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Original article

Analysis of impact of aeration modifications on strength parameters of concrete under fire conditions

Pawel Ogrodnik[*1]**, *Bartosz Zegardlo***[2]

[1] Department Faculty of Fire Safety Engineering, Main School of Fire Service, Poland
pogrodnik@sgsp.edu.pl

[2] University of Natural Sciences and Humanities in Siedlce, Poland
bart.z@wp.pl

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* Corresponding author

ABSTRACT

Modern dynamically developing building industry poses more and more complex challenges to building materials. Elevated constructions must satisfy a number of requirements including safety, durability and being environmentally friendly. The unfavorable impact of increased temperatures on the work of a construction structure is manifested by the change in the properties of the heated material and the occurrence of deformation, stresses and thermal scratches. These are particularly dangerous phenomena when they occur in elements with limited freedom of linear deformation. The purpose of the research presented in this article was to find a solution for concrete that is both resistant to spalling and characterized by high strength properties after heating. The main thesis put forward by the authors of the article is the assumption that deliberate concrete aeration will allow the introduction of evenly distributed micro air bubbles into its volume, which will constitute a reservoir for increasing the volume of water converting into water vapor as a result of a sudden increase in temperature. The presented schema enabled the assumption that the strength parameters of aerated concrete would decrease slightly in relation to non-aerated concrete, however it would be still possible to use in reinforced concrete constructions. As can be seen from the aforementioned analyzes, aeration modification can be an effective means of designing high temperature resistant concrete.

KEYWORDS

concrete, fire temperatures, strength

1. Introduction

In the present day, dynamically developing building industry poses more and more complex challenges to building materials. The erected building objects must be safe, durable and environmentally friendly. It is also frequently emphasized that in addition to the above characteristics, they should also meet the relevant economic criteria. Concrete is one of the most commonly used building materials, which ensure that objects made of it have abovementioned characteristics. Concrete composites are resistant to many aggressive factors, but on the other hand, only to a few unique corrosive phenomena. Considering the economic aspect, concrete is one of the cheapest construction materials.

Concrete is currently the most commonly used building material in the world, with an estimated world production of approximately 7 billion cubic meters a year, about three times larger than wood and nearly seven times than steel.

The economic development as well as rapid industrial growth in the developed world has influenced the main trends in construction, including in the field of concrete technology. Rising land prices in large metropolitan areas have resulted in the expansion of the residential and commercial areas, which has affected the progressive development of elevated and high-rise buildings. In the early 1980s, high strength of concrete was obtained by careful selection of components such as cement, aggregate, additives and admixtures. The next stage in the development of concrete technology was the appearance of silica dust and super-plasticizer products on the market. This action allowed the material to have a much higher compressive strength or frost resistance, while decreasing water absorption and water permeability. Such changes in characteristics have contributed to a significant increase in concrete durability [Dabrowski et al. 1982].

Despite the fact that concrete is non-combustible and is regarded as being of high temperature resistant, numerous unfavorable processes occur during a fire, which impair its quality and negatively affect the durability parameters. Under specific conditions of high humidity, the concrete may splinter in a fire. This phenomenon constitutes a threat to the safety of rescuers and the injured. The development of concrete technology should take this issue into account and aim to reduce it.

2. The impact of fire temperatures on concrete

The unfavorable influence of elevated temperatures on the operation of a construction structure is manifested in the change of the heated material's properties and the occurrence of deformations, stresses and thermal scratches. These are particularly dangerous phenomena when they occur in elements with limited freedom of linear deformation [Grabiec 1987].

Oftentimes, with an intensive fire source, concrete may not resist to the thermal load. Under the influence of heat, complex physical and chemical processes take place in the concrete, influencing its structure as well as volumetric and strength changes. As the temperature and operating time increase, the concrete's value in use decreases and in a borderline case a significant failure to the object may occur. As a result of the impact of elevated temperatures on concrete, it undergoes the following processes:

- evaporation of chemically unbound water,
- dehydration of cement binder minerals,
- decarbonation,

– thermal and form changes of aggregate minerals [Grabiec 1987; Runkiewicz et al. 1993].

The action of elevated temperatures causes that destructive to concrete chemical and physicochemical processes begin to occur in its components [Sawicz and Piasta 1981]. These processes have a significant impact on the behavior and strength of concrete structures during a fire [Abramowicz and Adamski 2002].

The first mentioned process – the evaporation of chemically unbound water takes place at the temperature of about 100°C. To a negligible degree and extent as well this phenomenon is desirable as it contributes to the increase in the compressive strength of concrete. However, the evaporation process cannot be abrupt. With a sudden rise in temperature, water contained in capillary pores, increasing its volume, exerts pressure on walls of the capillary pores in which is located. The increasing vapor pressure leads to local tensile stresses in their surroundings. As a result, when the tensile stresses exceed the tensile strength of concrete, damage to the composite structure may occur. This phenomenon occurs especially in the case of high strength concrete and takes the form of explosive splintering of concrete fragments, the so-called spalling.

Another destructive phenomenon is the dehydration in concrete, which generally develops with the increase of temperature and is already apparent at about 400°C. Dehydration that is dewatering of cement binder minerals reduces the strength of the binder, thus weakening the structure of concrete.

Decarbonation is a process that causes binder volumetric changes. This phenomenon occurs at about 700°C. The following reaction takes place in the cement binder:

$$CaCO_3 \rightarrow CaO + CO_2 \tag{1}$$

Although the presented decay significantly weakens the structure of concrete its effects can be much more destructive. In a fire, during the rescue operation, the cooling of the structure consisting in pouring concrete with water is commonly used. The water supplied – also a remaining after the rescue operation may be very unfavorable to the construction as the resulting calcium oxide is hydrated:

$$CaO + H_2O = Ca(OH)_2 \tag{2}$$

The phenomenon, regardless of whether it appears directly during the rescue operation or after it, is accompanied by a strong increase in the volume of calcium oxide. Water molecules, which rise when exposed to water, often violate the compact structure of the composite and consequently cause its decay [Abrams 1973; Bažant and Kaplan 1996].

Another reason for lowering the strength of the heat-soaked concrete is varied deformation values of the aggregate and the grout, which lead to the weakening of the force of adhesion between them. Incompatible volumetric changes are accompanied by chemical changes in the structure of the grout and aggregate. The intensity of their influence on the properties of concrete depends primarily on the rate of heating and the temperature [Abramowicz and Adamski 2002].

When it comes to the degradation of concrete strength, the cooling effect is also substantial. In components that have been flooded or immersed in water, much more reduced strength is recorded than in air-cooled elements [Kosiorek 1998].

In some studies, over time, gradual recovery of the strength of concrete damaged by heat soaking has been observed [Kosiorek 1998].

In Eurocode 2 PN-EN 1992-1-2. *Design of Concrete Structures. Part 1-2. General rules. Design due to fire conditions* [PN-EN 1992-1-2:2008 2008] the impact of temperatures during a fire on the strength of concrete has been presented. The dependence of the compressive strength of the concrete on its working temperature, adopted in the standard, is shown in Figure 1. It describes the coefficient kc(θ), which is the ratio of strength in temperature (θ) to the strength determined in the temperature of 20°C. Figure 1 indicates that concretes containing some of the most popular aggregates (limestone and those with high silicate content) behave in a similar way at high temperatures, albeit with a slight decrease in strength in the case of silicate aggregates. Concrete on silicate aggregate begins to melt at 1100°C, while concrete based on carbonate aggregate – at 1200°C.

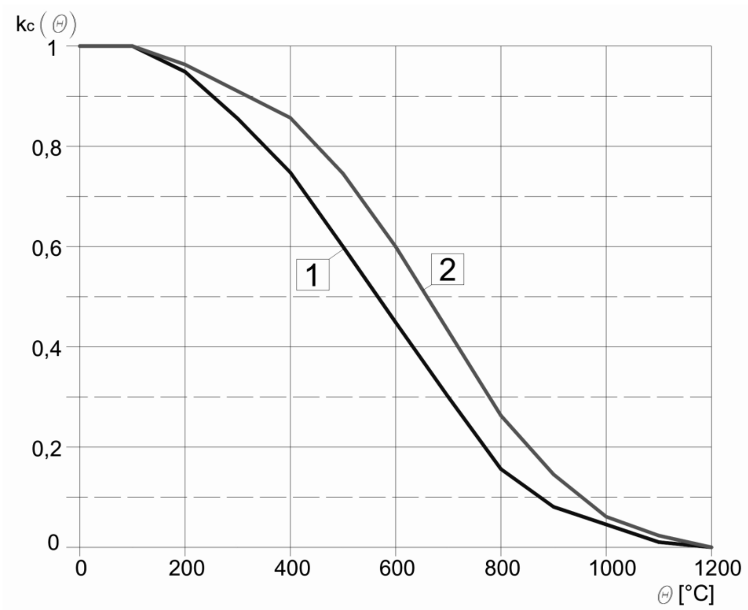


Fig. 1. Strengths of concrete on silicate (1) and carbonate aggregates (2) at high temperatures
Source: Own study based on [PN-EN 1992-1-2:2008 2008].

3. Analyzes of the impact of aeration modification on strength parameters of concrete affected by a sudden rise of temperatures – own research

3.1. Main assumptions and the purpose of the research

The issue of designing concrete that transfers loads at high temperatures is relatively familiar. Previous research works of the authors of the article allowed for the development of a concrete mix, the composition of which was based on calcium aluminate cement and unconventional aggregate produced from sanitary ceramic waste [Halicka et al. 2013; Ogrodnik et al. 2012]. This concrete tested in accordance with the norms for concrete used, for example, in the steel industry was characterized by very high strength parameters of up to about 55 MPa of compressive strength after heating. Nonetheless, the slow rise in temperatures is significant for this type of simulation. The loading of concrete samples with temperatures whose increases were rapid was followed by the occurrence of spalling, i.e. thermal splintering of concrete fragments. This destructive phenomenon was the reason for further research aimed at the elimination of this effect. The first tests were carried out on porous concrete, which contained large volumes of pores in its volume, allowing for free evaporation of capillary waters and thus the elimination of thermal splintering [Zegardlo and Ogrodnik 2016]. Spalling did not occur in these concretes in both normal humidity and high humidity environment during sudden temperature rises. However, their strength parameters were of about 5-6 MPa of compressive strength.

The purpose of the research presented in this article was to find a solution for concrete that is both resistant to spalling and characterized by high strength properties after heating. The main thesis put forward by the authors of the article was the assumption that deliberate concrete aeration will allow the introduction of evenly distributed micro air bubbles into its volume, which will constitute a reservoir for increasing the volume of water converting into water vapor as a result of a sudden increase in temperature. The presented schema enabled the assumption that the strength parameters of aerated concrete would decrease slightly in relation to non-aerated concrete, however it would be still possible to use in reinforced concrete constructions.

3.2. Heat treatment of samples

In the research planning phase efforts were made to ensure that the results achieved, beyond their cognitive values, could be used for engineering purposes. In the research held, during the samples' preheating, the temperature distribution on the surface of the standard concrete slab was adopted, which can be determined by the empirical dependence described by the relation [Bažant and Kaplan 1996; Bednarek and Krodkiewski 1987]:

$$T_p = 1250 - (1250 - T_o) \cdot erf \frac{K}{2 \cdot \sqrt{t}} \tag{3}$$

K – the material factor, depending on material density,

t – the fire duration [h],

T_o – the initial temperature of slab surface [°C],

T_p – theslab surface temperature from the heating side [°C],

erfx – the Gaussian error function, having no finite decay into elementary functions.

$$erfx = \frac{2}{\pi} \int_0^x e^{-x^2} dx \tag{4}$$

The PK1100 / 1 electric chamber furnace was used to heat the samples. The furnace is equipped with appropriate equipment and software for measuring the temperature during the preheating of concrete samples.

3.3. Samples for testing

The samples were prepared in cylindrical molds with a diameter of 10 cm and a height of 20 cm. The initial composition of the concrete mix was identical to that described in [Halicka et al. 2013]. However, the conditionality of the aeration efficiency required the preparation of a mixture of different consistency, which was achieved by increasing the batched water content by 20%. The concrete mix composition is shown in Table 1.

Table 1. The components of the concrete mixture used to make the samples

Component of the mixture	Quantity of the mixture component
Calcium aluminate cement	493.38 [kg/m^3]
Ceramic aggregate of the fraction 0-4 mm	991.37 [kg/m^3]
Ceramic aggregate of the fraction 4-8 mm	396.55 [kg/m^3]
Batched water – initial quantity + 20%	201.38 [kg/m^3] + 40.27 [kg/m^3]

Source: Own study

ISOLA LP A.E.A 2.5 manufactured by CEMEX in the amount of 0.75% by weight of cement, which in relation to 1 m^3 of concrete was 0.37 kg, served for the aeration. 12 aerated samples (N) and 12 non-aerated samples (BN) were prepared. After filling the molds the samples were vibrated and placed in a climatic chamber. One day after the samples were formed, they were taken out of the molds and subjected to further care in the climatic chamber. To minimize any damage caused by explosive spalling of concrete fragments in the furnace, the samples were pre-dried by being left for 14 days in dry conditions outside the chamber. From each of the presented series there were randomly selected 3 samples that had not been subjected to heating, the remaining 9 samples were subjected to heating as described above.

4. Research results

Strength tests were performed on Advantest 9 (Controls) testing machine. For each sample the compressive strength was determined. The results of the subsequent series of samples are presented in Table 2 and Figure 2.

The average strength of the concrete without aeration, which was not subjected to heating, was 60.51 MPa. The same concrete after heating had the lower average strength of 41.41 MPa. In the case of aerated concrete, its average strength is 49.88 MPa, while after heating it is 47.62 MPa.

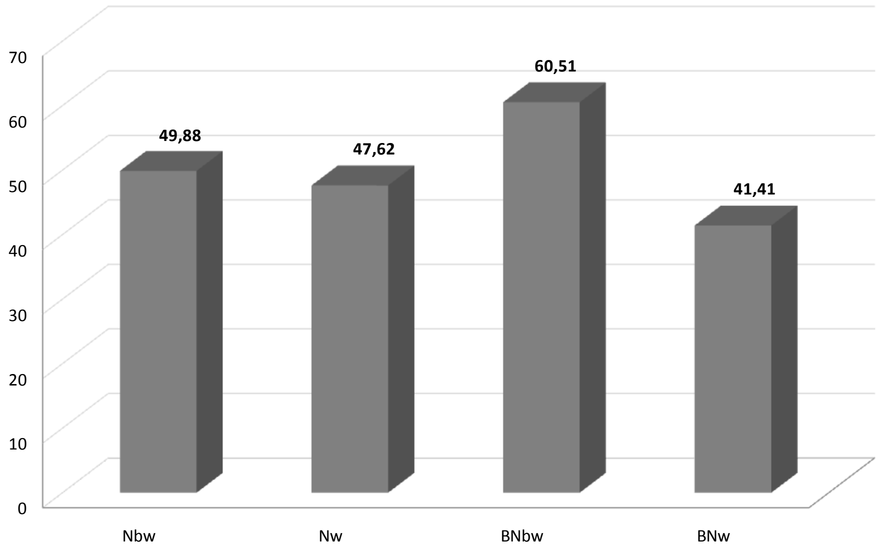
Table 2. The obtained results of compressive strength tests

No.	Sample label	Compressive strength [MPa]	Average strength [MPa]	Standard deviation [MPa]	Volatility index [%]
Non-heat-treated aerated concrete (Nbw)					
1	Nbw	51.42	49.88	2.33	4.67
2	Nbw	51.03			
3	Nbw	47.20			
Heat-treated aerated concrete (Nw)					
1	Nw	48.87	47.62	0.89	1.86
2	Nw	47.42			
3	Nw	47.20			
4	Nw	46.01			
5	Nw	48.58			
6	Nw	48.38			
7	Nw	47.50			
8	Nw	46.99			
9	Nw	47.75			
Non-heat-treated non-aerated concrete (BNbw)					
1	BNbw	63.20	60.51	3.77	6.23
2	BNbw	56.20			
3	BNbw	62.14			
Heat-treated non-aerated concrete (BNw)					
1	BNw	41.41	41.41	0.64	1.54
2	BNw	41.24			
3	BNw	41.36			
4	BNw	41.87			
5	BNw	40.56			
6	BNw	42.01			
7	BNw	40.38			
8	BNw	42.36			
9	BNw	41.44			

Source: Own study.

Conclusion

When analyzing the results of the research, attention should be paid to the significant influence of aerating on the strength parameters of non-heated concrete. The introduction of air pores through the aerating admixture led to the decrease in the strength of the concrete by 17.56%. However, this phenomenon is predictable in situations when concrete is aerated. The effect of the presented modification in the light of concrete's resistance to high temperatures was, however, advantageous. The drop in strength resulting from the thermal load of rapidly rising temperatures in the case of aerated concrete was 4.5%, while in the case of non-aerated concrete the value was 31.5%. Finally, the average values obtained for aerated concrete were also about 14% higher than for non-aerated concrete.



Nbw – non-heat-treated aerated concrete; Nw – heat-treated aerated concrete
BNbw – non-heat-treated non-aerated concrete; BNw – heat-treated non-aerated concrete

Fig. 2. Average compressive strength of concrete [MPa]
Source: Own study.

As can be seen from the aforementioned analyzes, the aeration modification can be an effective means of designing concrete resistant to sudden temperature rises occurring during a fire. However, the presented research should be supplemented by research on the mentioned concrete in humid environments, which will be more reliable and closer to the natural conditions of concrete's operation in constructions. The research was conducted as part of the statutory research work S/E-422/20/16.

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Conflict of interests

The author declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

ORCID

Pawel Ogrodnik https://orcid.org/0000-0003-3515-8505

Bartosz Zegardlo https://orcid.org/0000-0002-1292-3107

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Biographical notes

Pawel Ogrodnik – Sr. Capt. Dr. Eng., graduate of the Faculty of Construction and Sanitary Engineering of the Lublin University of Technology (specialization: building construction). In 2001 he started working at the Department of Applied Mechanics of the Main School of Fire Service. In 2006 he defended his doctoral dissertation on ‘Effect of temperatures during a fire on the adhesion between steel and concrete'. Author and co-author of dozens of scientific publications on the safety of construction and strength of materials.

Bartosz Zegardlo – Dr. Eng., graduate of the Faculty of Civil Engineering of the Warsaw University of Technology (specialization: building construction). Until 2008 a construction engineer in the function of a site manager and a designer. In 2008 he started working as a lecturer. In 2012, he obtained the unrestricted construction license authorizing him to manage construction works, and in 2014 unrestricted construction license authorizing him to design. In 2014 defended his doctoral dissertation on 'Application of sanitary ceramic waste as a special concrete aggregate'.

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