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The effect of cement replacement and homogenization procedure on concrete mechanical properties

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Abstract. Supplementary cementitious materials (SCM) are used in concrete for two main reasons – to reduce the amount of cement used and to improve material properties. A material that is more sustainable, durable, environmental friendly and economical compared to the traditional Portland cement concrete can be obtained. This paper investigates the effect of two important factors on mechanical properties of high-performance concrete (HPC) containing SCM. The first factor is the content of selected SCM, the second one is the homogenization procedure used for preparation of concrete. In the first part of the research program, 10 different mixtures were compared: reference mixture with no SCM and mixtures where 10 %, 20 % or 30 % of cement weight were replaced by microsilica, fly ash or metakaolin. In the second part, three mixtures with selected replacement levels were prepared by four different homogenization procedures and studied. Tests of bulk density, compressive strength, splitting tensile strength, flexural tensile strength, dynamic and static elastic modulus and depth of penetration of water under pressure were carried out for the tested mixtures. The best results were reached when cement was partially replaced by fly ash. Resistance of concrete to penetration of water under pressure was significantly improved by all SCM. The homogenization procedure in which the SCM was added to the mixture after water led to slightly better properties than the standard mixing technique in case of mixtures containing microsilica and metakaolin. The paper provides an extensive database that can serve as a benchmark for the design of HPC containing SCM.

1. Introduction

1.1. Object of study

The paper investigates the effect of two important factors on mechanical properties of high-performance concrete (HPC) containing supplementary cementitious materials (SCM). The first factor is the content of selected SCM, the second one is the homogenization procedure used for preparation of concrete. Ten different mixtures were compared (see table 2). The studied mechanical properties were compressive strength, splitting tensile strength, flexural tensile strength, dynamic and static elastic modulus and depth of penetration of water under pressure.

1.2. State of the art: Effect of SCM content on the properties of HPC

Comparable comprehensive work dealing with the influence of cement replacement by various SCM in various contents on various mechanical properties of high-performance concrete have not been found it the literature. However, some partial conclusions can be selected from the existing works as a reference for our research. Research works focused on similar materials (high-performance concretes with SCM without fibres, reaching compressive strength around 100 MPa and having water-to-binder ratio (*w/b*) between 0.20 and 0.30) have been selected. The values of the given characteristics at the age of 28 days are cited in all the cases.

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The most comprehensive study found is the work of Megat Johari et al. [1] who investigated the influence of SCM on compressive strength and elastic modulus of mixtures with w/b = 0.28. The used relatively low cement content of 450 kg/m^3 (OPC mixture) which was partially replaced by 5–15 % wt. of microsilica (SF5 – SF15 mixtures) or metakaolin (MK5 – MK15 mixtures) or 10–30 % wt. of fly ash (FA10 – FA30 mixtures). The results are summarized in table 1. In total, it can be stated that microsilica and metakaolin slightly improved the followed properties at all replacement levels, the use of fly ash led to mild deterioration with no clear dependence on the replacement amount.

Gesoglu et al. [2] studied the effect of microsilica and nanosilica addition on the properties of ultra-high performance concretes (UHPC). For mixtures without nanosilica (comparable with our study) they used 800 kg/m^3 of cement withoutmicrosilica first and then 720 kg/m^3 of cement with 80 kg/m^3 of microsilica (10 % replacement) at w/b = 0.20. The compressive strength was 115 MPa and 121 MPa respectively, the flexural tensile strength was 7.1 MPa and 7.9 MPa respectively. This means that cement replacement slightly improved the followed properties of concrete.

Zhang et al. [3] developed the artificial neural network model for estimation of strength of UHPC with SCM. They conducted a series of validation experiments. They focused on concretes with w/b =0.22 containing cement, fly ash and microsilica. The reference mix contained 875 kg/m^3 of cement and 44 kg/m^3 of microsilica. The other mixes contained 263 kg/m^3 of fly ash and a total of 656 kg/m^3 of cement and microsilica. The ratios of cement:microsilica differed from 14:1 to 3:1. For the reference concrete, 98 MPa compressive strength was reached. The strength of fly ash concretes varied between 85 and 108 MPa, almost linearly increasing with increasing microsilica content.

Table 1. Results of research of Megat Johari et al. [1].

Mixture	Compressive strength [MPa]	Static elastic modulus [GPa]	Dynamic elastic modulus [GPa]
OPC	86.7	44.6	50.0
SF5	105.7	46.1	53.5
SF10	113.9	47.1	54.2
SF15	117.5	48.3	55.0
FA10	85.7	43.7	49.6
FA20	84.3	43.1	48.8
FA30	82.1	42.4	48.2
MK5	91.5	45.7	52.9
MK10	103.7	45.5	51.8
MK15	103.4	46.3	52.2

Shi et al. [4] observed the influence of fly ash content and w/b on compressive strength, gas permeability and carbonation depth of HPC. The studied mixtures contained 550 kg/m^3 of cement with 0–60 % replacement by fly ash. For w/b = 0.25, the compressive strength increased from initial 81 MPa to 90 MPa at 30 % replacement and then decreased to 42 MPa at 60 % replacement. For w/b = 0.30, the strength uniformly decreased from 76 MPa to 40 MPa.

Poon et al. [5] developed HPC with high fly ash content, starting from the mixture containing 637 kg/m^3 of cement and further replacing 25 % and 45 % by the admixture at constant w/b = 0.24. The reference mixture reached 97 MPa compressive strength, which increased to 106 MPa at 25 % replacement and decreased to 89 MPa at 45 % replacement.

MuhdNorhasri et al. [6] dealt with the influence of standard metakaolin and nanometakaolin on UHPC properties. For mixes without nanometakaolin (comparable with our study) they used 800 kg/m^3 of cement without metakaolin and then 720 kg/m^3 of cement with 80 kg/m^3 of metakaolin (10 % replacement) at w/b = 0.20. The compressive strengths were 164 MPa and 168 MPa respectively, thus the effect of the admixture was negligible.

Tafraoui et al. [7] investigated UHPC with 20 % replacement of cement by microsilica and metakaolin. For 828 kg/m^3 of cement, 207 kg/m^3 of an admixture and w/b = 0.22 they reached the strengths of 98 MPa (microsilica) and 109 MPa (metakaolin).

In general, it can be said that cement replacements up to 30 % of cement weight have either positive or negligible effect on compressive strength of HPC. Higher replacements usually lead to unacceptable deterioration of mechanical properties.

1.3. State of the art: Effect of homogenization procedure on the properties of HPC

Research works focused on the effect of homogenization procedure on mechanical properties of HPC containing SCM are rather rare. Therefore, also works dealing with lower strength HPC (around 60 MPa) are cited in the following review.

Hiremath and Yaragal [8] focused on hardened properties of reactive powder concrete (900 kg/m^3 of cement, 180 kg/m^3 of silica fume, 180 kg/m^3 of quartz powder, w/b = 0.18). They experimented with the sequence of addition of compounds (microsilica before/after water, aggregate before/after water, water added in two or three steps), speed of mixing (25–150 rotations per minute – rpm) and mixing duration (10–30 min). Regarding the sequence of addition of compounds, the highest compressive strength of 128 MPa was reached when aggregate was added to wet mortar; the standard mixing procedure (adding water to dry mix of all constituents) led to 105 MPa. The study of mixing speed showed that 100 rpm was the most appropriate choice leading to 132 MPa strength; 117 MPa was obtained at 25 rpm, 121 MPa at 150 rpm. The most suitable mixing time was 15 min leading to 130 MPa compressive strength; 122 MPa was reached after 10 min of mixing and 109 MPa after 30 min. Further analysis has shown that excessively long or fast mixing can increase the percentage of pores in concrete, leading to reduced hardened properties.

Chang and Peng [9] studied the influence of sequence of addition of compounds and mixer type on properties of various HPC mixtures containing 300–600 kg/m^3 of cement and 80–160 kg/m^3 of fly ash (w/b = 0.4–0.5). Six different mixing procedures were compared. They obtained the best compressive strength (67 MPa) when the aggregate was added into the mix of cement with water and at the same time horizontal twin shaft mixer was used. However, almost the same result (66 MPa) was obtained when standard drum mixer and basic mixing method (first aggregate, then cement, then SCM, then all the water with superplasticizer at one moment) was used. Dividing the amount of waterwith superplasticizer in more doses did not have a positive effect.

Hemalatha et al. [10] investigated the effect of different types of mixers (ribbon type, pan, drum and Elrich) and the influence of time of addition of superplasticizer on properties of self-compacting HPC (various compositions, typically 450 kg/m^3 of cement, 100 kg/m^3 of fly ash, w/b = 0.38). The best compressive strength (67 MPa) was obtained with the use of Elrich mixer (forced action type mixer with variable speed), followed by standard pan mixer (58 MPa). No significant influence of time of addition of superplasticizer was noticed.

1.4. Study relevance

The reasons for the use of SCM in concrete are broadly known [11–13].By adding microsilica to concrete, fresh mix properties can be significantly improved. Bleeding of concrete can be avoided andpumpability is enhanced. The main advantages in case of hardened concrete are resistance to shrinkage, cracking, aggressive environmental conditions and penetration of water under pressure because of higher matrix density.

The main effect of fly ash is the deceleration of hydration of cement paste leading to lower hydration heat release and slower initial strength growth. Non-hydrated fly ash functions as microfiller, improving the density of cement matrix. It also improves the rheological properties of fresh concrete. It makes concrete more resistant to chemical aggressive agents. Concrete costs and carbon footprint reduction belong to other benefits of fly ash use.

Metakaolin contributes to the densification of structure and better rheology of concrete. It also improves compressive strength and resistance to deicing chemicals.

Considering the aforementioned effects, the design of high-performance concrete (HPC) mixture without the use of SCM is rather rare. In recent years, HPC became more common in civil engineering applications. Excellent compressive and tensile strength and exceptional durability are the main motivating factors for its exploitation in structural elements. However, the design of HPC mixtures is usually performed just based on the empirical experience, using trial-and-error method. Such an approach is lengthy, inefficient and expensive. To change the current practice and to proceed to modern controlled design methods, it is required to conduct a comprehensive and systematic research of the relations between the composition, homogenization process and properties of the material.

1.5. Objectives of the study

The objectives of the presented experimental program were:

- To quantify the effect of cement replacement by selected SCM – microsilica, fly ash and metakaolin – on a wide range of mechanical properties of HPC.
- To quantify the effect of changes in homogenization procedure on mechanical properties of HPC.
- To create an extensive database that could serve as a benchmark for further research works investigating this issue and as a guideline for concrete designers.

2. Methods

2.1. Investigated materials

The research was conducted for 10 different HPC mixtures. The reference mixture without SCM (labelled as REF in Table 2) and mixtures with 10 %, 20 % or 30 % cement replacement by three SCM – microsilica, fly ash or metakaolin (labelled as MIC, POP and MET with number denoting the replacement level in Table 2) – were produced. The selection of replacement levels was done based on the results of previous study [14] carried out on cement pastes that considered 0–80 % replacement levels. In accordance with the information found during the literature review, the study [14] showed that it was practically impossible to reach the mechanical parameters of HPC at replacements higher than 30 %. The workability of such mixtures was also very poor.

The composition of particular mixtures is given in Table 2. In all the cases, constant w/b = 0.26 was kept. The *k*-value concept was used to establish the required amount of water:

$$w/b = \frac{m_w}{m_c + k \cdot m_{SCM}} \tag{1}$$

Where m_w is the amount of water, m_c is the amount of cement and m_{SCM} is the amount of SCM in kg/m³. The k-value was considered 2.0 for microsilica, 0.4 for fly ash and 1.0 for metakaolin in accordance with [15]. The following cementitious materials were used (for detailed specification please refer to Tables 3 and 4 and Figure 1):

- Portland cement CEM 42.5 R, Českomoravský cement company, plant Mokrá.
- MicrosilicaStachesil S.
- Fly ash ETU EN 450 from ČEZ company, Tušimice II power plant. The fly ash was mixed from two fractions P1 and P2 in 2:1 ratio.
- MetakaolinMefisto L05 from company Českélupkovézávody.

Table 2a Composition of the mixtures – part 1.

Compound	Specification	REF [kg/m³]	MIC10 [kg/m³]	MIC20 [kg/m³]	MIC30 [kg/m³]
cement	CEM I 42,5 R	800	720	640	560
admixture	microsilica	0	80	160	240
	fly ash	0	0	0	0
	metakaolin	0	0	0	0
water	-	210	231	252	273
w/b	-	0.26	0.26	0.26	0.26
aggregate (basalt)	8/16	320	320	320	320
	4/8	390	390	390	390
	0/4	730	730	730	730
SPF	Stachement	25.0	33.0	33.0	33.0
fibres	13 + 25 mm, 1:1	0	0	0	0

Table 2b. Composition of the mixtures – part 2.

Compound	Specification	POP10 [kg/m3]	POP20 [kg/m3]	POP30 [kg/m3]	MET10 [kg/m3]	MET20 [kg/m3]	MET30 [kg/m3]
cement	CEM I 42,5 R	720	640	560	720	640	560
admixture	microsilica	0	0	0	0	0	0
	flyash	80	160	240	0	0	0
	metakaolin	0	0	0	80	160	240
water	-	197.4	184.8	172.2	210	210	210
w/b	-	0.26	0.26	0.26	0.26	0.26	0.26
aggregate (basalt)	8/16	320	320	320	320	320	320
	4/8	390	390	390	390	390	390
	0/4	730	730	730	730	730	730
SPF	Stachement	34.0	32.0	30.0	30.0	30.0	30.0
fibres	13 + 25 mm, 1:1	0	0	0	0	0	0

Table 3. Chemical composition of cementitious materials [%].

Compound	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	TiO_2
cement	64.2	19.5	4.7	3.2	3.2	1.3	-	-
microsilica	1.5	92.1	-	0.4	-	0.3	0.7	-
fly ash	4.2	48.8	24.2	12.5	1.2	0.7	1.4	1.4
metakaolin	-	54.1	40.1	1.1	-	-	0.8	1.8

Table 4. Additional characteristics of cementitious materials; x_{50} is median particle, x_{90} is 90 % quantile.

Compound	Specific surface area [m^2/g]	Bulk density [kg/m^3]	x_{50} [μm]	x_{90}[μm]
cement	0.37	3100	9.11	34.06
microsilica	15.0	2400	2.92	6.74
fly ash P1	-	-	40.41	183.84
fly ash P2	-	-	2.10	6.82
fly ash P1+P2 2:1	0.25	2000	5.89	124.35
metakaolin	12.7	2300	2.15	7.50

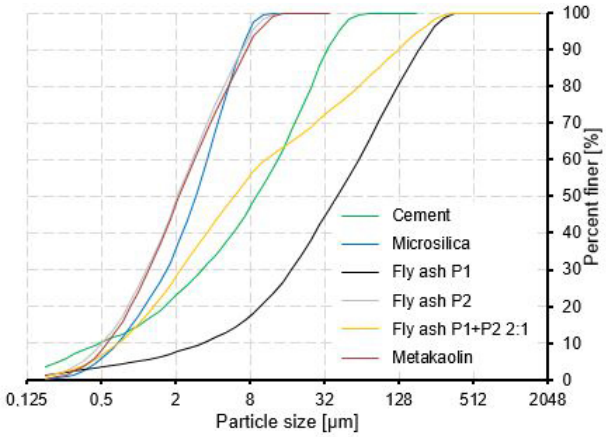

Figure 1. Particle size distribution curves of cementitious materials.

2.2. Homogenization procedures

The effect of homogenization procedure (namely the instant of addition of SCM into the mixer and the mixing time of SCM) was studied on three selected mixtures, namely MIC20, POP30 and MET20. All the mixes were prepared in standard pan laboratory mixer with centre shaft (pan fixed, scraper moving) and nominal volume of 80 litres at the speed of 30 rpm. For each mixture, four different mixing procedures were used:

- Procedure no. 1 (P1) was the standard one used for mixtures with different SCM content. At first, aggregate was homogenized, than cement was added, followed by silica fume and water with superplasticizer.
- In procedure no. 2 (P2), SCM was added before cement.
- In procedure no. 3 (P3), SCM was added as the last component (after the water with superplasticizer).
- Procedure no. 4 (P4) was the same as standard (P1), but the mixing time of SCM was increased from 180 s to 300 s.

Detailed schedule including mixing times is shown in Table 5. Before addition of each dry compound, the mixer was stopped. The water was added in the course of mixing.

Table5.Schedule of mixing procedures. The length of the step in seconds is given in the brackets.

Step no.	P1	P2	P3	P4
1	Aggregate 8/16+4/8 (20)	Aggregate 8/16+4/8 (20)	Aggregate 8/16+4/8 (20)	Aggregate 8/16+4/8 (20)
2	Aggregate 0/4 (20)	Aggregate 0/4 (20)	Aggregate 0/4 (20)	Aggregate 0/4 (20)
2	Cement (20)	SCM (180)	Cement (20)	Cement (20)
3	SCM (180)	Cement (20)	Water+SPF (60)	SCM (300)
4	Water+SPF (60)	Water+SPF (60)	SCM (180)	Water+SPF (60)

3. Results and Discussion

The tests of bulk density, compressive strength, splitting tensile strength, flexural tensile strength, dynamic and static elastic modulus and depth of penetration of water under pressure at the age of 28 days were carried out.

3.1. Bulk density

Bulk density was determined according to EN 12390-7 [16] on 100 mm cubes. Three values were measured for each mixture and averaged.

3.1.1 Effect of SCM content

Considering the high amount of fine compounds and the use of basaltic aggregate, the bulk densities are relatively high, slightly below 2500 kg/m^3. Lower values were reached for mixtures containing microsilica. In this case, the bulk density uniformly decreased with increasing admixture content. This was probably caused by the fact that water content increased with increasing admixture content as well, leading to increased porosity of hardened cement paste. For other mixtures, the bulk density was practically identical and independent on SCM content. The results are given in Table 6 and Figure 2.

Table6. Bulk density of mixtures with different SCM contents – results.

Mixture	Bulk density [kg/m^3]	Standard deviation[kg/m^3]
REF	2487	13.0
MIC10	2423	7.9
MIC20	2384	15.8
MIC30	2342	17.8
POP10	2489	26.4
POP20	2488	12.5
POP30	2468	9.5
MET10	2483	10.2
MET20	2507	18.0
MET30	2469	25.2

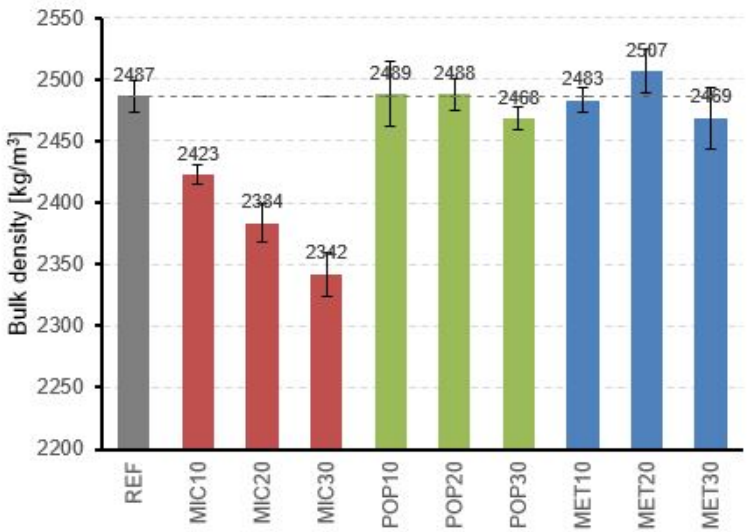

Figure 2. Bulk density of mixtures with different SCM contents – results.

3.1.2 Effect of homogenization procedure

It can be concluded that the bulk density was not influenced by the applied mixing procedure. The variations relative to procedure P1 did not exceed 2.5 %.The results are given in Table 7 and Figure 3 (for example, MIC20-3 is mixture MIC20 prepared by homogenization procedure P3).

Table7. Bulk density of mixtures with different homogenization procedures – results.

Mixture	Bulk density [kg/m^3]	Standard deviation[kg/m^3]
REF	2487	12.9
MIC20-1	2383	15.8
MIC20-2	2412	8.6
MIC20-3	2427	16.6
MIC20-4	2401	9.8
POP30-1	2468	9.6
POP30-2	2419	20.9
POP30-3	2472	10.3
POP30-4	2473	3.5
MET20-1	2507	18.1
MET20-2	2502	24.3
MET20-3	2524	17.2
MET20-4	2473	19.3

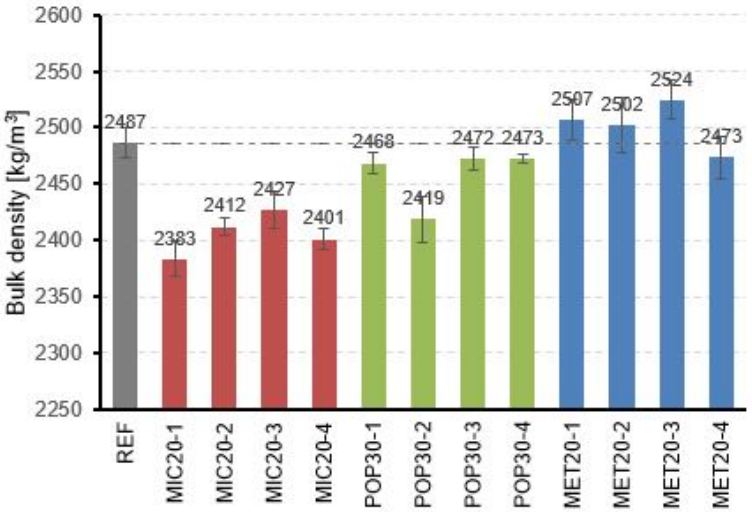

Figure 3. Bulk density of mixtures with different homogenization procedures – results.

3.2. Compressive strength

Compressive strength was determined according to EN 12390-3 [17] on 100 mm cubes. Six values were measured for each mixture and averaged.

3.2.1. Effect of SCM content

The reference mixture reached 105.9 MPa compressive strength. In case of microsilica use, the strength had decreasing tendency with increasing admixture content (corresponding to the decreasing trend of bulk density), but the measured values were very close to that of the reference mix. Replacement of cement by fly ash led to increase of strength above the reference value up to 125.3 MPa in case of POP30 mixture. Metakaolin did not affect the strength up to 20 % replacement, decrease was observed for 30 % replacement.The results are summarized in Table 8 and Figure 4.

Table8. Compressive strength of mixtures with different SCM contents – results.

Mixture	Strength [MPa]	Standard deviation[MPa]
REF	105.9	1.98
MIC10	109.3	2.84
MIC20	101.3	4.25
MIC30	97.7	6.77
POP10	106.6	7.85
POP20	120.8	1.25
POP30	125.3	2.39
MET10	108.9	2.92
MET20	110.3	4.50
MET30	96.7	4.04

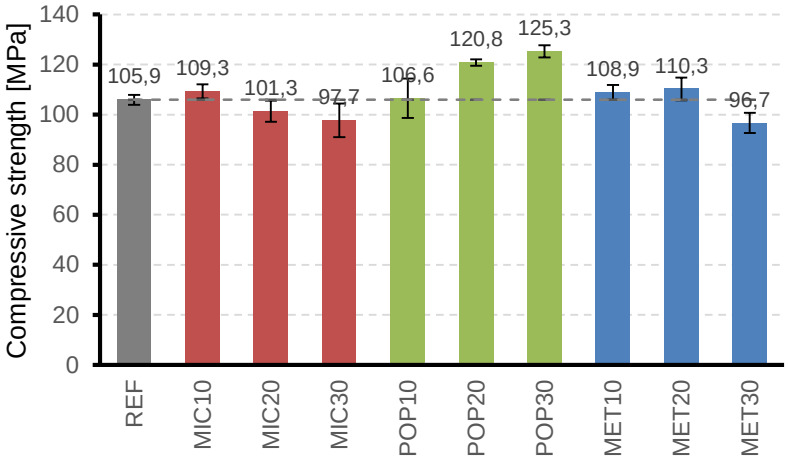

Figure 4 Compressive strength of mixtures with different SCM contents – results.

3.2.2 Effect of homogenization procedure.

Procedure P3 (SCM added after water with superplasticizer) gave better results than the other two alternative procedures (P2 and P4) for all types of SCM. It provided the highest strength of all the mixing procedures in case of microsilica and metakaolin. This can be attributed to the higher amount of water available for initial wetting of cement before the addition of SCM.

P2 (SCM added before cement) decreased the compressive strength of fly ash concrete by 30 MPa (25 %). Increase of mixing time (P4) led to 16 MPa (13 %) reduction. Microsilica and metakaolin concretes were practically unaffected by P2 and P4 mixing procedures. The results are given in Table 9 and Figure 5.

Table 9. Compressive strength of mixtures with different homogenization procedures – results.

Mixture	Strength [MPa]	Standard deviation [MPa]
REF	105.9	1.98
MIC20-1	101.3	4.25
MIC20-2	99.0	1.56
MIC20-3	113.8	6.81
MIC20-4	103.8	3.19
POP30-1	125.3	2.39
POP30-2	95.5	2.62
POP30-3	115.8	3.45
POP30-4	109.0	1.45
MET20-1	110.3	4.50
MET20-2	118.0	4.25
MET20-3	127.7	1.70
MET20-4	115.4	9.58

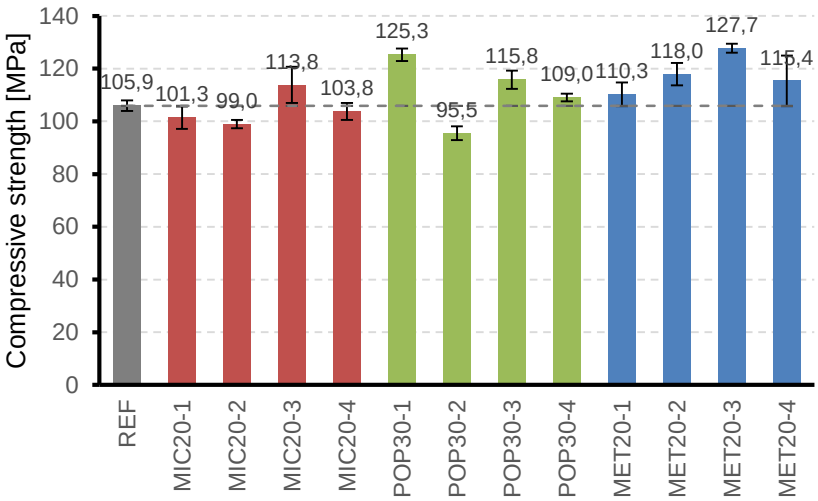

Figure 5 Compressive strength of mixtures with different homogenization procedures – results.

3.3. Tensile strength

Four-point flexural tensile strength was measured according to EN 12390-5 [18] on 100×100×400 mm prismatic samples for all the mixtures. Splitting tensile strength was measured according to EN 12390-6 [19] on 100 mm cubes for the mixtures with different SCM contents. Three values were measured for each mixture and each test and averaged.

3.3.1 Effect of SCM content

The tensile strengths measured by both types of tests were similar for most of the mixtures (with the exception of REF, MIC20 and MET20); the differences of average values did not exceed the size of the standard deviation. It is possible to say that the replacement of cement by microsilica or metakaolin led to overall decrease of tensile strengths compared to reference mixture, but no clear dependence on replacement percentage could be identified. In case of fly ash, the strength slightly increased with increasing replacement level.The results are summarized in Table 10 and Figure 6.

Table 10. Tensile strengths of mixtures with different SCM contents – results.

Mixture	Flexural t.s. $f_{ct,fl}$ [MPa]	Standard deviation [MPa]	Splitting t.s. $f_{ct,sp}$ [MPa]	Standard deviation [MPa]	Ratio $f_{ct,sp}/f_{ct,fl}$ [-]
REF	7.8	0.36	9.6	1.40	0.81
MIC10	6.7	0.43	7.5	1.22	0.89
MIC20	7.6	0.20	5.9	0.27	1.28
MIC30	6.5	0.29	5.8	0.68	1.12
POP10	8.6	0.18	8.2	0.70	1.04
POP20	8.5	0.36	8.8	0.96	0.96
POP30	9.1	0.43	8.6	0.16	1.06
MET10	7.5	0.59	7.3	0.52	1.03
MET20	6.5	0.91	9.1	0.45	0.71
MET30	7.9	0.38	7.9	0.34	1.01

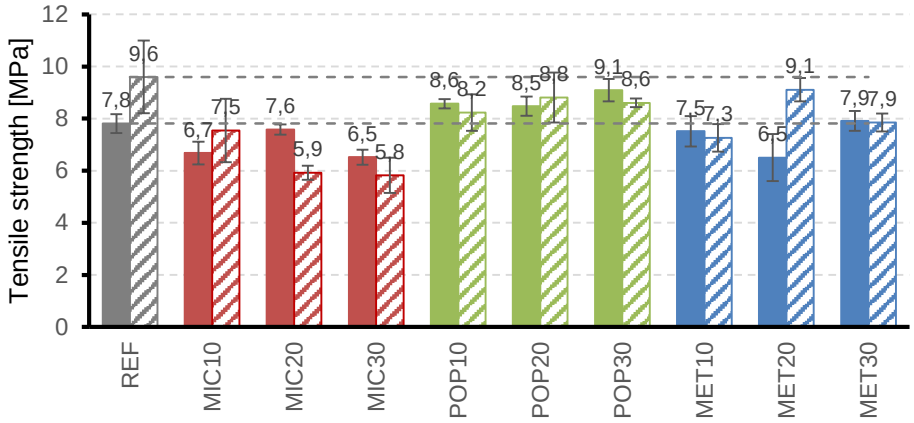

Figure 6. Tensile strength of mixtures with different SCM contents – results.
Solid columns – flexural tensile strength, hatched columns – splitting tensile strength.

3.3.2 Effect of homogenization procedure

With the exception of MET20-1, the strength obtained for one type of SCM by various mixing procedures was practically identical. No clear dependence on homogenization procedure was identified for any SCM. The results are given in Table 11 and Figure 7.

Table 11. Flexural tensile strength of mixtures with different homogenization procedures– results.

Mixture	Strength [MPa]	Standard deviation [MPa]
REF	7.8	0.36
MIC20-1	7.6	0.20
MIC20-2	8.1	1.66
MIC20-3	7.3	0.12
MIC20-4	8.0	0.53
POP30-1	9.1	0.43
POP30-2	8.2	0.23
POP30-3	8.5	0.10
POP30-4	9.0	0.54
MET20-1	6.5	0.91
MET20-2	7.9	0.66
MET20-3	8.7	0.66
MET20-4	8.4	0.06

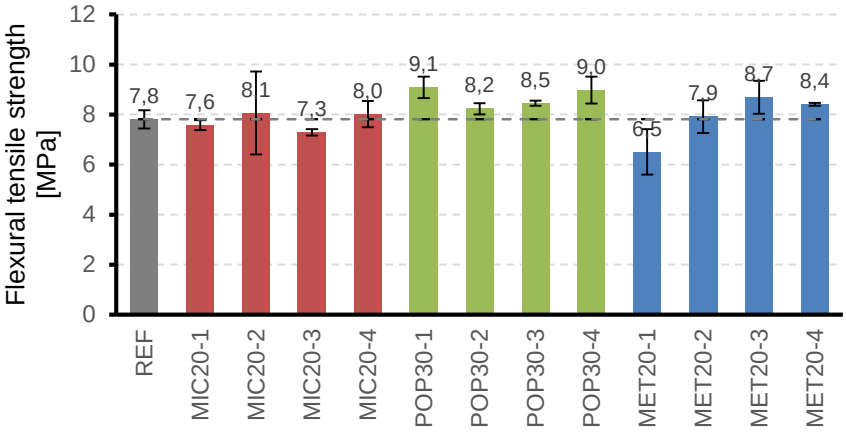

Figure 7. Flexural tensile strength of mixtures with different homogenization procedures – results.

3.4. Elastic modulus

Two types of elastic modulus were determined for each mixture with different SCM contents: dynamic one using the ultrasonic pulse method according to ČSN 73 1371 [20] and static one according to ISO 1920-10 [21]. Cylinders 100 mm in diameter and 200 mm in height were used for both tests. Only static modulus was measured for mixtures with different homogenization procedures. Three values were measured for each mixture and each test and averaged.

3.4.1 Effect of SCM content

The ratio between static and dynamic modulus varied between 0.8 and 0.9, the only exception being the reference mixture with 0.95 ratio. The static modulus of all the concretes with SCM was lower than that of the reference mixture. The dynamic modulus of concretes with metakaolin was lower that for the reference mixture; mixtures with microsilica and fly ash reached the values that were basically identical with the reference concrete. In case of microsilica and fly ash, the moduli increased with increasing replacement level; in case of metakaolin, they were practically constant.The results are summarized in Table 12 and Figure 8.

Table 12. Elastic modulus of mixtures with different SCM contents – results.

Mixture	Dynamic elastic modulus E_d [GPa]	Standard deviation [GPa]	Static elastic modulus E_s [GPa]	Standard deviation [GPa]	Ratio E_s/E_d [-]
REF	54.0	1.24	51.3	2.51	0.95
MIC10	51.3	2.57	42.2	3.12	0.82
MIC20	55.0	4.13	46.8	2.15	0.85
MIC30	55.9	1.23	48.1	3.56	0.86
POP10	51.3	3.65	46.2	2.08	0.90
POP20	55.0	2.97	49.5	1.34	0.90
POP30	55.9	1.73	49.8	3.39	0.89
MET10	48.7	3.46	39.0	2.03	0.80
MET20	51.2	1.94	41.9	2.22	0.82
MET30	47.9	1.87	39.7	1.31	0.83

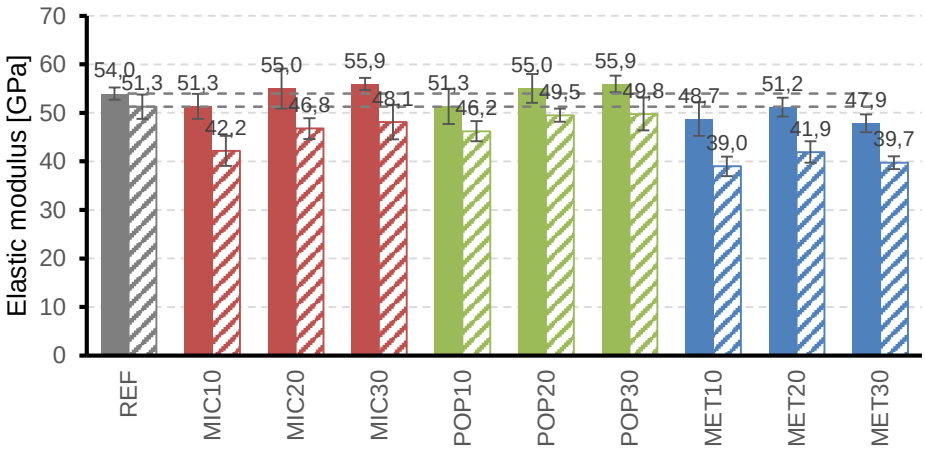

Figure 8. Elastic modulus of mixtures with different SCM contents – results.
Solid columns – dynamic modulus, hatched columns – static modulus.

3.4.2 Effect of homogenization procedure

Different tendencies were obtained for each type of SCM. In case of microsilica, the use of all alternative mixing procedures (P2, P3 and P4) lead to decrease of elastic modulus. No influence was observed in case of fly ash concrete. Metakaolin enriched mixtures prepared by any of the alternative procedures showed higher elastic modulus than the mixture prepared by standard procedure P1.The results are given in Table 13 and Figure 9.

Table 13. Static elastic modulus of mixtures with different homogenization procedure – results.

Mixture	Elastic modulus [GPa]	Standard deviation [GPa]
REF	51.3	2.51
MIC20-1	46.8	2.15
MIC20-2	39.8	3.49
MIC20-3	41.6	3.97
MIC20-4	40.7	2.70
POP30-1	49.8	3.39
POP30-2	49.5	2.90
POP30-3	51.0	3.97
POP30-4	50.4	3.22
MET20-1	41.9	2.22
MET20-2	52.9	2.30
MET20-3	52.5	2.77
MET20-4	45.5	3.19

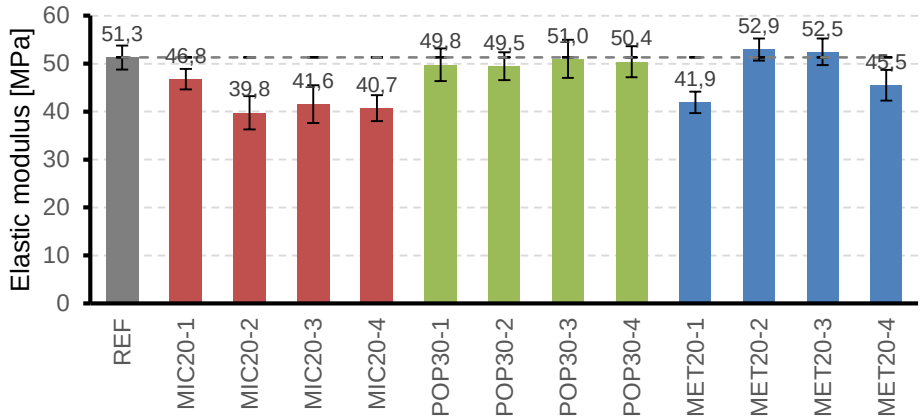

Figure 9. Static elastic modulus of mixtures with different homogenization procedures – results.

3.5. Depth of penetration of water under pressure

The test was performed only for mixtures with varied SCM content according to EN 12390-8 [22] on three 100 mm cubes for each mixture. Three values were measured for each mixture and averaged. Relatively high variance of results was experienced for some mixtures.

Reduction of the depth of penetration of water under pressure compared to the reference concrete was observed for all the mixtures with SCM, although it was quite negligible in case of MIC30 considering the size of the standard deviation. In case of microsilica and metakaolin, the depth of penetration increased with increasing admixture content. Fly ash appeared to be the most efficient admixture in this test; the depth of penetration significantly decreased with increasing cement replacement.The results are summarized in Table 14 and Figure 10.

Table 14 Depth of penetration of water under pressure of mixtures with different SCM contents – results.

Mixture	Depth of penetration [mm]	Standard deviation [mm]
REF	17.5	4.04
MIC10	10.5	1.73
MIC20	10.5	4.04
MIC30	17.0	1.15
POP10	9.0	5.77
POP20	3.0	1.15
POP30	0.8	0.29
MET10	6.0	1.15
MET20	7.0	2.31
MET30	10.0	1.15

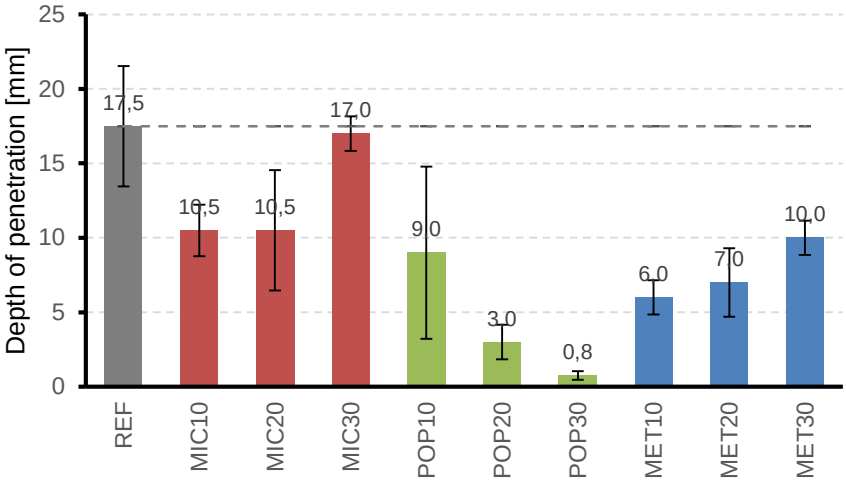

Figure 10 Depth of penetration of water under pressure of mixtures with different SCM contents – results.

4. Conclusions

The study provided a large database describing the changes of mechanical properties of the studied high-performance concretes containing supplementary cementitious materials. This database can be used for reference when designing and optimizing new HPC mixtures.

When varying the SCM content and using the standard homogenization procedure (P1), the best results were obtained when cement was partially replaced by fly ash. Compressive strength was improved by up to 18 % compared to reference concrete, flexural tensile strength increased by up to 16 % and the resistance to penetration of water under pressure was enhanced by up to 95 %. What is more, the beneficial influence of fly ash grew with increasing admixture content.

The most significant adverse effect of SCM was recorded in case of splitting tensile strength of microsilica mixtures, where the reduction reached 40 % compared to the reference concrete. However, this result was not fully confirmed by the flexural tensile strength measurement, which is generally considered more reliable. The decrease in this case was only up to 16 %. In case of cement replacement by metakaolin, static elastic modulus was reduced by up to 24 %, but again this was not confirmed by dynamic elastic modulus test that showed only 11 % reduction.

To sum up, it can be stated that partial replacement of cement by SCM up to 30 % cement weight did not affect the followed mechanical properties significantly. This is in accordance with the information found during the literature review. The only exception was the resistance to penetration of water under pressure that was improved by at least 40 % in all cases except MIC30 mixture.

After considering all the results obtained by different homogenization procedures, the most appropriate approach for mixtures containing microsilica and metakaolin seems to be P2, i.e. the addition of SCM into wet mix. Compressive strength was increased by this procedure; other properties were either increased or decreased by less than 10 %. Standard mixing procedure provided the best results for fly ash concretes. Increased mixing time did not lead to improvement of mechanical properties of HPC.

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References

1. Megat Johari, M.A., Brooks, J.J., Kabir, S., Rivard, P. Influence of supplementary cementitious materials on engineering properties of high strength concrete. Construction and Building Materials. 2011. 25. Pp. 2639–2648.
2. Gesoglu, M., Güneyisi, E., Asaad, D.S., Muhyaddin, G.F. Properties of low binder ultra-high performance cementitious composites: Comparison of nanosilica and microsilica. Construction and Building Materials. 2016. 102. Pp. 706–713.
3. Zhang, J., Zhao, Y., Li, H. Experimental Investigation and Prediction of Compressive Strength of Ultra-High Performance Concrete Containing Supplementary Cementitious Materials. Advances in Materials Science and Engineering. 2017. Vol. 2017. Article ID 4563164.
4. Shi, H., Xu, B., Zhou, X. Influence of mineral admixtures on compressive strength, gas permeability and carbonation of high performance concrete. Construction and Building Materials. 2009. 23. Pp. 1980–1985.

5. Poon, C.S., Lam, L., Wong, Y.L. A study on high strength concrete prepared with large volumes of low calcium fly ash. Cement and Concrete Research. 2000. 30. Pp. 447–455.
6. Muhd Norhasri, M.S., Hamidah, M.S., Mohd Fadzil, A., Megawati, O. Inclusion of nano metakaolin as additive in ultra high performance concrete (UHPC). Construction and Building Materials. 2016. 127. Pp. 167–175.
7. Tafraoui, A., Escadeillas, G., Lebaili, S., Vidal, T. Metakaolin in the formulation of UHPC. Construction and Building Materials. 2009. 23. Pp. 669–674.
8. Hiremath, P.N., Yaragal, S.C. Influence of mixing method, speed and duration on the fresh and hardened properties of Reactive Powder Concrete. Construction and Building Materials. 2017. 141. Pp. 271–288.
9. Chang, P.-K., Peng, Y.-N. Influence of mixing techniques on properties of high performance concrete. Cement and Concrete Research. 2001. 31. Pp. 87–95.
10. Hemalatha, T., Ram Sundar, K.R., Ramachandra Murthy, A., Iyer, N.R. Influence of mixing protocol on fresh and hardened properties of self-compacting concrete. Construction and Building Materials. 2015. 98. Pp. 119–127.
11. Aïtcin, P.-C. High-Performance Concrete. Informační centrum ČKAIT, Prague 2005.
12. Elahi, A., Basheer, P.A.M., Nanukuttan, S.V., Khan. Q.U.Z.: Mechanical and durability properties of high performance concretes containing supplementary cementitious materials. Construction and Building Materials. 2010. 24. Pp. 292–299.
13. Hela, R. Concrete admixtures. Beton TKS 2/2015. Pp. 4–10.
14. Chylík, R., Šeps, K. Influence of cement replacement by admixture on mechanical properties of concrete. Proceedings of the 12th fib PhD Symposium in Civil Engineering. 2018. Prague. Pp. 1267–1274.
15. ČSN EN 206+A1 Concrete – Specification, performance, production and conformity. ÚNMZ, Prague 2018.
16. ČSN EN 12390-7 Testing hardened concrete – Part 7: Density of hardened concrete. ÚNMZ, Prague 2009.
17. ČSN EN 12390-3 Testing hardened concrete – Part 3: Compressive strength of test specimens. ÚNMZ, Prague 2009.
18. ČSN EN 12390-5 Testing hardened concrete – Part 5: Flexural strength of test specimens. ÚNMZ, Prague 2009.
19. ČSN EN 12390-6 Testing hardened concrete – Part 6: Tensile splitting strength of test specimens. ÚNMZ, Prague 2010.
20. ČSN 73 1371 Non-destructive testing of concrete – Method of ultrasonic pulse testing of concrete. ÚNMZ, Prague 2011.
21. ČSN ISO 1920-10 Testing of concrete – Part 10: Determination of static modulus of elasticity in compression. ÚNMZ, Prague 2016.
22. ČSN EN 12390-8 Testing hardened concrete – Part 8: Depth of penetration of water under pressure. ÚNMZ, Prague 2009.

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Влияние процесса замещения цемента и гомогенизации на высокоэффективный бетон

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Ключевые слова: высокопрочный бетон; дополнительные вяжущие материалы; зольный унос; микрокремнезем; метакаолин.

Аннотация. Дополнительные вяжущие материалы (SCM) применяются при изготовлении бетонов по двум основным причинам – для уменьшения количества используемого цемента и улучшения их свойств. С их помощью возможно получить материал, являющийся более стойким, долговечным, экологически безопасным и экономичным по сравнению с традиционным портландцементным бетоном. В статье исследуется влияние двух важных факторов на механические свойства высокоэффективного бетона (HPC), содержащего SCM. Первым фактором является содержание выбранных дополнительных вяжущих материалов, вторым – вид процедуры гомогенизации, используемой при изготовлении бетона. В первой части исследования сравнивали 10 различных смесей: эталонная смесь без SCM, а также смеси, в которых 10, 20 или 30 % от массы цементы было заменено на микрокремнезем, летучую золу или метакаолин. Во второй части были изготовлены и изучены бетоны на основе трех смесей с различными уровнями замещения цемента дополнительными вяжущими материалами и четырех различных процедур гомогенизации. Для исследуемых составов определяли объемную плотность, прочности на сжатие, прочность на растяжение, динамический и статический модули упругости и глубину проникновения воды в бетон под давлением. Наилучшие результаты были достигнуты для смесей, в которых цемент частично был заменен на летучую золу. Устойчивость бетона к проникновению воды под давлением была значительно улучшена всеми SCM. Процедура гомогенизации, при которой SCM добавлялись к смеси после воды, позволила получить немного лучшие свойства бетонов, по сравнению со стандартной методикой смешивания применительно к смесям, содержащим микрокремнезем и метакаолин. В работе представлена обширная база данных, которая может служить эталоном для разработки HPC, содержащих SCM.

Список литературы

1. Megat Johari M.A., Brooks J.J., Kabir S., Rivard P. Influence of supplementary cementitious materials on engineering properties of high strength concrete // Construction and Building Materials. 2011. № 25. Pp. 2639–2648.
2. Gesoglu M., Güneyisi E., Asaad D.S., Muhyaddin G.F. Properties of low binder ultra-high performance cementitious composites: Comparison of nanosilica and microsilica // Construction and Building Materials. 2016. № 102. Pp. 706–713.
3. Zhang J., Zhao Y., Li H. Experimental Investigation and Prediction of Compressive Strength of Ultra-High Performance Concrete Containing Supplementary Cementitious Materials // Advances in Materials Science and Engineering. 2017. Vol. 2017. Article ID 4563164.
4. Shi H., Xu B., Zhou X. Influence of mineral admixtures on compressive strength, gas permeability and carbonation of high performance concrete. Construction and Building Materials. 2009. № 23. Pp. 1980–1985.
5. Poon C.S., Lam L., Wong Y.L. A study on high strength concrete prepared with large volumes of low calcium fly ash // Cement and Concrete Research. 2000. № 30. Pp. 447–455.
6. Muhd Norhasri M.S., Hamidah M.S., Mohd Fadzil A., Megawati O. Inclusion of nano metakaolin as additive in ultra high performance concrete (UHPC) // Construction and Building Materials. 2016. № 127. Pp. 167–175.
7. Tafraoui A., Escadeillas G., Lebaili S., Vidal T. Metakaolin in the formulation of UHPC // Construction and Building Materials. 2009. № 23. Pp. 669–674.
8. Hiremath P.N., Yaragal S.C. Influence of mixing method, speed and duration on the fresh and hardened properties of Reactive Powder Concrete // Construction and Building Materials. 2017. № 141. Pp. 271–288.
9. Chang P.-K., Peng Y.-N. Influence of mixing techniques on properties of high performance concrete // Cement and Concrete Research. 2001. № 31. Pp. 87–95.
10. Hemalatha T., Ram Sundar K.R., Ramachandra Murthy A., Iyer N.R. Influence of mixing protocol on fresh and hardened properties of self-compacting concrete // Construction and Building Materials. 2015. № 98. Pp. 119–127.

11. Aïtcin P.-C. High-Performance Concrete. Informační centrum ČKAIT, Prague 2005.
12. Elahi A., Basheer P.A.M., Nanukuttan S.V., Khan Q.U.Z.: Mechanical and durability properties of high performance concretes containing supplementary cementitious materials // Construction and Building Materials. 2010. № 24. Pp. 292–299.
13. Hela R. Concrete admixtures. Beton TKS 2/2015. Pp. 4–10.
14. Chylík R., Šeps K. Influence of cement replacement by admixture on mechanical properties of concrete. Proceedings of the 12th fib PhD Symposium in Civil Engineering. 2018. Prague. Pp. 1267–1274.
15. ČSN EN 206+A1 Concrete – Specification, performance, production and conformity. ÚNMZ, Prague 2018.
16. ČSN EN 12390-7 Testing hardened concrete – Part 7: Density of hardened concrete. ÚNMZ, Prague 2009.
17. ČSN EN 12390-3 Testing hardened concrete – Part 3: Compressive strength of test specimens. ÚNMZ, Prague 2009.
18. ČSN EN 12390-5 Testing hardened concrete – Part 5: Flexural strength of test specimens. ÚNMZ, Prague 2009.
19. ČSN EN 12390-6 Testing hardened concrete – Part 6: Tensile splitting strength of test specimens. ÚNMZ, Prague 2010.
20. ČSN 73 1371 Non-destructive testing of concrete – Method of ultrasonic pulse testing of concrete. ÚNMZ, Prague 2011.
21. ČSN ISO 1920-10 Testing of concrete – Part 10: Determination of static modulus of elasticity in compression. ÚNMZ, Prague 2016.
22. ČSN EN 12390-8 Testing hardened concrete – Part 8: Depth of penetration of water under pressure. ÚNMZ, Prague 2009.

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