowholes. Staining is also a common problem.

6.2.2 Water emulsions

Water emulsions are typically petroleum-based materials dispersed in water with the aid of polymers or surfactants. Water-based emulsions can also fall in the "reactive" category if they contain some type of reactive material such as fatty acid or tall oil. As emulsions contain water, they may cause rust. Another category for emulsions contains caustic materials which forms a barrier on the form.

6.2.3 Soaps

Soaps are surfactants. Application is relatively simple, but they are typically alkaline and often require special handling precautions. Soaps may also build up on the forms.

6.2.4 Nonreactive coatings with volatile solvents

These release agents are also typically petroleum-based. They contain waxes, rosins, silicones, soaps or synthetic resins, which act as a barrier between the form and the casting. After application to the form, the solvent evaporates, leaving a barrier and/or a reactive surface. The surface film normally transfers onto the concrete, which must be cleaned before applying paint, sealant or other coatings.

6.2.5 Waxes

Waxes include paraffin-based materials and even car-waxing compounds. They are difficult and labor-intensive to apply and will generally build up on forms in a short period of time. Waxes are nonreactive and more inclined to cause surface voids. The residue transferred to the concrete should be cleaned before applying paint or other coatings.

6.2.6 Biodegradable

A "biodegradable" product will return to its natural state within specified time limits. Reactive release agents typically contain weak acids derived from vegetable oils and/or animal fats, and all fall into the category of "fatty acids." Also included in this category are byproducts from paper manufacturers, such as lignosulfonates and tall oils.

Reactive form release agents fall into two primary categories namely vegetable oils and petroleum-based. Vegetable oil-based release agents are typically more environmentally friendly, biodegradable, non-photochemically reactive and renewable than petroleum-based. A large portion of the reactive release agents in use contain, however, petroleum-based carrying agents. Since only a small percentage of the right fatty acid is needed to get the job done, the majority of the release agent will be the petroleum-based carrying agent. An excessive amount of fatty acid in the release agent can result in the fatty acid migrating into the concrete, acting as a retarder and causing soft crumbly surfaces. High concentrations of fatty acids can, however, be used for conditioning and/or seasoning of forms.

Ichimiya et al (2005) studied the relation between type of form oil and pores on the concrete surface. A commercially available non-stick oily-type form releasing agent with principal component consisting of a paraffin type hydrocarbon was compared with a water based agent. The generation of surface voids was examined by image analysis. Concrete samples cast in forms with the water based form-releasing agent had fewer surface voids than samples cast with the oil-based agent. The surface voids in samples prepared in forms with water-based form releasing agent were, however, found to be covered by a thin layer of cement paste and were thus named “invisible” surface voids. The different surface qualities might be a result of altered cement hydration since some mould release agents, e.g. vegetable oils and water emulsions are known to retard the cement hydration of concrete close to the mould. Retarded hydration might results in bleed water accumulating at the vertical mould surface (Gram 2004).

During compaction of fresh concrete, the compaction energy transmitted to the forming panels can easily result in the film of applied release agent becoming partly embedded in the edge zone and partly, in an irregular fashion, in the surface. The release agent will weather after the formwork has been removed, leaving behind small pores of a size approximating the lower limits of visual inspection, up to dimensions of about one millimetre. These pores can erroneously be taken for air or water voids. Inclusion of form releasing agent tends to occur most readily when excessive amounts of release agents of certain kinds and types are applied, as a result of intensive compaction, with a not very rigid formwork and for soft concrete consistencies (Linder 1992).

6.2.7 Application of form releasing agents

Most barrier type form oils based on fatty acids release better when heavily applied to the form. However, heavy application of form oil causes the excess oil to bead up against the fresh cement paste which increases the chances for staining and blowholes. The performance of some release agents, however, is not affected by film thickness (ACI 303R-4). A number of options are available for application of form release agents. Spraying is the most common method and is a recommended method by some authors (Rau 2001), but swabbing, fogging, wiping and dipping are also acceptable methods. In all cases, a thin coat of form release is all that is needed and will help to minimize staining and surface defects. Any excess material should be removed subsequently since too thick or uneven application of the release agent could lead to staining and variations in the grey coloration of the concrete (Rau 2001). All form areas should be coated before placing reinforcement in the forms so the reinforcement can bond properly to the concrete (Waterloo 2003). Rusty forms, used as is, will promote sticking and staining. Rust should be removed, and the forms seasoned before returning to production.

6.3 Influence of formwork

The appearance of the concrete will be largely determined by the formwork skin and the arrangement and form of the ties. The quantity of water used to make a high-workable concrete is much higher than what is needed solely for cement hydration and consequently the mortar contains a pore solution. Part of this pore solution can be absorbed by the mould during casting. One differentiates, therefore, between absorbent and non-absorbent surfaces. The absorbency of the form surface is an important factor in determining the type of release agent (mould oil) that is applied.

Forms and liners that have moisture contents below saturation will absorb water from the fresh concrete, resulting in a darker concrete colour. The colour will vary with the absorptive capacity of the form. Form release agents will not solve this problem. ACI (303R-4) recommends sealing the surface of the absorptive form surfaces. It is unclear how this will affect the distribution of air bubbles on the surface.

Nonporous forms and form liners, including many polymers, elastomers, and steel, help according to ACI (303R-10) to produce the best visual impact surfaces. Lallemant et al. (2000) found, on the other hand, that tint heterogeneities occurred when mortars were cast in non-absorbent moulds (metal, plastic), while the tint was uniform for mortars kept in absorbent moulds (wood).

The following (commonly used) formwork materials have an absorbent surface.

6.3.1 Wood boarding

Nicely patterned surfaces of good quality can be realised using rough timber formwork (RILEM 2006). Formworks of wooden boards seem, moreover, to adsorb air bubbles near the surface (Heimdal and Mathisen 2001). It is well known that lumber forms affect the colour of the concrete. A mottled effect is achieved through variations in water absorption of different densities in the grain of the board surfaces. The softer grains of the wood will absorb more water from the surface of the fresh concrete, lowering the w/c ratio of the concrete, which causes a darker surface colour. With each use of wooden formwork, the darkening effect of the lumber on the concrete surface becomes less. When forms are reused several times, considerable variation in concrete surface colour and texture may be expected from the first use to the last unless the wood is treated. All form lumber should be obtained from the same source, and a form coating or sealer should be used to avoid reduced flow and colour differences.

The surface of the board may be worked in several ways. Rough sawn boards are strongly absorbent and produce a dark concrete surface. Wrot boarding (timber made smooth on one or more surfaces) is less absorbent, has a smoother texture and results in a lighter coloration. Sand blasting and brushing can be used to produce a textured surface.

Organic substances in the wood can result in a discoloured concrete surface, and wood sugars can cause dusting. Release agents cannot prevent either of these conditions. Dusting caused by wood sugar is, however, only significant in the first use. It may, therefore, be desirable to simulate a first use by coating a new form face with a cement slurry, washing it off and reapplying the form release agent. (ACI 303R-04, Rau 2001).

6.3.2 Chipboard

Chipboard is either pretreated or left rough and produces a surface similar to that of woodchip wallpaper.

6.3.3 Laminated or veneered boards (plywood)

Laminated or veneered boards may have a surface that is not coated with a film, so that the wood texture is visible in the face of the concrete or have up to 15 layers and a film coating on both faces producing a smooth surface with a pronounced porous texture. Extremely smooth surfaces can be obtained by means of plywood formwork (RILEM 2006). A number of small pores have, however, been observed for this type of formwork material (Johansen 1999).

6.3.4 Fibrous drainage matting

Fibrous drainage matting may sometimes be stretched over the face of the formwork to produce a high-quality finish almost without pores. Care should be taken that no creases are formed in the matting. Permeable formwork is a special class of cloth-lined formwork intended to produce improvements in the strength and durability of the surface of concrete. The bracing and the liner in the formwork are engineered to resist the pressure of plastic (fresh) concrete, but to allow trapped air and excess water to pass through and be removed during concrete movement and consolidation (vibration). This ensures a denser near-surface concrete with reduced permeability (Nolan et al. 1995).

The concrete curing is aided in two ways. In the critical period between pouring and stripping of the formwork, the water-rich liner acts like a curing membrane. Thereafter, upon stripping the reduced porosity of the surface means that there is no rapid moisture loss (Wilson 2000).

The quality of concrete near the surface ("covercrete") for depths up to 10 mm is usually acknowledged as being poorer than that in the interior ("heartcreat"). The reasons for this are generally attributed to effects of water gain and lack of curing. The result is a softer, more porous and permeable surface. Experiments using controlled permeable formwork have shown that the measured w/c ratios were lower and cement contents higher in the outer concrete zone than those used in the mix. These differences translated into enhanced concrete durability when tests for chloride ingress, carbonation, abrasion, porosity, permeability, surface strength and freeze/thaw resistance were performed (Wilson 2000).

Sato et al. (1989) have demonstrated that in a permeable form-based concrete, carbonation and salt penetration was reduced in speed by 60 % or more in comparison with concrete prepared with a conventional form. A porosity test showed that the total pore volume was decreased to 1/2 of the conventional specimen, at 0 - 7.5 mm in depth from the surface.

Arslan (2001) found that ordinary, vibrated concrete made with controlled permeability formwork had 20 times less blowhole area; 70 % higher surface hardness by Schmidt hammer; 4 times less depth of carbonation penetration and 5 times less depth of chloride penetration than concrete made with ordinary formwork.

The architectural merits of concrete cast with permeable formwork have generally not been emphasized because permeable formwork may produce a mottled and dark grey surface. The surface will be virtually bug hole free, but may not have a uniform colour (Farahmandpour 1992).

The following materials may be used where non-absorbent formwork is required:

6.3.5 Steel sheets

Steel sheets can result in extremely smooth, light-coloured surfaces (RILEM 2006). Steel plate formwork have, however, been found to have a greater tendency of producing air bubbles on the concrete surface than wood which is a more absorbing formwork material (Heimdal and Mathisen 2001, Johansen 1999). Steel sheets should be carefully cleaned to avoid rust stains on the concrete surface.

6.3.6 Plastic skins

Plastic skins produce extremely smooth surfaces, although it would seem that plastic coatings are not an ideal material for exposed concrete. Various prefabricated liners can be inserted in the formwork to produce different surface textures. The joints between these inserts should be impermeable (Rau 2001). Some plastic forming materials may produce a glossy concrete surface that should be used with caution as such surfaces exposed to the weather will soon loose some of their gloss due to the effects of wetting or drying and freezing and thawing. Repairs may, moreover, be difficult to match when the as-cast surface is glossy (ACI 303-R-04).

6.3.7 Plaster

Highly detailed forms can be made of plaster. The concrete is cast against these moulds and the plaster is then broken away from the finished concrete. An effective membrane-forming bond breaker should be used with plaster waste moulds. Use of solvent-based release agents is not recommended because most of these products may soak into the plaster, resulting in a defective release (ACI 303R-10).

6.4 Form removal

Care should be exercised during form removal to prevent sudden drops of concrete temperature or thermal shock. This is especially true when surface retarders have been used on large sections and cool water under pressure is used to expose aggregates. When concrete is being protected from extremely low temperatures, the rate of cooling should be gradual and not exceed 22 ^{o}C for the 24 h period following the termination of heat application. Loosening forms slightly, without complete removal, aids in gradual cooling and will minimize the occurrence of map cracking caused by thermal shock.

Early stripping after the concrete has attained its specified stripping strength of formwork or form liners is recommended as release agents generally do not continue to break the bond between formwork and hardened concrete after extended periods of time, such as 48 hours. Sticking can occur if forms are left in place much longer (ACI 303R-04).

7 Self compacting concrete, SCC

The fluidity of SCC and the elimination of vibration result in improved surface quality of the concrete. SCC has normally less bleeding tendency than vibrated concrete. It has a uniform quality, the binder phase is denser and there are fewer weakness zones between aggregates and paste.

SCC surfaces have been found to be smoother compared to normal vibrated concrete. Pour lines, bugholes, honeycombs, gravel grooves and other surface imperfections are also largely reduced (Johansen 1999, Gaimster and Foord 2000). SCC renders, moreover, improved microstructural features leading to potential improvements of strength, durability and surface quality (RILEM 2006).

An improved surface appearance is generally obtained with slump flow values greater than 610 mm with controlled rheological properties and minimal to no bleeding characteristics (ACI 237R-07). It is important to control the workability of the concrete over time since workability loss causes poor filling ability and thus surface defects (Gram 2004). Surface defects might also occur due to the retarding effect of the superplasticizer and/or low casting temperatures. During the prolonged setting time, the concrete may segregate or bleed, allowing water to be transported to the mould surface, where it may produce blowholes or stream upwards along the mould. Other contributing factors could be the interaction with the form releasing agent (type and thickness) applied to the moulds.

Free fall of SCC mixtures into walls, columns, or other deep sections should be avoided to avoid trapping air within the concrete. Vertical dropping of SCC directly into existing layers of already placed concrete can produce a vortex of new concrete influx into the old, carrying a significant amount of entrapped air that will be retained within the concrete.

Pumping SCC from the underneath of the formwork has proven to be beneficial when high demands of aesthetics are of importance. The problems with pores and potholes also tends to be less when the concrete has been fed from underneath through valves (RILEM 2006).

Inadequate or intermittent supply of SCC, when placed in drier and warmer ambient conditions may result in pour lines. Pour lines appear as dark, thin lines that can be distinguished between layers of concrete. These pour lines can be merely cosmetic or can indicate cold joints (ACI 237R-07).

Whenever possible, SCC should be deposited continuously and in layers of such thickness that no fresh SCC is placed on concrete that has hardened enough to cause a seam or plane of weakness. Some SCC have thixotropic characteristics, and may then be placed onto previously placed SCC that has gelled but not yet achieved initial set. ACI (237R-07) recommends in this case to use an internal or external vibrator for a 2- to 3-second duration to avoid pour lines in the piece. RILEM (2006) and Trägårdh (1999), however, advise against vibration of SCC and claims that any external vibration to remedy honeycombing or bugholes will do more damage than good. They have found that vibration can cause bleeding, sand-streaking, accumulation of pores and severe aggregate segregation within the unit.

During compaction, with hand held pokers or fixed vibrators, entrapped air in the concrete or in the border zone between the form and the concrete, can relatively easily be “pushed” upwards and out. For SCC, entrapped air has to be forced out by the moving concrete inside the formwork, with some help of gravitational forces. SCC should, therefore, be given the possibility to flow for at least a certain distance and casting all along the element should be avoided. The amount of pores is partly reflected by the casting rate. A high casting rate, with thick concrete layers, usually results in more blowholes compared to thinner layers and a lower casting rate. Low temperatures tend to give a higher porosity, especially if the formwork itself is cool, presumable depending on water separation at the border zone between the concrete and the formwork (RILEM 2006).

Some entrapped air near the formwork may escape if the formwork is permeable enough. Tight formwork materials, therefore, often results in more porosity and blowholes compared to permeable formwork materials. Badly cleaned or heavily worn surfaces have a tendency to induce more surface porosity compared to new, smooth surfaces. This is probably due to the fact that small air bubbles stick easier to dirty, rugged or bad cleaned surfaces. A thin coating of form release agent seems to be favourable in comparison to a thick layer since air bubbles apparently sticks harder to a thick layer of release agent. The choice of form release agents have shown to be more critical in regard to the appearance of the finished SCC structure, compared to vibrated concrete.

The formwork should be watertight (nonleaking) and grout-tight when placing SCC, especially when the mixture has relatively low viscosity. The need to design the formwork for water tightness is greater than conventional formwork so as to avoid honeycombs and surface defects. The use of foamed plastic sealing strip or moisture curing gunned silicone rubber provides effective means of sealing joints. Adhesive sealing tape is usually placed on panel joint with very good results (ACI 237R-07, RILEM 2006). When the forms are made of a material with no absorption capacity, permeable linings can be considered to prevent bug-holes from appearing

(RILEM 2006). The amount of SCC needed for one panel should be accurately estimated, as some colour differences can be expected with different batches. The top of the formwork should be covered to protect from rain. Even a small amount of rain can yield discolouring and sand stripes on the SCC surface.

SCC mixes are characterised by a moderate to higher amount of fines in the formulation, including various combinations of powders such as Portland cement, limestone filler, silica fume, fly-ash or ground granulated blast furnace slag. Thus, there might be very little or no bleeding and the concrete may thus be more sensitive to plastic shrinkage cracking. The tendency of plastic shrinkage increases, however, with the increase in the volume of fines. This situation is sometimes more complicated if the setting time is delayed because of the admixture effect. Curing to counteract longer term shrinkage is to be handled like what is done for vibrated concrete. It should be observed that due to a lower permeability of SCC, the drying rate and thus also the shrinkage rate might be slower (RILEM 2006).

Thus, SCC shows great potential to obtain good surfaces, in a way which is hard to get with vibrated concrete. SCC seems, however, to be more sensitive than vibrated concrete with regard to surface finishing, due to the way it is cast, the nature of the formwork, the type and thickness of applied release agent, temperature of the formwork and weather conditions (RILEM 2006).

8 Ongoing projects concerning surface quality

“Den synlige betonoverflade - – Forbedring og fornyelse af betons æstetiske kvaliteter” is a Danish Nanocem project (http://www.nanocem.org/partners/) which was initiated January 1st 2005 and which will terminated by the end of 2007. The project is implemented as a cooperation between 11 enterprises and research centres which represent all stages of construction. See www.synligbeton.dk for more information.

9 Summary

This state of the art report discusses parameters which influence quality and aesthetical impression of the concrete surface. The main focus has been on evenness of colour, occurrence of voids and pores and cracking due to drying shrinkage.

Surface voids can be avoided through careful selection of materials and quality workmanship.

The appearance of the concrete will largely be determined by the formwork skin and the arrangement of the form and ties. Evenness of colour is for instance influenced by the homogeneity of the binder and the absorption properties of the mould.

Formwork can be grouped as absorbing and non-absorbing. Absorbing formwork materials like timber seem to absorb air bubbles near the surface and render good surface qualities. Non-absorbing formwork materials can result in extremely smooth and light coloured surfaces, but may have a greater tendency for producing air bubbles than absorbing surfaces.

Permeable formwork is a special class of cloth-lined formwork which allow trapped air and excess water to be removed during concrete movement and consolidation. This type of formwork produces improvements in the strength and durability of the concrete surface. The architectural merits of concrete cast with permeable formwork have generally not been emphasized because permeable formwork may produce a mottled and dark grey surface.

Several types of form releasing agents exist in the market. These might be grouped in two groups, namely chemically reactive or barrier type. Chemically active release agents are most common for architectural concrete surfaces. It is not much published literature about the influence of form oil types on surface quality. Some reports do, moreover, not separate between barrier and reactive types of form releasing agents.

Form oils should be applied in accordance to the formwork material and in a thin layer. Excess form releaser might bead up against the fresh cement paste and increase the chances for staining and blowholes. Reactive form release agents might also retard the hydration of the cement close to the form. Retarded hydration might result in surface voids on the hardened concrete surface due to the formation of bleed water.

Efflorescence originating from lime precipitation can be avoided by use of cements with granulated blast furnace slag, fly ash or another pozzolanic material, use of tight formwork and protection of the concrete from transport of water or humidity which might wash lime out of the structure.

Cracking caused by drying shrinkage is influenced by water-cement ratio, cement type and fineness as well as admixtures and supplementary cementing materials which affect pore size distribution in the hardened paste. Type and amount of aggregates, drying and curing conditions and the type and shape of the specimen are also of importance. Conflicting results are reported for the influence of superplasticizers on drying shrinkage and effect of supplementary cementitious materials. These effects are possibly ruled by dosage and way of addition. Appropriate reinforcement and moist curing are well known countermeasures for drying shrinkage. Efforts have been made internationally to develop shrinkage compensating cements which contain expansive agents and shrinkage reducing admixtures which reduce the surface tension in the pore water.

SCC seems to be more sensitive than vibrated concrete with regard to surface finishing, due to the way it is cast, the nature of the formwork, the type and thickness of applied release agent, temperature of the formwork and weather conditions. However, SCC shows great potential to obtain good surfaces, in a way which is hard to get with vibrated concrete.

10 Future work

The following topics need further research:

- Influence of rheological parameters such as workability and workability retention on the surface quality (cold joints, blowholes, honeycombs)
- Influence of mix design, supplementary cementitious materials and admixtures on surface quality such as evenness of colour, porosity, surface cavities and efflorescence.
- Some shutter materials and release agents may produce what is apparently a better finish by permitting a thin film of grout to conceal the blowholes. This film may, however, be easily broken and removed by weathering. Further studies are needed in order to establish the

relations between type of form release agent (reactive or barrier) and mix design on the formation of pores (open/hidden).
- Studies of drying shrinkage and supplementary materials are contradictory. More work are need to find the influence of superplasticizers and supplementary cementitious materials on drying shrinkage and cracking as a function of dosage and way of addition (adding to or replacing cement).

Work is needed for the development of a Norwegian guideline covering concrete surface quality. Preliminary work for such a guideline could be to determine suitable measurement methods for surface quality.

11 References

ACI 303R-04, Guide to Cast-in-place Architectural Concrete Practice, 2004

ACI 237R-07; Self-Consolidating Concrete, 2007

Alsayed S.H., Influence of superplasticizer, plasticizer and silica fume on the drying shrinkage of high-strength concrete subjected to hot-dry field conditions, *Cem. Concr. Res.,* **28** (1998) 1405-1415

Arslan M., The effects of permeable formworks with sucker liners on the physical properties of concrete surfaces, *Constr. Build. Mat.* **15** (2001) 149-156

Berke N.S., Dallaire M.P., Hicks M.C., Kerkar A., New developments in shrinkage-reducing admixtures, Fifth CANMET/ACI conference on superplasticizers and other chemical admixtures in concrete, Rome (1997) 973-1000

Bentz D.P., Geiker, M.R., Hansen K.K., Shrinkage reducing admixtures and early age desiccation in cement pastes and mortars, *Cem. Concr. Res.,* **31** (2001) 1075-1085

Billberg P., Self-compacting concrete for civil engineering structures the Swedish experience, CBI Report 2:99 (1999).

Brooks J.J., Influence of mix proportions, plasticizers and superplasticizers on creep and drying shrinkage of concrete, *Magazine of Concrete Research* **41** (1989) 145-153

Brooks J.J., How Admixtures Affect Shrinkage and Creep, *Concrete International* **21** (1999) 35-38

Brooks J.J., Jiang X., The influence of chemical admixtures on restrained drying shrinkage of concrete, Fifth CANMET/ACI conference on superplasticizers and other chemical admixtures in concrete, Rome (1997) 249-266

CIB Report no. 24, commission W29, Tolerances on blemishes of concrete, (1973).

Collepardi M., Borsoi A., Collepardi S., Olagot J.J.O., Troli R., Effects of shrinkage compensating concrete under non-wet curing conditions, *Cem. Concr. Comp.,* **27** (2005) 704-708

DBV: Deutscher Beton- und Bautechnik-Verein E.V., Bundesverband der Deutschen Zementindustrie e.V.: Merkblatt “Sichtbeton”. Fassung August 2004. Berlin, Köln: Selbstverlag 2004

Delair S., Guyonnet R., Govin A., Guihot B., Maximilien S., Study of efflorescences forming process on cementitious materials, 12th International Congress on the Chemistry of Cement, Montreal Canada, W4-08.3 (2007)

Dow C., Glasser F.P., Calcium carbonate efflorescence on Portland cement and building materials, *Cem. Concr. Res.,* **33** (2003) 147-154

Engstrand J., Shrinkage reducing admixture for cementitious composition, *Con. Chem. J.* **4** (1997) 149-151

Farahmandpour K., Evaluation of Zemdrain, Report No. 260392, Construction Technology Laboratories, Inc., Skokie (1992)

Folliard K.J., Berke N.S., Properties of high-performance concrete containing shrinkage-reducing admixture, *Cem. Concr. Res.,* **27** (1997) 1357-1364

Gaimser R., Foors C., “Self-Compacting Concrete”, *Concr.* **34** (4) (2000) 23-25

Gettu R., Roncero J., On the long term response of concrete with a shrinkage reducing admixture, in Admixtures – Enhancing Concrete Performance Proceedings of the International Conference held at the University of Dundee, Scotland, UK (2005) 209-216

Ghaib M. A. A., Górski, J., Mechanical properties of concrete cast in fabric formworks, *Cem. Concr. Res.* **31** (2001) 1459-1465

Gram H.-E., Discussion of possible reasons Surface defects of SCC, *BFT* **8** (2004) 28-33

Greening N. R., Landgren R., Surface Discolouration of Concrete Flatwork, *Journal of the PCA Research and Development Laboratories,* **8** (1966) 34-50

Heimdal E., Mathisen A.E., “Use of SCC to achieve improved concrete surfaces”, The Third International RILEM Symposium on Self-Compacting Concrete, Reykjavik 2003, s. 609

Ichimiya K., Yamasaki T., Idemitsu T., “Influence of the wettability and angle of form on the characteristics of surface voids in self-compacting concrete”, The Fourth International RILEM Symposium on Self-Compacting Concrete, Chicago 2005, s. 937

Jianyong L., Yan Y., A study on creep and drying shrinkage of high performance concrete, *Cem. Concr. Res.* **31** (2001) 1203-1206

Johansen K., ”Selvkomprimerende betong, Statusrapport om internasjonal og nasjonal utvikling til og med desember 1999”. Report number: Norcem 9D4/R99033, (1999)

Justnes H., Autogenous Shrinkage of Cementitious Paste – State-of-the-Art, Proceedings of the Seventh CANMET/ACI International Conference on Recent Advances in Concrete Technology

(Ed. V. Mohan Malhotra), Las Vegas, USA, May 26-29, 2004, CANMET/ACI SP-222-14, pp. 199-21

Khatri R.P., Sirivivatnanon, Gross W., Effect of different supplementary cementitious materials on mechanical properties of high performance concrete, *Cem. Concr. Res.* **25** (1995) 209-220

Lallemant I., Rougeau P., Gallias J.L., Cabrillac R., Study of Local Tint Defects on Concrete Surfaces – Influence of Superplasticizers and Other Parameters, Sixth CANMET/ACI International Conference on Superplasticizers and Other Chemical Admixtures in Concrete, ACI international SP 195-32, 521-534 (2000)

Lemaire G., Escadeillas G., Ringot E., Evaluating concrete surfaces using an image analysis process, *Construction and Building Materials* **19** (2005) 604-611

Linder R., Pores, Blowholes; Wood Inclusion in fair-Faced Concrete Surfaces, Coatings and Floor Surfaces, Part 1, *Betonwerk + Fertigteil-technik,* **5** (1992) 67-74

Litzner H.-U., Goldammer K.-R., Philosophie des neuen DBV/BDZ-Merkblattes ”Sichbeton”, *Beton- und Stahlbetonbau* **100** (2005) 489-495

Manns W., Öttl C., Possible ways of early detection – On brown discolororation’s in concrete products, *BFT* **11** (2002) 32-47

Neville A.M., Properties of Concrete, 4th Ed. 1995, Pearson Education Limited, Essex, England

Nolan É., Basheer, P.A.M., Long, A.E., Effects of three durability enhancing products on some physical properties of near surface concrete, *Constr. Build. Mat.* **9** (1995) 267-272

Perenchio W.F., The drying shrinkage dilemma – some observations and questions about drying shrinkage and its consequence, *Concr. Constr.* **42** (1997) 379-383

PCA, Portland Cement Association, Types and causes of Concrete Deterioration, IS536.01, 2002

PCA, Portland Cement Association: http://www.cement.org/tech/cct_con_design_bugholes.asp

Rao G. A., Long-term drying shrinkage of mortar – influence of silica fume and size of fine aggregate, *Cem. Concr. Res.* **31** (2001) 171-175

Rau H., The Surface of a Concrete Building Element is a Reflection of the Formwork, Detail **1** (2001) 102-107

RILEM Technical Committee, ”Final report of RILEM TC 188-CSC ’Casting of self compacting concrete’”, *Mat. Struct.* **39** (2006) 937-954

Ronbing B., Jian S., Synthesis and evaluation of shrinkage-reducing admixture for cementitious materials, *Cem. Concr. Res.,* **35** (2005) 445-448

Sato K.; Tanaka K.; Suga K., “Surface quality improvement by permeable forms of concrete structures”, Kumagai Gumi Co. Ltd Institute of Construction Technology Material Research and Development Department, Japan (1989) p.3.7-3.16, PUBLISHER: CSIRO Division of Building, Construction and Engineering, Melbourne, Australia

Sugiyama T., Ohta A., Tanaka Y., Shrinkage Reduction Type of Advanced Superplasticizer, *ACI* **179** (1998) 189-200

Tazawa E., Ed. *Autogenous Shrinkage of Concrete,* E&FN Spon, London (1999)

Thomson M.S., Blowholes in concrete surfaces, *Concrete* **3** (1969) 64-66

Trägårdh J., "Undersökning av strukturen i olika betongkvaliteter: vibreringsfri, K80 och K45 betong", CBI uppdragsrapport nr. 99016, Stockholm, Sweden (1999)

Waterloo R.F., Form Release Agents - Defining, selecting and applying concrete form release agents. *MC Mag.* Winter 2003 http://www.precast.org/publications/mc/TechArticles/03_Winter_Form_Release_Agents.htm

Wilson D., Controlled permeability formwork – an answer to concrete surface durability problems?, *Concrete* **34** (2000) 56-57

Yamada K., Nakanishi H., Tamaki S., Yaguchi M., Kinoshita M., Working mechanism of a shrinkage-reducing superplasticizer of new generation, in Seventh CANMET/ACI International conference on recent advances in concrete technology (2004) 171-184