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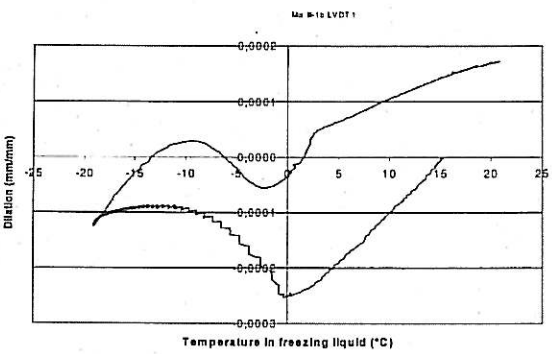
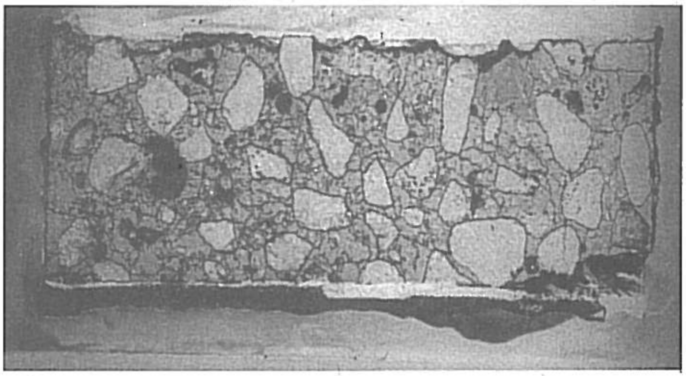
Nordtest Project 1389-98





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SUMMARY

Nordtest project 1389-98:
Measurement of internal cracking as dilation in the SS 13 72 44 frost test

by Stefan Jacobsen, Dirch Bager, Heikki Kukko, Tang Luping and Katja Nordström

In order to further develop the concrete frost test SS 13 72 44 for measurement of internal cracking as dilation, a series of tests were performed at five Nordic research laboratories. Dilation during freeze/thaw was measured in the SS 13 72 44 test with water or 3 % NaCl solution on the concrete surface and on identical specimens separating absorption and freeze/thaw. The latter denominated "classical frost dilation test" was similar to ASTM C671. Three non-air entrained OPC concretes with w/c = 0,31, 0,48 and 0,67 were tested. The mixes were denoted mix 1 (tested with 3 % NaCl), mix 2 and mix 3 (both tested with demineralized water). Internal cracking and surface scaling as well as increased degree of saturation during freeze/thaw were measured in all specimens during testing. Durability against internal cracking was assessed by determining "critical dilation" (i.e. before significant increase of dilation occurs in the next freezing) and "period of frost immunity" (i.e. period of water absorption until critical dilation is reached). This is based on that internal cracking occurs when the critical degree of saturation is reached.

In the SS 13 72 44 test the internal cracking was severe for all mixes giving periods of frost immunity of 3 - 19 days. Ultrasonic Pulse Velocity (UPV) was well suited to detect severe damage in the wet freeze/thaw test SS 13 72 44. The transit time increased linearly with the residual dilation (ε_{res}). Dilation was however more reliable than UPV measurements at low damage levels. Particularly in the classical test with separated freezing and absorption UPV gave no indication of cracking. Dilation measurements, however, showed that the period of frost immunity was exceeded. ε_{res} measured continuously with LVDT and Invar frames during 56 cycles in SS 13 72 44 showed that during the short period of frost immunity in SS 13 72 44 contraction takes place in the specimen. As the degree of saturation is increased sufficiently due to the accelerated liquid uptake in wet freeze/thaw, internal cracking in the form of large primary freezing dilation and permanent length change occurs. Period of frost immunity was found to be equal at the two laboratories carrying out the classical test, in spite of many differences in experimental details. The period of frost immunity for Mix 1 and 2 was longer than the test period of 59 days. Mix 3 had only 3 days of frost immunity. Critical dilation and period of frost immunity depended on whether dilation on first freezing (ε_f), dilation below zero ($\varepsilon_{0\text{--}20}$) or residual dilation ($\varepsilon_{res}$) were used. $\varepsilon_{0\text{--}20}$ appears to be the best parameter for dilation measurements using LVDT and Invar frames. It is concluded that dilation measurement to determine period of frost immunity is a reliable way of determining the resistance of concrete to internal cracking, both in the wet SS 13 72 44-test and with separated absorption and freeze/thaw where frost damage develops slower.

SAMMENDRAG

Måling av intern frostskade som dilatasjon i SS 13 72 44

For å videreutvikle frostprøvemetoden SS 13 72 44 for måling av intern skade har 5 nordiske forskningslaboratorier gjennomført en serie fryse/tineforsøk med hovedvekt på måling av intern frostskade som dilatasjon. Tre portlandsementbetonger (v/c = 0,31, 0,48, 0,67) ble utstøpt hos NBI og sendt til de deltagende laboratorier. Resultatene ble også sammenlignet med intern frostskade i prøving med adskilt vannoppsug og frosteksponering.

I SS 13 72 44, hvor intern oppsprekking var omfattende, økte ultralyds transittid lineært med residual dilatasjon. I den tidlige fase av frostskade ble imidlertid kontraksjon noen ganger observert, og ultralydhastighet virker dermed mindre pålitelig for deteksjon av intern skade. Særlig når vannoppsug og frosteksponering gjennomføres adskilt gir ikke ultralyd noen indikasjon på frostskade selv om det observeres økt lengde.

Det konkluderes med at SS 13 72 44 er velegnet for bestemmelse av intern frostskade ved dilatasjonsmåling. Dilatasjonsmålinger for bestemmelse av frostimmunitetsperiode er en pålitelig måte for måling av bestandighet mot intern frostskade. Dette gjelder både den våte SS 13 72 44 fryse/tine metoden og i ASTM C671-type testing hvor vannoppsug og frosteksponering er adskilt slik at frostskade utvikles mer langsomt.

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1. INTRODUCTION

SS 13 72 44 [1] is a test method for durability of concrete surfaces against frost and frost/salt scaling and also candidate for European reference frost durability test. Frost damage can in addition to surface scaling occur as internal cracking without visible surface damage. In [2] Ultrasonic Pulse Velocity (UPV) was studied for detection of internal cracking in SS 13 72 44. The objective of this Nordtest project has been to further develop SS 13 72 44 as a test for internal cracking by measuring dilation during freeze/thaw. Dilation measurement is a well known method for detecting frost damage as internal cracking [3-7].

The specimens in SS 13 72 44 have demineralized water or 3 % NaCl on the surface during freezing and thawing. This wet freeze/thaw leads to a much higher uptake than in capillary suction without freeze/thaw. Studies of dilation in wet freeze/thaw such as [2, 8, 9] have shown the progressive nature of damage in wet freeze/thaw. In porous building materials internal cracking occurs when a critical degree of saturation (S_{cr}) is exceeded during exposure to frost [10]. The longer time needed to reach S_{cr} the better is the frost durability against internal cracking. Dilation measurements during freezing give information about ice formation in the concrete and show whether the concrete is near or at its S_{cr}-value.

Dilation means expansion during freezing. The term "classical dilation test" is here used for frost testing of concrete where absorption is separated from freezing with continuous length change measurements. Various ways of performing this kind of testing will affect the degree of saturation and hence the resulting frost damage. In ASTM C671 [3] the specimens are frozen in a cooling liquid (kerosene) and returned to water in frozen condition to absorb more water. In the Finnish standard [5] both freezing and thawing takes place once in a sealed condition with presumably empty air voids and saturated capillary pores. In Fagerlunds test [4] several specimens are conditioned to varying degrees of saturation and frozen sealed once to determine $S_{cr.}$ The absorption characteristics of the concrete are measured separately. In the requirements for the Øresund project [6, 7] each specimen is frozen and thawed sealed only once after varying absorption periods. It could be that ASTM C671 is the most severe "classsical test" since each specimen is frozen several times. Furthermore the specimens are thawed in water causing accelerated absorption due to the suction due to the contraction of ice in the concrete during thawing. An other possibility is that Fagerlunds test is the most severe due to the predrying treatment before resaturation and freezing. Predrying is well known to increase the amount of freezeable water and hence damage potential in concrete largely.

In order to reach the objective of this project the concept period of frost immunity as defined in ASTM C671 [3] has been investigated in the SS 13 72 44 test [1]. In addition parallel classical tests have been performed on identical concrete specimens. The absorption period was similar to the 3 days suction + 56 days wet freeze/thaw in SS 13 72 44 so that the effect of accelerated liquid uptake in SS 13 72 44 on period of frost immunity could be assessed. Liquid uptake was monitored in both tests to assess ΔS in relation to internal cracking (dilation, loss of UPV and strength, crack formation).

2. EXPERIMENTAL

2.1 Participating laboratories, testing and concrete mixes

Five Nordic concrete laboratories participated in the test:

VTT: Technical Research Centre of Finland, Building Technology Dept., Esbo
NBI: Norwegian Building Research Institute, Oslo
LTH: Lund Institute of Technology, Sweden, Div. of Building Materials, Lund
SP: Swedish National Testing and Research Institute, Borås
AAP: Aalborg Portland, Denmark, Cement and Concrete Laboratories, Aalborg

All specimens were moulded, cured, sawn and sent by NBI who also coordinated the project.

2.1.1 Frost testing

Two different frost tests were performed:

- SS 13 72 44 standard "wet test" with measurements of scaling, dilation, UPV and weight change during the course of freeze/thaw with liquid on the top surface.
- "Classical dilation test" with separated absorption and frost exposure similar to [3]. The test scheme and specimen size of SS 13 72 44 were followed with regard to prestorage and resaturation. 6 freeze/thaw cycles using the SS 13 72 44 cycle were performed 1, 7, 14, 28, 42 and 56 days after the 3 day presuction period. Between the cycles the specimens were kept submerged at 20 °C. Dilation, UPV and weight were measured during test.

Table 1 : Frost tests performed at the various laboratories.

Lab.	Test	Dilation measurements following 3 day presuction
VTT	Classical dilation	During freeze/thaw in air at 1, 7, 14, 28, 42 and 56 days
NBI	Classical dilation	During freeze/thaw in cooling liquid at 1, 7, 14, 28, 42 and 56 days
SP	SS 13 72 44 dilation	Continously during 56 cycles in one specimen of each mix
LTH	SS 13 72 44 dilation	In 1st, 7th, 14th, 28th, 42nd and 56th cycle
AAP	SS 13 72 44 dilation	Residual dilation after 7th, 14th, 28th, 42nd and 56th cycle

The specified frost cycle for the experiments is given in table 2 below. This is the cycle in the latest revision of SS 13 72 44.

Table 2 : Freeze/thaw cycle (liquid in wet test, concrete surface in classical test).

Time (h)	0	4	12	16	20	24
Temperature (°C)	+ 20	- 4	- 20	-20	+ 20	+ 20

The temperature during the frost cycles were measured at all institutes on various locations on the specimens:

- in air or cooling liquid
- on specimen surface (SS 13 72 44: in liquid, classical test: under plastic foil)
- in centre of the slab specimens

Temperatures in the centre of the slabs were measured at NBI and VTT. At VTT thermocouples were moulded into the concrete. At NBI holes were drilled in the lateral side at half thickness (25 mm) and 75 mm in to the centre of the slab. The hole with thermocouple was then filled with epoxy using a thin injection tube so as to fill the hole completely.

2.1.2 Test schedule

Table 3 shows the test schedule for both test methods

Table 3: Test schedule for wet and classical test (separated absorption and freeze/thaw)

Date	Day	Procedure		
			Wet (SS 13 72 44) dilation	Classical dilation test
25-27.03.	0	Moulding	x	x
26-28.03	1	Demoulding -> 20 C water	x	x
03.04.98	7	Transfer specimens to stand. Clim. (SC)	x	x
17.04	21	Sawing/packing/warm transport	x	x
24.04	28	opening in SC/preparation in SC - drilling holes, gluing studs - gluing rubber	x x	x
24.04	28	Compressive strength		
		Keeping spec.'s at SC, preparing	x	x
02.05	36	Mix I	Pour de-mineralized water on surf.	Submerge in de-mineralized water
03.05	37	Mix II	Pour de-mineralized water on surf.	Submerge in de-mineralized water
04.05	38	Mix III	Pour de-mineralized water on surf.	Submerge in de-mineralized water
05.05	39	**Mix I**	**Measuring dilation in first cycle**	
			3 % NaCl on surface	Wrapped in foil
06.05	40	Mix I	Remove Invar frames, record scaling, weight and UPV, re-pour 3 % NaCl , return to cabinet	Remove Invar frames, unwrap, record weight and UPV transfer to 20 °C 3 % NaCl.
06.05	40	**Mix II**	**Measuring dilation in first cycle**	
			De-ionized water on surface	Wrapped in foil
07.05	41	Mix II	Remove Invar frames, record scaling, weight and UPV, re-pour de-min water, return to cabinet	Remove Invar frames, unwrap, record weight and UPV transfer to 20 °C de-min.water.
07.05	41	**Mix III**	**Measuring dilation in first cycle**	
			De-ionized water on surface	Wrapped in foil
08.05	42	Mix III	Remove Invar frames, record scaling, weight and UPV, re-pour de-min water, return to cabinet	Remove Invar frames, unwrap, record weight and UPV transfer to 20 °C de-min.water.
11.05	46	Mix I	Dilation in 7th cycle	Dilation after 6 days of abs.
Continued to 56 cycles or 56 days of absorption with 6 cycles			(+ 14, 28, 42 and 56 cycles)	(+ 14, 28, 42 and 56 days after 3 d)

2.1.3 Concrete mixes

Three non-air entrained concrete mixes were tested. 70 litre batches were made in a horizontally rotating counter current mixer. Dry materials were mixed for 1 minute followed by 2 minutes wet mixing with addition of the water initially and addition of the water reducer with some water after 1 minute. Strength was measured on 3 parallel 10 cm cubes cured in the same way as the frost test specimens. Suction porosity (capillary + gel pores) and macro porosity (air) of the hardened concrete was measured after approximately 4 months of curing at 65 % RH and 20 °C according to the PF-test [11,12] at NBI.

The cement was a Norwegian OPC anleggsement (CEM I 52,5 LA) produced at Dalen with 0.55 m-% equivalent Na_2O, a blaine of 360 m^2/kg and 3120 kg/m^3 density. The water reducer was Sikament 1000, a modified polymer with density of 1150 kg/m^3 and 27 % solid (presumably by mass) and 5.2 % equivalent Na_2O. The aggregate was gneiss granite from Årdal, Norway (mixed natural/crushed) conforming to NS 3099 "Standard aggregate for concrete testing". The density was 2670 kg/m^3 and the absorption 0,4 %. The aggregate frost durability is very good with less than 0.3 % mass loss both in the prEN 1367-1 aggregate frost test with water, and according to Nordtest project 1214-95 which is essentially the same test but using 1 % NaCl-solution. The grading is given in table 4.

Table 4 Grading of the combined aggregate

Sieve (mm)	0,063	0,125	0,25	0,5	1	2	4	8	11,2	16	32
%	1.2	2.8	6.1	12.1	26.8	37.1	47.5	58.1	75.1	87	100

Table 5 gives mix compositions and properties of fresh and hardened concrete.

Table 5 Concrete mixes (kg/m^3) and properties of fresh and hardened concrete

	Mix 1 (3 % NaCl)	**Mix 2** (demin. water)	**Mix 3** (demin. water)
Material:			
Cement	500	370	280
Aggregate	1775	1832	1889
Free/total water	155.6/160	177.7/185	188.4/196
Water reducer	3.75	0	0
w/c (free water)	0.31	0.48	0.67
Weight/volume	2436/0.981	2387/0.982	2365/0.986
(Theoretical air content)	(1.9 %)	(1.8 %)	(1.4 %)
Fresh concrete:			
Slump (mm)	40	170	180
Air (%)	1.8	1.9	2.4
Density	2488	2403	2360
Hardened concrete:			
f_{c28} (MPa)	94.4	62.6	36.0

2.2 Length change measurements and data from dilation curves

Length change was measured parallel to the surface at half thickness normal to the moulding direction on the 150 by 150 by 50 mm slabs. The slabs were sawn from 150 mm cubes according to SS 13 72 44. Various types of invar frames and LVDTs were used at the institutes mainly in accordance with the principles of ASTM C671. Also measuring studs varied. At NBI 16 mm long 8 mm diameter invar steel studs were glued with epoxy in holes drilled in the concrete. AT SP 10 mm long invar studs of 8 mm diameter were glued in drilled holes using "steel plastic". At LTH studs were glued directly to the surface. At AAP 35 mm long studs with 12 mm diameter in the part glued 25 mm into the concrete (epoxy in holes) and 8 mm diameter in the outside 10 mm. At VTT a brass plate was glued to the concrete surface for dilation measurements and a special spring system forced the LVDT to the surface. At LTH, SP and AAP the specimens were prepared according to SS 13 72 44. In addition there were holes in the insulation for the studs. Only LTH reported some problems with loose studs during freeze/thaw.

Figure 1 shows typical dilation curves when there is internal cracking in the concrete. Dilation means positive length change (ΔL/L) or expansion, whereas negative length change is termed contraction. Three different dilation values taken from this curve give information about internal damage of concrete due to frost:

- ε_f': ΔL/L on first freezing of water in the concrete (not clear in fig.1 but clear in fig. 5)
- $\varepsilon_{20\text{-}0}$ and $\varepsilon_{0\text{-}-20}$: ΔL/L from 20 to 0 °C (prefreezing contraction) and from 0 to –20 °C
- ε_{res}: residual expansion after freezing

The length change data were taken from the logged curves. This was done by reading the values from the worksheet graphics on the screen when pointing on the curve. The intercepts were used instead of performing linear regression. There are several arguments for this: the intensity of logging varied between the institutes, the amount of data makes this simplified procedure less time consuming, when there is damage the post freezing curve is often strongly non-linear in contrast to the the prefreezing contraction curve, as is seen in figure 1. Finally, in the ASTM C671 procedure it is mainly the nature of the length change curve during freezing that gives information about potential frost damage during a dilation experiment: ε_f, $\varepsilon_{20\text{-}0}$, $\varepsilon_{0\text{-}\text{-}20}$ and residual expansion.

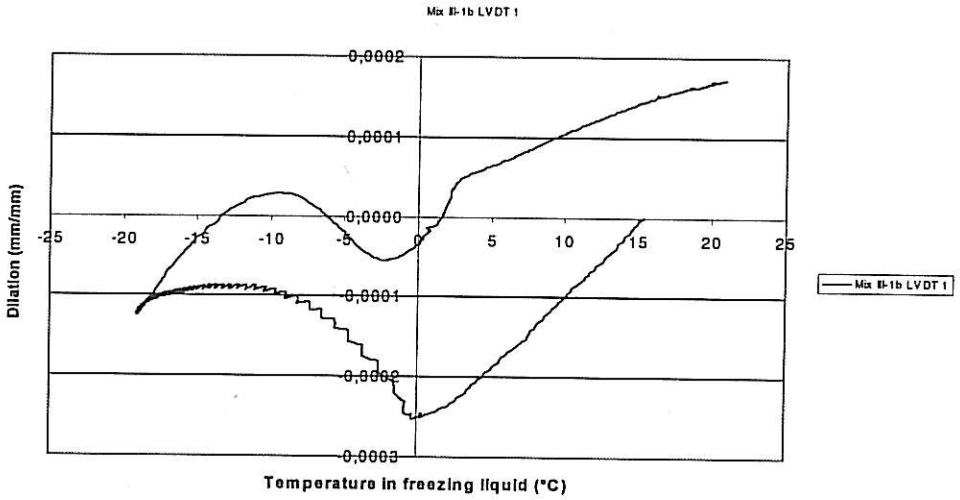


Figure 1: Dilation curve during wet freeze/thaw (LTH Mix 3, 7th cycle): pre-freezing contraction ($\varepsilon_{20\text{-}0}$) post-freezing expansion($\varepsilon_{0\text{-}\text{-}20}$) and residual expansion (ε_{res}) (ε_f is more clearly seen in figure 4)

At AAP only residual expansion was measured. This was done on all 4 parallel specimens normally and parallel to the moulding direction. The other measurements using Invar frames and LVDTs were made using two parallel specimens. At SP two parallel measurements of residual expansion were made mechanically at 0 and 56 cycles for mix 2 and 3, whereas one specimen was run in the Invar frame continuously for 56 cycles.

Invar frames, LVDTs and calibration procedures varied between the institutes but the principles are all based on ASTM C671 [3]. NBI performed a series of ten tests on the two Invar frames with an invar rod of equal quality. This gave linear correction coefficients α_{frame} with r^2 from 0.9882 to 0.9975 on cooling and 16 – 18 % coefficient of variation for α_{frame} (n = 10). A slight contraction was measured with the invar rod in the frame. This is assumed to be caused both by the LVDT and the frame (yoke, nuts, springs etc.) Together with α_{Invar} (thermal contraction coefficient given by the producer of the Invar alloy Nilo 36) this gave the dilation of the specimen:

$\varepsilon_{specimen} = \varepsilon_{measured} - \Delta T\ (\alpha_{frame} + \alpha_{Invar})$, with $\varepsilon_{measured}$ negative for contraction.

No efforts were made to standardize the equipment for performing the dilation measurements since the aim of the project was to develop the dilation test by measuring on identical concrete specimens. In all plots of dilation versus temperature used in this report it is the concrete surface temperature that is used. For the SS 13 72 44 test (SP, LTH, AAP) this means in the liquid, whereas for the classical test this means on the concrete surface under the plastic foil when cooling in air (VTT) and in the liquid when using glycol as cooling liquid (NBI). The important data from the dilation tests are:

Critical dilation: the dilation value measured before a significant increase in dilation occurred during the following freeze/thaw cycle. Minimum dilation taken into account is 0.5 * 10^{-4} as recommended in [3, 7]. Three different dilation values were taken from the curves:

- ε_f : direct dilation on freezing
- $\varepsilon_{20\text{-}0}/\varepsilon_{0\text{-}-20}$: deviation from prefreezing contraction (= dilation R in Finnish Standard [5])
- ε_{res}: residual expansion after completing a freeze/thaw cycle

Period of frost immunity: absorption time when the critical dilation is reached.

2.3 Ultrasonic pulse velocity

UPV was measured normally to the moulding direction at each side of the gage studs with 54 kHz transducers. At SP and AAP conic transducers were used. At SP the measurements were made on the concrete through holes in the rubber. At LTH, NBI and VTT 50 mm transducers where applied on the rubber (VTT) or on the concrete surface (NBI, VTT).

2.4 Uptake of liquid and change in degree of saturation - ΔS

In SS 13 72 44 the absorption was determined by weighing the surface dry specimen after each scaling measurement. Weight of scaled material corrected for evaporable water content (measured in the PF – test) was included. It was assumed that scaled material consisted of cement paste. In the classical dilation test weight increase was measured after each absorption period before freezing. ΔS (increase in degree of saturation) in the two tests (wet and classical) was calculated as ΔS assuming constant specimen volume of 1110 cm^3:

ΔS = liquid uptake/total pore volume

Total porosity was measured according to the PF-test [11, 12] at NBI and AAP. At NBI the porosity was determined after 3 months in the climatic chamber according to [12] (drying at 105 °C, water suction and pressure saturation at 10 MPa) whereas at AAP the specimens were saturated first (suction, 10 MPa pressure) before being dried. The test at AAP was performed at start and stop of test. Loss of specimen volume due to scaling is maximum approximately 1 kg/m^2 corresponding to 9 cm^3 = 9/1110 = 0.8 % by volume for the 15 cm slab. Maximum volume increase due to cracking is approximately 0.6 %. The error due to scaling and volume increase due to cracking will thus affect ΔS about 1 % which is small.

2.5 Scaling

Scaling was measured in the standard way by collecting scaled mass, drying at 105 °C for 24 hours and calculating as kg/m^2.

2.6 Reduced strength and cracks after SS 13 72 44 testing

At SP the SS 13 72 44 slabs were subjected to mechanical testing after freeze/thaw and the results were compared to those of a set of non-freeze/thaw tested slabs. Bending strength was measured on 15 x 4 x 4 cm prisms cut from slabs. Strength was measured on the resulting halves. The load was applied normally to the freezing direction. At AAP fluorescent impregnated polished sections were made of the slabs after stop of freeze/thaw testing at 112 cycles. Photos are given in appendix E.

3. RESULTS AND DISCUSSION

3.1 Frost cycles

Table 6 shows data on the frost cycles and figures 2 - 3 show typical freeze/thaw cycles.

Table 6: Freeze/thaw cycle characteristics

Institute	Measurement	Cooling rate (°C/h)	Min. temp (°C)
VTT	On surface (air)	15	- 23
NBI	On surface (by liquid)	2 (0 to -20)	- 20
SP	In liquid	3.5 (0 to -18)	- 18
LTH	In liquid	2.5 (0 to -18	- 18

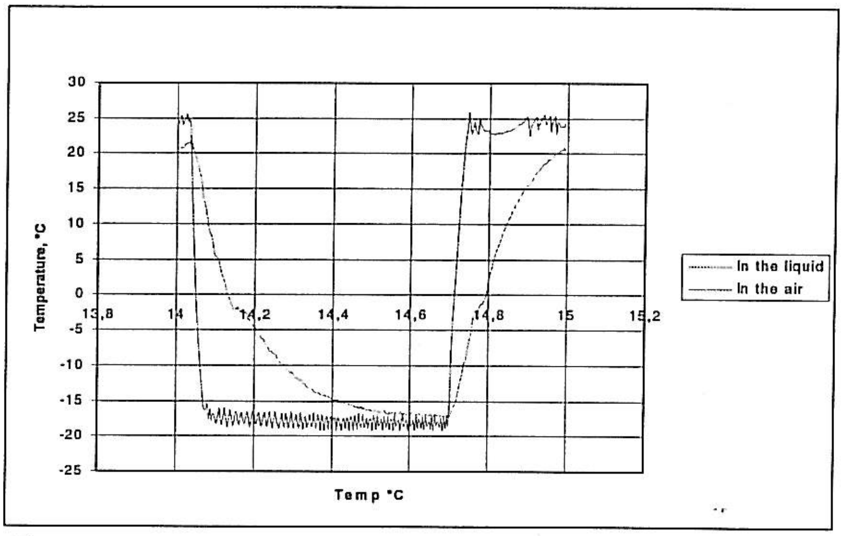


Figure 2: SP cycle in SS 13 72 44 wet freeze/thaw

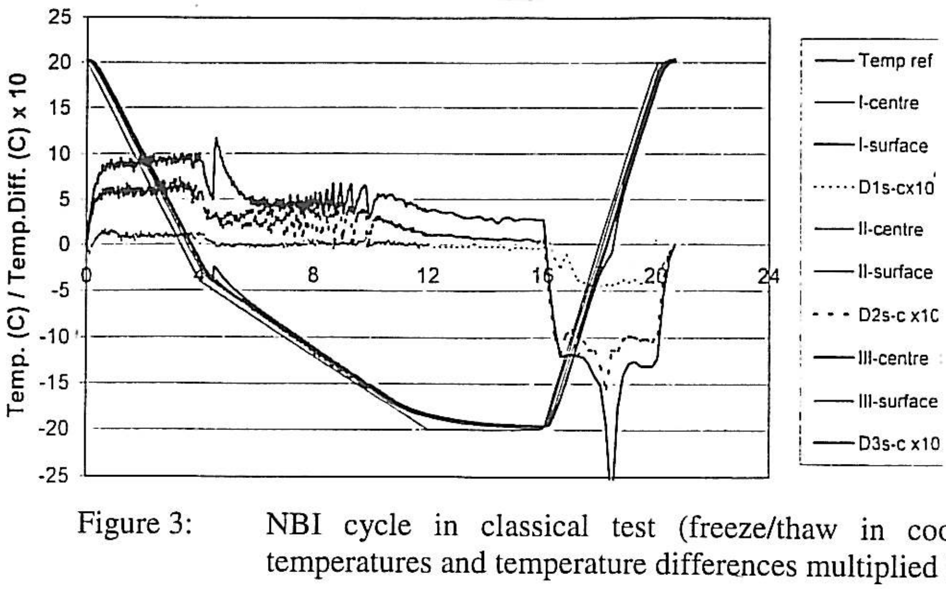


Figure 3: NBI cycle in classical test (freeze/thaw in cooling liquid) with actual temperatures and temperature differences multiplied by 10

The NBI-test with cooling liquid gives a quite flat temperature profile in the specimen. The maximum difference between surface and centre is 2,5 °C. It is measured on heating with 10 °C/h. At VTT the maximum difference between centre and surface is 13,5 °C. This is recorded on cooling with 15 °C/h cooling rate. The higher difference between surface and centre temperature at VTT is mainly caused by the insulating effect of the surrounding air thus slowing the heat transport out from and in to the specimen during cooling and heating respectively.

The main practical consequence of this is that the frost attack probably is more severe at VTT than at NBI due to both higher cooling rate and lower minimum temperature. The temperature difference between surface and centre, which would lead to some kind of strain gradient, is probably less important. It could be that the ice formation rate gets higher in the specimens at NBI since the heat is transported away very efficiently due to the cooling liquid. As we shall see there was no indication of that in the present experiments. The most visible effect is a much smaller lag between the cooling and the heating part of the temperature/strain curves at NBI than at the other laboratories.

3.2 Dilation

In general the variation between two parallel dilation curves was quite large when there was significant ice formation in the concrete. The minimum dilation considered when assessing ε_f, $\varepsilon_{20\text{-}0}$, $\varepsilon_{0\text{-}-20}$ and ε_{res} from the dilation curves was 0,5 * 10^{-4} as recommended in [3, 7]. The temperature when first freezing occurred generally varied a few degrees. Due to the rather large specimen size the maximum super cooling was in the order of 5 °C with fresh water. All temperature – length change curves are given in appendix D. The dilation data read from the curves are given in appendix C.

The mechanical measurements of residual expansion during SS 13 72 44 performed at AAP showed no sign of inhomogeneity between the two directions. The scatter was in general low and there was a linear correlation between UPV and length change. This is further discussed in [13].

3.2.1 Dilation on first freezing (ε_f)

At NBI and LTH dilation was logged so often that ε_f could be clearly deduced. Figure 4 shows an example of expansion on freezing in the classical test (NBI Mix 3, 56^{th} cycle). Also contraction was sometimes observed on freezing, see figure 5 (LTH Mix1 - 1^{st} cycle). Table 7 gives the numerical values.

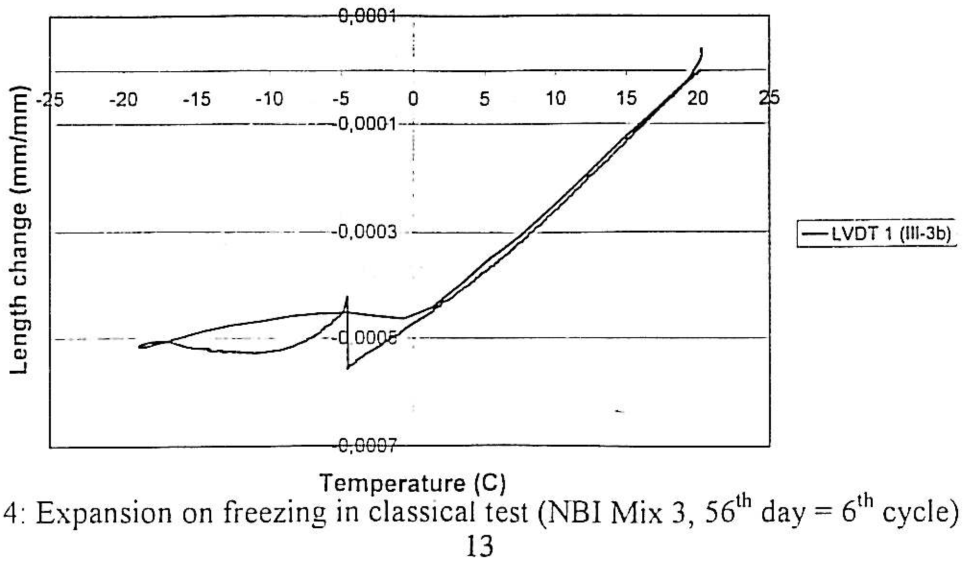


Figure 4: Expansion on freezing in classical test (NBI Mix 3, 56^{th} day = 6^{th} cycle)

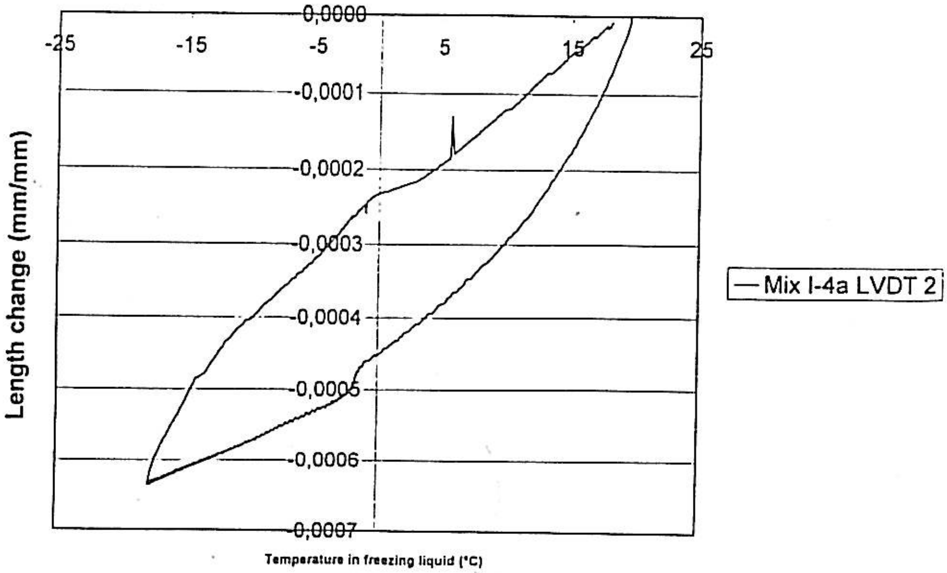


Figure 5: Contraction on freezing in SS 13 72 44 (LTH Mix1 - 1st cycle)

Table 7: Direct dilation on first freezing (ε_f) (* 10^{-4}), mean of two specimens

	Mix1						Mix2						Mix3					
	1	7/2nd	14/3rd	28/4th	42/5th	56/6th	1	7/2nd	14/3rd	28/4th	42/5th	56/6th	1	7/2nd	14/3rd	28/4th	42/5th	56/6th
NBI c	0			0	0	0	0	0	0	0	0	0	0.1	0.2	0.4	0.5	0.8	1
LTH w	-0.3		-0.1	0	0.6	0.2	-0.2	-0.5	-0.2	2	1.6	1.5	-0.4	0.3	1.9	2.7	4.1	3.3

Positive dilation on freezing of the pore water around -3 °C indicates potential internal cracking depending on the magnitude of this effect. The results show that the ice formation gets much higher in the wet test (LTH) than in the classical test (NBI). As will be seen later this is due to the much higher ΔS in SS 13 72 44 compared to what is observed in classical frost dilation testing.

No critical dilation is reached in the classical test based on ε_f for mix 1 and mix 2. For mix 3 ε_f increases steadily for each freezing. At NBI the increase is below 0.5 * 10^{-4} at each freeze/thaw cycle and therefore an accumulated length change = 0.4 * 10^{-4} is reached at 3rd freezing. The tensile strain caused by the direct ice formation alone on first freezing probably exceeded the fracture tensile strain of mix 3 at 14 or 28 days (3rd or 4th freezing).

The period of frost immunity in the classical dilation test is therefore not reached for mix 1 and 2 within the 59 days of test, whereas it is 3 + 6 + 6 = 15 days for mix 3.

In SS 13 72 44 internal damage occurs very rapidly for all three mixes. For mix 1 critical dilation is reached at 28 cycles whereas for mix 2 it is reached at 14 cycles. After that the dilation increases largely. For mix 3 critical dilation is reached on first freezing. The period of frost immunity is short for all mixes in the wet SS 13 72 44 test: 3 + 28 days, 3 + 14 days and 3 days for mix 1, 2 and 3 respectively.

3.2.2 Length change above and below zero ($\varepsilon_{20\text{-}0}/\varepsilon_{0\text{-}-20}$)

The length change above zero is the prefreezing thermal contraction of the specimen. Dilation below zero compared to the extrapolated prefreezing contraction reflects the formation of ice in the specimen and thereby internal damage. We here assume that the expansion must deviate from the prefreezing contraction by more than 0.5 * 10 $^{-4}$, as suggested in [3, 7]. There might of course also be other explanations for deviation from the prefreezing contraction, such as non-linearity of the length change measurements, inaccuracies and contraction due to thermodynamic phenomena. The results are given in table 8 and 9. $\varepsilon_{20\text{-}0}$ and $\varepsilon_{0\text{-}20}$ are all given for 20 °C, i.e. linear extrapolations are used in those cases where + 20 and – 20 °C were not reached.

Table 8: Prefreezing contraction ($\varepsilon_{20\text{-}0}$) (* 10 $^{-4}$), mean of two specimens

	Mix1						Mix2						Mix3					
	1	7/2nd	14/3rd	28/4th	42/5th	56/6th	1	7/2nd	14/3rd	28/4th	42/5th	56/6th	1	7/2nd	14/3rd	28/4th	42/5th	56/6th
VTT	-1.8		-3.6	-4.9	-4.9	-3.2	-3.5	-2.7		-3.6	-3.6	-3.3	-2.6	-3.3	-4.4	-4.1		-3.0
NBI	-2.9	-3.4			-4.0	-4.0	-3.0	-3.3	-3.7	-4.3	-4.9	-5	-3	-3.1	-3.4	-3.4	-4.1	-4
LTH	-3.7		-2.0	-5.4	-3	-3.1	-3.7	-3.5	-3.1	-2.5	-3.6	-2.8	-3.7	-3.5	-4.0	-3.2	-3.8	-3.9
SP			-4.1	-3.7		-4.4							-4.6	-4.6	-3.9	-4.0	-3.6	-3.6

The prefreezing contraction $\varepsilon_{20\text{-}0}$ have the following mean values and mean linear thermal expansion coefficients for the concrete:

Mix 1: $\varepsilon_{20\text{-}0}$ = 3.7 * 10 $^{-4}$/20°C = $\alpha_{concrete}$ =1.8 * 10 $^{-5}$/°C (CV = 26 %, n = 17)

Mix 2: $\varepsilon_{20\text{-}0}$ = 3.5 * 10 $^{-4}$/20°C = $\alpha_{concrete}$ =1.8* 10 $^{-5}$ /°C (CV = 19 %, n = 17)

Mix 3: $\varepsilon_{20\text{-}0}$ = 3.7 * 10 $^{-4}$/20°C = $\alpha_{concrete}$ =1.8 * 10 $^{-5}$/°C (CV = 14 %, n = 23)

$\alpha_{concrete}$ = 1.8 * 10 $^{-5}$/°C is somewhat higher than the typical value of about 1 * 10 $^{-5}$/°C. If we only use the 10 measurements performed on non-damaged concrete in the first cycle the mean value is 1.6 * 10 $^{-5}$/°C (CV = 22 %, n = 10).

Table 9 Dilation below zero ($\varepsilon_{0\text{-}-20}$) (* 10 $^{-4}$), mean of two specimens

	Mix1						Mix 2						Mix 3					
	1	7/2nd	14/3rd	28/4th	42/5th	56/6th	1	7/2nd	14/3rd	28/4th	42/5th	56/6th	1	7/2nd	14/3rd	28/4th	42/5th	56/6th
VTT	-1.7		-1.3	-2.3	-1.4	-3.3	-2.6	-2.6		-2.6	-2.3	-2.6	-2.2	-1.5	-1.9	+0.4		+0.5
NBI	-2.4	-3.0			-2.5	-2.6	-3.0	-2.9	-2.7	-2.9	-3.1	-3.3	-2.7	-1.9	-0.8	-0.8	-0.5	-0.4
LTH	-2.7		-0.9	0.9	0.2	-0.4	-1.6	-1.3	-0.9	+2.9	+2.8	+2.8	-1.8	+0.5	+3.9	+4.9	+5.5	+8.3
SP			-0.7	-0.1		-1.5							-1.5	-0.1	+1.1	+1.0	+1.4	+1.5

$\varepsilon_{0\text{-}-20}$ in table 9 is equal to the dilation R according to Finnish Standard [5]. In the classical dilation test there is no systematic increase in $\varepsilon_{0\text{-}-20}$ for mix 1 and mix 2 and thus no sign of damage. There is, however, clear damage in mix 3 at both NBI and VTT since $\varepsilon_{0\text{-}-20}$ is increasing steadily at increasing period of testing. The increase starts already at second freezing at both VTT and NBI, i.e. after 3 + 6 = 9 days of absorption. At NBI the increase in $\varepsilon_{0\text{-}-20}$ is lower than at VTT, but deviating increasingly from the pre freezing contraction at prolonged absorption. The reason for the higher damage at VTT is probably the lower minimum temperature and higher cooling rate.

Therefore, based on $\varepsilon_{0\text{-}-20}$ no critical dilation was detected for Mix 1 and Mix 2 up to 3 + 56 days in the classical test. The critical dilation for Mix 3 was -2.2 (VTT) - -2.7 (NBI) * 10 $^{-4}$ = -2.5 * 10 $^{-4}$. The scatter in the prefreezing contraction ($\varepsilon_{20\text{-}0}$) with CV = 14 - 26 % should be kept in mind when determining the critical dilation. 26 % of 2.5 * 10 $^{-4}$ = 0.7 * 10 $^{-4}$ is close to the recommended minimum detection of 0.5 * 10 $^{-4}$ given in [3]. Also the steady increase of $\varepsilon_{0\text{-}-20}$ between each absorption period is taken into account when determining the critical dilation, as recommended in [3]. The period of frost immunity is not reached for mix 1 and

mix 2 within the 59 day test period, i.e. it is larger than 53 days, whereas for mix 3 it is only 3 days.
In SS 13 72 44 (LTH and SP) $\varepsilon_{0\text{-}-20}$ is larger than in the classical test (VTT and NBI) as expected due to higher absorption. Critical dilation is probably reached between 1 and 7 cycles for all three mixes. The period of frost immunity is very short in this test for all mixes when using $\varepsilon_{20\text{-}0}$: 3 - 10 days.

3.2.3 Residual dilation - ε_{res}

Total length change was measured at two of the laboratories. SP performed continuous length change measurements with LVDT and Invar frames during all 56 cycles for one specimen of each of the three mixes. In addition, a mechanical gauge was used for mix 2 and mix 3 at 0 and 56 cycles for two parallel specimens. AAP measured length change using a mechanical gauge. This was performed on all four specimens for each mix. Residual dilation measured at the other three laboratories (VTT, NBI, LTH) is more uncertain since these are taken from start and end points of dilation curves. The invar frames were taken off the specimens between these successive measurements. Table 10 below shows the results.

Table 10 Accumulated residual dilation (ε_{res}) (* 10^{-4})

	Mix1						Mix2						Mix3					
	1	7/2nd	14/3rd	28/4th	42/5th	56/6th	1	7/2nd	14/3rd	28/4th	42/5th	56/6th	1	7/2nd	14/3rd	28/4th	42/5th	56/6th
VTT 1)	0.3		0.5	0.5	0.9	0.9	0.6	1.2		1.5	2	2.5	0.6	1.5	2.4	3.2		4.8
NBI 1)	-0.2				-4.3	-4.7	0.4	0.5	0.6	0.4	-0.3	-1.4	0.2	0.5	0.9	1.2	0.9	1.1
LTH 1)	-2.0		0.2	-0.8	0.1	1.2	0.7	0.9	2.7	2.7	3	4.1	0.1	1	2.4	4.6	5.2	6.6
SP 2)	-0.6	-1.6	-0.9	6.5	9.0	9.2	-0.3	-0.1	2.4	11.3	14.2	16.2	-0.1	0.6	4.9	11.2	15	16.6
SP 3)												26.2						25.5
AAP4)		0.8	3.1	25.8	37.6	47.3		1.4	6.4	17.6	25	32.6		4.1	16.0	29.9	43.2	51.0

1) taken from dilation curves for 6 cycles, 2) taken from continuous LVDT measurement
3) mechanical dilatometer on 2 parallel specimens at 0 and 56 cycles
4) mechanical dilatometer on 4 parallel specimens at 0, 7, 14, 28, 42 and 56 cycles

In SS 13 72 44 (LTH, SP, AAP) the results on ε_{res} are in line with the results on ε_f and $\varepsilon_{0\text{-}-20}$ in table 7 and table 9. The low values at LTH compared to SP an AAP are of course due to that only dilation in the 1st, 7th, 14th, 28th, 42nd and 56th cycle (i.e. in 6 cycles) were measured, and not the accumulated dilation in the other 50 cycles. In SS 13 72 44 there are discrepancies between the magnitudes of the LVDT-dilation and the gauge dilation at SP and AAP. The high expansion at AAP might be due to more internal cracking caused by a 14 day increased drying period due to strike (see also discussion in section 3.4 below). It is a well known effect that predrying increases the ice formation in the material [14]; more the harder the drying. Consequently the internal cracking has become more severe at AAP. This is in line with the increased scaling at AAP, see section 3.5, and the findings [15]. SPs measurements by both LVDT and gauge show some difference. The order of magnitude is however the same for the two types of measurements. Since there are so few parallel measurements no conclusion is drawn here.

For the classical test VTT is measuring positive residual dilation for all mixes based on intercept at 20 °C. NBI is sometimes measuring contraction for mix 1 and 2 and only expansion for mix 3. The results are in line with the $\varepsilon_{0\text{-}-20}$ - values given in table 9. One probable cause is the higher cooling rate and lower minimum temperature at VTT which would cause more expansion in line with observations on HCP [16]. In [16] slow cooling rates lead to lower expansion and for some specimens even to contraction.

Figure 6 shows accumulated residual dilation measurements performed continuously by LVDT at SP. The results show an initial contraction before damage occurrs at prolonged cycling. The contraction is in accordance with the observations in [16] for slow cooling rates. It is interesting to note that this apparent permanent deformation due to freezing induced shrinkage correlates to the observations of increased strength during early cycling in [2]. Clearly, more research is needed to understand whether there is actually damage at the very early stage of frost exposure or if the material is actually strengthened by the gel drying. The increased strength during early cycling [2] indicates that the length change in figure 6, particularly the contraction, is not caused by bending of the specimen due to the unidirectional frost attack. Figure 6 also shows how short the period of frost immunity can be in SS 13 72 44. Based on a damage criterion $\varepsilon_{res} > 0$, mix 1 has 3 + 16 days, mix 2 has 3 + 7 days and mix 3 has 3 + 5 days periods of frost immunity in SS 13 72 44. It should be noted that permanent contraction was never measured at AAP at 7 days probably due to a stronger ice formation resulting from the more severe predrying. As already discussed, the AAP specimens had probably only 3 days of frost immunity, i.e. damage started before 7 cycles for all mixes.

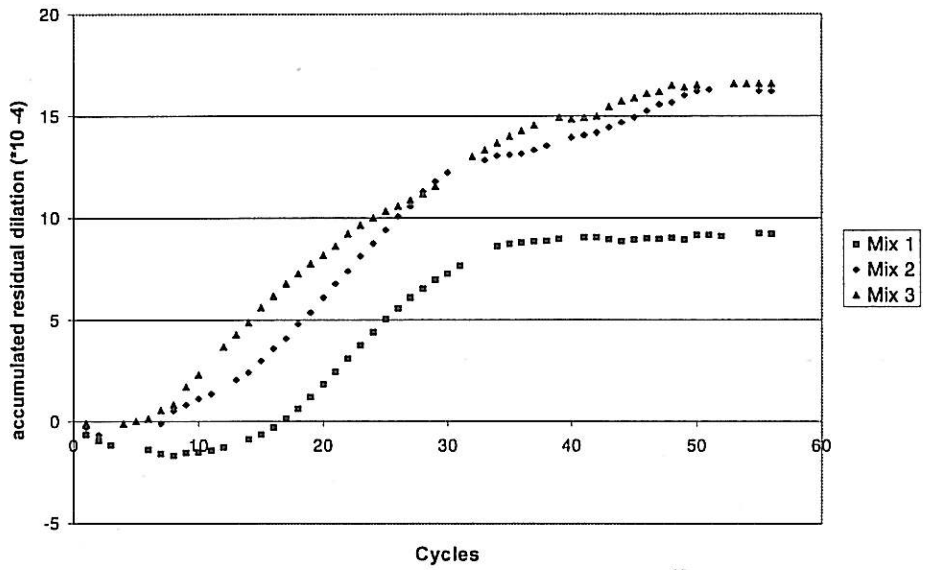


Figure 6: Length change versus number of cycles measured at SP.

3.3 Ultrasonic Pulse Velocity (UPV)

Figure 7 shows the evolution of UPV in the specimens in m/s (including rubber), whereas figure 8 shows the evolution in % of initial UPV.

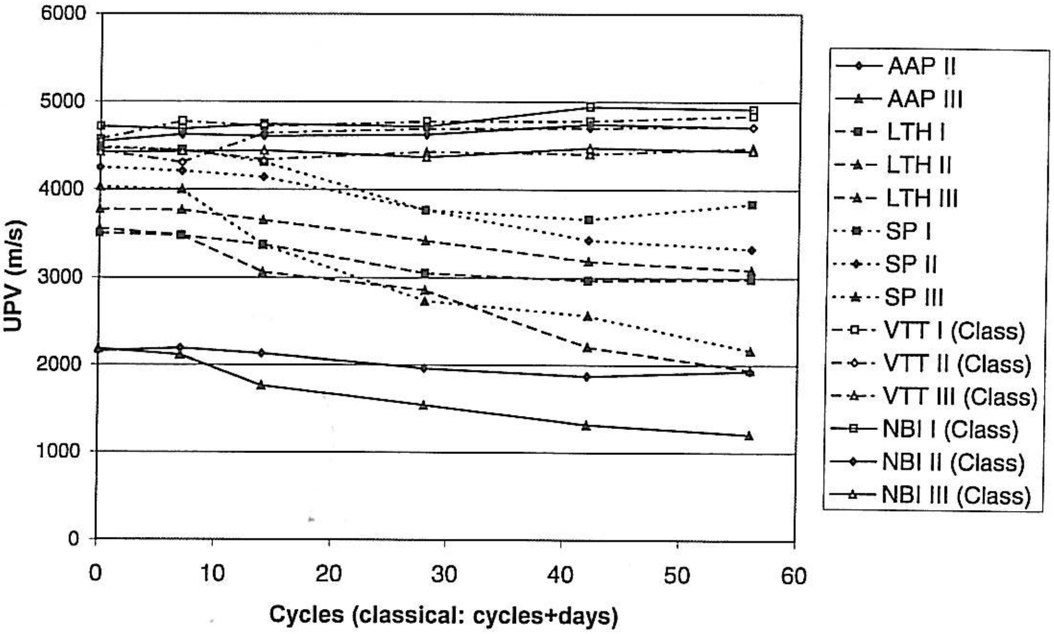


Figure 7: UPV during test (m/s)

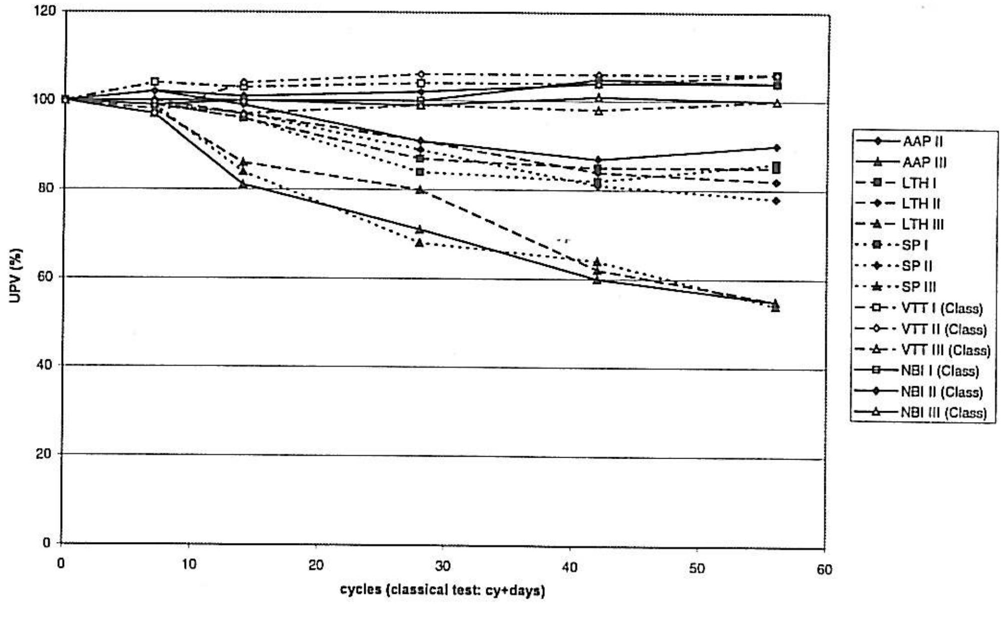


Figure 8 : UPV during test (% of initial UPV)

Figure 7 shows that the absolute values vary considerably between the laboratories. The initial UPV varies from about 2200 m/s to 4700 m/s for all three mixes. This is as expected from the results [2] due to differences in transducers and surfaces (on rubber, on concrete). The normalized values, however, show rather equal developments in damage in each of the two tests, see figure 8.

In SS 13 72 44 Mix 3 has the largest loss of UPV as expected and the results are very similar between the three institutes in spite of the differences in absolute values. Mix 1 and mix 2 have smaller loss of UPV. Mix 1 from AAP is excluded due to errors at least at 28 and 42 cycles. The results indicate internal cracking in all three mixes in SS 13 72 44 at the end of the test in line with the dilation measurements.

Figure 9 shows a plot of residual dilation and UPV measured at AAP. As can be seen a linear relation between UPV and dilation was observed when there was significant damage.

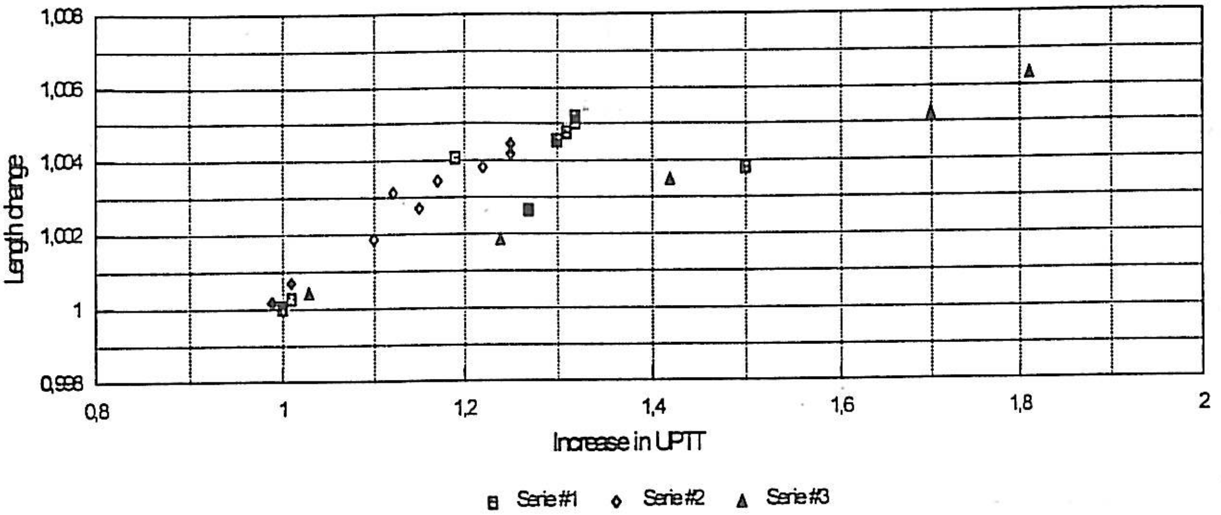


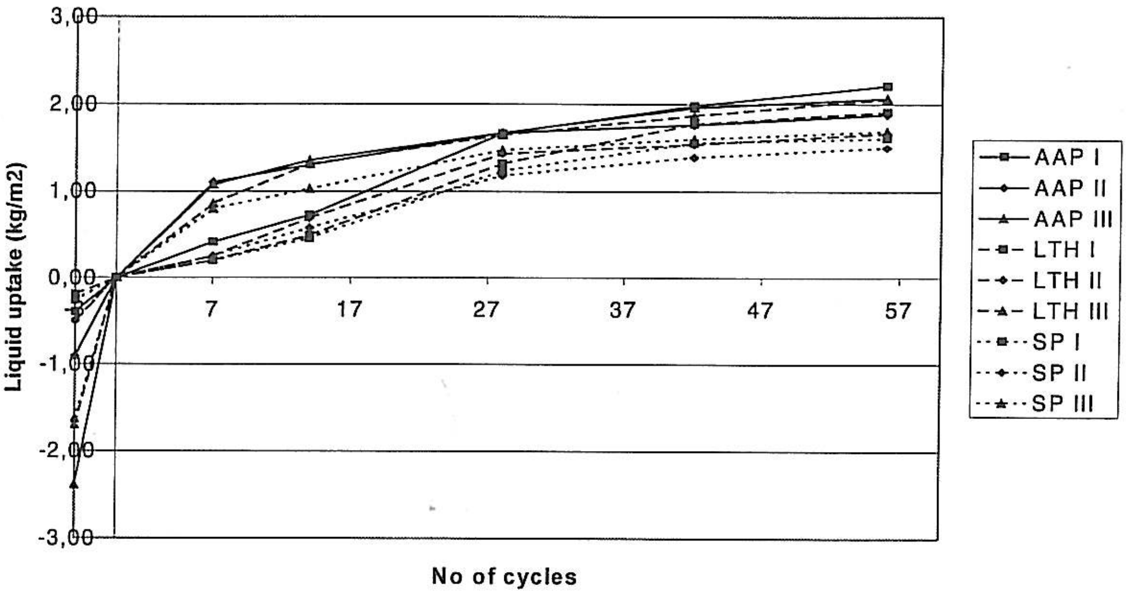
Figure 9: Linear relationship between increased Ultrasonic pulse transission time (UPTT) and length change observed at AAP in SS 13 72 44

Figures 7 and 8 show that in the classical test there is no indication of frost damage by UPV in any mix. There is even an indication of increased UPV for mix 1 and mix 2 at both NBI and VTT. For mix 3 there is no clear change. Apparently, the internal damage detected by the dilation measurements is not reflected by UPV. The reasons are probably lower sensitivity of this technique to initial small damage in the classical test where damage develops more slowly due to the absence of water on the outside during freeze/thaw and very few cycles. Furthermore, self-healing lets the ultrasonic waves bridge initial formation of microcracks during the water storage periods [17]. However, in the dilation test we know mix 3 had internal damage in terms of surpassed critical dilation. Hence UPV measurements are not recommended for the detection of early small frost damage in the classical frost dilation test.

3.4 Uptake of liquid, ΔS and discussion of dilation test criteria

In figures 10 - 12 absorption or increase in degree of saturation (ΔS) during test is shown for the two test methods. For SS 13 72 44 both kg/m^2 and ΔS are given.

Figure 10: Liquid uptake (kg/m²) in SS 13 72 44



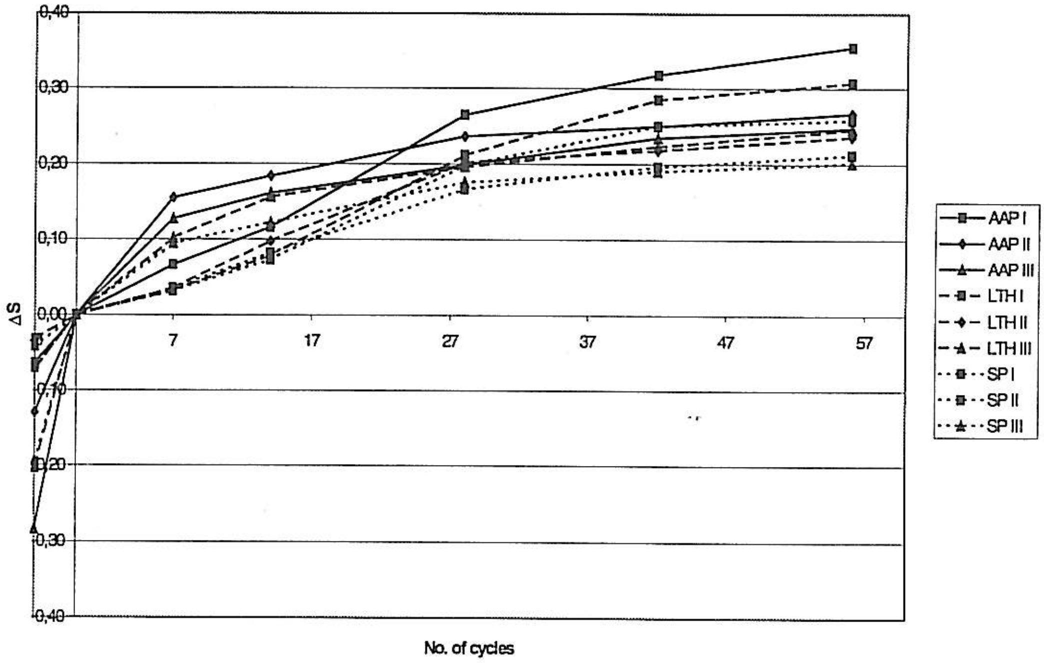


Figure 11: ΔS in SS 13 72 44

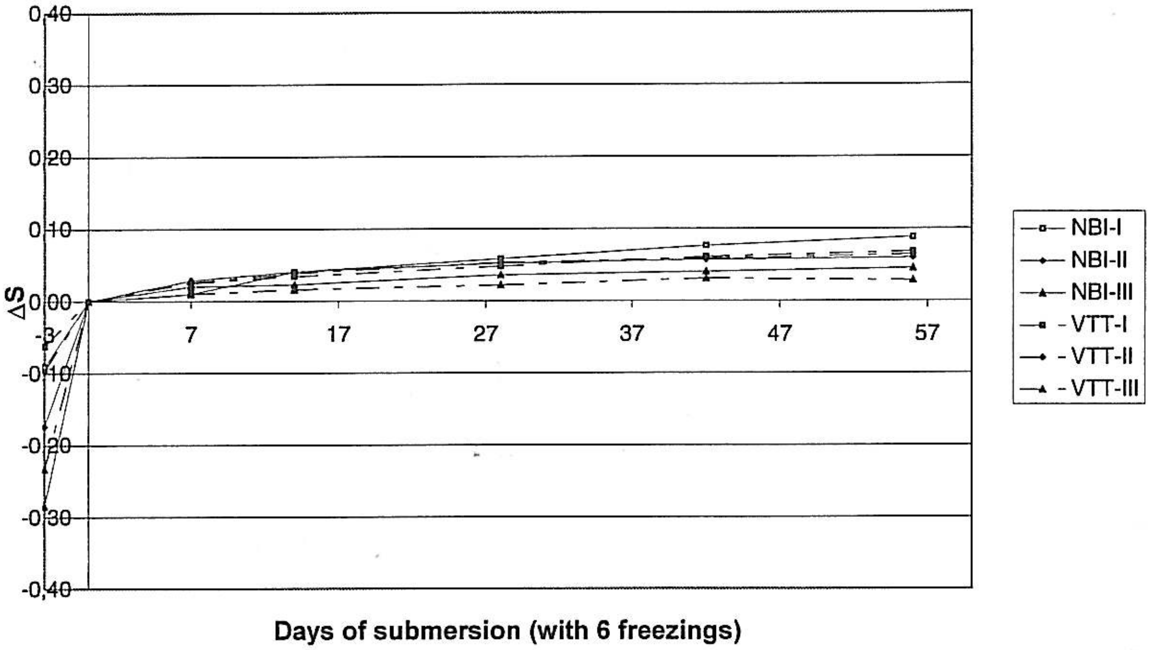


Figure 12: ΔS in classical frost dilation test

During the 3 day presuction period ΔS is similar in the two tests. There are some differences between the laboratories. At AAP the uptake is higher than at LTH and SP. This is due to the 14 day delay in the start of the test at AAP (strike) during which the specimens were left to dry in the climatic chamber.

In the classical dilation test the uptake before first freezing is higher at NBI than at VTT. The NBI specimens were kept in plastic bags in the climatic chamber when the specimens were shipped to the other laboratories. The shipped specimens were in similar plastic bags and packed in solid plywood boxes insulated with 20 mm expanded polystyrene on all sides. The NBI specimens may have been less tight than the transported specimens, resulting in more drying before opening the plastic bags. It is also probable that the temperature was higher in the NBI specimens stored in the laboratory than in the transported specimens, resulting in more evaporation and hydration in the NBI specimens.

After start of freezing and thawing the absorption gets much higher in the SS 13 72 44 specimens than in the classical dilation test. This is as expected due to the pumping effect caused by freezing and thawing [17]. By comparing figures 11 and 12 we see that at the end ΔS is approximately 3 times higher in SS 13 72 44 than in the classical test. Within each of the two test methods, however, the absorption is quite similar for the three concretes after start of freeze/thaw (presumably beyond the nick point absorption). The accelerated absorption caused by wet freezing and thawing clearly gives a large increase of absorption which is the cause of the more severe cracking in SS 13 72 44.

In table 11 critical dilation, period of frost immunity and ΔS-values at the end of the period of frost immunity are given.

Table 11: Critical dilation, period of frost immunity and ΔS obtained

Test	Mix	Critical dilation ($*10^{-4}$)			Period of frost immunity (days + cycles or days)			ΔS_{crit}
		ε_f	ε_{0--20}	ε_{res}	ε_f	ε_{0--20}	ε_{res}	(based on ε_{0--20})
							AAP SP	LTH SP
SS	1	0	**(-2.7)**	0	31	**(10)**	3-19	(.064+.075)/2= **0.069**
	2	-0.2	**-1.3**	0	17	**10**	3-10	(.106+.106)/2= **0.106**
	3	-0.4	**-1.7**	0	13	**3**	3-8	(.203+.194)/2= **0.199**
								VTT NBI
Classic	1	-	-	-	>53	**>53**	-	(.130+.179)/2 > **0.155**
	2	-	-	-	>53	**>53**	-	(.161+.234)/2 > **0.198**
	3	-0.4	**-2.5**	-	15	**3**	-	(.243+.305)/2 = **0.274**

The ΔS values in table 11 are calculated as absorption from the moisture state obtained after 3 weeks at 65 % RH/20 °C and 1 week of transport. ΔS is mainly of interest for comparison of the three mixes and two test methods. The different numerical values of ΔS at damage ("critical ΔS") between the two test methods partly reflect the fact that uniform saturation was not obtained in the specimens during test. Particularly in SS 13 72 44 a high degree of saturation in the top layer has been observed [18]. We also know that in the wet ASTM C666 procedure A freeze/thaw test the degree of saturation is increasing progressively from the surface and inwards [17]. This is confirmed by the critical ΔS values in table 11 which are obtained within the period of frost immunity based on ε_{0--20}. The critical ΔS is always lower in SS 13 72 44 since the critical degree of saturation is reached first in the top layer of the specimen resulting in progressive damage from the surface and inwards.

Important for the scope of this report is that the period of frost immunity was similar within the laboratories performing the same tests when based on the same dilation criteria. Residual dilation is not counted in. In spite of residual dilation beeing the simplest test to perform, the largest variation was found here. The reason is mainly that one of the two laboratories performing residual dilation measurements dried the specimens too much giving more severe cracking as already discussed. The three concretes investigated cover a rather wide range of concrete quality, except for that none of them were air entrained, see discussion under table 12 below. Proper air entrainment would probably have made all concretes durable against internal cracking in both tests and also made mix 1 durable against salt frost attack.

Many experimental details were not well harmonized, particularly in the classical test (cooling rate, minimum temperature, cooling medium, studs, invar measurement system etc). As seen in section 3.2.2 also the absolute values of dilation measurements varied between the laboratories. Still, based on ε_{0--20}, or the dilation factor R in [5], the concept "period of frost immunity" gave equal results for durability against internal cracking for the three mixes within each test method. The period of frost immunity was much shorter in SS 13 72 44 due to the pumping effect in this wet freeze/thaw test, as expected. This parameter should therefore only be used in SS 13 72 44 for structures or parts of structures that are freezing and thawing in direct contact with water or salt solution (e.g. pavements, tidal zone, dams). The classical dilation test applies to parts of structures that for some reason freeze in very wet condition without direct contact with water or salt solution. For many frost exposure situations the truth can be somewhere between the two situations. It can therefore sometimes be necessary to perform both types of test to have a proper evaluation of the durability against internal cracking in a given environment.

We therefore judge dilation testing for determination of durability against internal cracking using the concept "period of frost immunity" as robust and reliable.

3.5 Scaling

Scaling is shown in figure 13. The scaling is lower for the tests with water than for the tests with 3 % NaCl as expected. The ranking of the mixes is equal at the three institutes as follows:

- mix 1: Non acceptable salt/frost durability at all 3 laboratories ($m_{56} > 1$ kg/m^2)
- mix 2: Very good frost durability at all 3 laboratories ($m_{56} < 0.1$ kg/m^2)
- mix 3: Very good frost durability at all 3 laboratories ($m_{56} < 0.1$ kg/m^2)

The high scaling for mix I at AAP is due to the increased drying time at this laboratory. It is in line with earlier observations of increased scaling due to drying [19] and observations of effect on ice formation [14] and on internal cracking [15] by drying. Still all concretes had the same evaluation as at SP and LTH according to the test. No scaling was observed in the classical test, which is as expected since scaling only occurs in wet freeze/thaw when there is access to free liquid at the surface during freezing and thawing cycles.

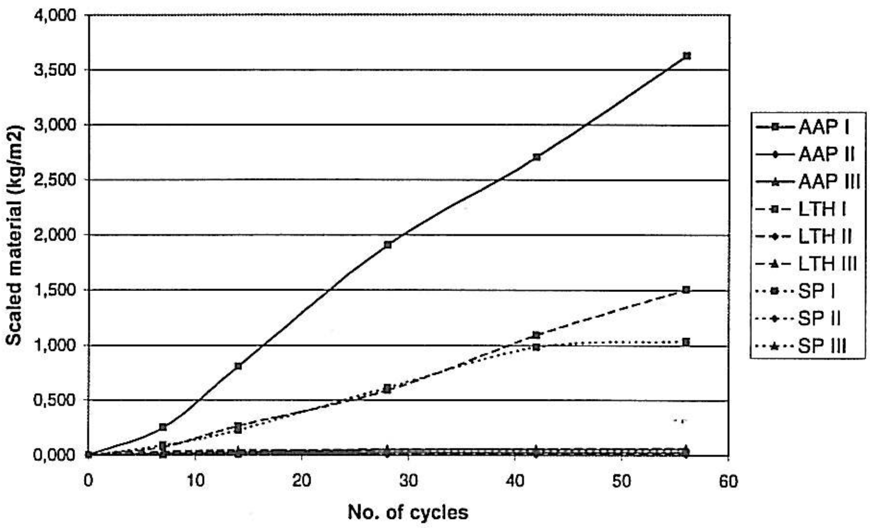
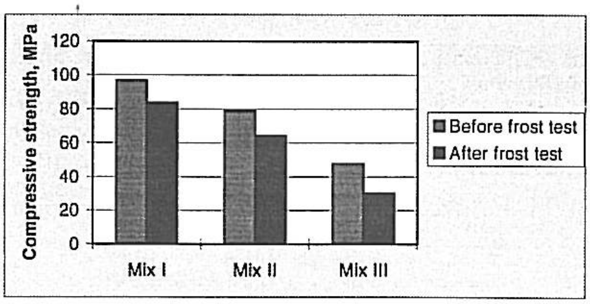


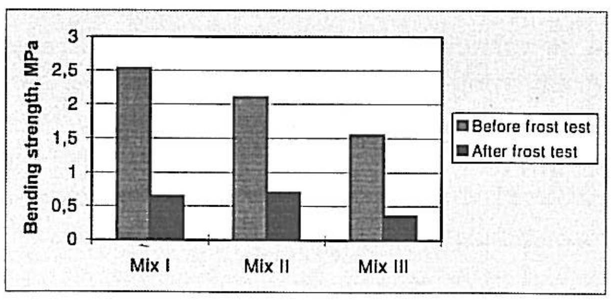
Figure 13 : Scaling vs. number of cycles

3.6 Reduced strength, increased porosity and cracking in SS 13 72 44

Figure 14 shows loss of compressive and bending strength due to the freeze/thaw exposure.

Figure 14: loss of compressive- and bending strength measured at SP after SS 13 72 44 test





Measurements were performed on four parallel specimens cut from the slabs at SP. As can be seen the percentage loss of bending strength is larger than the percentage loss of compressive strength. This is as expected from the visible cracks induced, see the photos of plane sections made at AAP after test in appendix E at the end of the report.

The porosity results are shown in table 12 below.

Table 12: Porosity [11, 12], NBI: dried before saturation, AAP: dried after saturation

	NBI before frost			AAP before frost		AAP water stored	AAP after frost
	$p_{suction}$	P_{macro}	p_{total}	p_{macro}	p_{total}	p_{total}	p_{total}
Mix I	10.9	1.7	12.6	0.5	5.2	7.4	11.2
Mix II	13.2	1.1	14.4	0.6	8.0	11.7	12.6
Mix III	14.7	2.3	17.0	0.6	11.1	15.5	not meas.

From table 12 we see by comparing NBI and AAP before frost that the porosity is higher when the specimens are dried before saturation, as expected. Drying before suction and pressure saturation probably gives the largest measurable pore volume in concrete, and much larger than the pore volume that can be occupied by freezeable water. The low macropore content obtained at AAP is in agreement with [12] where if was found that the specimens had to be dried first in order to be able to effectively fill up the macro voids when applying 10 MPa pressure. Then a very good correlation to air void content determined optically was obtained [12]. From the last two columns it is seen that the frost deterioration in wet freeze/thaw results in an increase of porosity. The higher porosity in "water stored" than in "before frost" reflects the higher degree of saturation attained during water storage. Finally it should be mentioned that all concretes have Poreprotection Factor (PF) lower than 0.20 – 0.25 and thus expectedly non-satisfactory frost resistance [15]:

$$PF = p_{macro} /(p_{macro} + p_{suction})$$

3.7 Scatter

The number of parallel specimens varied between the participating laboratories due to the different tests and measurements performed. Table 13 shows number of specimens used for the different tests at the different institutes.

Table 13: Number of parallel specimens used for the different frost tests

Test	VTT	NBI	LTH	SP	AAP
Dilation	2	2	2	1-2	4
Scaling	-	-	4	3	4
Absorption	2	2	4	3	4
UPV	2	2	4	3	4

In the dilation tests mainly two parallel specimens were used. No statistical evaluations of the results in this investigation have been performed other than the usual standard deviation and % coefficient of variation, see appendix. Some discussions on uncertainties are given for some of the measurements under the foregoing sections (dilation: uncertainty around 0.5 * 10^{-4}, coefficient of variation for the prefreezing contraction ε_{20-0} = 14 - 26 %, ΔS: uncertainty approximately 1 %).

4. CONCLUSIONS

In SS 13 72 44 it was found that residual length change increased proportionally to the increase of ultrasonic puls transition time. Furthermore, all three mixes suffered internal cracking in SS 13 72 44 both in terms of increased dilation on first freezing (ε_f), dilation below 0 °C ($\varepsilon_{0\text{-}-20}$) and residual dilation (ε_{res}) as well as UPV.

In the test similar to ASTM C671, here called classical dilation test, neither mix 1 with w/c = 0.31 nor mix 2 with w/c = 0.48 did reach their period of frost immunity. A submersion period of 59 days including 6 sealed freeze/thaw cycles was not sufficient to damage these concretes by frost. Mix 3 with w/c = 0.67, on the other hand, very quickly reached critical dilation based on $\varepsilon_{0\text{-}-20}$. The period of frost immunity was only 3 days. UPV was not able to detect internal damage at an early stage even though dilation measurements clearly showed damage.
The durability against internal cracking was equally ranked within the two test methods and five participating institutes when using dilation measurements even though several test details varied. It is recommended that internal cracking in SS 13 72 44 can be detected as UPV. However, residual length change is considered as a better test. UPV is not able to detect permanent frost damage in the form of internal cracking due to self healing. UPV is also less sensitive to internal cracking at a very early stage of frost damage. Self-healing is very likely to take place in the slow classical dilation test were frost damage develops rather slow. In SS 13 72 44 self-healing can take place if the test is delayed after cycling has started, for example due to problems with the freeze/thaw equipment. Only dilation measurement is therefore recommended to detect permanent internal frost damage.

We therefore judge dilation testing for determination of durability against internal cracking by measuring "critical dilation" and "period of frost immunity" as robust and reliable. LVDT and Invar frames should be used for determination of ε_f and $\varepsilon_{20\text{-}0}/\varepsilon_{0\text{-}-20}$, whereas ε_{res} should be measured by hand held gauge in classical dilation test. LVDT-measurements of ε_{res} in SS 13 72 44 should be performed continuously through the cycling without taking off the Invar frames.

5. REFERENCES

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Appendix A Scaling, absorption and UPV in SS 13 72 44

UPV in classical test

Nordtest scaling, liquid uptake and UPV in wet freeze/thaw												Scaling	Absorptio	UPV							
	g											(kg/m2)	(kg/m2)	(m/s)							
	0	7	14	28	42	56	70	84	98	112	-3	0	7	14	28	42	56	70	84	98	112
SCALING																					
AAP mixl																					
2a		4,97	10,25	24,54	1,32	6,42	1,34	1,24	1,38	0,98			0,22	0,68	1,77	1,83	2,11	2,17	2,23	2,29	2,33
2b		5,41	12,71	25,52	23,21	14,66	16,39	15,63	20,93	6,42			0,24	0,81	1,94	2,97	3,62	4,35	5,05	5,98	6,28
10a		5,28	12,52	24,33	24,08	37,98	38,02	7,91	18,88	14,84			0,23	0,78	1,87	2,94	4,63	6,32	6,87	7,51	8,17
15a		6,94	14,67	24,4	23,19	24,07	15,62	6,77	10,51	9,76			0,31	0,96	2,04	3,08	4,15	4,84	5,14	5,61	6,04
AAP I												0,000	0,251	0,808	1,906	2,704	3,627	4,420	4,771	5,346	5,701
VK (%)													18	14	6	22	30	39	39	41	43
AAP mixl																					
14a		0,11	0,06	0,37	0,02	0,03	0,13	0,06	0,04	0,01			0,00	0,01	0,02	0,02	0,03	0,03	0,03	0,04	
14b		0,22	0,23	0,09	0,03	0,04	0,1	0,01	0,05	0,01			0,01	0,02	0,02	0,03	0,03	0,03	0,03	0,03	
6a		0,13	0,14	0,27	0,02	0,12	0,09	0,03	0,07	0,02			0,01	0,01	0,02	0,02	0,03	0,03	0,04	0,04	
7b		0,18	0,26	0,04	0,02	0,01	0,15	0,07	0,11	0,01			0,01	0,02	0,02	0,02	0,02	0,03	0,03	0,04	
AAPII												0,000	0,007	0,016	0,023	0,024	0,027	0,032	0,034	0,037	
VK (%)													31	41	6	6	12	6	5	5	
AAP mixl																					
5a		0,57	0,36	0,44	0,12	0,13	1,35	0,86	3,58				0,03	0,04	0,08	0,07	0,07	0,13	0,17	0,33	
5b		0,37	0,14	0,62	0,13	0,09	1,28	0,92	2,22				0,02	0,02	0,05	0,06	0,06	0,12	0,16	0,26	
2b		0,16	0,24	0,35	0,15	0,08	1,47	0,35	1,37				0,01	0,02	0,03	0,04	0,04	0,11	0,12	0,19	
8b		0,39	0,19	0,41	0,21	0,27	1,98	0,19	0,17				0,02	0,03	0,04	0,05	0,07	0,15	0,18	0,17	
AAPIII												0,00	0,017	0,027	0,047	0,054	0,060	0,128	0,164	0,236	
VK (%)													45	38	24	20	20	15	13	31	

Nordtest scaling, liquid uptake and UPV in wet freeze/thaw												Scaling	Absorptio	UPV				
	g											(kg/m2)	(kg/m2)	(m/s)				
	0	7	14	28	42	56	70	84	98	112	-3	0	7	14	28	42	56	70
LTH mixI																		
4a		1,819	4,608	3,749	3,357	0,867							0,08	0,29	0,45	0,60	0,64	
6b		1,085	3,217	9,284	9,497	8,558							0,05	0,19	0,60	1,03	1,41	
7b		2,434	6,388	3,805	11,287	7,792							0,11	0,39	0,58	1,06	1,41	
11b		1,202	2,957	12,517	20,818	17,824							0,05	0,18	0,74	1,67	2,46	
LTH I												0,000	**0,073**	**0,263**	**0,690**	**1,089**	**1,478**	
VK (%)													38	37	20	40	51	
LTH mixII																		
1a		0	0	0,085	0	0,16							0,00	0,00	0,00	0,00	0,01	
6b		0	0	0,095	0	0,116							0,00	0,00	0,00	0,00	0,01	
9a		0	0	0,151	0	0,047							0,00	0,00	0,01	0,01	0,01	
12b		0	0	0,062	0	0,024							0,00	0,00	0,00	0,00	0,00	
LTH II												0,000	**0,000**	**0,000**	**0,004**	**0,004**	**0,008**	
VK (%)													#DIV/0!	#DIV/0!	38	38	37	
LTH mixII																		
1a		0,171	0,011	0,254	0,298	0,402							0,01	0,01	0,02	0,03	0,05	
1b		1,445	0,304	0,441	0,054	0,098							0,06	0,08	0,10	0,10	0,10	
7b		0,036	0,13	0,168	0	0,081							0,00	0,01	0,01	0,01	0,02	
13b		1,339	0,359	0,232	0	0,055							0,06	0,08	0,09	0,09	0,09	
LTH III												0,00	**0,033**	**0,042**	**0,054**	**0,068**	**0,066**	
VK (%)													100	94	80	70	59	

A2

Nordtest scaling, liquid uptake and UPV in wet freeze/thaw											Scaling	Absorptio	UPV				
	g										(kg/m2)	(kg/m2)	(m/s)				
	0	7	14	28	42	56	70	84	98	112	-3	0	7	14	28	42	56	70
SP mixI																		
7a		2,54	4,72	13,81	18,24	1,37							0,11	0,32	0,93	1,74	1,80	
15b		0,97	0,78	1,7	0,46	0,38							0,04	0,08	0,15	0,17	0,19	
3b		2,49	3,7	10,98	8,12	2,09							0,11	0,28	0,76	1,04	1,13	
9b																		
SP I												0,000	0,089	0,225	0,615	0,982	1,039	
VK (%)													45	58	68	80	78	
SP mixII																		
11a		0,12	0,13	0,29	0,22	0,64							0,01	0,01	0,02	0,03	0,08	
3a		0,11	0,11	0,21	0,38	0,07							0,00	0,01	0,02	0,04	0,04	
2b																		
8b																		
SP II												0,000	0,005	0,010	0,022	0,036	0,051	
VK (%)													6	9	18	5	32	
SP mixIII																		
8a		0,04	0,09	0,53	0,08	0,08							0,00	0,01	0,03	0,03	0,04	
12a		0,05	0,09	0,04	0,02	0,03							0,00	0,01	0,01	0,01	0,01	
4a		0,35	0,19	0,36	0,08	0,01							0,02	0,02	0,04	0,04	0,04	
10b																		
SP III												0,00	0,007	0,012	0,026	0,028	0,030	
VK (%)													120	87	63	62	59	

A3

Nordtest scaling, liquid uptake and UPV in wet freeze/thaw												Scaling	Absorptio	UPV							
	g											(kg/m2)	(kg/m2)	(m/s)							
	0	7	14	28	42	56	70	84	98	112	-3	0	7	14	28	42	56	70	84	98	112
ABSORPT											3d.pres.	kg/m2 incl. water in scaled off mass, assuming that scaled material is mainly cement paste)									
												Wsuc/(Wdry*paste fraction)				mixI = 1.0553/,323=1,164					
																mixII = 1,062/,305=1,203					
AAP mixI																mixIII= 1,078/,288=1,268					
2a	2795,6	2798,7	2794	2786,1	2788,6	2782,9	2782,1	2781,7	2781,9	2780,9	0,36	0,00	0,39	0,72	1,63	1,81	1,89	1,93	1,97	2,05	2,06
2b	2789,5	2791,8	2783,6	2774,9	2756,4	2742,9	2729,7	2716,9	2693,2	2689,5	0,40	0,00	0,38	0,68	1,61	1,99	2,15	2,41	2,65	2,68	2,84
10a	2782,8	2785,9	2778,2	2771,9	2752,5	2717,3	2679,6	2671,2	2653,9	2636,8	0,39	0,00	0,41	0,72	1,70	2,08	2,48	2,77	2,81	3,01	3,02
15a	2778,5	2780,7	2771	2762,1	2743,5	2721,9	2707,4	2703	2692,2	2682,4	0,40	0,00	0,46	0,78	1,65	2,02	2,31	2,47	2,63	2,69	2,76
AAP I											**0,40**	**0,00**	**0,41**	**0,72**	**1,66**	**1,98**	**2,21**	**2,39**	**2,61**	**2,61**	**2,67**
VK (%)											2		8	6	2	6	11	15	15	15	16
AAP mixI																					
14a	2754	2769,2	2782	2791,7	2793,7	2796,8	2797,9	2799,8	2800,4	2800,8	0,90	0,00	0,68	1,25	1,70	1,79	1,93	1,98	2,07	2,10	
14b	2737,7	2754,3	2765	2773,1	2774,9	2778,6	2780,7	2782,9	2782,9	2784,4	0,84	0,00	0,75	1,23	1,60	1,68	1,85	1,94	2,04	2,04	
6a	2728,9	2774,4	2757,3	2765,9	2768,6	2770,8	2773,7	2776	2776,3	2777,7	0,94	0,00	2,03	1,27	1,67	1,79	1,89	2,03	2,13	2,15	
7b	2718,5	2739,2	2750	2756,1	2758,3	2759,8	2763,9	2765,5	2766,8	2767,2	0,98	0,00	0,93	1,42	1,69	1,79	1,86	2,05	2,12	2,19	
AAPII											**0,91**	**0,00**	**1,10**	**1,30**	**1,67**	**1,76**	**1,88**	**2,00**	**2,09**	**2,12**	
VK (%)											6		57	7	3	3	2	2	2	3	
AAP mixI																					
5a	2675,7	2698,5	2704,7	2709,1	2715,4	2720,2	2729,9	2738,8	2737,3		2,46	0,00	1,04	1,33	1,55	1,83	2,05	2,55	2,98	3,08	
5b	2650,7	2675,8	2681,3	2691,1	2697,1	2701,2	2706,8	2719,2	2738,3		2,32	0,00	1,13	1,38	1,85	2,12	2,31	2,62	3,21	4,16	
2b	2672	2697,1	2702,1	2708,6	2715	2715,9	2722,9	2731,5	2732,9		2,34	0,00	1,12	1,36	1,66	1,95	2,00	2,38	2,78	2,90	
8b	2686,9	2708,2	2715,9	2722,6	2729	2729	2735	2742,4	2793,5		2,42	0,00	0,96	1,32	1,63	1,93	1,94	2,30	2,64	4,92	
AAPIII											**2,39**	**0,00**	**1,07**	**1,35**	**1,67**	**1,96**	**2,07**	**2,46**	**2,90**	**3,77**	
VK (%)											3		7	2	8	8	8	6	9	25	

Nordtest dilation: scaling, liquid uptake and UPV in wet freeze/thaw												Scaling	Absorptio	UPV				
		8										(kg/m2)	(kg/m2)	(m/s)				
	-3	0	7	14	28	42	56	70	84	98	112	-3	0	7	14	28	42	56	70
LTH mix I																			
4a	3163,8	3168,6	3171,4	3173,4	3184,6	3187,3	3187,7					0,21	0,00	0,21	0,50	1,16	1,43	1,49	
6b	3089	3093,6	3096	3097,9	3106,7	3106,6	3095,1					0,20	0,00	0,16	0,41	1,29	1,77	1,70	
7b	3071,5	3076,2	3078,2	3077,5	3088,2	3086,2	3079,1					0,21	0,00	0,21	0,51	1,19	1,68	1,77	
11b	3132,2	3136,4	3139,8	3143,6	3150,1	3134,7	3120,5					0,19	0,00	0,21	0,54	1,47	1,86	2,16	
LTH I												0,20	0,00	0,20	0,49	1,31	1,77	1,88	
VK (%)												6		14	11	5	10	8	
LTH mixII																			
1a	3084,1	3095,8	3101,3	3111,4	3126,9	3128,6	3132,3					0,52	0,00	0,24	0,69	1,39	1,46	1,64	
6b	3059,9	3072	3077,1	3086,3	3102,4	3104,8	3109,3					0,54	0,00	0,23	0,64	1,36	1,48	1,67	
9a	2996,7	3007,1	3012,7	3023,7	3041	3044,2	3046,4					0,46	0,00	0,25	0,74	1,51	1,66	1,76	
12b	3032	3043	3049,2	3058,4	3075,3	3078,2	3078,8					0,49	0,00	0,28	0,68	1,44	1,57	1,60	
LTH II												0,50	0,00	0,26	0,69	1,42	1,64	1,66	
VK (%)												7		8	6	5	8	4	
LTH mixIII																			
1a	2886,9	2923,4	2940,3	2951,5	2960	2965,9	2970,1					1,62	0,00	0,76	1,26	1,65	1,93	2,14	
1b	2948,4	2988,4	3009,8	3017	3024,1	3029,6	3034,7					1,78	0,00	1,03	1,37	1,71	1,96	2,19	
7b	2919,8	2961,6	2978	2989,4	2996,1	3000,3	3003,9					1,86	0,00	0,73	1,24	1,55	1,74	1,90	
13b	3005,9	3040,9	3059,4	3069,2	3075,9	3080,1	3083,2					1,56	0,00	0,90	1,35	1,68	1,85	1,89	
LTH III												1,70	0,00	0,86	1,31	1,64	1,87	2,06	
VK (%)												8		16	5	4	5	6	

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Nordtest dilation: scaling, liquid uptake and UPV in wet freeze/thaw													Scaling	Absorptio	UPV				
		g			-								(kg/m2)	(kg/m2)	(m/s)				
	-3	0	7	14	28	42	56	70	84	98	112	-3	0	7	14	28	42	56	70
SP mixI																			
7a	2764,2	2769,3	2770,7	2772,3	2776,7	2764,5	2763,5					0,23	0,00	0,19	0,51	1,41	1,81	1,84	
15b	2758,8	2766,1	2769,4	2772,9	2783,5	2789,5	2791,3					0,32	0,00	0,20	0,39	0,95	1,24	1,34	
3b	2775,3	2780,8	2782,3	2783,9	2790,8	2789,7	2788,1					0,24	0,00	0,20	0,46	1,33	1,60	1,64	
9b	2811,6	2817,5										0,26	0,00						
SP I												0,26	0,00	0,20	0,45	1,23	1,55	1,61	
VK (%)												16		2	12	20	18	15	
SP mixII																			
11a	2706,3	2715	2720,6	2728,6	2743,6	2749,2	2753,1					0,39	0,00	0,26	0,62	1,30	1,56	1,77	
3a	2709,8	2721,1	2725,5	2731,2	2742	2744,5	2745,3					0,50	0,00	0,20	0,46	0,85	1,08	1,12	
2b	2728,4	2739,5	2746	2754,2	2768,2	2773,7	2775,6					0,49	0,00	0,29	0,65	1,28	1,52	1,60	
8b	2731,5	2745,3										0,61	0,00						
SP II												0,50	0,00	0,25	0,58	1,17	1,39	1,50	
VK (%)												18		18	18	17	19	22	
SP mixIII																			
8a	2660,7	2699,4	2716,2	2722,2	2732,7	2734,7	2738					1,72	0,00	0,75	1,02	1,52	1,61	1,76	
12a	2629,2	2667,6	2684,8	2689,3	2700	2702,3	2704,1					1,72	0,00	0,76	0,96	1,44	1,54	1,63	
4a	2614,6	2648,5	2667,8	2672,6	2680,1	2684,3	2685,2					1,51	0,00	0,88	1,10	1,45	1,64	1,68	
10b	2621,8	2657,2										1,57	0,00						
SP III												1,63	0,00	0,79	1,03	1,47	1,60	1,69	
VK (%)												7		9	7	3	3	4	

Nordtest dilation: scaling, liquid uptake and UPV in wet freeze/thaw													Scaling (kg/m2)	Absorptio (kg/m2)	UPV (m/s)				
		0																	
	-3	0	7	14	28	42	56	70	84	98	112	-3	0	7	14	28	42	56	70
UPV													m/s						
		(us)																	
AAP mixI																			
2a		65,75	65,95	67,2	106,3	111,4	100,2	103,4	88,75	82,65	81,3		2281	2274	2232	1411	1346	1497	
2b		65,95	66,2	66,55	107,3	97,85	87,4	97,8	90,6	113,6	107,8		2274	2266	2254	1398	1533	1716	
10a		65,95	66	66,85	88,35	88,75	80	88,95	90,1	92,7	92,05		2274	2273	2244	1698	1690	1875	
15a		65,3	65,3	67,15	99,7	100,4	82,15	102,9	104	105,1	98,1		2297	2297	2234	1505	1494	1826	
AAP I													**2282**	**2278**	**2241**	**1503**	**1616**	**1729**	
VK (%)													0	1	0	9	9	10	
AAP mixII																			
14a		70,15	69,2	70,3	77,3	79	77,9	80,25	81,95	84,95	84,75		2138	2168	2134	1940	1869	1826	
14b		68,9	67,45	70,15	75,65	77,2	77,4	80,35	82,5	84,65	85,05		2177	2224	2138	1983	1943	1938	
6a		69,6	68,3	70,3	78,05	88,5	78,6	83,4	89,8	91,05	90,4		2155	2196	2134	1922	1734	1908	
7b		69,35	68,8	71,05	75,15	78,1	78,55	80,7	83,55	86,65	86,4		2163	2177	2111	1996	1921	1960	
AAPII													**2158**	**2191**	**2129**	**1960**	**1874**	**1933**	
VK (%)													1	1	1	2	5	1	
AAP mixIII																			
5a		70	73,5	87	90,35	106,7	124,2						2143	2041	1724	1660	1406	1208	
5b		65,6	67,05	83,85	106,5	146,9	120,5						2287	2237	1789	1408	1021	1245	
2b		69,8	72,35	85,75	100,1	111,4	124,2						2149	2073	1749	1499	1346	1208	
8b		70	71,55	83,9	94,3	100,6	129,2						2143	2096	1788	1591	1491	1161	
AAPIII													**2180**	**2112**	**1763**	**1639**	**1316**	**1205**	
VK (%)													3	4	2	7	16	3	

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Nordtest dilation: scaling, liquid uptake and UPV in wet freeze/thaw											
	0										
	-3	0	7	14	28	42	56	70	84	98	112
LTH mixI											
4a		44	44,95	45,6	47,2	51,1	49,7				
6b		43,2	43,05	44	57,4	52,8	53				
7b		42,2	43,15	45,6	48	48,7	51,4				
11b		41,85	41,6	42,7	47,85	48,95	47,9				
LTH I											
VK (%)											
LTH mixII											
1a		39,7	39,9	40,8	43,55	45,2	48,7				
6b		39,75	39,55	40,95	43,25	46,65	47,4				
9a		40	40,05	41,3	44,55	49	51,15				
12b		39,5	39,9	41,2	44,15	47,77	49,7				
LTH II											
VK (%)											
LTH mixIII											
1a		44,15	43,95	48	54,7	73,35	82,25				
1b		41,6	43,05	51	52,7	66,35	79				
7b		41,7	43,2	51,5	53,65	71,75	79				
13b		41,4	42,25	48	49,4	61,9	69,5				
LTH III											
VK (%)											

	Scaling	Absorptio	UPV				
	(kg/m2)	(kg/m2)	(m/s)				
-3	0	7	14	28	42	56	70
	3409	3337	3289	3178	2935	3018	
	3472	3484	3408	2813	2841	2830	
	3555	3476	3289	3281	3080	2918	
	3584	3608	3513	3128	3003	3132	
	3605	**3476**	**3376**	**3045**	**2966**	**2976**	
	2	3	3	10	3	4	
	3778	3759	3678	3444	3318	3212	
	3774	3793	3683	3468	3215	3165	
	3750	3745	3632	3387	3081	2833	
	3797	3759	3641	3398	3140	3018	
	3776	**3764**	**3663**	**3419**	**3184**	**3082**	
	1	1	1	1	3	4	
	3398	3413	3125	2742	2045	1824	
	3608	3484	2941	2848	2281	1899	
	3597	3472	2913	2798	2091	1899	
	3623	3550	3281	3038	2423	2158	
	3666	**3480**	**3060**	**2866**	**2206**	**1946**	
	3	2	5	4	8	8	

Nordtest dilation: scaling, liquid uptake and UPV in-wet freeze/thaw												Scaling	Absorptio	UPV				
		0										(kg/m2)	(kg/m2)	(m/s)				
	-3	0	7	14	28	42	56	70	84	98	112	-3	0	7	14	28	42	56	70
UPV																		
Class.																		
VTT mix I																		
1b		33,6	31,85	31,6	32	31,5	31,2						4464	4710	4747	4688	4762	4808	
14a		32,05	31	32	31,05	31,3	30,8						4680	4839	4688	4831	4792	4870	
VTT I													**4572**	**4774**	**4717**	**4759**	**4777**	**4839**	
VK (%)													3	2	1	2	0	1	
VTT II																		
2a		33,85	34,2	32,2	31,8	31,85	31,85						4431	4386	4658	4717	4695	4710	
10b		33,7	35,5	32,45	32,2	31,85	31,8						4451	4225	4622	4658	4710	4717	
VTT II													**4441**	**4306**	**4640**	**4688**	**4702**	**4713**	
VK (%)													0	3	1	1	0	0	
VTT III																		
6b		33,45	33,8	33,75	33,8	34	32,8						4484	4438	4444	4438	4412	4573	
15b		33,6	33,7	35,5	33,95	34,1	34,3						4464	4451	4225	4418	4399	4373	
VTT III													**4474**	**4444**	**4336**	**4428**	**4406**	**4473**	
VK (%)													0	0	4	0	0	3	

Nordtest dilation: scaling, liquid uptake and UPV in wet freeze/thaw													Scaling	Absorptio	UPV				
		g											(kg/m2)	(kg/m2)	(m/s)				
	-3	0	7	14	28	42	56	70	84	98	112	-3	0	7	14	28	42	56	70
SP mixI																			
7a		33,35	33,85	34,8	42,2	42,65	38,9						4498	4431	4310	3555	3517	3759	
15b		33,55	33,55	34,65	37,7	40,4	38,9						4471	4471	4328	3878	3713	3858	
3b		33,55	33,7	35	39,9	39,8	38,4						4471	4451	4288	3759	3759	3806	
9b																			
SP I													4480	4451	4308	3764	3663	3841	
VK (%)													0	0	1	6	4	2	
SP mixII																			
11a		35,15	35,45	36,15	39,05	43,45	44,45						4287	4231	4149	3841	3452	3375	
3a		35,15	35,45	36,45	41	45,6	47,05						4287	4231	4115	3659	3289	3188	
2b		35,6	36,1	36,15	39,4	42,45	43,95						4213	4155	4149	3807	3534	3413	
8b																			
SP II													4249	4206	4138	3769	3426	3326	
VK (%)													1	1	0	3	4	4	
SP mixIII																			
8a		36,75	37,1	46,05	58,45	62,85	79,25						4082	4043	3257	2566	2387	1893	
12a		36,75	37,4	42,35	58	56,15	57,95						4082	4011	3542	2679	2871	2588	
4a		38,25	38,05	45,4	50,8	56,85	74,55						3922	3942	3304	2853	2639	2012	
10b																			
SP III													4028	3999	3368	2733	2666	2164	
VK (%)													2	1	5	7	8	17	

Nordtest dilation: scaling, liquid uptake and UPV in wet freeze/thaw													Scaling	Absorptio	UPV				
		g											(kg/m2)	(kg/m2)	(m/s)				
	-3	0	7	14	28	42	56	70	84	98	112	-3	0	7	14	28	42	56	70
LTH mixI																			
4a		44	44,95	45,6	47,2	51,1	49,7						3409	3337	3289	3178	2835	3018	
6b		43,2	43,05	44	57,4	52,8	53						3472	3484	3409	2813	2841	2830	
7b		42,2	43,15	45,6	48	48,7	51,4						3555	3478	3289	3261	3080	2918	
11b		41,85	41,6	42,7	47,95	49,95	47,9						3584	3608	3513	3128	3003	3132	
LTH I													**3605**	**3476**	**3376**	**3046**	**2966**	**2976**	
VK (%)													2	3	3	10	3	4	
LTH mixII																			
1a		39,7	39,9	40,8	43,55	45,2	46,7						3778	3759	3876	3444	3319	3212	
6b		39,75	39,55	40,95	43,25	46,65	47,4						3774	3793	3863	3468	3215	3165	
9a		40	40,05	41,3	44,55	49	51,15						3750	3745	3632	3387	3081	2833	
12b		39,5	39,9	41,2	44,15	47,77	49,7						3797	3759	3841	3388	3140	3018	
LTH II													**3775**	**3764**	**3653**	**3419**	**3184**	**3082**	
VK (%)													1	1	1	1	3	4	
LTH mixIII																			
1a		44,15	43,95	48	54,7	73,35	82,25						3398	3413	3125	2742	2045	1824	
1b		41,6	43,05	51	52,7	68,35	78						3608	3484	2941	2848	2281	1899	
7b		41,7	43,2	51,5	53,65	71,75	78						3597	3472	2913	2798	2091	1899	
13b		41,4	42,25	46	49,4	61,9	69,5						3623	3550	3261	3038	2423	2158	
LTH III													**3666**	**3480**	**3060**	**2865**	**2205**	**1946**	
VK (%)													3	2	5	4	8	8	

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Appendix B Porosity/PF measured at NBI and AAP, ΔS in classical test

Nordtest Dilation: PF and degree of saturation during test (asuming that only suction pores are filled

		NBI				
		MixI		MixI	MixII	
		I8a	I13b		II13b	II5b
PF	mact 2/7	2733	2747		2690,1	2680,6
	m105 10/7	2640,05	2648,04		2595,21	2585,67
	msuc 10/8	2758,9	2772,8		2740,6	2734,1
	Vol	1112,2	1122,3		1115,1	1114,2
	mpress	2777,8	2792,5		2753,4	2746,6
	mpress/m105	1,052	1,054		1,061	1,062
	ε suc	10,7	11,1	**10,9**	13,0	13,3
	ε air	1,7	1,8	**1,7**	1,1	1,1
	PF	13,7	13,6	**13,7**	8,1	7,8
(ass. ε suc filled)	**S start**	0,863	0,864	**0,863**	0,919	0,922
Weight incr.		I 1a	I 12b		II 9b	II 1b
class.dil.test	før 3d	2758,6	2751,8		2703	2730
	før 1.d/sy	2771,6	2764,3		2731,2	2757,2
	før 7.d/sy	2773,4	2765,2		2736	2761,5
	før 14.d/sy	2777	2770		2738,1	2763,3
	før 28.d/sy	2779,8	2772,3		2739,7	2765,2
	før 42.d/sy	2782,3	2774,9		2740,6	2766
	før 56. d/sy	2783,9	2776,8		2741,6	2766
	ΔS - 3d			0,091		
Vmean=1110	**ΔS 7d**			**0,010**		
	ΔS 14d			**0,040**		
	ΔS 28d			**0,058**		
	ΔS 42d			**0,076**		
	ΔS 56d			**0,088**		
Density	cap.sat	2,481	2,471	**2,476**	2,458	2,454
	dry	2,374	2,359	**2,367**	2,327	2,321
	solid dry			**2,742**		

; and that volume is constant throughout test)

						VTT	
		MixII	Mix III		**Mix III**	MixI	
			III7a	III15a			
PF	mact 2/7		2567,2	2566,7			
	m105 10/7		2492,43	2489,52			
	msuc 10/8		2657	2652			
	Vol		1109,9	1108,7			
	mpress		2681,3	2678,9			
	mpress/m105		1,075	1,076			
	ε suc	**13,2**	14,8	14,7	**14,7**		
	ε air	**1,1**	2,2	2,4	**2,3**		
	PF	**7,9**	12,9	14,2	**13,5**		
(ass. ε suc filled)	**S start**	**0,921**	0,871	0,858	**0,865**		
Weight incr.			III 11b	III3b		I 14a	
class.dil.test	før 3d		2556,6	2602,3			2743,9
	før 1.d/sy		2610,2	2656,4			2752,5
	før 7.d/sy		2614,1	2660,1			2755,9
	før 14.d/sy		2614,4	2660,9			2757,1
	før 28.d/sy		2616,5	2663,6			2759,1
	før 42.d/sy		2617,1	2664,7			2760,9
	før 56. d/sy		2618,5	2665			2762,2
	ΔS - 3d	0,174			0,285		
Vmean=1110	**ΔS 7d**	**0,029**			**0,020**		
	ΔS 14d	**0,041**			**0,023**		
	ΔS 28d	**0,052**			**0,036**		
	ΔS 42d	**0,057**			**0,040**		
	ΔS 56d	**0,060**			**0,045**		
Density	cap.sat	**2,456**	2,394	2,392	**2,393**		
	dry	**2,324**	2,246	2,245	**2,246**		
	solid dry	**2,524**			**2,597**		

Nordtest Dilation: PF and de

			MixI	MixII			**MixII**
PF	mact 2/7						
	m105 10/7						
	msuc 10/8						
	Vol						
	mpress						
	mpress/m105						
	ε suc		**10,9**				**13,2**
	ε air		**1,7**				**1,1**
	PF		**13,7**				**7,9**
(ass. ε suc filled)	**S start**		**0,863**				**0,921**
Weight incr.		I 1b		II 2a		II 10b	
class.dil.test	før 3d	2774,3			2713,5	2725,8	
	før 1.d/sy	2783,1			2727,2	2739,2	
	før 7.d/sy	2786,8			2731,3	2743,5	
	før 14.d/sy	2788			2733,5	2745	
	før 28.d/sy	2789,8			2736	2747,1	
	før 42.d/sy	2791,8			2736,5	2748,2	
	før 56. d/sy	2792,5			2737,3	2749,4	
	ΔS - 3d		0,062				0,097
Vmean=1110	**ΔS 7d**		**0,025**				**0,026**
	ΔS 14d		**0,034**				**0,038**
	ΔS 28d		**0,048**				**0,053**
	ΔS 42d		**0,061**				**0,058**
	ΔS 56d		**0,068**				**0,064**
Density	cap.sat						
	dry						
	solid dry						

Nordtest Dilation: PF and de

		Mix III		**Mix III**
PF	mact 2/7			
	m105 10/7			
	msuc 10/8			
	Vol			
	mpress			
	mpress/m105			
	ε suc			**14,7**
	ε air			**2,3**
	PF			**13,5**
(ass. ε suc filled)	**S start**			**0,865**
Weight incr.		III 6b	III 15b	
class.dil.test	før 3d	2591	2629,3	
	før 1.d/sy	2624	2661,6	
	før 7.d/sy	2626,2	2663,3	
	før 14.d/sy	2627	2664,7	
	før 28.d/sy	2628,5	2665,5	
	før 42.d/sy	2630,2	2667	
	før 56. d/sy	2628,6	2667,7	
	ΔS - 3d			0,233
Vmean=1110	**ΔS 7d**			**0,010**
	ΔS 14d			**0,016**
	ΔS 28d			**0,022**
	ΔS 42d			**0,031**
	ΔS 56d			**0,028**
Density	cap.sat			
	dry			
	solid dry			

SERIE #1

INDLEDNING

Aktivitet	***Dato***	**#1-1**	**#1-2**	**#1-3**	**#1-4**	**#1-5**	**#1-6**	**#1-7**	
NBI-emne nr.		*I-2A*	*I-2B*	*I-10A*	*1-15A*	*1-5B*	*1-10B*	*1-6A*	
Vægt v. afsendelse	17/4	2760,5	2751,7	2745,0	2738,9	2798,2	2764,6	2764,0	
Prover modtages	24/4	⌘	⌘	⌘	⌘	X	X	X	
Vægt v. modtagelse	24/4	2758,3	2749,7	2743,1	2736,9	2796,0	2762,5	2762,0	
Vægtændring v transpoı	24/4	-2,2	-2,0	-1,9	-2,0	-2,2	-2,1	-2,0	
Pålimning af gummi		⌘	⌘	⌘	⌘	-	-	-	
Vægtmåling	16/5	2787,5	2780,4	2774,0	2769,5	-	-	-	
Genmætning	16/5	⌘	⌘	⌘	⌘	-	-	-	
Vægtmåling	19/5	2795,6	2789,5	2782,8	2778,5	-	-	-	
Vægtøgning før frosttesl	19/5	8,1	9,1	8,8	9,0	-	-	-	
Start frost-test	19/5	⌘	⌘	⌘	⌘	-	-	-	
Prøver til porøsitet	19/5	-	-	-	-	X	X	-	
Vandlagring		-	-	-	-	X	X	-	
Vejning	12/5	-	-	-	-	2806	2774	-	
Prøver til trykmætning	12/5	-	-	-	-	X	X	-	
Vejes [mssd]	14/5	-	-	-	-	2814	2782	-	
Vejes under vand [msut	14/5	-	-	-	-	1671	1654	-	
Densitet [kg/m3]	14/5	-	-	-	-	2462	2466	-	
Prøver til udtørring	14/5	-	-	-	-	X	X	-	
Tør prøvevægt [mdry]	15/5	-	-	-	-	2756	2722	-	Middel
Vandindhold [g/gdry]	15/5	-	-	-	-	0,021	0,022	-	0,022
Porøsitet [%]	15/5	-	-	-	-	5,1	5,3	-	

ARBEJDS- & MÅLESKEMA

SERIE #1

Aktivitet	*Dato*	#1-1	#1-2	#1-3	#1-4	#1-7
112 cycler	8/9	⚘	⚘	⚘	⚘	-
Prøve vejes		2780,9	2689,5	2636,8	2682,4	-
Isolering fjernes (saves evt. af)		⚘	⚘	⚘	⚘	-
Prøve vejes		1272	1204	1212	1198	-
Prøve -> vandlagring		⚘	⚘	⚘	⚘	-
Prøve vejes		1280	1214	1222	1208	2784
Prøve -> trykmætning		⚘	⚘	⚘	⚘	-
Prøve vejes [mssd]		1282	1218	1226	1212	2790
Prøve vejes under vand [msub]		752	715	717	710	1654
Densitet (mssd/(mssd-msub))		2,419	2,421	2,409	2,414	2,456
Prøve -> udtørring		⚘	⚘	⚘	⚘	-
Tør prøvevægt [mdry]		1224	1162	1168	1156	2706
Vandindhold [(mssd-mdry)/mdry]		0,047	0,048	0,050	0,048	0,031
Porøsitet [(mssd-mdry)/(mssd-msub)]		0,109	0,111	0,114	0,112 11.2	0,074
Prøve saves i to dele		⚘	⚘	⚘	⚘	-
Prøve -> vakuum		⚘	⚘	⚘	⚘	-
Prøve epoxyimprægneres		⚘	⚘	⚘	⚘	-
Prøve saves		⚘	⚘	⚘	⚘	-
Relativ ændring i passagetid v. 56 cycler		-	-	-	-	-
54Hz, konisk, PARALLEL		1,3	1,3	1,3	1,3	-
54Hz, konisk, VINKELRET		1,2	1,6	1,4	1,5	-
MIDDEL		1,3	1,4	1,4	1,4	-

Prøver #1 - #4 efter frost/tø prøvning	Vandindhold	0,048
	Porøsitet	0,112
Prøve #7, samme alder, men kontinuert vandlagret	Vandindhold	0,031
	Porøsitet	0,074

SERIE #2

INDLEDNING

Aktivitet	*Dato*	#2-1	#2-2	#2-3	#2-4	#2-5	#2-6	#2-7	
NBI-emne nr.		*II-14A*	*II-14B*	*II-6A*	*II-7B*	*II-8A*	*II-10A*	*II-3B*	
Vægt v. afsendelse	17/4	2722,9	2705,9	2697,4	2684,9	2724,4	2719,1	2691,7	
Prøver modtages	24/4	✻	✻	✻	✻	X	X	X	
Vægt v. modtagelse	24/4	2720,9	2703,8	2695,4	2682,9	2722,3	2717,1	2689,7	
Vægtændring v transpoı	24/4	-2,0	-2,1	-2,0	-2,0	-2,1	-2,0	-2,0	
Pålimning af gummi		✻	✻	✻	✻	-	-	-	
Vægtmåling	17/5	2733,7	2718,8	2707,8	2696,5	-	-	-	
Genmætning	17/5	✻	✻	✻	✻	-	-	-	
Vægtmåling	20/5	2754,0	2737,7	2728,9	2718,5	-	-	-	
Vægtøgning før frosttest	20/5	20,3	18,9	21,1	22,0	-	-	-	
Start frost-test	20/5	✻	✻	✻	✻	-	-	-	
Prøver til porøsitet	20/5	-	-	-	-	X	X	-	
Vandlagring		-	-	-	-	X	X	-	
Vejning	12/5	-	-	-	-	2740	2732	-	
Prøver til trykmætning	12/5	-	-	-	-	X	X	-	
Vejes [mssd]	14/5	-	-	-	-	0.5 2748	2742 0.6	-	
Vejes under vand [msuk	14/5	-	-	-	-	1612	1614	-	
Densitet [kg/m3]	14/5	-	-	-	-	2419	2431	-	
Prøver til udtørring	14/5	-	-	-	-	X	X	-	
Tør prøvevægt [mdry]	15/5	-	-	-	-	2654	2656	-	Middel
Vandindhold [g/gdry]	15/5	-	-	-	-	0,035	0,032	-	0,034
Porøsitet [%]	15/5	-	-	-	-	8,3	7,6	-	

ARBEJDS- & MÅLESKEMA

SERIE #2

Aktivitet	*Dato*	#2-1	#2-2	#2-3	#2-4	#2-7
112 cycler	9/9	⚘	⚘	⚘	⚘	-
Prøve vejes		2800,8	2784,4	2777,7	2767,2	-
Isolering fjernes (saves evt. af)		⚘	⚘	⚘	⚘	-
Prøve vejes		1736	1754	1754	1690	
Prøve -> vandlagring		⚘	⚘	⚘	⚘	-
Prøve vejes		1752	1768	1770	1706	2714
Prøve -> trykmætning		⚘	⚘	⚘	⚘	-
Prøve vejes [mssd]		1756	1774	1774	1710	2720
Prøve vejes under vand [msub]		1024	1033	1031	993	1595
Densitet (mssd/(mssd-msub))		2,399	2,394	2,388	2,385	2,418
Prøve -> udtørring		⚘	⚘	⚘	⚘	-
Tør prøvevægt [mdry]		1666	1682	1680	1618	2588
Vandindhold [(mssd-mdry)/mdry]		0,054	0,055	0,056	0,057	0,051
Porøsitet [(mssd-mdry)/(mssd-msub)]		0,123	0,124	0,127	0,128 12.6	0,117
Prøve saves i to dele		⚘	⚘	⚘	⚘	-
Prøve -> vakuum		⚘	⚘	⚘	⚘	-
Prøve epoxyimprægneres		⚘	⚘	⚘	⚘	-
Prøve saves		⚘	⚘	⚘	⚘	-
Relativ ændring i passagetid v. 56 cycler		-	-	-	-	-
54Hz, konisk, PARALLEL		1,2	1,2	1,3	1,2	-
54Hz, konisk, VINKELRET		1,2	1,2	1,2	1,2	-
MIDDEL		1,2	1,2	1,3	1,2	-

Prøver #1 - #4 efter frost/tø prøvning	Vandindhold	0,056
	Porøsitet	0,126
Prøve #7, samme alder, men kontinuert vandlagret	Vandindhold	0,051
	Porøsitet	0,117

SERIE #3

INDLEDNING

Aktivitet	*Dato*	#3-1	#3-2	#3-3	#3-4	#3-5	#3-6	#3-7	
NBI-emne nr.		*III-5A*	*III-5B*	*III-2B*	*III-8B*	*III-6A*	*III-9A*	*III-14A*	
Vægt v. afsendelse	17/4	2623,2	2601,9	2618,9	2632,7	2648,0	2616,6	2569,0	
Prover modtages	24/4	※	※	※	※	X	X	X	
Vægt v. modtagelse	24/4	2621,2	2599,8	2616,9	2630,7	2645,8	2614,6	2566,9	
Vægtændring v transpoı	24/4	-2,0	-2,1	-2,0	-2,0	-2,2	-2,0	-2,1	
Pålimning af gummi		※	※	※	※	-	-	-	
Vægtmåling	18/5	2620,3	2598,4	2619,4	3632,5	-	-	-	
Genmætning	18/5	※	※	※	※	-	-	-	
Vægtmåling	21/5					-	-	-	
Vægtøgning før frosttest	21/5	-2620,3	-2598,4	-2619,4	-3632,5	-	-	-	
Start frost-test	21/5	※	※	※	※	-	-	-	
Prøver til porositet	21/5	-	-	-	-	X	X	-	
Vandlagring		-	-	-	-	X	X	-	
Vejning	12/5	-	-	-	-	2678	2648	-	
Prøver til trykmætning	12/5	-	-	-	-	X	X	-	
Vejes [mssd]	14/5	-	-	-	10/1559 = 0.6	2688	2658	11/1543 = 0.65	
Vejes under vand [msuł	14/5	-	-	-		1559	1543		
Densitet [kg/m3]	14/5	-	-	-	-	2381	2384	-	
Prøver til udtørring	14/5	-	-	-	-	X	X	-	
Tør prøvevægt [mdry]	15/5	-	-	-	-	2566	2532	-	Middel
Vandindhold [g/gdry]	15/5	-	-	-	-	0,048	0,050	-	0,049
Porositet [%]	15/5	-	-	-	-	10,8	11,3	-	

ARBEJDS- & MÅLESKEMA

SERIE #3

Aktivitet	*Dato*	#3-1	#3-2	#3-3	#3-4	#3-7
112 cycler	10/9	⚘	⚘	⚘	⚘	-
Prøve vejes		2737,3	2738,3	2732,9	2793,5	-
Isolering fjernes (saves evt. af)		⚘	⚘	⚘	⚘	-
Prøve vejes						-
Prøve -> vandlagring		⚘	⚘	⚘	⚘	-
Prøve vejes						2602
Prøve -> trykmætning		⚘	⚘	⚘	⚘	-
Prøve vejes [mssd]						2612
Prøve vejes under vand [msub]						1512
Densitet (mssd/(mssd-msub))		FEJL	FEJL	FEJL	FEJL	2,375
Prøve -> udtørring		⚘	⚘	⚘	⚘	-
Tør prøvevægt [mdry]						2442
Vandindhold [(mssd-mdry)/mdry]		FEJL	FEJL	FEJL	FEJL	0,070
Porøsitet [(mssd-mdry)/(mssd-msub)]		FEJL	FEJL	FEJL	FEJL	0,155
Prøve saves i to dele		⚘	⚘	⚘	⚘	-
Prøve -> vakuum		⚘	⚘	⚘	⚘	-
Prøve epoxyimprægneres		⚘	⚘	⚘	⚘	-
Prøve saves		⚘	⚘	⚘	⚘	-
Relativ ændring i passagetid v. 56 cycler		-	-	-	-	-
54Hz, konisk, PARALLEL		FEJL	FEJL	FEJL	FEJL	-
54Hz, konisk, VINKELRET		FEJL	FEJL	FEJL	FEJL	-
MIDDEL		FEJL	FEJL	FEJL	FEJL	-

Prøver #1 - #4 efter frost/tø prøvning	Vandindhold	n.a.
	Porøsitet	n.a.
Prøve #7, samme alder, men kontinuert vandlagret	Vandindhold	0,07
	Porøsitet	0,155

Appendix C Dilation data

Dilation x 10 -4	Cy.	**VTT Mix 1** freez	VTT Mix 1 20-0	VTT Mix 1 0--20	VTT Mix 1 res	Σres	VTT **Mix 2** freez	VTT Mix 2 20-0	VTT Mix 2 0--20	VTT Mix 2 res	Σres	VTT **Mix 3** freez	VTT Mix 3 20-0	VTT Mix 3 0--20	VTT Mix 3 res	Σres
	1		-1,8	-1,7	0,3	0,3		-3,5	-2,6	0,6	0,6		-2,6	-2,2	0,6	0,6
	2															
	3															
	4															
	5															
	6															
	7							-2,7	-2,6	0,6	1,2		-3,3	-1,5	0,9	1,5
	8															
	9															
	10															
	11															
	12															
	13															
	14		-3,6	-1,3	0,2	0,5							-4,4	-1,9	0,9	2,4
	15															
	16															
	17															
	18															
	19															
	20															
	21															
	22															
	23															
	24															
	25															
	26															
	27															
	28		-4,9	-2,3	0	0,5		-3,6	-2,6	0,3	1,5		-4,1	0,4	0,8	3,2
	29															
	30															
	31															
	32															
	33															
	34															
	35															
	36															
	37															
	38															
	39															
	40															
	41															
	42		-4,9	-1,4	0,4	0,9		-3,6	-2,3	0,5	2					
	43															
	44															
	45															
	46															
	47															
	48															
	49															
	50															
	51															
	52															
	53															
	54															
	55															
	56		-3,2	-3,3	0	0,9		-3,3	-2,6	0,5	2,5		-3	0,5	1,6	4,8

Dilation x 10 -4	Cy.	**NBI Mix 1** freez	NBI Mix 1 20-0	NBI Mix 1 0--20	NBI Mix 1 res	Σres	**NBI Mix 2** freez	NBI Mix 2 20-0	NBI Mix 2 0--20	NBI Mix 2 res	Σres	**NBI Mix 3** freez	NBI Mix 3 20-0	NBI Mix 3 0--20	NBI Mix 3 res	Σres
	1	0	-2,9	-2,4	0,04	0,04	0	-3	-3	0,4	0,4	0,1	-3	-2,7	0,2	0,2
	2															
	3															
	4															
	5															
	6															
	7	0	-3,4	-3	-0,2	-0,2	0	-3,3	-2,9	0,1	0,5	0,2	-3,1	-1,9	0,3	0,5
	8															
	9															
	10															
	11															
	12															
	13															
	14						0	-3,7	-2,7	0,1	0,6	0,4	-3,4	-0,8	0,4	0,9
	15															
	16															
	17															
	18															
	19															
	20															
	21															
	22															
	23															
	24															
	25															
	26															
	27															
	28						0	-4,3	-2,9	-0,2	0,4	0,5	-3,4	-0,8	0,3	1,2
	29															
	30															
	31															
	32															
	33															
	34															
	35															
	36															
	37															
	38															
	39															
	40															
	41															
	42	0	-4	-2,5	-4,1	-4,3	0,1	-4,9	-3,1	-0,7	-0,3	0,8	-4,1	-0,5	-0,3	0,9
	43															
	44															
	45															
	46															
	47															
	48															
	49															
	50															
	51															
	52															
	53															
	54															
	55															
	56	0	-4	-2,6	-0,4	-4,7	0,1	-5	-3,3	-1,1	-1,4	1	-4	-0,4	0,2	1,1

Dilation x 10 -4

Cy.	**LTH Mix 1** freez	LTH Mix 1 20-0	LTH Mix 1 0--20	LTH Mix 1 res	Σres	LTH **Mix 2** freez	LTH Mix 2 20-0	LTH Mix 2 0--20	LTH Mix 2 res	Σres	LTH **Mix 3** freez	LTH Mix 3 20-0	LTH Mix 3 0--20	LTH Mix 3 res	Σres
1	-0,3	-3,7	-2,7	-2	-2	-0,2	-3,7	-1,6	0,7	0,7	-0,4	-3,7	-1,8	0,1	0,1
2															
3															
4															
5															
6															
7						-0,5	-3,5	-1,3	0,2	0,9	0,3	-3,5	0,5	0,9	1
8															
9															
10															
11															
12															
13															
14	-0,1	-2	-0,9	2,2	0,2	-0,2	-3,1	-0,9	1,8	2,7	1,9	-4	3,9	1,4	2,4
15															
16															
17															
18															
19															
20															
21															
22															
23															
24															
25															
26															
27															
28	0	-5,4	0,9	-1	-0,8	2	-2,5	2,9	0	2,7	2,7	-3,2	4,9	2,2	4,6
29															
30															
31															
32															
33															
34															
35															
36															
37															
38															
39															
40															
41															
42	0,6	-3	0,2	0,9	0,1	1,6	-3,6	2,6	0,3	3	4,1	-3,8	5,5	0,6	5,2
43															
44															
45															
46															
47															
48															
49															
50															
51															
52															
53															
54															
55															
56	0,2	-3,1	-0,4	1,1	1,2	1,5	-2,8	2,8	1,1	4,1	3,3	-3,9	8,3	1,4	6,6

Dilation
x 10 -4

Cy.	**SP Mix 1** freez	SP Mix 1 20-0	SP Mix 1 0--20	SP Mix 1 res	SP Mix 1 Σres	**SP Mix 2** freez	SP Mix 2 20-0	SP Mix 2 0--20	SP Mix 2 res	SP Mix 2 Σres	**SP Mix 3** freez	SP Mix 3 20-0	SP Mix 3 0--20	SP Mix 3 res	SP Mix 3 Σres
1				-0,6	-0,6				-0,3	-0,3	0	-4,6	-1,5	-0,2	-0,1
2					-0,9					-0,7					
3					-1,2										
4															-0,1
5															0
6					-1,4										0,13
7				-0,4	-1,6				-0,3	-0,1	0	-4,6	-0,1	0,41	0,55
8					-1,7					0,53					0,8
9					-1,6					0,81					1,7
10					-1,5					1,11					2,29
11					-1,4					1,35					
12					-1,3										3,67
13										2,05					4,27
14	-0,1	-4,1	-0,7	-0,4	-0,9				-0,3	2,4	0	-3,9	1,1	1	4,85
15					-0,7					2,98					5,6
16					-0,3					3,59					6,15
17					0,13					4,09					6,75
18					0,62					4,78					7,24
19					1,2					5,37					7,73
20					1,83					6,08					8,15
21					2,44					6,76					8,6
22					3,1					7,38					9,21
23					3,74					8,12					9,64
24					4,39					8,74					9,99
25					5,02					9,4					10,3
26					5,57					10,1					10,6
27					6,09					10,6					10,9
28	0	-3,7	-0,1	-0,5	6,51				0,57	11,3	0	-4	1	0,6	11,2
29					6,96					11,8					11,5
30					7,25					12,2					
31					7,64										
32															13
33										12,8					13,3
34					8,61					13,1					13,7
35					8,72					13,1					14
36					8,79					13,2					14,3
37					8,86					13,3					14,5
38					8,87					13,5					
39					8,96										14,9
40										13,9					14,8
41					9,04					14					14,9
42				0	9,04				-0,5	14,2	0	-3,6	1,4	0,8	15
43					8,94					14,4					15,4
44					8,85					14,7					15,7
45					8,93					14,9					15,9
46					8,99					15,2					16,1
47					8,95					15,6					16,2
48					9					15,6					16,5
49					8,93					16					16,4
50					9,15					16,2					16,5
51					9,15					16,3					
52					9,09										
53															16,6
54															16,6
55					9,23					16,2					16,6
56	0	-4,4	-1,5	-0,1	9,19				0	16,2	0	-3,6	1,5	0	16,6

Dilation
x 10 -4

Cy.	**AAP Mix1 res**	AAP Mix1 Σres	**AAP Mix2 res**	AAP Mix2 Σres	**AAP Mix3 res**	AAP Mix3 Σres
1						
2						
3						
4						
5						
6						
7		0,8		1,4		4,1
8						
9						
10						
11						
12						
13						
14		3,1		6,4		16
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						
25						
26						
27						
28		25,8		17,6		29,9
29						
30						
31						
32						
33						
34						
35						
36						
37						
38						
39						
40						
41						
42		37,6		25		43,2
43						
44						
45						
46						
47						
48						
49						
50						
51						
52						
53						
54						
55						
56		47,3		32,6		51

	Mix 1	Mix 2	Mix 3
1	-0,6	-0,3	-0,1
2	-0,9	-0,7	
3	-1,2		
4			-0,1
5			0
6	-1,4		0,13
7	-1,6	-0,1	0,55
8	-1,7	0,53	0,8
9	-1,6	0,81	1,7
10	-1,5	1,11	2,29
11	-1,4	1,35	
12	-1,3		3,67
13		2,05	4,27
14	-0,9	2,4	4,85
15	-0,7	2,98	5,6
16	-0,3	3,59	6,15
17	0,13	4,09	6,75
18	0,62	4,78	7,24
19	1,2	5,37	7,73
20	1,83	6,08	8,15
21	2,44	6,76	8,6
22	3,1	7,38	9,21
23	3,74	8,12	9,64
24	4,39	8,74	9,99
25	5,02	9,4	10,3
26	5,57	10,1	10,6
27	6,09	10,6	10,9
28	6,51	11,3	11,2
29	6,96	11,8	11,5
30	7,25	12,2	
31	7,64		
32			13
33		12,8	13,3
34	8,61	13,1	13,7
35	8,72	13,1	14
36	8,79	13,2	14,3
37	8,86	13,3	14,5
38	8,87	13,5	
39	8,96		14,9
40		13,9	14,8
41	9,04	14	14,9
42	9,04	14,2	15
43	8,94	14,4	15,4
44	8,85	14,7	15,7
45	8,93	14,9	15,9
46	8,99	15,2	16,1
47	8,95	15,6	16,2
48	9	15,6	16,5
49	8,93	16	16,4
50	9,15	16,2	16,5
51	9,15	16,3	
52	9,09		
53			16,6
54			16,6
55	9,23	16,2	16,6
56	9,19	16,2	16,6

Continuous dilation in SS 137244 (SP)

Summary of the Dilation Test Results - Length Change in mm

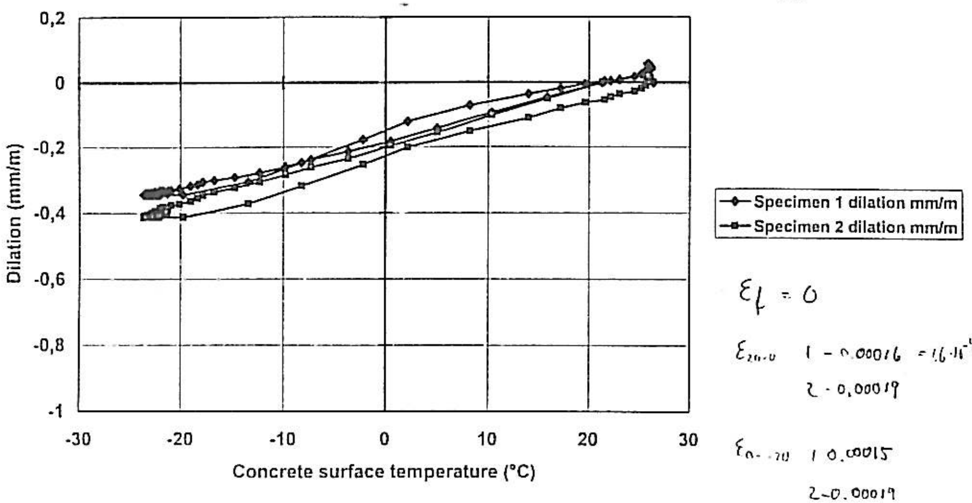
	I-3B	I-9B		II-2B	II-8B		III-4A	III-10B	
	ΔL	ΔL	ΣΔL	ΔL	ΔL	ΣΔL	ΔL	ΔL	ΣΔL
Cycle 1	**-0,0763**	**-0,0096**	**-0,0096**	**-0,0210**	**-0,0069**	**-0,0069**	**-0,0086**	**-0,0013**	**-0,0013**
Cycle 2		-0,0046	-0,0142		-0,0031	-0,0100			
Cycle 3		-0,0033	-0,0175						
Cycle 4								-0,0006	-0,0019
Cycle 5								0,0013	-0,0006
Cycle 6		-0,0036	-0,0211					0,0025	0,0019
Cycle 7	**-0,0080**	**-0,0033**	**-0,0244**	**-0,0030**	**-0,0017**	**-0,0017**	**0,0059**	**0,0063**	**0,0082**
Cycle 8		-0,0005	-0,0249		0,0097	0,0080		0,0038	0,0120
Cycle 9		0,0016	-0,0232		0,0043	0,0122		0,0135	0,0255
Cycle 10		0,0004	-0,0228		0,0044	0,0166		0,0089	0,0344
Cycle 11		0,0013	-0,0215		0,0037	0,0203			
Cycle 12		0,0021	-0,0194					0,0206	0,0550
Cycle 13					0,0105	0,0307		0,0091	0,0641
Cycle 14	**0,0072**	**0,0062**	**-0,0132**	**-0,0092**	**0,0052**	**0,0360**	**0,0193**	**0,0096**	**0,0738**
Cycle 15		0,0032	-0,0099		0,0087	0,0447		0,0103	0,0840
Cycle 16		0,0053	-0,0046		0,0091	0,0538		0,0082	0,0922
Cycle 17		0,0064	0,0019		0,0075	0,0613		0,0090	0,1012
Cycle 18		0,0074	0,0093		0,0104	0,0717		0,0074	0,1086
Cycle 19		0,0087	0,0180		0,0089	0,0805		0,0074	0,1160
Cycle 20		0,0094	0,0274		0,0106	0,0912		0,0062	0,1222
Cycle 21		0,0092	0,0366		0,0102	0,1014		0,0068	0,1290
Cycle 22		0,0093	0,0459		0,0093	0,1107		0,0092	0,1381
Cycle 23		0,0102	0,0561		0,0111	0,1218		0,0064	0,1446
Cycle 24		0,0096	0,0657		0,0093	0,1311		0,0053	0,1499
Cycle 25		0,0096	0,0753		0,0100	0,1411		0,0049	0,1548
Cycle 26		0,0084	0,0836		0,0100	0,1511		0,0038	0,1586
Cycle 27		0,0076	0,0913		0,0075	0,1586		0,0044	0,1630
Cycle 28	**0,0096**	**0,0063**	**0,0976**	**-0,0022**	**0,0107**	**0,1693**	**-0,0183**	**0,0047**	**0,1677**
Cycle 29		0,0068	0,1044		0,0072	0,1765		0,0054	0,1731
Cycle 30		0,0044	0,1087		0,0070	0,1835			
Cycle 31		0,0059	0,1146						
Cycle 32								0,0221	0,1951
Cycle 33					0,0089	0,1924		0,0044	0,1996
Cycle 34		0,0146	0,1292		0,0034	0,1958		0,0053	0,2049
Cycle 35		0,0015	0,1308		0,0007	0,1965		0,0049	0,2098
Cycle 36		0,0011	0,1318		0,0008	0,1973		0,0041	0,2139
Cycle 37		0,0011	0,1329		0,0026	0,1999		0,0039	0,2178
Cycle 38		0,0001	0,1331		0,0031	0,2031			
Cycle 39		0,0013	0,1344					0,0058	0,2236
Cycle 40					0,0059	0,2089		-0,0010	0,2225
Cycle 41		0,0012	0,1356		0,0018	0,2107		0,0010	0,2235
Cycle 42	**0,0004**	**0,0000**	**0,1356**	**-0,0097**	**0,0018**	**0,2126**	**-0,0119**	**0,0011**	**0,2246**
Cycle 43		-0,0014	0,1341		0,0038	0,2164		0,0071	0,2316
Cycle 44		-0,0013	0,1328		0,0038	0,2201		0,0042	0,2358
Cycle 45		0,0011	0,1340		0,0034	0,2236		0,0022	0,2380
Cycle 46		0,0009	0,1348		0,0050	0,2286		0,0032	0,2413
Cycle 47		-0,0005	0,1343		0,0047	0,2333		0,0013	0,2425
Cycle 48		0,0007	0,1350		0,0012	0,2346		0,0046	0,2472
Cycle 49		-0,0012	0,1339		0,0056	0,2402		-0,0014	0,2457
Cycle 50		0,0033	0,1372		0,0028	0,2430		0,0017	0,2475
Cycle 51		0,0002	0,1373		0,0013	0,2443			
Cycle 52		-0,0010	0,1363						
Cycle 53								0,0011	0,2486
Cycle 54					0,0008	0,2450		-0,0001	0,2485
Cycle 55		0,0022	0,1385		-0,0016	0,2434		0,0001	0,2486
Cycle 56	**-0,0013**	**-0,0007**	**0,1378**	**0,0001**	**-0,0002**	**0,2432**	**-0,0083**	**0,0000**	**0,2485**

Appendix D Dilation curves

VTT	4 pages	(pages 1 – 4)
NBI	4 pages	(pages 5 – 8)
LTH	5 pages	(pages 9 – 13)
SP	16 pages	(pages 14 – 30)

Chart Betongyta

MIX 1. 1st cycle. Deformation as a function of concrete surface temperature



$\varepsilon_f = 0$

ε_{20-0} 1 − 0.00016 = 1.6·10⁻⁴
2 − 0.00019

ε_{0--20} 1 0.00015
2 − 0.00019

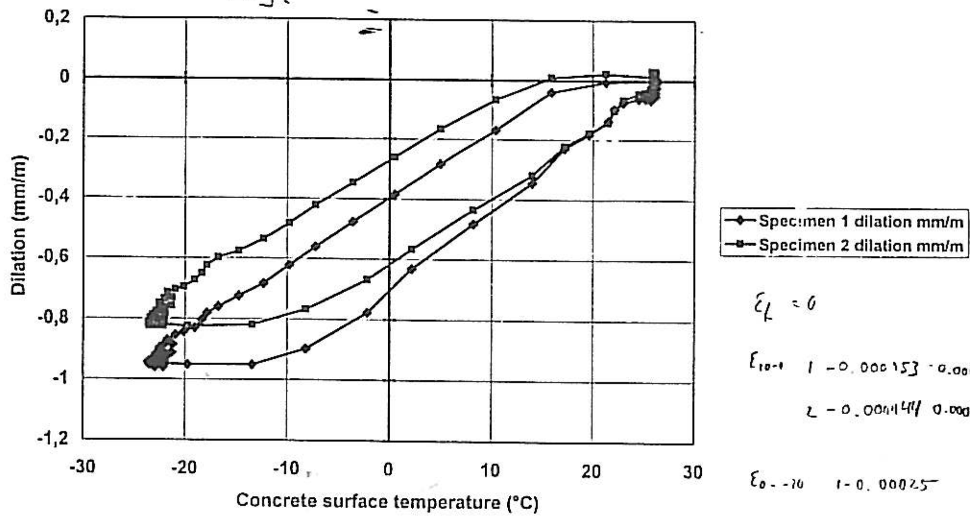
ε_{res} 1 + 0.053
2 + 0.018

Page 1

Chart Betongyta

MIX 1. Deformation as a function of concrete surface temperature

28cy.



$\varepsilon_f = 0$

ε_{10-0} 1 − 0.000153 · 0.00053
2 − 0.000144 0.00044

ε_{0--20} 1 − 0.00025
2 − 0.00071

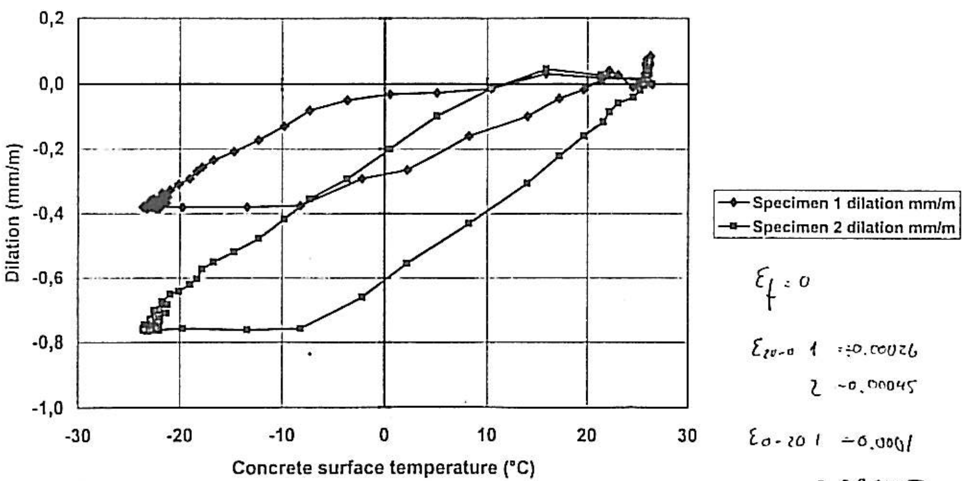
ε_{res} 1, 2 ~ 0

Page 1

D1

Chart Betongyta

MIX 1. 14th cycle. Deformation as a function of concrete surface temperature



$\varepsilon_f = 0$

ε_{20-0} 1 = −0.00026
2 − 0.00045

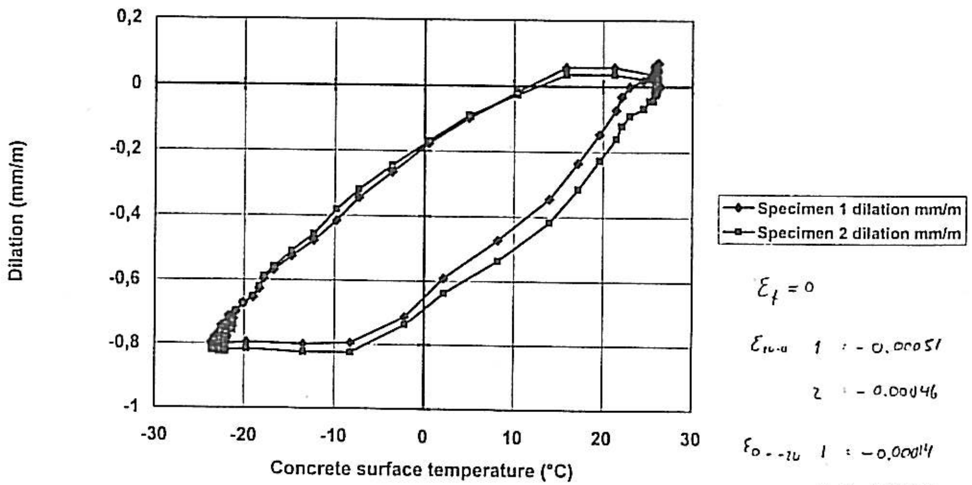
ε_{0-20} 1 − 0.0001
2 − 0.00015

ε_{res} 1 − 0
...

Page 1

Chart Betongyta

MIX 1. 42nd cycle. Deformation as a function of concrete surface temperature



$\varepsilon_f = 0$

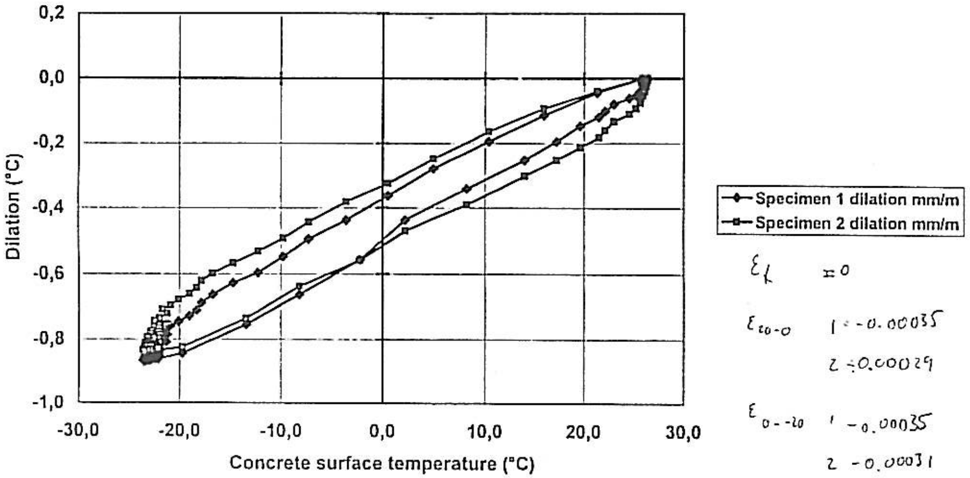
ε_{20-0} 1 − 0.00051
2 − 0.00046

ε_{0--20} 1 − 0.00014
2 − 0.00015

ε_{res} 1 + ...
...

Page 1

MIX 1. 56th cycle. Deformation as a function of concrete surface temperature



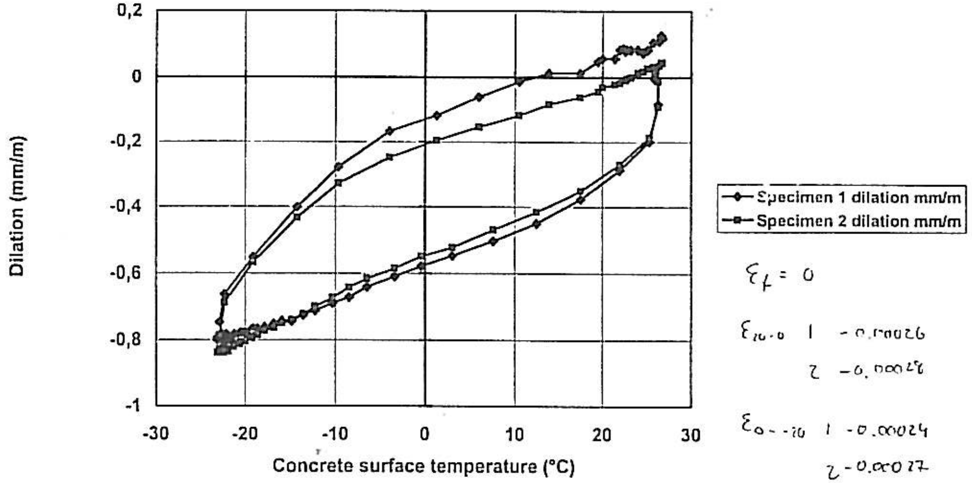
ε_f = 0

ε_{20-0} 1 -0.00035
2 -0.00029

ε_{0--20} 1 -0.00035
2 -0.00031

ε_{res} 1 ~0
2 ~0

MIX 2. 7th cycle. Deformation as a function of concrete surface temperature



ε_f = 0

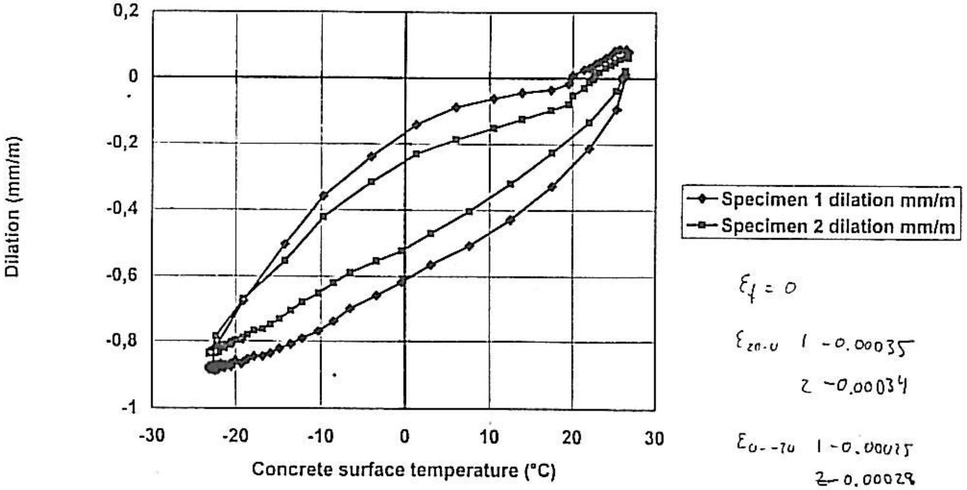
ε_{20-0} 1 -0.00026
2 -0.00028

ε_{0--20} 1 -0.00024
2 -0.00027

ε_{res} 1 +0.00008
2 +0.000031

D2

MIX 2. 1 st cycle. Deformation as a function of concrete surface temperature



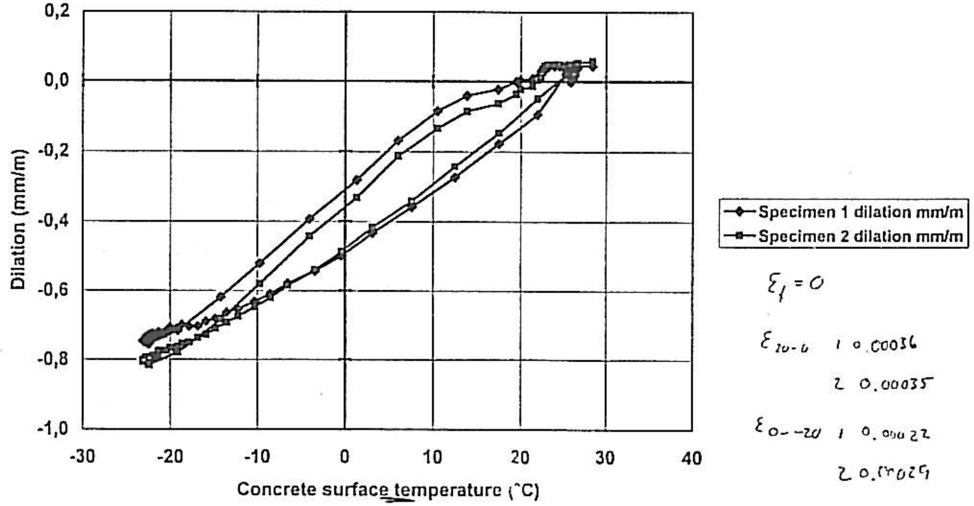
ε_f = 0

ε_{20-0} 1 -0.00035
2 -0.00034

ε_{0--20} 1 -0.00025
2 -0.00028

ε_{res} 1 +0.00075

MIX 2. 28th cycle. Deformation as a function of concrete surface temperature



ε_f = 0

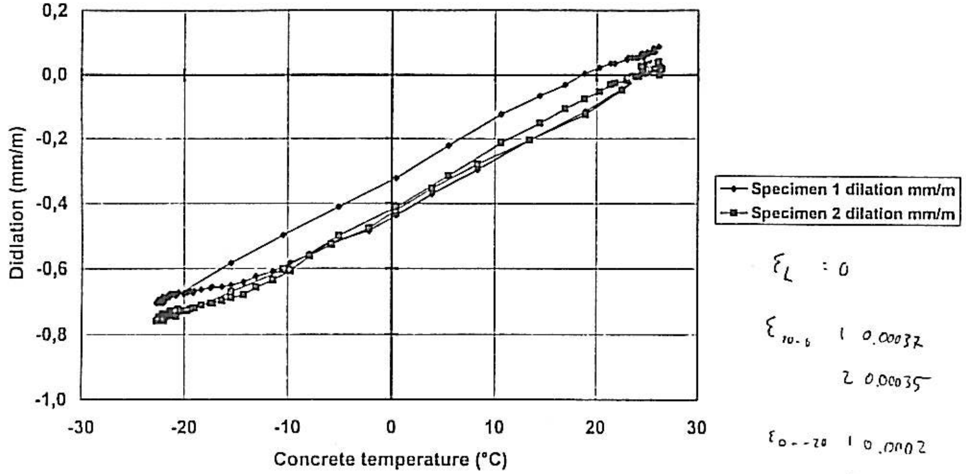
ε_{20-0} 1 0.00036
2 0.00035

ε_{0--20} 1 0.00022
2 0.00029

ε_{res} 1 +0.000012
2 +0.000044

Chart Betongyta

MIX 2. 42nd cycle. Deformation as a function of concrete surface temperature



ε_L : 0

ε_{20-0} 1 0.00032
2 0.00035

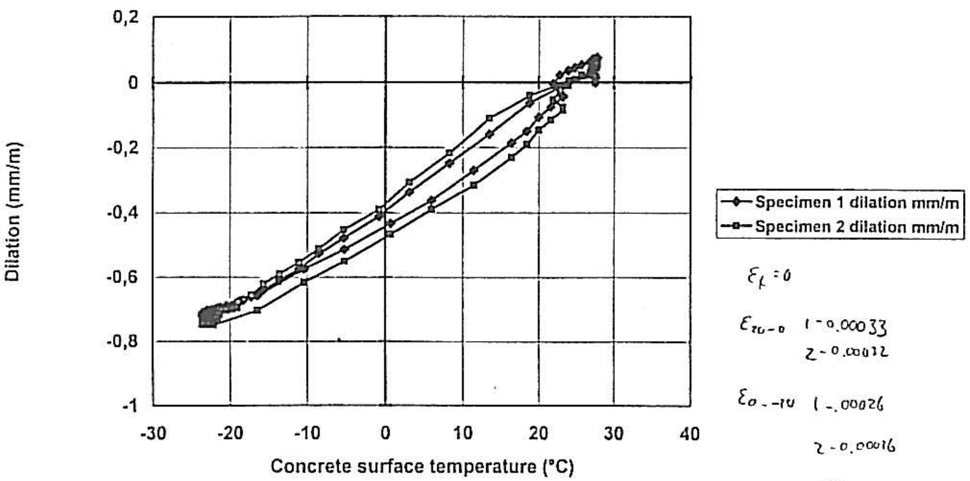
ε_{0--20} 1 0.0002
2 0.00026

ε_{res} 1 0.00006
2 0.00004

Page 1

Chart Betongyta

MIX 2. 56th cycle. Deformation as a function of concrete surface temperature



ε_L = 0

ε_{20-0} 1 -0.00033
2 -0.00032

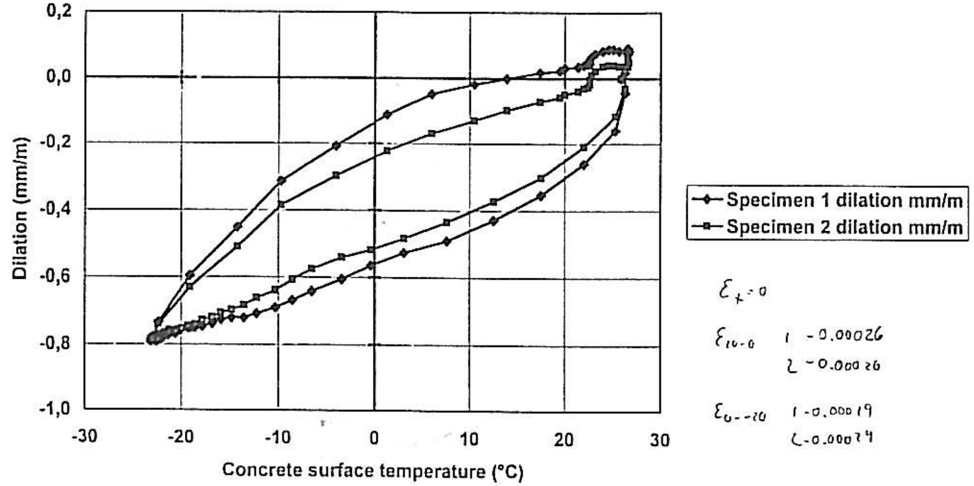
ε_{0--20} 1 -.00026
2 -0.00016

ε_{res} 1 +0.00004
2 +0.00005

Page 1

Chart Betongyts

MIX 3. 1st cycle. Deformation as a function of concrete surface temperature



ε_L = 0

ε_{20-0} 1 -0.00026
2 -0.00026

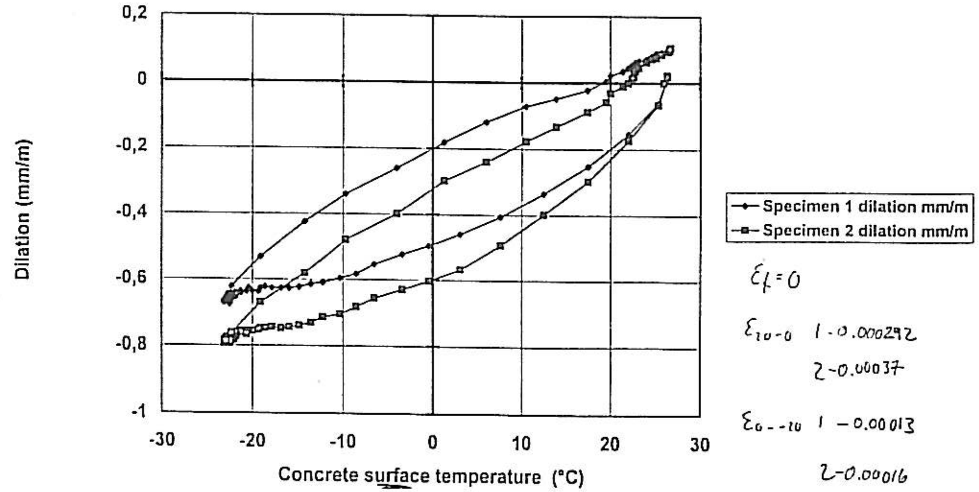
ε_{0--20} 1 -0.00019
2 -0.00024

ε_{res} 1 +0.00008
2 +0.00004

Page 1

Chart Betongyta

MIX 3. 7th cycle. Deformation as a function of concrete surface temperature



ε_L = 0

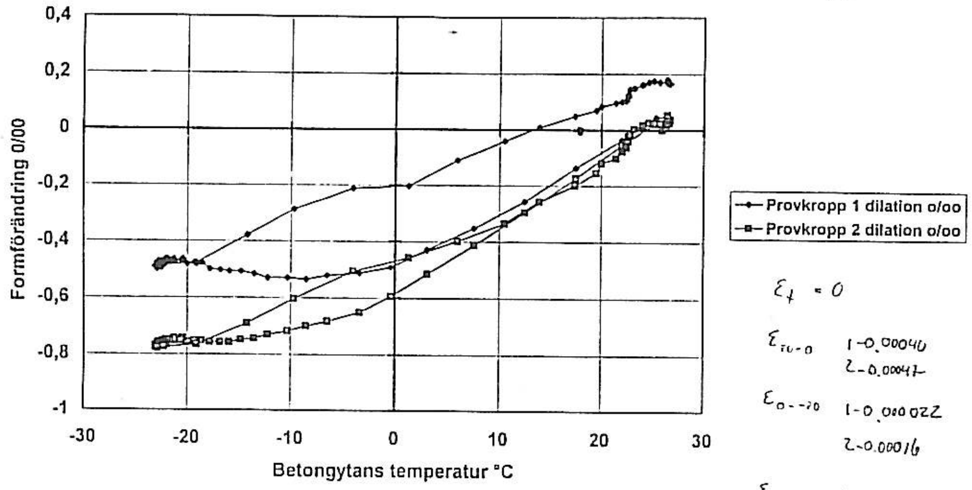
ε_{20-0} 1 -0.000292
2 -0.00037

ε_{0--20} 1 -0.00013
2 -0.00016

ε_{res} 1 +0.00009

Page 1

MIX 3. 14 cykeln. Formförändring som funktion av betongytans temperatur



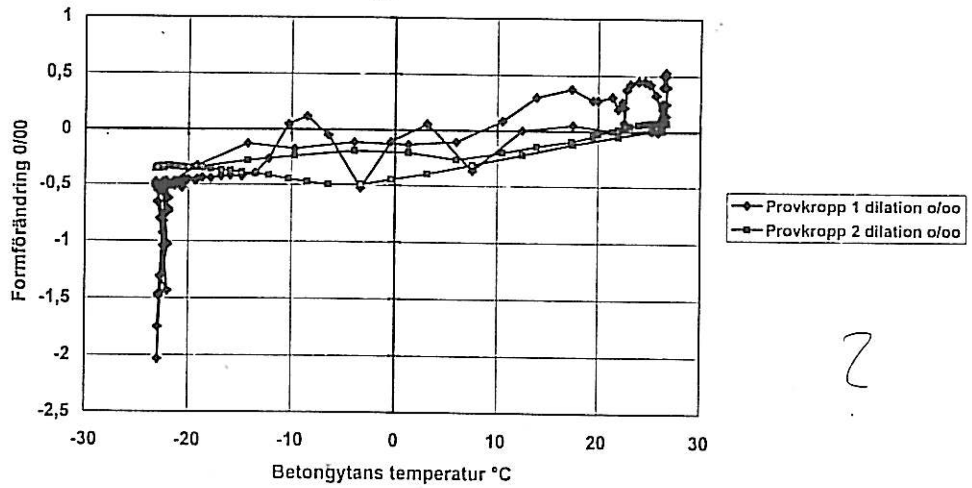
$\varepsilon_t = 0$

ε_{10-0} 1 -0.00040
2 -0.00047

ε_{0--20} 1 -0.000022
2 -0.00016

ε_{ks} 1 +0.00013
2 +0.00005

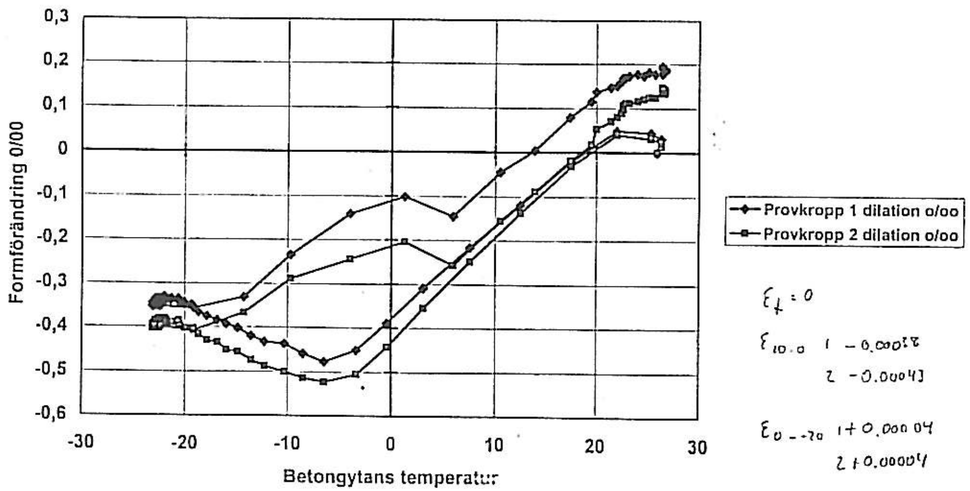
MIX 3. 42 cykeln. Formförändring som funktion av betongytans temperatur



2

D4

MIX 3. 28 Cykeln. formförändring som funktion av betongytans temperatur



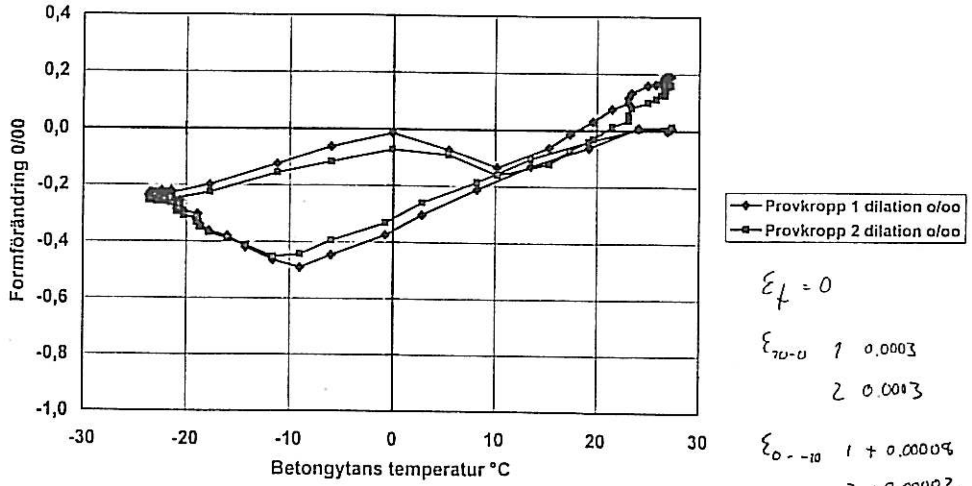
$\varepsilon_t = 0$

ε_{10-0} 1 -0.00038
2 -0.00043

ε_{0--20} 1 +0.00004
2 +0.00004

ε_{ks} 1 +0.000019
2 +0.00014

MIX 3. 56 cykeln. Formförändring som funktion av betongytans temperatur



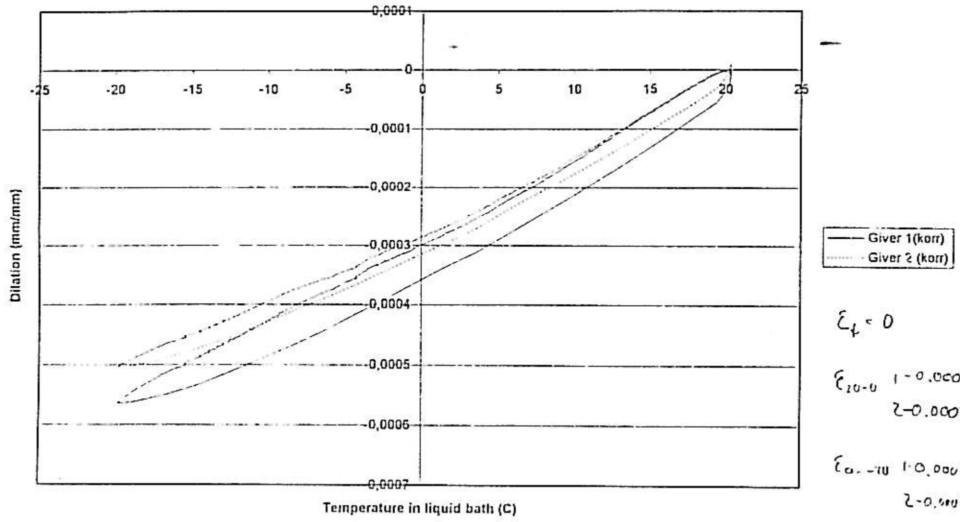
$\varepsilon_t = 0$

ε_{10-0} 1 0.0003
2 0.0003

ε_{0--10} 1 +0.00008
2 +0.00002

ε_{KS} 1 +0.00018
2 +0.00014

Mix 1 - 1. cycle



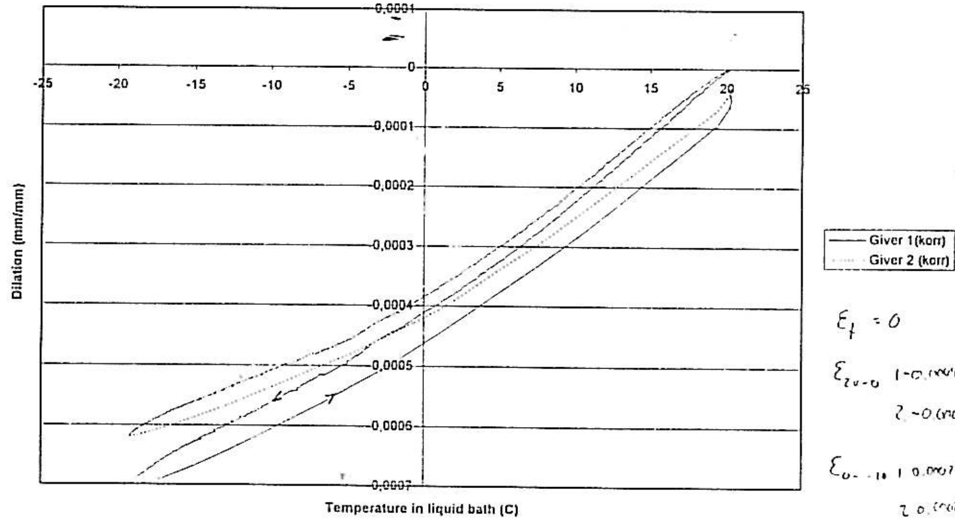
$\varepsilon_t = 0$

ε_{20-0} 1-0.00028
2-0.00030

ε_{0--20} 1-0.00078
2-0.00020

ε_{res} 1 -3.2·10^{-8}
2 7.6·10^{-6}

Mix 1 - 42. cycle



$\varepsilon_t = 0$

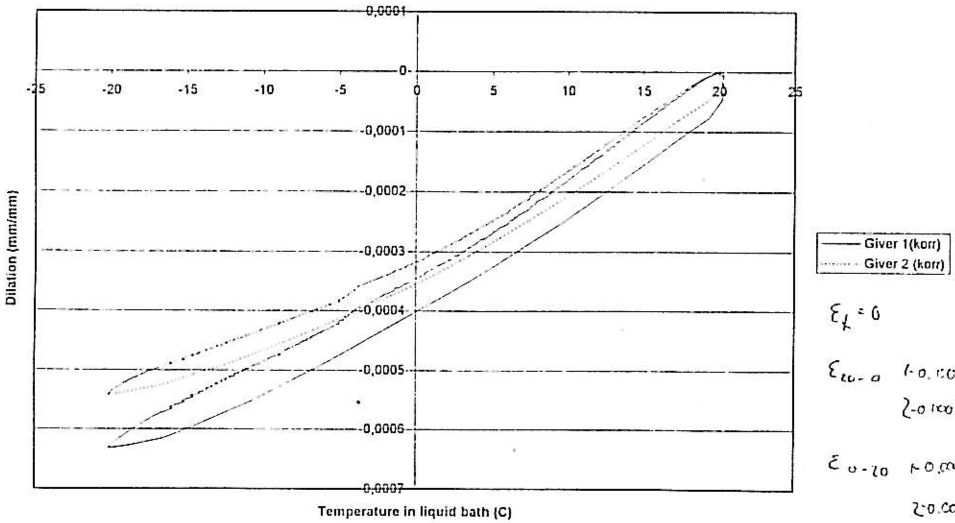
ε_{20-0} 1-0.00041
2-0.00038

ε_{0--10} 1 0.00079
2 0.00020

ε_{res} 1-0.000046
2-3.5·10^{-5}

D5

Mix 1 - 7. cycle



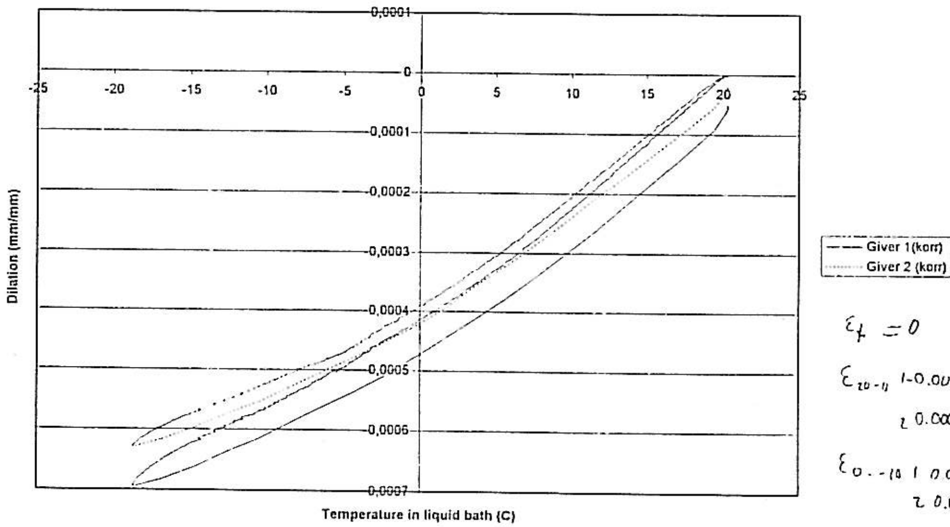
$\varepsilon_t = 0$

ε_{20-0} 1-0.00035
2-0.00032

ε_{0-20} 1-0.0028
2-0.00032

$\bar{\varepsilon}_{res}$ 1 -3.6·10^{-5}
2 -1.3·10^{-6}

Mix 1 - 56 cycle



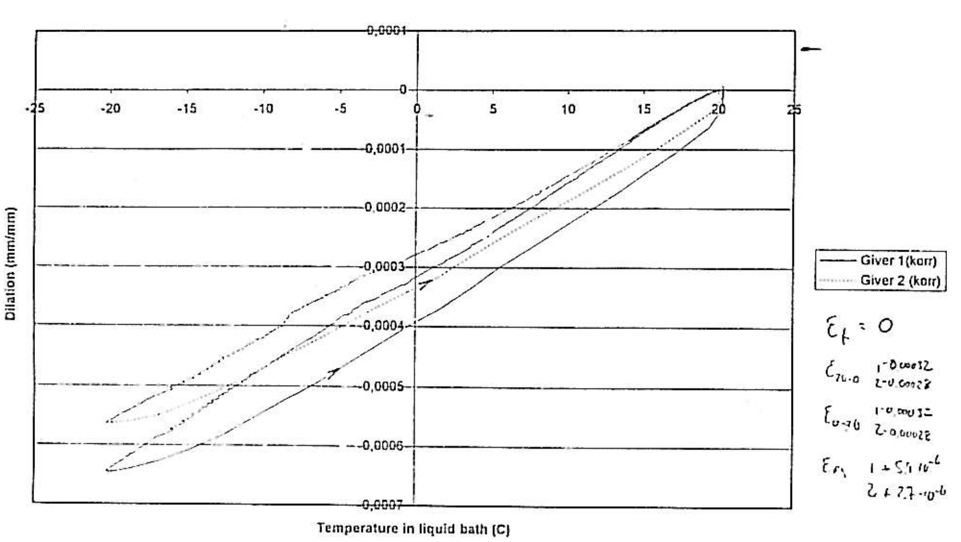
$\varepsilon_t = 0$

ε_{20-0} 1-0.00041
2 0.00039

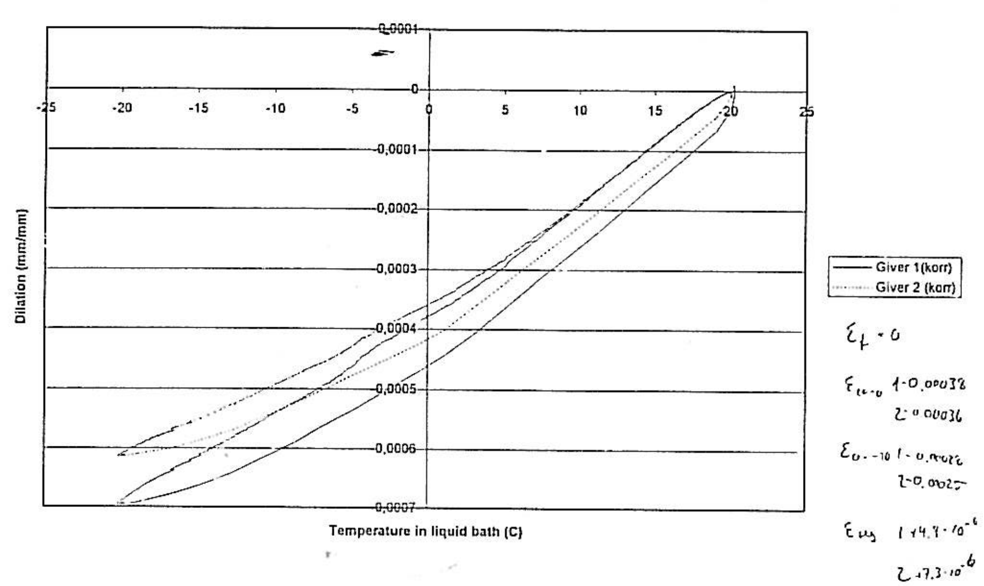
ε_{0--10} 1 0.00016
2 0.00024

ε_{res} 1 -5.2·10^{-5}
2 -2.4·10^{-5}

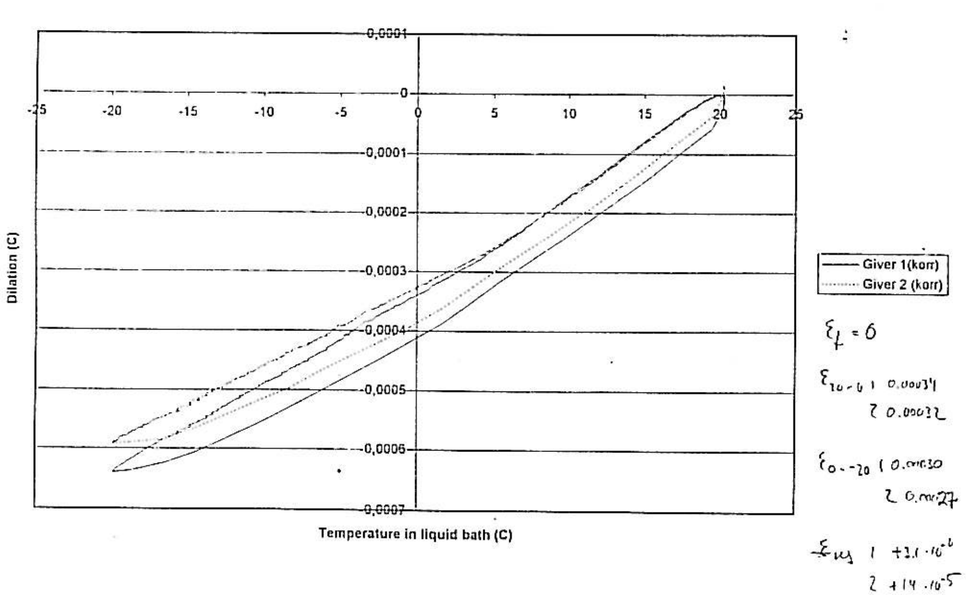
Mix 2 - 1. cycle



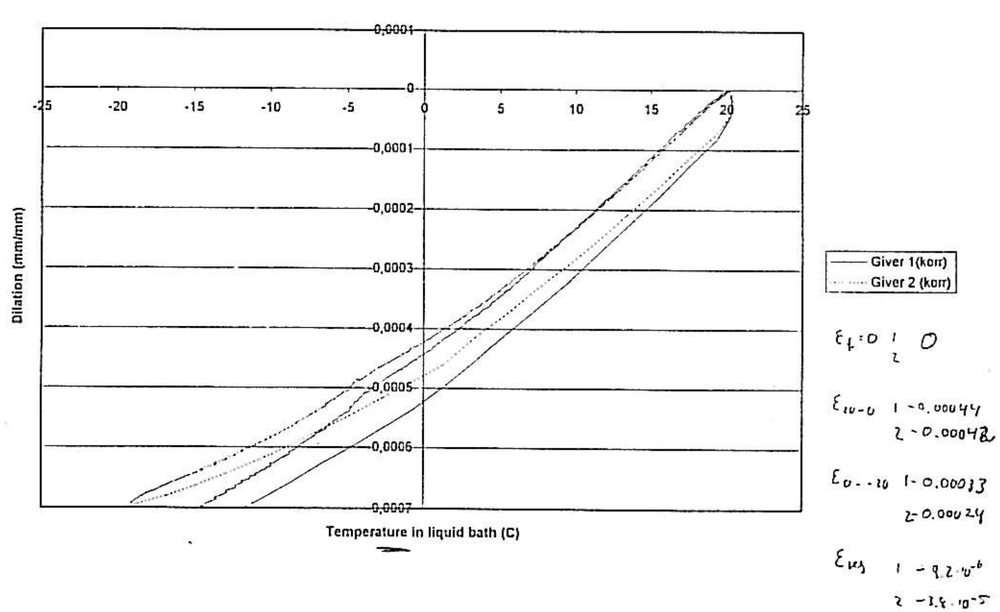
Mix 2 - 14. cycle



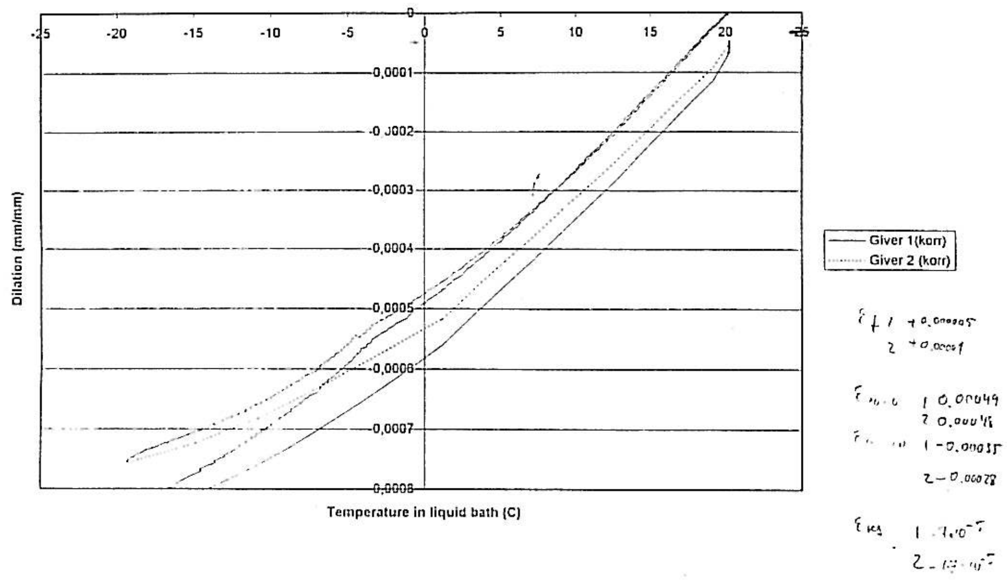
Mix 2 - 7 cycle



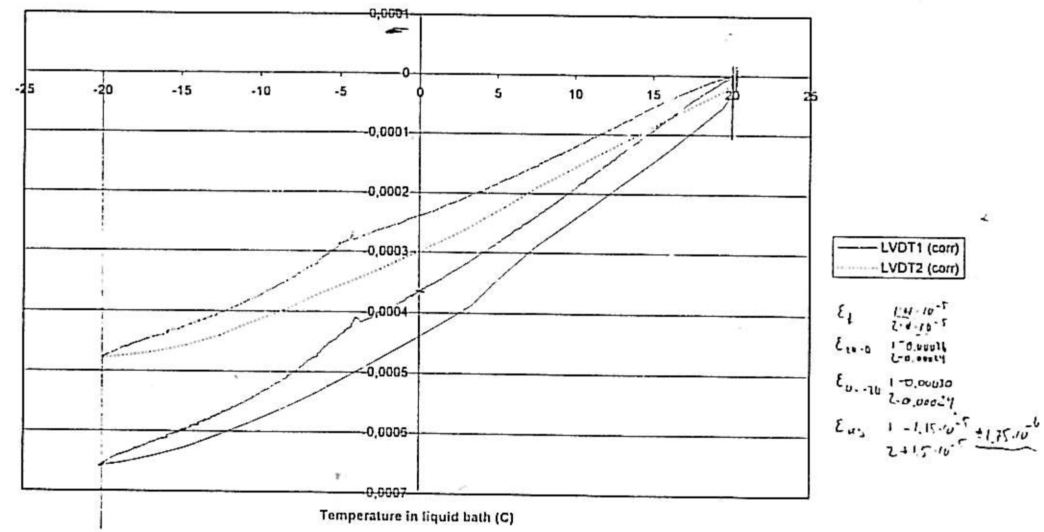
Mix 2 - 28. cycle



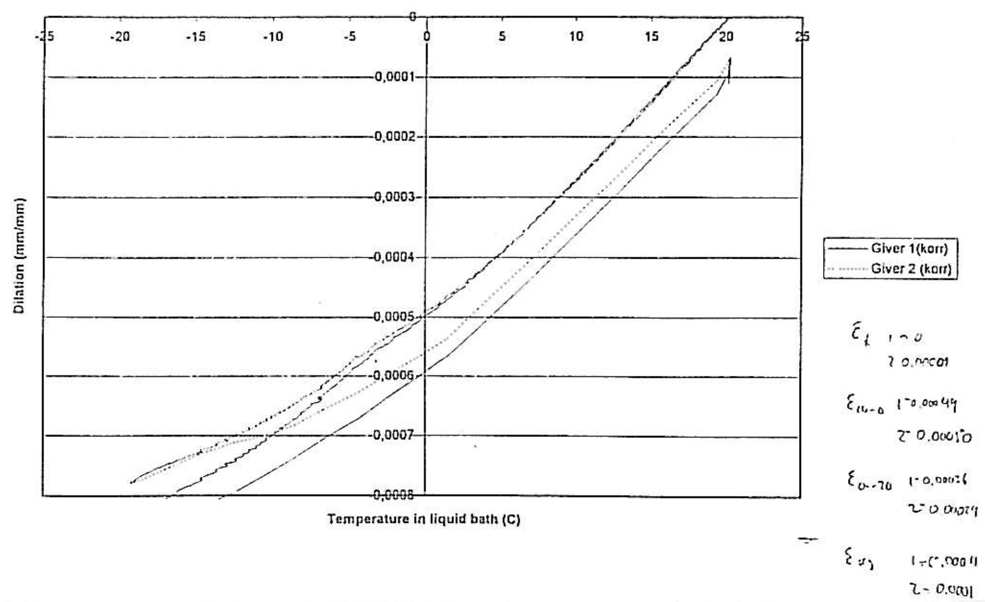
Mix 2 - 42. cycle



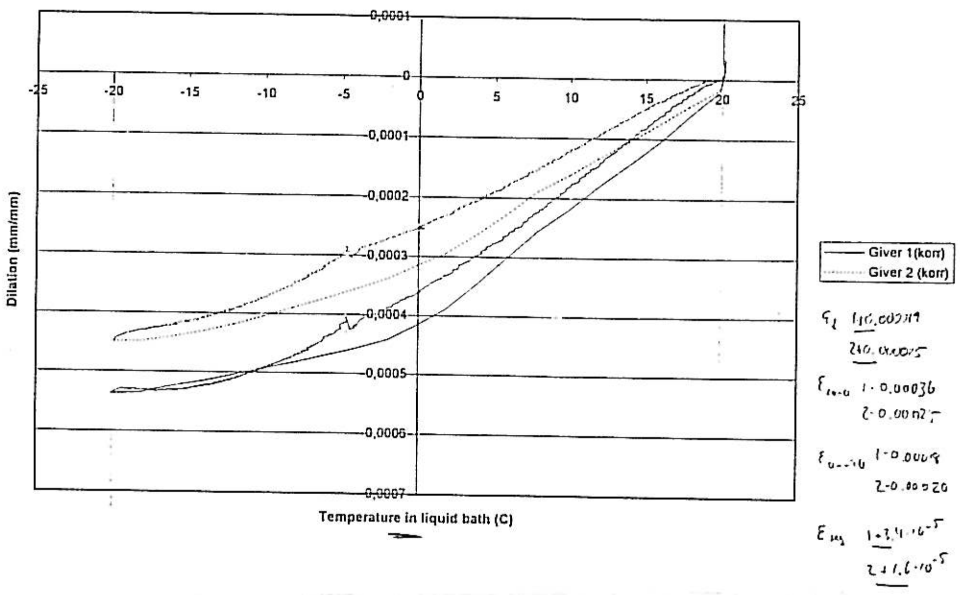
Mix 3 - 1. Freezing

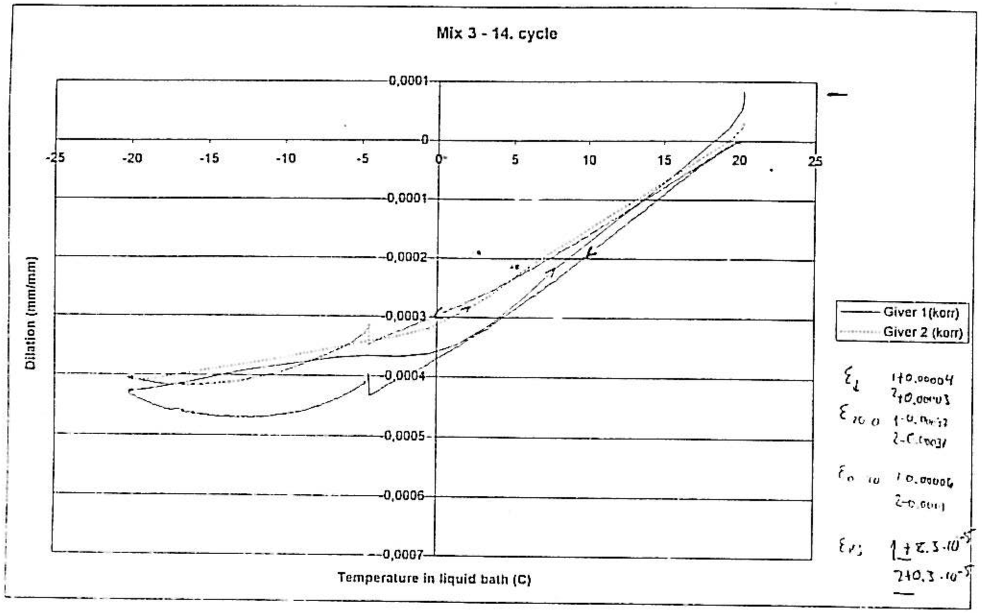


Mix 2 - 56. cycle

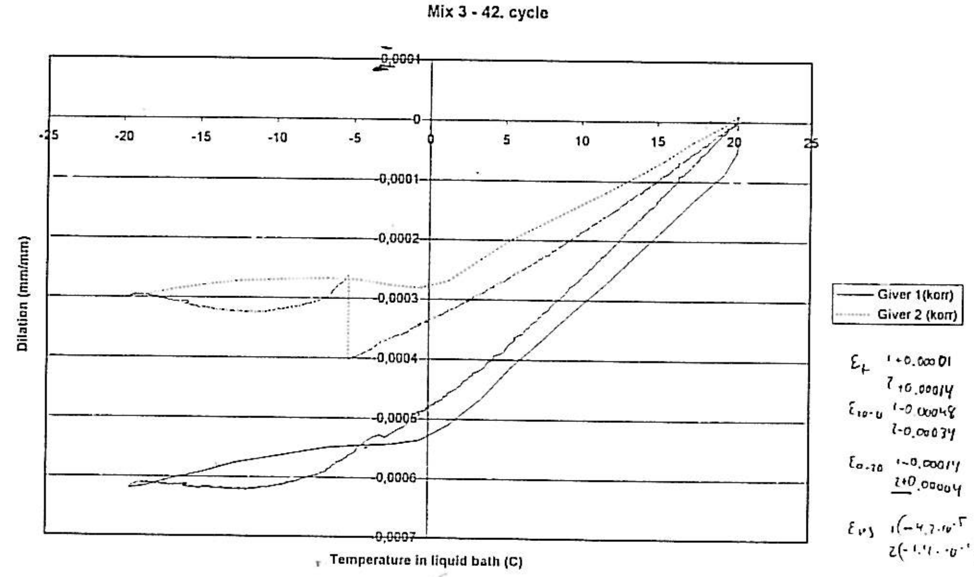


Mix 3 - 7th cycle

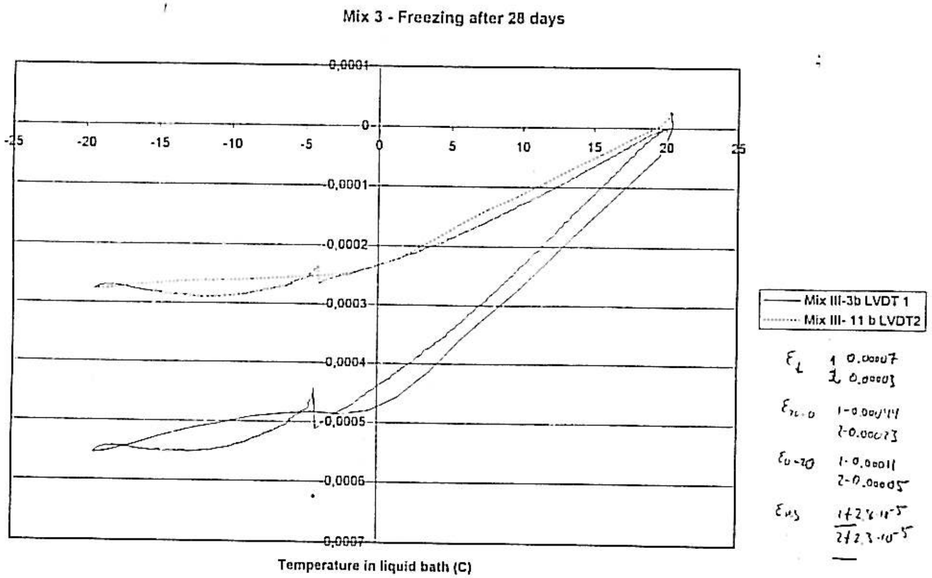




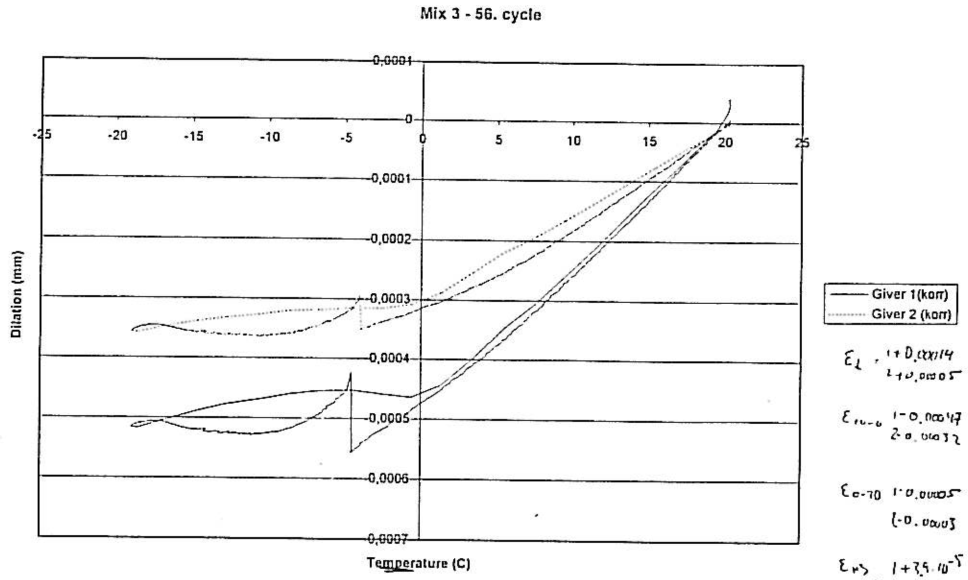
ε_L 1 +0.00004, 2 +0.00003
ε_{20-0} 1 -0.00032, 2 -0.00031
ε_{0-20} 1 0.00006, 2 -0.0001
ε_{rs} 1 +2.3·10^-5, 2 +0.3·10^-5



ε_L 1 +0.00001, 2 +0.00014
ε_{20-0} 1 -0.00048, 2 -0.00034
ε_{0-20} 1 -0.00014, 2 +0.00004
ε_{rs} 1 (-4.7·10^-5, 2 (-1.1·10^-5)

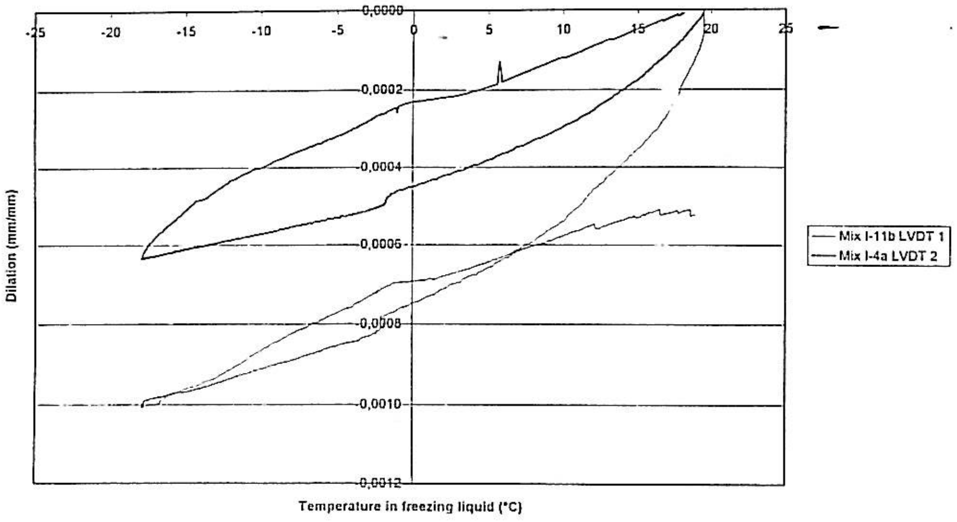


ε_L 1 0.00007, 2 0.00003
ε_{20-0} 1 -0.00044, 2 -0.00023
ε_{0-20} 1 -0.00011, 2 -0.00005
ε_{rs} 1 +2.8·10^-5, 2 +2.3·10^-5

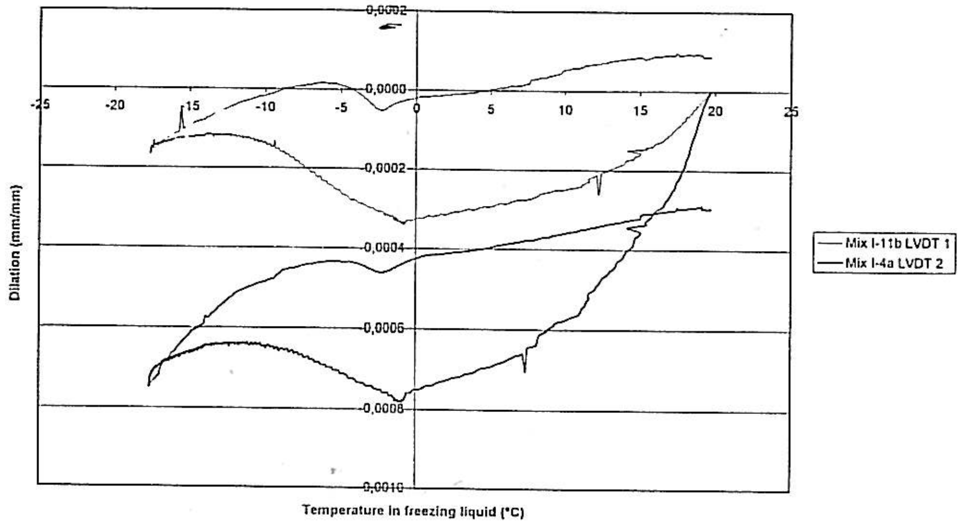


ε_L 1 +0.00014, 2 +0.00005
ε_{20-0} 1 -0.00047, 2 -0.00032
ε_{0-20} 1 -0.00005, 2 -0.00003
ε_{rs} 1 +3.5·10^-5, 2 -6·10^-6

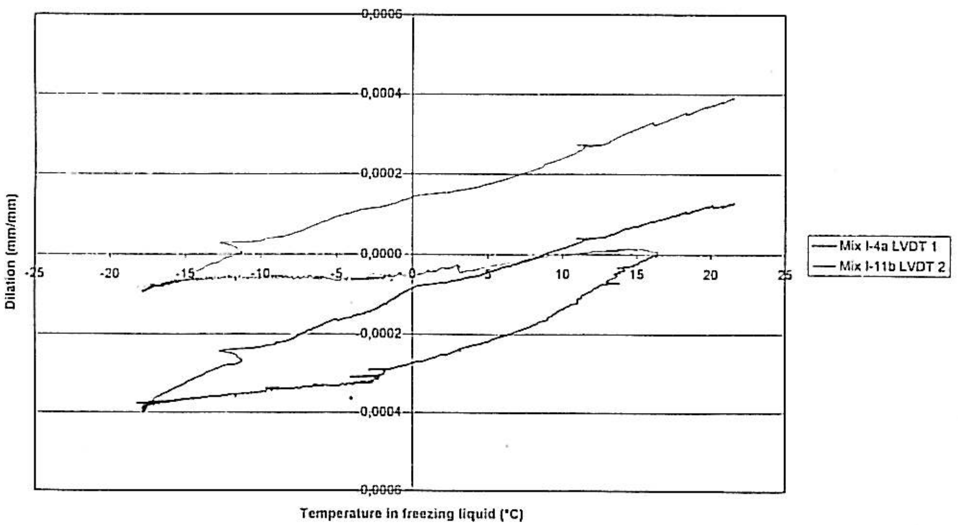
Mix 1 - Freezing after 1 day



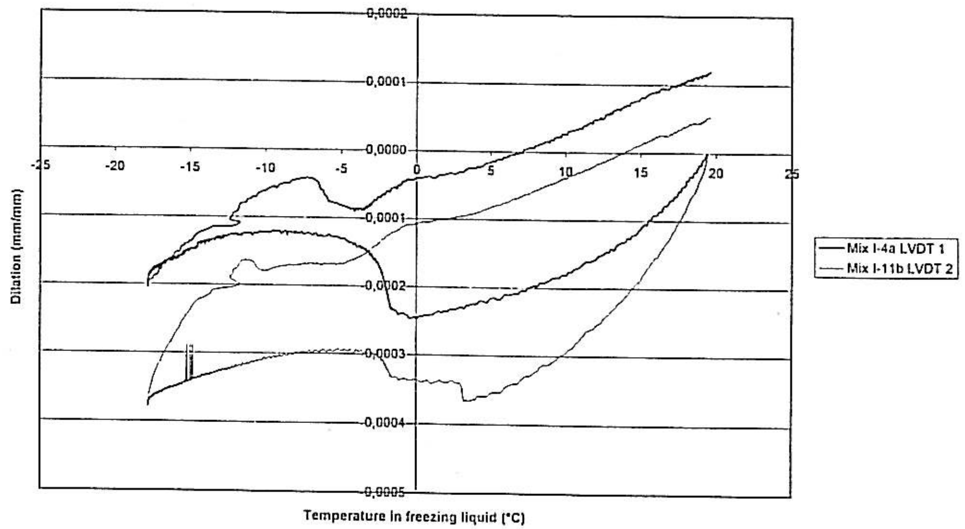
Mix 1 - Freezing after 28 days

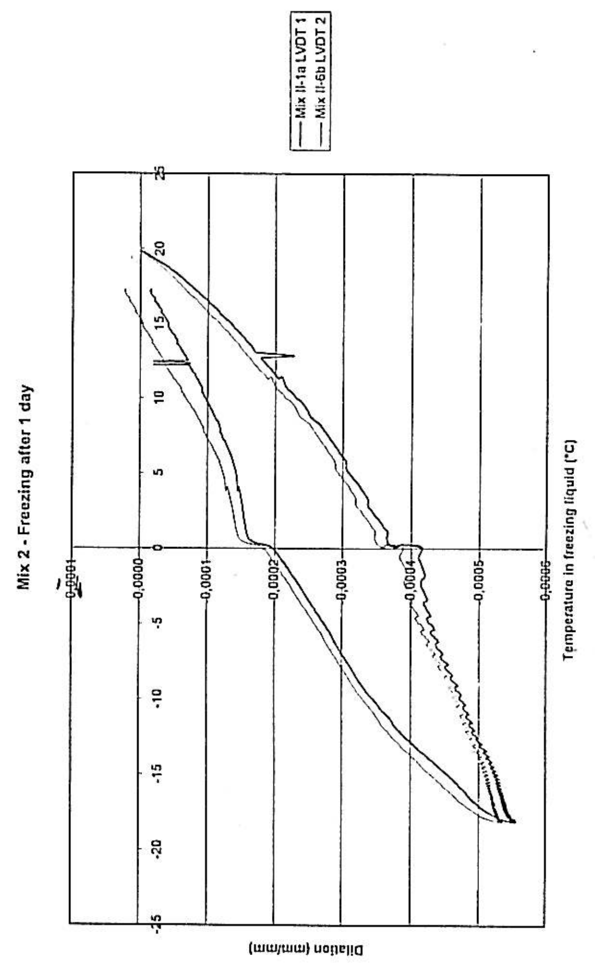


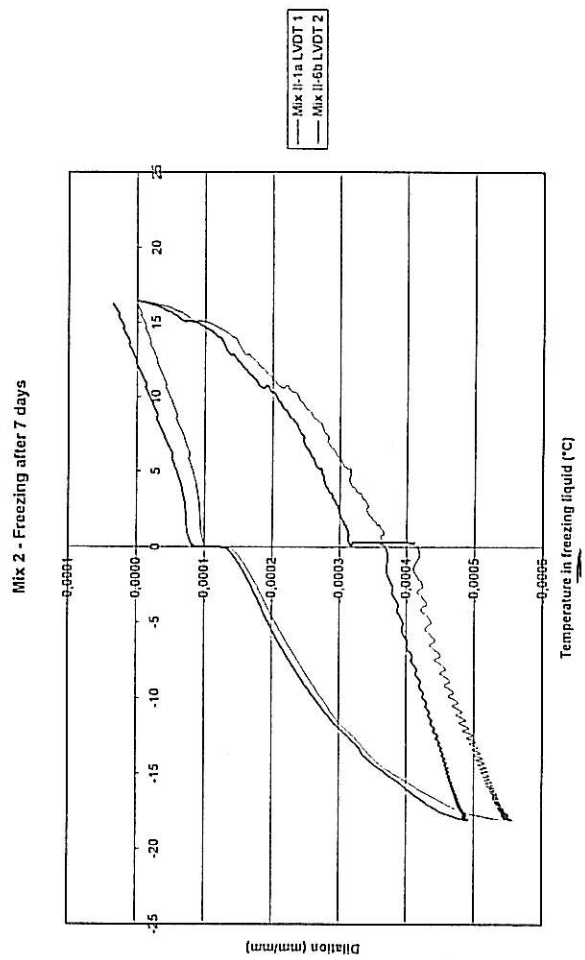
Mix 1 - Freezing after 14 days

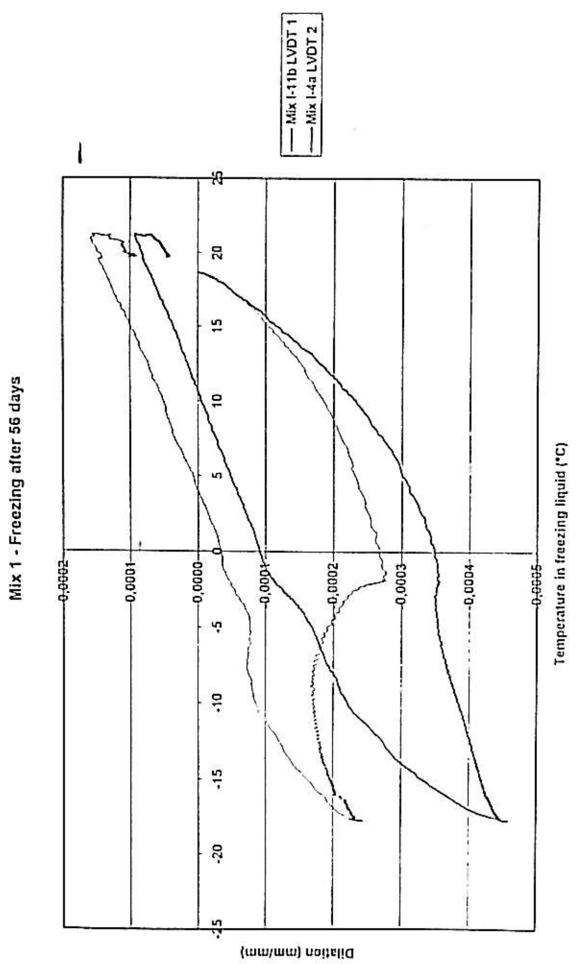


Mix 1 - Freezing after 42 days

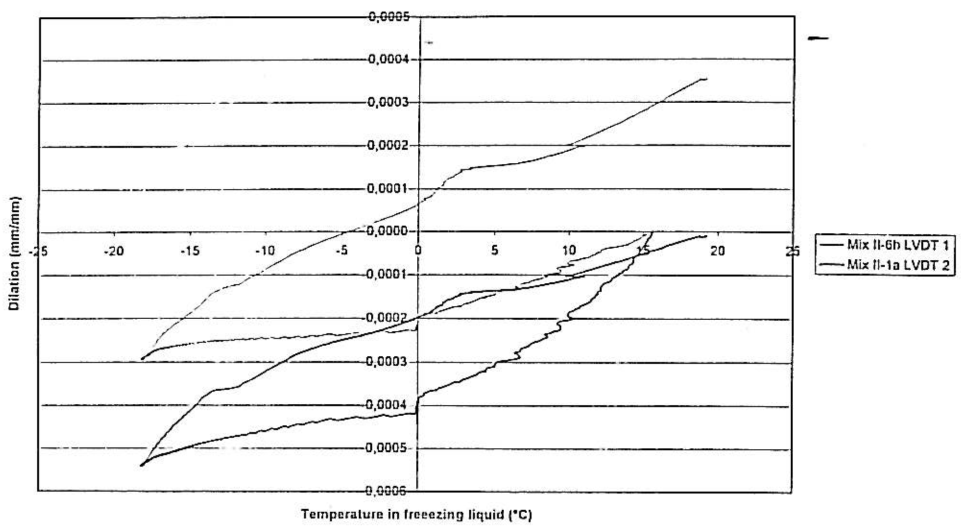



Mix 2 - Freezing after 1 day
Mix II-1a LVDT 1
Mix II-6b LVDT 2
Dilation (mm/mm)
Temperature in freezing liquid (°C)

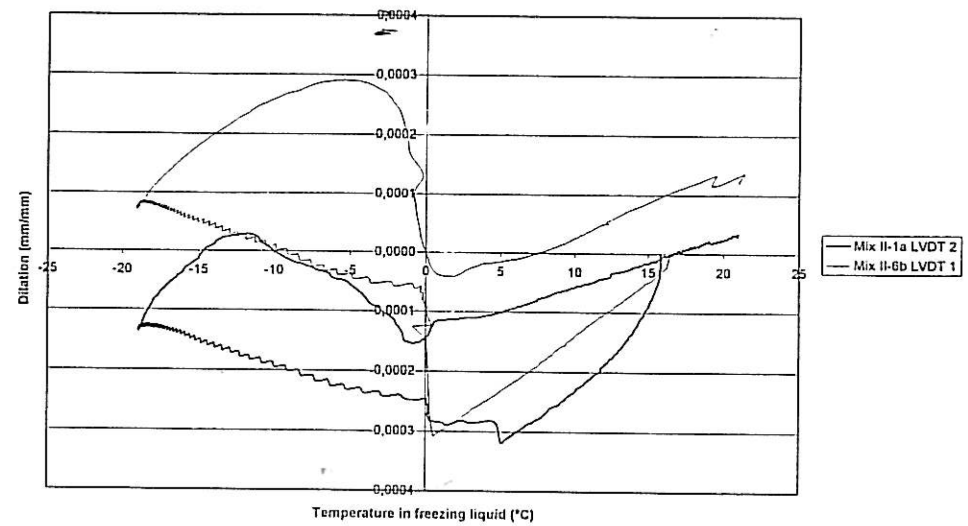

Mix 2 - Freezing after 7 days
Mix II-1a LVDT 1
Mix II-6b LVDT 2
Dilation (mm/mm)
Temperature in freezing liquid (°C)


Mix 1 - Freezing after 56 days
Mix I-11b LVDT 1
Mix I-4a LVDT 2
Dilation (mm/mm)
Temperature in freezing liquid (°C)

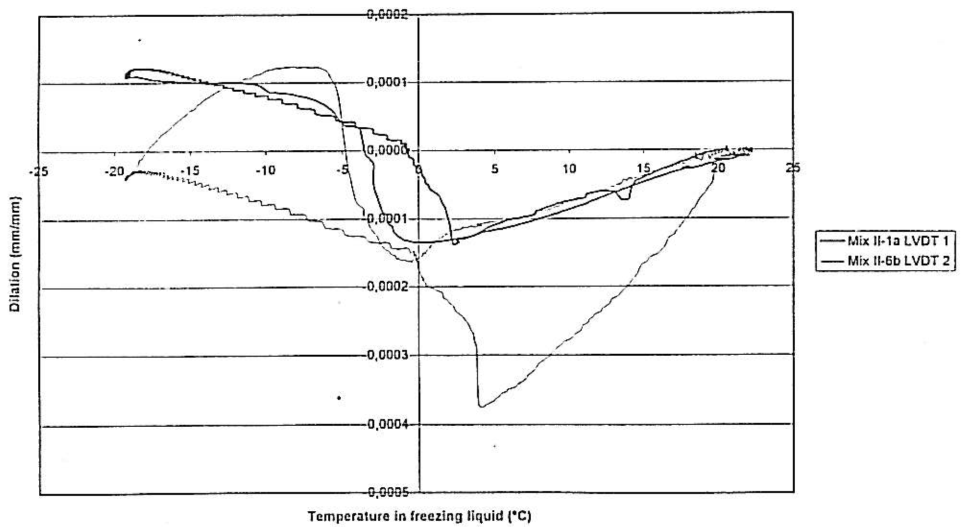
Mix 2 - Freezing after 14 days



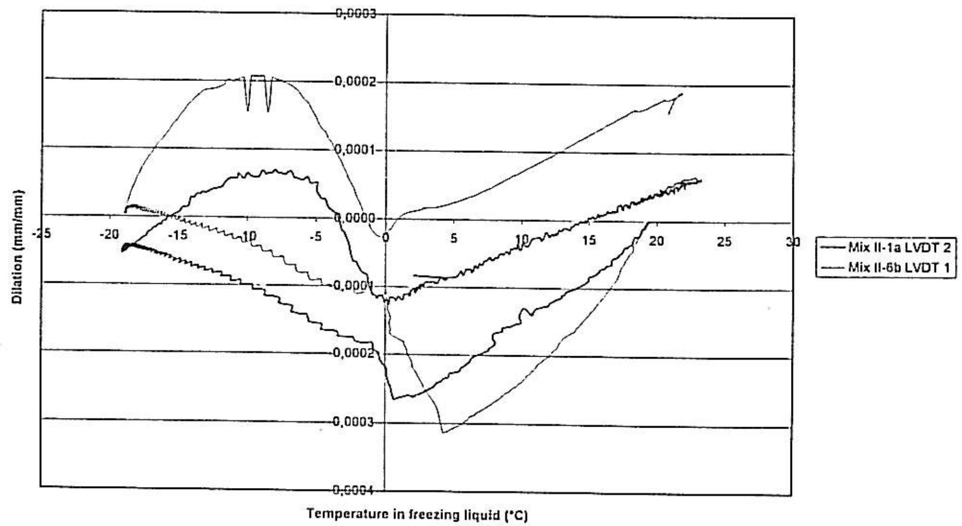
Mix 2 - Freezing after 42 days



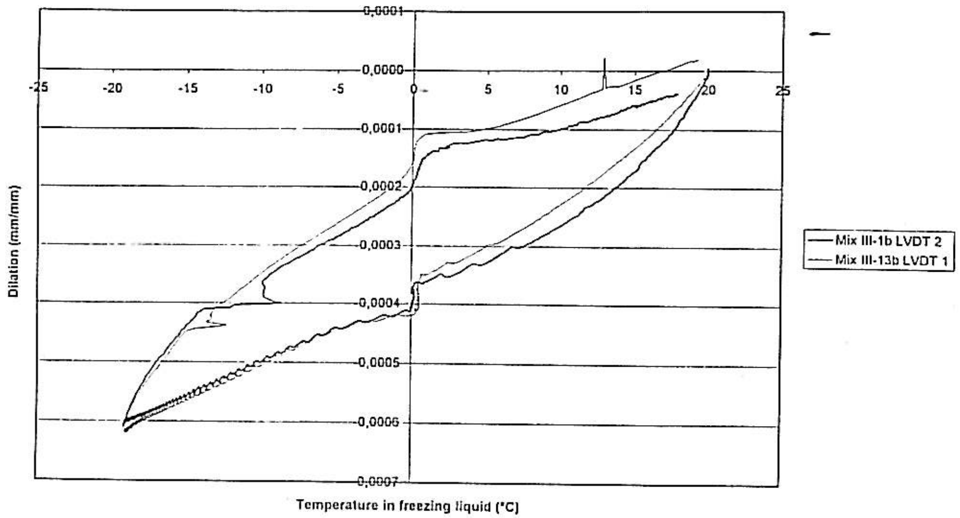
Mix 2 - Freezing after 28 days



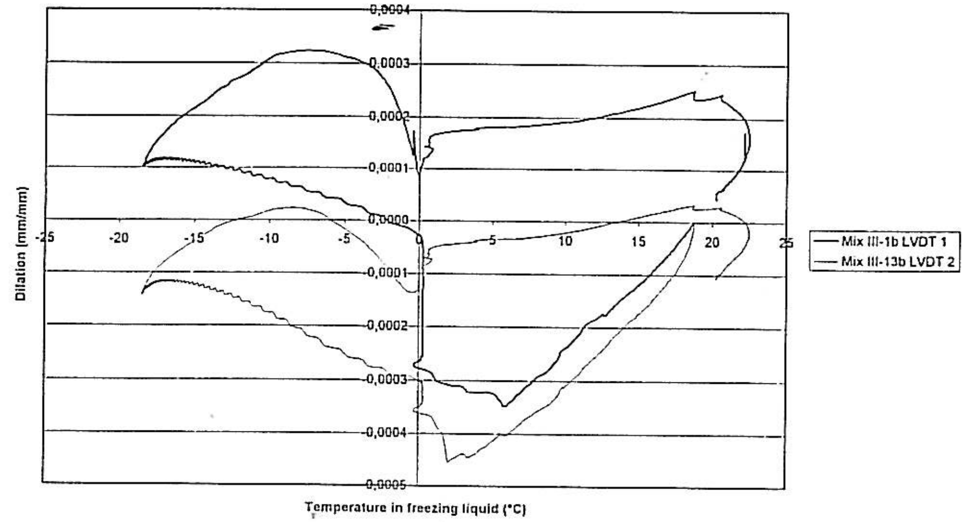
Mix 2 - Freezing after 56 days



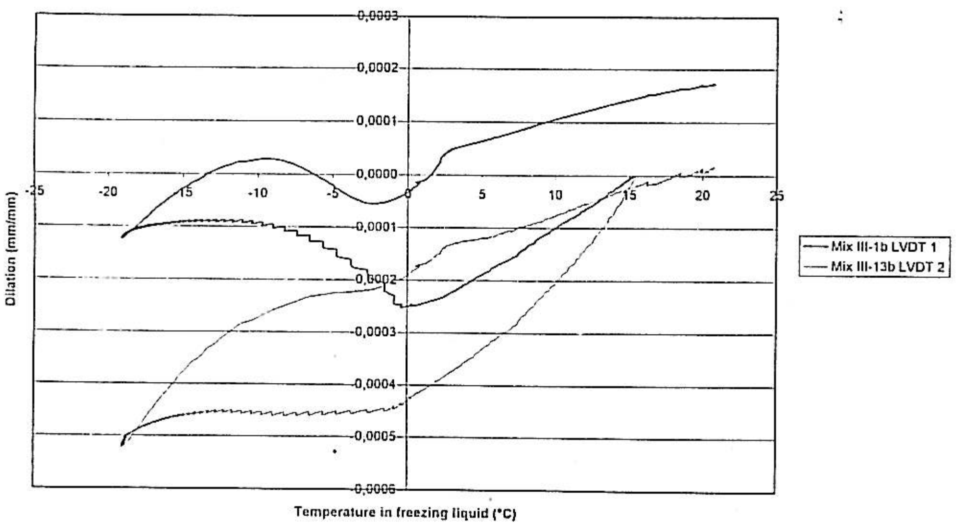
Mix 3 - Freezing after 1 day



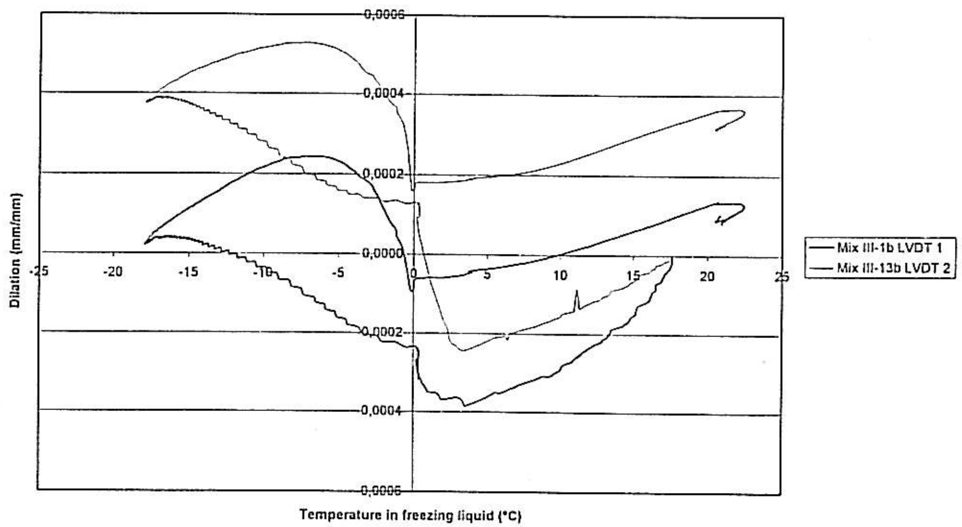
Mix 3 - Freezing after 14 days

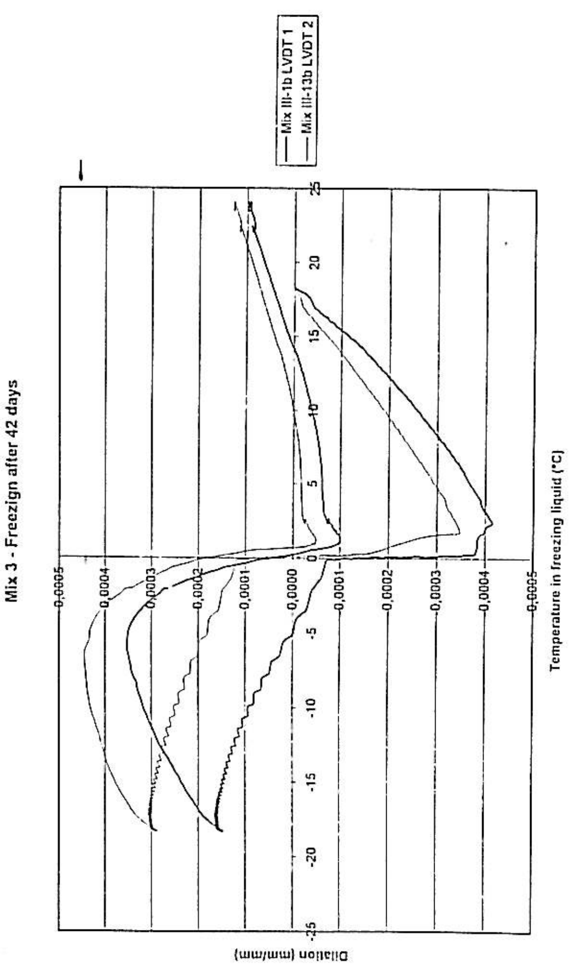


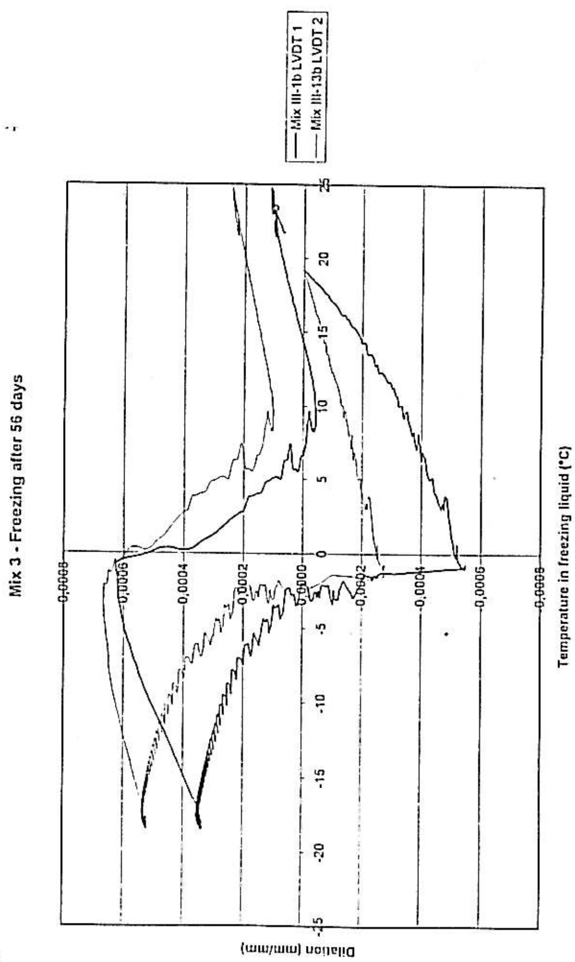
Mix 3 - Freezing after 7 days



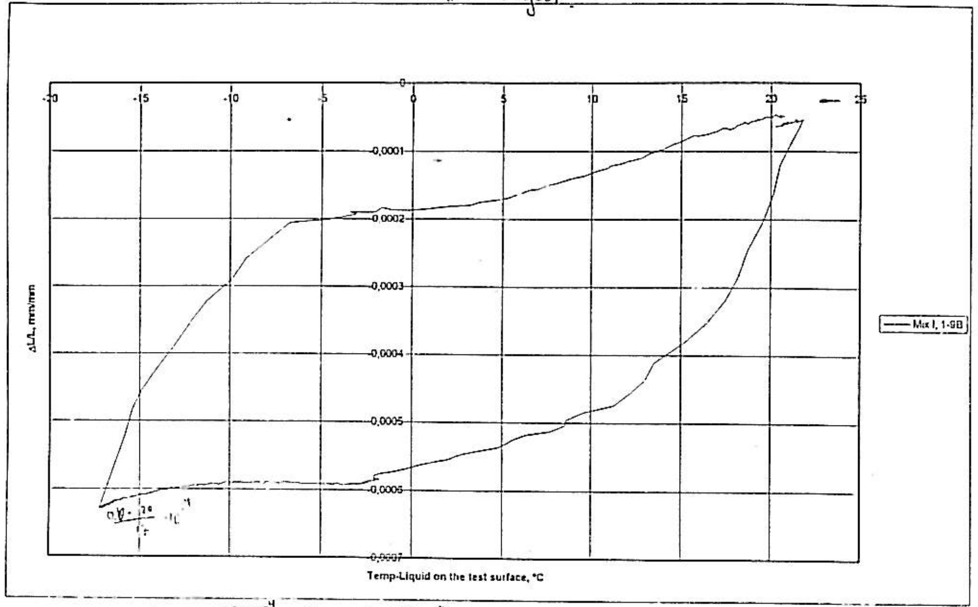
Mix 3 - Freezing after 28 days




Mix 3 - Freezign after 42 days
Mix III-1b LVDT 1
Mix III-13b LVDT 2
Dilation (mm/mm)
Temperature in freezing liquid (°C)


Mix 3 - Freezing after 56 days
Mix III-1b LVDT 1
Mix III-13b LVDT 2
Dilation (mm/mm)
Temperature in freezing liquid (°C)

Mix 1 - 14 cycles

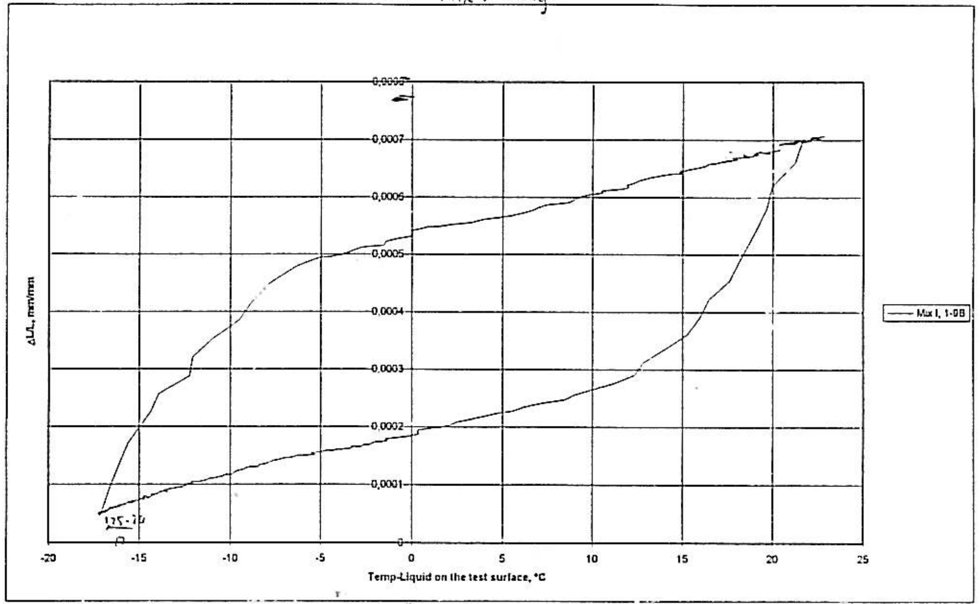


ε_L −0,1·10⁻⁴ $\varepsilon_{0..-10}$: −0,7·10⁻⁴

ε_{20-0} : −4,1·10⁻⁴ ε_{rs} : +0,1·10⁻⁴

Sida 1

Mix 1 - 56 cy



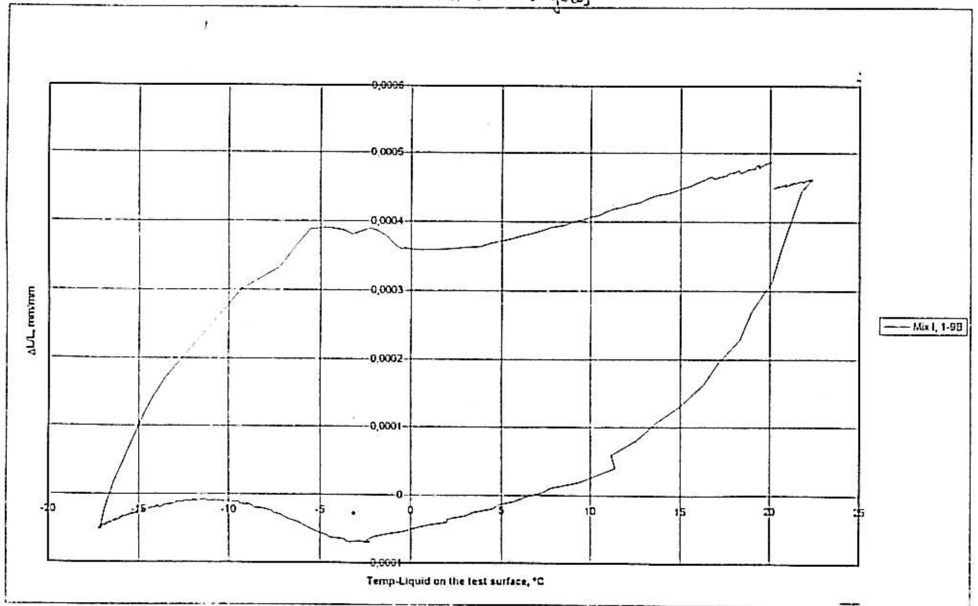
ε_L : ~0 $\varepsilon_{0..-10}$: ÷1,5·10⁻⁴

ε_{20-0} : −4,4·10⁻⁴ ε_{rs} : ~0.

Sida 1

Blad1 Diagram 1

Mix 1 - 28 cycles



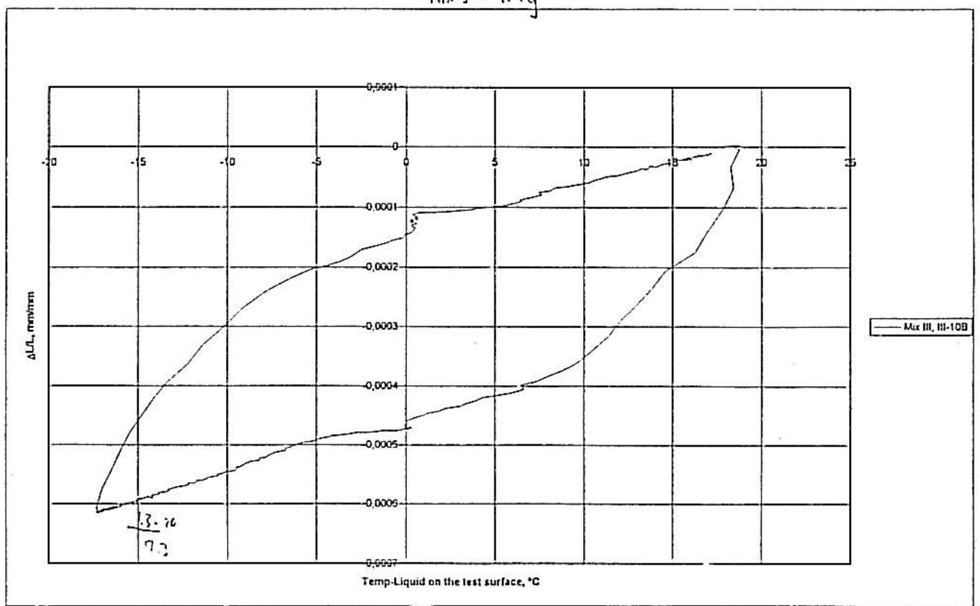
ε_L : ~0 $\varepsilon_{0..-10}$: −0,05·10⁻⁴

ε_{20-0} : −3,7·10⁻⁴

Sida 1

Blad1 Diagram 1

Mix 3 - 1. cy



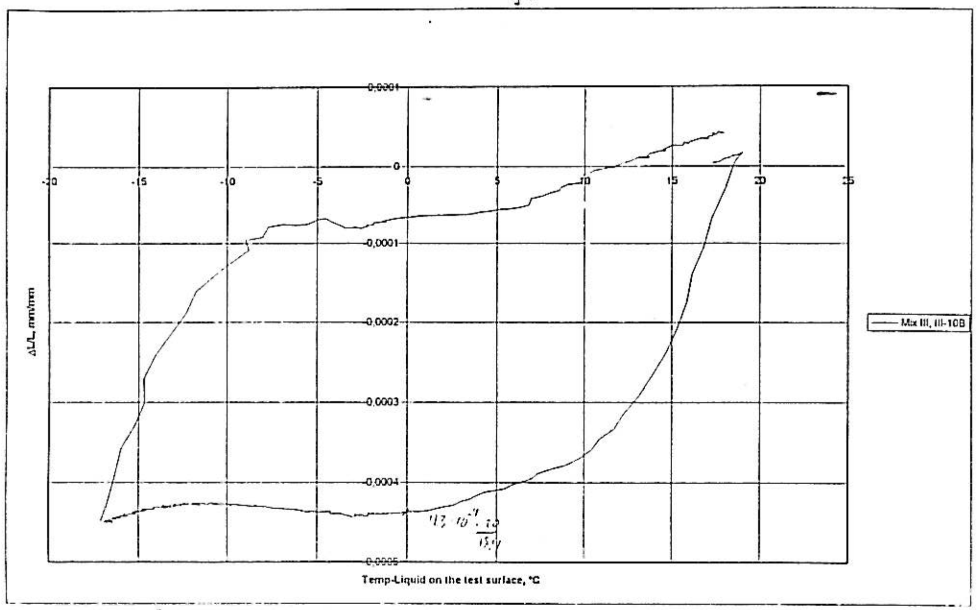
ε_L : ~0 $\varepsilon_{0..-10}$: −1,5·10⁻⁴

ε_{20-0} : −4,6·10⁻⁴ ε_{rs} : ~0

Sida 1

Blad1 Diagram 1

Mix 3 - 7cy.



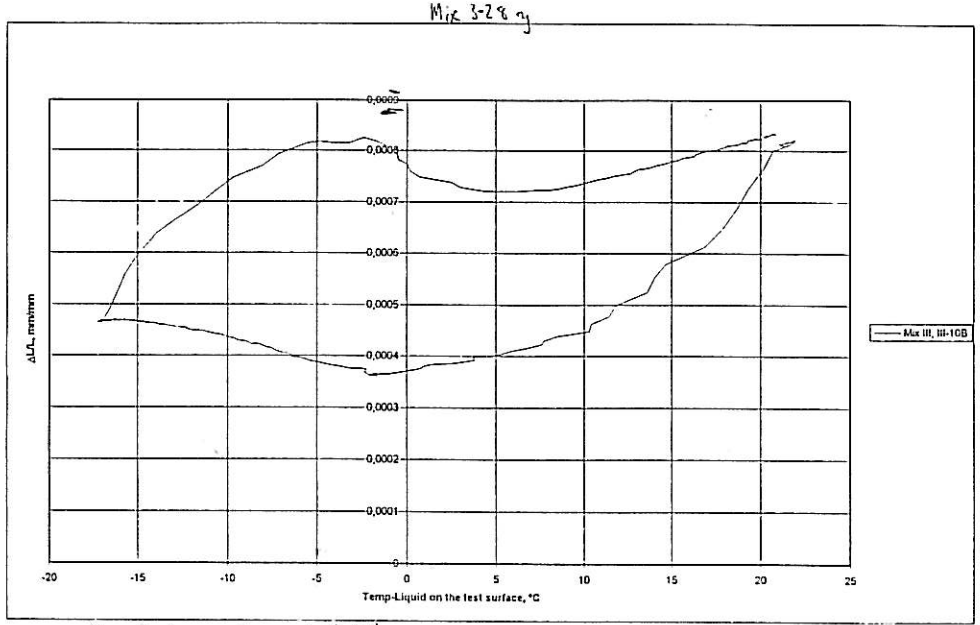
ε_L : 0 ε_{0--20} : -0.12

Sida 1

ε_{20-0} : -4.6 ε_{rs} : +0.6

Blad1 Diagram 1

Mix 3-28 cy



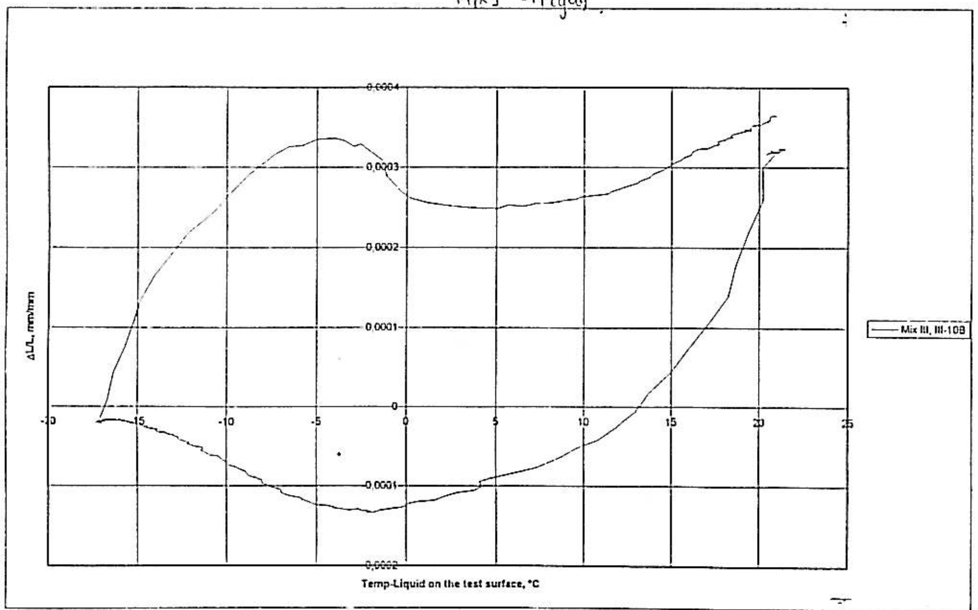
ε_L : ~0 ε_{0--20} : $+1 \cdot 10^{-4}$

Sida 1

ε_{20-0} : $-4 \cdot 10^{-4}$ ε_{rs} : $+0.6 \cdot 10^{-4}$

Blad1 Diagram 1

Mix 3 - 14 cycly.

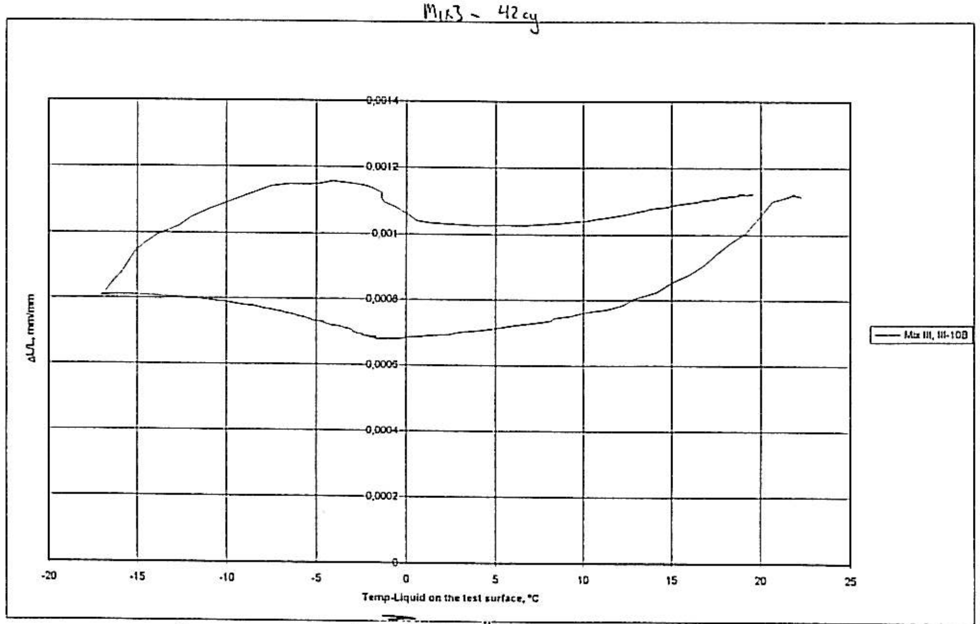


ε_L : ~0 ε_{0-20} : $+1.1 \cdot 10^{-4}$

Sida 1

Blad1 Diagram 1

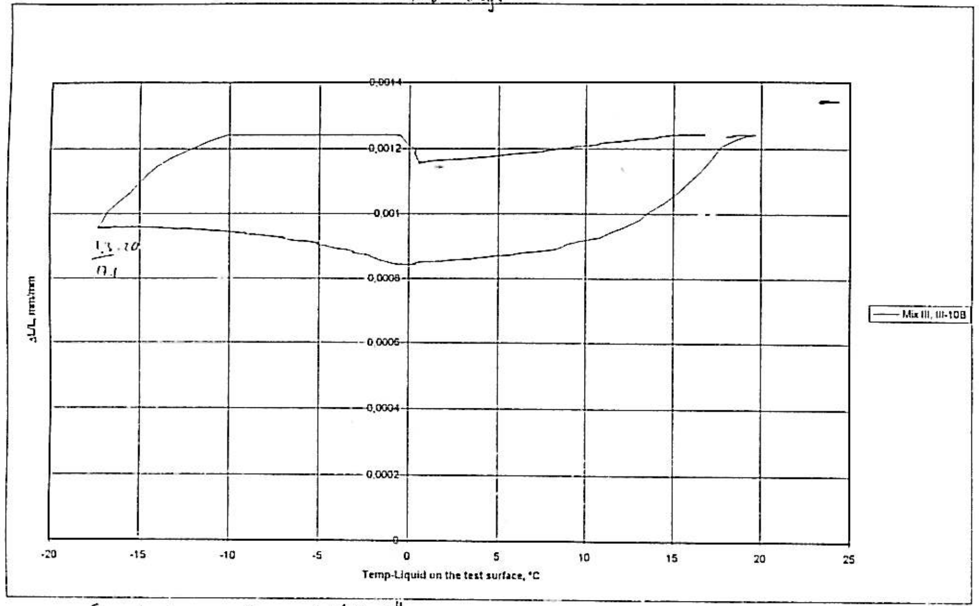
Mix 3 - 42 cy



ε_L : ~0 ε_{0--20} : $+1.4 \cdot 10^{-4}$

Sida 1

Mix 3 - 56 cy.



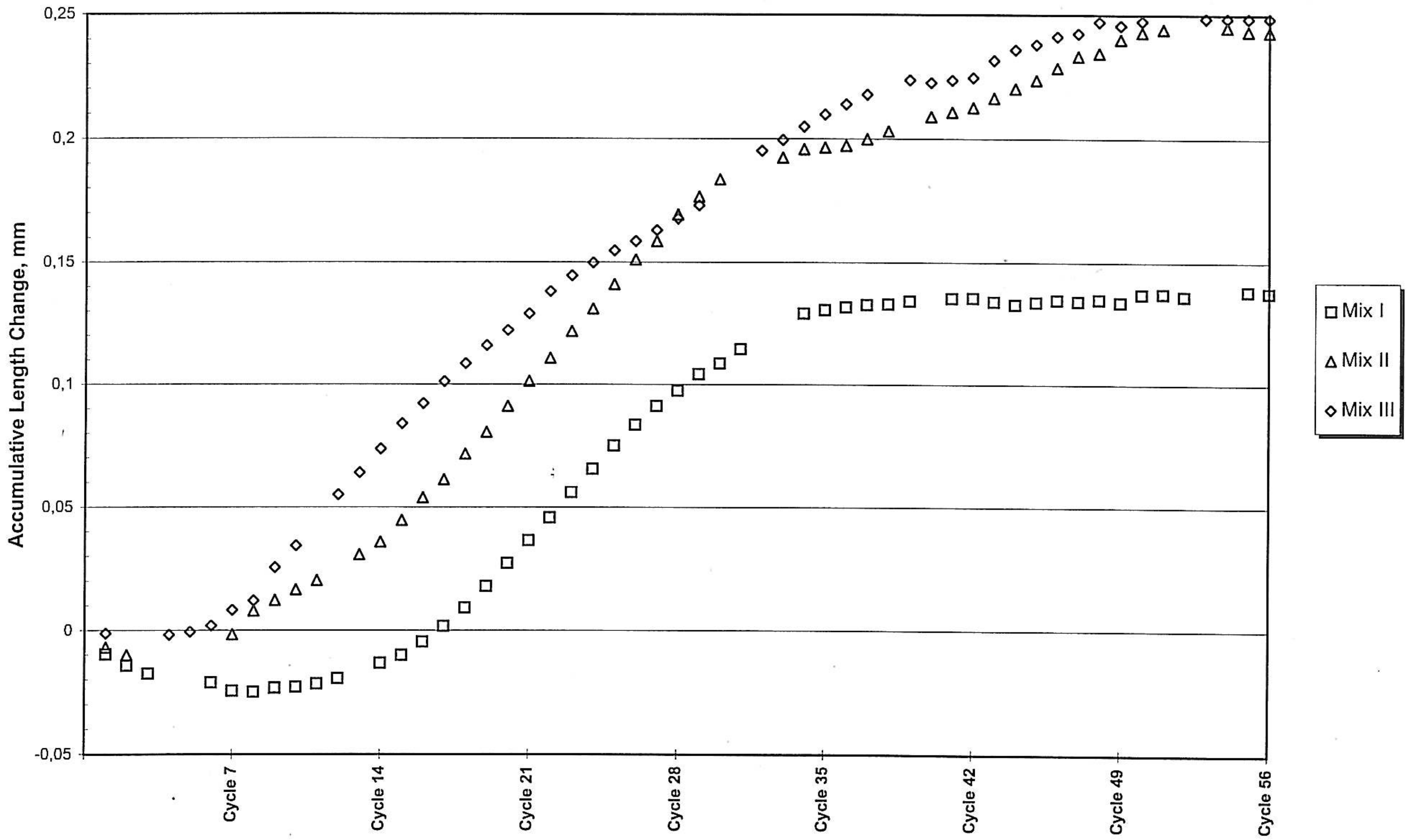
ε_L : ~0 $\quad\varepsilon_{0..-10}$: $+1,5\cdot10^{-4}$

Sida 1

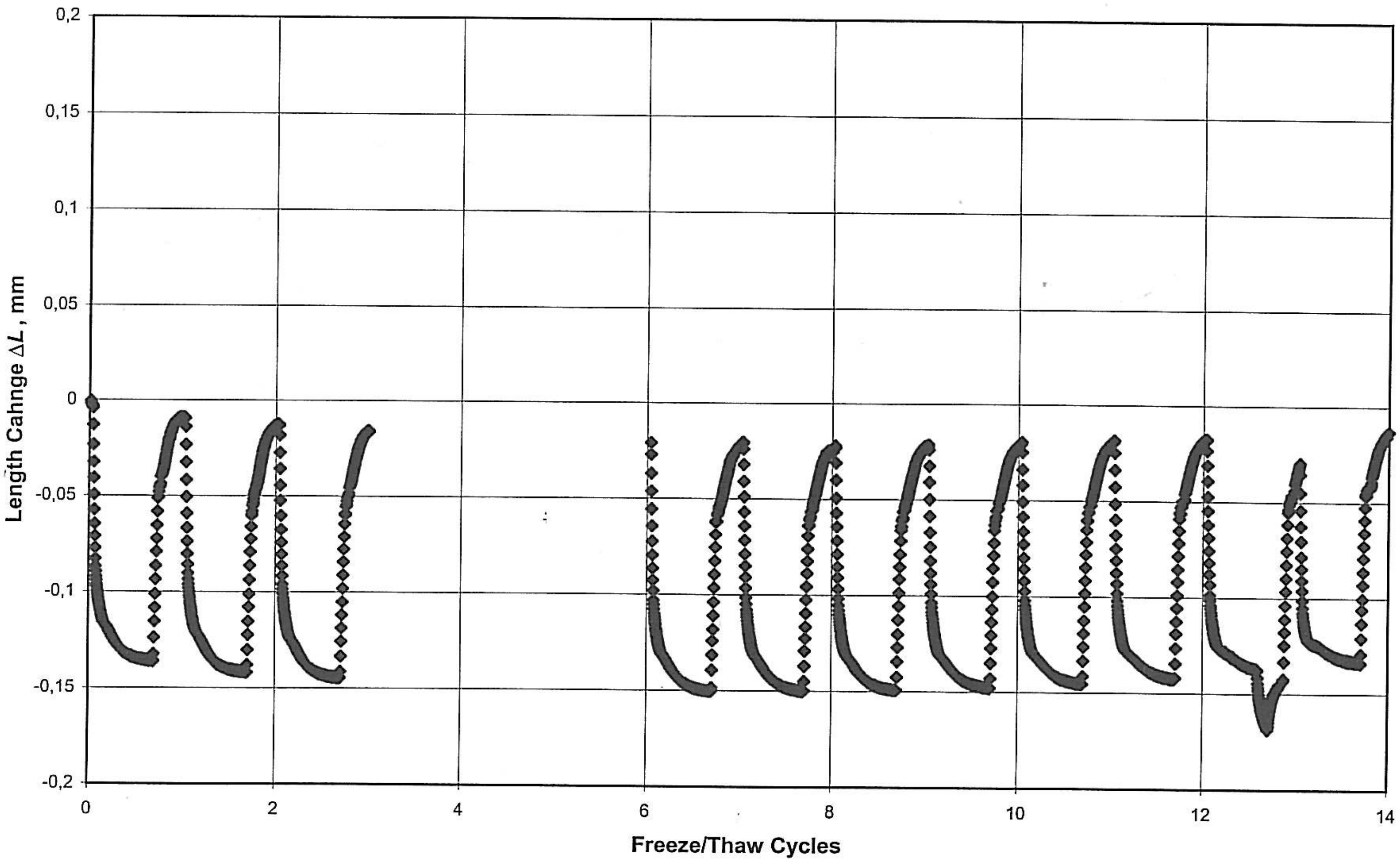
ε_{20-0} : $-3,6\cdot10^{-4}$ $\quad\varepsilon_{res}$: ~0.

D16

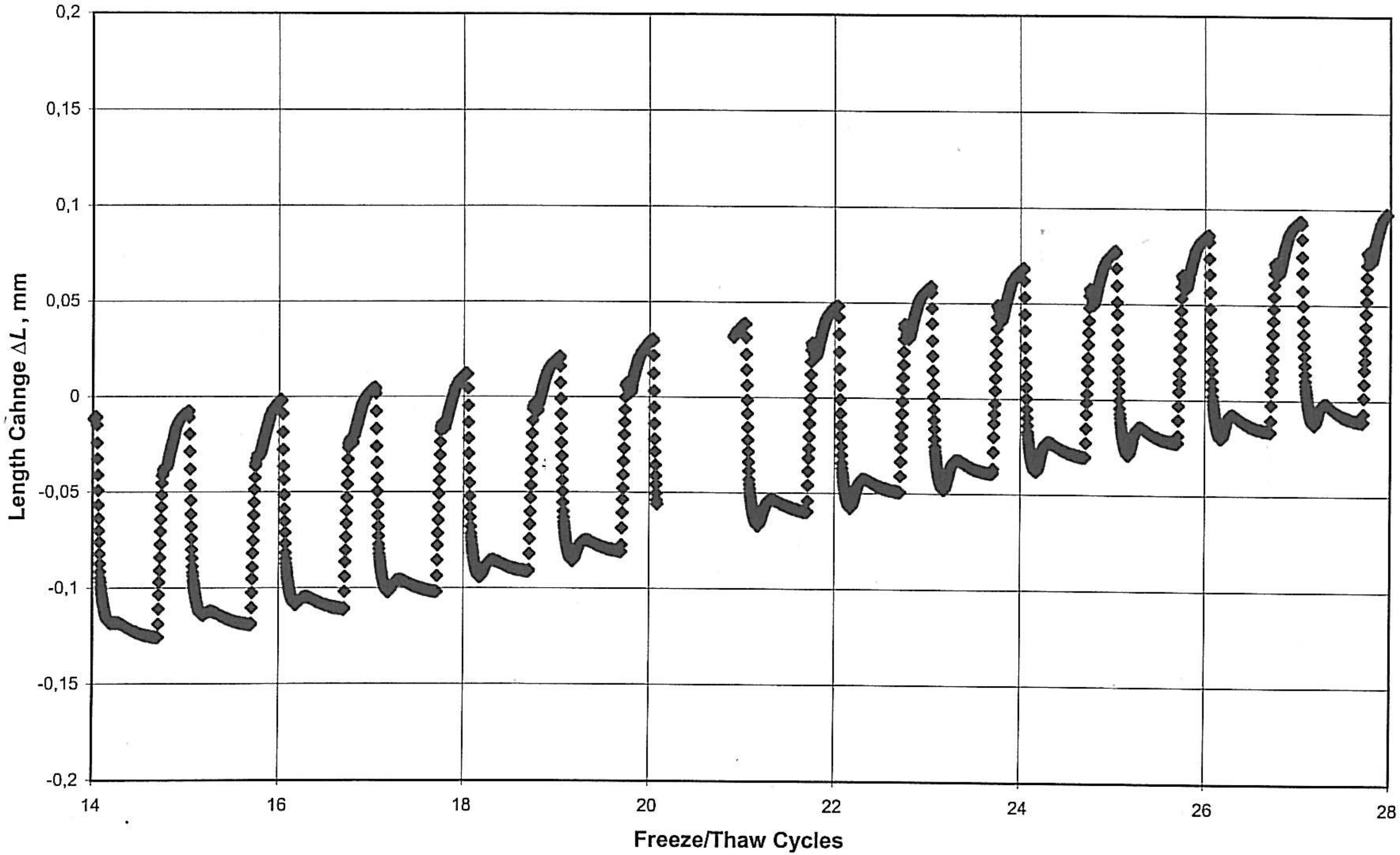
Fig Diagram 1

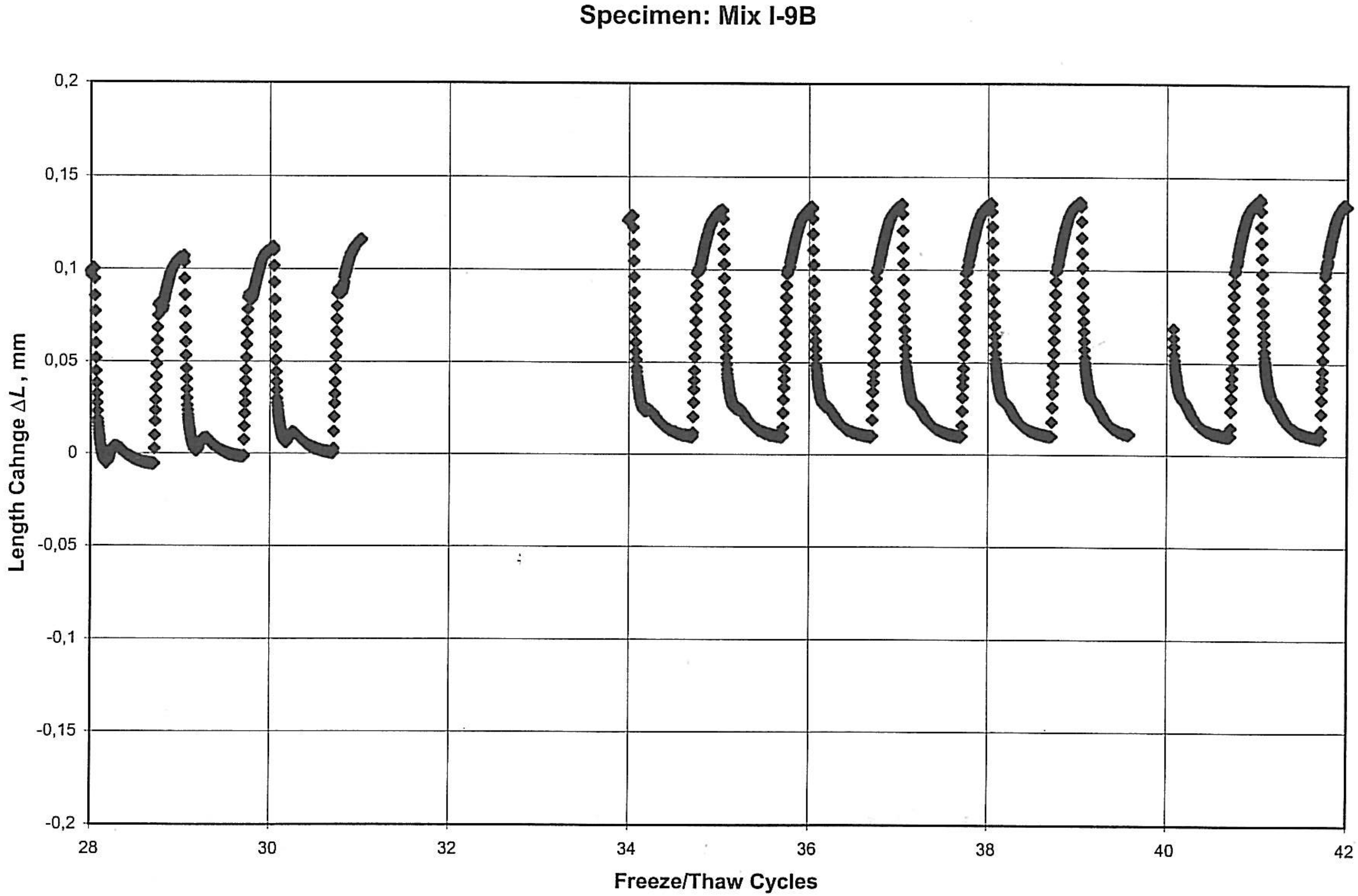


Specimen: Mix I-9B



Specimen: Mix I-9B




Specimen: Mix I-9B
Length Cahnge ΔL, mm
0,2
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
-0,2
28
30
32
34
36
38
40
42
Freeze/Thaw Cycles

Specimen: Mix I-9B

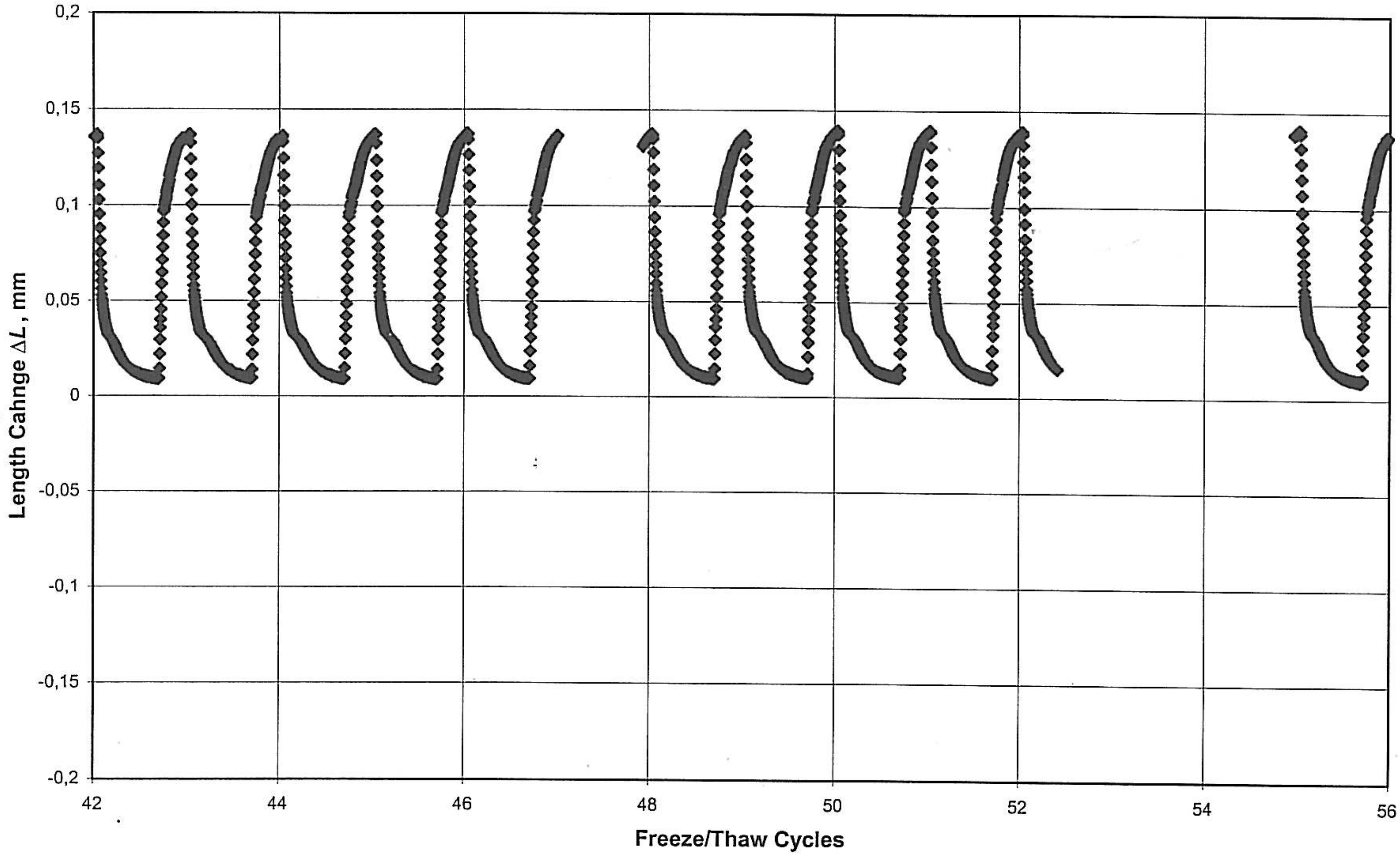
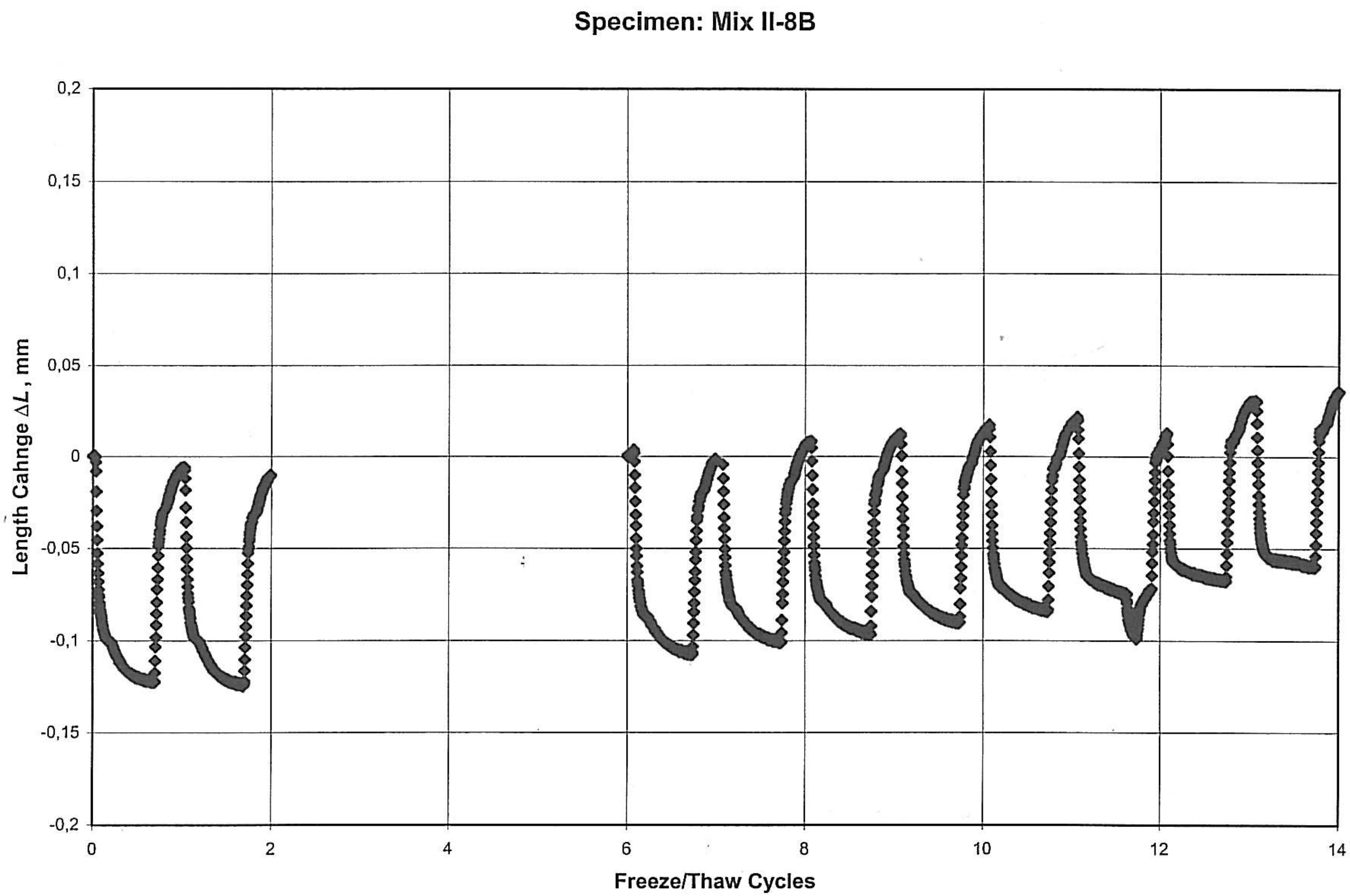
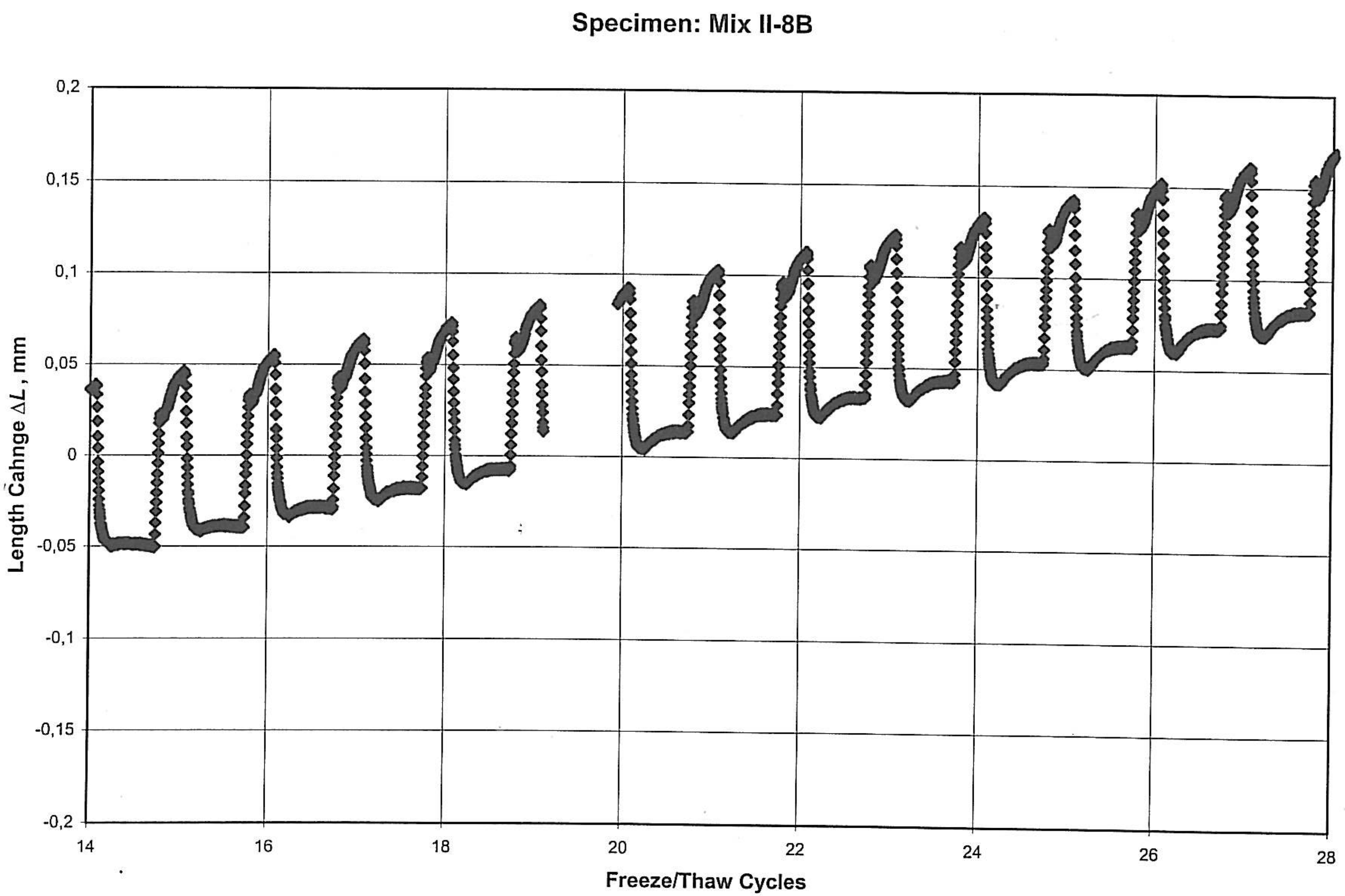
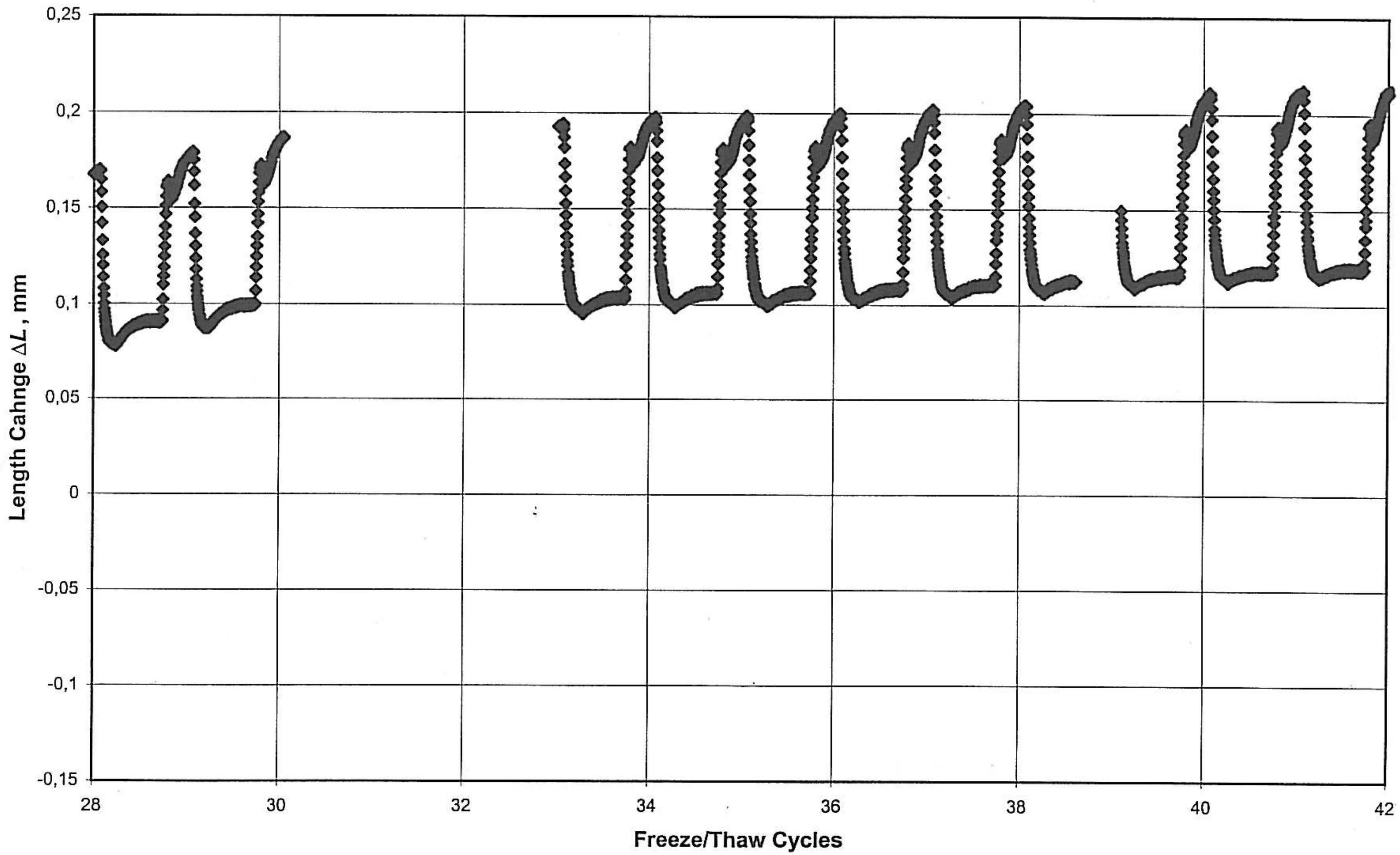


Fig Diagram 2

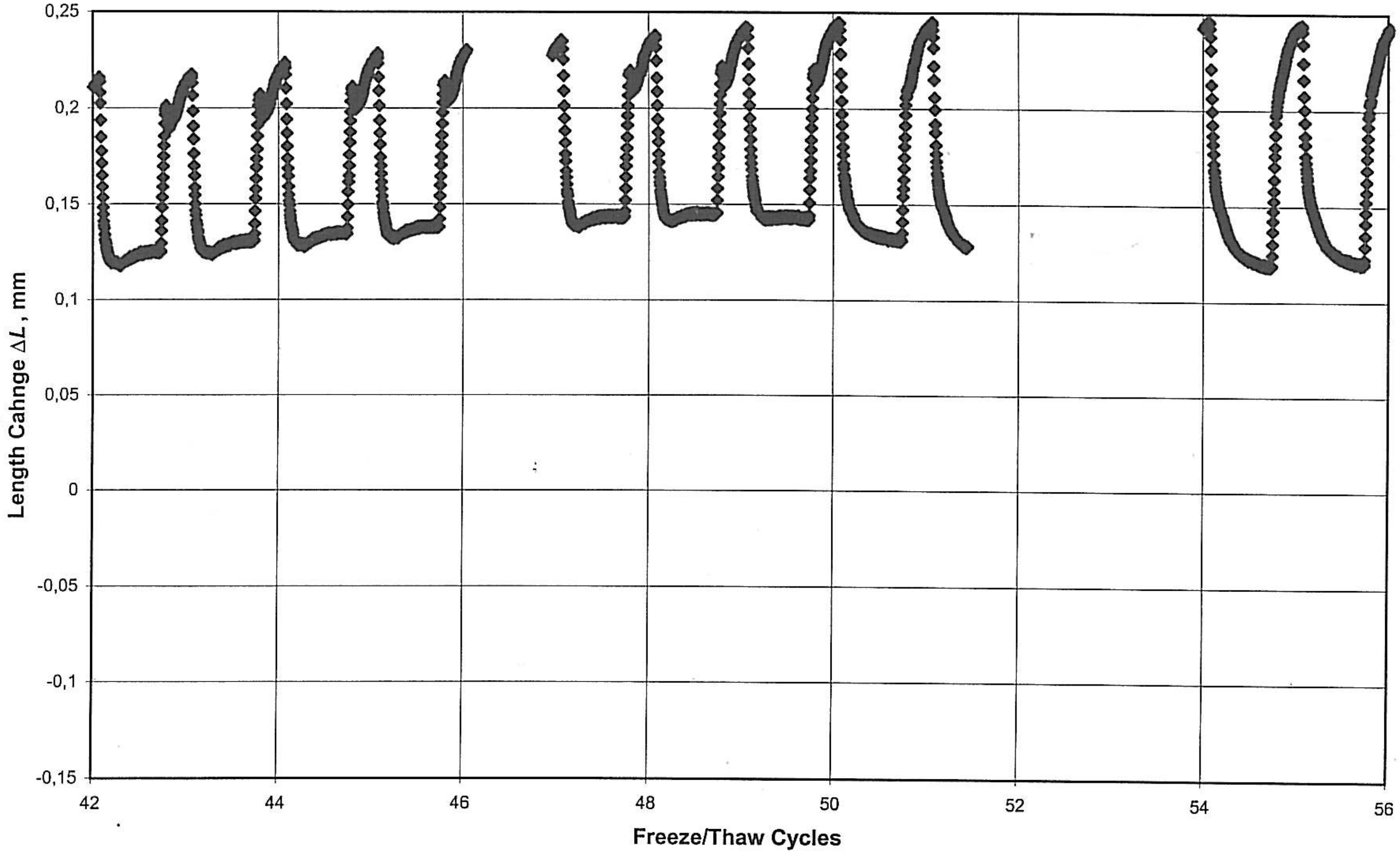



Specimen: Mix II-8B
0,2
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
-0,2
Length Cahnge ΔL , mm
14
16
18
20
22
24
26
28
Freeze/Thaw Cycles

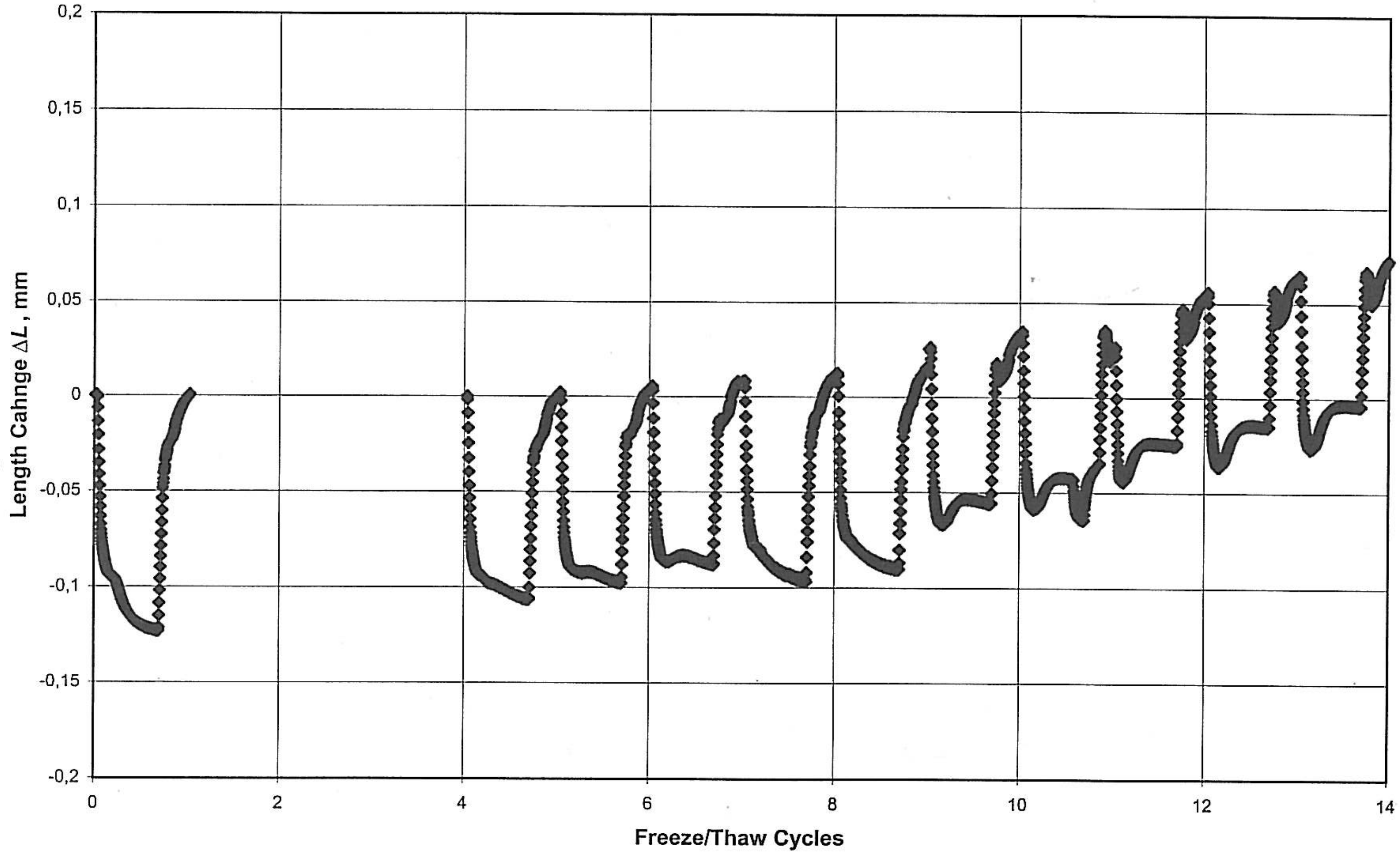
Specimen: Mix II-8B



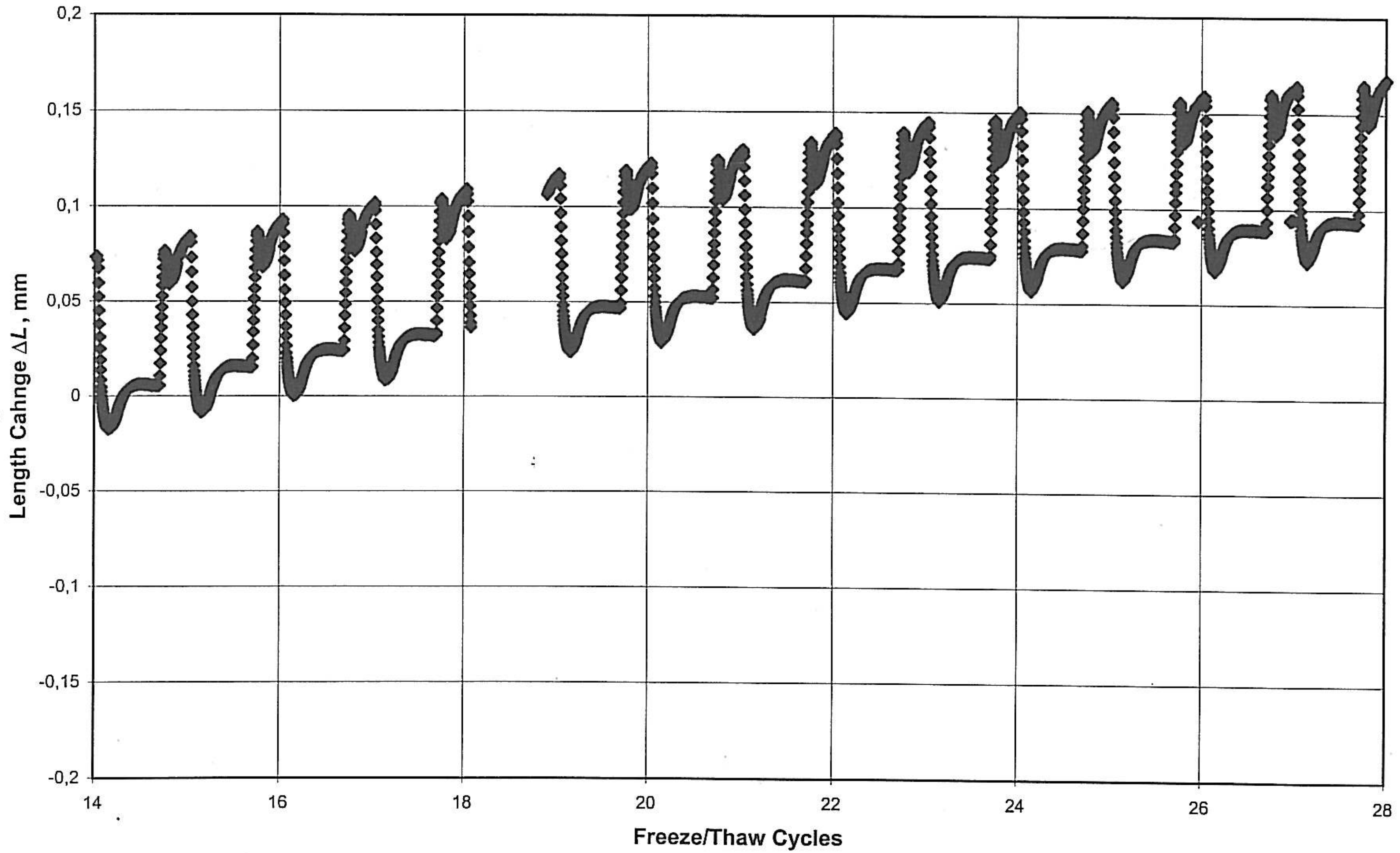
Specimen: Mix II-8B



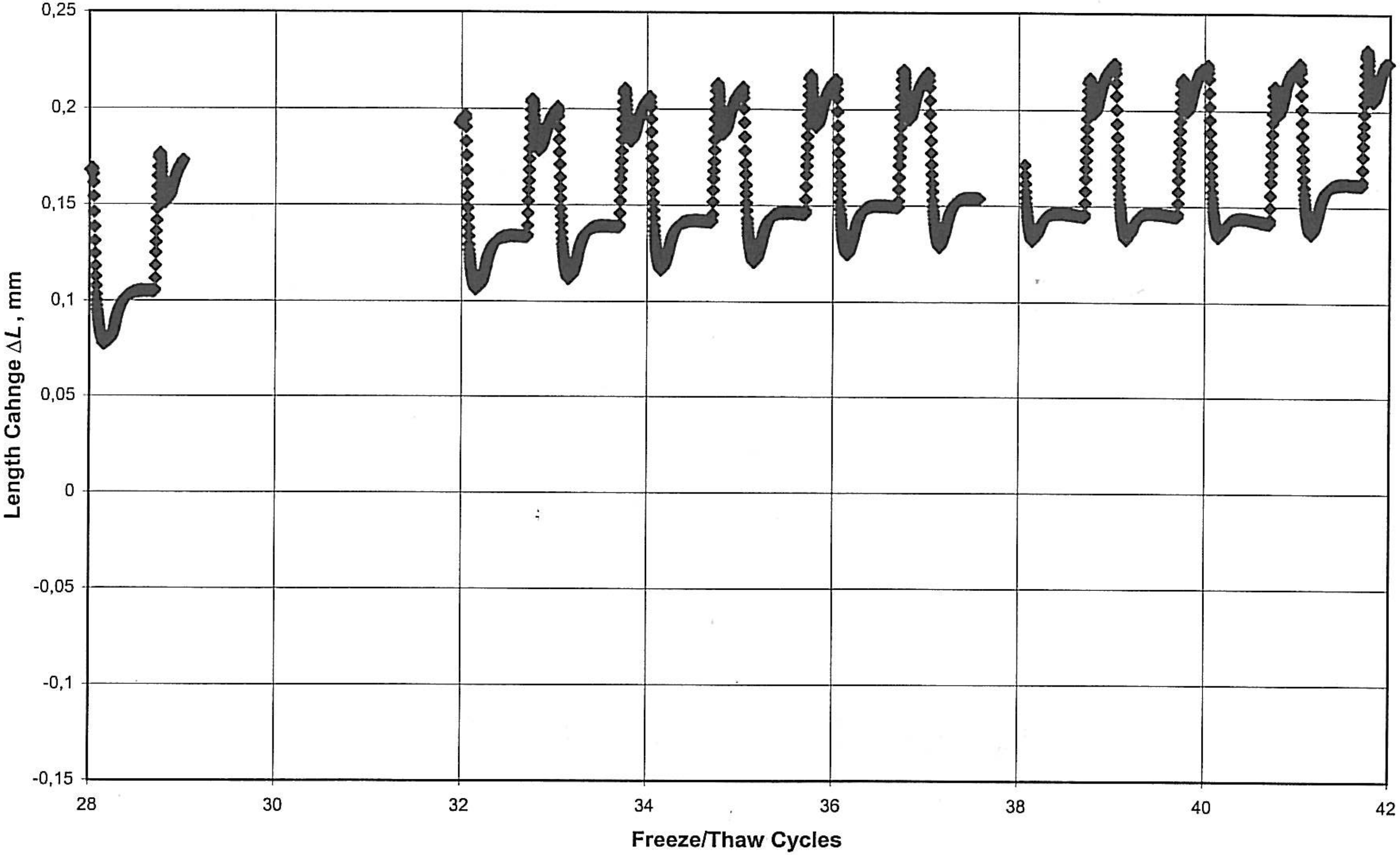
Specimen: Mix III-10B

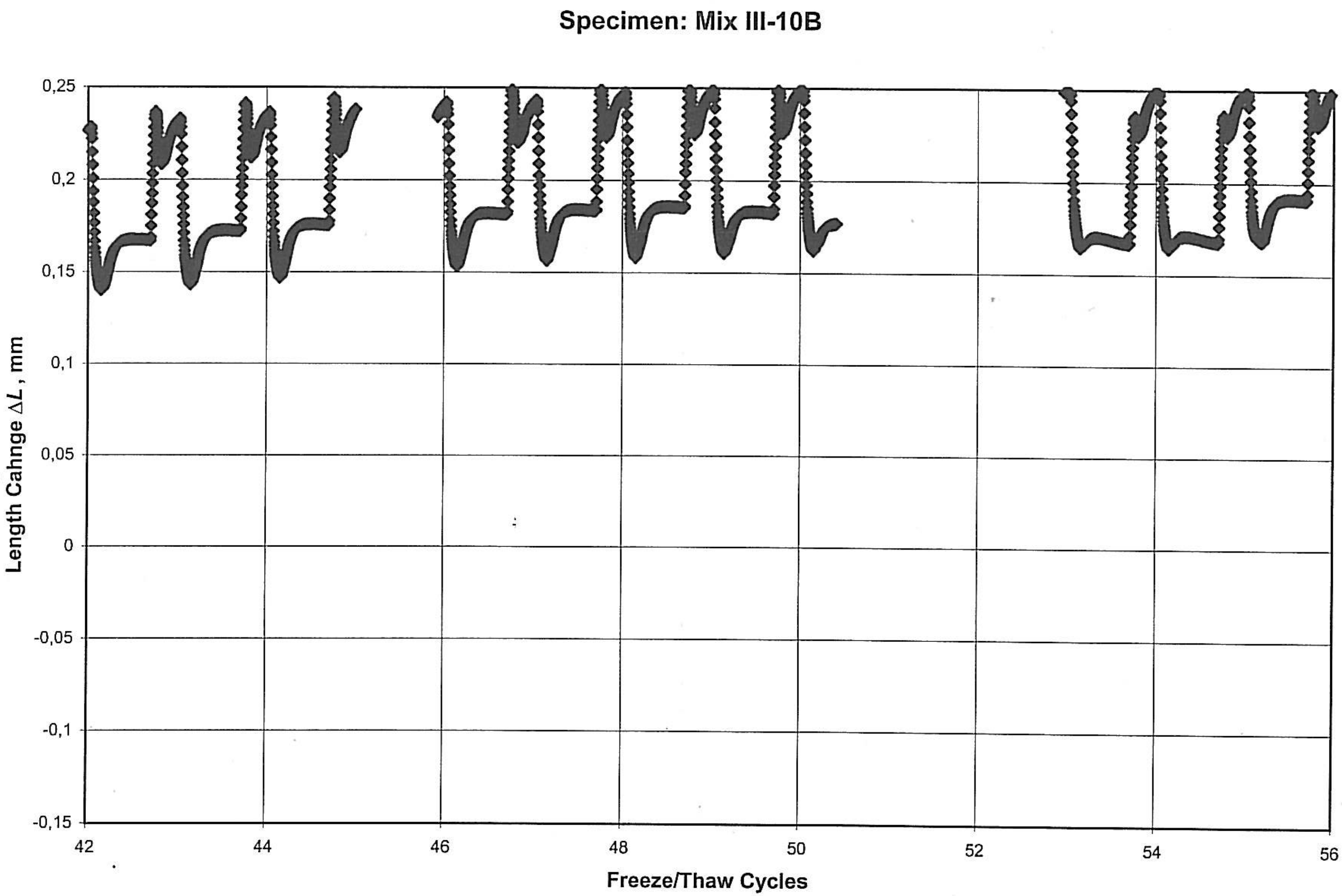


Specimen: Mix III-10B



Specimen: Mix III-10B




Specimen: Mix III-10B
Length Cahnge ΔL , mm
0,25
0,2
0,15
0,1
0,05
0
-0,05
-0,1
-0,15
42
44
46
48
50
52
54
56
Freeze/Thaw Cycles

Appendix 5: Fluorescent impregnated polished sections, SS137244 specimens, 112 cycles

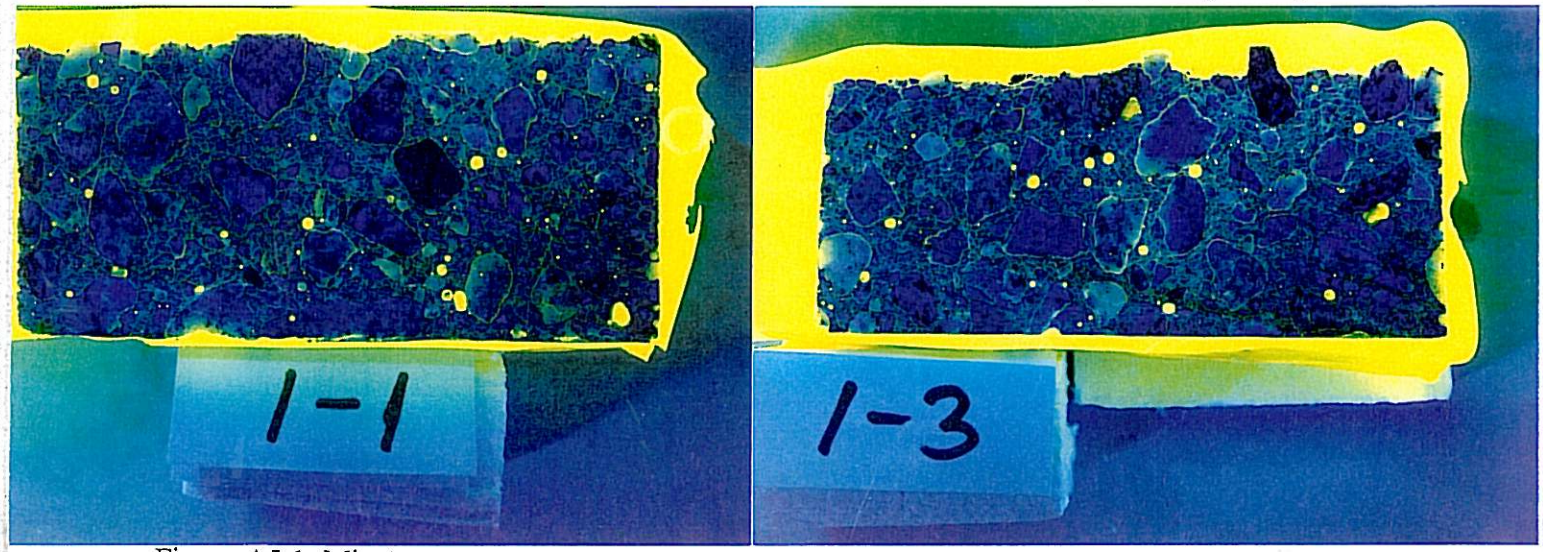


Figure A5.1 Mix 1

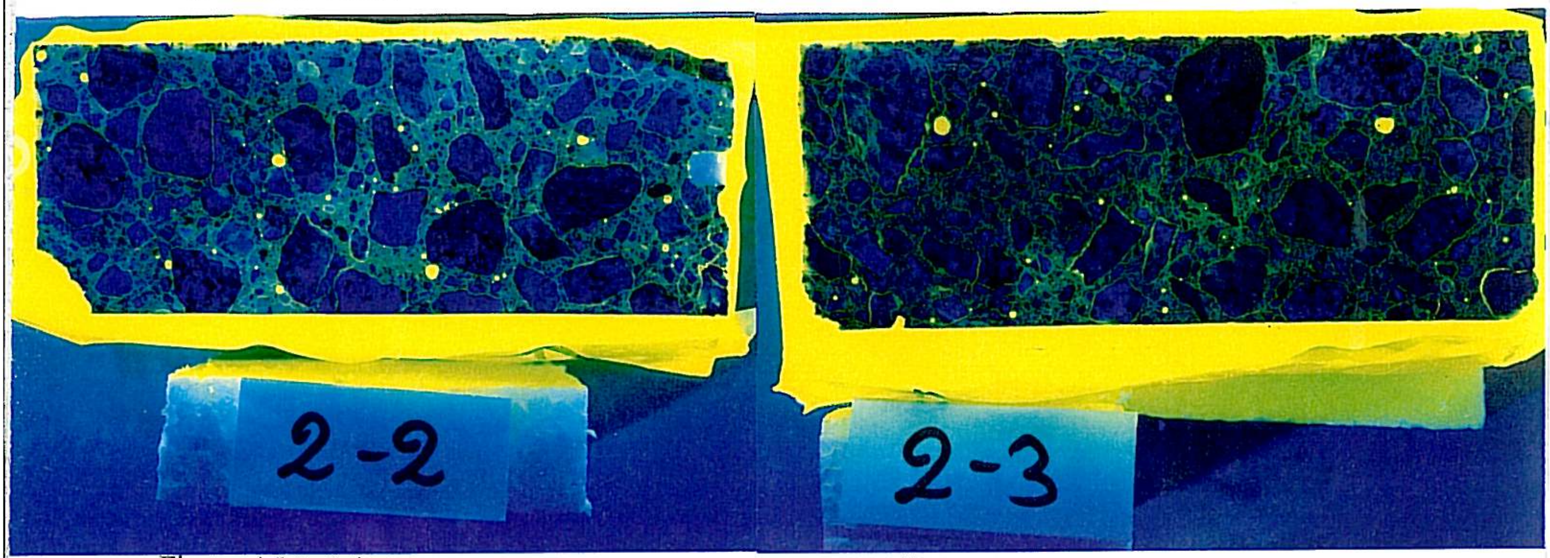


Figure A5.2 Mix 2

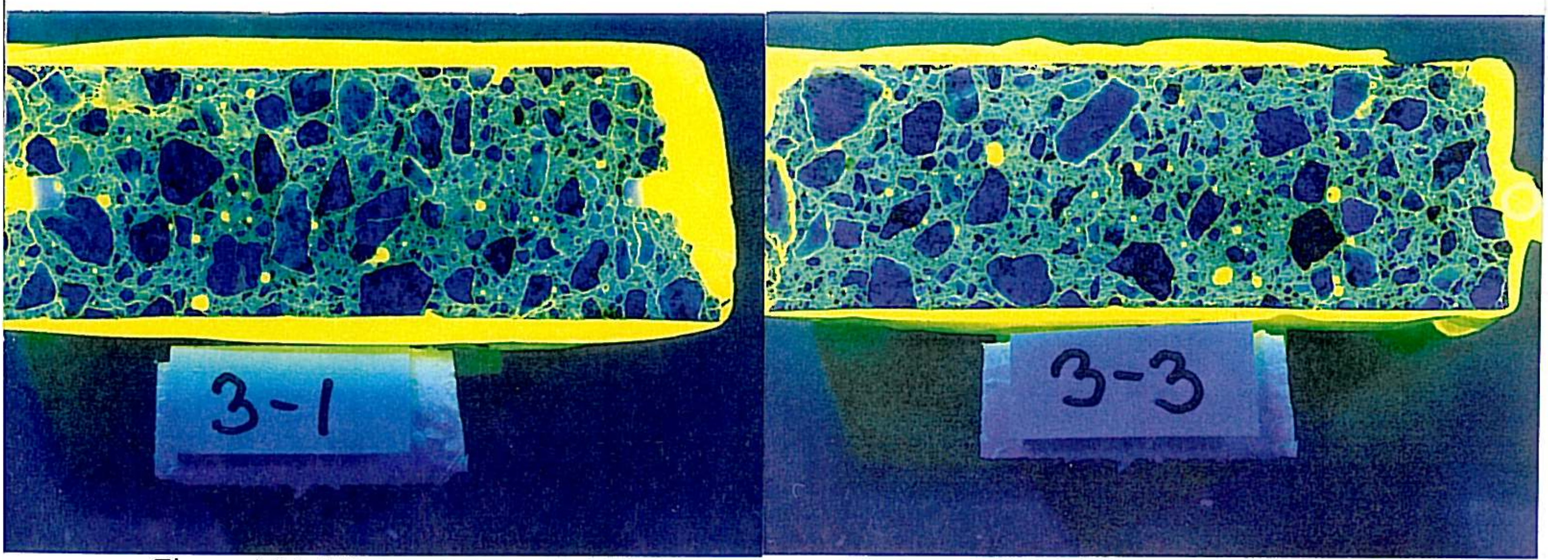


Figure A5.3 Mix3