A NEW CONCRETE MIX DESIGN – PILOT APPLICATION FOR A ROAD BRIDGE PARAPET

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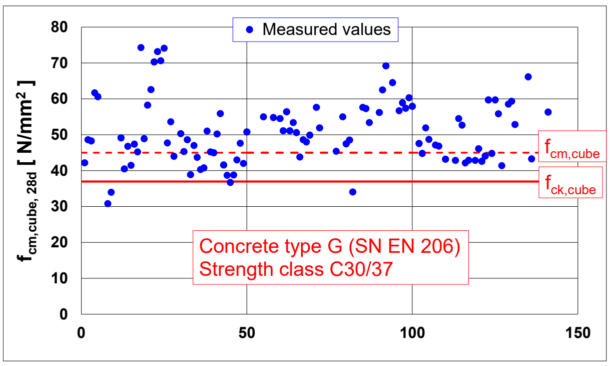
Abstract

The limiting values of concrete compositions, even in the case of so-called designed concrete according to SN EN 206 [1], does not always lead to satisfactory results with regard to structural application: frequently elevated strengths, in particular excessive tensile strength, may prove to be a source of unacceptable crack widths, and, thus, compromises durability. This led Federal Roads Office (FEDRO) to investigate alternative concepts for developing a more suitable design of concrete mixes, also allowing for taking other aspects into account, such as sustainability indicators. The performance concept without limitation of the concrete composition, based on a draft proposal for an Annex ND to SN EN 206, was tested for a new design of concrete, covering the exposure classes XC4(CH), XD3(CH) and XF4(CH), with a constraint on the maximum compressive strength. The developed concrete was successfully used in a pilot application for a 126 m long bridge parapet as part of a rehabilitation project for the Tuscherz Bridge on National Road 05, Switzerland. The use of CEM III/B cement in reduced quantities has resulted in a significant decrease in clinker consumption compared to current type G concretes with sufficient strength and durability properties and, additionally, with significant positive implications on the sustainability (lower energy consumption and carbon emission).

INTRODUCTION

The majority of concrete elements in highway construction need, among other demands, to be designed for a high resistance to environmental exposure. In order to achieve the requirements of the exposure classes, the current Swiss concrete standards [1] impose limits of the concrete composition, in particular the minimum cement content and maximal w/c ratio, which often leads to in-situ strengths that exceed the project-required values. It should be noted that the standards do not define an upper bound for mechanical strengths. Figure 1a) shows the statistic of the 28d mean compressive strengths of type G concretes, with a nominal strength class C30/37. The type G concrete is most frequently used for the elements exposed to road environment. The results mainly concern bridge elements and retaining walls of Federal Roads Office (FEDRO) construction sites carried out in the last 10 years.



a)

b)

Figure 1 – a) Measured compressive strengths of type G concrete used in recent FEDRO construction sites (mean values of mostly 3 cubes from four major concrete producers in the western part of Switzerland); b) unfavourable crack distribution on a parapet mostly due to over-strengths of in-situ concrete.

While this additional strength may be beneficial for heavily reinforced and, in particular, prestressed members, where the detailing is governed by ultimate limited state, in case of reinforcement design governed by serviceability in particular with regard to crack control in the case of constrained deformation, it may lead to some undesirable phenomena. If the tensile strengths are significantly higher than the value used for minimal reinforcement design, the underestimation of crack opening can bring into question the durability of the element or its tightness in the case of water pressure. This can be the case for long continuous and constrained elements, such as retaining walls, bridge parapets and curbs, or water treatment tanks. Figure 1b) shows an example of undesired crack pattern, with insufficient crack distribution, thus crack openings that exceed serviceability limit values for severe exposure conditions.

A number of parameters are associated with an accurate minimal reinforcement design that allows for crack control, as discussed below. In the present work, FEDRO is focusing on the tensile strengths, related to compressive strengths, as one of the parameters that is directly proportional to crack opening and distribution. The approach of preventively increasing the reinforcement ratio, without having a control over the maximal expected material strength, is not considered a satisfactory or sustainable solution. The research is therefore directed towards the alternative method for a concrete mix design, which allows a reduction of the strength to necessary level, while fulfilling durability requirements.

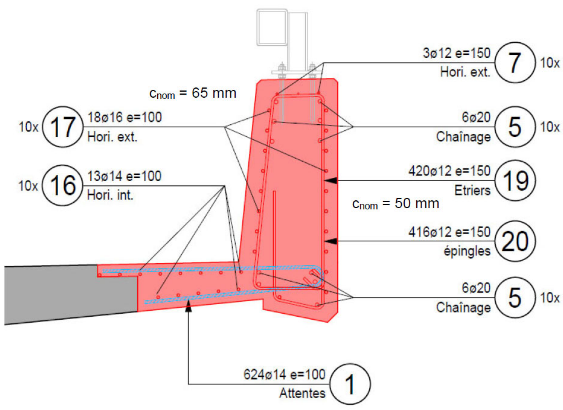
A real and rather simple performance-based concept, based on a draft proposal for an Annex ND to SN EN 206 [3], was applied for this aim, as explained in Chapter 2 and 3.

Finally, the objective was to apply the new concrete beyond the laboratory scale and evaluate its suitability for manufacturing (production in a concrete plant, transport and casting) and its behaviour on structural level. A rehabilitation project of the Bridge on National Road 05, at Tuscherz rail station, was chosen for a first pilot application: the concrete is tested in 126 m long parapet.

PROJECT

The bridge at Tuscherz was rehabilitated in the frame of an ordinary maintenance programme, aiming to assure the security for the exploitation, and to preserve the substance. The analysis has shown that the structural safety of this prestressed concrete structure is ensured, thus no structural strengthening was required. Only the parapets (Figure 2), which no longer complied with the normative requirements, had to be completely rebuilt. The new parapets had been designed according to Suisse standards for H2 containment level, here as a 90 cm high concrete wall with a guardrail on top. This geometry, and the casting phases of approximately 60 m of length were considered to provide good preconditions for testing of a new concrete mix design.

a)



b)

Figure 2 – a) Bridge over the rail station area in Tuscherz (Canton Berne / Switzerland), before rehabilitation; b) cross section of the new concrete parapet with c_{nom} = 65 mm (inner face) and 50 mm (outer face).

Minimum reinforcement to control the crack widths

In addition to appropriate execution measures, such as early-age concrete cure, the minimum reinforcement plays a dominant role in controlling crack opening and distribution. Various models, with different level of complexity and accuracy, can be used to predict cracking in structural elements.

According to the Swiss code for concrete structures [2], crack opening can be directly correlated to the tensile stress in reinforcement bridging the crack, σ_s. At the onset of cracking, σ_s shall be limited to an admissible value, $\sigma_{s,adm}$, which mainly depends on the exposure level and rebar diameter. In case of axial tensile solicitations, e.g. a restrained continuous retaining wall or parapet under imposed deformation due to shrinkage or temperature, the minimal amount of reinforcement, $A_{s,min,}$ can be determined according to the following expression:

$$A_{s,min} * \sigma_{s,adm} \geq f_{ctd} * A_{ct,i} \quad \text{Eq. 1}$$

where $A_{ct,i}$ is the surface of reinforced concrete section which cracks and f_{ctd} is the design value of tensile strength of concrete. Thus, the minimal reinforcement area is a direct function of concrete tensile strength. If the *in-situ* tensile strength is significantly higher than the value assumed for design, the insufficient reinforcement section will lead to premature yielding of reinforcement and the formation of few cracks with uncontrolled crack openings instead of the expected/desired network of evenly distributed fine cracks.

Requirements on concrete

For parapets, exposed to carbonation, frost and de-icing salts action, a concrete type G according to the Swiss standards [1, 2] is usually required. For the pilot application, two types of concrete were specified in the execution specification, in order to allow for a direct *in-situ* comparison, in particular with regard to crack distribution and crack widths:

- conventional concrete type G according to [1] is used for the parapet on the north side, and
- a new concrete mix, here designated as “concrete type G-ND”, was developed for the parapet on the south side, in accordance with the performance-based concept described in [3].

Table 1 to 3 summarise the requirements on the concrete composition, on fresh and hardened concrete properties. The development of this new type of concrete is described in Chapter 3. The demanded strength class is C20/25, but the upper limit for the 28d compressive strength is given based on the mean cube strengths of the next higher strength class, C25/30, i.e., 38 N/mm^2.

Table 1 – Requirements on concrete composition

Constituent	Concrete type G	Concrete type G-ND
Basic document	SN EN 206 [1]	Annex ND [3]
Cement type	Acc. to SN EN 206 [1]	No requirement. This project: CEM III/B
Minimum cement content	≥320 kg/m^3	No requirement
Mineral additions (type I and II)	Acc. to SN EN 206 [1]	Acc. to SN EN 206 [1]
w/c or w/c_{eq}	≤0.45	No requirement
k-value concept (type I and II)	Acc. to SN EN 206 [1]	Not applied; k = 1
Entrained air	No requirement. It is in the responsibility of the concrete producers to choose a reasonable value with the duty to fulfil the requirements on XF4, see Table 3b. Verification by testing.	

Table 2 – Requirements on fresh concrete

Fresh concrete property	Test method	Concrete type G	Concrete type G-ND
Consistence class	SN EN 12350-05	F4	F4
Bleeding water	Annex ND-1 [4]	No requirement	≤50 l/m^3
Extent of segregation	Annex ND-2 [5]	No requirement	≤2.0

Table 3a – General requirements on hardened concrete

Hardened concrete property	Concrete type G	Concrete type G-ND
General	According to SN EN 206 [1]	According to Annex ND [3]
Strength class	C30/37	C20/25
Maximum 28d cube strength	No requirement	≤ 38 N/mm^2
Exposure classes (CH)	XC4, XD3, XF4	XC4, XD3, XF4
Maximum aggregate size	32 mm	32 mm
Chloride content class	0,10	0,10

Table 3b – Durability requirements on hardened concrete

Hardened concrete property	Concrete type G	Concrete type G-ND
Carbonation resistance: SIA 262/1, Annex I [6]	No requirement. No test required	No requirement [1)]. Testing required.
Chloride resistance: SIA 262/1, Annex B [6]	$10 \cdot 10^{-12}$ m^2/s	$10 \cdot 10^{-12}$ m^2/s
Freeze thaw resistance: SIA 262/1, Annex C [6]	$m \leq 200$ g/m^2 or $m \leq 600$ g/m^2 and $\Delta m_{28} \leq (\Delta m_6 + \Delta m_{14})$	$m \leq 200$ g/m^2 or $m \leq 600$ g/m^2 and $\Delta m_{28} \leq (\Delta m_6 + \Delta m_{14})$
ASR resistance: MB 2042 [7]	Pass concrete performance test	Pass concrete performance test. This project: no requirement due to the use of CEM III/B

[1)] *Requirements for the carbonation resistance will be defined for new projects.*

DEVELOPMENT OF THE CONCRETE MIX

Background

Most of the current provisions in SN EN 206 [1] have been valid now for more than 15 years and have contributed to adapting concrete production to the changed conditions (e.g., new types of cement with different effects on concrete properties) and needs (e.g., demands for more sustainable concretes). Of particular importance in Switzerland was the inclusion of specifications for durability properties and the associated test methods in the SN EN 206 [1] and SIA 262/1 [6] standard. This development subsequently also formed the basis for the release procedures for the use of new cements, mineral additions and new combinations of cement types and mineral additions.

The current provisions, however, make it increasingly difficult to really use the existing potential of concrete. In particular, the rigid specifications of the w/c or w/c_{eq}-ratio and the minimum cement content are a hindrance. The concrete is overdetermined by today's specifications, as both composition and (durability) properties are required.

With today's knowledge of concrete technology and the experiences over more than 10 years now available, as well as with the established Swiss test methods, better adapted as well as more economical and sustainable concretes can be produced. Therefore, the specifications in the concrete standard must be adapted or supplemented.

For the concept of equivalent concrete performance (ECPC) as well as for the concept of equivalent performance of combinations of cement and mineral additions (EPCC), according to clauses 5.2.5.3 and 5.2.5.4 of SN EN 206 [1], no specific regulations exist in Switzerland and can therefore not be applied. The new provisions proposed in the Annex ND [3] follow the principles of the two concepts and extend them.

The proposal for a new national Annex ND [3] to the Swiss standard SN EN 206 [1] should make it possible to produce performance-based concretes, i.e., concrete for specific construction projects or with specific properties without the user (purchaser) of the concrete having to worry about the concrete composition.

In the Annex ND [3] new tests are needed to characterise the fresh concrete properties, i.e., bleeding, and segregation resistance [8]. Drafts for these tests have been elaborated [4, 5]. The bleeding test used here is also described in a guide to tremie concrete for deep foundations [9].

Preliminary tests (laboratory, ready mix concrete plant)
Figure 3 shows the scheme of the development of a new mix design according to Annex ND [3]. The starting point is the void volume of the aggregate mix which is going to be used for the concrete production. This must be determined according to SN EN 1097-3. Then, the volume of the composition of the paste is optimised to fulfil the requirements on fresh and hardened concrete. The key elements are:

1. The volume of the paste of a given concrete shall be such that the paste sufficiently fills the void volume of the aggregate mix used and results in robust fresh concrete properties.
2. The composition of the binder B (cement and mineral additions type II) and the volume of the paste (L) as well as the w/B-value or the w/L-value shall be chosen in such a way that all required fresh and hardened concrete properties are achieved and the corrosion protection of the reinforcement, if any, is ensured.

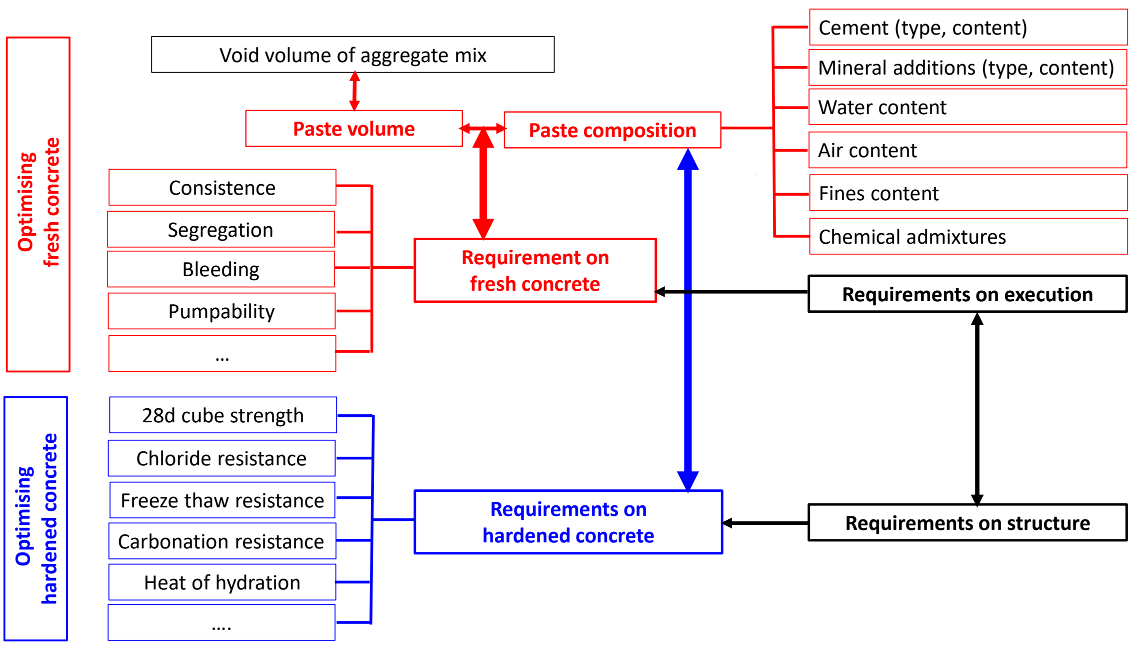


Figure 3 – Scheme for the concrete mix design based on the provisions given in Annex ND [3].

The paste volume (L) is calculated taking into account the density of the paste components. Paste constituents are cement (z), mineral additions (ZS), fillers (FÜ), solids in the admixtures (ZM) and water (w) as well as a specified proportion of the fine fraction of the aggregate (FG) and a specified proportion of the entrained air (LU). For fillers, the definition in SN EN 12620 applies.

$$L = \frac{z}{\rho_z} + \frac{ZS}{\rho_{ZS}} + \frac{FÜ}{\rho_{FÜ}} + a\ \frac{FG}{\rho_{FG}} + \frac{FM}{\rho_{FM}} + \frac{w}{\rho_W} + b \cdot \frac{1000 \cdot LU}{100};\ \text{l/m}^3 \qquad \text{Eq. 2}$$

z, ZS, FÜ, FM and w	contents according to the mix composition, kg
FG	average of the fines of the aggregates, kg
LU	average of the entrained air, Vol.-%
a, b	constants ($0 \leq a, b \leq 1$, e.g., 0.5).

Based on the concept described above, several preliminary trials were conducted in the laboratory as well as in the concrete plant to optimise the volume and the composition of the paste. For this, the fresh and hardened concrete properties have been assessed repeatedly. The void volume of the aggregate mix used for the concrete trials was 29.5 Vol.-%. The number of silos of the concrete manufacturer was limited what restricted the flexibility of the development, so that not all possibilities could be fully exploited. The results of these pre-tests are summarised in Table 4.

Table 4 – Optimised concrete recipe based on Annex ND [3]

Constituent	Content
Cement CEM III/B	250 kg/m^3
Mineral additions Type I (limestone powder, d_{50} = 5.5µm)	25 kg/m^3
w/B ratio (water/binder-ratio)	0.60
Paste volume	300 l/m^3
Superplasticiser	0.20% (not fixed)
Air entraining agent	0.40%
Retarder (only for one out of three concreting days)	0.30%

Prototype

In June 2021, a prototype was concreted on the construction site with the concrete recipe according to Table 4. The results of the tests are summarised in the Tables 5 and 6.

The casting results, i.e., fresh and hardened concrete properties as well as the appearance of the demoulded concrete surface, satisfied concrete manufacturer, construction company and as well FEDRO as client. Although not all concrete requirements were perfectly met, very likely due to the increased w/B ratio compared to the indications in the Table 4, the concrete recipe was accepted and approved for execution.

Both, the north and south side parapet with the type G and G-ND concrete, respectively, being of a light colour, have been coated with a pigmented hydrophobic impregnation to reach a better landscape integration.

Table 5 – Fresh concrete properties.

Parameter	Results
Flow class (flow diameter), SN EN 12350-5	F4 (500 mm)
Entrained air, SN EN 12350-7	6.5%
Density, SN EN 12350-7	2230 kg/m^3
Air temperature	17 °C
Concrete temperature	19 °C
w/B	0.63
Bleeding [4]	27 l/m^3
Segregation [5]	2.0

Table 6 – Hardened concrete properties.

Parameter	Results
28d cube strength, SN EN 12390-3	23.3 N/mm^2
In-situ 42d strength of six cores ∅ 100 mm	34.2 ± 2.9 N/mm^2
Carbonation resistance, Annex I [6]	9.8 mm/a$^{1/2}$
Chloride resistance, Annex B [6]	6.8 · 10^{-12} m^2/s
Freeze thaw resistance (mass loss 890 g/m^2), Annex C [6]	Medium
Shrinkage, SN EN 12390-16	-0.37 ‰
Splitting tensile strength (double-punch test, Barcelona test) [10, 11]	2.29 N/mm^2
E-modulus, SN EN 12390-13	23.9 kN/mm^2

EXECUTION OF THE CONCRETE WORK

Results

At the end of September and in the first half of October 2021, the parapet on the south side was concreted on three days (Figure 4). The results of the fresh and hardened concrete tests are available for two days. For the second day, these are incomplete, as the commissioned laboratories had staff absences (pandemic situation, vacation). Figure 5 shows a bright and smooth concrete surface.

The results of the fresh and hardened concrete tests are summarised in the Tables 7 and 8.

Figure 4 – Concreting on 2021-10-11.

Figure 5 – Appearance of the concrete surface after demoulding.

Table 7 – Fresh concrete properties of the execution

Parameter	Results of concreting		
	30.09.2021, 07:10	30.09.2021, 09:59	15.10.2021, 10:05
Flow class, SN EN 12350-5	F5 (560 mm)	F3 (460 mm)	F2 (350 mm)
Entrained air, N EN 12350-7	5.9%	6.0%	7.2%
Density, SN EN 12350-6	2300 kg/m^3	2280 kg/m^3	2280 kg/m^3
Air temperature	13 °C	14 °C	7.1 °C
Concrete temperature	22 °C	22 °C	16 °C
w/B	0.63	0.57	0.55
Bleeding [4]	39 l/m^3		9.3 l/m^3
Segregation [5]	2.2	1.5	1.6

Table 8 – Hardened concrete properties of the execution

Parameter	Results of concreting		
	30.09.2021, 07:10	30.09.2021, 09:59	15.10.2021, 10:05
28d cube strength, SN EN 12390-3	28.6 N/mm^2	31.5 N/mm^2	34.9 N/mm^2
Carbonation resistance Annex I [6]	9.6 mm/a$^{1/2}$	7.8 mm/a$^{1/2}$	9.5 mm/a$^{1/2}$
Chloride resistance Annex B-[6]	5.7 · 10^{-12} m^2/s		3.6 · 10^{-12} m^2/s
Freeze thaw resistance (mass loss) Annex C [6]	high (290 g/m^2)		high (180 g/m^2)
Shrinkage, SN EN 12390-16	-0.370 ‰		-0.311 ‰

Requirement on fresh concrete
The scatter of the flow diameter and w/B ratio was large. Thus, the requirements on flow class and w/B ratio were not always fulfilled.

Requirement on strength
The requirement on the 28d cube strength, i.e., the maximum value of 38 N/mm^2, could be met. The strength development up to 91d corresponds to the expectation (Figure 6). In comparison, the strength development of concrete type G, is much faster and the 28d compressive strength is over 90% higher.

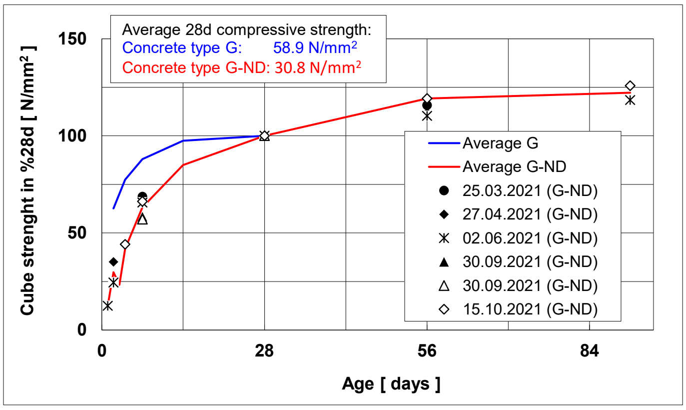


Figure 6 – Strength development of concrete type G-ND (results of the preliminary tests and of the prototype are included) compared to the results of concrete type G.

Requirement on chloride and freeze thaw resistance
The required chloride and freeze thaw resistance could be met.

Carbonation resistance

The carbonation coefficient as a measure for the carbonation resistance – determined according to Swiss testing standard [6] – varies with an average around 9.0 mm/a$^{1/2}$. Generally, the values are slightly higher than those found in an earlier research project [12] (Figure 7a). It can be recognised that the square-root of time law is not perfectly fulfilled (Figure 7b). The carbonation coefficient decreases over time as could be very well observed in long term studies under sheltered exposure conditions (XC3) in Wildegg as well as in other places [12]. The analysis of the lab results of the test for this project (Figure 7c) gave an averaged slope of about -0.11. In Figure 7d the carbonation depth as a function of time for different exposure conditions is shown. The details of the calculations will be given in the project's final report. It can be seen from Figure 7d that under the lab conditions as well as outside under sheltered conditions the carbonation depth after 50 years is between 30 and 40 mm. Under humid conditions (80% RH) the carbonation depth is much lower. It can be expected that under XC4 conditions with the influence of rain that the carbonation depth will be somewhere in between, very likely lower than 30 mm.

Of course, under the combined action of carbonation of the concrete cover and chloride ingress the corrosion process might start earlier. This will be studied in the next years. Nevertheless, it can be expected that this will not lead to any problems during the service life of 50 years, since the reinforcement cover is greater than 55 mm (c_{nom} = 65 mm) on this, severely exposed side.

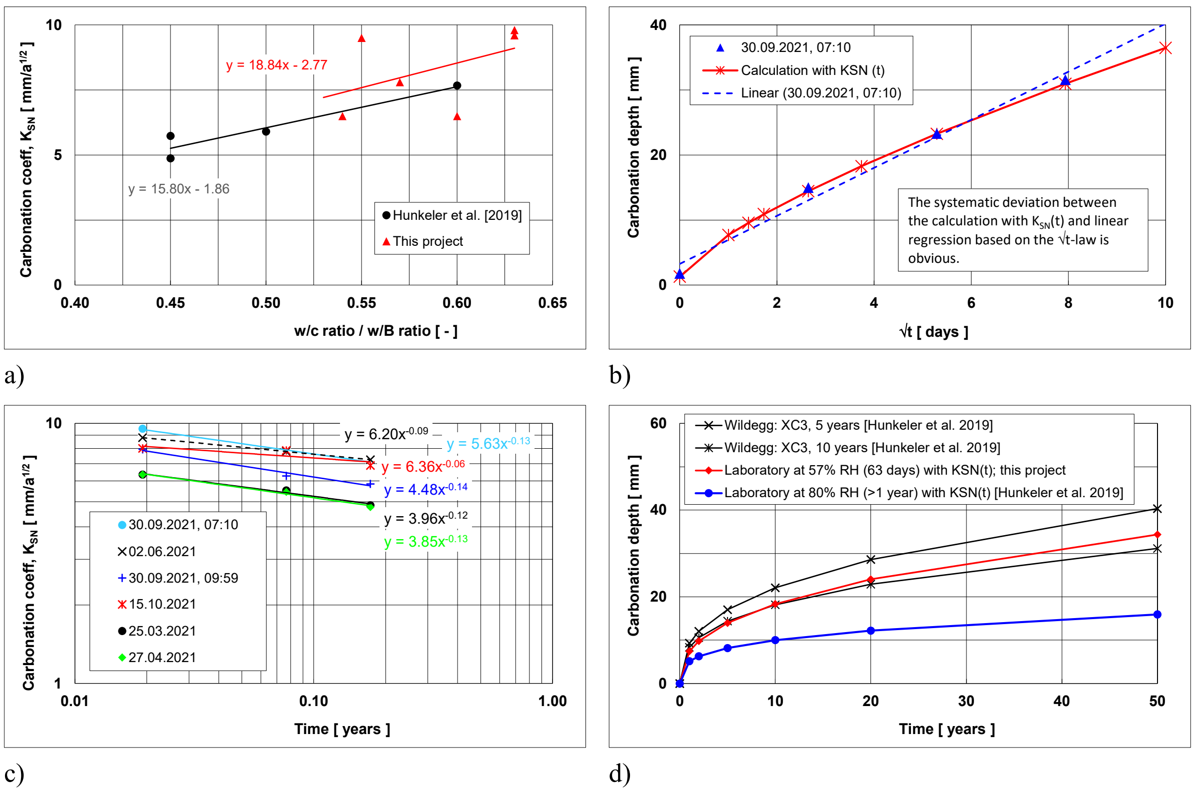


Figure 7 – a) Dependence of the carbonation coefficient K_{SN} on w/c or w/B ratio; b) Analysis of the time-law; c) Time dependent carbonation coefficient under standard testing conditions; d) Calculated carbonation depth as a function of time for different exposure conditions. Details will be given in the final report.

CONCLUSIONS

The mix design used for the pilot application presented in this paper has proven to be robust and leads to satisfactory results: good workability, good surface quality, 28d-cube strength less than required 38 N/mm^2, a high chloride and freeze-thaw resistance, as well as a sufficient carbonation resistance. It also has a much lower ecological impact than concrete mixes according to the current standard (e.g., concrete type G), considering the reduction of the cement content of more 20% and the reduction of about 70% of the clinker content compared to concretes with CEM II/A-LL.

RECOMMENDATIONS FOR FURTHER RESEARCH

- Further evaluation of the new concrete mix design for other concrete applications (e.g., bored piles) and for other concrete compositions (e.g., with other cement types and mineral additions) to optimise the properties, e.g., chloride and carbonation resistance or heat of hydration
- Verification of the predicted time course of the carbonation depth
- Investigation of the chloride ingress
- Investigation of the long-term effects of the combined action of chloride ingress and carbonation of the concrete cover.
- Comparison between theoretical results from cracking behaviour prediction models and in-situ measurements data (periodic measurement of crack widths and crack spacing).
- Identifications of possibilities for further improvements of cracking behaviour prediction models.

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