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Mechanical and Hydric Properties of High-Performance Concrete Containing Natural Zeolites

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Abstract**—**Mechanical and water transport properties of high performance concrete (HPC) containing natural zeolite as partial replacement of Portland cement are studied. Experimental results show that in the investigated mixes the use of natural zeolite leads to an increase of porosity, decrease of compressive strength and increase of moisture diffusivity and water vapor diffusion coefficient, as compared with the reference HPC. However, for the replacement level up to 20% of the mass of Portland cement the concretes still maintain their high performance character and exhibit acceptable water transport properties. Therefore, natural zeolite can be considered an environmental friendly binder with a potential to replace a part of Portland cement in concrete in building industry.

Keywords**—**Natural zeolites, high-performance concrete; hydric properties, mechanical properties

I. INTRODUCTION

NATURAL materials were used as supplementary cementitious materials (SCM) since ancient times, due to their pozzolanic properties. In the old Rome, fine volcanic (pozzolanic) ashes were used in a mixture with lime. At present natural pozzolanas are used as SCM for Portland cement concrete mainly in the countries where they are easily available. Natural zeolites are probably the most often used natural SCM. However, zeolite concrete is a much less frequent subject of investigation as compared for instance with silica fume, metakaolin, fly ash or ground granulated blast furnace slag as SCM.

In the analyses of properties of concrete containing zeolites as SCM the various investigators concentrated mainly on mechanical properties which are commonly considered the most important for any type of concrete [1], [2]. Pozzolanic activity of zeolites was also a widely studied subject [3]-[5]. Other properties were measured only seldom.

Water sorptivity of concrete with zeolite additive was investigated by Chan and Ji [6], Ikotun and Ekolu [7], chloride diffusion by Chan and Ji [6], Ahmadi and Shekarchi [8], oxygen permeability by Ikotun and Ekolu [7], Ahmadi and Shekarchi [8]. Thermal properties of autoclaved aerated concrete with zeolite addition were measured by Karakurt et al. [9].

In this paper, mechanical and water transport properties of high performance concrete containing natural zeolite as partial replacement of Portland cement are studied and compared with reference high performance concrete.

II. MATERIALS

The high performance concrete mixtures presented in Table I were prepared with Portland cement CEM I 42.5 R as the main binder. A part of cement was replaced by natural zeolites. The chemical composition of cement and natural zeolites is shown in Table II.

TABLE I
COMPOSITION OF STUDIED CONCRETES

Component	BZ-ref	BZ10	BZ20	BZ40
CEM I 42.5 R	484	436	387	305
Natural zeolites	-	48	97	179
Aggegates 0-4 mm	812	812	812	812
Aggegates 8-16 mm	910	910	910	910
Plasticizer Mapei Dynamon SX	5.3	5.3	5.3	5.3
Water	171	194	221	244

TABLE II
CHEMICAL COMPOSITION OF CEMENT AND NATURAL ZEOLITES

Component	Amount (mass %)	
	Cement	Zeolites
SiO_2	21.89	68.15
Al_2O_3	5.60	12.30
Fe_2O_3	3.75	1.30
CaO	62.33	2.63
MgO	1.04	0.90
K_2O	0.92	2.80
Na_2O	0.11	0.75
TiO_2	0.30	0.20
P_2O_5	0.17	-
SO_3	2.88	-

The measurement of material parameters of hardened concrete mixes was done (unless mentioned otherwise) after 28 days of standard curing. It took place in a conditioned

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laboratory at the temperature of 22±1°C and 25-30% relative humidity.

III. EXPERIMENTAL METHODS

A. Basic Physical Properties

Among the basic properties, the bulk density, matrix density and open porosity were measured using the water vacuum saturation method [10]. Each sample was dried in a drier to remove majority of the physically bound water. After that the samples were placed into the desiccator with deaired water. During three hours air was evacuated with vacuum pump from the desiccator. The specimens were then kept under water not less than 24 hours. The measurement was done on the samples with the dimensions of 50 x 50 x 20 mm.

B. Mechanical Properties

The measurement of compressive strength was done using the hydraulic testing device VEB WPM Leipzig 3000 kN. The apparatus consists of a stiff loading frame having the capacity of 3000 kN. A constant strain rate of 0.1 – 0.2 MPa s^{-1} was imposed on the 150 x 150 x150 mm specimens. The tests were performed according to ČSN EN 12390-3 [11].

C. Liquid Water Transport Properties

The water sorptivity was measured using a standard experimental setup. The specimen was water and vapor-proof insulated on four lateral sides and the face side was immersed 1-2 mm in the water. Constant water level in tank was achieved by a Mariotte bottle with two capillary tubes. One of them, inside diameter 2 mm, was ducked under the water level, second one, inside diameter 5 mm, was above water level. The automatic balance allowed for recording the increase of mass. The water absorption coefficient A (kg/m^{2}s$^{1/2}$) was then calculated using the formula

$$i = A \cdot t^{\frac{1}{2}}, \tag{1}$$

where i (kg/m^2) is the cumulative water absorption, t is the time from the beginning of the suction experiment. The water absorption coefficient was then used for the calculation of the apparent moisture diffusivity in the form [12]

$$\kappa_{app} \approx \left(\frac{A}{w_c} \right)^2, \tag{2}$$

where w_c (kg/m^3) is the saturated moisture content.

In the experimental work 5 specimens of 50 x 50 x 20 mm were used.

D. Water Vapor Transport Properties

The wet cup method and dry cup method were employed in the measurements of water vapor transport parameters [10]. In the dry cup method the sealed cup containing silica gel was placed in a controlled climatic chamber with 50% relative humidity and weighed periodically. For wet cup method sealed cup containing water was placed in an environment with 50% relative humidity. The measurements were done at 25°C in a period of two weeks. The steady state values of mass gain or mass loss determined by linear regression for the last five readings were used for the determination of water vapor transport properties.

The water vapor diffusion coefficient D (m^2/s) was calculated from the measured data according to the equation

$$D = \frac{\Delta m \cdot d \cdot R \cdot T}{S \cdot \tau \cdot M \cdot \Delta p_p}, \tag{3}$$

where Δm is the amount of water vapor diffused through the sample (kg), d the sample thickness (m), S the specimen surface (m^2), τ the period of time corresponding to the transport of mass of water vapor Δm (s), Δp_p the difference between partial water vapor pressure in the air under and above specific specimen surface (Pa), R the universal gas constant, M the molar mass of water, T the absolute temperature (K).

On the basis of the water vapor diffusion coefficient D (m$^{2/}$s), the water vapor diffusion resistance factor μ (-) was determined using equation (4)

$$\mu = \frac{D_a}{D}, \tag{4}$$

where D_a is the diffusion coefficient of water vapor in the air.

In the experimental work 3 cylindrical specimens with the diameter 105 mm and thickness 20 mm were used.

IV. EXPERIMENTAL RESULTS

A. Basic Physical Properties

The basic physical properties of studied materials measured by the water vacuum saturation method are shown in Table 3. The bulk density of the analyzed concretes decreased with the increasing amount of natural zeolites. The open porosity increased in the corresponding way. The values of matrix density were almost the same (within a 3% limit) for all studied concretes.

TABLE III
BASIC PHYSICAL PROPERTIES OF STUDIED MATERIALS

HPC	ρ (kg/m^3)	ρ (kg/m^3)	Ψ (%)
BZ-ref	2244	2590	13.4
BZ10	2194	2601	15.7
BZ20	2132	2601	18.0
BZ40	2036	2623	22.4

B. Mechanical Properties

Fig. 1 shows that the compressive strength of studied concretes decreased with the increasing amount of natural zeolites used as the replacement of Portland cement. The 7-days strengths were similar for the reference concrete and BZ10. For higher amounts of natural zeolites in the mix the compressive strength was significantly lower which was an expected outcome, taking into account the pozzolanic properties of zeolites. The values of compressive strength after 28 days showed that up to the 20% replacement level the concretes still maintained their high performance character but for BZ40 a 50% decrease was observed which was not satisfactory. The differences in compressive strength after 360 days were very similar to 28 days.

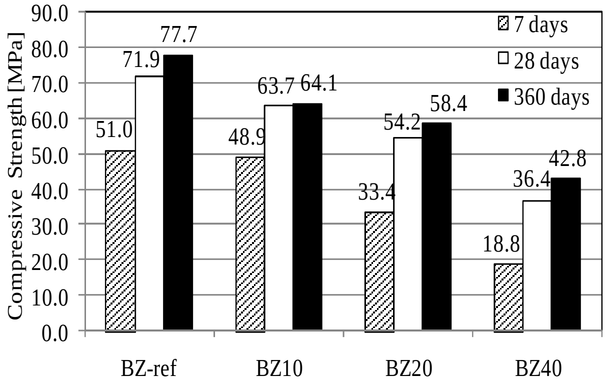

Fig. 1 Compressive strength of studied materials

C. Liquid Water Transport Properties

The results of water sorptivity measurements are presented in Table 4. We can see that the increase of open porosity with increasing mass of pozzolanic admixtures led to a significant enhancement of liquid water transport. The moisture diffusivity of BZ40 was about five times higher than reference concrete. Similarly as with the compressive strength, 20% replacement level could be considered a reasonable limit, as for the liquid water transport parameters.

TABLE IV
LIQUID WATER TRANSPORT PROPERTIES OF STUDIED MATERIALS

HPC	A (m^2/s)	κ (m^2/s)
BZ-ref	0.0086	4.3E-09
BZ10	0.0096	3.9E-09
BZ20	0.0153	7.4E-09
BZ40	0.0317	2.1E-08

D. Water Vapor Transport Properties

Table V shows that the water vapor diffusion coefficient of studied materials increased with increasing amount of natural zeolites in the mix which was in accordance with the open porosity data in Table 3. The measured data also revealed that the values of water vapor diffusion coefficient corresponding to the lower values of relative humidity (5/50 %) were always lower than those for higher relative humidity values (97/50 %). This is related to the partial transport of capillary condensed water in the wet-cup arrangement [13].

TABLE V
WATER VAPOR TRANSPORT PROPERTIES OF STUDIED MATERIALS

	5/50%		97/50%	
HPC	D (m^2/s)	μ (-)	D (m^2/s)	μ (-)
BZ-ref	2.2E-07	106.7	2.6E-07	89.8
BZ10	2.8E-07	81.9	3.3E-07	68.9
BZ20	3.9E-07	58.8	4.9E-07	49.5
BZ40	6.5E-07	35.4	9.0E-07	29.8

V. CONCLUSIONS

Experimental results presented in this paper confirmed that natural zeolites can be considered an environmental friendly binder with a potential to replace a part of Portland cement in concrete in building industry. However, it was shown that although from both environmental and economical points of view it would be desirable to use its highest possible amounts in concrete production, the extent of Portland cement replacement which could be chosen in preparation of high performance concrete mixes had certain limitations. The main limiting parameter was found the compressive strength. For higher replacement levels than 20% of mass of cement the compressive strength decreased very fast and the produced concrete lost its high performance character. The water transport parameters increased with increasing amount of zeolites in the mix relatively fast but for the replacement level up to 20% they could still be considered satisfactory. Water vapor transport parameters increased with the increasing amount of natural zeolites as well but the enhanced water vapor transport did not present any danger from the point of view of concrete durability. In a summary, we can state that concrete with the replacement of Portland cement by natural zeolites in the amount of 20% by mass was the most suitable solution among the mixes analyzed in this paper.

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