CURING OF CONCRETE

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Abstract

In the EN 13670 “Execution of Concrete Structures” guidelines are given for the curing. In Switzerland these guidelines were slightly modified and introduced into the standard SIA 262 “Concrete Constructions”. The concept of the requirements for curing is based in one table on the strength development related to the specified strength. In a second table, the length of the curing period is given in number of days. The number of days depends on the reactivity of the concrete (r-value), the curing class and the temperature of the concrete surface. In a research project, funded by the Swiss Road Authorities, ASTRA, it was investigated if the different approaches (strength development and fixed number of days) lead to similar concrete properties and if these regulations are valid for durability properties like the resistance against carbonation, chloride and freeze-thaw and de-icing salt resistance as well.

1. INTRODUCTION

1.1 General

In the last decades it was recognized that most of the damages on concrete constructions were caused by an insufficient durability and not an insufficient strength. The quality and the thickness of the cover concrete determine in most cases the durability of concrete constructions with respect to the rebar corrosion which is nowadays the dominating damaging process. The properties of the cover concrete depend not only on the composition but also on the placement, the environmental conditions and the curing. To obtain a sufficient concrete quality, it is therefore necessary to have sound requirements on the curing. A proper curing is necessary to protect the concrete from a too early drying, harmful vibrations, too high thermal gradients, too low temperatures and erosion in the case of rain fall. This paper focusses mainly on the aspect of drying on the concrete properties.

Nowadays the quality control of the concrete is made in Switzerland on separately manufactured concrete specimens and not the construction itself. Gouws et al. [1] compared the properties of concrete in the construction with that of separately manufactured specimens. The capillary water uptake and the chloride migration coefficient were about ¼ higher on cores taken from the structure compared to cores taken from specimens. Due to the differences in concrete quality between separately manufactured concrete specimens and the concrete structure, the SN EN 13791 “Assessment of in-situ compressive strength in structures and precast concrete components” reduces the strength requirements of cores taken from the structure by 15 % compared to the strength of the separately manufactured concrete specimens.

1.2 Curing regimes according to SIA 262

In the issue 2013 of standard SIA 262 “Concrete Structures” detailed information is supplied for the curing. This is based on the regulations and the informative annex F of the EN 13670:2009 “Execution of concrete structures”. The designer must determine the curing class (Tab. 1). The curing period depends on the curing class, the development of the concrete strength in the structure and the specified strength class of the concrete. The development of the concrete strength and the strength class of the concrete are determined on specimens stored in the laboratory under water at 20 °C.

In the SIA 262 as well as the EN 13670 it is assumed that the relevant (durability) properties of the concrete are linked to the (development of the) strength. As an alternative table 23 is provided in the SIA 262 (or informative annex F in EN 13670) which gives the curing period in days. This is displayed in Tab. 2 for rapid and medium strength development; the standard provides information for slow and very slow strength development, too. The curing class 2 usually applies in Switzerland to indoor (XC2), class 3 (XC4) to outdoor and class 4 to severe outdoor conditions (XD3, XF4).

Table 1: Table 4 of SN EN 13670 (=Table 22 of SIA 262); the line “requirement” is only included in the SIA 262 and not the EN 13670

Curing class	**1**	**2**	**3**	**4**
period (hours)	12[1)]	-	-	-
Percentage of specified characteristic 28 days compressive strength	-	35 %	50 %	70 %
requirement		standard	increased	high
[1)] Provided the set does not exceed 5 hours, and the surface concrete temperature is equal to or above 5 °C.				

Table 2: Minimum curing period according to tab. 23 of SIA 262 (=annex F of EN 13670)

		Minimum curing period for curing classes 2, 3 and 4[a] [days]					
Concrete strength development at 20 °C		rapid $r = f_{cm,2}/f_{cm,28} \geq 0.50$			medium $0.50 > r = f_{cm,2}/f_{cm,28} \geq 0.30$		
Curing class		2	3	4	2	3	4
$T_{concrete\ surface}$ [°C]	$t \geq 25$	1,0	1,5	3	1,5	2,5	5
	$25 > t \geq 15$	1,0	2,0	5	2,5	4	9
	$15 > t \geq 10$	1,5	2,5	7	4	7	13
	$10 > t \geq 5$[b]	2,0	3,5	9	5	9	18
[a] Plus any period of set exceeding 5 h. [b] For temperatures below 5 °C, the duration should be extended for a period equal to the time below 5 °C.							

1.3 Aim of the research project

The aim of the research project, funded by the Swiss road authorities, ASTRA, was to investigate, if the requirements given in the standard SIA 262 for the curing period (based on strength development or number of days) are appropriate for the durability properties.

2. INVESTIGATIONS

The Swiss standard SN EN 206-1 requires for the exposure class XD3 (chloride induced corrosion, alternating wet and dry) due to durability constraints a w/c-ratio of not more than 0.45 and 0.50 for XD1 (chloride induced corrosion, moderately wet). Therefore concrete having a w/c of 0.45 was manufactured to minimize the number of tests and costs. According to the standard SN EN 206-1 the concrete types D – G, which are used for the exposure classes XD3 and XD1, have a compressive strength class of C30/37. Two concrete types, one with a rapid hardening cement of the type CEM I 42,5 N (concrete A) and another with a slow hardening cement of the type CEM III/B 32,5 R (concrete B) were manufactured. In supplementary investigations concrete with cement CEM I and an air entraining agent (AEA) was investigated. In the first set of investigations both concrete types were stored in the laboratory at 6 °C and 80 % r.h. and at 20 °C and 70 % r.h. In the second set specimens of the same concrete types were stored outside (fig. 1).

Following curing regimes were applied:

- Wrapping in plastic sheet for different periods of time
- Stored under water for different periods of time
- Application of a curing compound, paraffin containing wax, 150 g/m^2 (CC)
- Use of controlled permeable formwork (CPF) to de-water the cover concrete

Figure 1: Outdoor storage

Following hardened concrete properties were determined at an age of 28 days, if not otherwise stated:

- compressive strength according to SN EN 12390-3,
- carbonation resistance, chloride resistance, water conductivity, freeze thaw and de-icing salt resistance and air permeability according to SIA 262/1.

One test comprises the testing of 1 to 5 specimens. The given results represent the mean value of the tested specimens according to SIA 262. No replica tests were made. According to SIA 262/1 the outer 5 to 10 mm of the concrete specimens must be cut off if the chloride resistance or the water conductivity have to be determined. Since this part of the concrete is mostly influenced by the curing, tests were also made where this part was not cut off. All durability tests were made on the original cast surface it not mentioned otherwise.

For all tests (except carbonation) cubes having an edge length of 150 mm were cast and cured according to the planned regime. On the cubes itself compressive strength and air permeability were determined. For the other tests specimens were drilled or cut from the cubes. The carbonation resistance was tested on prisms 120 mm x 120 mm x 360 mm. Selected results from [3] are presented subsequently.

2. RESULTS

2.1 Storage in the laboratory

2.1.1 Compressive strength

In figure 2 the development of the compressive strength with time is shown. Concrete A with the rapid hardening cement CEM I developed faster the strength than concrete B with the more slowly hardening cement CEM III/B. Both concrete types reached a compressive strength of more than 50 N/mm^2 at 28 days. This is higher than necessary to fulfill the requirements for the compressive strength class C 30/37. The higher strength is caused by the prescribed w/c-ratio. The necessary curing period at 20 °C according to tab. 1 for the curing classes 2 to 4 would be:

- Concrete A: 1 day for the curing classes 2 to 4
- Concrete B: 3 days for curing classes 2 and 3 and approx. 4 days for curing class 4

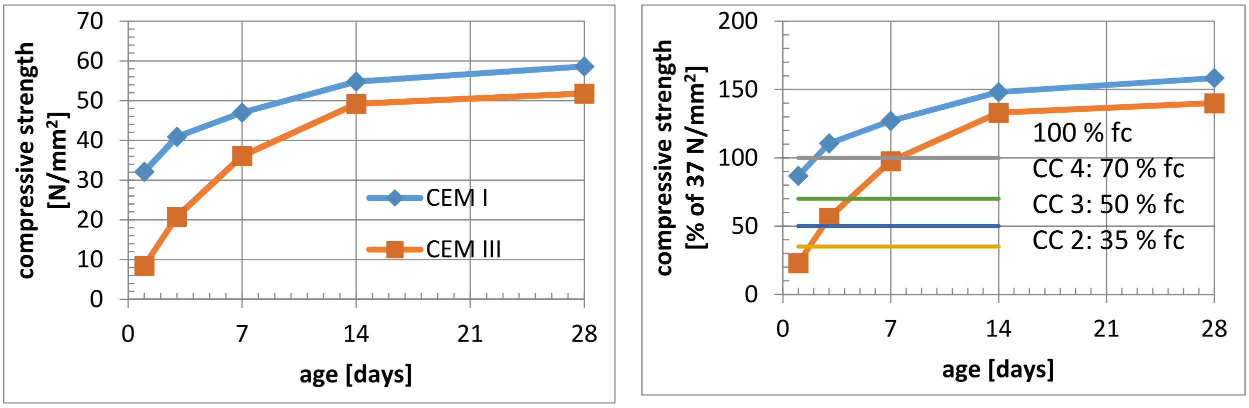


Figure 2: Development of the compressive strength of concrete A with CEM I and concrete B with CEM III/B absolutely (left) and relative (right) to the specified characteristic strength at 28 days. The specimens were covered with plastic sheets and stored at 20 °C.

2.1.2 Chloride resistance

The influence of the different curing regimes and storage conditions on the chloride migration coefficient can be seen in figure 3. The higher the chloride migration coefficient, the lower the chloride resistance. Concrete A with CEM I, stored at 6 °C, had a chloride migration coefficient between 6 and 10 x 10^{-10} m^2/s. When stored under plastic sheets and tested on the original cast surface, the chloride migration coefficient decreased with increasing storage time. If the concrete was stored under water or the outer part of the specimens were cut off, no or only a minor influence of the length of the curing period is visible. A storage under water for less than 14 days decreases the chloride migration coefficient more than a storage under plastic. If concrete A was stored at 20 °C, the chloride migration coefficient was equal or higher (6 – 14 x 10^{-12} m^2/s) compared to the storage at 6 °C. The influence of the length of the curing period is at 20 °C more pronounced than at the storage at 6 °C. The curing compound was as effectively as more than 7 days storage under plastic or 3 days in water. The CPF was as effectively as a storage of 14 days under water.

Concrete B with CEM III/B, stored at 6 °C, had a chloride migration coefficient significantly lower than concrete A. This can be attributed only to the cement type and not the curing. If the outer part of the concrete cover was cut off, storage under water and under plastic had the same effect. If the original cast concrete surface is tested, the chloride migration coefficient decreased with increasing curing period (plastic sheet, water). If concrete B was stored at 20 °C, the chloride migration coefficient was higher compared to the storage at 6 °C. The influence of the duration of the curing was more pronounced at 20 °C than at 6 °C. The curing compound and the CPF were very effective.

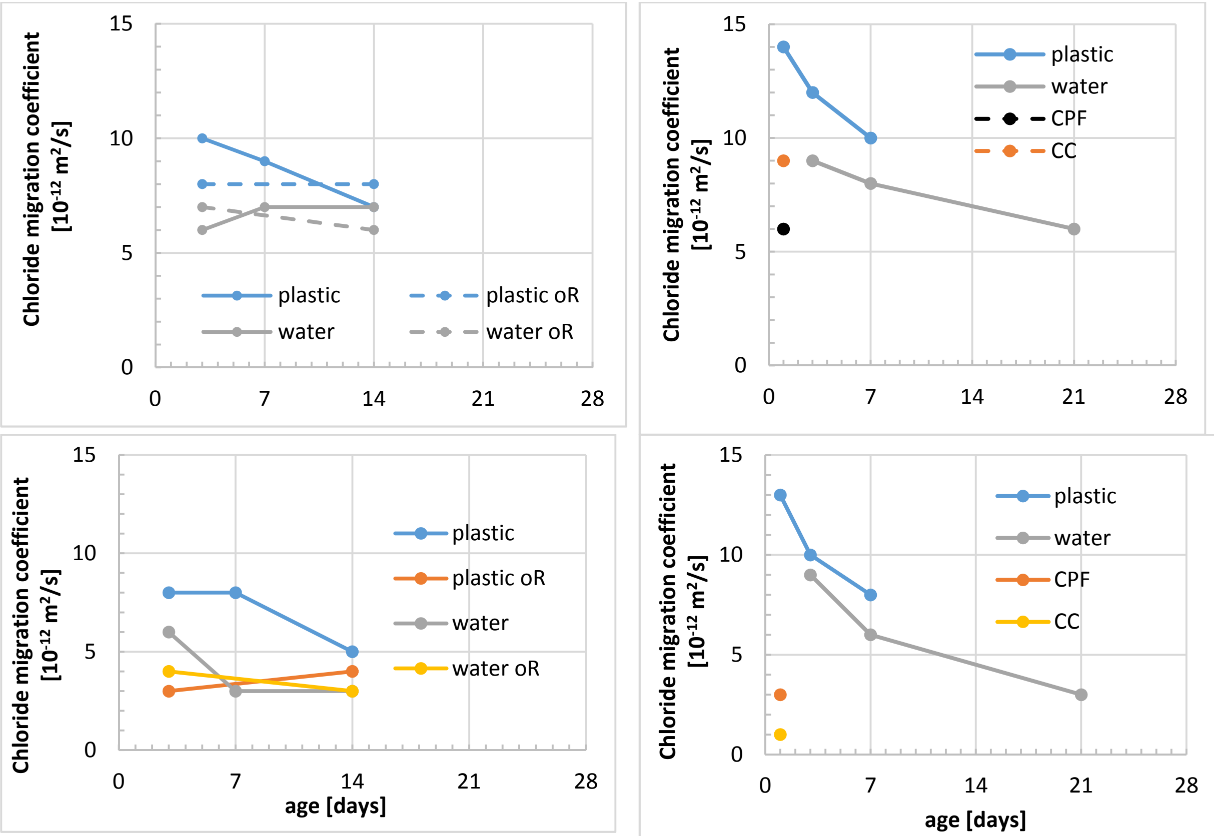


Figure 3: Influence of the curing regime and storage temperature (6 °C: left column, 20 °C: right column) on the chloride migration coefficient for concrete A with CEM I (upper line) and concrete B with CEM III/B (lower line); indoor storage, oR: without outer part of cover concrete; CPF: controlled permeable formwork; CC: Curing compound

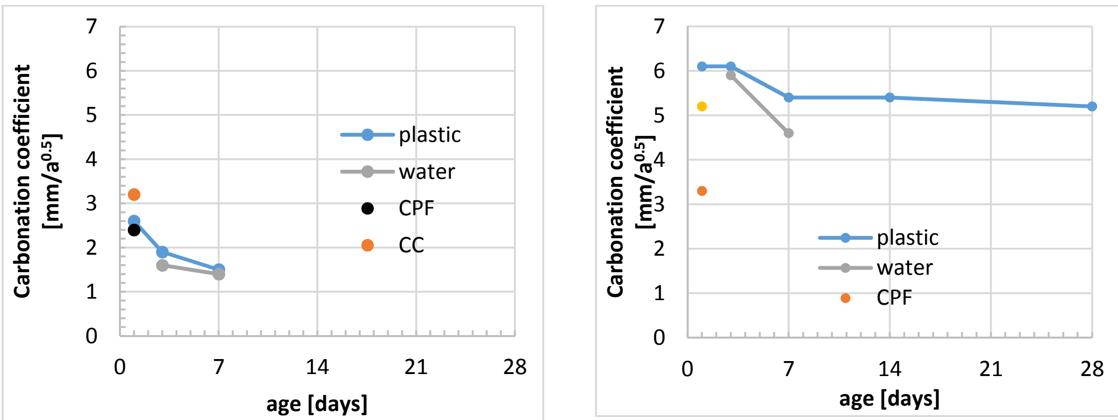


Figure 4: Influence of the curing regime on the carbonation coefficient for concrete A with CEM I (left) and concrete B with CEM III/B (right); 20 °C; CPF, CC: see fig. 3

2.1.3 Carbonation resistance

The higher the carbonation resistance the lower the carbonation coefficient. The influence of the length of the curing period, the type of curing and the storage temperature were similar to the chloride migration coefficient (fig. 4). The influence of the cement type was, as expected, opposite compared to the chloride migration coefficient: concrete A with CEM I performs much better than concrete B with CEM III/B. The curing compound was not very effective in the case of concrete A with CEM I stored at 20 °C. For concrete B with CEM III/B it was as effective as a storage for 28 days under plastic or approx. 5 days in water. The CPF leads to better results than the curing compound and was more effective for concrete B than for concrete A.

2.2 OUTDOOR STORAGE

The climate during the four weeks lasting outdoor storage is given in table 3. The data of the climate was recorded approx. 2 km from the storage facility (fig. 1). When the curing was finished, the specimens were further stored at the outside facility without protection until the age of testing. The aim was to investigate three climatic conditions. It can be seen in table 3 that the storage conditions at the aimed 5 – 10 °C and 10 – 15 °C were rather similar.

For all properties the influence of the storage temperature was less pronounced compared to the constant indoor climate (fig. 5). The curing compound was in most cases effective.

Table 3: Climate data [2]

aim [°C]	temperature [°C]			relative humidity [%]			rain [mm]	sunshine [h]
	min	∅	max	min	∅	max		
5-10	3	12	25	29	73	93	34	33
10-15	6	13	23	28	74	92	23	35
15-25	14	23	33	25	62	91	20	71

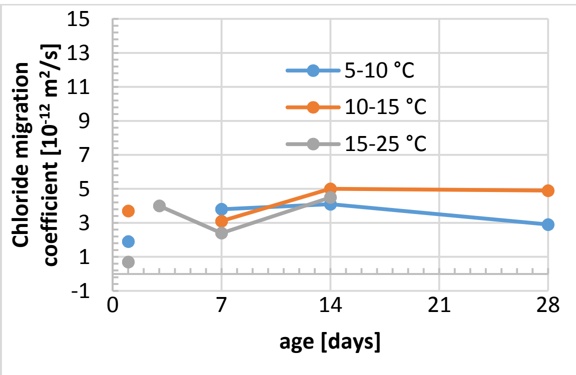
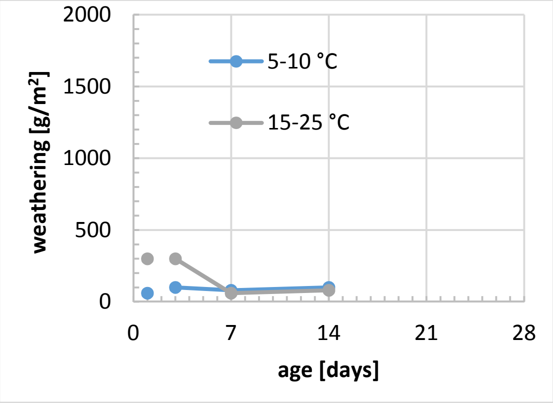


Figure 5: Influence of the curing regime and the storage temperature on the chloride migration coefficient of concrete B with CEM III/B. Dots at an age 1 day: use of curing compound CC

Concrete A with CEM I and the AEA had in general a low weathering which means a high freeze thaw and de-icing salt resistance (fig 6). At higher storage temperatures a up tp three day lasting storage under plastic or the use of the curing compound resulted in a slightly higher weathering. If concrete without AEA was tested, the weathering was in general higher compared to the concrete with AEA. No influence of the storage temperature or the curing duration could be found. Higher storage temperatures resulted for concrete A without AEA in a higher weathering, too. Concrete A without AEA had a high freeze thaw and de-icing salt resistance (200 g/m^2), when tested according to the standard SIA 262/1 (up to 28 days storage in water)



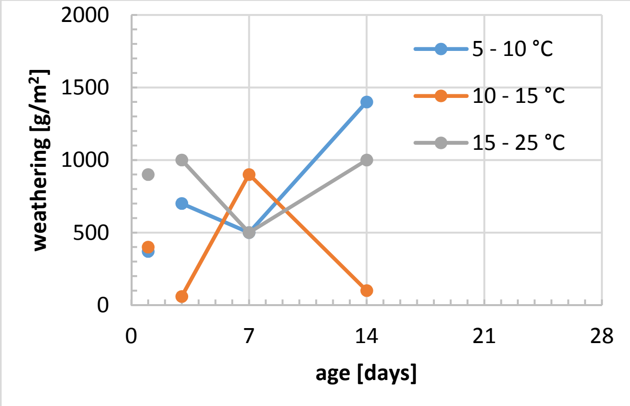


Figure 6: Influence of the curing regime and the storage temperature on the weathering of concrete A with CEM I and AEA (left) and concrete A with CEM I without AEA (right). Dots at an age of 1 day: curing compound

3. DISCUSSION

If the specimens were stored in the laboratory the influence of the storage temperature on the concrete properties was outstanding for all investigated properties. If the specimens were stored at 6 °C and having the worst curing regime no worse (in most cases better) properties resulted compared to a storage at 20 °C with the best curing regime. For the outdoor storage the influence of the storage temperature on the concrete properties was by far not as significant. The curing compound and the CPF were in most cases effective.

The reasons for a more durable concrete, stored at lower temperatures, are as following: due to a different mineral formation (crystallization) the fabric of the concrete becomes denser at lower temperatures. Additionally, at higher temperatures micro cracks may affect negatively the concrete quality. At higher temperatures dense shells might be rapidly formed around the cement grains resulting e.g. in high early strength, but which retard the further hydration. These effects are considerably influenced by the type of cement and mineral addition. The reasons for the less pronounced influence of the temperature during the outdoor storage are:

- In the laboratory at the constant climate a continuous drying and no condensation of water vapour occurs; during the outdoor storage a water supply can occur due to condensation and rain fall.
- If concrete is covered by a plastic sheet or with the curing compound, water from condensation or rain fall cannot penetrate into concrete. Only in the case of a worse curing (no plastic, no CC) water can penetrate into concrete.
- The temperatures vary outdoor resulting in a different crystallization of minerals.

To check if the curing regime according to SIA 262 and EN 13670 leads to the desired concrete quality, in table 4 the curing period according to table 22 and 23 of the SIA 262 is given. Additionally, the curing period determined in the experiments is displayed. A sufficient curing period was defined in such a way that the relevant concrete property fulfils the requirements for the conformity control of SN EN 206-1. It must be emphasized that by this definition the potential of the concrete for a better performance is not regarded. It can be seen in table 4 that the curing periods based on the requirements by table 23 are much longer than by table 22. The curing periods given by table 23 are sufficient for storage temperatures below 20 °C. For storage temperatures at or above 20 °C and the following concrete compositions the curing periods given by the standard SIA 262 (EN 13670) were not sufficient:

- The chloride resistance of concrete A with CEM I is insufficient if the curing is made with a plastic sheet and the necessary curing period is based on the requirement given by table 22 or 23. If the concrete is stored under water it was not clear if the curing period given by table 22 is sufficient (age not tested); the curing period given by table 23 was sufficient.
- The carbonation resistance of concrete B with CEM III/B was always insufficient when stored under plastic sheet. If the concrete was stored under water, the curing period given by table 22 was too short and that according to table 23 sufficient.

Table 4: Necessary curing periods for selected properties, determined acc. to SIA 262/1, according to the standards SIA 262 and EN 13670 and from experiments;

concrete, property	**temp. [°C]**	**Necessary curing period [days]**					
		SIA 262 (EN 13670)		based on test results			
		tab. 22	tab. 23	plastic	water	CC	CPF
A, Chloride migration coefficient: 10 x 10^{-12} m^2/s	6	< 3	9	3	< 3	-	-
	12	< 3	7	7	-	Yes	Yes
	20	< 3	5	7	3	Yes	Yes
	23	< 3	5	3	-	Yes	-
B, Chloride migration coefficient: 10 x 10^{-12} m^2/s	6	7	30	< 3	<< 3	-	-
	12	7	21	<< 7	-	Yes	-
	20	< 3	12	3	< 3	Yes	Yes
	23	< 3	12	<< 3	-	Yes	-
A, carbonation coefficient 5 $mm/a^{0.5}$	20	< 3	5	< 1	< 1	Yes	Yes
B, carbonation coefficient 5 $mm/a^{0.5}$	20	< 3	12	> 21	7	No	Yes

4. CONCLUSIONS

The curing periods given in table 22 and 23 in the SIA 262 (EN 13670) are not for all storage temperatures, concrete properties and concrete compositions sufficient.

For some concrete properties and concrete compositions the curing periods in SIA 262 are much too long. Therefore an insufficient curing according to the requirements given in SIA 262 or EN 13670 must not always result in an insufficient concrete quality.

Low temperatures (< 15 °C) are benefical for the properties except the early strength.

The influence of the storage temperature on the concrete properties differed significantly depending whether the storage was indoor or outdoor.

If concrete is used which has a strength much higher than the specified (e.g. precast concrete) very short curing periods result according to the requirements in the standard.

Curing with a water supply results, especially at temperatures above 15 °C to a higher quality compared to a storage under plastic sheets. More details will be given in [3].

REFERENCES

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[2] Climate data station Niederlenz, www.wetterstation-niederlenz.ch

[3] Jacobs, F. (2014): Efficiency and testing of curing regimes for concrete.- VSS-report in preparation