Engineering Solid Mechanics 9 (2021) 335-346

Contents lists available at GrowingScience

Engineering Solid Mechanics

homepage: www.GrowingScience.com/esm

High-strength concretes based on anthropogenic raw materials for earthquake resistant high-rise construction

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ARTICLEINFO

Article history:
Received 10 November 2020
Accepted 19 January 2021
Available online
19 January 2021

Keywords:
Anthropogenic raw materials
Crushed concrete
Crushed brick
Disposal
Filled binder
High-strength concretes

ABSTRACT

This work is devoted to development of optimum recipes of high-strength concretes based on filled binders with fine-milled anthropogenic mineral filler intended for earthquake resistant high-rise monolithic construction. The optimum recipes of concretes in this work have been developed on the basis of computations and experimental designing of cast concrete mixes with chemical additives and anthropogenic mineral fillers, as well as destructive inspection methods as the most precise for analysis of physicomechanical and deformation properties of concrete. The following raw materials have been used for production of high-strength concretes: natural quartz sands with the fineness modulus F.M. = 1.7-1.8; crushed limestone with the particles sizes of 5-20 mm; water reducing chemical additives and hardening retarder to control specifications of concrete mixes; plain Portland cement, grade PTs 500 D0; anthropogenic mineral additives (fillers) in the form of crushed concrete and ceramic bricks. Optimum recipes of monolithic concretes have been designed using anthropogenic raw materials including normal concrete grades with compressive strength of M30-M40 and high-strength concrete grades of M50-M80, characterized by high homogeneity of cement stone with significantly finer pores and lower shrinkage. Herewith, it has been established that fine-milled anthropogenic mineral filler in the form of crushed concrete and ceramic bricks at the ratio of 70:30, respectively, efficiently influences specifications of concrete mixes on their basis significantly increasing resistance of the mix against sedimentation and water gain. It has been established that the developed high-strength concretes based on filled binders with fine-milled anthropogenic mineral filler are characterized by high freeze–thaw resistance (from F400 to F600) and water tightness (W14 and higher), which is a solid base providing high lifecycle of such concretes.

1. Introduction

Nowadays monolithic buildings and structures are erected using both conventional concretes, grades M7.5-M30, and new efficient concrete composites: high-strength, non-shrink, expansive, self-stressing, and others, including those based on new composite or filled binders (Alekseev et al., 2018; Barabash and Zubchenko, 2015; Shadykanov, 2019; Kaprielov et al. 2017). In addition, production and implementation of such concretes in the world continuously grow. Thus, it was reported that in the twentieth century only in Russia more than 23 billion tons of concrete were produced (Volkov and Zvezdov, 2004).

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doi: 10.5267/j.esm.2021.1.004

The most promising of the aforementioned composites for high-rise monolithic construction, including the seismic regions of the world, are multicomponent high-strength concretes, their production technology and specifications vary significantly from those of regular (Bataev et al., 2017). Herewith, the production technology of such concretes should be reduced to the concept of steady development of energy and resource saving, which is characterized by production of long-term green composites based on local raw materials requiring for minimum transportation and maintenance costs (Kuprina et al., 2014; Piatak et al., 2015). While the issue of efficient use of local raw and anthropogenic materials in normal and standard concretes is to some extent solved, including certain practical recommendations, then in the case of high-strength concretes for high-rise construction, where a set of factors influencing their quality should be considered, this issue is still important. For a long time, the compressive strength of concrete was considered as its major specification taken into account upon selection of raw materials and recipes of concretes. Nowadays, due to modern engineering approaches to production of concretes, as well as raw materials and semi-finished products, it is possible to control efficiently not only their physicomechanical or operational properties, but also technological and rheological performances of concrete mixes, such as fluidity, viability, shrink resistance, required strength at early stages, etc. Modern approaches to selection of optimum recipes of concretes make it possible at the stage of designing and operation to provide the required parameters of long lifetime: resistances against shocks, freeze–thaw, wear, water tightness etc. Such requirements can be met mainly due to modern chemical additives: modifiers of structure of concrete mix and concrete.

It is known that concretes for high-rise construction should satisfy stringent requirements to quality of raw materials, homogeneity and consistency of recipes, reliability and stability of structures, etc. For concretes operating in seismic regions, the issue of recipe selection and provision of properties of designed composite requires for even higher attention. Such concretes should be characterized by higher strength, plasticity, and extra-long lifetime. Moreover, in terms of engineering essence, the production of concretes of hydration hardening is sufficiently complicated chemical interaction of components since the concrete structure formation is stipulated by complex chemical reactions, hence, physicochemical, operational, and other properties of concrete stone mainly depend on initial raw materials. Therefore, stringent control is required for quality of raw materials for concrete as well as for all stages of its production.

Analysis of scientific works (Lesovik et al. 2012; Volodchenko et al., 2015; 2016; Suleymanova et al., 2014) devoted to high-strength concretes demonstrates that their production is generally related with the use of expensive imported materials, which influences the cost of final products. High-strength concretes were investigated in the works by (Kim & Kim, 1996; Aitcin, 1998; Skazlic & Bjegovic, 2005; Shi et al., 2015; Richard & Cheyrezy, 1995, Sharifi et al. 2020, Rooholamini et al. 2018a,b) and some other researchers (Murtazaev et al., 2018; Kapustin et al. 2017; Mohajerani et al. 2019; Bartoleto, 2015), where peculiar features of production technologies of such concretes were described together with the role of mineral additives upon formation of their structure. Thus, Kim and Kim (1996) and Aitcin (1998) determined that finely dispersed mineral additives significantly decreased the content of portlandite and ettringite, leading to filling of capillary pores with newly formed products, and, as consequence of decrease in porosity, high strength of such concretes was achieved.

Requirements to raw materials for development of high-strength concretes, described by Aitcin (1998), Skazlic et al. (2005), and Shi et al. (2015), are mainly related with the necessity to use high amount of binder (about 440-550 kg/m^3) with the lowest amount of liquid phase (B/C = 0.22–0.4), optimization of particle size distribution of fillers (fineness module of sand F.M. = 2.5-3, recommended particle size of crushed stone: 10-15 mm, no flaky grains, etc.), application of mineral fillers (fine-milled additives of various essence to decrease porosity of cement stone), etc. Brittleness and destruction pattern of high-strength concretes were studied by Richard and Cheyrezy (1995), where it was recommended to improve fracture viscosity of concrete by micro-reinforcement. In addition, in order to develop concrete with the strength of about 150 MPa, some researchers such as (Shi et al., 2015; Richard & Cheyrezy,

1995) propose to decrease B/C to 0.13, stating that in this case, maximum density of concrete can be achieved. In Russia production of high-strength concretes was studied by (Alekseev et al., 2018; Kaprielov et al. 2017; Bataev et al., 2017; Lesovik et al. 2012; Dem'yanova, 2013; Nesvetaev et al. 2003; Berg, Shcherbakov and Pisanko, 2012) and others. Analysis of compositions and properties of raw materials, including anthropogenic substances, confirms existence of various reserves of raw materials for efficient development of production of modern construction composites (Murtazaev et al., 2019; Bazhenov, 2011; Patil et al., 2016). In addition to natural raw materials, there are abundant anthropogenic wastes in the region. They are mainly comprised of demolition wastes after the known events of the 1990-s and the early 2000-s, which amount to about 60% of total amount of construction wastes: crushed concrete and bricks (Olzvoibaatar, 2019; Rakhimbayev et al. 2016; Lesovik et al., 2019).

On the basis of world experience of production of high-strength concretes, it is possible to state that upon rational approach and application of modern chemical modifiers of concrete structure, various mineral additives, as well as efficient equipment for activation of raw materials and homogenization of mix, it is possible to recommend recipes of high-strength concretes based on anthropogenic raw materials. On the basis of the performed analysis, this work is aimed at development of optimum recipes of high-strength concretes based on filled binders with fine-milled anthropogenic mineral filler, intended for earthquake resistant high-rise monolithic construction. The following issues should be solved:

- Selection of anthropogenic mineral fillers;
- Development of recipes of filled binders with fine-milled anthropogenic mineral filler and investigation into their properties;
- Development of optimum recipes of high-strength concretes based on filled binders with fine-milled anthropogenic mineral filler, intended for earthquake resistant high-rise monolithic construction, and analysis of their physicomechanical and deformation properties.

The authors believe that the high interest to the use of secondary crushed concrete is attracted by possibility to use it as fine-milled mineral component in mixed or so called filled binders characterized by improved specifications and physicomechanical properties, they can be applied for production of high-strength concretes, including those for monolith high-rise construction in seismic regions all over the world.

2. Materials

Natural sand from Chervlen deposit (Chechen Republic) was used as a fine filler with the following properties: fineness module F.M. = 1.7-1.8; dusty and clayish particles: 1.7-1.9%; void factor: 40.8%; density: $\rho_{real} = 2{,}617$ kg/m^3; density $\rho_{bulk} = 1{,}512$ kg/m^3. Crushed stones from Argun and Sernovodsk deposits (Chechen Republic) with particle sizes of 5-20 mm were used as coarse filler. Straight cement, grade PTs 500 D0 (AO Chechentsement) with normal consistency (NC) = 25.5%, specific surface area: 325.2 m^2/kg, water gain $\leq 18\%$, and setting times: 2 h 15 min (initial) and 3 h 40 min (final), was used as a binder in the experiments. Content of clinker minerals characterizing the binder composition was as follows: $C_3S = 59\%$; $C_2S = 16\%$; $C_3A = 8\%$; $C_4AF = 13\%$. The following plasticizing additives were applied:

1. Produced by POLIPLAST: Linamiks PK super-plasticizing agent (fluid) and Linamiks RS hardening retarder (fluid) based on polyoxyethylene derivatives of polymethacrylic acid;
2. Produced by OOO TOKAR (Vladikavkaz): D-5 complex multifunctional additive (dry powder) according to State standard GOST 24211-2008.

Linamiks PK was added to concrete mixes based on filled binders (FB) together with tempering water in minor amount (from 0.3 to 0.4% of binder weight), since FB already contained the D-5 additive with plasticizing properties. Linamiks RS retarder was added in the amount of 0.7% of binder weight aiming at increased storability of concrete mixes (7-8 h and higher). Anthropogenic mineral fillers (AMF) for high-strength concretes were obtained by mechanical activation of raw stock, namely: crushed concrete and ceramic bricks, in a MV-20-EKS laboratory ball mill to achieve specific area of 450-600 m2/kg. Average milling time was 4-6 min.

Compressive strength of concretes was determined at the ages of 1, 3, 7, and 28 days on references samples with the sizes of 100×100×100 mm after holding under ambient humidity ($\varphi = 95\pm5\%$, $t = 20\pm2°C$). Chemical composition of initial raw materials as well as macro- and microstructure of the concretes was determined using Quanta 3D 200i microscope. All experiments were carried out in shared facility centers of Grozny State Oil Technical University in 2018–2019.

3. Results

For development of optimum recipes of high-strength concretes, two grades of FB with fine-milled AMF were developed and analyzed (Table 1) and their recipes are given in Table 2 in wt%.

Table 1. Properties of FB with fine-milled AMF

Binder	NC,%	S_{sp} of binder, m^2/kg	Real density, kg/m^3	Water gain,%	Setting time, h - min		Activity, MPa
					initial set	final set	
FB-75:25	17	558	2,986	15.5	3-40	5-30	71.3
FB-60:40	19	577	2,905	14.7	3-55	5-35	60.7
PTs M500 D0 (Chechentsement)	26	325	3,115	18.0	2-15	3-40	52.6

Table 2. Composition of filled binder (FB) materials

FB grade	FB-75:25	FB-60:40
PTs M500 D0 (Chechentsement)	75%	60%
AMF based on crushed concrete	16%	27%
The same, based on crushed bricks	7%	11%
D-5 additive	2%	2%

Since designs of high-rise buildings are generally based on concretes of various hardness classes (M40, M75-M80 and others), it was planned to develop optimum recipes of high-strength concretes, including standard grades M30-M40 and high-strength grades M50-M80, with complex usage of anthropogenic raw materials. Herewith, the recipes were developed also for production of high-workability (cast) concrete mixes with slump of standard cone amounting to 22±2 cm, which corresponded to P5 grade in terms of workability applied in modern monolithic construction as the most efficient concrete mixes requiring for lower power consumptions during pumping via pipelines of concrete pumps and subsequent vibratory compaction. Recipes and properties of concrete mixes of higher storability and operation lifetime are summarized in Table 3. In addition to strength properties of the developed concretes, the authors studied their deformation performances, including elasticity module E_0 and deformation module E of concrete, ultimate deformations, Poisson's coefficient determined in accordance with State standard GOST 24452-80 on prism samples with square cross section of 100×100×400 mm. The mentioned performances are especially important for concretes intended for carrying structures of buildings and facilities intended for static and dynamic loads in seismic regions.

The obtained properties of high-strength concretes based on anthropogenic raw materials are summarized in Table 4. While comparing the obtained experimental data for concretes based on filled binders (Table 4) with available strength properties of concretes based on conventional Portland cement, it is possible to observe the difference in dynamics of concrete strength (Fig. 1).

Table 3. Recipes and properties of concrete mixes based on anthropogenic raw materials

No.			Components in concrete mix, kg/m^3								Specifications			
			Broken stones		Sand	Binder			Additive					
	Concrete grade	Required strength, MPa	Argun	Sernovodsk	Chervlen	FB-60:40	FB-75:25	Water	Linamiks PK (wt% of cement)	Linamiks RS (wt% of cement)	B/C	Density, kg/m^3	Slump, cm	Storability, h
1.	M30 (M400)	39.3	1,000	-	855	385	-	161	1.1 (0.3)	2.5 (0.7)	0.45	2,398	23	7.0
2.	M40 (M500)	52.4	1,000	-	795	435	-	158	1.3 (0.3)	3.0 (0.7)	0.36	2,407	21	7.0
3.	M45 (M600)	58.9	1,000	-	765	470	-	162	1.4 (0.3)	3.3 (0.7)	0.34	2,427	23	8.0
4.	M55 (M700)	72.0	-	1,000*	735	-	540	161	1.6 (0.3)	3.8 (0.7)	0.31	2,451	23	8.5
5.	M60 (M800)	78.6	-	1,000*	685	-	600	165	1.8 (0.3)	4.3 (0.7)	0.30	2,462	21	9.0
6.	M80 (M1000)	104.7	-	1,000*	620	-	700	170	2.1 (0.3)	4.9 (0.7)	0.32	2,481	24	10.0

Remark: * – enriched broken stones, particle size: 5-20 mm, crushability: M1,200;

Table 4. Properties of high-strength concretes based on anthropogenic raw materials

Recipe No. from Table 2	Concrete grade	ρ_C, kg/m^3	Compressive strength at the age of …, MPa					R_{PR} / R	R_{tb}	$E_б \cdot 10^3$, MPa	Deformation ε, mm/m		Poisson coefficient μ	Concrete shrinkage, mm/m	W_M, wt%	W	F
			R				R_{PR}				longitudinal ε_1	transversal ε_2					
			1 day	3 days	7 days	28 days	28 days										
1.	M30 (M400)	2,336	14.3	31.7	41.1	46.7	38.3	0.82	4.8	43.5	2.08	0.49	0.237	0.62	2.7	W14	F400
2.	M40 (M500)	2,352	17.8	38.9	51.7	58.1	47.6	0.82	5.7	44.8	1.99	0.47	0.235	0.60	2.7	W14	F400
3.	M45 (M600)	2,358	22.3	45.5	59.9	65.8	54.6	0.83	6.4	46.2	1.96	0.46	0.234	0.55	2.5	W16	F500
4.	M55 (M700)	2,365	26.4	54.1	69.6	77.3	65.7	0.85	8.2	47.5	1.96	0.45	0.228	0.40	2.4	W18	F500
5.	M60 (M800)	2,383	29.5	59.8	75.3	85.4	72.6	0.85	8.6	52.4	1.95	0.43	0.222	0.36	2.4	W20	F600
6.	M80 (M1000)	2,408	40.9	81.8	106.1	115.3	99.2	0.86	9.7	54.5	1.90	0.40	0.210	0.31	2.2	W20	F600

Remarks: ρ_c – density of concrete, kg/m^3; R – compressive cube strength of concrete, MPa; R_{PR} – compressive prism strength of concrete, MPa; R_{PR}/R – prism to cube strength ratio characterizing its uniformity; R_{tb} – bending tensile strength of concrete, MPa; $E_c \cdot 10^3$ – elasticity module of concrete, MPa; ε – deformation of concrete, mm/m; ε_1 – longitudinal deformation of concrete, mm/m; ε_2 – transversal deformation of concrete, mm/m; μ – Poisson coefficient (coefficient of transversal deformation); W_w – water absorption of concrete, wt%; W – grade of concrete in terms of water tightness; F – grade of concrete in terms of freeze–thaw resistance.

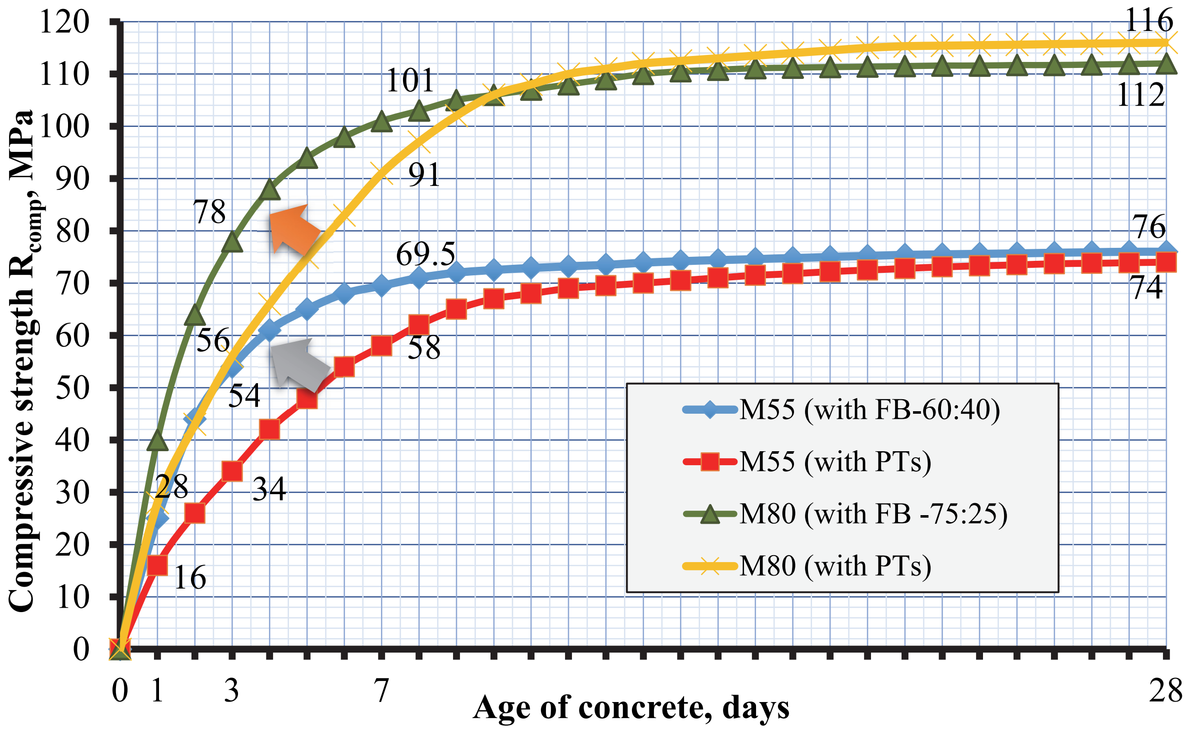

Fig. 1. Strength properties of concrete as a function of binder type

Aiming at analysis of homogeneity of the considered concrete mixtures based on anthropogenic raw materials, the authors studied coefficient of prism strength of concretes as a function of their compositions and binder types with varied fraction of clinker constituent and fine-milled anthropogenic filler. The obtained data illustrating experimental dependences of prism strength R_{PR} of the developed concretes using various binders on their cube strength R were compared with available data of researchers in Russia (Figs. 2 and 3).

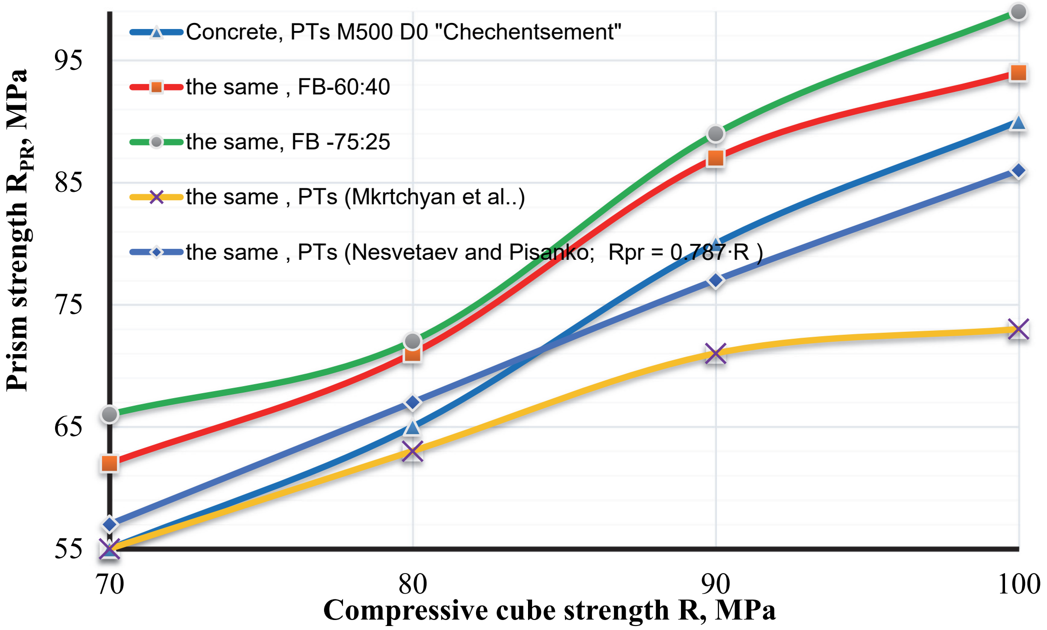

Fig. 2. Prism strength R_{PR} as a function of cube strength R with various binders

The plots in Fig. 3 illustrate the coefficient of prism strength as a function of cube strength, that is, $R_{PR}/R=f(R)$, based on experimental and published data using Eqs. (1) and (2).

$$R_{PR}/R = (0.77\text{-}0.00125\ R), \tag{1}$$

where R is the cube strength, MPa; R_{PR} is the prism strength, MPa.

$$R_{PR} = (0{,}77 \cdot b - 0{,}00125R)R, \tag{2}$$

where b is the adjusting coefficient for high-strength concretes equaling to $1.123+0.00115(R-60)$; $R \geq 60$ MPa.

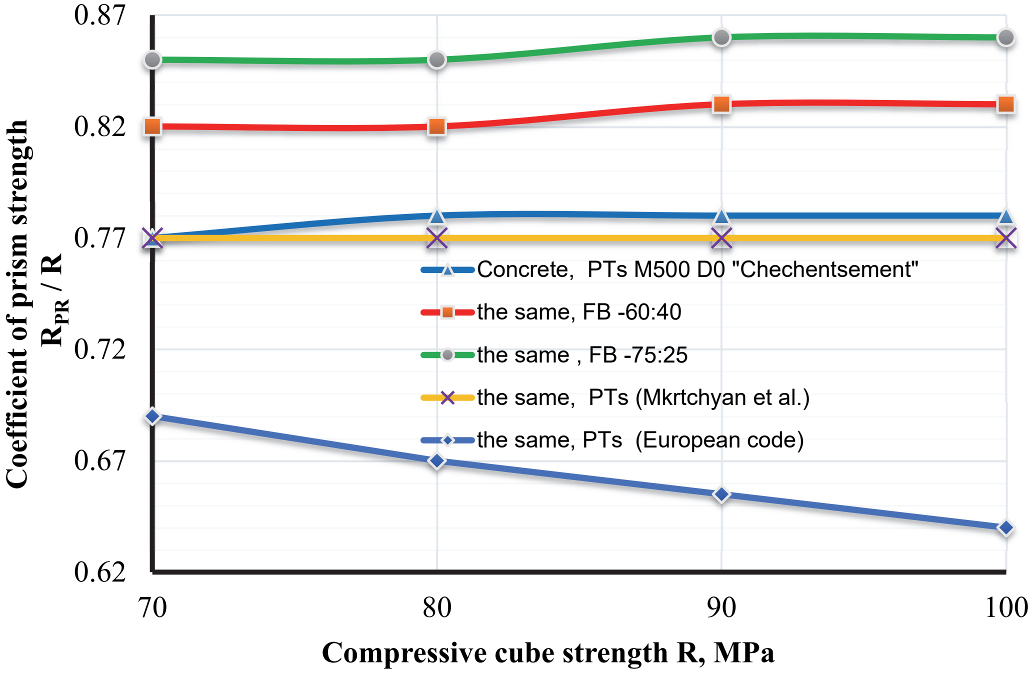

Fig. 3. Coefficient of prism strength as a function of concrete strength with various binders

It was established that the elasticity module increased with prism strength of concrete (Fig. 4). Herewith, the curve varies insignificantly from the data presented by Nesvetaev et al. (2003).

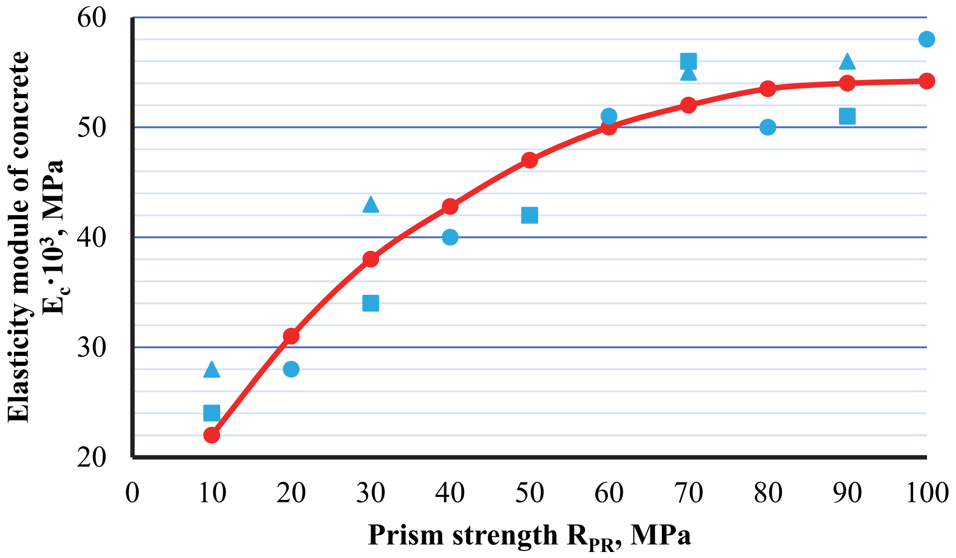

Fig. 4. Elasticity module of high-strength concrete with fine-milled AMF as a function of its prism strength

4. Discussion

On the basis of the obtained results, it is possible to state that concretes based on fine-milled anthropogenic fillers are characterized by superior features in comparison with conventional concretes based on Portland cement. In particular, this refers to retention of workability of concrete mixes, dynamics of strength in the first days of hardening, deformation properties of concrete, etc. (Figs. 1-4). Herewith, retention (or viability) of concrete workability (fluidity, consistence, etc.) is obviously one of the major performances of quality. In this regard, the authors studied rheological and engineering properties of concrete mixes, in particular, their fluidity, storability, water gain, segregation, etc. As can be seen in Table 4, the considered recipes (special recipes of concretes) based on filled binders and special additives are characterized by higher storability (8–10 h). Good retention of workability of concrete mixes results in integer monolith structure without formation of cold joints in emergency cases related with machinery faults, disruption of mix supply, etc. After termination of retarding action of additive, these mixes are sufficiently rapidly hardened in early age (1-3 days), which improves efficiency of reusability of formworks, thus, sharply reduces construction timing, which is especially important in modern construction. In the case of precast concrete units, such feature of the proposed recipes of concretes (high storability, rapid hardening, and others) would allow to reduce time of production of the structures, and in some cases, to eliminate partially or completely steam treatment of concrete.

Thus, the increase of strength properties of concretes based on FB in the age of 1…3 days is accelerated by 1.5-2 times: the strength of concrete based on FB in the age of one day is about 33-36% in comparison with the designed strength, and in the age of three days, it equals to 65-75%. In the age of seven days, the strength of this concrete is about 85-90% of the designed value. This differs significantly from the performances of standard recipes with conventional Portland cement. The performances of conventional concretes in the age of 1, 3, and 7 days are 23-26, 34-37, and 65-70% of the designed strength, respectively. Such dynamics of concrete hardening are attributed to complex effect of chemical modifiers in the recipes of concrete and filled binder. The D-5 additive in concrete acting as a plasticizing agent in the initial period of concrete tempering also acts to some extent as accelerator. Due to such action on the properties of concrete mix and concrete, the D-5 is a multifunctional additive positively affecting rheological and engineering properties of the mix as well as physicomechanical and operational performances of concrete. Similar effect on the properties of concrete mix and concrete is exerted by Linamiks PK, which accelerates concrete hardening in early age. Such dynamics of rapid hardening make it possible to load structural elements in early age (1…7 days after erection).

Replacement of conventional Portland cement with filled binders significantly increases the prism strength R_{PR} towards the cubic strength R, significantly reducing the difference between them. Thus, if the coefficient of prism strength (that is, R_{PR}/R) does not exceed 0.78-0.80, then in the case of the considered concretes, it is about 0.82-0.86. Herewith, R_{PR}/R increases significantly upon conversion to filled binders of higher grades and decreases upon increase in the fraction of AMF (Fig. 2). The coefficient R_{PR}/R for normal concretes is determined usually by equation (1) as explained in previous works: (Alekseev et al., 2018; Barabash and Zubchenko, 2015; Shadykanov, 2019; Kaprielov et al. 2017; Volkov and Zvezdov, 2004; Bataev et al., 2017; Mohajerani et al. 2019; Bartoleto, 2015; Dem'yanova, 2013). This dependence was studied by researchers in Russia and abroad for various concrete grades up to M45-M50, it allowed to determine R_{PR}/R with sufficient accuracy. For high-strength concretes, Eq. (1) was nearly not studied. Despite some works by Russian researchers devoted to increase in the prism strength of various concretes, they are not sufficient for application of these dependences to high-strength concretes, their recipes and properties depend on numerous factors in comparison with concretes of lower grades. In European codes, the coefficient of prism strength of high-strength concretes is often used as a constant equaling to 0.8. The Russian scientist Berg presents this dependence as $R_{PR} = f(R)$, mentioning its linear pattern. Herewith, some Russian scientists recommend using this coefficient equaling to 0.78. On the basis of complex studies of concretes of various grades, Eq. (2) with consideration for additional adjusting coefficient *b*, which provides confidence more than by 97-98% was proposed in the literature.

Comprehensive studies of deformation properties of concretes were performed by many researchers. However, there are few studies devoted to concretes based on anthropogenic raw materials. In this regard, the authors studied deformation properties for high-strength concretes based on secondary raw materials, which was also very important for materials used in seismic regions. The module of elasticity of concrete based on secondary raw materials, equaling to $40.2 \cdot 10^3 – 54.5 \cdot 10^3$ MPa, depends on their strength as well as on the strength and type of applied fine and coarse filler. Herewith, the module of elasticity of concrete increases with its strength.

The produced concretes are also characterized by moderate ultimate longitudinal ε_1 and transversal ε_2 deformations (ε_1 = 1.93-2.32 mm/m, ε_2 = 0.41-0.66 mm/m). For comparative analysis, it is possible to mention ε_1 and ε_2 of conventional recipes, which are usually in the range of 3.2-3.6 mm/m and 1.9-2.0 mm/m, respectively. The curves of ε_1 and ε_2 as a function of recipe and properties of concrete demonstrate that the longitudinal and transversal deformations decrease with the increase in the strength of concrete and addition of anthropogenic mineral filler.

The coefficient of transversal deformation (or the Poisson's coefficient μ) of the considered concretes equaling to 0.210-0.285 also depends on the strength of concrete: μ decreases with the increase in the strength of concrete. It proves the existence of brittle destruction of concretes of higher grades. Structure modification of concrete mix using mineral and chemical filler influences not only the module of elasticity but also the destruction pattern of cement matrix, thus increasing the elasticity of concrete. Herewith, the ultimate longitudinal deformations and the deformation itself of the considered high-strength concrete are reflected by the linear pattern. The experiments show that plastic deformations of the modified concrete can be observed upon loading of reference samples at $\sigma = (0.48\text{-}0.52)\,R_{PR}$. Straight concretes generally start to exhibit plastic deformations already at $\sigma = 0.3R_{PR}$. Therefore, meaningful property and analysis of structure imperfection of the considered high-strength concrete are based on plasticity comprised of its complete deformations determined upon loading of reference samples to stresses equaling to $\sigma = 0.5R_{PR}$ with subsequent decrease in external impact (unloading of samples).

Residual plastic deformations ε_{PL}^{RES} of straight concrete were set to 0.12-0.14 mm/m, whereas for the plasticized high-strength concretes based on mineral and chemical additives, this indicator did not exceed 0.11 mm/m, which was in average by 23% lower than for the reference. Insignificant (not more than 11–19%) variation of the module of elasticity of the considered recipes upon loading to $\sigma = 0.9R_{PR}$ evidences elasticity of high-strength concrete. Analysis and experimental data processing of reference straight recipes show noticeable decrease in the module of deformation of concrete at early stages of loading, that is, already at $\sigma = 0.5R_{PR}$. Herewith, the module of deformation decreases to 44-46%.

High elasticity of high-strength concretes was confirmed by high Hooke's coefficient or coefficient of elasticity k (for the considered concretes: k = 0.90-0.94). Using the deformation indicators of reference samples upon axial compression according to the procedure proposed by Berg, it is difficult and sometimes impossible to determine the upper $R^v{}_T$ and the lower $R^\circ{}_T$ parametric points of microcrack formation, which evidences that the structure of the considered concretes experiences only volumetric compaction to the level of its loading equaling to $0.93\text{-}0.95R_{PR}$.

The Poisson's coefficient in all cases was 0.21-0.28, and the upper boundary of microcrack formation $R^v{}_T = 0.87R_{PR}$ was observed only for the reference concrete without additives and with B/C = 0.49. In other samples it was impossible to determine the parameters of microcrack formation even upon loading to $0.9R_{PR}$. Such behavior of the considered high-strength concretes based on secondary raw materials is in agreement with the known experimental results of modified concretes punished in (Alekseev et al., 2018; Kaprielov et al., 2017; Dem'yanova, 2013; Nesvetaev et al. 2003; Berg et al. 2012).

5. Conclusion

FB recipes with the activity of 60-71 MPa with fine disperse AMF have been developed and analyzed, namely, on the basis of crushed concrete and ceramic bricks with the ratio of 70:30, respectively; herewith, the filler fraction in FB was 25 and 40% of binder weight.

Efficiency of the developed FB with fine-milled anthropogenic filler has been proved resulting in production of fluid concrete mixes for high-rise monolithic construction.

On the basis of anthropogenic raw materials, optimum recipes of concrete mixes have been developed with cone slump corresponding to grade P5 and storability more than 8 h for development of high-strength concretes.

Physicomechanical properties of high-strength concretes on the basis of anthropogenic raw materials, grades M60-M80, have been studied, the increase in time of their strength as a function of binder type has been analyzed. It has been established that hardening of concretes based on FB in the early age (1-3 days) is accelerated by 1.5-2 times. Thus, the strength of concrete based on FB in the age of 1 day is about 33-36% of the designed level, and in the age of 3 days, it is as high as 70%. The hardness of concrete based on FB in the age of 7 days is about 85-90% of the designed level, which is significantly higher than the performances of conventional recipes based on standard Portland cement. It has been proved that the coefficient of prism strength (that is, the ratio R_{PR}/R) of concretes based on FB is in the range of 0.82-0.86, and in the case of concretes based on standard Portland cement, it is below 0.78.

Deformation properties of high-strength concretes based on anthropogenic raw materials have been studied. It has been established that the module of elasticity of the proposed recipes of high-strength concretes based on anthropogenic raw materials is in the range of $40.2 \cdot 10^3$–$54.5 \cdot 10^3$ MPa depending on the concrete strength and filler type. Herewith, the higher is the concrete strength, the higher is its module of elasticity.

It has been experimentally demonstrated that the ultimate longitudinal ε_1 and transversal ε_2 deformations of high-strength concretes with finely dispersed AMF are 1.93-2.32 mm/m and 0.41-0.66 mm/m, respectively. For straight concretes of regular recipe, they equal in general to $\varepsilon_1 = 3.2\text{-}3.6$ mm/m and $\varepsilon_2 = 1.9\text{-}2.0$ mm/m. The longitudinal and transversal deformations decrease with the increase in the concrete strength and the fraction of fine-milled AMF.

It has been established that the Poisson's coefficient μ (the coefficient of transversal deformation) of high-strength concretes with fine-milled AMF is in the range of 0.21-0.285. It has been detected that with the increase in the concrete strength, the Poisson's coefficient of high-strength concretes decreases, which evidences more brittle structure of such concretes with the increase in their compressive strength.

It has been proved that high-strength concretes based on FB with fine-milled AMF are characterized by high strength (higher than 100 MPa), freeze–thaw resistance (F400-F500), water tightness (W14 and above), and optimum deformation performances meeting the requirements for seismic construction, forming consistent base and providing high lifetime of such concretes. Therefore, the challenges of investigations in this field are stipulated by urgent necessity to solve the problems of disposal of anthropogenic raw materials in the form of construction wastes, amounting to about one third of total process wastes, as well as by competitive advantages of new construction materials on their basis comprised of wide availability of such raw materials and low prime cost of ready products, which allows to apply such materials for monolithic construction nearly without limitations.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research, project No. 18-48-200001 “High quality concretes with improved performances based on local natural and anthropogenic raw materials”.

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