WATER ABSORPTION PROPERTIES, MOISTURE STATE AND NUMBER OF FREEZE-THAW CYCLES IN A REPAIRED CONCRETE BRIDGE DECK

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ABSTRACT

Data are lacking regarding absorption rates of de-icing water at relevant conditions in mature concrete with low w/c-ratio. Field tests have, therefore, been conducted outdoors. The result shows that relatively large quantities of water and NaCl can be absorbed during the winter. Cyclic absorption of de-icing water is the dominating ingress mechanism for chloride ions in the outer 0-15 mm of concrete in de-icing environments.

Key words: Water absorption, chloride absorption, relative humidity

1 INTRODUCTION

This paper is part of a large investigation where the overall aim is to predict the overall service lives of concrete bridge decks repaired with bonded concrete overlays /1-4/. The research regarding corrosion and chloride ingress in concrete is intense today. However, the mechanisms on the surface are often not dealt with even though the absorption/desorption of de-icing water in the outer 0 to 15 mm of the concrete probably controls the ingress of chloride ions in a de-icing environment. The absorption of chloride ions in concrete subjected to capillary suction has been studied by Volkvein /5/, Halford /6/, and McCarter et. al. /7, 8/ for relatively young concrete with higher w/c-ratios than the concrete overlays in this study. The absorption of chloride contaminated water in concrete subjected to Cyclic Wetting and Drying (CWD) has also been studied /8-14/. However, the drying periods and the drying conditions used were not representative for Swedish conditions and the results could not be used by the author.

Parrot /15/ showed that the amount of water absorbed was a lot less for concrete stored in situ than stored in lab and that in-situ samples were needed to get relevant results. Unsheltered concrete absorbed 30 g/m² after 4 h while a sheltered surface absorbed 640 g/m² of water /15/. Fagerlund and Svensson /16/ concluded that the Relative Humidity (RH) in unsheltered concrete was higher than in sheltered. Sosoro and Reinhard /17/ found that the absorption rate was higher for concrete with low Degree of Capillary Saturation (DCS) than for samples with high DCS. The author concluded that there was a need, due to the effects of the moisture state on the amount of water absorbed, to investigate the RH in-situ for repaired concrete bridge decks.

Volkvein /5/ also measured the absorption rates for 0 %, 1,8 %, 6,2 % and saturated NaCl-solutions. The absorption rate increased with 35 % in saturated NaCl-solution but decreased with 35 % in a 6,2 % NaCl-solution compared to pure water, i.e. no clear trend could be distinguished.

Due to the lack of relevant data and the influence of concreting procedures, the author conducted both a capillary suction test for the mature concrete aged in-situ and a CWD-test outdoors where the duration of the cycles was based on meteorological data /14/. The absorption duration was 6 h (mean duration of precipitation) and the drying duration was 66 h.

The aims of the paper are to: (i) Quantify the absorption properties for mature concrete, aged in-situ, with low w/c-ratios. (ii) Quantify the amount of water absorbed during CWD in conditions fairly relevant for a de-icing environment. Both pure and simulated de-icing water (based on measurements) is used. (iii) Quantify the RH in a concrete flat slab, repaired with a bonded concrete overlay, to investigate if and how changes in the environment affected the RH at different depths from the surface. The results could be used for future conditioning of samples before absorption test and to estimate the risk for future corrosion. (iv) Quantify the number of freeze-thaw and salt freeze-thaw cycles at different depths of the repaired concrete flat slab.

2 CAPILLARY SUCTION TESTS

A capillary suction test of the mature concrete samples with low w/c-ratio was conducted. Only two to four samples from each overlay were tested due to lack of specimens and the results may be uncertain but the test can at least be an indicator. Eight bridges (overlays) took part in the large investigation but only three will be discussed here and only the results from Gullmarsplan Bridge will be discussed in detail. The compositions of the three overlays are given in Table 1. For more information, see /4/.

Table 1. Composition of concrete

Bridge	Year of repair	w/c	Cement kg/m^3	Large aggregate kg/m^3	Fine aggregate kg/m^3	Air %	SP[1] kg/m^3	V_f[2] kg/m^3	f_{cc}[3] MPa
Umeå	1987	0,36	450	815 Porphyry	825	6,5	1,5	55	60
Långhals	1987	0,42	375	868 Granite	885	6	1	-	47
Gullmarsplan	1993	0,33	520	815 Porphyry	815	5	Yes	60	60

[1] Super plasticizer. [2] Steel fibre volume [3] Characteristic compressive (cube) strength at time of repair

Punkki and Sellevold /18/ studied the effect of drying procedure and DCS on concrete with a w/b-ratio of 0,39. Drying at 105 °C changed the absorption properties and gave suction curves with sharp knick points no matter of the DCS. Samples that instead were dried at 50 °C showed different suction curves depending on the DCS and the resistance numbers and capillary numbers were hard to establish due to lack of a knick point. The maximum temperature in an overlay in Stockholm was 40 °C /19/ and drying at 105 °C was not representative and the samples were not pre-dried at 105 °C.

Samples U12, U13, L12 and L13, taken from the overlays in 1995, were instead preconditioned for 2,5 years in a storage room at the Department of Structural Engineering. The temperature was 19 °C (± 2 °C) and the RH was 60 % (± 10 %). The samples had been cut into slices with a thickness of 20-35 mm due to other testing. The different height may affect the results but the author did not want to cut the specimens again since any cutting technique would have altered the moisture state. The tallest core from each bridge absorbed the largest amount of water while the shortest absorbed the least. The DCS at the start of the absorption test is given in Table 2.

The samples were placed on plastic meshes in sealed containers. The mesh allowed the samples to freely absorb water. The water reached 2 to 3 mm on the sides of the samples. The weight gain was measured by the author after 1, 5, 15, 30 and 60 min and after 2, 3, 4, 5, 6, 7, 8, 9 and 24 h and then once every day until day 9. The samples were thereafter weighed twice a week until day 61 when all samples were submerged for two months. The scale had an accuracy of 0,01 g and all samples were wiped off with a damped tissue before weighing.

The sides of the samples were not covered with epoxy but the errors are believed to be small. The vapour pressure in the container was close to saturation and vapour may be transported both in and out of the sides of the samples. All samples were treated similarly and a comparison may be appropriate anyhow. The use of epoxy as sealing may cause epoxy to penetrate into pores of the sample. The pores will not participate in the absorption and the amount of water absorbed and the porosity are underestimated /16/.

2.1 Results from absorption test

The results are presented in Table 2. The capillary number, *k*, is defined as (see Fig. 1):

$$k = \frac{W_k}{\sqrt{t_k}} \qquad \text{kg/m}^2\sqrt{\text{s}}$$

The resistance number, *m*, is defined as:

$$m = \frac{t_k}{h^2} \qquad \text{s/m}^2$$

where

W_k = amount of water absorbed at the knick point, kg/m^2

t_k = time, s

h = height of the sample, m

The capillary porosity, *P*c, is defined as:

$$P_c = \frac{M_s - M_{105}}{V} \cdot 100 \qquad \%$$

where :

M_s = Weight of sample after 2 months absorption and 2 months submerged, kg

M_{105} = Weight of sample after drying at 105 ° C untill constant weight, kg

V = Volume of the sample, dm^3

The degree of capillary saturation, *DCS*, is defined as:

$$DCS = \frac{M_{ini} - M_{105}}{M_s - M_{105}} \cdot 100 \qquad \%$$

where :

M_{ini} = Weight of sample at the start of the absorption test, kg

M_{105} = Weight of sample after drying at 105 ° C untill constant weight, kg

M_s = Weight of sample after 2 months of absorption and 2 months of ponding, kg

The shape of the absorption curves for the samples from Umeå Bridge was different than the one from the samples from Långhals Bridge see Fig. 1 and Fig. 2. The capillary and the resistance number are, therefore, hard to establish for the samples from Umeå Bridge and may be even meaningless due to the lack of a well-defined knick point /18/. However, the author has tried to establish the capillary and the resistance number according to Fig. 1 merely for easy comparison of the different concretes and the result are summarised in Table 2.

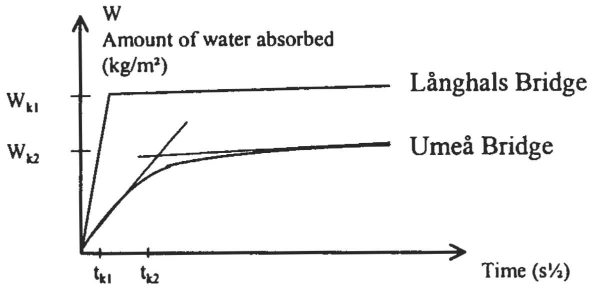

Fig. 1 Definition of the parameters used to characterise the water absorption properties.

Table 2. Result from water absorption test

Sample	h mm	Density[1] kg/m^3	P_c %	DCS %	t_k min	m s/m^2	Depth[2] 6 h mm	W_k kg/m^2	k kg/m^{2}s^{0,5}	Abs[3] 6 h kg/m^2	Water uptake[4] %
U12	25,2	2360	12,8	50	2250	$21\cdot10^7$	10	1,448	0,0039	0,546	0,5
U13	32,5	2360	11,2	51	3180	$18\cdot10^7$	11	1,793	0,0041	0,609	0,4
U mean		2360	12,5	50		$20\cdot10^7$	10		0,0040	0,578	0,4
L12	32,4	2340	12,0	35	760	$43\cdot10^6$	22	2,017	0,0095	1,348	0,5
L13	31,9	2310	12,2	36	790	$47\cdot10^6$	22	2,043	0,0094	1,379	0,4
L mean		2320	12,1	36		$45\cdot10^6$	22		0,0094	1,364	0,4
GPL 1.2	24,7	2380	13,4	44	1700	$17\cdot10^7$	11	1,681	0,0053	0,738	0,6
GPL 4F	28,5	2380	12,5	45	1840	$14\cdot10^7$	13	1,767	0,0053	0,826	0,6
GPL 4G	30,7	2360	13,9	45	2640	$17\cdot10^7$	11	2,103	0,0053	0,833	0,4
GPL mean		2380	13,3	45		$16\cdot10^7$	12		0,0053	0,799	0,5
GPL98	30,0	2340[5]	15,1	80						0,043	1,0

[1] At 60 % RH. [2] Calc. ingress depth after 6 h. [3] Measured absorp. after 6 h. [4] Two months ponding. [5] At 80 % RH.

The resistance and the capillary numbers and the densities were similar for samples U12 and U13. The shape of the absorption curves were similar to the ones by Punkki and Sellevold /18/. The capillary numbers were twice as high and the resistance number were 50 % less than in /20/ for concrete with w/c-ratio of 0,33.

The overlay at Långhals Bridge had a w/c ratio of 0,42 and the result from the absorption test shows that the overlay was homogenous, which indicates good workmanship. The ingress rate was the highest in the test and the knick point is clearly defined.

The results from the cores at Gullmarsplan Bridge should be looked upon differently than the results from the other bridges. Samples GPL 1.2, GPL 4F and GPL 4G were cored from the overlay after six months and have thereafter been stored at the Department (60 % RH ±10 % and 19 °C ± 2 °C) for three and a half years. The hydration process was probably slow due to the dry conditions and the degree of hydration may be lower than for the other overlays. The hypothesis may be supported by the shape of the curves, see Fig. 2. The ingress rate is higher at the start, the amount of water absorbed is larger and the knick point is clearer for the samples GPL 1.2, GPL 4F and GPL 4G than for cores U12 and U13. The shape of the curves was quite similar to the curves of cores L12 and L13 (w/c-ratio 0,42) stored outdoors for eight years. The capillary number was four times as high for samples GPL 1.2, GPL 4F and GPL 4G as in /20/ for concrete with identical w/c-ratio but approximately 19 months old and water cured for eight months. The resistance number was two to three times less than in /20/. These differences may partly be due to different degree of hydration.

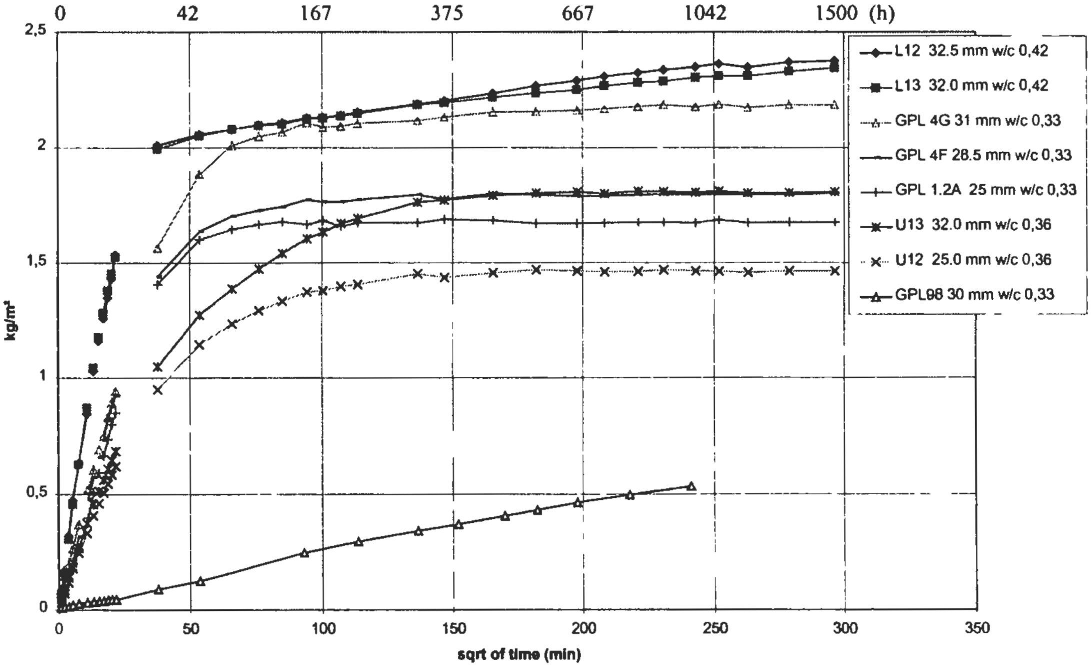

Fig. 2 Water absorption as a function of time.

A new core, GPL98 was drilled out of the overlay on Gullmarsplan Bridge the 6th May 1998 at the same location as the previous cores. The weather had been cold and it rained 16 mm from May 1st to May 5th. The core was drilled in 10 min with a water-cooled drill and thereafter wiped off, put in sealed plastic bags and taken in to lab. The core's lower part was cut with a liquid cold saw to get and flat end and the core was wetted for another ten minutes. It was thereafter wiped off and put in plastic bag for 16 h before the absorption test started. The procedures probably increased the moisture content slightly. The (un-cut) top part of the core with the laitence intact was placed in the water.

The absorption rate and the amount of water absorbed were low, see Fig 2. The absorption curve was more or less linear (square root of time). The waterfront reached the top of the sample after 6 days but the absorption rate did not decrease. The concrete may already have reached the knick point due to water absorption in field during the rainy weather. However, the slope of the curve for core GPL98 was higher than for the other cores after they reached their knick points. The DCS was higher at the start for core GPL98 than for the other samples, see Table 2. (The RH in the top part of overlay at the same occasion is shown in Fig. 8 and Fig. 10.) The results from the absorption tests indicate that the DCS affect the water absorption significantly. The high and steady ingress rate for core GPL98 at later stages may indicate that the pore size distribution is different for samples stored in lab than for samples stored outdoors. It may be the coarser pores, and the air-pores that were being filled. The main part of the capillary pores close to the surface may already have been filled after several days of precipitation. The absorption of water (and chloride ions) may, therefore, be limited during the de-icing season.

Core GPL98 absorbed approximately twice as much water (10,5 kg/m^3) during two months ponding as the other samples from Gullmarsplan Bridge. One explanation may be that core GPL98 had not, to any larger extent, filled its coarser pores in the upper part during the suction test due to high degree of hydration and short absorption duration. When core GPL98 was ponded, the access to the large voids in the upper part of the core was easier than before while the coarser pores in the other three cores had already been filled.

2.2 Influence of aggregates on the water absorption

The absorption properties of concrete may be affected by the type, size and content of the aggregates used since the ITZ between aggregate and paste may contribute to the water transport /21/. The ITZ may act as "highways" for the water. Drawer /22/ found that the penetration depth increased with increased aggregate size and smooth aggregates and that water penetrated faster in the ITZ than in the paste. The concrete overlays on Gullmarsplan Bridge and Umeå Bridge used porphyry as large aggregate to improve the wear resistance. Porphyry has a smooth texture and fatty surface that may result in a weaker and more porous ITZ. Water drops appeared on top of the porphyry aggregates on top of the cores from Gullmarsplan Bridge, which indicated that the fastest way was through the ITZ. Similar observations were made for samples U12 and U13 but the amount of water was less.

3 CYCLIC WETTING AND DRYING (CWD)

The specimens previously tested for water absorption were exposed to one-sided CWD. The samples had been submerged for two months after the first absorption test. If most of the capillary pores were assumed to be filled, the samples start the CWD from at least somewhat equal DCS. The moisture content converged towards the mean in-situ moisture content during the CWD and the DCS after some cycles was of the same magnitude as measured in-situ.

3.1 Test set-up

The samples were covered with double plastic bags except on one side to simulate one-sided drying and wetting. The double plastic bag was kept in place with six heavy rubber bands around the concrete specimen in two layers. The samples were weighed after every drying period (66 h with the exposed surface upward) and absorption (6 h) period, see Fig. 3.

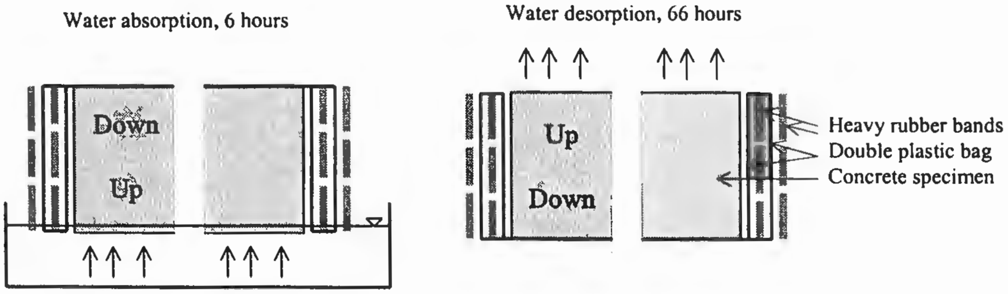

Fig. 3 Schematic sketch of the test set-up for CWD

The testing started in late August 1998 and continued to mid January 1999. The samples were kept outdoors, sheltered from precipitation and fairly sheltered from wind and sun, until December the 8th when they were brought indoors. The absorption took place outdoors (until December the 8th) and when the temperature was below the freezing point 8,2 g/dm³ NaCl (5 g/dm³ of chloride ions) was added to the water to prevent freezing. The chloride content was fairly similar to the average chloride content found in de-icing water in situ /23/.

3.2 Sources of errors

The use of plastic bags and heavy rubber bands are probably not completely "watertight". Water molecules may be transported on the inside of the plastic bags despite the pressure from the rubber bands. The plastic bags may not be completely tight with respect to water vapour but the loss of water by diffusion through the plastic is probably small compared to the amount of water absorbed and desorbed. The errors seemed to be limited since well-cured and dense cores from the same overlay behaved similarly.

3.3 Results from CWD-test

The mean amount of water absorbed and desorbed in each month is shown in Table 3. Samples that absorbed large amount of water in the first absorption test also absorbed and desorbed more water in each cycle than samples that absorbed small amounts of water in the first test. Samples with large capillary porosity (from the same bridge) both absorbed and desorbed more water than samples with less capillary porosity.

Table 3. Result from water the CWD-test

Sample	*h* mm	Density kg/m³	P_c %	August Abs/desorb kg/m²	September Abs/desorb kg/m²	October Abs/desorb kg/m²	November Abs/desorb kg/m²	Lab Abs/desorb kg/m²
U12	25,2	2360	12,8	0,112/0,178	0,137/0,142	0,148/0,141	0,145/0,135	0,250/0,237
U13	32,5	2360	11,2	0,094/ 0,158	0,120/0,125	0,112/0,109	0,127/0,118	0,188/0,178
U mean		2360	12,5	0,103/0,168	0,128/0,133	0,130/0,125	0,136/0,128	0,219/0,208
L12	32,4	2340	12,0	0,076/0,138	0,090/0,103	0,098/0,094	0,098/0,086	0,176/0,184
L13	31,9	2310	12,2	0,110/0,156	0,127/0,138	0,122/0,116	0,128/0,113	0,208/0,214
L mean		2320	12,1	0,093/0,147	0,108/0,120	0,110/0,105	0,113/0,097	0,192/0,199
GPL 1.2	24,7	2380	13,4	0,099/0,138	0,131/0,134	0,150/0,141	0,142/0,133	0,212/0,211
GPL 4F	28,5	2380	12,5	0,094/0,135	0,105/0,112	0,125/0,120	0,121/0,108	0,207/0,201
GPL 4G	30,7	2360	13,9	0,134/0,176	0,142/0,144	0,151/0,144	0,138/0,129	0,213/0,202
GPL mean		2380	13,3	0,109/0,150	0,126/0,130	0,141/0,135	0,134/0,123	0,211/0,205
GPL 98	30,0	2340	15,1	-	0,095/0,126	0,078/0,075	0,095/0,090	0,151/0,147

3.4 Influence of environment

All samples lost more water than they gained during August. In September, the amount of water desorbed had decreased meanwhile the amount of water absorbed had increased and the two were fairly equal. The use 5 g/dm³ of chloride ions in the water started the 8th of November but the effect was small. All samples increased their water content during November, which indicates that concrete water may accumulate water during the winter.

During the subsequent indoor testing, all samples desorbed and absorbed 40 % to 95 % more water than in October, see Table 4 and predictions on the CWD-properties should be based on the performance in the right environment. The convective depths, defined as the zone where the colour change from dark to bright due to the change in moisture content, were established by examining the samples after the sealing was removed (66 h at 20 °C and 45 % RH). The depths are uncertain but a trend may be clear. The higher the w/c-ratio the deeper convective depth. The calculated penetration depth after 6 h, see Table 2, were in the same orders.

Table 4. Comparison of results from the indoor and outdoor (October) CWD-test

Sample	DCS outdoor October	DCS indoor	Absorption indoor/outdoor October	Desorption indoor/outdoor October	Convective depth indoors after 6 h mm	First absorption/CWD
U12	0,94	0,89	1,69	1,68	10-14	3,7
U13	0,94	0,90	1,68	1,63	12-14	5,4
U mean	0,94	0,90	1,68	1,66		4,4
L12	0,94	0,83	1,80	1,96	12-14	13,8
L13	0,94	0,83	1,70	1,84		11,3
L mean	0,94	0,83	1,74	1,90		12,4
GPL 1.2	0,95	0,88	1,41	1,50		4,9
GPL 4F	0,93	0,89	1,66	1,68	14	6,6
GPL 4G	0,96	0,93	1,41	1,40		5,5
GPL mean	0,95	0,90	1,50	1,51		5,7
GPL 98	0,84	0,79	1,94	1,96	9-12	0,6

All samples increased the amounts of water desorbed during a warm desorption period with low RH. The amount of water absorbed during the subsequent absorption period was also higher after a dry and warm period than after a "wet" period. The drying periods were mainly varied from 66 h to 72 h but 90 h was used occasionally and 145 h and 215 h were used once. The effect was small since most of the water was lost during the first twelve hours. The effect of the absorption duration was small since most of the water was absorbed during the first two hours.

The overall response to environmental changes was the same for all samples and the ranking between different samples was more or less the same no matter of the exposure conditions. There was no clear relationship between the behaviour in the first absorption test and the CWD-test. This implies that CWD-tests have to be conducted to foresee the absorption behaviour in de-icing environments.

The samples from Långhals Bridge (w/c-ratio 0,42) absorbed less water than the samples from Umeå Bridge (w/c-ratio 0,36). This shows that concrete with a w/c-ratio of 0,42 may behave just as good (with respect to CWD) as concrete with a w/c-ratio of 0,36.

The effect of temperature on the amount of water absorbed was small. The use of NaCl in the absorption water when the temperature was at the freezing point slightly increased the amount of water absorbed. This shows that relatively large quantities of de-icing water can be absorbed even though the temperature is below 0 °C, which in turn indicates that capillary suction is the main mechanism for the ingress of chloride ions in a de-icing environment.

All samples absorbed more water during the first six hours in the first absorption test than they did during six hours absorption in the CWD-test, see Table 4. The ratio between the two varies for the samples from different bridges but a trend can be distinguished. The ratio for Umeå Bridge was lower than for Gullmarsplan Bridge and the ratios for Långhals Bridge were the highest. The observations indicate that the ratio increases with increased w/c-ratio

3.5 Amount of water desorbed

The samples decreased the amount of water desorbed during the first cycles, see Fig. 4, meanwhile the amount of water absorbed was more or less the same. This indicates that the amount of water absorbed is insensitive to small changes in moisture content in the concrete during the first cycles. Samples GPL 1.2A, GPL 4F and GPL 4G desorbed similar and fairly large amount of water meanwhile sample GPL98 desorbed less water than all other samples. The sample was the only one with an un-cut exposed to the CWD, which may indicate that an un-cut surface may absorb less water than a cut surface.

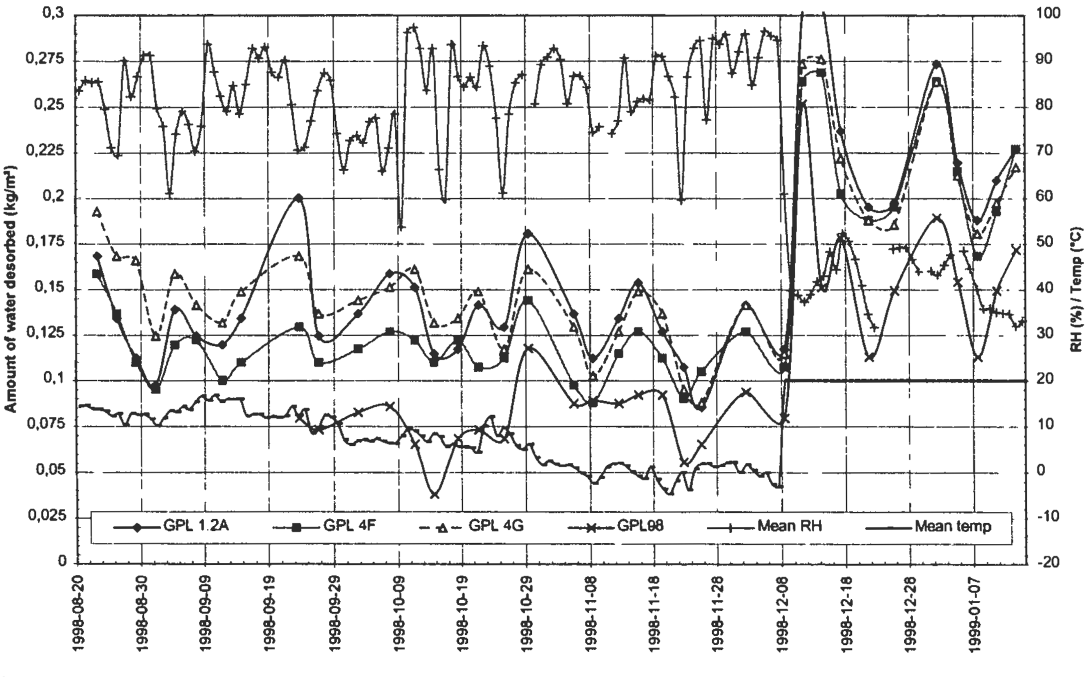

Fig. 4 Amount of water desorbed, as function of time for concrete specimens from Gullmarsplan Bridge. 36 cycles from August 1998 to January 1999.

3.6 Amount of water absorbed

The amount of water absorbed during the first cycles was quit stable, see Fig. 5, and the samples decreased their moisture content. Samples that desorbed large amount of water also absorbed large amount of water. The ranking between the samples was unaltered and all samples behaved similarly to environmental changes.

Samples GPL 1.2A, GPL 4F and GPL 4G absorbed different amount of water. This was also the case in the first absorption test. Sample GPL 4G (13,4 % capillary porosity) that absorbed the largest amount of water, also desorbed the largest amount and sample GPL 4F (12,1 %) that absorbed the least also desorbed the least amount of water.

Sample GPL98 absorbed small amounts of water and the difference between samples GPL 1.2A, GPL 4F and GPL 4G and sample GPL98 was large. This indicates that the outdoor exposure had been beneficial for the hydration process and densified the microstructure. The amount of water absorbed during the first six hours of suction in the first absorption test (0,043 kg/m²) was fairly similar to the amount of water absorbed in six hour during the autumn. The observation indicates that the CWD-test is reliable.

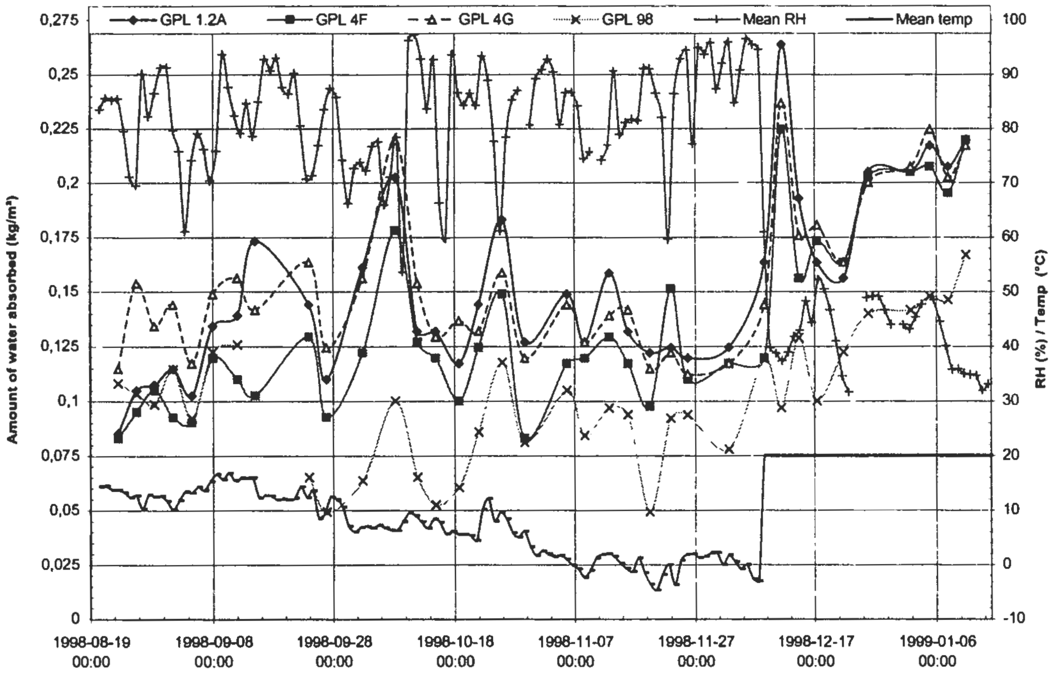

Fig. 5 Amount of water absorbed as function of time for concrete specimens from Gullmarsplan Bridge. 36 cycles from August 1998 to January 1999.

3.7 Detailed investigation during one wetting and drying cycle

In early September, the fourth absorption and the fifth desorption periods were monitored at close intervals, see Fig. 6. The specimens were weighed after 30 min, 1 h, 2 h, 3 h, 4 h, 5 h and 6 h of absorption. During the desorption period, the specimens were weighed after 30 min, 1 h, 2 h, 3 h, 5 h, 8 h, 16,5 h and then every 12 h.

The overall absorption behaviour observed in the first absorption test was maintained in the CWD-test. All samples had bi-linear absorption curves in the CWD-test. Samples that absorbed water fast in the absorption test also absorbed water fast in the absorption period in the CWD-test. Sample GPL 1.2 was still absorbing water after 6 h while the other two samples more or less had stopped their water absorption.

The drying process slowed down after 5 h and most of the water earlier absorbed was lost in only 8 h in fairly dry weather. The weather was warmer, drier and windier the 3rd of September (19 °C, 45 % RH and 3 m/s) than the 2nd (16 °C, 55 % RH and 1 m/s) and the samples lost slightly more water during the day of the 3rd than the 2nd September. The samples absorbed water from the ambient air during both the second and the third night. The temperature decreased during the nights to approximately 8 °C and the RH was above 95 %. This indicates that water is absorbed from the ambient air when the RH is higher in the air than in the concrete surface.

The water content in the specimens was less after the fifth drying period (20 °C and 50 % RH) than after the fourth (12 °C and 80 % RH). The water content was also less after the fifth absorption period than after the fourth. These observations show that the mean water content in the concrete was decreasing during a drying period of warm and dry weather.

Sample GPL 4G absorbed larger amount of water than GPL 1.2A and GPL 4F. This was also the case during the first absorption test and the capillary porosity of sample GPL 4G was higher than for the other two samples. Sample GPL 4G had the highest absorption rate initially but after the (sharp) knick point was reached the absorption rate was low. This behaviour is often associated with a coarse pore system. Sample GPL 1.2 had higher capillary porosity than sample GPL 4F and the former sample absorbed and desorbed more water than the latter, which shows that capillary porosity affects the CWD properties significantly.

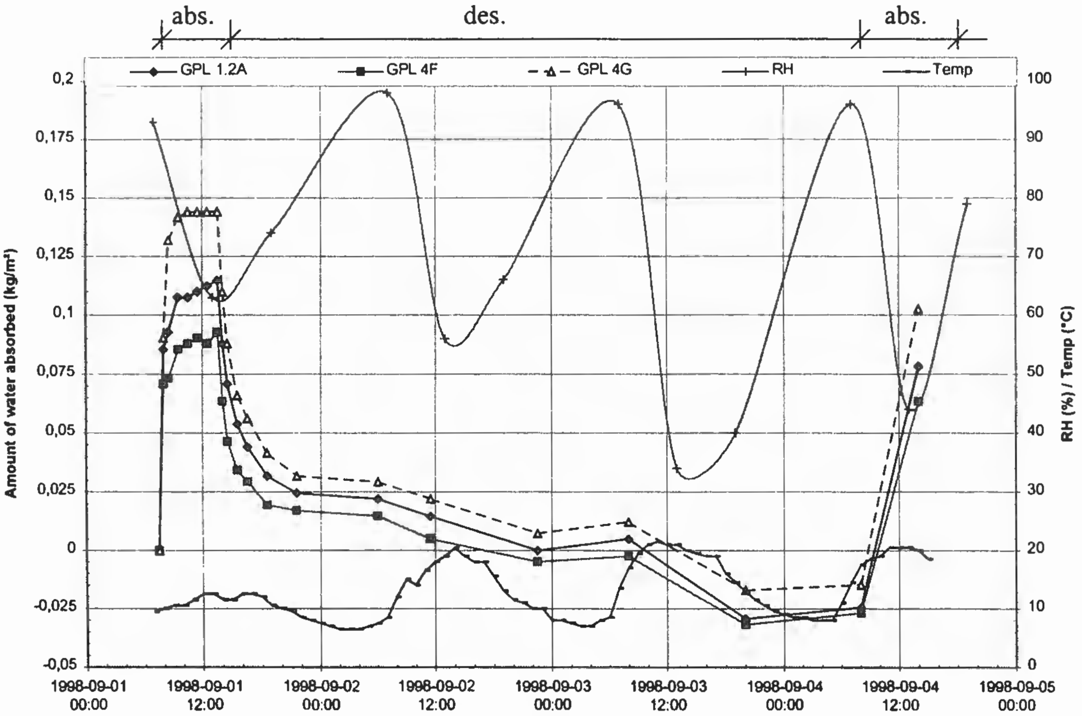

Fig. 6 Fourth absorption period and fifth desorption and fifth absorption periods for samples from Gullmarsplan Bridge

4 RELATIVE HUMIDITY IN A CONCRETE OVERLAY

Field data regarding the moisture state and temperature in concrete bridge decks is needed in order to predict service life of bridge decks since it affects almost every deterioration mechanism of reinforced concrete. Different systems for measuring the RH in concrete are available and the author has used a system provided by Sahlén Moisture Control LTD due to its reasonable price, easy to use software and robustness.

Ten Sahlén sensors (temperature and RH sensors) were installed in the overlay (7 sensors) at Gullmarsplan Bridge and in the old concrete slab (3), see Fig. 7. The temperature and the RH were measured every hour and collected in data loggers. A comprehensive description of the test site, the test set-up and more test results is given in /19/.

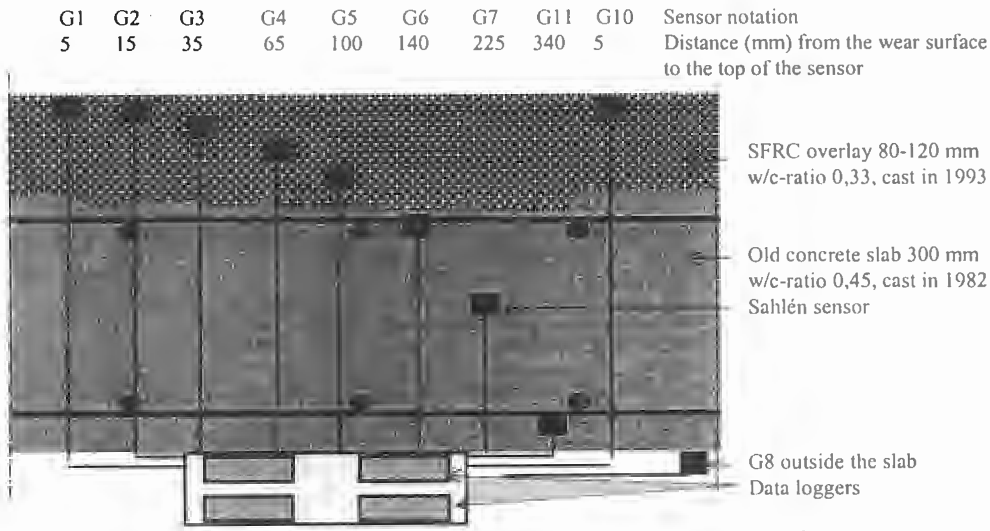

Fig. 7 Location of Sahlén sensors at Gullmarsplan Bridge.

The test set-up has been in service for two and a half years. Some RH-devices have failed but the temperature devices are still working. To continuously measure the RH in concrete with low w/c-ratio exposed to precipitation, de-icing agents and temperature variation of 60 °C is difficult. The sensors may drift, the sealing may wear down due to traffic and strains due to moisture and temperature etc. The absolute values of the RH-readings may, therefore, be incorrect but the principal response to changes in the environment during the year may still be correct and the readings may therefore still be valuable.

4.1 Results from RH-readings

The readings from sensors G3 (35 mm) and G4 (65 mm) in the overlay, extending over almost two years are shown in Fig. 8. The sensors were installed in November 1996 and the RH was low during the winter but increased substantially during the spring of 1997. The increase was mainly due to the increased temperature in the overlay /24/. An increase of 30 °C could increase the RH with approximately 9 % (units). This was also the case for the sensors during the spring. The temperature increased from –5 °C to 25 °C and the RH-readings increased from 88 % to 98 %. This indicates that the overall behaviour may be correct even though the absolute values may be somewhat incorrect.

When the temperature dropped in September 1997, the RH in the overlay decreased. Sensor G3 returned to its RH-level before the increase in April. This indicates that the RH-readings are somewhat reliable and that the variations are mainly caused by temperature variations. However, the RH-readings from sensor G4 did not return to the same level as before the temperature raised in April 1997. The RH-readings in October and November of 1997 were approximately 3 % above the readings from sensor G3. This may be due drift of the sensor or leakage of the sealing.

Both sensors presented stable readings during the winter 1997-1998. In late April 1998 the temperature in the overlay increased again and so did also the RH-readings. The RH-readings during the summer of 1998 was in the same order as the previous summer. However, it took longer time to reach the maximum RH-readings than previous summer due to the cold and wet summer of 1998.

The temperature decreased in late August and so did also the RH-readings for sensor G3. However, the decline was less than the previous year indicating that that something happened with the sensor. The hypothesis is be supported by the response of sensor G4, which did not decrease its RH-readings as the temperature decreased during the autumn of 1998.

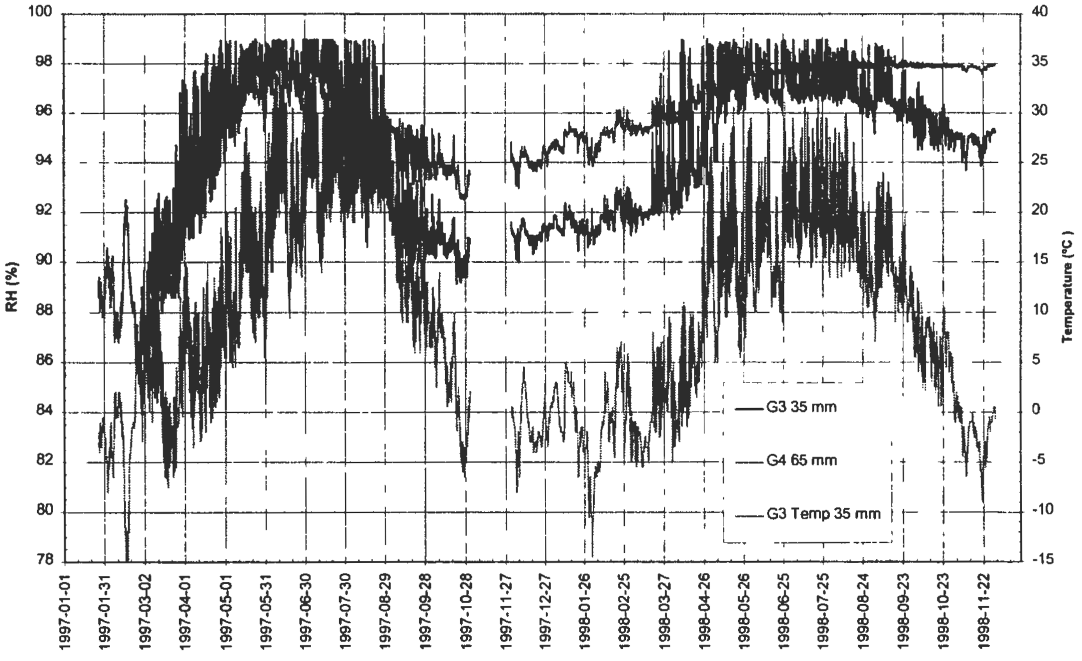

Fig. 8 RH readings for sensors G3 and G4 and temperature for G3 at Gullmarsplan Bridge.

The absolute values in Fig. 8 are probably somewhat incorrect. Fig. 10 shows is the RH-distribution the 6th of May 1998 measured in laboratory with samples taken from the overlay with a jackhammer. The RH was approximately 88 % at the surface and 72 % at 20 mm from the surface while sensor G3 at 35 mm read 98 % and sensor G4 read 97 %. The author believes that the measurements conducted in laboratory are more correct than the readings from the Sahlén sensors.

Three sensors were installed in the old concrete flat slab. The slab was cast in 1983 with concrete with a w/c-ratio of 0,45 and its moisture properties differ from the properties of the concrete overlay. The moisture diffusivity and the moisture capacity are higher than for the overlay and these factors may cause the sensors to respond at different rate to changes in the concrete. Further, all sensors were installed from the top of the slab except sensor G11 that was installed from the soffit. Sensor G11 is, therefore, not vulnerable to impact from traffic.

The readings from sensor G11 from the 3rd of October 1997 (when sensor G11 was installed) to the 30th of November 1998 are shown in Fig. 9. The bottom part of sensor G11 was covered with fresh mortar with similar w/c-ratio as the old concrete slab. The high RH-readings at the start of the measurements were due to the fresh mortar that increased the RH in the air surrounding the sensor. The drying process of the mortar proceeded quickly during the first month due to the small amount of mortar and some self-desiccation may also have occurred.

In early December 1997, the RH increased for sensor G11 and it continued to increase through March 1998. The increase may be due to the high RH in ambient air (approximately 90 %). The temperature decreased with 18 °C at the end of January and the RH decreased too.

Sensor G3 and sensor G11, even though located at different depths and in concrete with different properties, showed almost identical RH-readings (91 to 92 %) during the winter 1997/1998. This was close to the RH in the ambient air. However, in April 1998 the readings from the two sensors started to deviate. The RH in the soffit decreased while the RH in the top part of the overlay increased. This could be due to the different exposure condition where the overlay is exposed to rain, snow, solar heating and long wave radiation. The decrease in the RH in the soffit is probably due to the decrease of the RH in the ambient air in April. The temperature increase is also less for the concrete at the soffit than for the overlay and the increase of the RH due to temperature is therefore less for the concrete at the soffit than for the overlay. The effect of the temperature on the RH is also less for the old concrete (w/c-ratio of 0,45) than for the concrete overlay (0,33) /24/ and the soffit does not receive any rain. The net effect may be that the RH at the soffit decreases in the spring and summer while the RH in the overlay increases.

The RH in the concrete at the soffit continued to decrease until mid August 1998. It was, thereafter, steady until early October when the temperature in the ambient air dropped, the RH in the ambient air increased and the RH in the concrete increased. The RH in the concrete in November 1998 was in the same level as in November the year before. The observations show that the concrete interacts with the environment and that the measurements are at least qualitatively reliable.

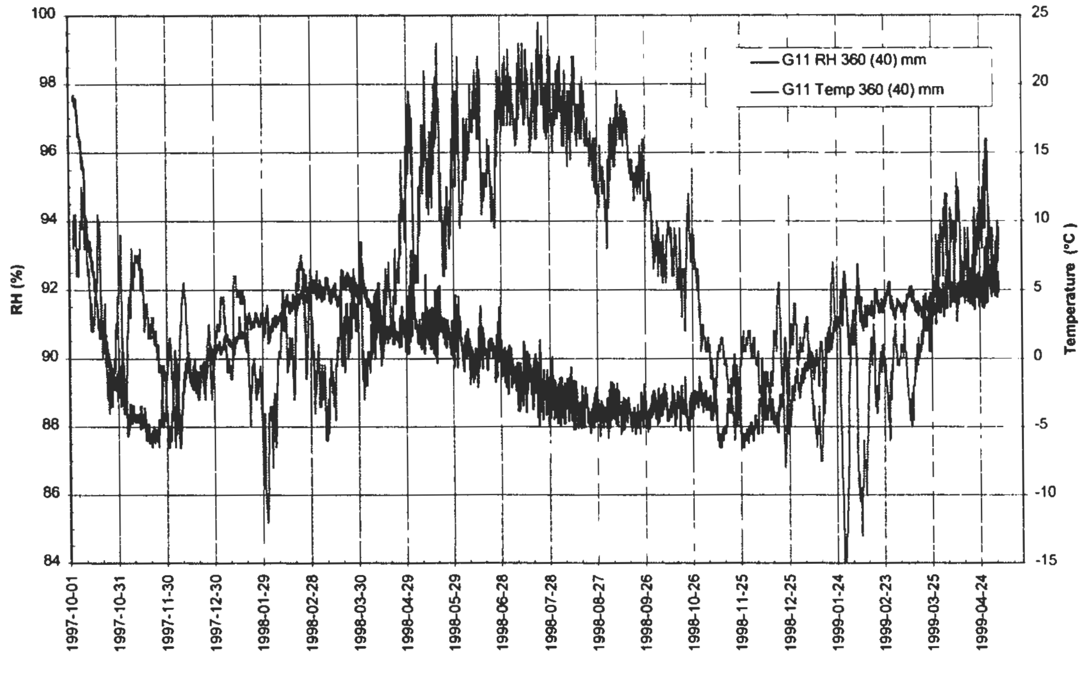

Fig. 9 RH and temperature readings at the soffit of the concrete flat slab at Gullmarsplan Bridge.

The yearly average RH (1st December 1997 to 1st December 1998) at the depth of the lower reinforcement in the flat slab was 90 %. The corrosion rate may be high if corrosion is initiated in the lower reinforcement /24/. It may, therefore, be reasonable to ignore the corrosion propagation stage in service life predictions for the reinforcement in the soffit. The yearly variation of the RH was only 5 % (units).

4.2 Relative humidity measured in laboratory for field samples

The RH was also measured in lab, see Fig. 10, on samples taken with a jackhammer on the 6th of May 1998. The samples were taken only 1 m from the Sahlén sensors. The samples were immediately put in airtight glass-containers and transported to the laboratory at the Department of Building Materials at Chalmers University, where the RH was measured. The measurements were done in a climate room with stable temperature and the errors were ± 1,0 % /25/. The main errors in the results are probably due to the difficulties in establishing the exact location where the samples were taken. The author estimates the error to be ±2 mm. Each sample was taken from a 5 mm thick zone and the mean values of the sampling depths are used.

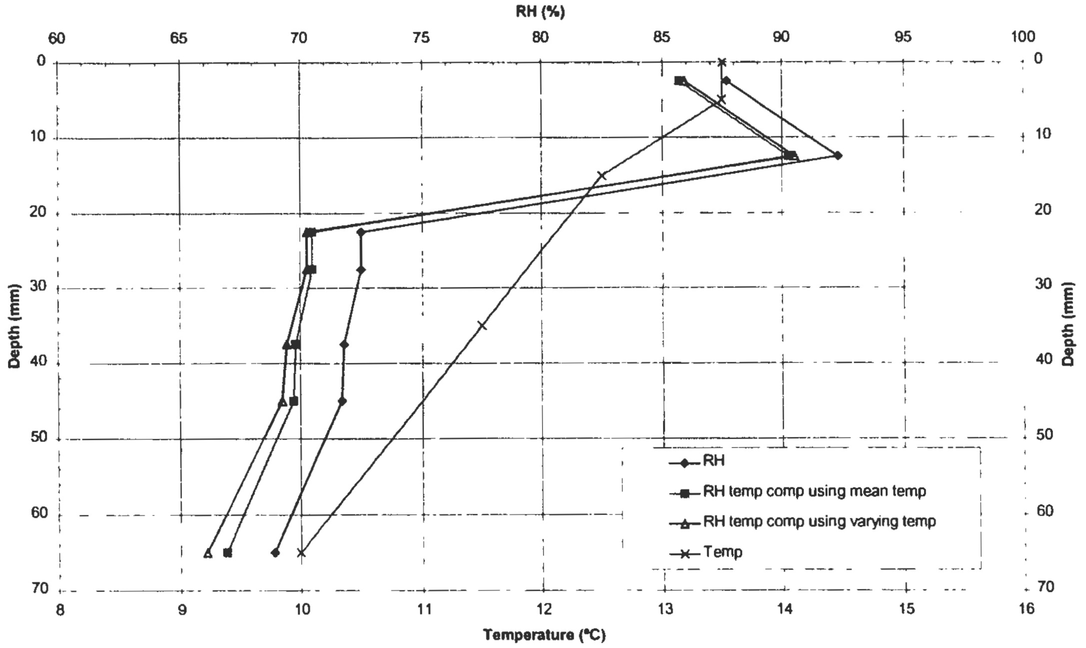

Fig. 10 RH and temperature in the concrete overlay at Gullmarsplan Bridge, 6th of May 1998.

The temperature in the overlay at 10 a.m. (when the RH-samples were taken) is also shown in Fig. 10. The curve (samples) named "RH" in Fig 10 shows the non-temperature-compensated RH readings. However, the temperature in the laboratory (19,4 °C) differed from the temperature in the bridge deck and the readings were, therefore, compensated. An increase of 0,3 %/°C was used by the author /24/ to compensate for the temperature difference. Two approaches have been used. In the first approach, the mean temperature in the overlay (12,2 °C) was used and the difference was 7,2 °C. The increase of the RH was calculated to 2 %. The temperature compensated RH values using the mean temperature is therefore 2 % less than measured in laboratory.

The second approach uses the measured temperature distribution in the overlay and compensates the RH in every point. The curve named "RH comp using varying temp" shows the result. The difference between the two approaches is negligible due to the small temperature differences in the overlay.

The weather had been cold for the time of year (mean temperature of 6 °C) and wet (16 mm of precipitation) during four days before the samples were taken. The rained stopped on the morning of the day when the samples were taken and the wear surface was dry during sampling. The distribution of the RH probably reflects the weather conditions before the sampling. The RH at 2,5 mm is less than at 12,5 mm indicating an outward drying process.

The non-temperature-compensated RH in the interior parts of the overlay was low. The RH was 72 % at 22,5 mm and the RH decreased steadily to 68 % at 65 mm. The measurements, showing only a limited RH-gradient, indicate stable conditions in this part of the overlay. The low RH could be due to self-desiccation in the overlay due to the low w/c-ratio (0,33). It could also be due to the fact that the soffit of the concrete flat slab is open to air and the overlay may, therefore, dry out through the soffit.

No matter of the causes, the measurements indicate that the RH in the overlay below 20 mm (temperature compensated or not) is so low that a corrosion process (carbonation or chloride initiated) in the overlay would only proceed at slow rate /24/. The RH-measurements further indicate that the concrete is only slightly affected by precipitation below 20 mm from the surface. The DCS could only be established as a mean value for the top 30 mm of the overlay (GPL98) and the mean DCS was 0,8.

5 NUMBER OF FREEZE-THAW CYCLES (FTC)

The number of Freeze-Thaw Cycles (FTC) each year for a concrete element is valuable information in order to predict the service life with respect to frost damages. The temperatures in the slab at Gullmarsplan Bridge and in the ambient air (at the soffit of the slab) were measured every hour. If a criterion for freezing and thawing of pore water in concrete is established, the number of FTC at different depths of the concrete flat slab can be evaluated.

The author has used three different criteria for the freezing of pore water. The first criterion was that water freezes and thaws at 0 °C and the second was that water freezes and thaws at –2 °C. Finally, the effect of super-cooling was taken into consideration and the pore water was said to freeze at –2 °C (super-cools) and thaw at 0 °C /26/.

The overall result indicates that for each sampling depth the two first criteria yield the same number of FTC in Stockholm during the winter of 1997/1998, see Table 5. The top part of the concrete flat slab had the largest number of FTC and the middle part had the least number. All parts of the slab had fewer FTC than ambient air.

Sensor G3 at 35 mm, registered larger number of FTC than sensor G4 at 65 mm. The observation indicates that the interior part of the overlay experiences fewer FTC than the exterior parts. Similar observations were made by Krus /26/ using numerical simulations.

Sensor G11 located 40 mm from the bottom of the slab (340 mm from the top) registered almost the same number of FTC as sensor G3 using the two first criteria. This indicates that the concrete at the bottom of the slab has the same number of FTC as the top and that the microclimate (solar radiation, long wave radiation etc), therefore, does not affect the number of FTC significantly at the depth of 35 mm.

Table 5 Temperature data and the number of freeze-thaw cycles from 97 10 03 to 98 10 03

Sensor	Depth mm	Min temp °C	Max temp °C	Average temp °C	Freeze-thaw cycles 0 °C	Freeze-thaw cycles –2 °C	Freeze-thaw cycles –2/0 °C[2]
G1	5	-11,5	37	8,2	37	39	21
G2	15	-10,5	37	8,8	34	32	16
G3	35	-12	33,5	8,3	32	32	18
G4	65	-12	31,5	8,5	27	29	16
G11	340 (40)[1]	-12	24,5	7,6	33	32	14
G8	Outside[3]	-13,5	25	7,6	77	47	32

[1] Distance from the bottom (soffit) of the slab. [2] Pore water is assumed to freeze at –2 °C but thaw at 0 °C. [3] At the soffit of the flat slab and protected from sun, wind and precipitation.

However, ice does not melt until the temperature increases above 0 °C and if the effect of super-cooling was taken into account the overall result was the same but the number of FTC decreased with approximately 50 %. This was also found by Krus /26/. Sensors G2, G3 and G4 registered more or less the same number of FTC. Sensor G11 registered slightly less number of FTC than sensors G2, G3 and G4 and significantly less number than sensor G1.

The simulated number of FTC for a concrete slab with a thickness of 500 mm in Stockholm an average winter was 27 at the surface, 15 at 50 mm from the surface and 10 at 100 mm from the surface /26/ using the same super-cooling criterion as the author. The number of FTC at 50 mm from the surface corresponds well with the measured values at 35 and 65 mm from the surface for the 400 mm thick concrete flat slab at Gullmarsplan Bridge. The measurements indicate that the method proposed by Krus /26/ can be used to predict the number of FTC in concrete members subjected to temperature variations.

De-icing agents were used at approximately 70 occasion between the 3rd of October 1997 and the 3rd of October 1998 /4/. Sensor G1 registered approximately 20 freezing occasions (using any of the three criteria) when de-icing agents had been spread on the wear surface the same day or the day before. The number, even though not exact, shows that freezing and thawing of the wear surface in combination with de-icing agents occur frequently. Adequate salt-frost-resistance is, therefore, necessary for the concrete in order to provide a durable concrete overlay. The "mean" chloride content in the de-icing water or slush present on the overlay after the use of de-icing agents was approximately 6 g/l (10 g/l NaCl). Chloride content of 30 g/l (50 g/l NaCl) was also recorded at different occasions. The Borås-method (SS 13 72 44) uses a NaCl content of 30 g/l, which is considered as the worst exposure /24/. The observations indicate that the chloride content used in the Borås-method is realistic.

The largest freezing rate recorded for sensor G1 (5 mm) was 1 °C/h (from 0 °C to –2 °C in two hours) and it was recorded on the 2nd of April 1998 at 8 p.m. The day had been warm and the temperature in the surface of the overlay at 4 p.m. was 5,5 °C. The temperature then dropped to –5 °C at 4 a.m. the following morning, i.e., the temperature decreased with a mean rate of approximately 0,9 °C/h. The temperature in the ambient air decreased from 0,5 °C at 4 p.m. to –3,5 °C at 2 p.m. (-3,5 °C at 4 p.m. too). A freezing rate of 0,5 °C/h was observed for sensor G1 at several occasions during the winter.

6 CONCLUSIONS

The first absorption test and CWD-test have shown that good workmanship (proper consolidation and curing etc.) is almost as important as using low w/c-ratios in achieving dense concrete with low water absorption. Concrete mixes with low w/c-ratios have the potential to be dense and have low water absorption but the properties may easily be ruined due to improper workmanship.

The absorption properties for the samples from Umeå Bridge (w/c-ratio 0,36) were very different compared to the samples from Långhals Bridge (w/c-ratio 0,42). This indicates that the influence of the w/c-ratio is strong for mature concrete aged in situ.

The CWD-test showed that relatively large quantities of de-icing water could be absorbed in only 6 h by concrete with low w/c-ratios even at temperature below the freezing point. This indicates that water absorption is the dominating mechanism for chloride ingress in the outer 0-15 mm of concrete with low w/c-ratio in de-icing environments.

The environment affected both the amount of water absorbed and desorbed in the CWD-test. Water can be absorbed from the ambient air during a cold night with high RH.

The results using the Sahlén-gauges show a cyclic response of the concrete over the year, both at the top of the slab (overlay) and at the soffit. The RH was similar during the winter but in the spring, the RH increased in the overlay while it decreased at the soffit. The result using the Sahlén-gauges deviates from the results obtained by removing concrete with a jack-hammer and analyse the RH in laboratory. The latter method is more reliable and the RH-readings showed that the RH at 20 mm and further down in the overlay was low and stable. This indicates that concrete with low w/c-ratio is only affected by precipitation to a depth of 20 mm. The RH-readings obtained from the overlay with the Sahlén sensors are probably wrong.

The number of FTC in a concrete flat slab is dependent on the freeze-thaw-criterion used. The effect of super-cooling decreases the number FTC with 50 %. The number of FTC decreases with depth from the surface. The measured number of FTC was close to the numbers obtained by Krus /26/ using a numerical model and statistical weather data.

Due to the frequent use of de-icing agents, the number of salt-freeze-thaw-cycles for the wear surface could also be high. Adequate salt-frost-resistance is, therefore, necessary for the concrete in order to provide a durable concrete overlay.

7 ACKNOWLEDGEMENTS

Appreciation is expressed to Prof. Johan Silfwerbrand for support and advice throughout the project and to the Swedish National Road Administration for providing funding. The author would also like to thank M.Sc. Alf Andersen for help with some of the measurements and to M.Sc. Anders Ivarsson, SL AB, for the electric installations.

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