# EFFECT OF AGE, CEMENT TYPE, MODERATE SHIFT IN TEMPERATURE AND WATER-CEMENT RATIO ON SELF-DESICCATION IN SILICA FUME CONCRETE

Bertil Persson, M.Sc., Lic. Tech., CIV.ENG.
Div. Building Materials, Lund University, Box 118, 221 00 Lund

## ABSTRACT

This article outlines an experimental and numerical study on the effect of cement type, silica fume, w/c, age and moderate shift of temperature on self-desiccation and strength of concrete. For this purpose 81 sealed cylinders made of 9 concretes with w/c varying between 0.32 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. Self-desiccation was studied after sealed curing at three different temperatures. The measurement was done at 1 and 6 months' age at three temperatures. The results indicated high influence of age, cement type and w/c on self-desiccation. The study was performed at Lund Institute of Technology, Lund University 1997-1998.

Keywords: Alkali-effect, Compressive strength, High Performance Concrete, Internal Relative Humidity, Self-desiccation, Silica fume.

## 1. INTRODUCTION

### 1.1 Background

The chemical shrinkage that takes place during hydration of water to cement is the fundamental cause of self-desiccation /1/. The specific volume of the hydrated water in the gel of concrete is reduced by about 26% compared with the specific volume of water in the capillary pores /2/. Especially at low w/c < 0.38 the effect of self-desiccation becomes more pronounced 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 the self-desiccation concrete with low w/c deforms even with sealed curing, free of imposed stresses (autogenous shrinkage) /4,5/. Furthermore low-w/c concrete especially with silica fume may exhibit a rather 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/.

## 1.2 Objective of the study

The main aim of the study was to ascertain the influence of cement type, w/c, silica fume, age and moderate shift in temperature on internal relative humidity, RH, due to self-desiccation in concretes with w/c varying between 0.32 and 0.50. The effect of self-desiccation on the RH properties was secured by studying concrete at 1 and 6 months' age. The effect of cement type was ascertained by studies on low- and normal-alkali cement. Half of the number of specimens that were made with normal-alkali cement was blended with 5% silica fume as calculated on the basis of the cement content. Finally, the effect of temperature changes was studied at three levels varying between 18.5 °C and 23 °C. Another aim was to observe the effect of cement type, silica fume and temperature on the compressive strength of concrete with sealed curing.

## 1.3 General layout of the work

Nine different types of concrete were examined. After sealed curing at three different temperatures (18.5, 20.5 and 23 °C) the concrete strength was tested at 1 month's age. RH was measured on pieces of crushed concrete at the mentioned temperatures at 1 and 6 months' age. The density of the concrete was studied in the fresh state and after sealed curing for 28 days.

# 2. EXPERIMENTAL

## 2.1 Materials and studied concretes

The concretes had good rheological properties. The 28-day 100-mm cylinder compressive strength exceeded 20-40 MPa (comparable with 25-50 MPa 150-mm cube strength). The mix design was based on theoretical optimisation of the grading curve in the fresh concrete in order to obtain good workability /14/. The w/c varied between 0.32 and 0.50. The slump of the concretes varied between 80 and 180 mm. It was possible to mix, transport and cast HPC with existing methods. Low-alkali and normal-alkali cement was used. Appendix 1 gives the chemical composition of the cements /15/. Nine types of concrete were studied, 9 cylinders of each quality, in all 81 cylinders. Properties of the aggregate are given in Appendix 2 /16/. First of all the dry material was mixed for ½ minute. Then the water with air-entrainment was added and mixed for another ½ minute. Finally, the plasticisers were added and mixed for 3 minutes. Workability, density and air-content of the concretes were studied in the fresh state. 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, compressive 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 (18.5 °C) in a climate chamber, 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 replaced in the climate chambers where the initial curing took place. The weight of the cylinders was established before and after the 28-day tests.

### 2.3 Experimental methods

The cylinder with the plastic tube was weighed. Then, all concrete cylinders were weighed and measured separately. The plastic tube was weighed separately in order to detect any increase due to moisture uptake. The cylinder was placed centric in a hydraulic press device and the loading applied at 1 MPa/s. Minimum 5-mm fragments from the concrete used in the compressive testing were filled in glass tubes 150 mm long and 22 mm in diameter. The temperature of the fragments and that of the climate chamber were adjusted to each other for 1 day. Then the internal relative humidity, RH, was measured by a dew-point meter (Protimeter) for 22 h. The probe of the dew-point meter was entered into the glass tube and tightened against the glass with an expanding rubber ring.

## 3. INTERNAL RELATIVE HUMIDITY, RH, AT 1 MONTH'S AGE

### 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, Appendix 3. 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 of the curing temperature, especially at w/c= 0.38, i.e. between 0.5 and 2.5 MPa/°C. Figure 1 shows the air content in the concretes in the fresh state and after curing and the estimated losses of air content. (About 1.5% of increase in air content was related to the chemical shrinkage that takes place during the hardening of the cement paste.) Figure 2 gives the strength versus w/c of the concretes. Besides an increase with lower w/c, a substantial increase of strength was observed for silica fume concretes. At early ages the efficiency factor of silica fume is quite large, perhaps as high as 7 at 28 days' age, but then decreasing with the age of the concrete. After 7 years no effect at all of silica fume on the compressive strength was observed /17/.

### 3.2 Internal relative humidity, RH, in concrete dependent on the curing temperature

Figures 3-5 show the difference in RH between curing at 20.5 °C and 23 °C compared with 18.5 °C (ASTM-calibration /18/). Figure 6 shows that a small average effect 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 effect 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).

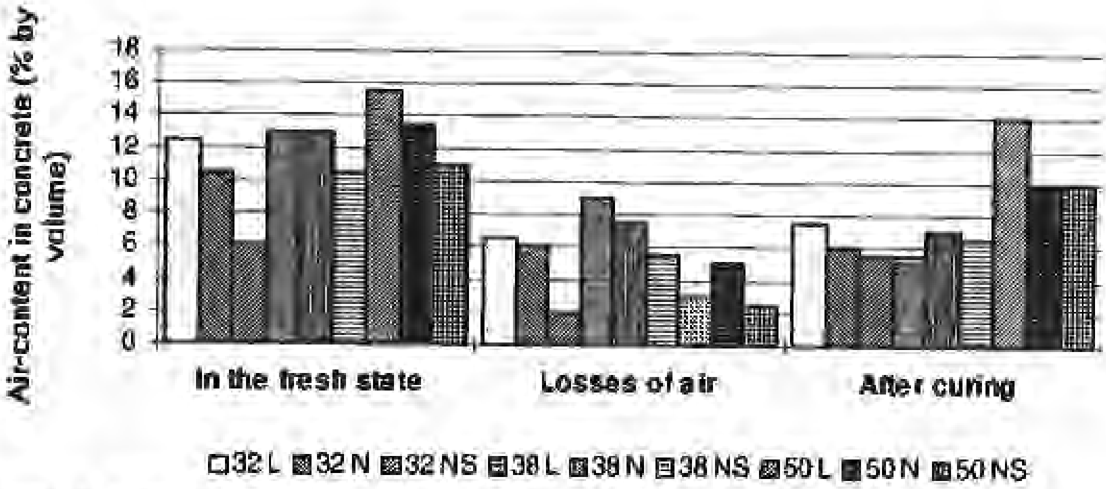

Figure 1. Estimated losses of air content in the concretes in the fresh state and after curing. L= low-alkali cement, N = normal-alkali cement, NS= N + 5% silica fume, 32= w/c (%).

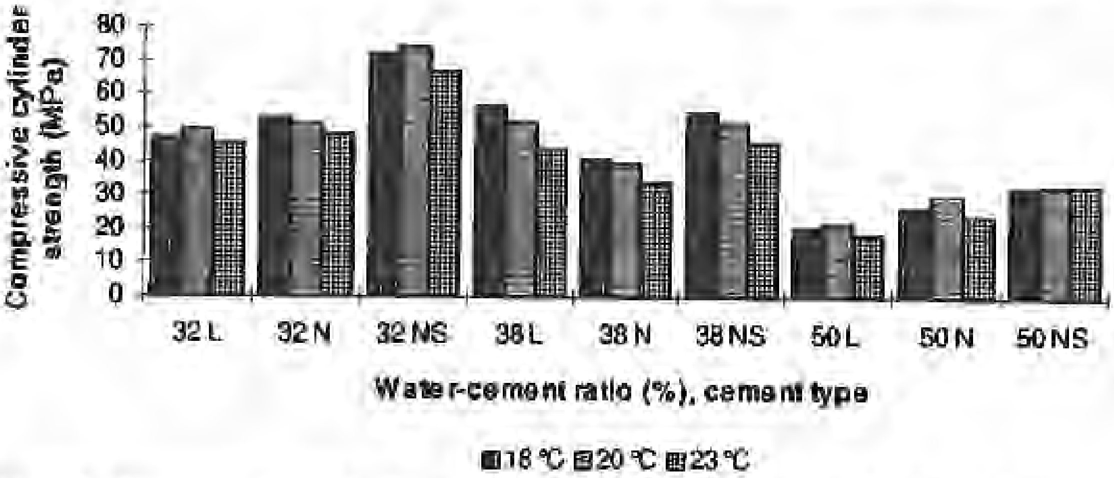

Figure 2. Compressive cylinder strength versus w/c of the concretes. L= low-alkali cement, N = normal-alkali cement, NS= N + 5% silica fume, 32= w/c (%).

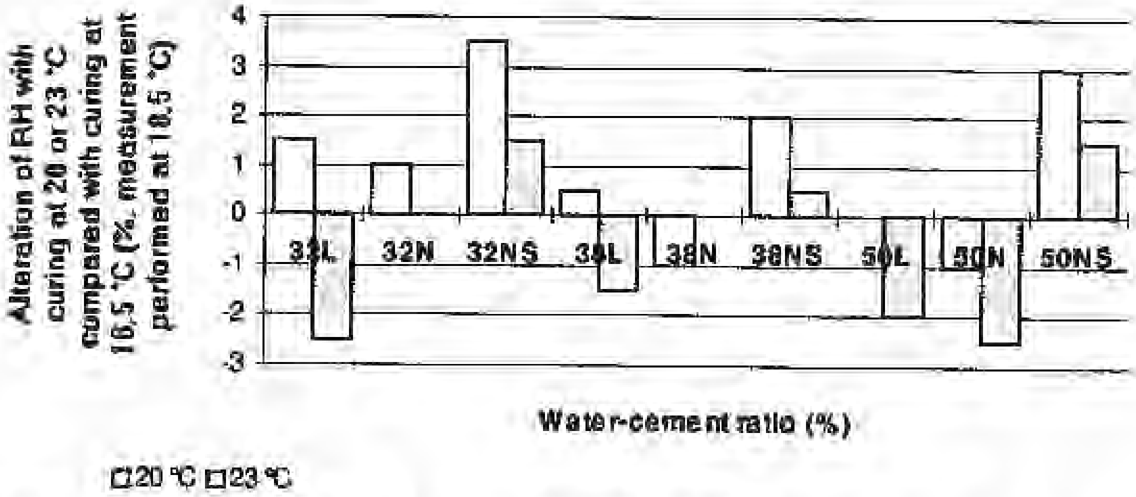

Figure 3. Alteration of RH with curing at 20.5 °C and 23 °C compared with curing at 18.5 °C (measurement performed at 18.5 °C).

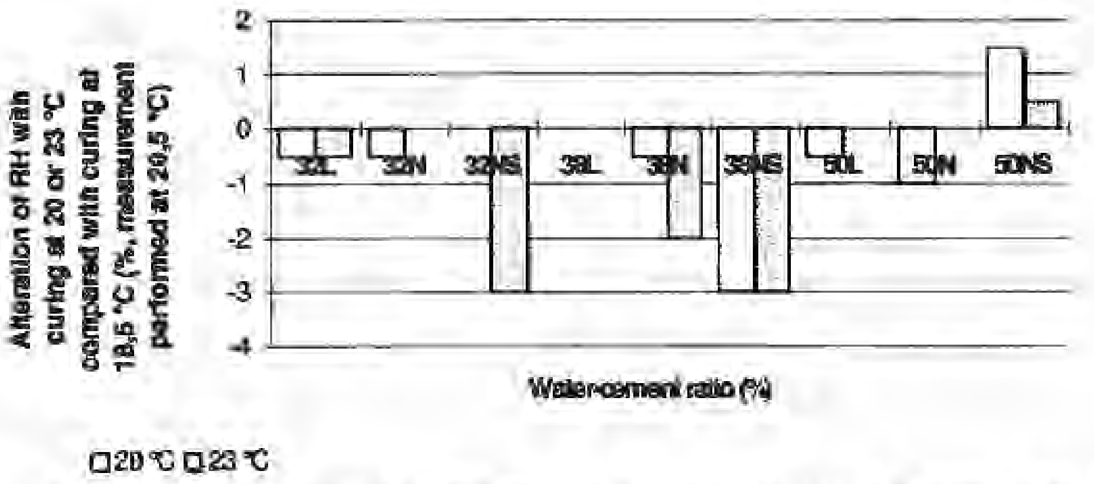

Figure 4. Alteration of RH with curing at 20.5 °C and 23 °C compared with curing at 18.5 °C (measurement performed at 20,5 °C).

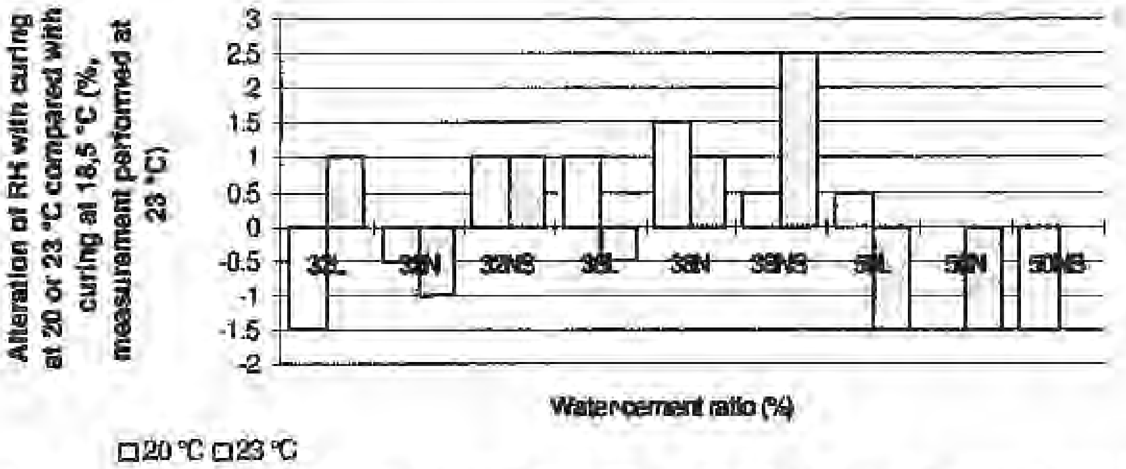

Figure 5. Alteration of RH with curing at 20.5 °C and 23 °C compared with curing at 18.5 °C (measurement performed at 23 °C).

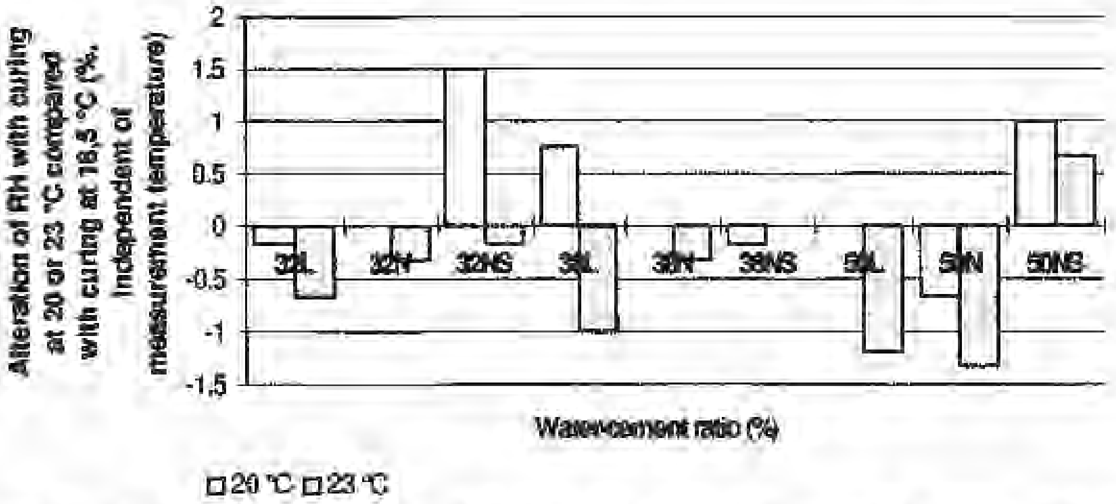

Figure 6. Alteration of RH with curing at 20.5 °C and 23 °C compared with curing at 18.5 °C (independent of temperature of measurement).

Table 1. Difference in RH dependent on curing temperature (%, ASTM-calibration /18/).

| Curing at | 18.5 °C | | 20.5 °C | | 23 °C | | 18-23 °C | |
|---|---|---|---|---|---|---|---|---|
| Measurement at | 20.5 °C | 23 °C | 20.5 °C | 23 °C | 20.5 °C | 23 °C | 20.5 °C | 23 °C |
| Average | 1.1 | - 0.6 | - 0.6 | - 1 | 0.1 | 0.1 | 0.2 | - 0.5 |
| Standard deviation | 1.6 | 1.6 | 1.2 | 1.4 | 1.1 | 1.2 | 0.7 | 0.6 |

### 3.3 RH in concrete dependent on the temperature of measurement

Figures 7 - 9 show the difference in RH between measurement at 20.5 °C and 23 °C compared with 18.5 °C. Figure 10 shows that the observed average effect of measurement 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 effect 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).

Table 2. Difference in RH dependent on measurement temperature (%, ASTM /18/).

| Measurement at | 18.5 °C | | 20.5 °C | | 23 °C | | 18 - 23 °C | |
|---|---|---|---|---|---|---|---|---|
| Curing at | 20.5 °C | 23 °C | 20.5 °C | 23 °C | 20.5 °C | 23 °C | 20.5 °C | 23 °C |
| Average | 0.6 | - 1.3 | - 0.9 | - 0.3 | .04 | - 0.2 | - 0.1 | - 0.6 |
| Standard deviation | 1.6 | 1.8 | 2 | 2.2 | 1.2 | 1.1 | 1 | 1.5 |

### 3.4 Effect of cement type and silica fume on RH when w/c was held constant

Figure 11 shows the effect of cement type and silica fume on RH compared with RH in concrete based on low-alkali cement when w/c was held constant, i.e. Figure 11 shows the decline of 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. Perhaps variations in RH versus w/c were owing to the available amount of pore solution for the probe to react properly.

### 3.5 Effect of cement type and silica fume on RH when RH was held constant

Figure 12 shows the effect of cement type and silica fume on RH compared with RH in concrete based on low-alkali cement when RH was held constant, i.e. Figure 12 shows the decline of RH. The effect of cement type and silica fume on RH varied between - 2 and - 9%.

## 4. SOURCES OF ERROR AND ACCURACY

### 4.1 Variations in w/c of the concrete due to the moisture content in the sand

The planned 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 variations. The moisture varied between 3% and 4.8%, which produced a w/c-variation of maximum ± 0.02.

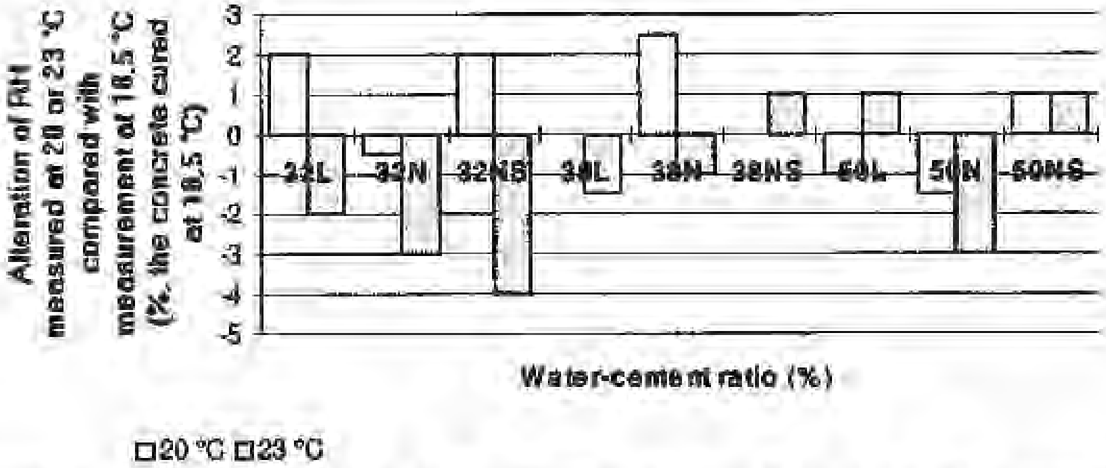

Figure 7. Alteration of RH with measurement at 20.5 °C and 23 °C compared with measurement at 18.5 °C (curing at 18.5 °C).

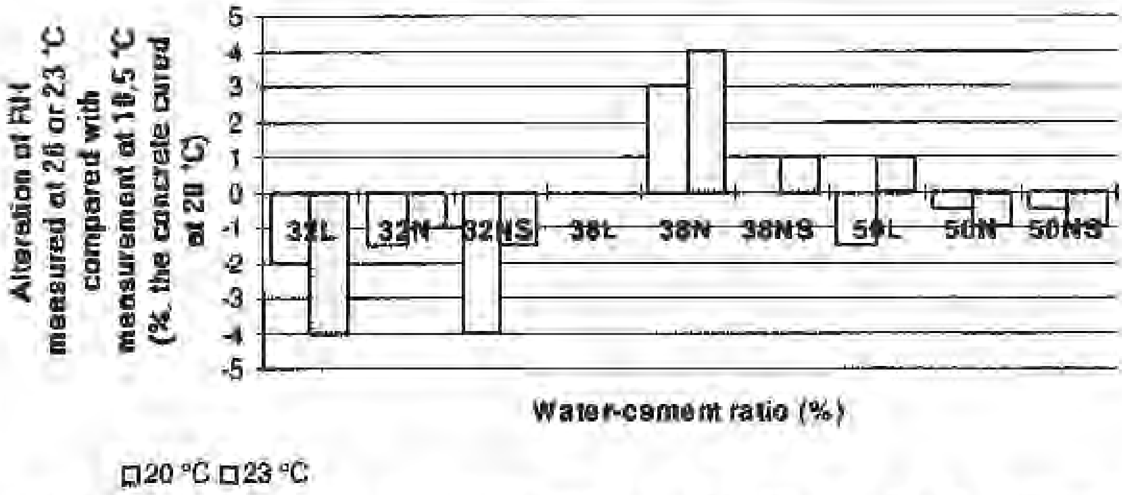

Figure 8. Alteration of RH with measurement at 20.5 °C and 23 °C compared with measurement at 18.5 °C (curing at 20.5 °C).

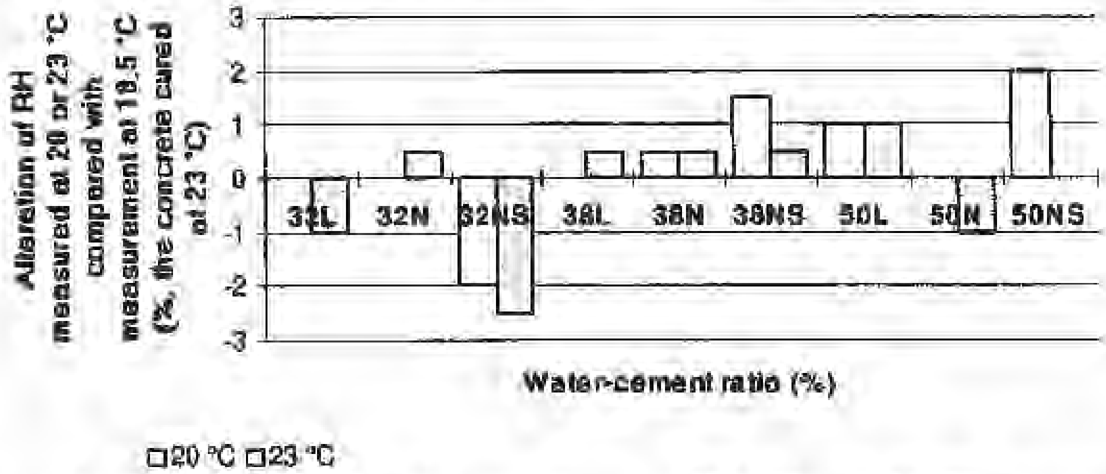

Figure 9. Alteration of RH with measurement at 20.5 °C and 23 °C compared with measurement at 18.5 °C (curing performed at 23 °C).

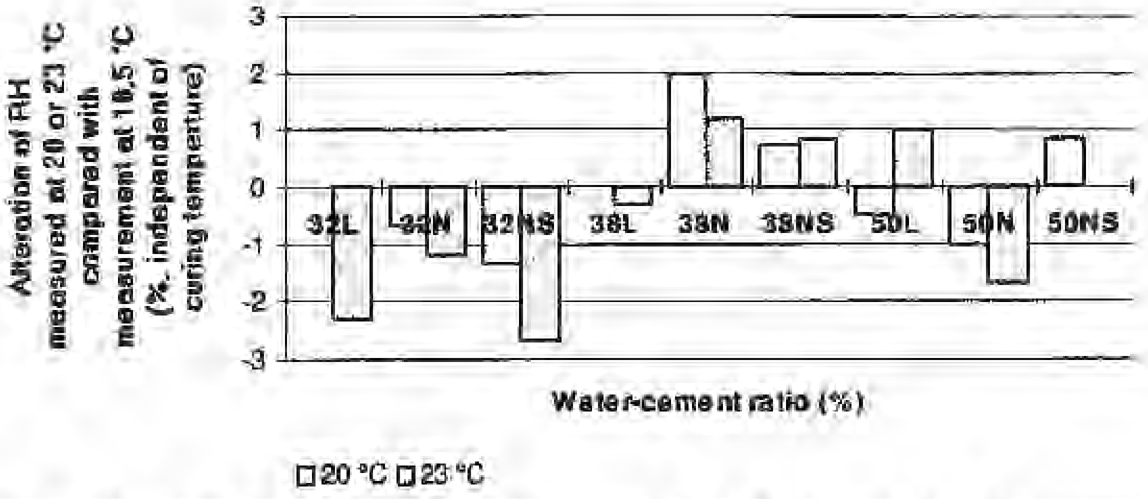

Figure 10. Alteration of RH with measurement at 20.5 °C and 23 °C compared with measurement at 18.5 °C (independent of temperature of curing).

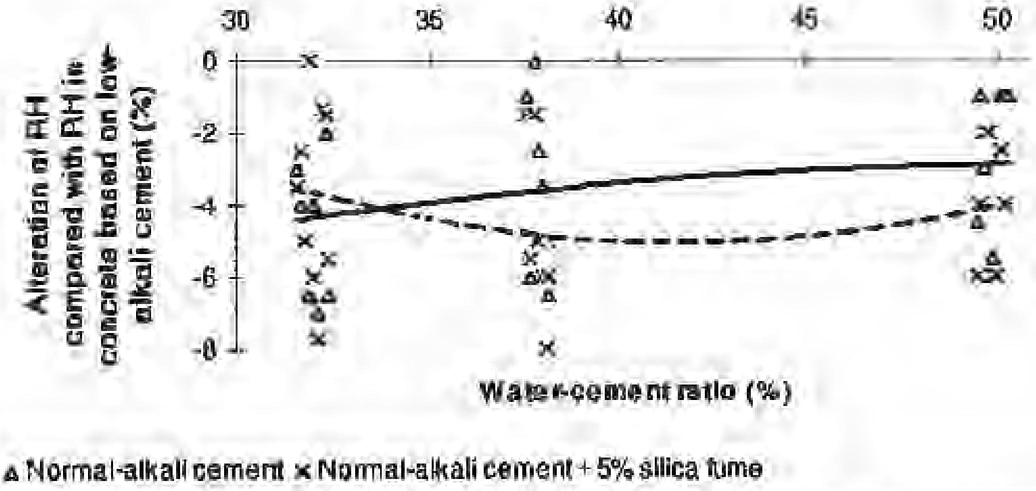

Figure 11. Effect of cement type and silica fume on RH versus w/c compared with RH in concrete based on low-alkali cement.

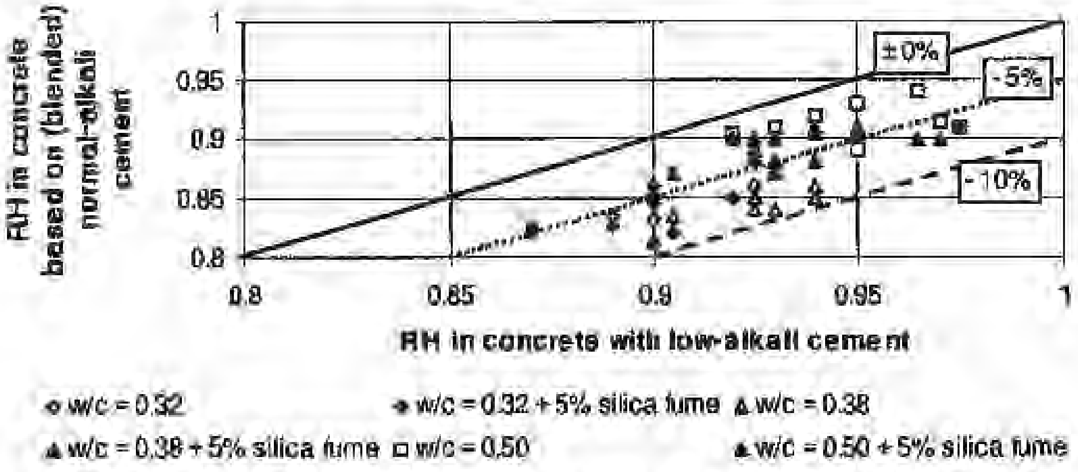

Figure 12. Effect of cement type and silica fume on RH versus RH compared with RH in concrete based on low-alkali cement.

## 4.2 Moisture weight losses during handling and curing of the cylinders

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. Figure 13 shows the moisture losses through different kinds of moisture insulation:

1. Butyl rubber clothing
2. Aluminium foil
3. 3-mm plastic pipe

Aluminium foil showed no loss of moisture at all but required a certain time for application. The moisture losses during the time of application were much larger than the losses observed with rubber clothing or plastic pipes. Table 3 shows the measured net moisture losses from the specimens during the 28-day curing time. Moisture uptake (+) was observed in some cases, probably due to measurement faults or/and adsorption of moisture in the plastic pipe.

Table 3. Moisture losses by weight from the specimens during the 28-day curing time (%).

| Concrete | 32L | 32N | 32NS | 38L | 38N | 38NS | 50L | 50N | 50NS |
|---|---|---|---|---|---|---|---|---|---|
| 18 °C | - 0.05 | - 0.03 | - 0.05 | - 0.03 | - 0.08 | - 0.04 | - 0.09 | + 0.06 | + 0.07 |
| 20.5 °C | - 0.08 | + 0.03 | - 0,06 | - 0.03 | + 0.01 | - 0.04 | - 0.10 | - 0.04 | - 0.04 |
| 23 °C | - 0.03 | - 0.05 | - 0.03 | - 0.10 | - 0.01 | - 0.06 | - 0.12 | - 0.05 | + 0.05 |

As observed in Table 3, the moisture losses were small, hardly detectable, and may not have affected RH in the specimens. (Compared with the cement content in the concrete, c, the observed moisture losses, $w_e$, were less than $w_e/c < 0.006$ kg/kg.)

## 4.3 Calibration of the hydraulic press device and the dew-point meters

The hydraulic press device was calibrated 1 year before the measurement of strength was performed. The calibration showed index + 13 kN, i.e. the strength given in Figure 2 is generally to be increased by 2 MPa. 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 Figure 10 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/. 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.

Table 4. RH in saturated salts.

| 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 |

During calibration of the salts the solution was placed in a glass tube insulated from variations in the ambient temperature with heat insulation. The solution of the salt was separated from the RH-probe by a partial 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. Figure 14 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/ showed about 2% higher RH than calibration with the humidity generator, Figures 15 and 16.

## 5. RH IN SEALED CONCRETE AT 6 MONTHS' AGE

### 5.1 Effect of cement type and silica fume on RH when w/c was held constant

Figure 17 shows the effect of cement type and silica fume on RH compared with RH in concrete based on low-alkali cement when w/c was held constant, i.e. Figure 17 shows the decline of 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. Perhaps variations in RH versus w/c were due to the available amount of pore solution for the probe to react properly.

### 5.2 Effect of cement type and silica fume on RH when RH was held constant

Figure 18 shows the effect of cement type and silica fume on RH compared with RH in concrete based on low-alkali cement when RH was held constant, i.e. Figure 18 shows the decline of RH. The effect of cement type and silica fume on RH varied between - 2 and - 9%.

## 6. ANALYSES OF SELF-DESICCATION

### 6.1 Effect of age, w/c, cement type and/or silica fume on RH (Ø)

Figures 19-22 give data on RH (Ø) versus w/c and $(w/c)_{eff} = w/(c + 2 \cdot s)$ for the tested concretes (1 and 6 months' age). From Figures 19 and 20 the following equation was calculated:

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

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

Table 5. Constants in equation (1)

| Cement type, silica fume | A | B | C | D | $R^2$ [accuracy, equation (2)] |
|---|---|---|---|---|---|
| Low-alkali | 0.0378 | 0.185 | - 0.042 | 0.83 | 0.63 |
| Normal-alkali | 0.0588 | 0.219 | - 0.059 | 0.79 | 0.75 |
| Normal-alkali + 5% silica fume | 0.0351 | 0.223 | - 0.051 | 0.78 | 0.49 |

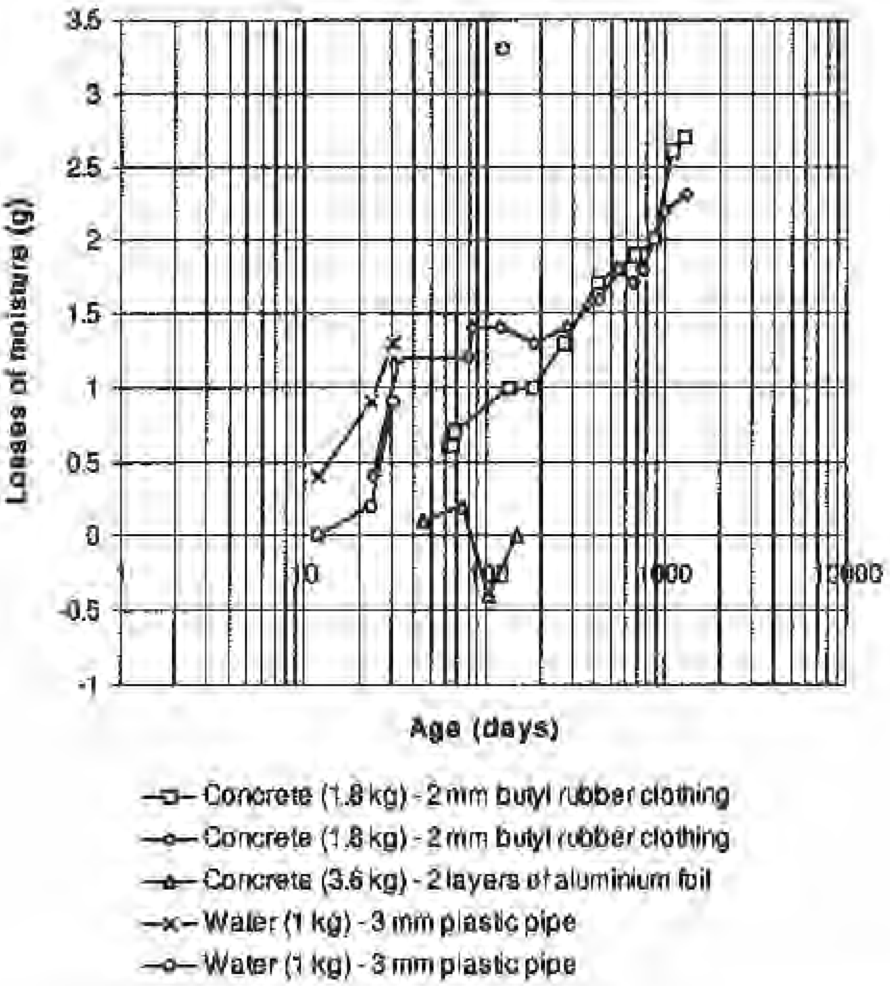

Figure 13. Moisture losses through different kinds of moisture insulation: butyl rubber clothing, aluminium foil or 3-mm plastic pipe.

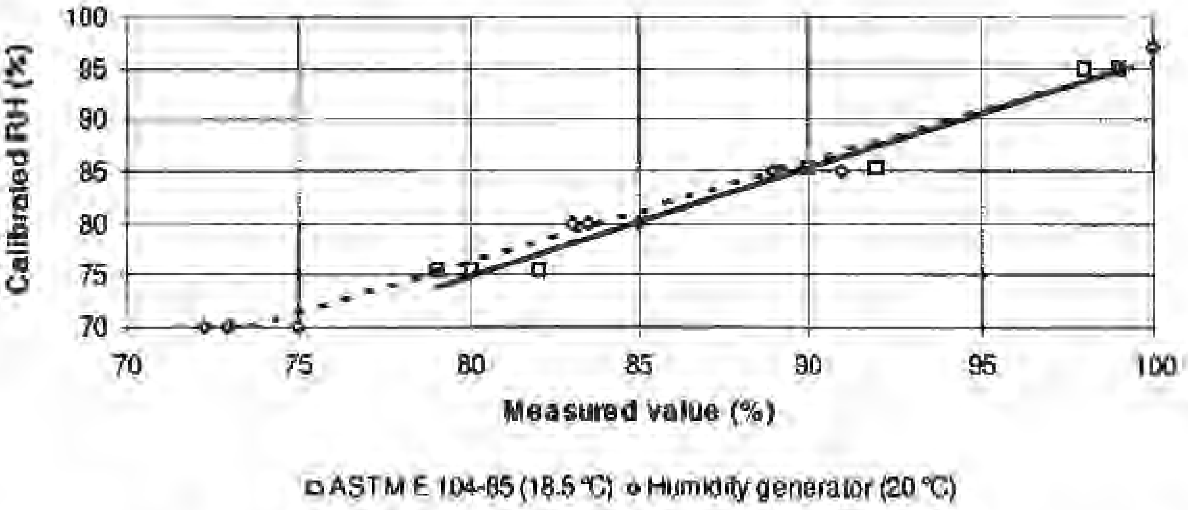

Figure 14. RH calibrated according to ASTM E 104-85 (18.5 °C), /18/, and according to humidity generator (20 °C).

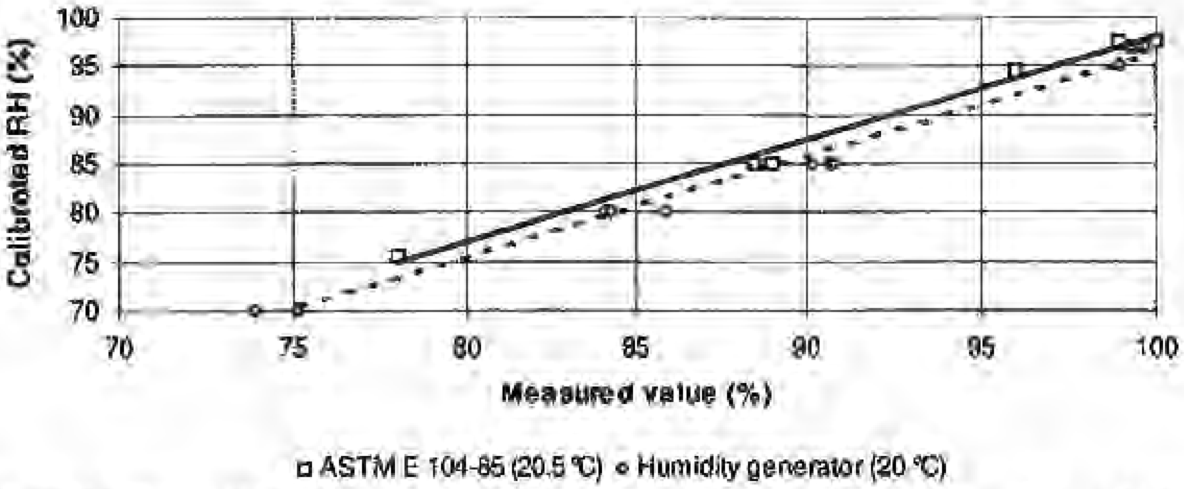

Figure 15. RH calibrated according to ASTM E 104-85 (20.5 °C), /18/, and according to humidity generator (20 °C).

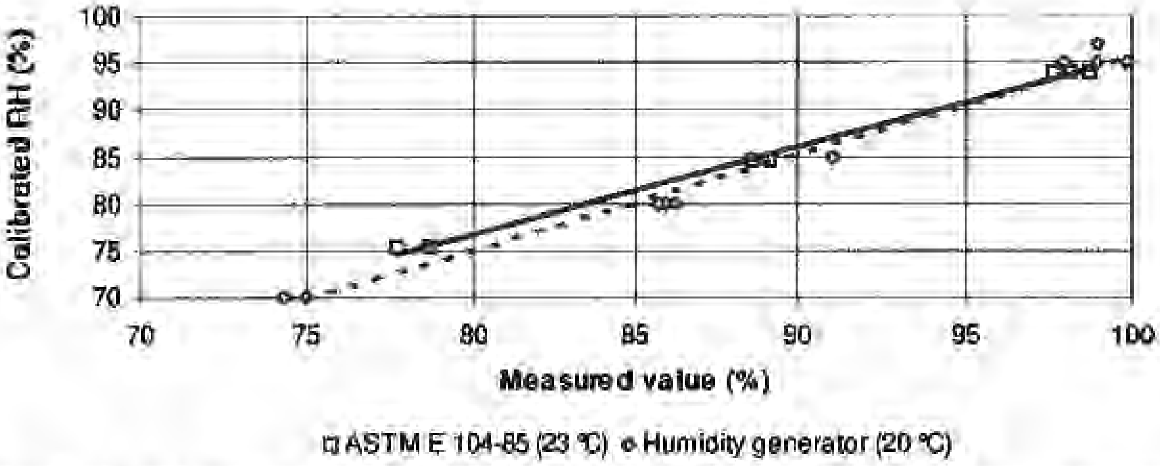

Figure 16. RH calibrated according to ASTM E 104-85 (23 °C), /18/, and according to humidity generator (20 °C).

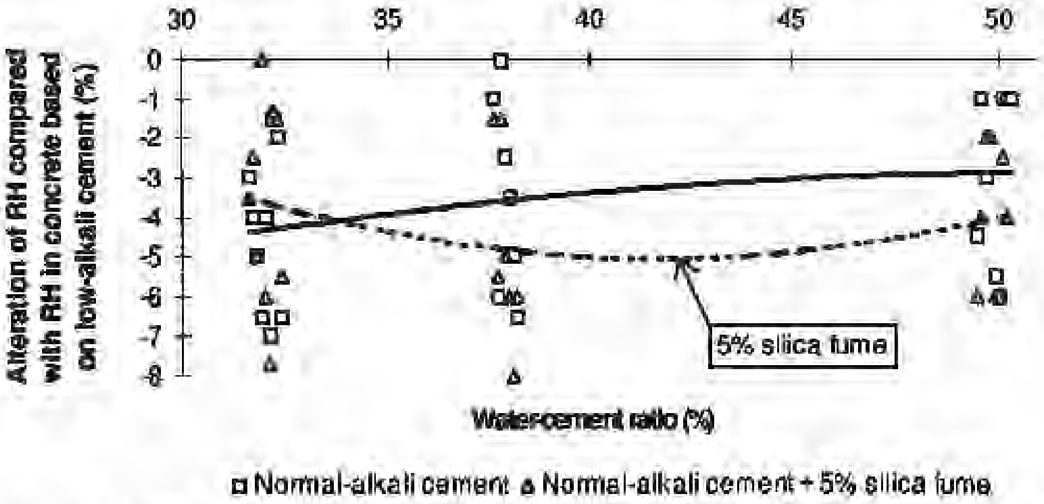

Figure 17. Effect of cement type and silica fume on RH versus w/c compared with RH in concrete based on low-alkali cement.

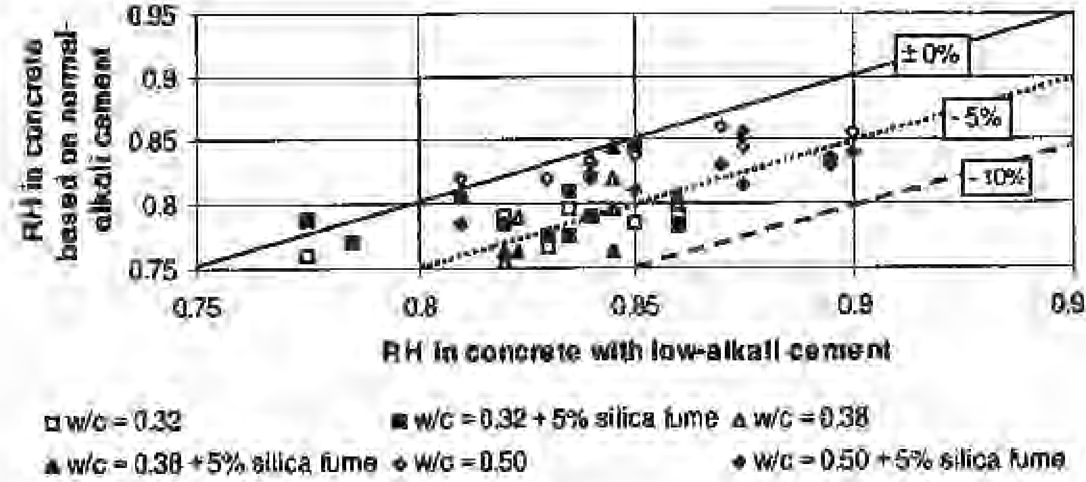

Figure 18. Effect of cement type and silica fume on RH versus RH compared with RH in concrete based on low-alkali cement. Six months' age.

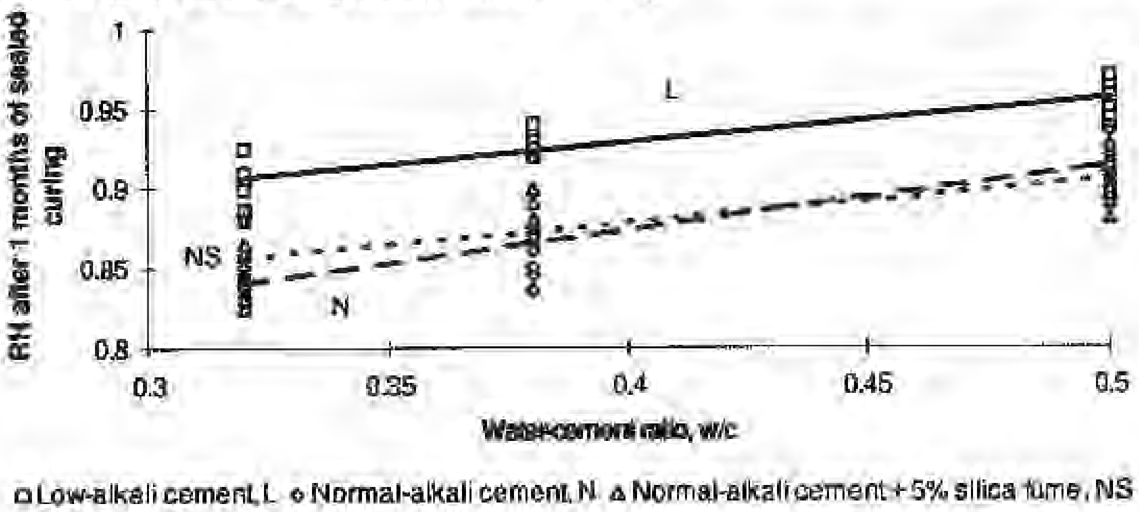

Figure 19. RH versus w/c, 1 month's age.

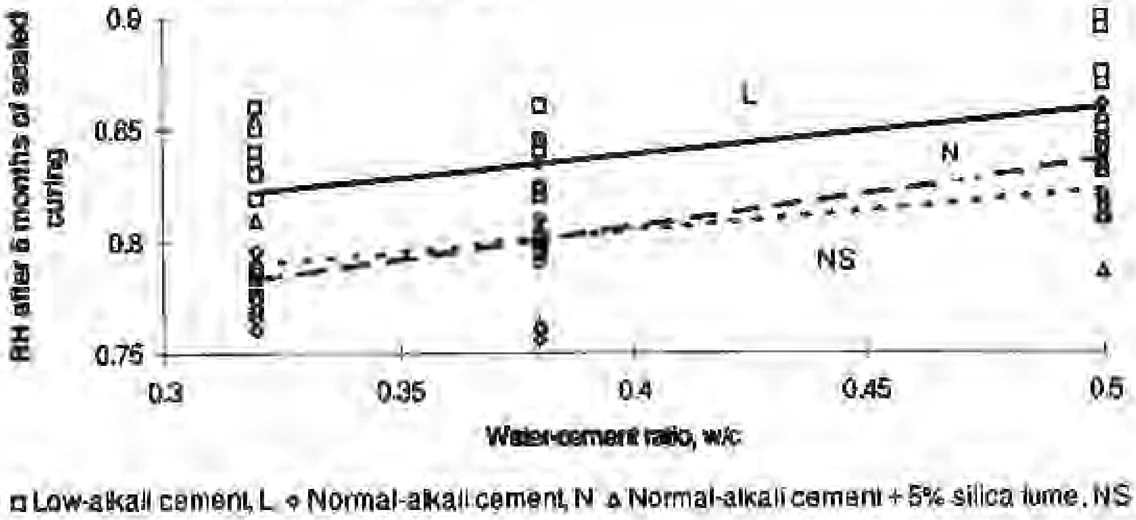

Figure 20. RH versus w/c, 6 months' age.

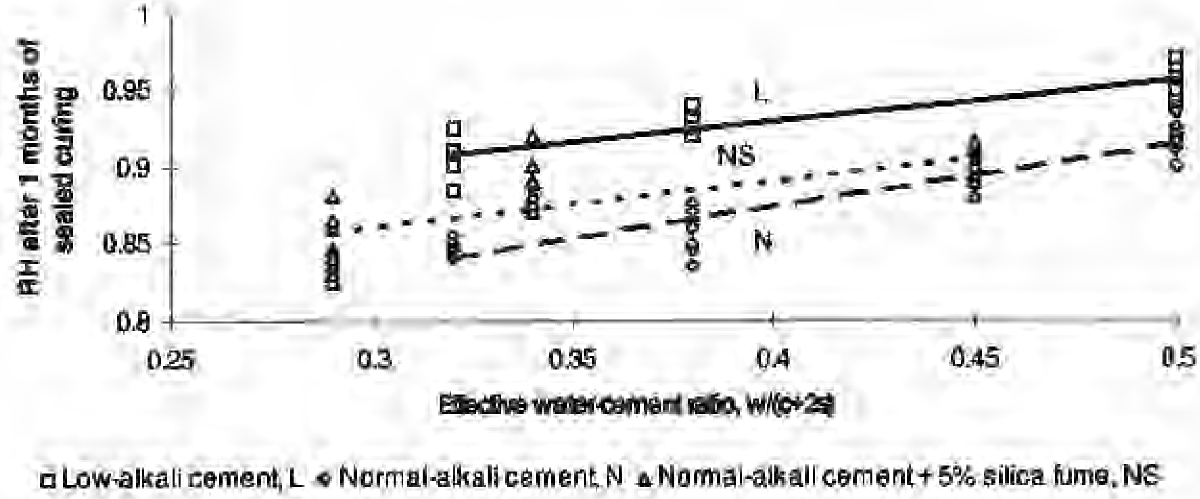

Figure 21. RH versus $(w/c)_{eff}$, 1 month's age.

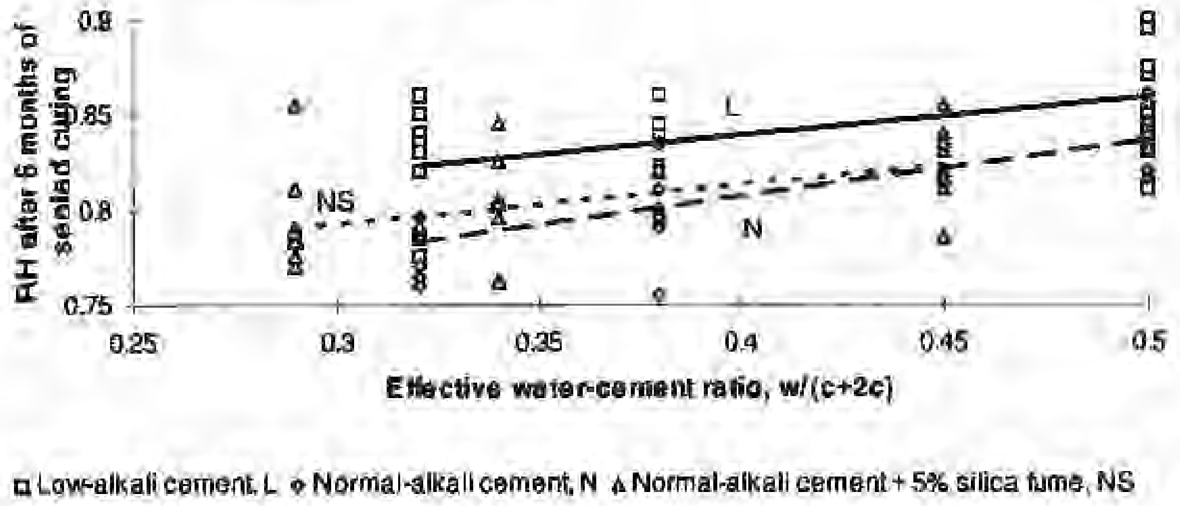

Figure 22. RH versus $(w/c)_{eff}$, 6 months' age.

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

Figures 19 and 20 confirm the results that concrete 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 effect of silica fume was less than the effect of normal-alkali cement, Figures 19-20. 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 the cements, Appendix 1. However, the remaining clinker components, Belite, $C_2S$, Aluminate, $C_3A$, and Ferrite, $C_4AF$, varied quite a lot between the cements studied. The content of alkalis, $K_2O$ and $Na_2O$, most probably also affected RH in the concrete.

## 6.2 Comparison with other research

The present results were compared with studies on 8 concretes made of 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 as calculated on the basis of the 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 /23,24/. RH in the concrete, Ø, cured at 20 °C was correlated to age and w/c:

$$Ø_S(t,w/c)=1.13\cdot[1-0.065\cdot\ln(t)]\cdot(w/c)^{0.24\cdot[1-0.1\cdot\ln(t)]}\ \{1<t<15\text{ m};\ 0.2<w/c<0.6\}\ \{R^2=0.76\}\quad(3)$$

$$Ø(t,w/c)=1.09\cdot(w/c)^{0.17\cdot(1+0.0451\cdot t)}\quad\{1<t<15\text{ months};\ 0.2<w/c<0.6\}\quad\{R^2=0.54\}\quad(4)$$

ln(t) denotes the natural logarithm of age, t, in months (m)
$R^2$ denotes an accuracy parameter given in equation (2)
S denotes 10% silica fume

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

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

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

S5 denotes 5% silica fume

Table 6 provides a comparison between RH measured in the concretes of this project and RH estimated according to equations (5) and (6).

Table 6. Measured RH at 1 month's age and RH estimated according to equations (5) and (6).

| w/c | Low-alkali cement | Estimation equation (6) | Differences in RH | Normal-alkali cement with 5% silica fume | Estimation equation (5) | Effect of the cement type, ΔØ |
|---|---|---|---|---|---|---|
| 0.32 | 0.903 | 0.890 | 0.013 | 0.855 | 0.875 | - 0.02 |
| 0.38 | 0.923 | 0.917 | 0.006 | 0.874 | 0.906 | - 0.032 |
| 0.50 | 0.954 | 0.964 | - 0.01 | 0.906 | 0.960 | - 0.054 |

The estimation of RH according to equation (6) coincided reasonably well with the measured RH. Concrete based on normal-alkali cement and 5% silica fume exhibited significantly larger differences between measured and estimated RH due to the effect of components of the cement, which means that the content of alkalis, $K_2O$ and $Na_2O$, probably affected RH in the concrete.

## 7. SUMMARY AND CONCLUSIONS

The article presents an experimental and numerical study on self-desiccation and strength of 9 concretes at 28 days' age. Furthermore the self-desiccation was studied at 6 months' age. In all 81 concrete cylinders were studied. The following conclusions were drawn:

- Self-desiccation of concrete was mainly dependent on w/c and age but fairly independent of moderate variations in curing temperature. 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.
- 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).
- The calibration of dew-point meters was preferably performed at the temperature of measurement (± 0.5 °C). Two °C 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 (22b) and also during the time of calibration of dew-point meters (22b). The same requirements probably apply for other types of probes.
- Concrete with normal-alkali cement obtained 5% lower RH than with low-alkali cement. RH in concrete with normal-alkali cement was not significantly affected by 5% silica fume.
- Strength was reduced by 11% when the curing temperature was increased from 18 to 23 °C.

## 8. ACKNOWLEDGEMENT

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## Appendix 1

Composition of the cements /15/.

| Component/Cement type | 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 /16/.

| Type of aggregate/Property | Elastic modulus | Compressive strength | Split tensile strength | Ignition losses |
|---|---|---|---|---|
| Quartzite sandstone, Hardeberga | 60 GPa | 332 MPa | 15 MPa | 0.3% |
| Natural sand, Åstorp | | | | 0.8% |
| Granulated silica fume (fineness: 17.5 $m^2/g$) | | | | 2.3% |

## Appendix 3

Mix design (kg/m$^3$ dry material) and properties of the studied concretes /14/.

| Material/Concrete mix | 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 0 mm (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-entraining agent (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 |
| Aggregate to cement ratio | 4.2 | 4.2 | 4.2 | 4.6 | 4.6 | 4.6 | 5.8 | 5.8 | 5.8 |
| Slump (mm) | 90 | 100 | 80 | 140 | 170 | 150 | 200 | 180 | 180 |
| Density in 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 losses, ΔA (%)[3)] | 6.5 | 6.0 | 2 | 9.0 | 7.5 | 5.5 | 3.0 | 5.0 | 2.5 |
| Air-content after curing (%)[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)[3)] | 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 |
| Strength decline (MPa/°C) | 0.5 | 1 | 1.1 | 2.5 | 1.3 | 1.7 | 0.5 | 0.6 | 0 |

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