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Durability Properties of High Performance Foamed Concrete

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Abstract

Foamed concrete (FC) is promising material in modern building industry because of simple technology and wide range of properties may be achieved. Basic problems of FC are shrinkage and decreased strength, comparing to aerated autoclaved concrete. In the case of wet and cold climate, durability also plays in an important role. The paper discussed the possibilities for creating durable high performance FC by applying intensive mixing technology and using modifying micro admixtures. Characteristics of FC, such as strength, density, water absorption, carbonization and frost resistance, are discussed as the basic components of durability. Properties of different compositions of FC were tested and compared. Technological methods for obtaining high performance concrete are summarized. It is pointed out, that creating of more durable FC makes possible to increase life cycle of material and promote rational use of natural resources.

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Keywords: Foamed concrete; cavitation; carbonization; water absorption; frost resistance.

1. Introduction

Light weight concretes still are an important material in modern building industry. It combines positive properties of constructive and insulation materials and is characterized by moderate strength, low density and ripping thermal properties. Cellular concrete composed on mortar matrix and specially created system of air cells, which occupies up to 85 % of material volume. High porosity limits potential of mechanical strength, but high volume of open pores is the main reason of increased water absorption and drying shrinkage. These properties are to be taken into account, especially in the case of wet and cold climate.

Two types of cellular concrete are traditionally used in nowadays. The first type is autoclaved cellular concrete which is chemically aerated using special gas producing admixture. The most popular one is autoclaved gas silicate concrete, which is obtained from lime and silicate component.

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Technology of this concrete requires special steam pressure chamber, therefore, only small-sized prefabricated elements can be produced, such as wall blocks and plates. FC is other kind of cellular concrete, it is produced by aeration of cement mortar using foaming agents [1]. FC is more universal material and it may be applied both for monolithic and prefabricated constructive elements. Controlling the ratios of cement, sand, water and foaming agent, a wide range of densities achieved, depending on its application. In previous studies researchers developed dry density values between 240 to 1800 kg/m^3 and compressive strength for 28-day from 0.2 to 91.3 MPa [2]. FC is produced from cement mortar, foaming agent and don't requires additional thermal treatment. Simple technology and good water resistance also are the advantages of FC. Table 1 present basic classification of aerated concrete and their basic physical, mechanical and thermal properties.

Table 1.Classification of lightweight concrete.

Concrete type	Density, kg/m^3	Thermal conductivity λ, W/mK	Compressive strength, MPa
Constructive FC	600-2000	0.2-1	6-60
Constructive FC for insulating	350-600	0.15-0.2	1-6
Ultra lightweight foam concrete	<350	0.04-0.15	0.1-2

At the same time, FC has lower strength, comparing to autoclaved gas silicate concrete with the same density. Developing technology of high performance FC should be focused on achieving higher compressive strength in lower density or to reach lower density in sufficient compressive strength. Aerated concretes, especially materials of low density and autoclaved gas silicates, are characterized by high open porosity and increased water absorption capacity.

Shrinkage is a serious problem of FC. Reasons of shrinkage are autogenesis shrinkage which is associated with chemical process of cement hydration, but drying shrinkage deals with loss of water. Low density FC and autoclaved gas silicate concrete especially could be very sensitive against water action and requires long-term drying. This fact causes reduction of strength, increasing heat conductivity and increases the risk of damages during freezing and thawing cycles. Although FC when normal exploitation has not subjected to direct freeze-thaw cycles in water saturated condition, it may be moistened with water during construction process or in result of incorrect exploitation. Therefore, high water resistance is necessary condition for increasing durability. Another type of shrinkage is caused by carbonation of portlandite mineral $Ca(OH)_2$ which is long-term process and depends on permeability [3].

Properties of FC depend on mix composition and the method of mix preparation, therefore two directions for achieving high performance properties should be mentioned. One direction implies the use of technology of intensive mixing, including the effects of turbulence and cavitation. The second implies development of composition of FC mix, using special chemical and mineral admixtures and fibers.

Mixing technology takes effect on concrete's density, strength and geometry of air cells. The method of pre-foaming includes generation of basic matrix by substantive aquatic foams. Technique of foam preparation affects the quality of FC by bubble size. The other method – mixed foaming – provides producing of foam in cellular structure in FC by mixing base ingredients with active agents [4]. Use of pre-foaming method can provide two types of foam – wet and dry. Dry foams are more stable than wet foams and produce two to five times smaller size of bubbles (< 1 mm). First type of foam spray over a fine mesh while other type of foam are produced by compressed air into mixing chamber [5]. One of the FC components is the foaming agent (surface active admixture), which is responsible for creating air bubbles in cement paste [6].

Method of intensive mixing has many advantages, for example, provides homogenous mix, promotes accelerated hydration and effective use of cement, and keeps together fine aggregate and agglomerated cement. Intensity of mixing depends on speed of mixing elements. Traditional low speed mixers is characterized by speed about 2 m/s, turbulence 2-10 m/s and effect of cavitation may be achieved in speed >15 m/s. FC compositions prepared in turbulence mixer with effect of cavitation, has been evaluated in this study.

Modern technologies of high performance FC provide use of micro and nano admixtures and fibers, which provide microstructure of high performance FC by making thinner walls of cells [7,8]. A lot of investigations prove effectiveness of active pozzolanic admixtures on FC[9] and industrial by-products, such as fly ash and silica fume (SF) on FC[3]. Researches of last decades discovered that combining micro admixtures with nano admixtures (< 100 nm) are more effective than using them separate. Using fly ash (70% to 50% of mixture composition) as replacement of sand, dry density values can be reduced from 7% to 20% (from 1318-787 kg/m^3 to 1224-650 kg/m^3) by foam volume of 20% to 50% of mixture composition. But compressive strength of 28-day was developed from 10.7-1.23 MPa to 17.8-1.96 MPa by the same foam volume (20% to 50%) [10].

Adding fibers allows to increase tensile strength, to reduce the risk of shrinkage and to stabilize fresh mix. The effectiveness of fibers depends on elastic module, tensile resistance and ultimate deformation (see Table 2). Use of polypropylene (PP) fibers (in length of 12 mm and ration of 1-3 kg/m^3) reduces fragility of FC [1]. According to theory of composite materials, elastic module of fibers has to be higher than matrix of FC.

Table 2. Fiber properties.

Fiber type	Density, g/cm^3	Modulus of elasticity, MPa	Tensile strength, MPa	Breaking elongation, %
PP	0.9	3500-8000	400-700	10-25
Carbon	2.0	200000-250000	2000-3500	1.0-1.6
Fiberglass	2.6	7000-8000	1800-3850	1.5-3.5
Basalt	2.6	7000-11000	1600-3200	1.4-3.6

Researchers [11] investigated durability properties of foamed concrete with synthetic and natural fibers. It is found out that use of AR-glass fiber has the lowest percentage value of drying shrinkage. Carbon fibers have the highest elastic module (Table 2), but it have low bond to cement stone. Glass fibers increase mechanical strength and decrease shrinkage of FC, what is relevant factor to sustainability of FC.

Mugahed Arman, Farzadina and Abang Ali [2] have reviewed ingredients and preparation methods of FC. Physical and mechanical properties of FC also are reviewed in literature, such as compressive strength, density, thermal conductivity and etc. At the same time, there is still limited literature on microstructure of FC and its durability. In accordance with American Concrete Institute definition, “durability is the ability to last a long time without significant deterioration”. A durable material helps the environment by conservation resources and reducing wastes. Durable material minimizes environmental impacts of repair and replacement because the production of replacement building materials depletes natural resources [12,13].

Durability implies the effect of external (environmental) factors, such as changes of temperature, water, humidity and internal factors, such as shrinkage (main source of cracking).

Summarizing reviewed sources of information, two group of method can be mentioned, which allows to improve durability properties of FC: modifying mix by active micro/nano components and applying advantage mixing techniques. Durability is complex problem of FC, durability components water absorption, shrinkage, carbonation and frost resistance.

The aim of this study is to investigate the potential of adding pozzolanic admixtures and use of intensive mix technology in order to achieve high performance and durable FC.

2. Materials and methods

2.1. Materials and mix preparation

Experimental mixes of FC were industrially produced with high-speed turbulence mixer. In accordance with producer information, the speed of rotation mixing tools is close to 15 m/s, therefore it capable to initiate the effect of cavitation. Raw components were dosed by weight with accuracy +2%.

The following raw components were used for experimental mixes: normal type Portland Cement CEM I 42.5 N (main binding agent), natural washed sand with fractions 0/1 mm – filling component, which also promotes foam formation during mixing. Silica fume (SF) grade 920D (by Elkem) and metakaolin (industrial by-product) in amounts of 2 and 3% correspondingly – are used as active pozzolanic admixture and supplementary cementing materials. SF is characterized by fine particles (in the range of 1 μm up to 15 nm) and extremely high specific surface area.

Synthetic foaming agent was added during mixing in amount of 0.35-0.6% by cement weight. The amount of foaming agent and the rate of sand, cement and water was adjusted experimentally depending on require density of FC (in accordance with producer technological regulations).

PP fibers (chopped in length 12 mm) and carbon fibers [7] (diameter 7 μm, length 12 mm) also were used. As references material, samples of autoclaved gas silicate concrete with density of 400 kg/m^3 and 500 kg/m^{3}are used.

Designations of experimental compositions are summarized in the Tab 3. Samples were prepared, cured in moist air conditions (RH>90%) first 3 weeks and tested in the age >28 days.

2.2. Testing methods

The samples are measured by accuracy of ± 1mm and weighted by accuracy of ± 1g.Compressive strength of FC samples was determined of hydraulic testing machine with accuracy of 1% (according to LVS EN 771-3).There are different methods for testing water uptake of building materials: water uptake which determines total water absorption capacity after immersing in water; surface absorption tube test (RILEM 11.4) and water capillary absorption during one-side immersing. The last two methods are more appropriate for light-weight materials which really can be subjected by water attack during short time. Capillary water absorption was determined as mass of capillary penetrated water from exposed surface after immersing samples in water in a depth of 10 mm.

Depth of carbonation was tested according to LVS CR 12793:2003, the samples after 28 days of moist curing were conditioned for 1 year in air-dry laboratory conditions. For the test, indicator phenolphthalein solution was sprayed on the splitted surface and boundary area of un-carbonated FC turned red.

Frost resistance was tested by subjecting to freezing-thawing cycles (-20/+20^{o}C) of samples which immersed by one-side in de-ionized water (according to LVS CEN/TS 12390-9) and surface scalling was controlled.

3. Results and discussion

The following groups of samples were evaluated (Table3). The first group of sample is high density FC (>1200 kg/m^3), produced in turbulence mixer: reference composition (REF), mix with silica fume (SF) and combination of SF and carbon fiber (SF/C). Low density FC PB400 is produced in highly intensive mixer with effect of cavitation. Two types of commercially available gas silicate concrete (second group of samples) are used as reference samples (GB400 with density 400 kg/m^3 and GB500 with density 500 kg/m^3).

Basic results are summarized in the Table 3. Evaluating results, it may be concluded that the samples of aerated silicate autoclaved concrete (GB400 and GB500) has the highest values of absorption, but FC produced intensive mixer (PB400) has twice less water absorption. This phenomenon can be explained by type of pore system: non-autoclaved FC is characterized by partially closed pore system [14] but autoclaved gas silicate has open porosity caused by effect of high temperature and pressure during thermal treatment. High density FCs (REF, SF and SF/C) are characterised by the least water absorption (see Fig. 1). Positive effect of silica fume on water resistance and strength can be explained by formation of more compact microstructure of cement matrix thanks to filling gaps between cement grains and pozzolanic reactions [15].Composition with carbon fiber and silica fume (SF/C) has the highest mechanical strength, it is explained with higher density and lower porosity of those mixtures, comparing to FC without pozzolanic admixtures (REF).

Table 3. Mix designations and basic properties.

Density class	Designation	Water/ cement	Sand/ cement	Density, kg/m^3	Compressive strength 28days, MPa	Depth of carbonation, mm	Frost resistance, cycles

HD	REF	0,8	0,6	1210	12,6	<2	100
HD	SF	0,8	0,6	1210	13,7	<2	100
HD	SF/C	0,8	0,6	1360	18,2	<2	100
LD	PB400*	0,77	0	410	1,22	-	50
LD	GB400	-	-	400	2,4	-	10
LD	GB500	-	-	500	3,6	-	10
LD	I (3.6.)	1,1	0,4	530	1,3	6	20
MD	II (3.6.)	0,9	0,3	657	2,2	6	20
MD	III (3.6.)	0,9	0,5	712	3,0	4	30
LD	IV (3.6.)	1,4	0,8	476	0,7	10	15
LD	VII (3.6.)	1,4	0,5	415	0,5	14	15
LD	IX (3.6.)	1,4	0,5	433	0,6	17	15
MD	I (21.6.)	1,1	0,7	795	2,9	2	35
MD	II (21.6.)	1,1	0,6	672	1,8	2	35
MD	III (21.6.)	1,1	0,7	618	1,6	<4	35
MD	IV (21.6.)	1,2	0,8	573	1,9	<4	35

Designations: HD- high density, MD-median density, LD-low density.

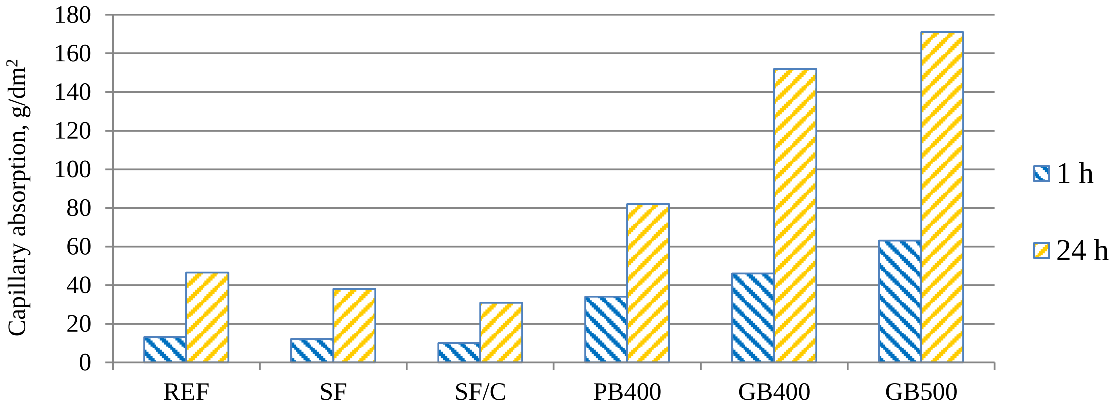

Fig. 1. Results of capillary absorption.

1.1. Depth of carbonation

Carbonation is process of transformation of $Ca(OH)_2$ to $CaCO_3$. Usually carbonation don't take important effect to compressive strength, but carbonization processes causes shrinkage of hydrated cement paste. Results of practical testing carbonation depth for different density FC are showed in the Fig. 2. Analysing measuring results of carbonation depth for samples of different density, it may be concluded, that the highest values of carbonation corresponds to lower value of density (up to 17 mm for low density FC) and highest value of water to cement ratio (W/C). Carbonation depth for median and high density FC were less than 6 mm - see Table 3.

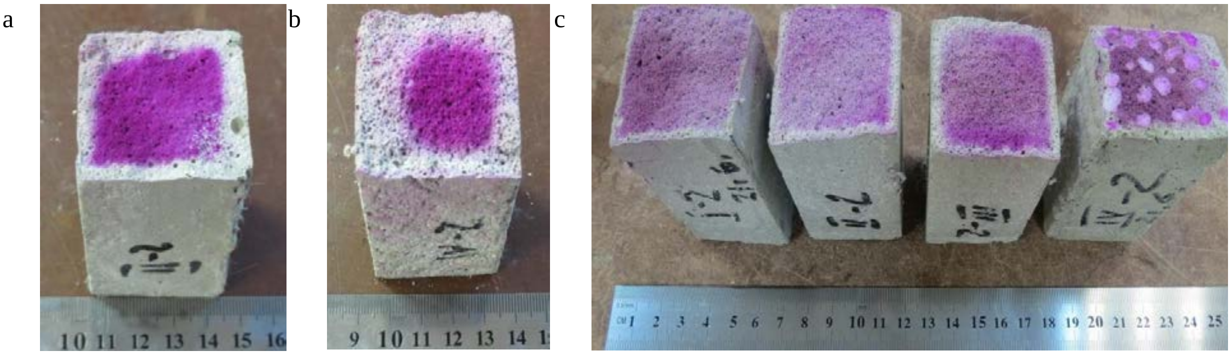

Fig. 2. Depth of carbonation for FC of different densities. (a) Median density sample II (3.6.) with high W/C ratio: carbonation 6 mm; (b) Low density sample IV(3.6.) with high W/C ratio: carbonation 10 mm; (c) Median density sample I-IV (21.6): carbonation 2-4 mm.

1.2. Frost resistance

Analyzing experimental data, it may be noted that correlation between water absorption, depth of carbonation and compressive strength is recognized. Results show low value of frost resistance of commercially produced gas silicate concrete by 10 cycles (see Fig.3b, d). It can be explained with extremely high open porosity and insufficient amount of closed (reserve) pores. FC with the same density show higher frost resistance by value of 25 cycles (2.5 times more). The highest result of frost resistance belongs to high density FC samples with silica fume and carbon fibers. No any damages was observed after 76, 100 cycles and moderate surface scaling <1500 g/m^2 after 130 cycles, thereby frost resistance can be evaluated as 100 cycles which is comparable with normal concrete. It must be noted, that the same samples has the maximum values of compressive strength and the lowest values of water capillary absorption. Median density FC has mediocre values of frost resistance (samples in Fig. 3a). It may be concluded, that the highest values of frost resistance corresponds to lower value water to cement ratio (W/C) and highest strength and density.

c d

Fig. 3. (a) FC I-IV(3.6) produced in turbulence mixer after 40 cycles; (b) Gas silicate concrete after 10 cycles; (c) FC produced in turbulence mixer after 76 and 130 cycles; (d) Gas silicate concrete after 16 cycles.

1.3. Correlation density - Compressive strength

Taking into account the results of strength and densities, the corresponding correlation diagram is built up for different FC compositions produced in industry and in laboratory (see Fig.4). The relation close to parabolic is obtained. The authors suggest to consider as an effective compositions, which are situated above the averaged curves, and to consider as non-effective compositions, which are situated below the averaged curves.

Consequently, mix compositions REF, SF, SF/C and PB400 may be considered as effective (high performance), but composition above the curve as non-effective.

Therefore, in the further development of FC technology attention should be focused on use of turbulence mixers with cavitation effect and simultaneous use of reactive pozzolanic admixtures, shrinkage reducing components and other possible improving components, such as carbon nano-tubes [12, 8]. With regard to the mixing process, mixing with cavitation effect allows to achieve more homogenous mix and destroys agglomerated particles of cement and silica fume.

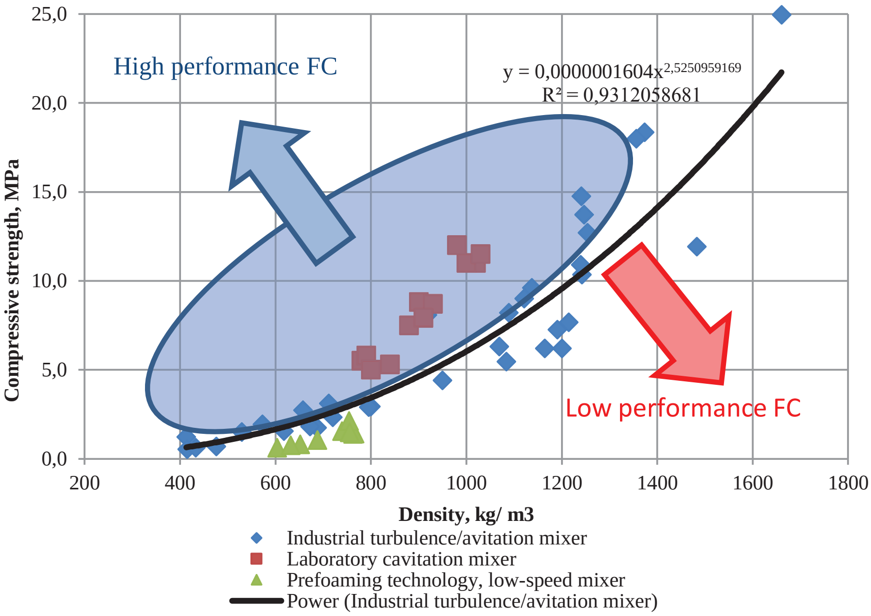

Fig. 4. Correlation density – compressive strength.

It can be considered that laboratory produced FC by turbulence/cavitation mixer is more likely similar to high performance FC (they are above the correlation line). It is explained that higher compressive strength fits to one range of density or similar compressive strength can achieve by lower density. Therefore will be improved ripping thermal properties.

4. Conclusions

Durability of FC is to be considered as an important problem, especially in the conditions of wet and cold climate. Main components of durability are mechanical strength, water absorption and frost resistance. Shrinkage (including carbonation shrinkage) also should be taken into consideration. Low density and high open porosity of material accelerates carbonation processes. Possible shrinkage, caused by carbonation, also increases the risk of cracking and loss of durability.

The use of pozzolanic admixtures and turbulence mixing technology (with effect of cavitation) makes possible to produce more water resistant and durable FC. It is explained microstructure with dominating closed porosity.

Commercially used aerated silicate low density concrete has the least durability (10 cycles), but FC produced in turbulence mixer has frost resistance 100 cycles, which is comparable with normal concrete.

The use of high performance FC with improved durability increases exploitation time and duration of life cycle. In that way will be achieved rational use of natural resources and minimizing energy consumption during building life cycle, therefore, material becomes more sustainable.

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