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Consequence of cement constituents, mix composition and curing conditions for self-desiccation in concrete

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ABSTRACT

This article outlines an experimental and analytical expression study on the consequence of cement constituents, mix composition and curing conditions as regards self-desiccation in concrete. For this purpose nine concretes with three values of w/c (0.32, 0.38 and 0.50), based on two types of Portland Cement, were manufactured. Five per cent silica fume was used in one third of the concretes as calculated on the basis of the cement content. The measurements were done at 1 and 6 months' age. An analysis of the conditions of the measurements was performed. Parallel tests were performed on strength. The results indicated high influence of w/c, age and cement type on self-desiccation. The curing conditions only influenced internal relative humidity and strength. The study was performed at Lund Institute of Technology 1997-1998.

RÉSUMÉ

Cet article expose les grandes lignes d'une étude numérique expérimentale portant sur les composants du ciment, la composition des mélanges et les conditions de durcissement par rapport à l'autodessication du béton. Neuf bétons fabriqués à base d'un mélange d'eau/ciment variant entre 0,32 et 0,50 et sur deux types de ciment Portland ont été retenus pour cette étude. Un tiers des bétons contenait 5% de fumée de silice et a été calculé sur la base du contenu du ciment. Les mesures ont été réalisées sur des bétons âgés de 1 et 6 mois. Des tests sur la résistance ont été effectués en parallèle. Les résultats montrent que le rapport eau/ciment, l'âge et le type de ciment sur l'autodessication ont une grande influence. Les conditions de durcissement ont seulement influencé les mesures de l'humidité relative interne. Cette étude a été réalisée entre 1997 et 1998 au sein du Lund Institute of Technology.

1. BACKGROUND, AIM AND GENERAL SCHEME OF THE STUDY

1.1 Background

The chemical shrinkage that takes place during the hydration of cement is the fundamental cause of self-desiccation [1]. The specific volume of the hydrated water in the CSH gel is reduced by about 26% compared with the specific volume of the water in the capillary pores [2]. The influence of self-desiccation becomes especially pronounced at low w/c < 0.38 due to the decreased size of the capillary pores [3]. Self-desiccation influences the properties of the young concrete as well as the long-term behaviour of the concrete, *i.e.* deformations, stability and durability. Due to self-desiccation concrete with low w/c deforms even in sealed curing, free of imposed stresses (autogenous shrinkage) [4, 5]. Furthermore, low-w/c concrete with silica fume exhibits a very low long-term increase of the compressive strength due to self-desiccation, which may influence the long-term stability and durability [6]. Favourable parameters related to self-desiccation are low internal relative humidity close to the reinforcement bars, which may decrease the rate of corrosion [7]. Frost resistance and scaling of materials and structures is clearly improved due to self-desiccation since an air-filled volume is created due to the chemical shrinkage, as mentioned above [8-10]. A low amount of built-in moisture during the construction time is another favourable property of low-w/c concretes caused by self-desiccation [11-13].

Editorial Note
Dr. B. Persson is a RILEM Senior Member. He participates in the work of TC EAS: 'Early age shrinkage induced stresses and cracking in cementitious systems'.

1.2 Aim of the study

The main aim of the study was to ascertain the influence of cement type, w/c, silica fume and age on internal relative humidity, RH, due to self-desiccation in concretes with w/c varying between 0.32 and 0.50. The influence of age on the RH was determined by studying concretes at 1 and 6 months' age. The influence of cement type was evaluated by studies of low-and normal-alkali cement. Half of the specimens were made with normal-alkali cement blended with 5% silica fume (dry weight of cement). Additional objective was to evaluate the influence of cement type, silica fume and temperature on the compressive strength of concrete in sealed curing.

1.3 General scheme of the work

Nine different types of concretes were examined. After sealed curing strength was tested at 1 month's age. RH was measured on fragments of crushed concrete at 18, 20.5 and 23°C temperature at 1 and 6 months' age. The density was studied in the fresh state and after sealed curing for 28 days.

2. MATERIAL, SPECIMENS, EXPERIMENTAL METHODS AND PRECISION

2.1 Materials and studied concretes

Low-alkali and normal-alkali cement was used. Appendix 1 gives the chemical composition of the cements [14]. The properties of the aggregate are given in Appendix 2 [15]. Nine types of concretes were studied, 9 cylinders of each quality, in all 81 cylinders. The w/c varied between 0.32 and 0.50. The mix design of the concrete was based on theoretical optimisation of the grading curve in the fresh concrete [16]. First of all the dry material was mixed for 1/2 minute. Then the water with air-entrainment was added and mixed for another 1/2 minute. Finally the plasticisers were added and mixed for 3 minutes. The concretes had good rheological properties. Workability, density and air-content of the concretes were studied in the fresh state. The slump of the concretes varied between 80 and 180 mm. In the fresh state it was possible to mix, transport and cast HPC with existing methods. The 28-day 100-mm cylinder compressive strength exceeded 20 MPa (comparable with 25 MPa 150-mm cube strength). Appendix 3 shows the mix design of the concretes and the main properties in the fresh and the cured state.

2.2 Specimens and curing conditions

Density, strength and self-desiccation after sealed curing of the concretes were studied for cylinders 200 mm long and 100 mm in diameter. The mixing of the material took place at 22°C. Directly after mixing, one third of the moulds with concrete were stored at constant temperatures in a climatic chambers, one third at 18.5°C, one third at 20.5°C and one third at 23°C. After demoulding at one day's age, the specimens were immediately sealed from moisture by insulation with 3 mm plastic tubes and placed again in the climatic chambers where the initial curing took place. The weight of the cylinders was established before and after the 28-day studies.

2.3 Experimental methods

The concrete cylinder with the plastic pipe was weighed in order to control possible moisture losses. Then all concrete cylinders were also weighed and measured separately. The plastic pipe was weighed separately in order to detect any increase in weight due to moisture uptake. The strength of the concrete was obtained in compression. The cylinder was placed centric in a hydraulic press device and the loading rate applied was 1 MPa/s. Immediately after the strength tests, concrete fragments (minimum 5 mm in size) from the concrete used in the compressive testing, were filled in glass tubes, 200 mm long and 22 mm in diameter. The glass tubes were continuously tightened by a rubber plug during the filling of the concrete. Concrete holds about 10.000 times more water per volume than air, which makes the measurement of moisture in air connected to the pores of the concrete possible. The small amount of moisture that is supplied by the concrete to the air around the measurement device does not effect RH in the concrete, provided that the air volume is limited. However, the temperature control of the measurement is essential. After the tube was totally filled, the temperature of the concrete fragments was adjusted to the measurement temperature (18.5, 20.5 or 23°C) for 1 day. The probe of the measurement device, a dew-point meter, was inserted into the glass tube and tightened against the glass with an expanding rubber ring. The internal relative humidity, RH, was then measured by a dew-point meter for 22 h at the adjusted temperature in question. If the RH did not come to stability after 22 h the measurement continued until a constant RH was obtained. Calibration was performed of the measurement device according to two methods.

2.4 Sources of error

The following sources of error were observed during the study:

1. Variations in w/c of the concrete due to the moisture content in the sand and the gravel.
2. Moisture losses during the handling and curing of the cylinders.
3. Calibration faults regarding the hydraulic press device and the dew-point meters.

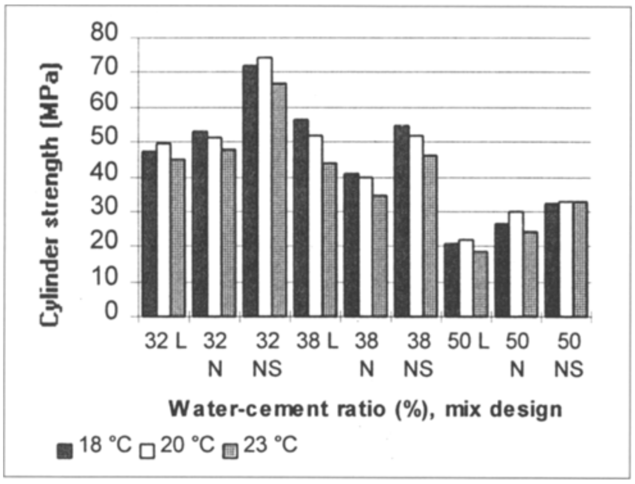

Fig. 1 – Strength versus mix design. L= low-alkali cement, N = normal-alkali cement, NS = N + 5% silica fume, 38 = w/c (%).

3. SELF-DESICCATION AND STRENGTH

3.1 Density and compressive strength

Appendix 3 provides the density and compressive strength after curing for 28 days. The fall in air-content was estimated from the difference in density between the fresh and the cured state of the concrete. The losses of air content in the concrete were quite large. However, the high amount of air-entrainment was required in order to maintain good workability at the low w/c (low mixing water content) shown in Appendix 3. Otherwise much larger cement content would have been required. The air-entrainment replaced a good part of the water during the casting. The compressive strength decreased slightly with a moderate increase in the curing temperature, especially at w/c= 0.38, *i.e.* between 0.5 and 2.5 MPa/°C. Fig. 1 gives the strength versus w/c and type of the concretes. Besides an increase at lower w/c, a substantial increase in strength was observed for silica fume concretes. At early ages the efficiency factor of silica fume is quite large, as high as 7 at 28 days' age, but then decreasing. After 7 years no influence of silica fume on the strength was observed [17].

3.2 Internal relative humidity, RH

Figs. 2-4 show the difference in RH between curing at 20.5°C and 23°C compared with 18.5°C (ASTM-calibration [18]). Fig. 5 shows that small average influence of curing at 20.5°C was observed. At 23°C RH was on average 0.5% lower than RH with curing at 18.5°C, *i.e.* the influence of a moderate temperature change on RH was small (hardly detectable). Table 1 gives the standard deviation and the average difference in RH of the measurements. The maximum standard deviation was 1.6% (curing at 18.5°C) and the maximum average standard deviation 0.7% (independent of curing temperature and measured at 20.5°C).

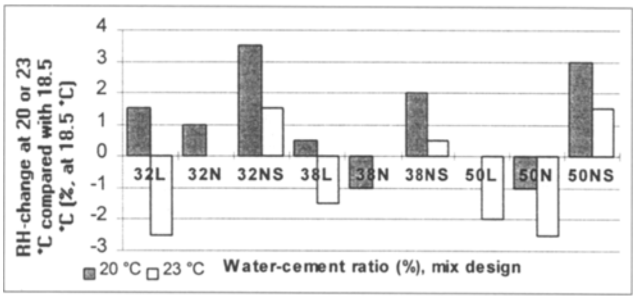

Fig. 2 – Change in RH with curing at 20.5°C and 23°C compared with curing at 18.5°C (measurement at 18.5°C). L= low-alkali, N = normal-alkali, S = 5% silica fume, 32 = w/c (%).

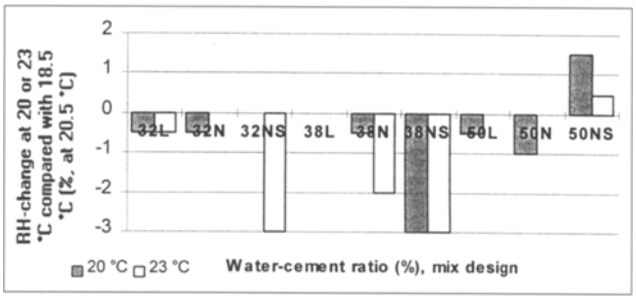

Fig. 3 – Change in RH with curing at 20.5°C and 23°C compared with curing at 18.5°C (measurement at 20.5°C). L= low-alkali, N = normal-alkali, S = 5% silica fume, 32 = w/c (%).

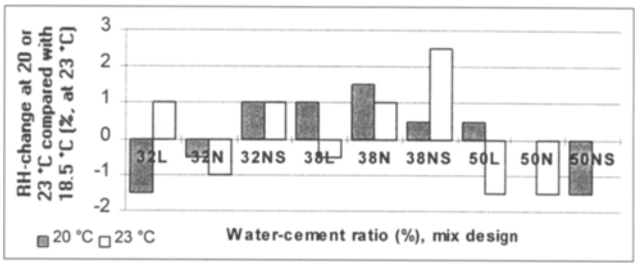

Fig. 4 – Change in RH with curing at 20.5°C and 23°C compared with curing at 18.5°C (measurement at 23°C). L= low-alkali, N = normal-alkali, S = 5% silica fume, 32 = w/c (%).

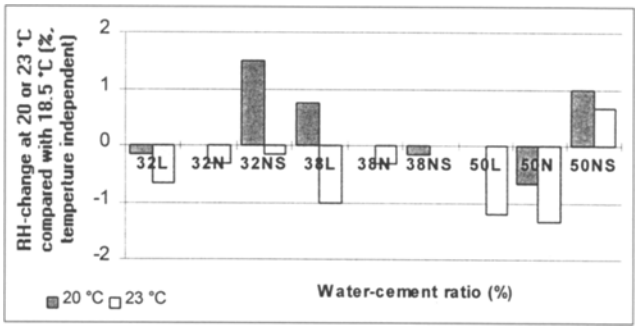

Fig. 5 – Change in RH with curing at 20.5°C and 23°C compared with curing at 18.5°C (independent of temperature of measurement).

3.3 Influence of temperature on self-desiccation

Figs. 6-8 show the difference in RH between measurement at 20.5°C and 23°C compared with 18.5°C. Fig. 9 shows that the observed average influence of mea-

Table 1 RH-difference dependent on curing temperature (%, ASTM-calibration [18])

Curing (°C)	Measurement (°C)	Variance (°C)	Standard deviation
18.5	20.5 23	1.1 -0.6	1.6 1.6
20.5	20.5 23	-0.6 -1	1.2 1.4
23	20.5 23	0.1 0.1	1.1 1.2
18-23	20.5 23	0.2 -0.5	0.7 0.6

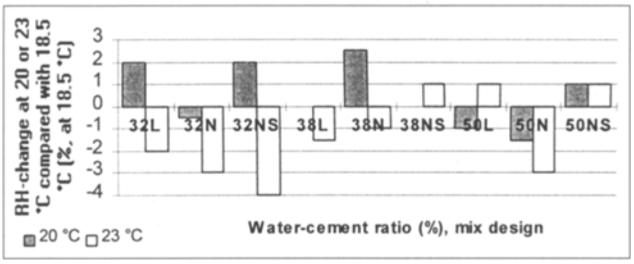

Fig. 6 – Change in RH with measurement at 20.5°C and 23°C compared with measurement at 18.5°C (curing at 18.5°C). L= low-alkali, N = normal-alkali, S = 5% silica fume, 32 = w/c (%).

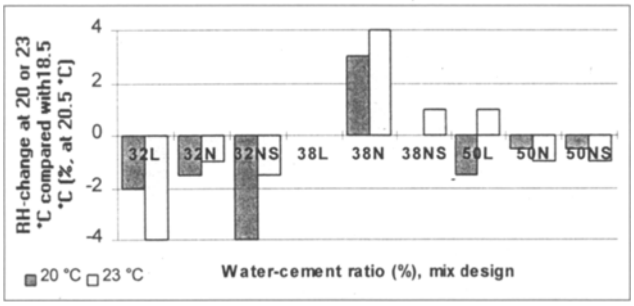

Fig. 7 – Change in RH with measurement at 20.5°C and 23°C compared with measurement at 18.5°C (curing at 20.5°C). L= low-alkali, N = normal-alkali, S = 5% silica fume, 32 = w/c (%).

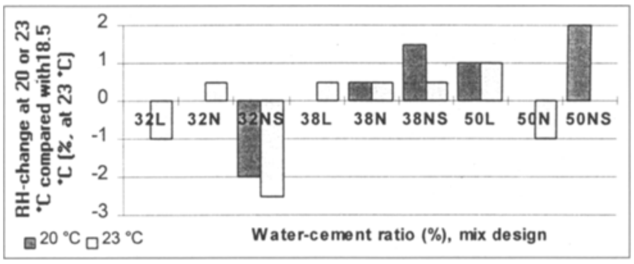

Fig. 8 – Change in RH with measurement at 20.5°C and 23°C compared with measurement at 18.5°C (curing at 23°C). L= low-alkali, N = normal-alkali, S = 5% silica fume, 32 = w/c (%).

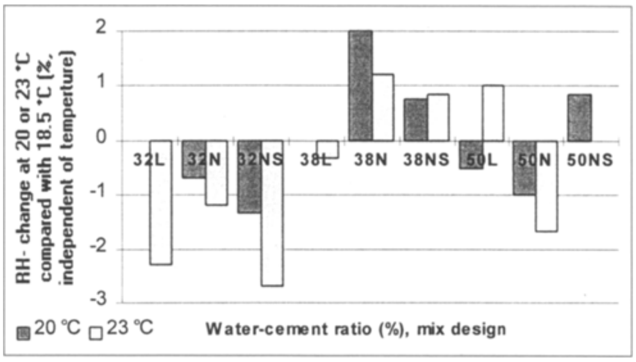

Fig. 9 – Change of RH with measurement at 20.5°C and 23°C compared with measurement at 18.5°C (temperature independent). L= low-alkali, N= normal-alkali, S = 5% silica fume, 32 = w/c (%).

Table 2. Difference in RH dependent on measurement temperature (%, ASTM-calibration [18])

Curing (°C)	Measurement (°C)	Variance (°C)	Standard deviation
18.5	20.5 23	0.6 -1.3	1.6 1.8
20.5	20.5 23	-0.9 -0.3	2 2.2
23	20.5 23	0.4 -0.2	1.2 1.1
18-23	20.5 23	-0.1 -0.6	1 1.5

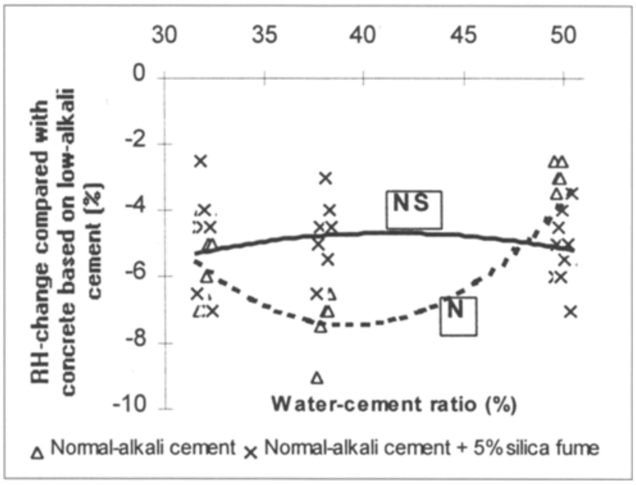

Fig. 10 – Influence of cement type and silica fume on RH versus w/c compared with RH in concrete based on low-alkali cement, 28 days' age.

surement at 20.5°C was –0.1% RH. At 23°C RH was on average -0.6% lower than when it was performed at 18.5°C. The influence of moderate temperature change at measurement on RH was thus hardly detectable. Table 2 gives the standard deviation and the average difference in RH. The maximum standard deviation was 2.2% (curing at 23°C) and the maximum average standard deviation 1.5% (independent of measurement temperature of the concrete cured at 23°C).

3.4 Influence of cement type and silica fume on self-desiccation

Fig. 10 shows the influence of cement type and silica fume on RH compared with RH in concrete based on low-alkali cement and without silica fume when w/c was

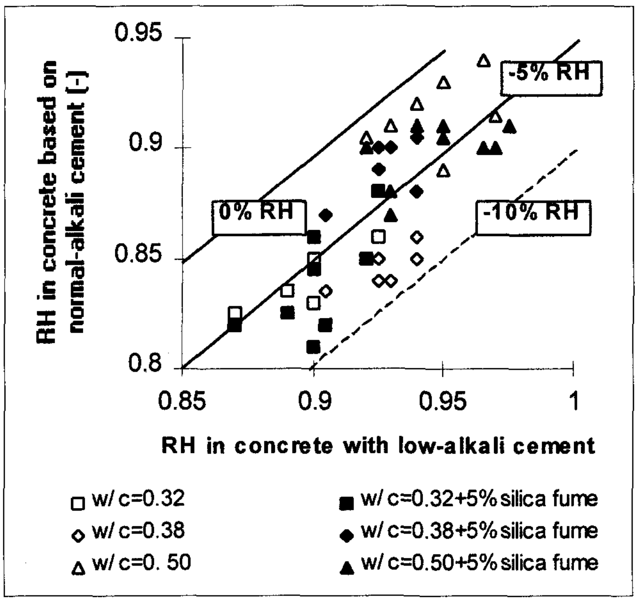

Fig. 11 – Influence of cement type and silica fume on RH compared with effect on RH in concrete based on low-alkali cement.

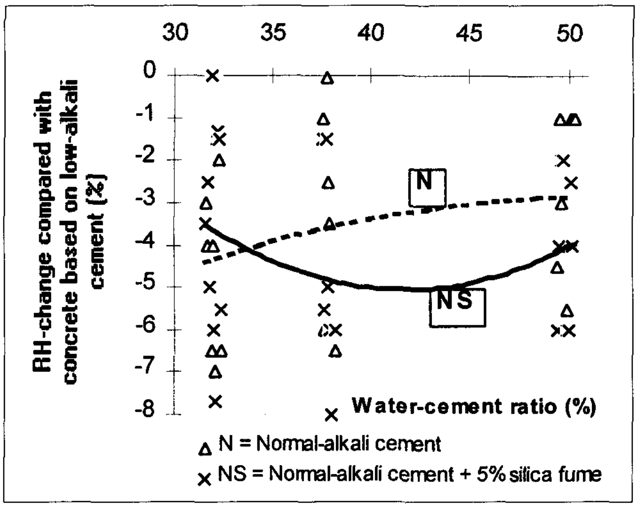

Fig. 12 – Influence of cement type and silica fume on RH versus w/c compared with RH in low-alkali cement concrete. Six months' age.

held constant (the decline in RH). Part of the decline in RH due to the cement type (which varied between 4 and 8% at 28 days' age) was dependent on the so-called alkali-effect [19]. However, when silica fume was added to the concrete the pozzolanic reaction slightly reduced the alkali-effect. At w/c = 0.40 the RH decline for a normal-alkali cement based concrete was about 8% RH. For same cement blended by 5% silica fume the RH decrease only about 5%, Fig. 10.

3.5 Influence of cement type and silica fume on RH when w/c was held constant

Fig. 11 shows the RH values of concretes based on normal-alkali cement, with or without silica fume, versus the RH of concretes based on low-alkali cements (the decline of RH at constant w/c). The effect of cement type and silica fume on RH varied between -2 and -9%.

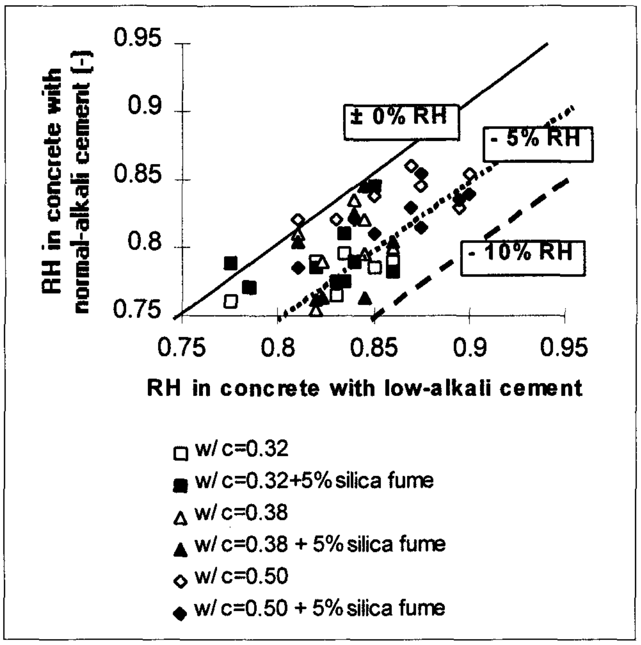

Fig. 13 – Influence of cement type and silica fume compared with RH in concrete based on low-alkali cement. Six months' age.

3.6 Influence of cement type and silica fume at 6 months' age

Fig. 12 shows the RH values at 6 months' age of the concretes based on normal-alkali cement, with or without silica fume, versus the RH values of concretes based on low-alkali cement (the RH was held constant), *i.e.* Fig. 12 shows the decline of RH due to the mix composition. Part of the decline in RH due to the cement type (which varied between 3 and 4% at 6 months' age) was dependent on the alkali-effect [19]. However, the alkali-effect seemed to be less pronounced at 6 months' age than at 28 days' age at which age it varied between 4 and 8% RH. Fig. 13 shows the influence of cement type and silica fume on RH compared with RH in concrete based on low-alkali cement when RH was held constant. The influence of cement type and silica fume on RH varied between 0 and -9%.

4. PRECISION

4.1 The w/c-variations in concrete due to the moisture content in the sand

The sand was planned to have a moisture content varying between 3% and 4%. This variation in the moisture content would have produced concrete with ± 0.01 in variation of w/c. However, recalculations of w/c on the basis of the measured moisture content in the sand of each batch of concrete showed larger variation of the moisture content. The moisture varied between 3%

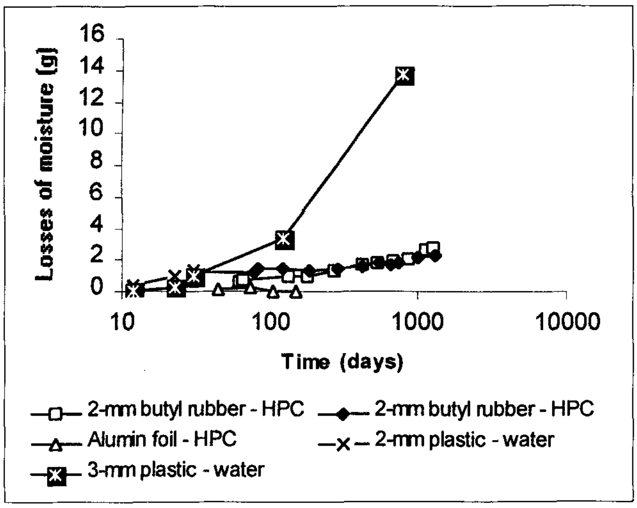

Fig. 14 – Moisture losses through different kinds of moisture insulation.

Table 3 – Measured moisture losses from specimens during the 28 day curing time (%)

Concrete	18°C	20.5°C	23°C
32L	-0.05	-0.08	-0.03
32N	-0.03	+0.03	-0.05
32NS	-0.05	-0.06	-0.03
38L	-0.03	-0.03	-0.10
38N	-0.08	+0.01	-0.01
38NS	-0.04	-0.04	-0.06
50L	-0.09	-0.10	-0.12
50N	+0.06	-0.04	-0.05
50NS	+0.07	-0.04	+0.05

Notations: L= low-alkali, N = normal-alkali, S = 5% silica fume, 32= w/c (%).

Table 4 – RH in saturated salts [18]

Type of salt	18.5 °C	20.5 °C	23 °C
NaCl	75.53	75.46	75.37
KCl	85.35	85.03	84.65
KNO_3	94.89	94.53	94.03
K_2SO_4	97.69	97.57	97.42

and 4.8%, which produced a concrete with −0.01, +0.025 in variation of w/c.

4.2 Effect of handling and curing of the cylinders on moisture losses at curing

The specimens were cast in steel moulds and then, after demoulding, quickly placed in the 3-mm thick plastic pipe. Moisture-proof plugs tightened the ends of the pipe. Fig. 14 shows the moisture losses through different kinds of moisture insulation: butyl rubber clothing, aluminium foil or 3-mm plastic pipe. Aluminium foil showed no loss of moisture at all but required a certain time for application. Table 3 shows the measured net moisture losses from the specimens during the 28-day curing time. Moisture uptake (+) was observed in some cases. The moisture losses were hardly detectable. From 28 days' age until 6 months' age the concrete was stored in glass pipes tightened by rubber plugs, probably with no measurable moisture losses.

4.3 Calibration of the dew-point meters

It was essential to set the time of measurement of the dew-point meters sufficiently long. It was found that 14 h was required to obtain stability of moisture between the pores in the concrete and the probe of the dew-point meter [3]. The time of measurement thus was set at 22 h. It was also essential to limit the number of measurements to two on the same sample. Otherwise systematic faults may occur [20]. The results in Fig. 9 show that a negative temperature dependence existed (about 0.6% lower RH at 5°C higher temperature), which was in contrast to other results [21, 22]. Normally RH in concrete increases with temperature. Before the measurement of RH in the concretes took place a standard calibration with a humidity generator was performed at 20°C. Calibration of the dew-point meters was performed afterwards according to the saturated salt method ASTM E 104-85 [18]. RH produced by the saturated salt was adjusted to the current temperature of measurement according to Table 4. During calibration of the salts the solution was placed in a glass tube insulated from variations in the ambient temperature. The solution of the salt was separated from the RH-probe by a partially permeable membrane. The temperature of the salt was stabilised at the specific temperature for 3 days before the calibration took place. The calibration was performed for 22 h. Fig. 15 shows that the two calibration methods coincided reasonably well at 18.5°C. However, at 20.5°C and 23°C a difference of about 2% RH existed. Calibration with [18] at 20.5 and 23°C showed about 2% higher RH than calibration with the humidity generator, Figs. 16 and 17. It was concluded that relevant RH-analyses can be performed after salt-calibration [18].

5. ANALYSIS ON SELF-DESICCATION

5.1 Influence of age, w/c, cement type and/or silica fume on RH (Ø)

Figs. 18-21 present data on RH (Ø) versus w/c and $(w/c)_{eff} = w/(c+2\cdot s)$ for the concretes studied (1 and 6 months' age). From Figs. 18 and 19 the following equation was calculated (the significance parameter of the equation, R^2, given to the right in Table 5 and should be >0.5):

$$Ø = [A \cdot \ln(t) + B] \cdot (w/c) + C \cdot \ln(t) + D \qquad (1)$$

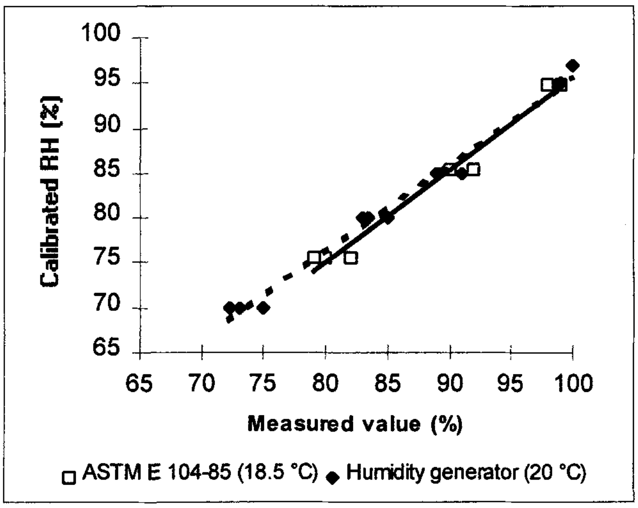

Fig. 15 – Calibration according to ASTM E 104-85 (18.5°C) and according to humidity generator (20°C) [18].

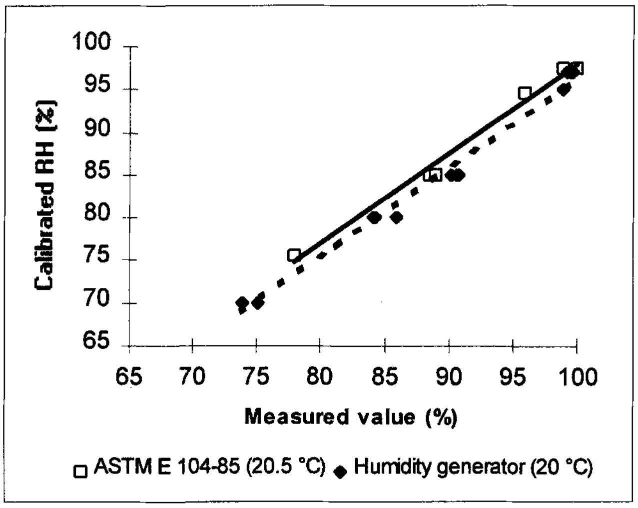

Fig. 16 – Calibration according to ASTM E 104-85 (20.5°C) and according to humidity generator (20°C) [18].

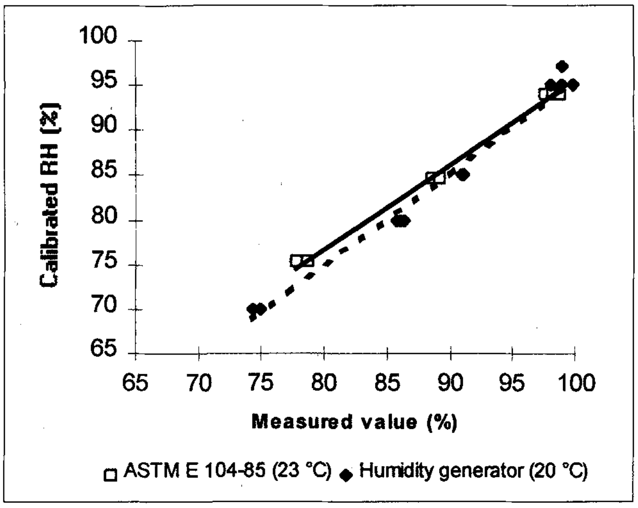

Fig. 17 – Calibration according to ASTM E 104-85 (23°C) and according to humidity generator (20°C) [18].

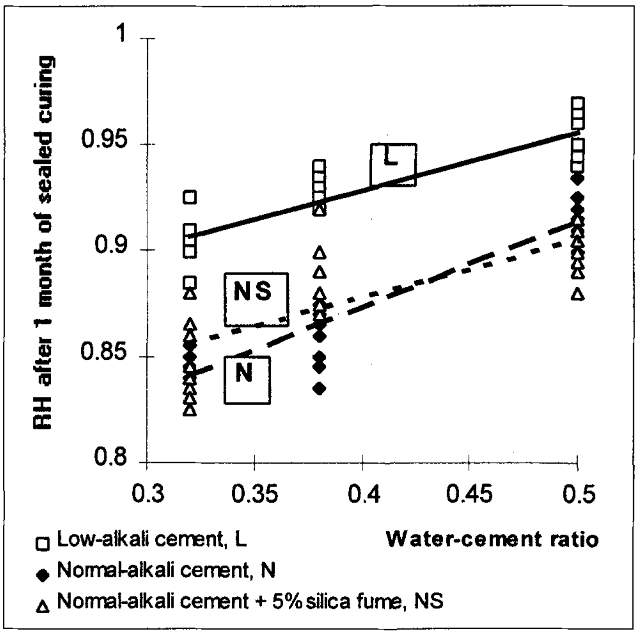

Fig. 18 – RH versus w/c, 1 month's age. L= low-alkali, N = normal-alkali, S = 5% silica fume, 32= w/c (%).

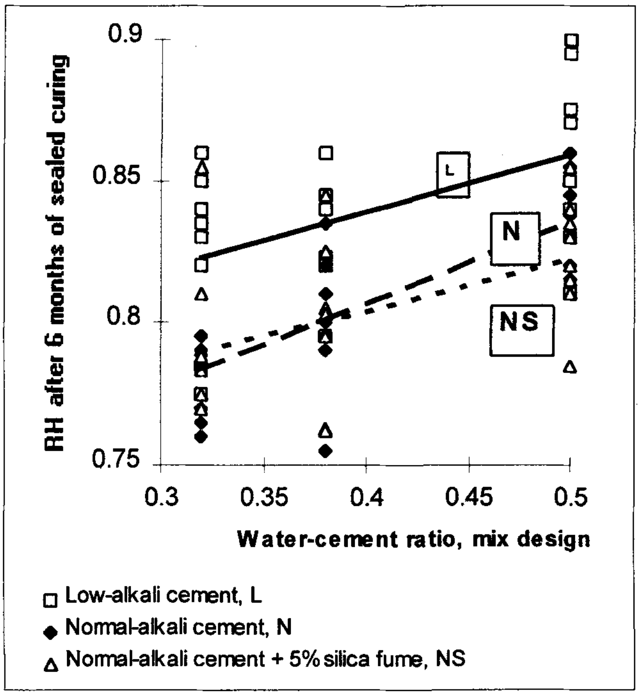

Fig. 19 – RH versus w/c, 6 months' age. L= low-alkali, N = normal-alkali, S = 5% silica fume, 32= w/c (%).

ln(t)	denotes the natural logarithm of the concrete age, t, in months
A, B, C, D	denotes constants (Table 5)
Y_i	denotes the measured value
Y_m	denotes the average measured value.

$$R^2 = 1 - \frac{\sum (Y_i - Y_m)^2}{\left(\sum Y_i^2\right) - \frac{\left(\sum Y_i^2\right)}{n}} \qquad (2)$$

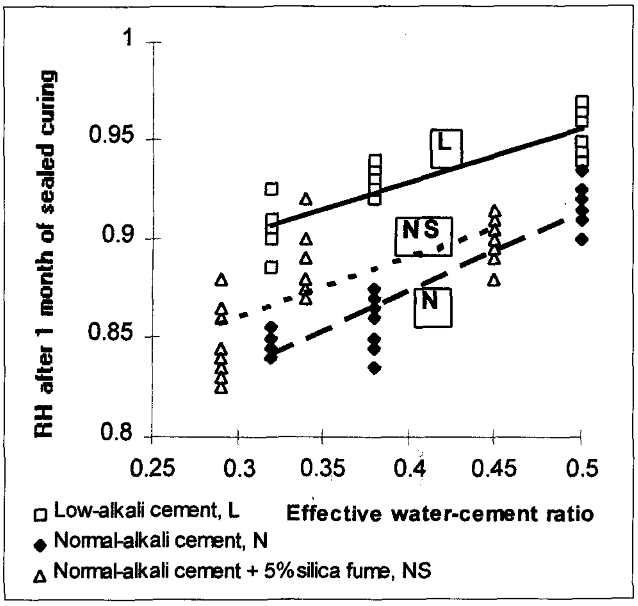

Fig. 20 – RH versus (w/c)eff = w/(c+2·s), 1 month' age. L= low-alkali, N = normal-alkali, S = 5% silica fume, 32= w/c (%).

Table 5 – Constants in equation (1) (per mil)					
Cement, silica fume	A	B	C	D	R2
Low-alkali (L)	37.8	185	-42	830	630
Normal-alkali (N)	58.8	219	-59	790	750
N + 5% silica fume (NS)	35.1	223	-51	780	500

Equation (1) shows the highest significance ($R^2 = 0.75$) for RH versus w/c in concretes with normal-alkali cements and the lowest ($R^2 = 0.5$) for RH in concretes with the same cement blended with 5% silica fume. Figs. 18 and 19 demonstrate again the results that concretes based on normal-alkali cement with or without 5% silica fume exhibits about 5% RH-decline compared with low-alkali cement based concrete. At low w/c the influence of silica fume added to the normal-alkali cement was less than the influence of normal-alkali cement alone, Figs. 18-19. Normal-alkali cement exhibited about 5% lower RH after self-desiccation than low-alkali cement. The so-called alkali-effect [19] and probably also the chemical composition of the cement affected the degree of self-desiccation, RH.

The component of Alite, C_3S, was the same in both cements. However, the remaining clinker components, Belite, C_2S, Aluminate, C_3A, and Ferrite, C_4AF, varied significant between the cements studied. The content of alkalis, K_2O and Na_2O, also probably affected RH in the concrete. However, the effect of alkalis on RH was not experimentally supported by this study.

5.2 Comparison with other research

The present results were compared with studies on 8 concretes made with the same type of cement [23]. The w/c varied between 0.22 and 0.58. The concretes were made in large elements, 250 kg each. Half of the concretes contained 10% silica fume by weight of cement content. More than 230 RH-measurements were done in plastic pipes in the concrete elements at ages varying between 1 and 15 months. Some measurements were performed at 90 months' age [23]. The RH in the concrete, Ø, cured at 20 °C was correlated to age and w/c:

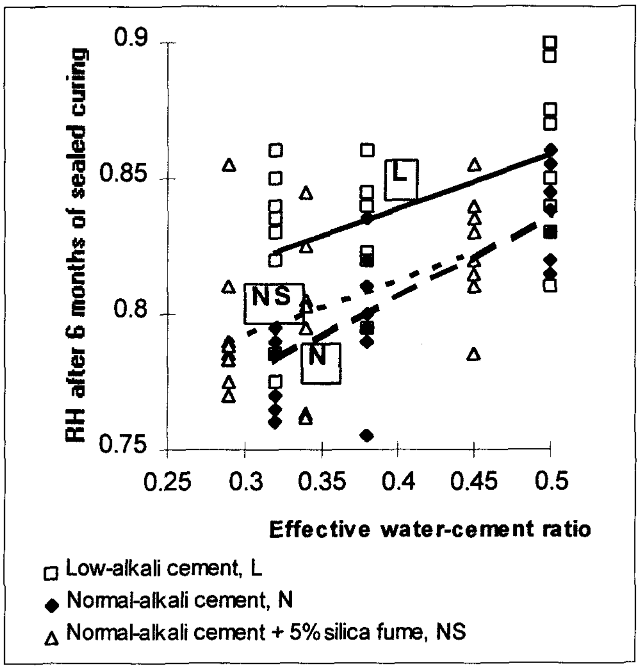

Fig. 21 – RH versus the effective water-cement ratio, (w/c)eff = w/(c+2·s), 6 months' age. L= low-alkali, N = normal-alkali, S = 5% silica fume, 32= w/c (%).

$$\varnothing_S(t,w/c) = 1.13\cdot[1-0.065\cdot\ln(t)]\cdot(w/c)^{0.24\cdot[1-0.1\cdot\ln(t)]} \quad \{1<t<15\text{ m}; 0.2<w/c<0.6\} \tag{3}$$

$$\varnothing(t,w/c) = 1.09\cdot(w/c)^{0.17\cdot(1+0.0451\cdot t)} \quad \{1<t<15\text{ months}; 0.2<w/c<0.6\} \tag{4}$$

The following equations were obtained for 1 month's age and/or 5% silica fume:

$$\varnothing_{S5}(1,w/c) = 0.55\cdot[(w/c)^{0.18} + (w/c)^{0.24}] \tag{5}$$

$$\varnothing(1,w/c) = 1.09\cdot(w/c)^{0.18} \tag{6}$$

ln(t)	denotes the natural logarithm of age, t, in months (m)
S	denotes 10% silica fume
S5	denotes 5% silica fume

Table 6 – Measured RH and RH estimated according to equations (5) and (6)			
Method	w/c= 0.32	w/c= 0.38	w/c= 0.50
Low-alkali cement	0.903	0.923	0.954
Equation (6)	0.890	0.917	0.964
Difference in RH	0.013	0.006	-0.01
Normal-alkali cement with 5% silica fume	0.855	0.874	0.906
Equation (5)	0.875	0.906	0.960
Influence of cement type, ΔØ	-0.020	-0.032	-0.054

Table 6 provides a comparison between RH measured at 1 month's age in the concretes of this project and RH estimated according to equations (5) and (6). The estimation of RH according to equation (6) agreed reasonably well with the measured RH. Concretes of normal-alkali cement and 5% silica fume exhibited significantly larger differences between measured and estimated RH due to the influence of components of the cement. Autogenous shrinkage occurs when RH in sealed concrete decreases due to chemical shrinkage of the water [5, 24]. The relationship between RH and shrinkage was linear, Fig. 4 [25]. Recently it was shown that a significant relationship exists between the C_3A and C_4F content and autogenous shrinkage [26]. The influence of these components was ten times as large as that of C_2S and C_3S. Based on estimations of $\Delta\varnothing$ given in Table 6 and the degree of hydration shown in Table 7, [27-31], the following equation was obtained:

$$\Delta\varnothing = 6\cdot\Delta(C_3A)\cdot\alpha_{C3A} + 8.6\cdot\Delta(C_4AF)\cdot\alpha C_{4AF} - k\cdot\Delta(K_2O) \qquad (7)$$

Notations in equation (7):

Δ denotes difference in a property between low-alkali and normal-alkali cement (by weight)

α denotes degree of hydration

$\varnothing$ denotes the internal relative humidity.

In [26] the effect of the cement type on autogenous shrinkage has been established for several cements. In this study only two types of cements were studied with differed properties. However, since autogenous shrinkage and self-desiccation are close related phenomena [5], it seemed logical that the cement composition also effected self-desiccation similar to autogenous shrinkage.

6. CONCLUSIONS

The following conclusions were drawn:

1. Self-desiccation of concrete was mainly dependent on the w/c and the age of the concrete. RH at self-desiccation was fairly independent of moderate variations in the curing temperature. Very small variations of temperature at the time of measurement (± 0.5°C) did not affect the measured RH, provided that the dew-point meter was calibrated at the same temperature.
2. The maximum standard deviation of the measurements was 1.5% RH given a small shift of temperature during the time of measurement (± 0.5°C). The average standard deviation was 0.7% RH under the same assumption, *i.e.* small shift in temperature during the time of measurement (± 0.5°C).
3. The calibration of dew-point meters was preferably performed at the temperature of measurement (± 0.5°C). Two-degree differences in temperature during the measurements of RH caused a systematic fault of ≈ ± 1.5%RH, which normally means that the measurement is regarded as inaccurate. The recommendation is to maintain ± 2°C during the curing time of the concrete but ± 0.5°C during the time of measurement of RH (22h) and also during the time of calibration of dew-point meters (22h). The same requirements probably apply for other types of probes.
4. The strength was reduced when the curing temperature was increased from 18°C to 23°C.
5. Concrete with normal-alkali cement had a 5% lower RH than concrete with low-alkali cement.
6. RH in concrete with normal-alkali cement was not significantly affect by 5% silica fume.
7. Concrete with normal-alkali cement, with and without silica fume, displayed other small differences in the mix composition that probably not effected the development of RH.
8. The chemical composition of the cement had a substantial influence on the measured self-desiccation mainly due to the so-called alkali-effect.

Table 7 – Adopted 28-day degree of hydration in estimation of equation (7) [27-29]

w/c	α_{C3A}	α_{C4AF}	k
0.32	0.67	0.45	-5
0.38	0.74	0.53	-4.7
0.50	0.83	0.62	-6.6
0.65	0.93	0.74	-

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APPENDICES

Appendix 1 - Composition of the cements [14]

Cement Component	Low-alkali cement (%)	Normal-alkali cement (%)
CaO	65	62
SiO_2	21.6	20
Al_2O_3	3.5	4.4
Fe_2O_3	4.4	2.3
MgO	0.78	3.5
K_2O	0.58	1.4
Na_2O	0.05	0.2
SO_3	2.07	3.7
CO_2	0.14	1.9
Ignition losses	0.47	2.4
C_2S	21	14
C_3S	57	57
C_3A	1.7	8
C_4AF	13	7
Blaine fineness	305 m^2/kg	364 m^2/kg
Density	3210 kg/m^3	3120 kg/m^3

Appendix 2 - Properties of aggregate and silica fume, s.f. [15]

Material	Sandstone	Sand	s.f.
Elastic modulus	60 GPa		
Compressive strength	332 MPa		
Split tensile strength	15 MPa		
Ignition losses	0.25%	0.8%	2.3% 1)

1) fineness: 17.5 m^2/g.

Appendix 3 - Mix design (kg/m3 dry material) and properties of the studied concretes

Material/Concrete	32L	32N	32NS	38L	38N	38NS	50L	50N	50NS
Quartzite sandstone 12-16 mm	669	686	725	532	535	549	407	417	434
Quartzite sandstone 8-12 mm	137	141	149	258	259	266	320	329	343
Natural sand 0-8 mm	704	722	763	747	750	771	830	852	887
Natural sand (filler)	107	110	93	43	43	44	32	33	34
Cement (Appendix 1)	395	405	428	343	345	354	274	281	293
Granulated silica fume, s	-	-	21	-	-	18	-	-	15
Air-entrainment (fir oil, g)	43	44	50	34	35	35	26	26	27
Superplasticiser (melamine)	3.4	3.5	3.6	1.7	1.7	1.8	0.9	0.9	1.0
Water-reducing agent	1.7	1.8	1.9	0.9	0.9	0.9	1.0	1.1	1.1
Total water incl. moisture	127	131	137	131	131	135	136	138	144
Water-cement ratio, w/c	0.32	0.32	0.32	0.38	0.38	0.38	0.50	0.50	0.50
Air content (% by volume)	12.5	10.5	6.0	13.0	13.0	10.5	15.5	13.5	11.0
Aggregate content	0.75	0.75	0.75	0.76	0.76	0.76	0.80	0.80	0.80
Slump (mm)	90	100	80	140	170	150	200	180	180
Density - fresh state (kg/m^3)	2145	2200	2330	2090	2100	2175	2000	2050	2150
28-day cylinder density 1)	2280	2330	2370	2280	2260	2290	2060	2150	2200
curing at 18°C (kg/m^3) 2)	2290	2330	2350	2300	2260	2280	2040	2150	2210
curing at 20.5°C (kg/m^3) 2)	2290	2320	2390	2290	2270	2310	2100	2180	2190
curing at 23°C (kg/m^3) 2)	2270	2340	2380	2260	2250	2290	2040	2130	2210
Air-content loss, ΔA (%) 3)	6.5	6.0	2	9.0	7.5	5.5	3.0	5.0	2.5
Air-content - cured (%) 4)	7.5	6.0	5.5	5.5	7.0	6.5	14.0	10.0	10.0
28-day cylinder strength 1)	47	51	71	51	38	51	20	27	33
curing at 18°C (MPa) 2)	47.0	53.0	72.0	56.5	41.0	54.5	20.5	26.5	32.5
curing at 20.5°C (MPa) 2)	49.5	51.0	74.0	52.0	39.5	52.0	21.9	30.0	33.0
curing at 23°C (MPa) 2)	45.0	48.0	67.0	44.0	34.5	46.0	18.5	24.0	33.0

1) average of 9 cylinders, 2) average of 3 cylinders, 3) $100\cdot[(\rho_{28d}/\rho_{fresh})-1]$ *%, 4)* $A_{fresh}-\Delta A+1.5\%$*, L = low-alkali cement, N= normal-alkali, NS= normal-alkali cement and 5% silica fume, 32 = w/c (%)*