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Properties of Concrete Exposed to Running Fresh Water for 24 years.

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ABSTRACT

A total of nine concretes, comprising three cement types, incorporation of fly ash, superplasticized high strength concrete and high performance concrete with microsilica, have been monitored during 24 years of exposure to running fresh water under Danish outdoor climatic conditions. The compressive strength development has been measured, and durability aspects have been assessed after 6 and 21 years of exposure, with very positive results.

Key words: Blended cement, fly ash, microsilica, high performance concrete, long-term exposure, compressive strength development, long-term compressive strength, cementing efficiency factor, durability.

1. INTRODUCTION

The project described in the present paper was initiated by Aalborg Portland A/S in 1979. The aim of the project was to investigate the long term performance of a number of concrete compositions which were newly developed and consequently were untried at the time.

It was decided to produce a number of full scale precast units using the different types of concrete, and incorporate these units as “steps” in a fish-ladder for a local lake. In that way the new concretes would be easily accessible for periodic inspection over the following many years.

Inspection results up to the age of 14 years were reported in [1], and durability aspects were reported briefly at 21 years age in [2]. The present paper presents and incorporates results after 24 years, obtained in connection with the decommissioning of the fish-ladder.

2. EXPERIMENTAL

2.1 Materials

The cements used were a normal portland cement (CEM I 42.5), a low- alkali sulphate resistant cement (CEM I 42.5-SR), and a blended portland-flyash cement (CEM II /B-V 42.5).

The CEM I 42.5-SR cement was the first Danish cement produced without clay as a raw material. Instead, ground quartz sand and fly ash were used to contribute silicon and aluminium to the raw mix. It was produced as a sulphate resisting cement with a low C_3A content, and with a low alkali content, too.

Blended cement containing fly ash was new in Denmark as well. The cement for the present project was produced by separately grinding normal Portland cement to a Blaine-fineness of 388 m^2/kg and fly ash to a Blaine-fineness of 515 m^2/kg, and subsequently mixing 70 wt% ground cement with 30 wt% ground fly ash.

The chemical and physical data for the cements, fly ash and microsilica (condensed silica fume) are shown in Table 1.

Table 1 – Chemical and physical data for cement, fly ash and microsilica.

		CEM I 42.5	CEM I 42.5 SR	CEM II / B-V 42.5	Fly ash	Micro silica
Used in concrete mixture No.		2, 5, 6, 7, 8, 9, 10	3	4	5	8, 9, 10
Chemical analysis						
SiO_2	[%]	21.38	25.75	29.74	50.58	>90
Al_2O_3	[%]	4.93	1.46	12.06	28.71	
Fe_2O_3	[%]	2.97	1.72	3.7	4.69	
CaO	[%]	64.51	67.2	47.76	6.05	
MgO	[%]	1.24	0.56	1.36	1.35	
SO_3	[%]	2.37	1.82	2,00	0.68	
Loss on ignition	[%]	0.9	1.19	3.18	7.83	
K_2O	[%]	0.63	0.04	0.59	0.73	
Na_2O	[%]	0.32	0.17	0.29	0.23	
Eq. Na_2O	[%]	0.74	0.2	0.68	0.71	
C_3A (calculated)	[%]	8.0	1.0	-		
Physical tests						
Fineness						
Passing 45 µm	[%]	83.5	96.8	96.1	82.9	100
Blaine	[m^2/kg]	363	299	436	367	20000
Density	[kg/m^3]	3150	3170	2890	2230	2200
Compressive strength (EN 196-1)						
1 day	[MPa]	11.7	8.8	8.9		
2 days	[MPa]	21.5	17.6	20.9		
7 days	[MPa]	40.5	30.3	35.5		
28 days	[MPa]	53.6	49.9	49.0		
56 days	[MPa]	59.1	61.7	60.8		
90 days	[MPa]	60.8	66.1	65.9		

* Consists of 70 wt% ground portland cement (Blaine: 388 m^2/kg) and 30 wt% ground fly ash (Blaine: 515 m^2/kg)

The chemical admixtures used were an air entraining admixture, a lignosulphonate based plasticizing admixture, and a naphthalene sulphonate based superplasticizing admixture.

The fine aggregate was from an inland deposit, and the coarse aggregate consisted of 8-12 mm and 12-16 mm sea dredged gravel.

2.2 Mix design

The project comprised a total of 9 concrete mixtures. The mix designs are shown in Table 2.

Table 2 – Mix design, fresh concrete properties, and compressive strength

No.		2	3	4	5	6	7	8	9	10
Designation		Reference	CEM I 42.5	CEM II/B-V	FA-	HSC			HPC	
		CEM I 42.5	SR	42.5	addition	no air entr.	air entr.	10 v.% MS	30 v.% MS	50 v.% MS
Mix design (nominal)										
Cement (C)	[kg/m3]	330	330	310	290	400	330	530	415	294
Fly ash (FA)	[kg/m3]				125					
Microsilica (MS)	[kg/m3]							42	125	209
Water (W)	[kg/m3]	160	160	150	160	115	102	120	113	105
Fine aggregate	[kg/m3]	710	800	722	664	772	772	698	705	714
Coarse aggr. 8-12 mm	[kg/m3]	535	533	541	498	579	579	524	530	536
Coarse aggr. 12-16mm	[kg/m3]	535	445	541	498	579	579	523	530	536
Admixture type*		AE	AE	AE	AE+P	SP	AE+SP	SP	SP	SP
W/C		0.48	0.48	0.48		0.29	0.31			
W/(C+0.4FA+2MS)		0.48	0.48	0.48	0.47	0.29	0.31	0.20	0.17	0.15
W/(C+FA+MS)					0.39			0.21	0.21	0.21
Paste vol. fraction incl. air		0.31	0.30	0.29	0.35	0.26	0.24	0.32	0.32	0.31
Fresh concrete properties										
Slump	[mm]	30	20	20	10	20	10	150	60	110
Vebe	[s]	2.6	7.0	4.5	6.3	9.8	15.0	0.0	5.3	-
Density	[kg/m3]	2277	2330	2302	2280	2450	2418	2472	2424	2445
Air content	[%]	4.9	3.9	3.8	4.0	2.0	3.6	1.5	2.2	1.9
Compressive strength (cast test cylinders, water cured at 20°C)										
1 day	[MPa]	12	14	10	11	30	31	51	50	36
7 days	[MPa]	30	35	30	28	58	55	75	85	82
28 days	[MPa]	38	44	40	45	72	66	95	115	114
90 days	[MPa]	42	50	52	56	82	78	115	135	133
1000 days (2.7 yrs.)	[MPa]	48	60	59	65	94	83	116	137	147
2280 days (6.2 yrs.)	[MPa]	52	65	60	71	102	94	125	143	158
Compressive strength (drilled cores)										
5000 days (13.7 yrs.)	[MPa]	46	62	52	51	76	80	100	118	117
8760 days (24.0 yrs)	[MPa]	61	78	61	75	104	107	131	131	158

* AE: Air entraining admixture, P: Plasticizing admixture, SP: Superplasticizing admixture

Concrete No. 2 served as the reference concrete and was designed to serve in an aggressive environment according to the Danish code. It was prepared at a water/cement ratio of 0.48 and with an air content of 4.9 %, using a traditional Danish portland cement (Concrete No. 1 which was used for ladder unit No. 1 was unsuccessful and was therefore not included in the project).

Concrete No. 3 had a mix design essentially similar to that of the reference, but was prepared with the new low alkali, sulphate resisting cement.

Concrete No. 4 also had a mix design essentially similar to that of the reference but used blended cement (fly ash cement). The fineness of the cement was chosen to provide the same 28 day compressive strength as the reference.

Concrete No. 5 was prepared with separately added fly ash and was designed to yield a 28 day compressive strength equal to that of the reference, assuming a cementing efficiency factor of the fly ash equal to 0.3, i.e. about 40 kg/m^3 of cement was replaced by 125 kg/m^3 of fly ash.

Concrete No. 6 was a "high strength concrete" (HSC) without air entrainment, having the very low water/cement ratio 0.29. Using a high dosage of superplasticizing admixture led to an acceptable workability of the concrete despite the fact that the cement paste volume fraction of the concrete was significantly lower than that of the reference. At the time concrete of this type had been utilised in truss concrete girder bridge structures in Japan and were expected to attain some interest in Denmark as well. The concrete had no air entrainment, in expectation of the low water/cement ratio securing its frost resistance.

Concrete No. 7 was similar to No. 6 except for the air content. This concrete was intended to have an air content of 4-6 %, allowing for a lower cement content, and securing frost resistance.

Concrete Nos. 8, 9, and 10 were all high performance concretes, containing microsilica, efficiently dispersed by a very high dosage of superplasticizing admixture. The concretes had an extremely low water/(cement + microsilica) ratio - 0.21 – and no air entrainment. Nos. 8, 9, and 10 had increasing content of microsilica, corresponding to 10, 30, and 50 % by volume of cement + microsilica. These mixtures were precursors of the later Densit® line of cement based high performance products.

2.3 Precast concrete units

Nine precast concrete units were produced, each using one of the experimental concretes, and each eventually forming one step of the fish ladder. The individual unit was formed as an “inclined box”, 2.9 m long, 0.9 m wide, and 1.15 m high, as shown in Figure 1. The units were produced at a precast concrete plant in the summer of 1979 and installed on site in September 1979. The appearance of the fish ladder in July 2001 can be seen in Figure 2.

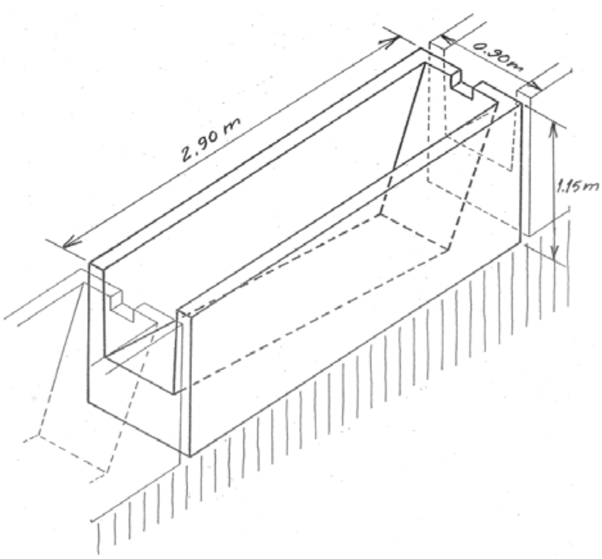

Figure 1 – Sketch of the precast concrete unit, forming one step of the fish ladder

Figure 2 - Photograph of the fish ladder (July 2001) [2]

2.4 Exposure conditions

The concrete surface was differently exposed in the various parts of each unit. Part of the surface was permanently submerged in the running fresh water, part of it was exposed to the ambient climatic conditions, including freezing and thawing, while either in a predominantly dry state or located in a “splash zone”.

2.5 Compressive strength

Test cylinders ø 100 mm x 200 mm for compressive strength measurement were cast in connection with production of the box units and were water cured at 20°C until testing up to the age of 6 years. At 14 and 24 years age cores (ø 95 mm x 140-150 mm) were drilled from the units and used for compressive strength determination.

2.6 Evaluation of durability

Ultrasonic velocity was measured at selected locations of the box units immediately after demoulding, then after transport and installation, and periodically up to the age of 1½ years. The results showed that no damages had been incurred during handling, transport and assembly of the units.

Durability was evaluated by microscopic analysis of thin sections prepared from cores taken from the bottom plate of the box units at 6 years age, and from cores taken from the overflow area at 21 years age.

3. RESULTS AND DISCUSSION

3.2 Compressive strength

The compressive strength of concrete Nos. 2-4 is shown in Figure 3.

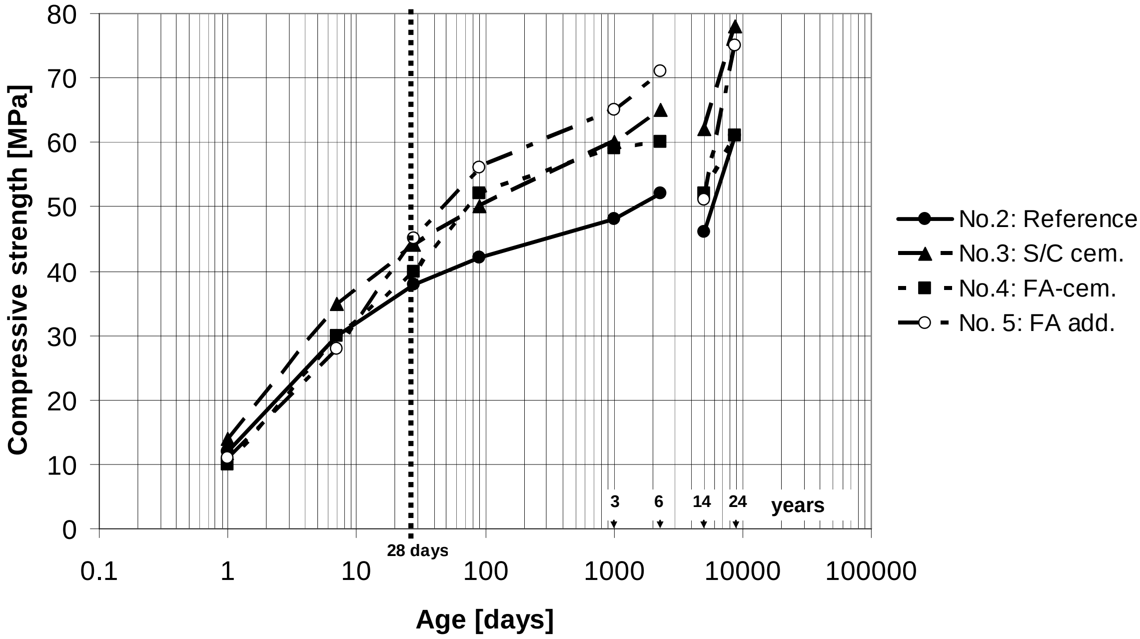

Figure 3 – Compressive strength development of concrete Nos. 2-5

The data points up to 6 years age originate from testing based on the cast and water cured specimens, and it is seen that the compressive strength systematically increases over that period, as expected. The 14 and 24 year strengths have been measured on drilled cores. At 14 years age the compressive strength result is apparently lower than at 6 years, where after the strength increases from 14 years to 24 years and reaches a level at 24 years significantly above that at 6 years. This pattern suggests that it is the nature of the specimens that is responsible for this behaviour. It has been reported [3] that cast specimens can yield as much as 25-55 % higher compressive strength than cored specimens. On the other hand, part of the “discrepancy” might be explained by the maturity of the cored samples being significantly lower than that of the cast specimens which have been cured at a constant temperature of 20°C. However, since we do not have a reliable tool to convert core results to cast cylinder results, we are left with the observation that at least there seems to be a significant strength increase in the period from 6 years to 24 years.

The reference concrete exhibits a strength gain of 37 % from 28 days to 6 years of age, and another 17 % increase from 6 to 24 years. The sand/chalk cement leads to significantly higher concrete strengths than the ordinary portland cement, perhaps because it has a higher content of both C_3S and C_2S. The blended cement meets its goal of producing a 28 day concrete strength similar to that of the reference, and gives significant further strength gain up to 6 years. From 6 years to 24 years, however, there does not seem to be any noticeable strength increase. The fly ash addition in concrete No. 5 apparently has a higher cementing efficiency factor than expected, and leads to a large concrete strength gain during the entire period up to 24 years.

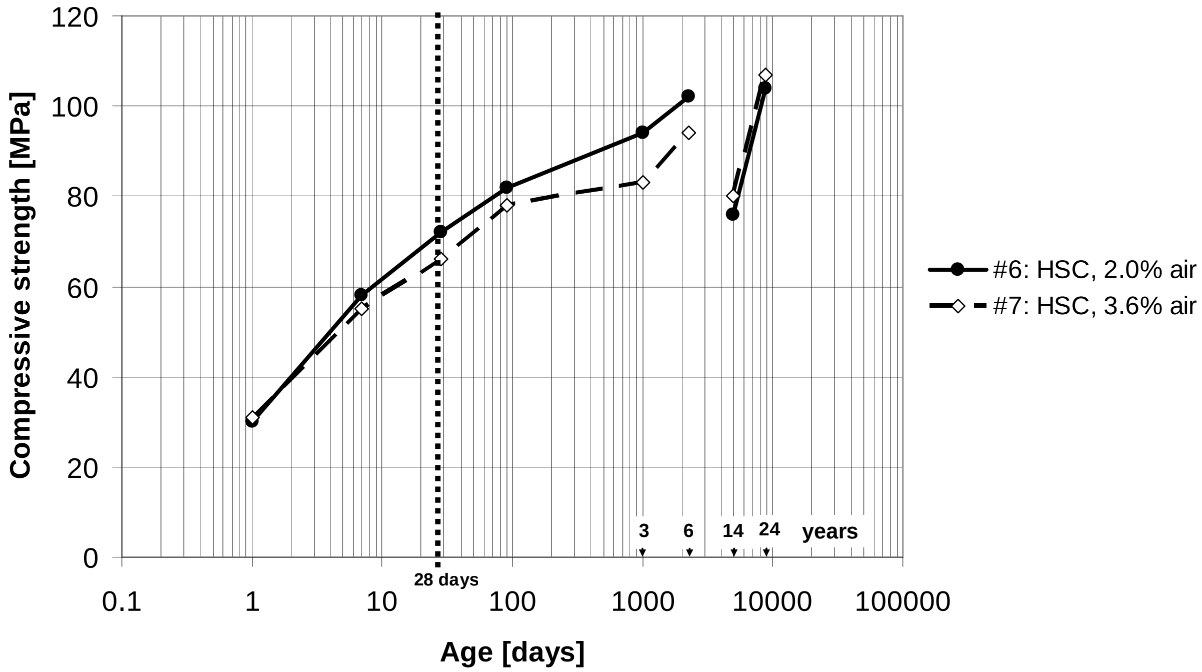

Figure 4 – Compressive strength development of concrete Nos. 6-7

The compressive strength development of the two high strength concretes is shown in Figure 4. Again, significant strength gain is noted beyond 28 days and during the entire period up to 24 years.

Figure 5 shows the compressive strength development of the three high performance concretes.

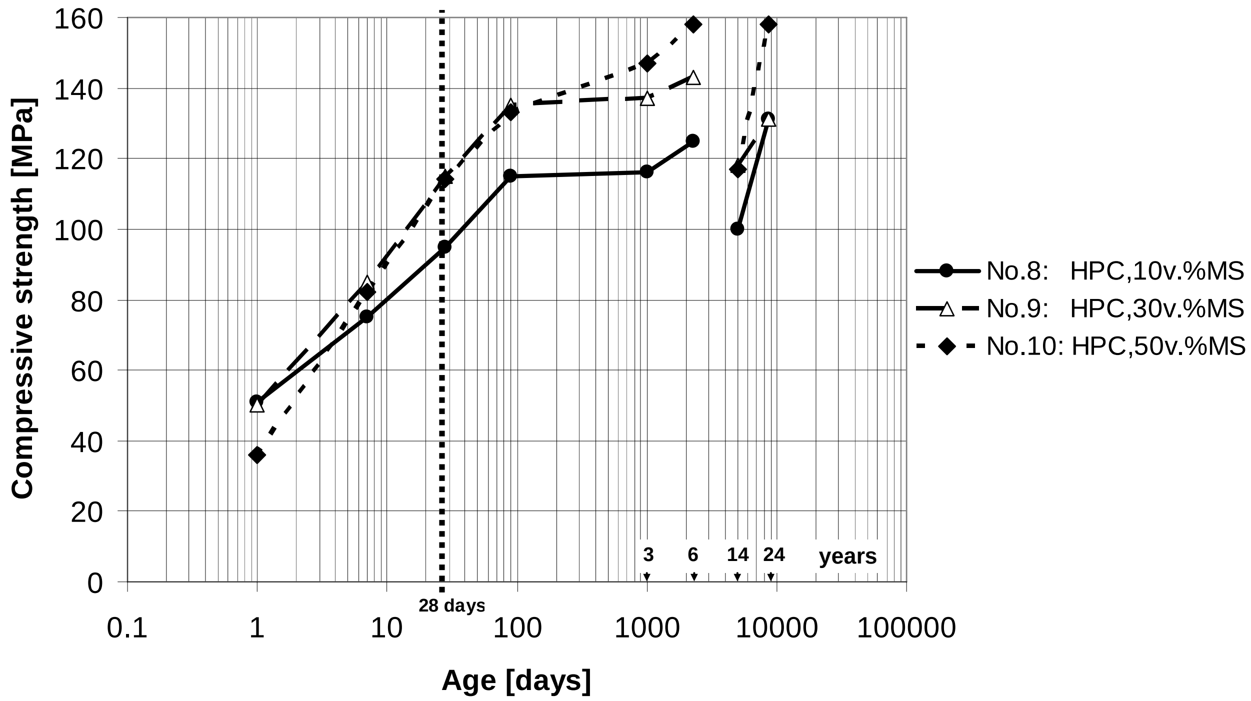

Figure 5 – Compressive strength development of concrete Nos. 8-10

The 28 day strengths range from 95 to 114 MPa and the compressive strengths further increase to 125-158 MPa at 6 years age. The 24 year strength with a microsilica content of 10 % by volume is distinctly higher than the 6 year strength, with 30 % microsilica the compressive strength apparently drops somewhat from 6 to 24 years, while it remains constant with 50 % microsilica. However, due to the non-systematic behaviour, and due to the fact that the cores probably underestimate the compressive strength it appears likely that at least there is no significant strength decrease at later ages in the dense concretes with microsilica, contrary to what has been sometimes suggested in the technical literature.

3.3 Durability

The results of thin section analysis by microscopy on samples taken at 6 years age [1] from the bottom plates and 21 years age [4] from the overflow area are summarised in Table 3.

A more or less continuous carbonate layer was observed outermost on all samples at 21 years age. It had a sharp border to the paste, indicating that the layer had been formed as a result of efflorescence. This was not seen on the 6 year samples which were taken from the water covered bottom plates.

The entrained air seemed to be well distributed, some minor depositions were found in the voids, and carbonation depths were found to be modest. Microcracks in the hardened paste were particularly found in the dense concretes containing microsilica, as expected. The observations after 21 years were generally not much different from those at 6 years, and no durability problems were observed.

Table 3 – Results of thin section analysis.

	No.	Age (years)	Air entrainment*	Substance in voids*	Paste microcracks	Carbonation depth (mm)	Thickness of carbonate layer (mm)
REF.	2	6	Non-hom.	Some ettr.	Some	0.4 - 1.0	-
		21	Fairly hom.	Some ettr.	A few	0.1 - 1.2	≈ 0.6
S/C-cement	3	6	Hom.	Ettr., CH, CĈ	Some	0.1 - 0.7	-
		21	Fairly hom.	Ettr., CH, CĈ	Some	0.1 - 0.2	Up to 2.0
FA-cement	4	6	Hom.	Little ettr. & CĈ	A few	0.1 - 0.7	-
		21	Hom.	Little ettr. & CĈ	A few	0.3 - 1.0	Up to 2.0
FA-addition	5	6	Hom.	Little ettr.	A few	0.1 - 0.7	-
		21	-	-	-	-	-
HSC, 2.0% air	6	6	None	CH, CĈ	Some	0.1 - 0.7	-
		21	-	-	-	-	-
HSC, 3.6% air	7	6	Hom.	Little ettr.	Many	0.4 - 1.0	-
		21	Hom.	Little ettr. & CH	Some	-	Up to 2.5
HPC, 10% MS	8	6	None	None	Many	0.1 - 0.4	-
		21	None	None	Some	Up to 0.3	Up to 2.5
HPC, 30% MS	9	6	None	None	Many	0.1 - 0.3	-
		21	None	Little CĈ	Many	Up to 0.2	Up to 2.0
HPC, 50% MS	10	6	None	Little CĈ	Many	Up to 0.1	-
		21	None	None	Many	0	Up to 0.5

* Hom.: homogeneous, Ettr.: Ettringite, CH: Calcium hydroxide, CĈ: Calcium Carbonate

In connection with dismantling the fish-ladder cores were drilled from the concrete units, cut in half and epoxy impregnated. Visual and microscopic inspection of these samples revealed no sign whatsoever of deterioration of any of the cores.

4. CONCLUSIONS

A total of nine concretes, comprising special cements, incorporation of fly ash, superplasticized high strength concrete and high performance concrete with microsilica, have been investigated during 24 years of exposure to running fresh water under Danish outdoor climatic conditions. The results lead to the following conclusions:

– None of the concretes investigated show any sign of durability problems after 24 years of exposure to running fresh water

– A large number of microcracks were observed in the hardened paste of dense non-air-entrained concrete with microsilica. However, the microcracks had no adverse effect on frost resistance after 24 years of exposure in a wet/humid environment

– All concretes showed a 30-50% strength increase from 28 days to 6 years, and a significant strength increase from 14 to 24 years.

– No sign of late strength loss of dense microsilica containing concrete was observed, despite the presence of microcracks

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