Experimental analysis of the thermal behavior of concrete

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Abstract:

Introduction/purpose: When concrete structural members are subjected to fire and then exposed to slow or rapid cooling, there are various changes affecting density, porosity, thermal damage, speed of sound propagation, modulus of elasticity, compressive strength, absorptivity, etc. The heavy use of concrete to build structures on the one hand and the problem of fires on the other require a deep understanding of the effect of fire on the *structural behavior of concrete, especially after cooling. So far, the two cooling methods used to put out a possible fire have been water and free air. Our objective is to experimentally analyze the use of the extinguisher as the third method of cooling concrete exposed to high temperatures.*

Methods: To achieve our objective, a series of mechanical and physical tests waw carried out on specimens 40 mm in diameter and 40 mm in height, exposed to high temperatures of 200, 400, and 600 °C. These test samples were then subjected to three different cooling regimes, namely: free air, water immersion, and extinguisher use.

Results: The results clearly show that the use of the extinguisher is more appropriate than the other two cooling methods, namely, natural cooling and immersion in water.

Conclusion: The results from this experimental study could be of practical use when trying to extinguish a possible fire in a concrete structure.

Key words: concrete, fire, experimental analysis, extinguish, water, free air.

Introduction

Because of its many advantages over other construction materials, such as simple workmanship, durability, strength, and ease of implementation, concrete has become the primary structural material in the construction of nearly all buildings (Kodur, 2014).

Fire is one of dangerous threats that attack structures. Compared to steel, which has a low thermal conductivity, and to wood, which is rapidly combustible, concrete construction material is characterized by its good fire resistance; however, it can lose part of its resistance (Annerel & Taerwe, 2009; Ingham, 2009). The type of cement, the nature of the aggregate, the dimensions of structural elements, the porosity and the moisture content of concrete as well as its thermal properties are all factors which determine the degree of fire resistance (Akçaözoğlu, 2013). The fire resistance is increased with the increase in the dimensions of a concrete element (Tanaçan et al, 2009).

During their lifetime, concrete structures can be subjected to high temperatures during fire or near furnaces and reactors. It will then lead to the deterioration of the structural quality of concrete.

In China, recent statistics show that in 2018 alone, there were 237,000 fires, including almost 107,000 in residential buildings (Bi et al, 2020). Fires can start in tunnels and buildings alike (Annerel & Taerwe, 2009; Khoury, 2000; Du et al, 2018; Tomar & Khurana, 2019; Zhao et al, 2019). This indicates that the occurrence of fire misfortunes is becoming more and more common, which affects the safety of structures and leads to significant economic deficits (Hertz, 2005; Aïtcin, 2003; Liu et al, 2019).

Under high temperatures, physical properties change and chemical transformations occur in the cementitious matrix, leading to a deterioration of its mechanical characteristics (Hertz, 2005; Aïtcin, 2003; Liu et al, 2019; Hammoud et al, 2014; ACI, 1989; Khoury et al, 2007; European Commissions, 1992; CEN, 1994; CEN, 2002; CEN, 2004; Bazant & Kaplan, 1996; Phan & Carino, 2000). They also participate in the growth of shrinkage, transient creep, and changes in durability (Pihlajavaara & Kesler, 1972). Mechanical properties such as strength, modulus of elasticity, and volume stability of concrete are significantly reduced during these exposures (Li et al, 2012). Free water in pores and part of chemically bound water in hydrated cement paste are released and a large amount of energy is consumed due to exposure to high temperatures (Su et al, 2014).

This special situation implies the need to assess the safety of concrete structures with regard to possible fires. This analysis is therefore an essential task to ensure the structural safety of concrete structures (Hammoud et al, 2014). In practice, concrete structural elements must fulfill the fire safety requirements defined in the design codes for building structures (ACI, 2007; ACI, 2008; CEB, 2002).

According to the literature, the analysis of the behavior of concrete under high temperatures has been the subject of numerous works, leading to appreciable results (Zhai et al, 2019). We quote:

Wang et al (Wang, 2014) conducted static compression tests and a Split Hopkinson Pressure Bar Impact (SHPB) test on concrete specimens 75 mm in diameter and 55 mm in height. These specimens are heated to high temperatures of 100 to 900 °C and then cooled naturally.

Tao et al (Tao et al, 2011) conducted a compression test on concrete cylinders 50 mm in diameter and 35 mm in height under rapid heating from 200 to 600 °C using microwaves.

Shi et al (Shi et al, 2014) performed SHPB compression-shock tests on cylindrical specimens 98 mm in diameter and 50 mm in height. These concrete blocks are subjected to high temperatures of 200 to 800 °C and are cooled by natural cooling or cold water.

Under different applied loading levels, Jia et al (Jia et al, 2011ab) carried out compression-impact tests on concrete specimens 50 mm in diameter and 35 mm in height. Using microwaves, these concrete specimens were quickly heated to 200–650 °C.

Under various projectile velocities, Li et al (Li et al, 2012) performed an impact compression experiment on a SHPB device and concrete specimens 98 mm in diameter and 48 mm in height heated to 200–800 °C.

Similarly, Su et al (Su et al, 2014) carried out the same tests but on specimens 49 cm high.

SHPB impact compression tests and numerical simulations on concrete blocks 70 mm in diameter and 35 mm in height heated to 200-800 °C were developed by Huo et al (Huo et al, 2013).

Previous experimental and numerical research revolves around micromechanics and constitutive models of concrete at high temperature (Huo et al, 2013; Gawin et al, 2011; Ezekiel et al, 2013; Jia et al, 2011ab; Bangi & Horiguchi, 2012; Noumowe, 2005; Tenchev & Purnell, 2005; Van der Heijden et al, 2007; Wang & Shang, 2014; Lu, 2011; Zhai et al, 2014; Zhang et al, 2013, Carstensen et al, 2013). They analyze the mechanical properties of concrete at high temperature or after high temperature (Ma et al, 2015). However, the analysis of the behavior of concrete cooled after high temperatures has yet to be fully investigated (Zhai et al, 2019).

In turn, Zhai et al (Zhai et al, 2014) conducted impact compression tests on concrete specimens. These test specimens of 35 MPa compressive strength are heated to high temperatures of 200 to 800 °C and are then cooled naturally or in water.

This article is an experimental contribution analyzing the effect of the cooling mode on the thermal behavior of concrete. Until now, the cooling methods used were natural cooling or immersion in water. Through this work, we used natural cooling, water, and a new mode of cooling, powder extinguishers.

To achieve our objective, we carried out mechanical tests on compressive strength, thermal damage, and dynamic modulus of elasticity, and tested physical properties: porosity, density, and speed of sound propagation. These tests were carried out while hot and after cooling. The samples tested were exposed to high temperatures: 200 °C, 400 °C, and 600 °C. After exposure to these temperatures, the samples were then cooled using air, water, and powder extinguishers.

Materials used and sample preparation

Cement

The cement used is Portland cement composed of the CPJ CEM II/B-L 32.5 N type, with a minimal resistance of 32.5 MPa at 28 days. Tables 1, 2 and 3 respectively give the chemical, mineralogical, and physical composition of the cement used in this study.

Table 1 – Chemical composition of cement
Таблица 1 – Химический состав цемента
Табела 1 – Хемијски састав цемента

CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	Na_2O	MgO
60.10	18.13	3.25	2.56	2.71	0.26	0.22	1.75

Table 2 – Mineralogical composition of cement according to Bogue
Таблица 2 – Минералогический состав цемента (Bogue)
Табела 2 – Минералошки састав цемента (Bogue)

Element	C_3S	C_2S	C_3A	C_4AF
Content (%)	71.976	50.488	4.280	7.790

Table 3 – Physical characteristics of cement
Таблица 3 – Физические свойства цемента
Табела 3 – Физичка својства цемента

Characteristics	Values
Apparent density (g/cm^3)	4000
Absolute density (g/cm^3)	1065
Start of setting (minute)	2990
End of setting (minute)	150 ± 30
Normal consistency (%)	230 ± 50

Water composition

For the manufacture of test specimens, we used drinking water distributed by the public service network. The results of the chemical analysis of this water are summarized in Table 4.

Table 4 – Chemical analysis of water composition
Таблица 4 – Химический анализ состава воды
Табела 4 –Хемијска анализа састава воде

Ca	Mg	Na	K	Cl	SO_4	CO_3	NO_3	Fe	pH	Organic material
32.86	51.36	38.00	0.00	113.60	65.46	368.44	12.22	0.03	7.88	0.18

Aggregates

In this analysis, we used continuous crushed gravel of 3/8 mm in size and quarry sand of 0/4 mm in size.

Preparation of the samples

The dimensions of the specimens used in this study are: the diameter ϕ = the height h = 40 mm. For the preparation of the samples, we adopted the quantities given in Table 5:

Table 5 – Formulation of micro-concrete Kg/m3
Таблица 5 – Состав микробетона, кг/м3
Табела 5 – Формулација микробетона kg/m3

Cement	Sand 0/4	Gravel 3/8	Water	Super-plasticizer	E/C
350	616	1143	202	17.5	0.57

The samples were covered with plastic film to avoid any water exchange with the external environment and were stored in the laboratory at a controlled room temperature of 20 ± 2°C.

The specimen heating and cooling

The specimens were classified into four groups (G_1, G_2, G_3 and G_4). We measured the mass and speed of propagation of sonic waves before exposing the samples to temperatures of 200, 400, and 600 °C.

The three groups of specimens (G_1, G_2 and G_3) were subjected to maximum temperatures of 200°C, 400°C and 600°C, respectively.

The specimens were heated with a constant temperature rise rate equal to 5 °C/min up to the test temperature. Then, to stabilize the thermal field, these specimens were kept at the target temperature for one hour.

The last step was the temperature drop ramp of 1°C/min down to an ambient temperature. On the other hand, the fourth group (G_4) was maintained at an ambient laboratory temperature equal to 20°C. For each group, we used a cooling mode for one minute. For 24 hours after the cooling stage, for each specimen, we calculated the mass and the speed of propagation of sonic waves.

Results and discussion

Density

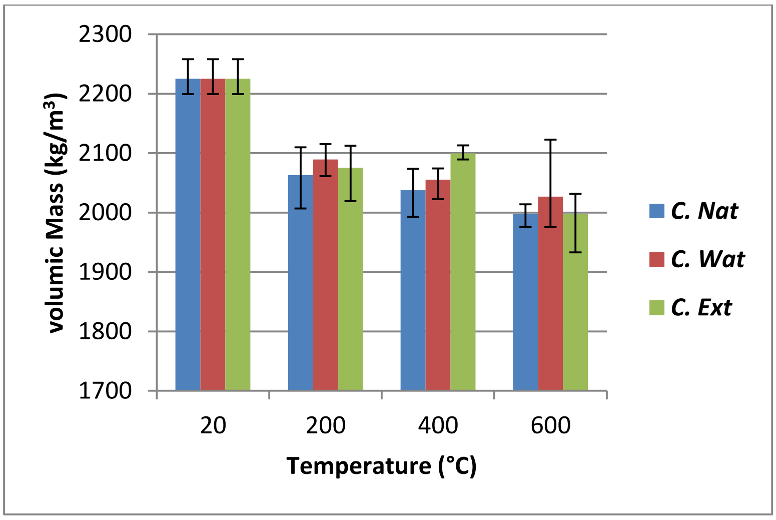

Figure 1 – Effect of temperature and the cooling mode on density
Рис. 1 – Влияние температуры и режима охлаждения на плотность
Слика 1 – Утицај температуре и начина хлађења на густину

Table 6 – Effect of temperature and the cooling mode on density (Kg/m3)
Таблица 6 –Влияние температуры и режима охлаждения на плотность (кг/м3)
Табела 6 –Утицај температуре и начина хлађења на густину (kg/m3)

	20 °C	600 °C	Kg/m^3	%
C. Nat	2225	1998	227	10.2
C. Wat	2225	2027	198	8.9
C. Ext	2225	1998	227	10.2

C. Nat: natural cooling
C. Wat: water cooling
C.Ext : extinguisher cooling

Figure 1 shows the effect of temperature and the cooling mode (air, water, and extinguisher) on density. When the temperature increases, the density of the samples decreases for the three cooling modes. Table 6 shows that the density drop between 20 and 600 ° C is the same, 10.2%, in both natural and extinguisher cooling. On the other hand, it is a little lower for rapid cooling by immersion in water, at 8.89%.

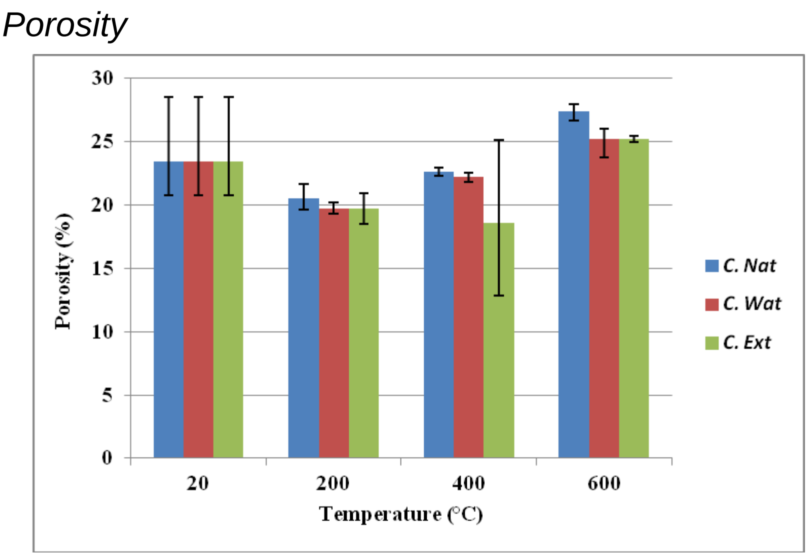

Figure 2 – Effect of temperature and the cooling mode on porosity
Рис. 2 – Влияние температуры и режима охлаждения на пористость
Слика 2 –Утицај температуре и начина хлађења на порозност

Table 7 – Effect of temperature and the cooling mode on porosity (%)
Таблица 7 – Влияние температуры и режима охлаждения на пористость (%)
Табела 7 – Утицај температуре и начина хлађења на порозност (%)

	20 °C	600 °C	%
C. Nat	23.45	27.38	14.3
C. Wat	23.45	25.24	7.1
C. Ext	23.45	25.21	7.0

Figure 2 shows the effect of temperature and the cooling mode (air, water, and extinguisher) on porosity. It was discovered that the porosity value increases in lockstep with increasing temperature from 20 °C to 600 °C.

Table 7 shows that with natural cooling, porosity increases twice as compared to the other two cooling modes.

The speed of sound propagation

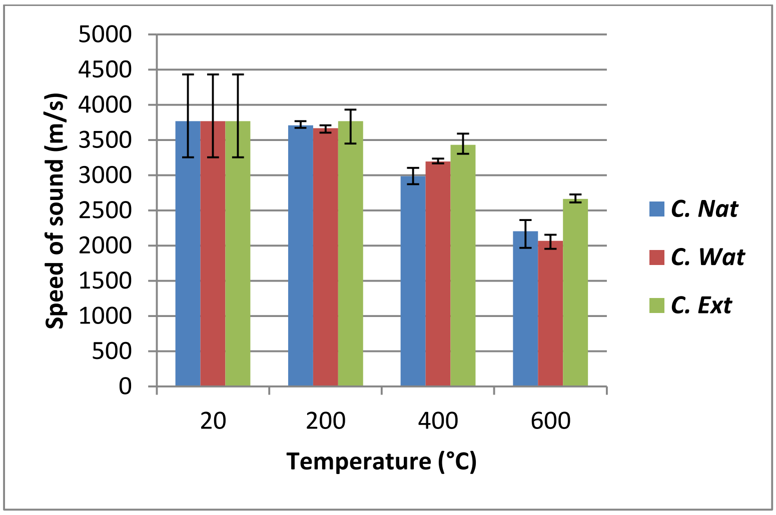

Figure 3 – Effect of temperature and the mode of cooling on the speed of sound propagation
Рис. 3 – Влияние температуры и режима охлаждения на скорость распространения звука
Слика 3 –Утицај температуре и начина хлађења на брзину ширења звука

Table 8 – Effect of temperature and the mode of cooling on the speed of sound propagation (m/s)
Таблица 8 – Влияние температуры и режима охлаждения на скорость распространения звука (м/с)
Табела 8 – Утицај температуре и начина хлађења на брзину ширења звука (m/s)

	20 °C	600 °C	m/s	%
C. Nat	3769	2206	1563	41.47
C. Wat	3769	2068	1701	45.13
C. Ext	3769	2666	1103	29.27

Figure 3 shows the effect of temperature and the mode of cooling (air, water, and extinguisher) on the speed of sound propagation. It clearly shows that the speed of propagation decreases with increasing temperature. Table 8 shows that with sprinkler cooling, the speed of sound propagation is significantly lower than with the other two cooling methods.

Elasticity dynamic modulus

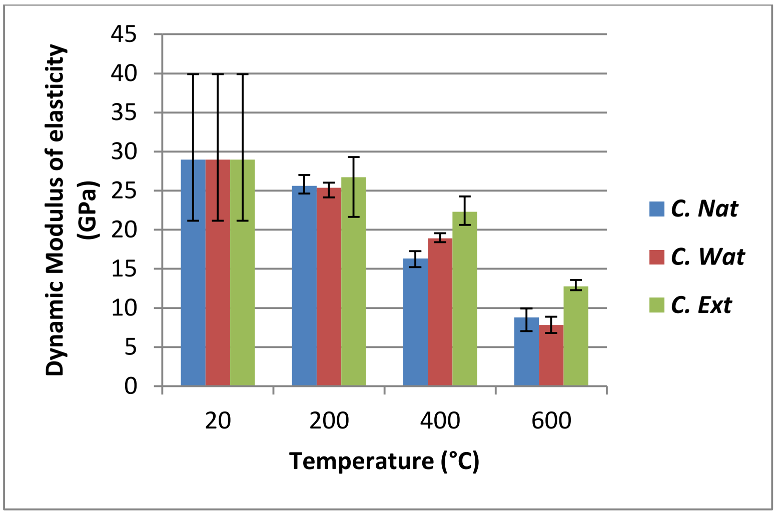

Figure 4 – Effect of temperature and the mode of cooling on the dynamic modulus of elasticity
Рис. 4 – Влияние температуры и режима охлаждения на динамический модуль упругости
Слика 4 –Утицај температуре и начина хлађења на динамички модулус еластичности

Table 9 – Effect of temperature and the mode of cooling on the dynamic modulus of elasticity (GPa)
Таблица 9 – Влияние температуры и режима охлаждения на динамический модуль упругости (гПа)
Табела 9 – Утицај температуре и начина хлађења на динамички модулус еластичности (GPa)

	20 °C	600 °C	Gpa	%
C. Nat	28.99	8.78	20.21	69.7
C. Wat	28.99	7.82	21.17	73.03
C. Ext	28.99	12.77	16.22	55.95

In Figure 4 we have shown the effect of temperature and the mode of cooling (air, water, and extinguisher) on the dynamic modulus of elasticity. When temperature increases, the dynamic modulus of elasticity of the samples decreases. Table 9 clearly shows that with quench cooling, the drop in the dynamic modulus of elasticity is absolutely lower than with the other two cooling modes.

Compressive strength

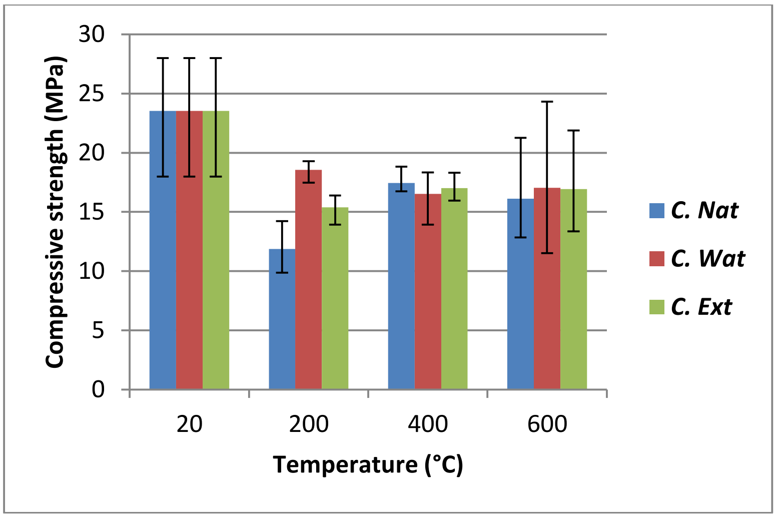

Figure 5 – Effect of temperature and the mode of cooling on compressive strength
Рис. 5 – Влияние температуры и режима охлаждения на прочность при сжатии
Слика 5 – Утицај температуре и начина хлађења на компресивну снагу

Table 10 – Effect of temperature and the mode of cooling on compressive strength (MPa)
Таблица 10 – Влияние температуры и режима охлаждения на прочность при сжатии (мПа)
Табела 10 – Утицај температуре и начина хлађења на компресивну снагу (MPa)

	20 °C	600 °C	Mpa	%
C. Nat	23.53	16.12	7.41	31.5
C. Wat	23.53	17.02	6.51	27.7
C. Ext	23.53	16.93	6.6	28.0

Figure 5 shows the effect of temperature and the cooling mode (air, water, and extinguisher) on compressive strength. We notice that resistance decreases with increasing temperature. This loss of resistance can reach 40%.

Table 10 clearly shows that compressive strength is practically the same for all three cooling modes.

Thermal damage

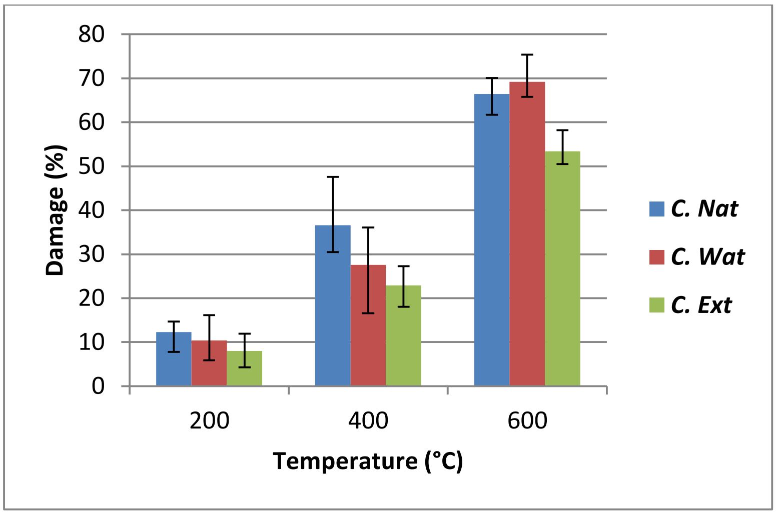

Figure 6 – Variation in thermal damage as a function of temperature and the cooling mode
Рис. 6 – Изменение термического повреждения в зависимости от температуры и режима охлаждения
Слика 6 – Варијација термалног оштећења у зависности од температуре и начина хлађења

Table 11 – Variation in thermal damage as a function of temperature and the cooling mode (%)
Таблица 11 – Изменение термического повреждения в зависимости от температуры и режима охлаждения (%)
Табела 11 – Варијација термалног оштећења у зависности од температуре и начина хлађења (%)

	20 °C	600 °C	%
C. Nat	12.301	66.42	81.5
C. Wat	12.301	69.15	82.2
C. Ext	12.301	53.42	77.0

In Figure 6, we show the effect of temperature and the mode of cooling (air, water, and extinguisher) on the variation of thermal damage. We note, for the three cooling modes, that damage increases with the increase in temperature. It is clear the thermal damage is a little lower with the use of the extinguisher as a means of cooling.

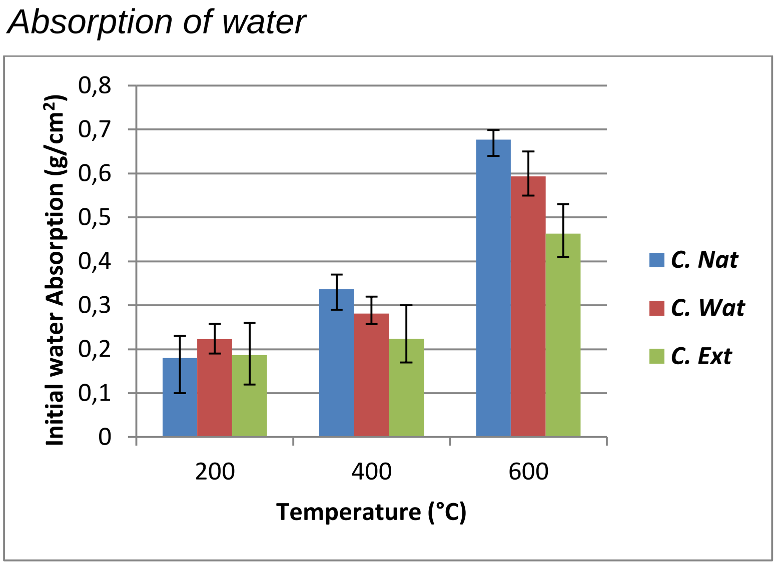

Figure 7 – Effect of temperature and the mode of cooling on initial water absorption
Рис. 7 – Влияние температуры и режима охлаждения на начальное водопоглощение
Слика 7 –Утицај температуре и начина хлађења на иницијалну апсорпцију воде

Table 12 – Effect of temperature and the mode of cooling on initial water absorption (g/cm2)
Таблица 12 – Влияние температуры и режима охлаждения на начальное водопоглощение (г/см2)
Табела 12 – Утицај температуре и начина хлађења на иницијалну апсорпцију воде (g/cm2)

	20 °C	600 °C	g/cm²	%
C. Nat	0.23854	0.6773	0.43876	64.8
C. Wat	0.23854	0.5933	0.35476	59.8
C. Ext	0.23854	0.4633	0.22476	48.5

Figure 7 shows the effect of temperature and the cooling mode (air, water, and extinguisher) on initial water absorption. It is observed that water absorption increases with increasing temperature, particularly at 600 °C. In addition, it is found that water absorption under cooling with the extinguisher is always lower compared to the other two cooling modes. We notice in Table 12 that the use of the extinguisher to put out fire has less absorptivity compared to the two other cooling methods.

Conclusion

The primary goal of this paper is to provide an experimental contribution to the study of the effect of a mode on the behavior of micro-concretes exposed to high temperatures. In this study, the temperatures used are those tested in the majority of previous studies; they are 200, 400, and 600 °C.

Until now, two cooling modes have been used to extinguish fire: one slow, which is natural cooling; and the second fast, which is water cooling. Through this research attempt, we have examined a third mode of cooling; it is the extinguisher. This cooling process practically constitutes an intermediate mode between a slow one and a fast one. For better compression, we carried out mechanical tests concerning compressive strength, thermal damage, modulus of elasticity, and other physical properties: porosity, density, and speed of sound propagation. These tests were carried out hot and after cooling on specimens previously exposed to temperatures of 20°C, 200°C, 400°C, and 600°C.

According to the results obtained (Figures 1 to 7 and Tables 6 to 12), it can be concluded that cooling by the extinguisher presents the most suitable mode for extinguishing a fire of up to 600 °C.

Overall, the analysis of the parameters analyzed (Figures 1 to 7 and Tables 6 to 12) leads us to suggest using the powder extinguisher in the process of extinguishing fire in concrete structures exposed to temperatures up to 600 °C.

In a future study, we will try to analyze the effect of cooling time on the thermal behavior of ordinary concrete as well as to extend this study to other existing concrete types.

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Экспериментальное исследование тепловых свойств бетона

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Резюме:

Введение/цель: При воздействии огня, а также при быстром или медленном охлаждении частей бетонного сооружения происходят различные изменения плотности, пористости, скорости распространения звука, модуля упругости, прочности на сжатие, водопоглощения и пр. Эти процессы также могут вызвать термическое повреждение. Широкое использование бетона в строительстве, с одной стороны, и проблемы, вызванные воздействием огня, с другой, требуют углубленного понимания влияния огня на поведение бетонной конструкции, особенно после охлаждения. До сих пор для тушения пожара использовались два метода охлаждения: водой и свободным потоком воздуха. Цель данной статьи — экспериментально исследовать использование огнетушителя как третьего способа охлаждения бетона, подвергающегося воздействию высоких температур.

Методы: Для достижения цели исследования была проведена серия механических и физических испытаний образцов диаметром 40 мм и высотой 40 мм, подвергнутых воздействию высоких температур 200, 400 и 600 °C. Затем испытуемые образцы были подвергнуты трем различным режимам охлаждения, а именно: свободным потоком воздуха, водой и огнетушителем.

Результаты: Результаты однозначно показывают, что использование огнетушителя целесообразнее, чем два других метода охлаждения, а именно: воздухом и водой.

Выводы: Результаты этого экспериментального исследования могут быть полезны на практике при тушении пожара в бетонном сооружении.

Ключевые слова: бетон, пожар, экспериментальное исследование, тушение, вода, воздух.

Експериментална анализа изложености бетона термичким променама

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ОБЛАСТ: материјали, грађевинарство
ВРСТА ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Када су делови бетонске структуре изложени дејству ватре, а затим брзом или спором хлађењу, долази до различитих промена у густини, порозности, термичком оштећењу, брзини ширења звука, модулусу еластичности, компресивној снази, апсорпцији, итд. Раширена употреба бетона у грађевинарству, с једне стране, и проблеми настали услед изложености пожару, с друге стране, захтевају детаљно разумевање утицаја ватре на понашање структуре бетона, нарочито после хлађења. До сада су коришћена два метода хлађења за гашење ватре – водом и слободним струјањем ваздуха. У раду је експериментално анализирано коришћење противпожарног апарата као трећег начина за хлађење бетона изложеног високим температурама.

Методе: Извршена је серија механичких и физичких испитивања узорака, пречника 40 mm и висине 40 mm, изложених високим температурама од 200, 400 и 600 °C. Затим су тест-епрувете подвргнуте хлађењу на три различита начина: слободним струјањем ваздуха, потапањем у воду и коришћењем противпожарног апарата.

Резултати: Резултати јасно показују да је коришћење противпожарног апарата погодније од преостала два метода хлађења, тј. природног хлађења на ваздуху и натапања водом.

Закључак: Резултати ове експерименталне студије могли би да имају практичну примену при гашењу евентуалног пожара у некој бетонској структури.

Кључне речи: бетон, ватра, експериментална анализа, гашење, вода, природно струјање ваздуха.

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