PROPERTIES OF WATERTIGHT CONCRETE WITH DIFFERENT DESIGN APPROACH

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ABSTRAKT

Předmětem článku je shrnutí diplomové práce autora, která se zabývá porovnáním celkem pěti variant betonových směsí navržených pro vodonepropustné betonové konstrukce, tzv. bílé vany. Hlavní důraz byl kladen na omezení tvorby trhlin, respektive jejich šířky, vznikající v konstrukci, neboť právě trhliny jsou častou příčinou poruch těchto typů konstrukcí. Za tímto účelem byl proveden komplexní experiment, ve kterém byly varianty betonových směsí podrobeny zkouškám čerstvého a ztvrdlého betonu. Hlavními sledovanými parametry byly mechanické vlastnosti betonu: pevnost v tlaku, pevnost v příčném tahu, statický modul pružnosti a hloubka průsaku tlakovou vodou. Dále bylo sledováno smrštění betonu při různých způsobech uložení vzorku a vývin teplot od hydratačního tepla po průřezu konstrukce. Získané výsledky byly dále aplikovány v teoretickém výpočtu šířky trhliny podle *fib* Model Code for Concrete Structures 2010. Výpočet šířky trhliny přináší zajímavé výsledky a jasně demonstruje jaký parametr čerstvého betonu má největší vliv na tvorbu trhlin v rané fázi jeho zrání.

KLÍČOVÁ SLOVA

vodonepropustný beton • bílá vana • hydratační teplo • smrštění betonu • šířka trhliny

ABSTRACT

The subject of the article is a brief summary of author's diploma thesis which deals with a comparison of five concrete mixes designed for watertight concrete structures, so-called white tanks. The main emphasis was placed on the limitation of crack widths. Cracking may cause leagake, which would be a significant obstacle of a reliable function of these structures. For this purpose, a complex experiment was conducted, where the different types of concrete were subjected to the tests of fresh and hardened concrete. The main monitored parameters were mechanical properties of concrete: compression strength, splitting tensile strength, static modulus of elasticity, and depth of penetration of water under pressure. Shrinkage of concrete was also monitored in different environmental conditions. Heat of hydration was measured in early stage of hardening. Obtained results were further applied in a theoretical calculation of crack width using the *fib* Model Code for Concrete Structures 2010. Calculation of crack widths brought interesting results and demonstrated which parameter of fresh concrete has the most influence on the crack development in the early phase of concrete maturation.

KEYWORDS

watertight concrete • white tank • heat of hydration • shrinkage of concrete • crack width

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1. INTRODUCTION

To ensure a suitable function of a watertight structure (so-called "white tank") it is necessary to pay attention to several aspects of the design. First of all, detailed design documentation has to be drawn taking into account the simplest transfer of loads to the foundation joint, design of sufficient amount of reinforcement, and adequate tightening elements to ensure water-tightness of all joints and openings. It is equally important to use a concrete mixture of suitable composition which provides resistance against penetration of water under pressure and eliminates cracking as much as possible.

Cracks are most often a consequence of tensile stresses which are induced mostly by uneven volumetric changes during the hydration, maturation, and subsequent drying of concrete. Predominantly, heat released during the hydration process can cause a large temperature gradient between the core and surface of the structure which can cause stress exceeding the current tensile strength of concrete and thus causing cracks in the structure. Also drying shrinkage can have a severe impact on volumetric changes later on during the service life of the structure.

Considering only the concrete mixture, there are several ways to limit the number of cracks and their width in the watertight structure. One approach is to use an admixture that can react with water present in the cracks and a create crystalline formation filling the cracks and making the concrete waterproof again. The second option is to avoid the creation of cracks preferably by reducing volumetric changes induced by temperature gradients and by shrinkage. One way to reduce the temperature gradient is to limit the content of clinker in cement, e.g. using blast-furnace cement (BFC). Another approach could be using steel fibers for carrying the tension in concrete. In the following section, an experiment is described investigating five different concrete mixes to reduce crack width by improving the properties of concrete. The results are taken from the author's diploma thesis (Hlavsa 2020).

2. EXPERIMENT

2.1. Concrete mixes

Five different concrete mixtures were investigated in this experiment. Specification of the concrete was determined as C 30/37 with exposure classes X0, XC1-4, XD1-2, XF1, XA1-2. Depth of penetration of water under pressure was limited to 35 mm. The compressive strength of the concrete was tested after 90 days. This specification was selected due to high demand by contractors for this type of structures. Two types of cement were used for this experiment: portland slag cement (PSC) CEM II/B-S 32,5 R (cement plant Radotín) and blast-furnace cement (BFC) CEM III/B 32,5 L -

Table 1: *Composition of concrete mixes.*

Materials	Concrete mix REF	XYP	PCO	FIB	PSH	Unit
PSC	x	x	-	x	-	$kg\,m^{-3}$
BFC	-	-	x	-	x	$kg\,m^{-3}$
Fly ash	12.3	12.3	25	12.3	25	%
w/c	0.40	0.41	0.42	0.39	0.40	-
Addition	-	CA	-	SF	SRA	-
Amount	-	20	-	20	1.5	$kg\,m^{-3}$

CA - crystalline admixture
SF - steel fibers
SRA - shrinkage-reducing admixture

LH/SR (cement plant Mokrá). Natural excavated aggregate was used with a maximum size of the grain 22 mm. Designation of individual concrete mixes and their composition can be seen in Table 1. Concrete mix REF is a basic and also a reference concrete mixture for this experiment. It contains PSC and has no additional ingredient for improving the properties of concrete. In contrast to the mix REF, the mix XYP contains a crystalline admixture, while the mix FIB contains in contrast to the mix REF steel fibers (50/1 mm). The second group of concrete mixes is those containing BFC. Concrete mixes PCO and PSH are specially designed for watertight concrete structures according to recommendations for concrete mixture composition in (Lohmeyer & Ebeling 2013). The concrete mix PCO is basic with no additional ingredient, while the mix PSH contains an additional shrinkage-reducing admixture (SRA). Since the experiment was conducted in a concrete producing company TBG Metrostav s.r.o, the cement content and the aggregate content is the company's know-how and cannot be published. Furthermore, fly ash is listed only in percent to the weight of cement. The experiment was carried out in a single day, so that the results could be reasonably compared. The mixing sequence followed the order of concrete mixes stated in Table 1. Time breakes between the individual mixing of mixes were approximately 30 to 45 minutes.

2.2. Testing procedures

The testing procedures are described in detail in (Hlavsa 2020). Compressive strength and splitting tensile strength of concrete were tested on cubes with an edge length of 150 mm and at specimen age of 2, 7, 28, and 90 days. Depth of penetration of water under pressure was tested on cubes with an edge length of 150 mm and at specimen age of 90 days. All the above tests were conducted according to valid standards of ČSN EN 12390. Static modulus of elasticity was tested on cylinders with a base diameter of 150 mm and height 300 mm and at specimen age of 2, 7, and 28 days according to valid standard ČSN ISO 1920-10.

The development of temperatures induced by heat of hydration was measured on concrete blocks with a size of 1.6x0.8x0.8m. Six sensors were placed in the body throughout the height of the cross-section (see cross-section in Figure 1). The sensors were placed in the middle of the body in line with the vertical axis. Values were recorded with an automatic data logger for the duration of 7 days with recording interval of 5 minutes.

Drying shrinkage was measured on cylinders with a base diameter of 150 mm and height 300 mm. A strain gauge was embedded in the middle of the cylinder to measure the volumetric changes of concrete. Three types of specimen placements were used for each concrete mix. One specimen was poured into a plastic mould and placed into a case with an outdoor environment. The second specimen was poured into a steel mould and was also placed into the case with the outdoor environment. The third specimen was poured into a plastic mould, the exposed surface of the concrete was insulated with plastic foil and the specimen was put into a tub with water to prevent drying shrinkage. The goal of the third specimen placement was to capture autogenous shrinkage. After 9 days, the specimens placed in the case were unmoulded. After 43 days, the specimens in the tub with water were unmoulded and placed into the case with outdoor environment. Values were recorded by an automatic data logger every 5 minutes for the first 9 days, from that age every hour. After 85 days, all specimens were placed into an indoor environment with stable surrounding conditions and the values were recorded with a handheld measuring device every week.

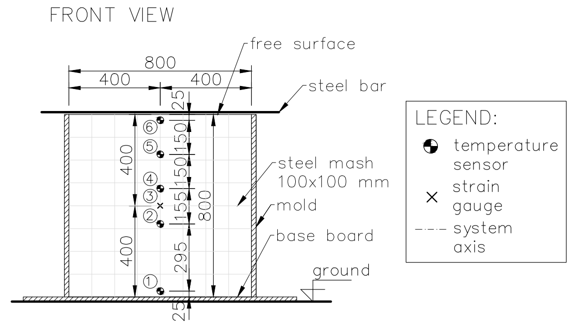

Figure 1: *Cross-section of the massive concrete block for measurement of the development of temperatures with the positions of sensors throughout the height of the cross-section.*

2.3. Calculation of crack width

The results obtained in the experiment were subsequently used in a simplified calculation of crack width and necessary reinforcement needed to limit crack width according to valid standards. For the calculation, only stresses induced by heat of hydration during the hydration process were considered. The calculation follows a procedure stated in (*fib* Model Code 2010).

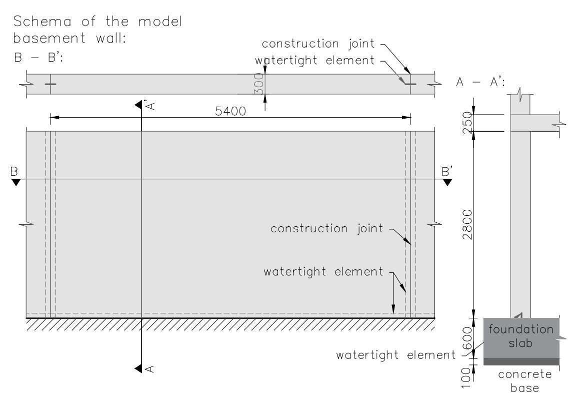

Figure 2: *Schema of the model basement watertight wall for the crack width calculation.*

The following assumptions were made. A model basement wall which is a part of a white tank structure of a residential building is considered (see Figure 2). The wall is 0.3 m thick, 2.8 m tall and one segment is 5.4 m long. The wall is embedded into a foundation slab with a thickness of 0.6 m. According to (Vítek et al. 2015), the model wall is classified with crack width limitation of 0.2 mm. From the results, the following values were used. Temperature gradient (ΔT_{max}) between the core and surface of the massive concrete block measured during the experiment. At the time of the highest temperature gradient ($t_{max,T}$) the remaining parameters were determined: coefficient of thermal expansion (α_c), static modulus of elasticity (E_c) and effective tensile strength of concrete (f_{ct}). For purpose of the calculation, only the crack formation phase was considered. Horizontal reinforcement is designed closer to the surface with 14 mm diameter bars, 150 mm spacing and 40 mm of cover layer.

3. RESULTS AND DISCUSSION

3.1. Mechanical properties of concrete

In this section, obtained results are discussed. Throughout the graphic presentation of the results, the same colours for individual concrete mixes are used.

Results of the compressive strength of concrete can be seen in Figure 3. At the early age, compressive strength of concrete mixes with BFC was lower than for the concrete mixes with PSC, which is in accordance with the parameters of the types of cement used for the different concrete mixtures. After 90 days, the strength of mixes with BFC is higher by about 17 %. Additionally, no positive impact on the compressive strength of concrete mix with crystalline admixture was observed.

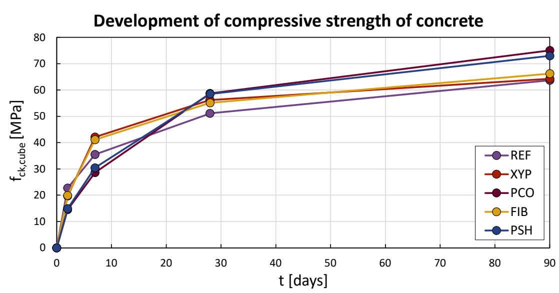

Figure 3: *Development of compressive strength of concrete for different concrete mixes.*

Results of the splitting tensile strength of concrete can be seen in Figure 4. The same pattern is observed as for the compressive strength. Mixes with BFC have a lower splitting tensile strength at the specimen age of 2 and 7 days, but at the later stage, the strength is higher. An interesting observation is that the strength does not increase after the 28th day. Also, no effect of steel fibers on splitting tensile strength was observed.

Results of the static modulus of elasticity of concrete can be seen in Figure 5. The graph demonstrates that the modulus of elasticity depends mostly on the type of aggregate that is used in the concrete mixture. Since the aggregate was the same for all concrete mixes, the development of modulus of elasticity is almost identical for all five concrete mixtures.

Results of the penetration of water under pressure can be seen in Figure 6. Due to the high variability of the results, which is very common for this testing method, a set of three specimens were tested for each concrete mix. Regardless, high variability was also observed in this experiment. Dashed line designates the average value out of the three specimens for each concrete mix. The difference between the individual concrete mixes is negligible and thus the results can be considered equal.

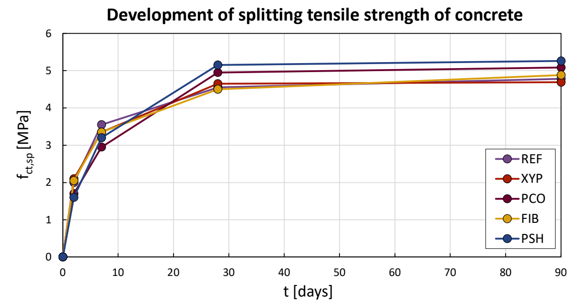

Figure 4: *Development of split tensile strength of concrete for different concrete mixes.*

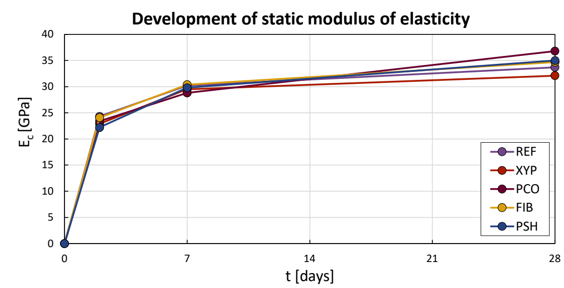

Figure 5: *Development of static modulus of elasticity of concrete for different concrete mixes.*

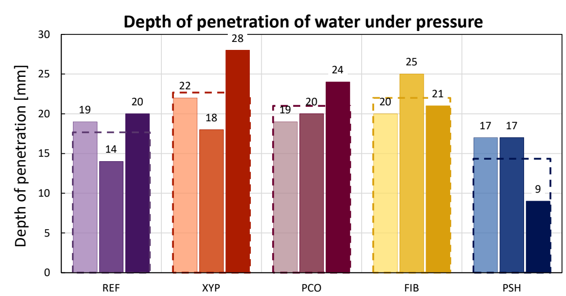

Figure 6: *Depth of penetration of water under pressure for different concrete mixes.*

3.2. Temperature gradient

The development of temperature in the core of massive concrete block for the individual concrete mixes can be seen in Figure 7. Values were recorded with sensor 2 (see Figure 1). Results indicate the different hydration process of mixes with PSC and BFC, but also an effect of crystalline admixture on the delay of the setting of concrete. The highest recorded temperature differs between mixes with PSC and BFC by approximately 7 °C. The vertical lines in the graph represents a point in time with the highest recorded temperature for each concrete mix. Furthermore, the highest recorded temperature with time when it was reached is noted in the graph. A small difference can be observed between the same mixes (PCO and PSH). This inconsistent course could be caused by different time of mixing of each mix.

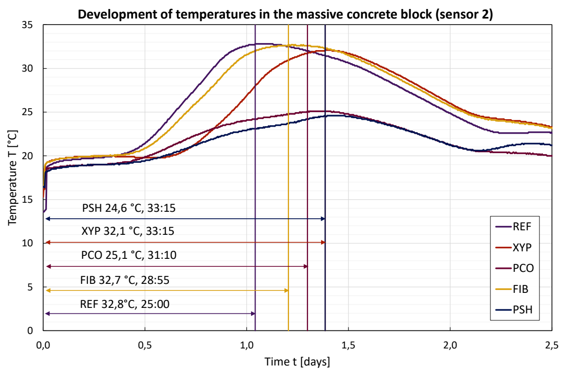

Figure 7: *The development of temperature recorded with sensor 2 in the core of massive concrete blocks.*

Temperature gradient between the sensor 2 and the sensor measuring air temperature can be seen in Figure 8. It should be noted, that the sensor measuring air temperature was insufficiently shaded. This fact manifested in peaks that can be observed in the line representing temperature of air, which subsequently influenced the temperature gradient as well. Temperature gradient of concrete mixes with PSC reached, at one point, over 20 °C. Such a value increases the risk of crack formation dramaticaly. While temperature gradient of concrete mixes with BFC only reached around 14 °C. The highest recorded temperature gradient is used in further crack width calculations.

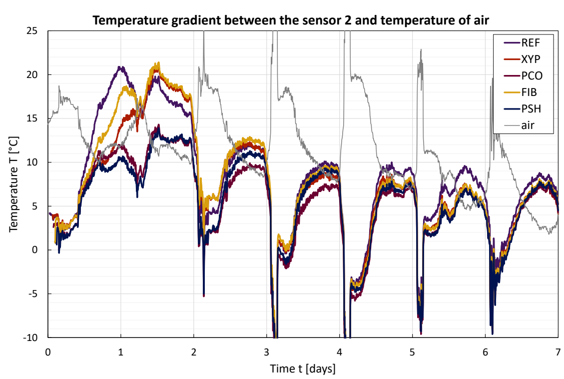

Figure 8: *The development of temperature gradient between the sensor 2 and the sensor measuring air temperature.*

3.3. Drying shrinkage

Results of drying shrinkage recorded on cylinders with strain gauge can be seen in Figure 9 through Figure 11. In the first 85 days, the recorded values are significantly scattered. This phenomenon is due to the placement of the specimens with a high frequency of vibrations caused by a nearby traffic and frequently changing outdoor climate. After the 85th day, the specimens were placed into an indoor environment with stable conditions and so the scatter in the recorded values was eliminated. The placement of specimens in the tub with water and insulation with plastic foil did not work as expected. Water got underneath the plastic foil and to the specimen. Therefore, instead of autogenous shrinkage a phenomenon called swelling of concrete occurred. An interesting fact is that for all concrete mixes the swelling occurred almost at the same rate and reached a value around 65 $\mu m \cdot m^{-1}$ in 43 days. After the change of environment to air-exposed, drying shrinkage occurred for all concrete mixes. The most interesting observation is about the behavior difference of cement at the early age of concrete. Whereas mixes with PSC tend to swell while still in the mould, the mixes with BFC shrink from the very beginning. This created a significant difference in recorded shrinkage between those two groups of mixes. At first, the mixes with PSC reported lower shrinkage values than mixes with BFC. This difference got smaller over time until the recorded values of shrinkage were higher for mixes with PSC. The overall smaller shrinkage for mixes with BFC is caused by the limited content of mixing water in the mixtures. The shrinkage development of concrete mixes with PSC is almost the same. No significant effect of the crystalline admixture or steel fibers on shrinkage was observed. On the other hand, the SRA reduced the shrinkage in contrast to the PCO mix with no SRA by about 37 % in plastic mould placement. Although for other specimen placements, the reduction of shrinkage was not so noticeable. The specimens placed into the steel mould reported, with an exception of the PCO mix, overall higher shrinkage values than specimens placed into the plastic moulds. This phenomenon could be caused by the higher thermal conductivity of the steel mould which affected the hydration process of concrete.

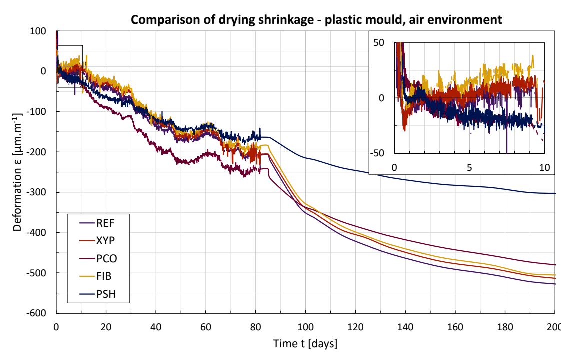

Figure 9: *Comparison of drying shrinkage - plastic mould, air environment.*

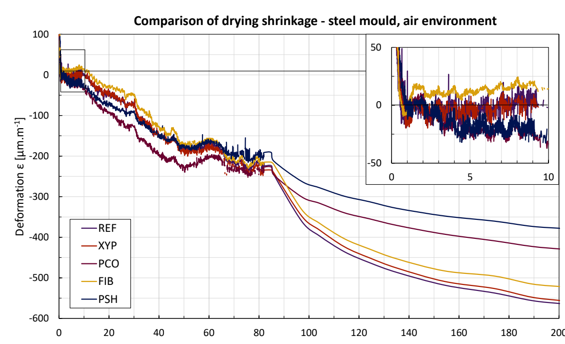

Figure 10: *Comparison of drying shrinkage - steel mould, air environment.*

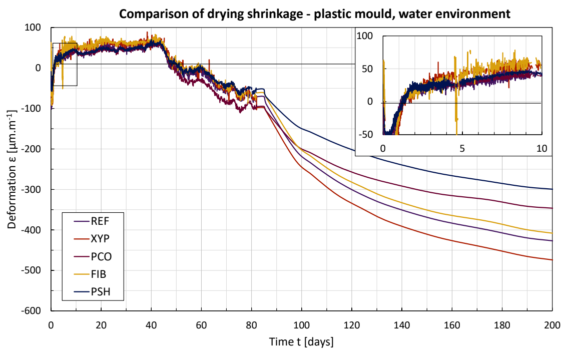

Figure 11: *Comparison of drying shrinkage - plastic mould, water environment.*

3.4. Calculation of crack width

Results of the crack width calculation can be seen in Table 2. Abbreviations used in the table are explained as follows: temperature of fresh concrete (T_{fc}), temperature of sensor 2 (T_{s2}), air temperature (T_{air}), tensile stress in the concrete (σ_{ct}), steel ratio ($\rho_{s,ef}$), area of the steel (A_s), crack width (w_d). Only for mixes REF and FIB, the stress induced by heat of hydration exceeded the current tensile strength of concrete. Concrete mix XYP closely complied due to the delay of hydration process by the crystalline admixture and therefore a delay of maximum temperature peak. Concrete mixes with BFC complied with a significant reserve. The necessary steel ratio and crack width closely correlate with the stresses in concrete. Lower the stresses, smaller the crack width, and requirement of reinforcement. It is important to mention, that the comparison stated in Table 2 is not entirely correct since all the concrete mixes were mixed and poured at a different time and therefore the measured specimens had slightly different surrounding conditions during the hydration process.

Table 2: *Results of the crack width calculation.*

Property	Concrete mix REF	XYP	PCO	FIB	PSH	Unit
T_{fc}	18,3	18,1	17,3	18,0	17,3	°C
T_{s2}	32,5	31,3	25,0	32,1	24,6	°C
T_{air}	11,6	10,7	10,7	10,7	10,7	°C
ΔT_{max}	20,9	21,1	14,3	21,4	13,9	°C
$t_{\mathrm{max,T}}$	0,92	1,48	1,44	1,42	1,40	day
α_c	15,2	13,8	13,9	13,9	14,0	$\cdot 10^{-6}\mathrm{K}^{-1}$
E_c	11,2	16,9	16,8	17,1	15,5	GPa
f_{ct}	0,83	1,40	1,10	1,31	1,01	MPa
σ_{ct}	0,96	1,33	0,90	1,37	0,81	MPa
σ_{ct}/f_{ct}	**1,16**	**0,95**	**0,82**	**1,05**	**0,81**	-
$\rho_{s,ef}$	0,731	0,870	0,707	0,886	0,669	%
A_s	858,9	1022,3	830,7	1041,1	786,1	mm^2
w_d	**0,143**	**0,199**	**0,135**	**0,205**	**0,122**	mm

4. CONCLUSIONS

The experiment comparing five different concrete mixes for white tank structures can be summarized into several conclusions:

- Strength of concrete is influenced primarily by the type of cement. Adding the crystalline admixture to the concrete mixture improves the compressive strength of concrete at the age of 7 and 28 days, but does not improve it after 90 days. Steel fibers do not improve the splitting tensile strength of concrete. Furthermore, splitting tensile strength increases after 28 days negligibly. The static modulus of elasticity has the fastest development with percent value over 80 % after 7 days.
- The static modulus of elasticity is primarily influenced by the type of aggregate.
- Depth of water penetration under pressure is the same for all concrete mixes.
- Concrete mixes with BFC have significantly lower development of heat of hydration, thus a smaller temperature gradient between the core and surface of the structure. The temperature gradient is highly dependant on the temperature of the surrounding environment and even slight differences can influence the hydration process. Finally, the crystalline admixture delays the hydration process by approximately 8 hours.
- A different cement behaviour was observed during the early stage of the shrinkage process. If the specimens are still in the mould, the concrete mixes with PSC tend to swell, while the concrete mixes with BFC tend to shrink from the beginning. The overall shrinkage is smaller for concrete mixes with BFC than for mixess with PSC. Furthermore, the shrinkage-reducing admixture significantly reduces the shrinkage, while crystalline admixture or steel fibers have no impact at all.
- Calculation of crack width proved, that the biggest influence on the crack origin and on the crack width has the stress induced by the heat of hydration of concrete, respectively by the temperature gradient between the core and surface of the structure. According to *fib* Model Code for Concrete Structures 2010 procedure, the tensile strength of the model basement wall is exceeded only for the concrete mixes REF and FIB. The time of pouring, setting time of concrete, and development of hydration process have a great impact on stresses induced in the structure and thus on potential crack width or steel ratio requirement.

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