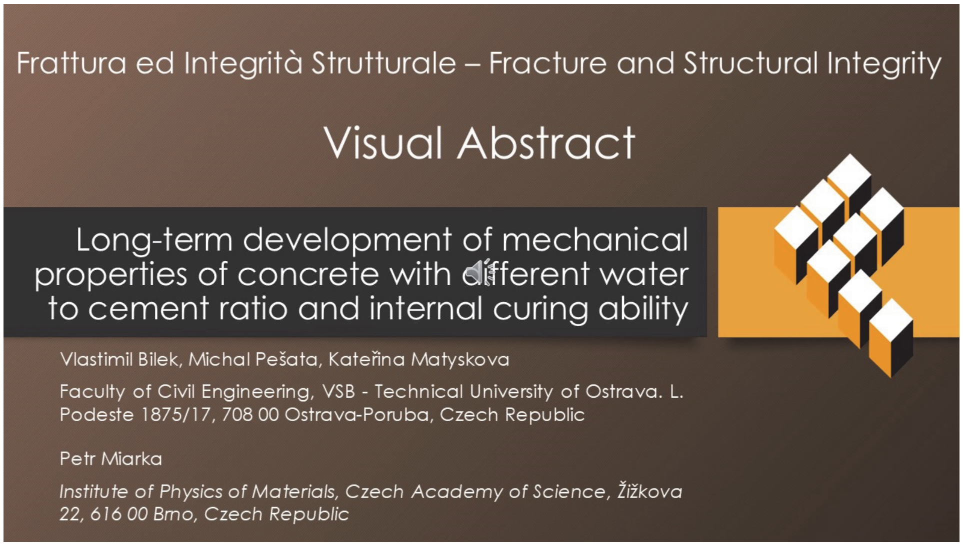
Long-term development of mechanical properties of concrete with different water to cement ratio and internal curing ability

Vlastimil Bilek, Michal Pešata, Kateřina Matyskova
Department of Building Materials and Diagnostics of Buildings, Faculty of Civil Engineering, VSB - Technical University of Ostrava, L. Podeste 1875/17, 708 00 Ostrava-Poruba, Czech Republic
vlastimil.bilek@vsb.cz, http://orcid.org/0000-0001-6433-4892
michal.pesata@vsb.cz, katerina.matyskova@vsb.cz

Petr Miarka
Institute of Physics of Materials, Czech Academy of Science, Žižkova 22, 616 00 Brno, Czech Republic
miarka@ipm.cz . http://orcid.org/0000-0003-2345-6792



Frattura ed Integrità Strutturale – Fracture and Structural Integrity

Visual Abstract

Long-term development of mechanical properties of concrete with different water to cement ratio and internal curing ability

Vlastimil Bilek, Michal Pešata, Kateřina Matyskova

Faculty of Civil Engineering, VSB - Technical University of Ostrava. L. Podeste 1875/17, 708 00 Ostrava-Poruba, Czech Republic

Petr Miarka

Institute of Physics of Materials, Czech Academy of Science, Žižkova 22, 616 00 Brno, Czech Republic

Citation: Bilek, V., Pešata, M., Matyskova, K., Miarka, P., Long-term development of mechanical properties of concrete with different water to cement ratio and internal curing ability, Fracture and Structural Integrity, 71 (2025) 263-272.

Received: 18.09.2024
Accepted: 19.10.2024
Published: 28.11.2024
Issue: 01.2025

KEY WORDS. Bending strength, Compressive strength, Concrete, Self-curing, Water to cement ratio.

INTRODUCTION

The main difference between usual and high-performance concrete (HPC) is a low water to cement ratio (w/c) or water to binder ratio (w/b). This results in an increased significance of autogenous shrinkage and. subsequently. the formation of inner microcracks in the case of HPC. As Aïtcin [1, 2] states with respect to Powers [3], water reacts with Portland cement in two ways: 1) Chemically, water reacts with Portland cement to form C-S-H gel. Portlandite, and other hydration products. 2) Physically, water forms the so-called "gel water". In this process, water molecules are physically bonded to hydrates, but the water does not react chemically.

During the hydration process, the absolute volume of the hardened cement paste is reduced. This results in the concrete becoming more porous. with a volume of approximately 8 % pores [1-3]. Some of the pores form narrow capillaries. At an early stage of the hardening process, capillaries are completely saturated with mixing water. However. if the mixing water is consumed during the hydration process, some of the capillaries will dry out or simply remain empty. The water in these capillaries forms a meniscus and evokes attractive forces on the capillary walls [4]. As the water in concrete is consumed during cement hydration, only capillaries with a smaller radius remain filled with water, which leads to a reduction in the radius of the meniscus and an increase in the attractive forces. This phenomenon is ongoing during the drying process, which constantly reduces the water in the capillaries and meniscus radii. This also results in increased attractive forces, thus causing self-desiccation shrinkage, which results in the contraction of the cement paste volume. Microcracks arise as a consequence of this phenomenon. The secondary effect of this phenomenon is that cement hydration stops due to the lack of water. This process of cement hydration with microcrack formation is shown in Fig. 1.

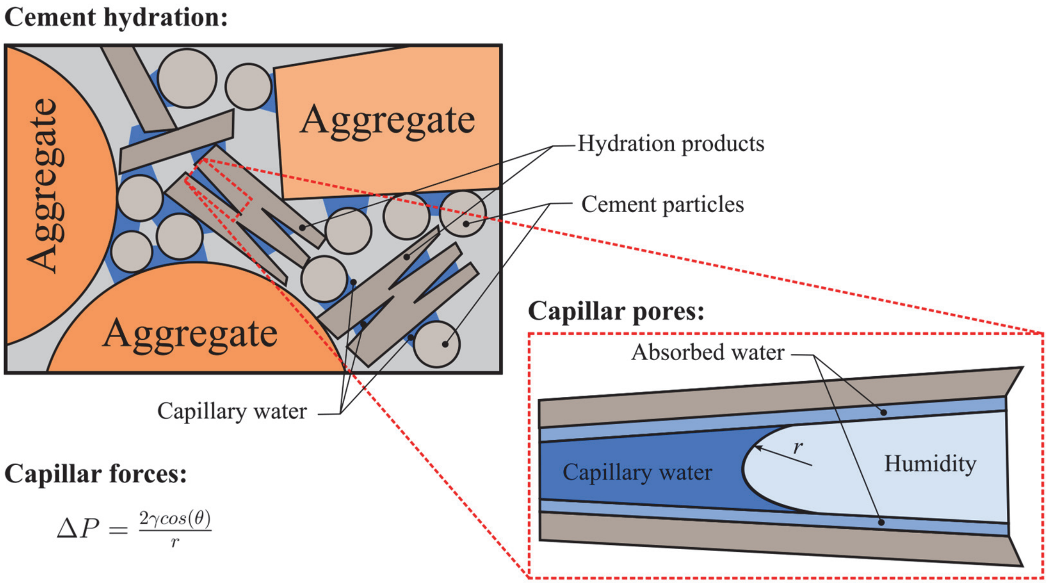


Figure 1: Schematic illustration of cement hydration process with capillary water.

As Jensen and Hansen stated [5], when the water to cement ratio (w/c) is equal to or greater than 0.42, concrete contains enough water for cement hydration and capillary filling. The volume contraction is minimal. On the other hand, when the w/c ratio is below 0.42, the stress from menisci in the fine capillaries causes shrinkage of the hardened cement paste.

The HPCs have a w/c < 0.42, which leads to a notable effect of self-desiccation. This is the main difference between usual concrete and HPC. The shrinkage can be mitigated using shrinkage reducing admixtures, which reduce the surface tension of water (pore solution) in the menisci and the attraction forces in the fine capillaries [6]. On the other hand, internal curing could be used to solve this problem. The internal curing of concrete is carried out using soaked porous aggregates. which provide additional water to the HPC mix. Mixing water is consumed during hydration and is replaced with water from the porous aggregates. More cement particles are able to hydrate and the effect of self-desiccation is also reduced [7, 8].

In this paper, concretes with water to cement ratios of 0.50. 0.40. 0.30 and 0.20 were prepared and their long-term mechanical properties were measured. Porous light-weight aggregates (LWA) in dosages of 10% and 20 % were used for internal curing as a partial replacement of fine aggregates in some of the concrete types. Two curing conditions were studied i.e., specimens cured under water and specimens wrapped in foil. Foil prevents water exchange with the environment. The strengths were measured at the ages of 28. 91. 365 and 720 days.

EXPERIMENTAL PROCEDURE

In this section, we present the composition of the mixtures studied, with a focus on the different water to cement ratios. Next, we briefly present the testing procedures used to obtain mechanical and fracture properties. This is followed by a brief introduction to frost resistance testing.

Composition of Mixtures

Concretes with water to cement ratios w/c = 0.50. 0.40. 0.30 and 0.20 were prepared to measure the long-term development of mechanical properties. Sand 0/4 mm and crushed granite 4/8 mm were used as aggregates. A polycarboxylate based superplasticizer was used to enhance of (the)workability of the mixtures. Light-weight porous water saturated aggregates (LWA) – expanded clay – were used for internal curing in some of the concrete mixtures. The mixture compositions are presented in Tab. 1.

w/c or **w/b**		0.50	0.40	0.30	0.30	0.30	0.20	0.20
Crushed LWA	[%]	0	0	0	10	20	0	10
CEM I 42.5 R	[kg]	450	450	450	450	450	650	650
Silica fume	[kg]	0	0	0	0	0	70	70
Ground limestone	[kg]	0	0	0	0	0	80	80
Water	[kg]	225	180	135	135	135	150	150
Superplasticizer	[kg]	1.5	9	11	11	11	30	30
Sand 0/4 mm	[kg]	990	1050	1110	930	740	885	740
Crushed ag. 4/8 mm	[kg]	700	740	780	780	780	610	610
Crushed LWA 0/4	[kg]	0	0	0	86	172	0	71

Table 1: Composition of studied concrete types per 1 m^3.

In some of the concrete types, 10% and 20 % of the total volume of aggregates were replaced with LWA fraction 0/4. i.e. only sand was partially replaced with light-weight aggregate Liapor® D 0/4 500. The absorption of the LWA was measured and it was 33 %. This is different from the value given by the producer – 15 %. The absorption had to be measured in accordance with EN 1097-6 [9] together with the volume density of the LWA with a result of 1260 kgm^{-3}.

The fraction Liapor® D 0/4 500 is a waste product from the production of a larger fraction of this aggregate. The reason for using crushed fine LWA is its high absorption and the possibility of uniform distribution of the grain of soaked LWA particles in hardened cement paste. This is done to increase the possibility of internal curing of the HPC mixture.

Prior to mixing. the accurate dosage of dry LWAs was put into the container with the water dosage. Additional water to the mass of 80 % from the mixing water (from Tab. 1) was added into the container. The LWAs were left in the container to absorb water for 48 hours before mixing. The soaked LWAs were put into the mixer and the container was washed with the remaining mixing water to achieve the right amount of soaked LWAs in the mixer. In this way, fully soaked LWAs and the current volume of water corresponding to the w/b ratio was moved into the mixer. All types of aggregates used are presented in Fig. 2.


(a) (b) (c)

Figure 2: Comparison of used aggregates – (a) fine natural aggregate sand 0/4. (b) – expanded clay fine aggregate Liapor® D 0/4 500 and (c) – crushed aggregated high-quality granite 4/8.

The original aim of this study was to compare the strength development of concrete with different water to cement ratios w/c and the effectiveness of internal curing in the case of HPC. However. in order to achieve good workability in the case of HPC with w/c < 0.30, some mineral admixtures were used as part of the binder. The first admixture was white silica fume. which enhances workability and reduces the stickiness of the mixtures. The other was ground limestone. The mixture design of the used concrete with w/b = 0.20 can be found in [10].

Mixing and testing procedures

The concrete mixtures were mixed in a laboratory mixer, the batch volume was 20 litres. The mixing time was 3 minutes for the concrete type with a w/c higher than 0.20 and 6 minutes for the concrete with w/b = 0.20. As the maximum size of aggregates was only 8 mm. prisms 40 × 40 × 160 mm^3, were selected for bending strength measurements while prism fragments were used for compressive strength tests in accordance with EN 196-1 [11]. Additionally. 100 mm cubes were made to test compressive strengths. Prisms 80 x 80 x 480 mm^3 were prepared for testing fracture properties.

Moulds with concrete were covered with polyethylene (PE) foil for 24 hours to avoid evaporation of water. After demoulding, half of the specimens were fully wrapped with PE-foil to avoid the exchange of water with the environment and the other half of the specimens were stored in water at a temperature of (20 ± 3)°C. Compressive and bending strengths, dynamic modulus of elasticity and fracture toughness were measured at the ages of 28. 91 and 365 days. The modulus of rupture, i.e. the tensile strength after bending measured on notched beams during fracture tests. was also calculated. Fracture properties and static modulus of elasticity are discussed in other papers [12, 13].

Frost resistance testing

Frost resistance of concrete can be evaluated using the frost resistance index - $I_{F\&T}$. This is expressed as follows:

$$I_{F\&T} = \frac{property\ of\ \ frosted\ specimens}{property\ of\ reference\ specimens} \times 100\ \left[\%\right] \tag{1}$$

The frosted beams are subjected to freezing and thawing (F&T) cycles. In accordance with Czech norm CSN 73 1322 [14] one cycle represents 4 hours in a freezer at -20°C followed by 2 hours in water at +20°C. In this paper, we have selected 125 F&T cycles as sufficient. If frost resistance index $I_{F\&T}$, exceeds 75% after a relevant number of cycles, i.e. 125, the concrete is considered as frost resistant. Beams of 100 × 100 × 400 mm^3 are normally used to test frost resistance. In this paper, beams of 40 × 40 × 160 mm^3 were used to reduce the mixture volume.

Bending and compressive strengths as well as (dynamic) modulus of elasticity, together with volume density, are considered to be properties most frequently used in practical applications. These properties are measured on reference beams cured in water or in some other way (in this case fully wrapped with PE-foil) and frosted beams.

RESULTS AND DISCUSSION

Below we present measured compressive and bending strengths of concrete and HPC with respect to w/c or w/b ratio and different curing methods see Tab. 2. Afterwards, the modulus of rupture is presented and discussed. Then, the internal curing capability of LWA is presented – see Tab. 3 - and the results found are discussed. Lastly, the frost resistance of the studied concrete and HPC is presented and discussed.

Compressive strength

Compressive strengths of the concretes are presented in Tab. 2 and Fig. 3. The differences between the foil and water cured beams are very small, but the foil wrapped specimens showed slightly higher values (for w/b < 0.5). This may be due to the filling of the pores, especially in the surface layer, with water, which is non-compressible. This water can promote failure of the specimens under compressive loading. In the case of concrete with w/c = 0.50 the concrete is sufficiently porous to allow water to penetrate. The hydration is probably more complete, more cement grains are hydrated and the strength of the water cured cubes is higher. However, the original assumption was different: concrete with w/c = 0.50 contains enough water for a relatively complete hydration and there would not be significant difference between the strengths of foil-wrapped and water cured cubes.

		w/b = 0.20		w/c = 0.30		w/c = 0.40		w/c = 0.50	
		foil	water	foil	water	foil	water	foil	water
Bending strength [MPa]	28 days	13.3 ± 0.5	17.8 ± 0.4	9.3 ± 0.3	9.1 ± 0.3	8.2 ± 0.5	7.3 ± 0.4	7.1 ± 0.2	7.3 ± 0.1
	91 days	10.7 ± 0.2	16.2 ± 0.7	9.6 ± 0.5	9.15 ± 0.5	9.6 ± 0.3	9.5 ± 0.5	7.3 ± 0.3	-
	365 days	12.8 ± 0.1	17.5 ± 1.1	11.0 ± 1.3	10.6 ± 0.4	9.4 ± 0.3	9.2 ± 0.5	6.6 ± 0.4	7.9 ± 0.6
	720 days	13.6 ± 0.7	16.7 ± 0.8	10.2 ± 0.5	10.2 ± 0.7	8.7 ± 0.6	9.6 ± 0.5	7.4 ± 0.6	8.7± 0.4
Compres. Strength [MPa]	28 days	136.6±3.1	129.2±3.2	78.6 ± 3.5	73.3 ± 2.0	69.9 ± 3.6	64.1 ± 1.5	45.0 ± 1.0	49.0 ± 3.9
	91 days	135.9±3.6	135.4±4.1	83.2 ± 3.4	86.4 ± 2.9	77.8 ± 1.5	71.0 ± 3.9	51.0 ± 1.5	62.1 ± 3.9
	365 days	139.0±3.0	136.4±3.3	95.3 ± 2.6	94.0 ± 1.8	81.7 ± 3.7	80.3 ± 3.4	49.8 ± 1.6	63.9 ± 2.1
	720 days	140.4±2.1	145.6±2.6	95.7 ± 3.0	89.9 ± 2.9	82.9 ± 3.2	80.5 ± 3.1	49.8 ± 3.5	66.7 ± 1.2
Modulus of rupture [MPa]	28 days	8.7 ± 0.5	9.1 ± 0.3	7.0 ± 0.7	6.7 ± 0.4	6.4 ± 0.7	5.9 ± 0.5	5.3 ± 0.7	5.2 ± 0.2
	91 days	9.7 ± 0.4	-	6.7 ± 0.2	-	5.9 ± 0.3	-	5.3 ± 0.1	-
	365 days	8.5 ± 0.2	9.6 ± 0.3	9.5 ± 0.2	7.6 ± 0.3	7.9 ± 0.2	6.4 ± 0.2	6.3 ± 0.3	5.5 ± 0.2
	720 days	9.2 ±0.4	10.3 ± 0.5	8.9 ± 0.4	7.8 ± 0.4	8.2 ± 0.6	7.1 ± 0.3	6.55 ± 0.5	5.95 ± 0.3

Table 2: Values of mechanical properties. Arithmetic mean and standard deviation from three measured values, respectively from 6 values in the case of compressive strength.

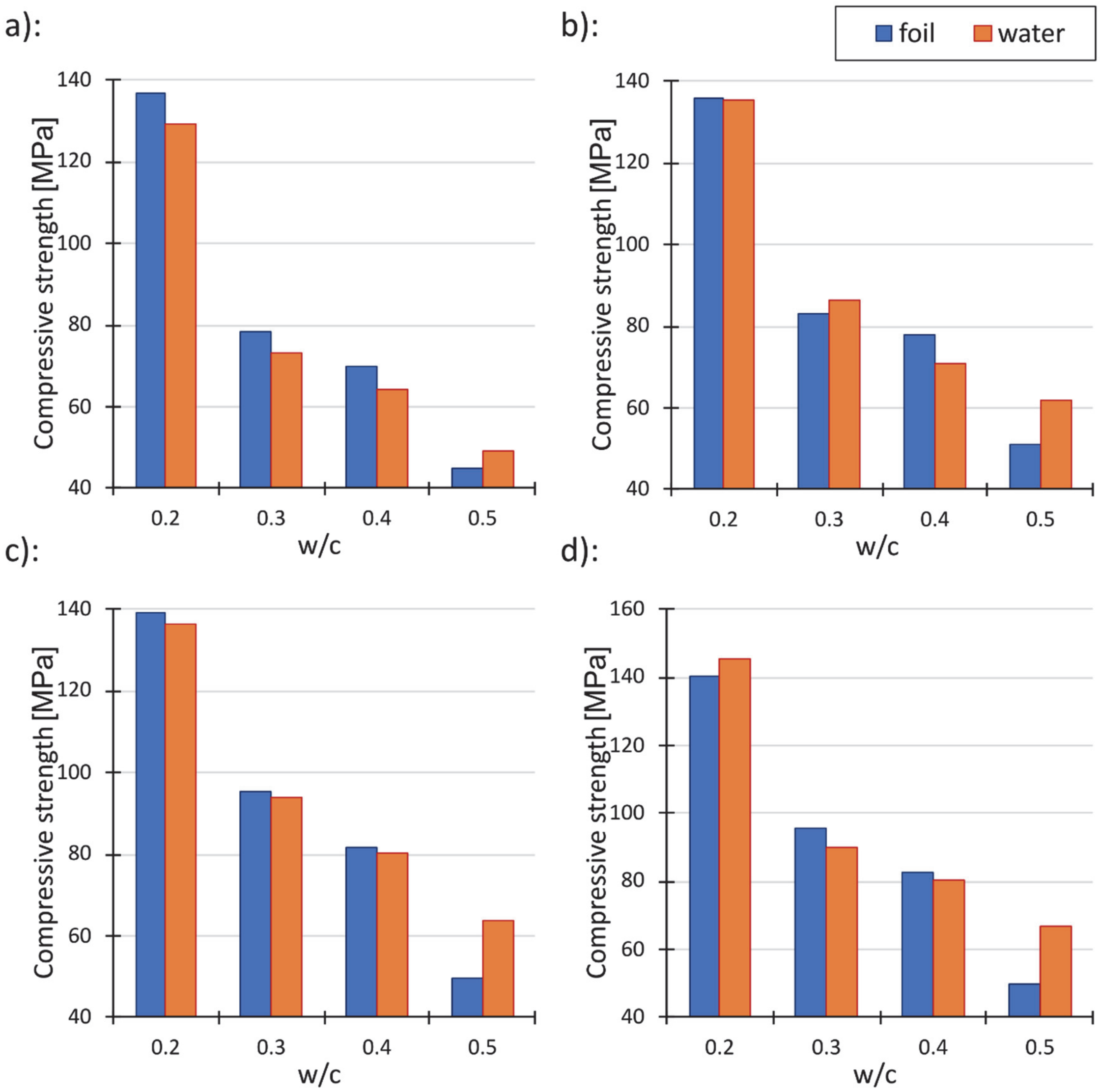


Figure 3: Measured compressive strength of concretes with different w/b cured in foil or in water at various ages a) 28 days. b) 91 days. c) 365 days. and d) 720 days.

Bending strengths

The results are even more surprising than for compressive strengths.

Fig. 4 shows three-point bending strengths of the prepared concretes. Concrete with a lower w/c value could show a water deficiency and (micro)cracking of the hardened cement paste, due to self-desiccation. However, the development of bending strength does not show this. Foil-wrapped specimens show the same or higher values than water cured specimens in the case of w/c = 0.30 and 0.40. Probably the water deficiency and (micro)cracking is not critical in the case of these w/c. HPC with w/b = 0.20 shows the expected development. water curing enhances bending strengths. Water was not able to penetrate inside, the volume density of water cured and foil wrapped specimens are nearly the same. However, better surface layer properties are likely to influence the bending strength values.

The lower strengths of the prisms stored in water may be the result of swelling of the C-S-H gel. Another reason for the lower strengths of the samples treated in water may be the redistribution of bonds in the C-S-H gel and the weakening of Ca-O bonds and H-bonds, as discussed by Hou et al. [15, 16].

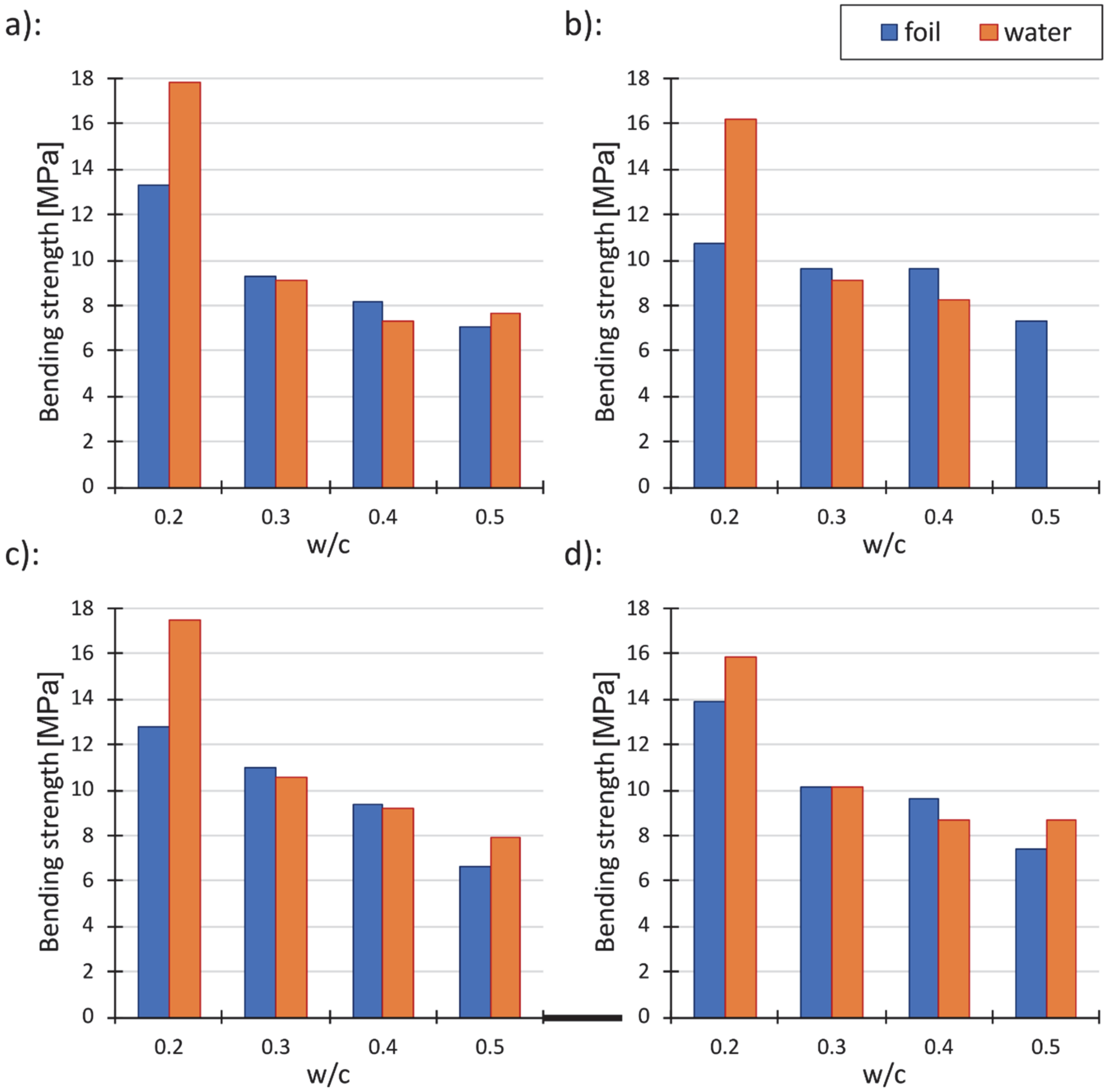


Figure 4: Three-point bending strengths of concretes with different w/b cured in foil or in water at various age a) 28 days. b) 91 days. c) 365 days. and d) 720 days.

Modulus of rupture

As the bending strength can be especially affected by the properties of the concrete surface, the modulus of rupture, which is bending strength tested on the notched beams during the fracture tests, reflects the properties of the central area of the cross section of the prisms. The measured values of the modulus of rupture at different ages are presented in Fig. 5. At 28 days of age, there are only minor differences between water and foil cured specimens when w/b = 0.20. At the age of 91 days only foil-wrapped specimens were measured. The strength of the concrete with w/b = 0.20 increased slightly, but the strengths of concrete with w/c = 0.30 and 0.40 decreased slightly. The decrease may be due to water deficit and self-desiccation shrinkage. Nonetheless, all of the measured values of the modulus of rupture increase significantly at the ages of 365 and 720 days. In the case of concrete with w/b = 0.20 it is likely that water can penetrate the concrete during long water curing.

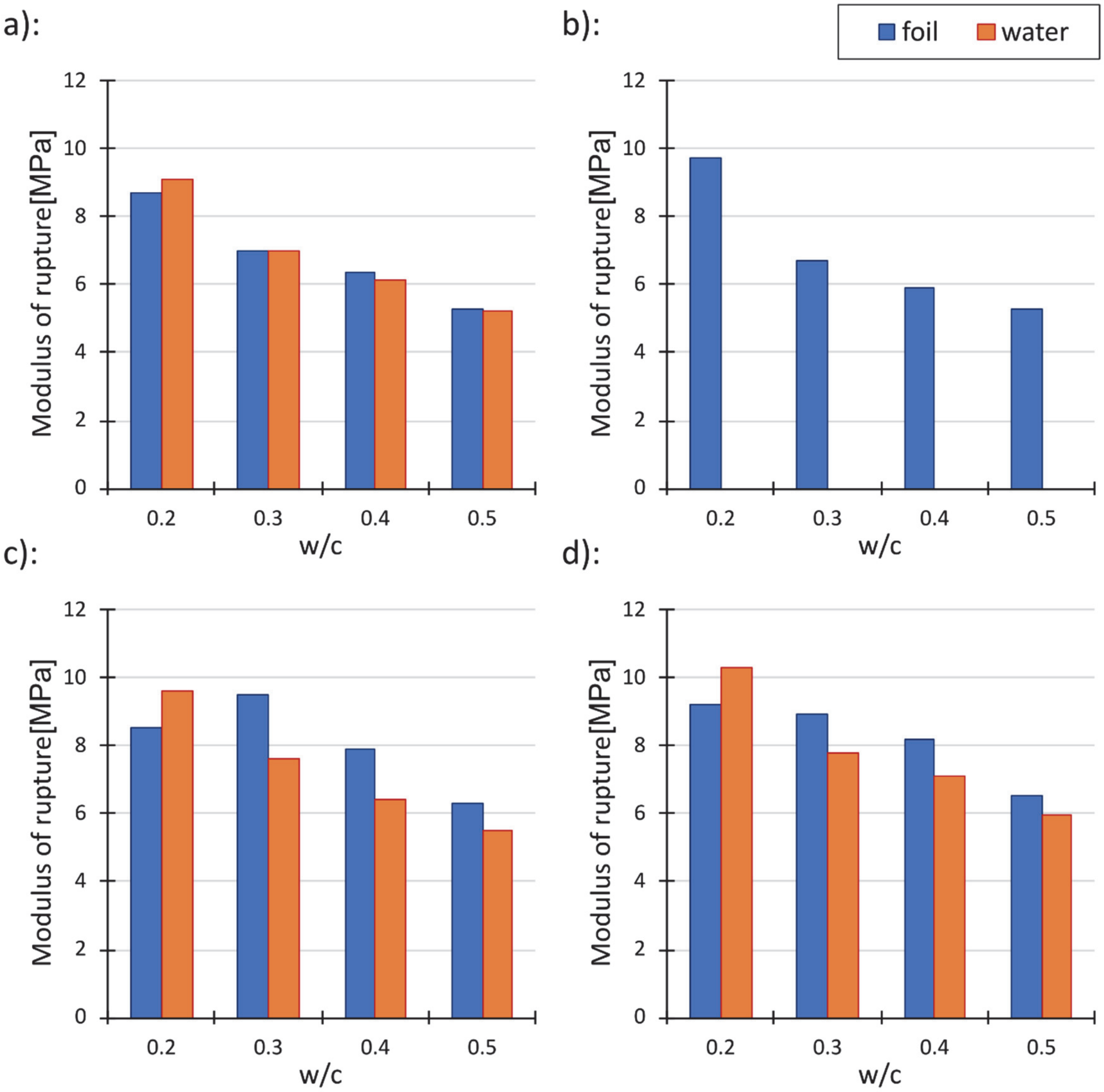


Figure 5: Modulus of rupture of concretes with different w/b cured in foil or in water at various age a) 28 days. b) 91 days. c) 365 days. and d) 720 days.

Effect of internal curing for concrete with w/c = 0.30

Concerning the compressive strengths, the concretes with LWA do not reach the same compressive strengths as the concretes with aggregates of high quality (natural siliceous sand). The compressive strength of the concretes decreases with increasing aggregate replacement, see Tab. 3 and Fig. 6. Some potential of hydration enhancement due to water from saturated aggregates is not sufficient to increase compressive strength.

The situation is different for bending strengths. Concrete with the replacement of 10 % of natural sand with LWA shows similar values as the reference concretes. In this case, the number of microcracks is probably reduced and this effect will outweigh the effect of the poorer quality of LWA. The replacement of 20 % decreases the bending strengths – the effect of the inferior quality of LWA probably exceeds the effect of the additional water responsible for hydration.

			w/c = 0.30		w/b = 0.20	
		0 % LWA	10 % LWA	20 % LWA	0 % LWA	10 % LWA
bending	28 days	9.3 ± 0.3	9.7 ± 0.1	7.9 ± 0.2	13.3 ± 0.5	11.9 ± 0.4
strength	91 days	9.6 ± 0.5	9.6 ± 0.2	8.6 ± 0.2	10.7 ± 0.2	10.4 ± 0.4
[MPa]	365 days	11.0 ± 1.3	10.7 ± 0.3	9.7 ± 0.7	12.8 ± 0.1	10.2 ± 0.5
Compres.	28 days	78.6 ± 3.5	68.5 ± 0.4	59.8 ± 0.4	141.8 ± 0.3	129.5 ± 2.2
Strength	91 days	83.2 ± 3.4	76.0 ± 0.4	65.8 ± 1.0	144.5 ± 1.3	146.6 ± 1.3
[MPa]	365 days	95.3 ± 2.6	88.3 ± 1.9	81.8 ± 1.3	1458.8 ± 2.9	149.5 ± 4.8

Table 3: Bending strengths and compressive cube strengths of concretes with LWA. Arithmetic mean and standard deviation from three measured values

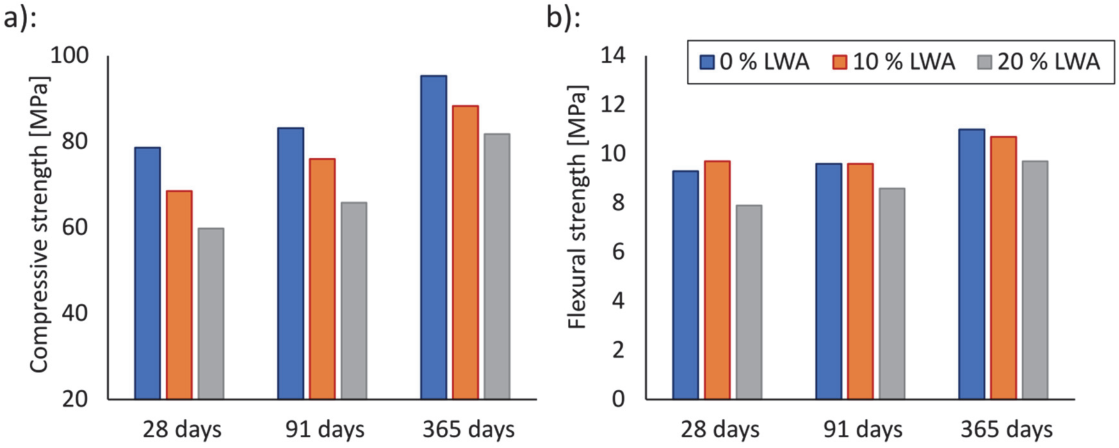


Figure 6: Measured compressive a) and b) three-point bending strength of concrete mixtures with w/b = 0.30 and with partial replacement of 10 % and 20 % of natural sand with LWA.

Effect of internal curing for concrete with w/b = 0.20

The internal curing of the concrete with w/b = 0.20 shows slightly different trends than the other mixtures. The measured compressive and flexural strengths of the concrete with LWA are presented in Fig. 7.

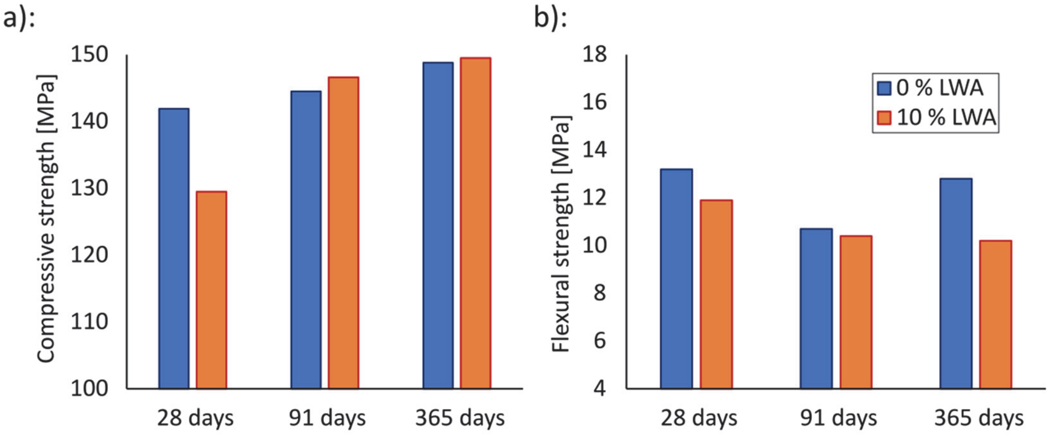


Figure 7: Measured a) cube compressive and b) three-point bending strength of concrete with w/b = 0.20 and with partial replacement of 10 % of natural sand with LWA.

In this case the compressive strength is not affected at the ages of 91 and 365 days. the concretes with LWA show the same values as the reference concrete. It is interesting to note that at the age of 28 days the measured strength of the internally cured specimens is lower than that of the reference specimens. A different tendency was expected. On the other hand, the development of the bending strengths does not agree with the general assumption.

The reference specimens show higher strengths, especially at the age of 365 days. The decrease of values between 28 and 91 days can be explained by the formation of microcracks due to self-desiccation. However, the increase of strengths at the latter age of the reference concrete and the constant strength of the internally cured specimens is unexpected. Probably the amount of LWA is not optimal.

Frost resistance

Contrary to the previous results, all concretes without self-curing show poor frost resistance, $I_{F\&T} < 75$ %. In the previous investigation, beams with a cross-section 100 × 100 mm were used and similar concretes made from ordinary Portland cement with w/c = 0.40 and 0.30 showed satisfactory $I_{F\&T}$. In the case of larger specimens. some surface cracks are probably not as significant as in the case of beams with a cross-section of 40 × 40 mm. The results of frost resistance are presented in Tab. 4. Frost resistance indexes are expressed in terms of volume density (I_{VD}), compressive strength (I_c) and bending strength (I_b).

	w/c = 0.50 0 % LWA		w/c = 0.40 0 % LWA		w/c = 0.30 0 % LWA		w/c = 0.30 10 % LWA		w/c = 0.30 20 % LWA		w/b = 0.20 0 % LWA		w/b = 0.20 10 % LWA	
	foil	water	foil	water	foil	water	foil	water	foil	water	foil	water	foil	water
I_{VD}	98	97	100	99	100	100	100	99	101	98	100	100	100	100
I_{c}	14	23	29	34	59	89	96	97	96	85	120	95	129	87
I_{b}	47	33	68	99	87	96	101	96	108	45	97	100	100	94

Table 4: Frost resistance of concretes at the age of 365 days.

Concrete with w/c = 0.30 at the age of 28 days shows better frost resistance in the case of water cured beams. This is consistent with the assumptions. In the case of foil-wrapped specimens, surface microcracking due to self-desiccation shrinkage, may reduce the frost resistance of foil cured beams, particularly in terms of bending strength. The good frost resistance of foil cured concrete with w/c = 0.30 and 10 % or 20 % LWA is recorded. In this case, the internal-curing of microcracks was probably quite effective and also the water during storage of the specimens in water between freezing can help to heal surface microcracks.

All specimens with w/b = 0.20 show a high frost resistance index and good frost resistance. The frost resistance indexes of the foil-wrapped specimens concrete without and with LWA are nearly identical. The same is true for water cured specimens with and without LWA. This means that LWA doesn´t have a negative effect on the frost resistance of high-performance concrete.

CONCLUSIONS

In this study, various mixtures of high-performance concrete (HPC) with different water to cement ratios were studied at various ages of curing. The HPC mixtures of w/c = 0.3 were mixed with light-weight aggregates (LWA) to increase the possibility of internal self-curing of the mixture. In addition, the mixtures with w/b = 0.2 were mixed using mineral admixtures as a partial replacement of Portland cement.

Two curing conditions were studied: 1) concrete samples were left in water and 2) concrete samples were wrapped in PE-foil to prevent water exchange with the environment. Under these curing conditions, compressive strength, flexural strengths and the modulus of rupture were measured according to European standards at different ages. The selected concrete ages were 28, 91, 365 and 720 days.

Internal curing of the concrete with w/c = 0.30 was not effective in terms of strength. The strengths decrease as the high-quality sand is replaced by low strength LWAs. On the other hand - internal curing can improve the frost resistance of HPC even though LWA reduces the bending and compressive strengths.

In the case of concrete with w/b = 0.20, the effect of internal curing was quite positive. Strengths and frost resistance were comparable with concrete without LWA.

Further experiments with concrete with water to binder ratio 0.20 will be necessary to record a positive effect of the soaked LWA on the mechanical properties. Research continues with the replacement of the expanded clay aggregates by recycled concrete or construction demolition waste.

ACKNOWLEDGEMENT

This paper was created as part of the project No. CZ.02.01.01/00/22_008/0004631 Materials and technologies for sustainable development within the OP JAK Program financed by the European Union and from the state budget of the Czech Republic.

DATA AVAILABILITY

The data used in this study is available at: 10.5281/zenodo.10400646

REFERENCES

[1] Aïtcin, P.-C. (2014). The problems with high strengths and low w/c ratio concretes. Cement-Wapno-Beton, 2, pp.127-137.
[2] Aïtcin, P.-C. (2011). Sustainability of concretete Concrete. Spoon Press. London. UK, 301p.
[3] Powers, T.C. (1968). The properties of fresh concrete. John Wiley and Sons. New York, 664p.
[4] Tazawa, E. (1988). Autogenous shrinkage of concrete. F FN Spon. London, 406p.
[5] Jensen, O.M., Hansen, P.E. (2001). Water-entrained cement-based materials I. Principles and theoretical background. Cement and Concrete Research 31, pp. 647-654. DOI: 10.1016/S0008-8846(01)00463-X
[6] Aïtcin. P.-C., Flatt, R.J. (2015). Science and technology of concrete admixtures. Woodhead publishing, 540p.
[7] Mahmoodi, S., Sadeghian, P., (2019). Self-Healing Concrete: A Review of Recent Research Developments and Existing Research Gaps. 7th International Conference on Engineering Mechanics and Materials. CSCE Annual Conference Laval, QC, Canada, MA11-1 – MA11-10.
[8] Qureshi, T., Al-Tabbaa, A., (2020). Self-Healing Concrete and Cementitious Materials. DOI: 10.5772/intechopen.92349.
[9] EN 1097-6 (2014). Tests for mechanical and physical properties of aggregates. Part 6: Determination of particle density and water absorption, Appendix C.
[10] Bilek, V., Fiala, C., Hájek, P. (2018). High Performance Concrete for Sustainable Building Elements and Strustures. Proceeding of 3rd Int. Conf. Advances in Science Technology of Concrete. Mumbai. Excel India Publichers. New Delhi.
[11] EN 196-1 (2005) - Methods of testing cement - Part 1: Determination of strength.
[12] Bilek, V., Soucek, K., Khestl, F., Bujdos, D., Seitl, S. (2023). Mechanical and Fracture Parameters of Concretes with Different Water to Cement Ratio in Two Different Conditions of Curing. Procedia Structural Integrity 43. pp. 107-112. DOI: 10.1016/j.prostr.2022.12.243.
[13] Bilek, V., Prochazka, L., Khestl, F., Bujdos, D., Seitl, S. (2023). Self-healing Capacity of Differently Cured Concretes – Fracture Characteristic Development. AIP Conf. Proc. 2848, 020026. DOI: 10.1063/5.0145025.
[14] CSN 73 1322 - Determination of frost resistance of concrete.
[15] Hou, D., Ma, H., Yu, Z., Li, Z. (2014). Calcium silicate hydrate from dry to saturated state: Structure. dynamics and mechanical properties. Acta Materialia 67, pp. 81-94.
[16] Wang, P., Duan, Y., Zheng, H., Chen, Z., Wang, M., Wang, X., Li, H., Hou, D. (2023). Molecular structure and dynamics of water on the surface of cement hydration products: Wetting behavior at nanoscale. Applied Surface Science 611, 155713. DOI: 10.1016/j.apsusc.2022.155713.