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Effect of high temperature and cooling conditions on aerated concrete properties

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ABSTRACT

In this study, effect of elevated temperatures and various cooling regimes on the properties of aerated concrete is investigated. Air cooled materials are tested at room temperature and in hot condition right after the fire. Water quenching effect is determined by testing the material in wet condition right after the quenching and in dry condition at room temperature. Unstressed strength of the material tested hot is relatively higher than air cooled unstressed residual strength up to 600 °C. On the other hand, water quenching decreases the percentage of the strength particularly when the material is wet right after the quenching; strength is lost gradually as the temperature rises. As a result, if the quenching effect is disregarded, temperature rise does not have a considerable effect on the strength of the aerated concrete approximately up to 700–800 °C. It is able to maintain its volumetric stability as well. However, more care needs to be taken in terms of its use above 800 °C for fire safety.

1. Introduction

Concrete is an inorganic material and high temperature and its duration decrease the concrete strength and its durability. Fire resistance of concrete is primarily affected by factors like the temperature, duration and condition (multiple or one-way effect-direct flame contact-hot gas or radiation) of the fire. The type of aggregate and cement used in its composition, the porosity and moisture content of concrete, its thermal properties, and sizes of structure members and their construction type are the other factors that determine the level of fire resistivity of the material. An increase in the size of structural members increases fire resistance. As a two phase composite material, the behavior of the cement matrix in fire is more important than its dispersed phase. Fire resistance of aggregates is generally high.

To determine the resistance of concrete samples exposed to high temperature, there are three test methods available for finding the residual compressive strength of concrete at elevated temperatures: stressed test, unstressed test, and unstressed residual strength test. The first two types of the tests are suitable for accessing the strength of concrete during high temperatures, while the later is excellent for finding the residual properties after the high temperature. In the stressed test, specimens are restrained by a preload prior to and throughout the heating process. In the unstressed test, the specimens are heated without restraint. Both stressed and unstressed specimens are loaded to failure under uniaxial compression when the steady-state temperature is reached at the target temperature. The unstressed residual property test method is designed to provide property data of concrete at room temperature after exposure to elevated temperatures [1,2]. It was found that the last method gives the lowest strength and is therefore more suitable for getting the limiting values [3].

On the other hand, the type of cooling (in air and water) affects the residual compressive and flexural strength, the effect being more pronounced as the temperature increases [2]. According to Peng et al. the behavior of concrete under high temperature conditions more or less different from the standard fire condition. Residual mechanical properties reported in most previous literature might be overestimated, where natural cooling was usually employed. And proper evaluation of fire resistance of concrete needs more experimental data obtained under various cooling regimes such as water spraying or water quenching where they cause different stresses in reinforced concrete members at high temperature and the structural member can lose load bearing capacity [4].

The effect of high temperatures on the mechanical properties and durability of lightweight, normal, or high strength concrete have been investigated by many researchers in order achieve fire resistant material since the 1940s [3,5–7]. However, very few researches related to the fire resistance of cellular concrete have been carried out [8,9]. Aerated concrete in which air-voids are entrapped in the mortar matrix by means of a suitable aerating agent is produced from cement or lime, silica sand and sometimes pozzolanic materials and classified as lightweight concrete. Based on the method of pore-formation it is classified into three groups:

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air-entraining method (gas concrete), foaming method (foamed concrete) and combined method. Aerated concrete can be non-autoclaved (NAAC) or autoclaved (AAC) based on the method of curing. The compressive strength, drying shrinkage, absorption properties etc. directly depend on the method and duration of curing. Once it is cured enough, the concrete foam is stripped from its mold, sliced into blocks or slabs of the required size. A wide range of densities (300–1800 kg/m^3) can be obtained thereby offering flexibility in manufacturing products for specific applications (structural, partition and insulation grades). Heat transfer through porous materials is affected by conduction, and at high temperatures, by radiation. The good fire resisting property of aerated concrete is where its closed pore structure pays rich dividends, as heat transfer through radiation is an inverse function of the number of air–solid interfaces traversed. The homogeneous character of the material and its low thermal conductivity and diffusivity suggest that cellular concretes might possess excellent fire resistance properties and hence its use does not involve any risk of spread of flames. In practice, fire resistance properties markedly superior to those of ordinary dense concrete where the presence of coarse aggregate leads to differential rates of expansion, cracking and disintegration [8,10].

However, although the material has lower thermal conductivity and thermal expansion coefficient than structural lightweight concrete which delays the effective temperature of the fire to reach it's core, under various cooling conditions this may cause big temperature differences in the section of the material and may destroy the material due to the diverse thermal expansions. The previous study conducted by the authors tested only the unstressed residual strength of the cellular concrete where natural cooling was applied [9].

Thus, the main objective of this research is to examine the unstressed residual and unstressed strength of the aerated concrete at elevated temperatures by considering the effect of various cooling regimes. In the tests, temperatures of 21, 100, 200, 400, 600, 800, and 965 °C were chosen for ease of observation of the test results. All series were exposed to same temperatures. Compressive and splitting strengths of the cellular concrete which were exposed to high temperatures and cooled differently (in air and in water) were compared with each other and then compared with the samples which were not heated.

2. Experimental study

Aerated concrete tested in the experimental study was provided directly by the manufacturer. The commercial name of the product is called G4. The material properties are given in Table 1 [11].

Table 1
Properties of the material used in the experimental study

G4 type aerated concrete		Physical properties	
Mechanical properties		Specific density (g/cm^3)	2.60
Modulus of elasticity (MoE) (kN/mm^2)	1.950–2.0	Unit weight (g/cm^3)	0.6
Compressive strength (N/mm^2)	~4	Pore Proportion (%)	75
Tensile strength (N/mm^2)	~0.5	Pore size (mm)	0.5–1.5
Flexural strength (MoR) (N/mm^2)	~0.7	Thermal conductivity (W/m K)	0.14
Shear strength (N/mm^2)	~1.1	Thermal expansion coefficient (m/m °C)	0.8×10^{-5}

Tests were planned under two different cooling conditions: air cooled and water quenched. All the specimens were kept at room temperature (20–21 °C) and constant humidity (60 ± 0.05%R.H) until they reached equilibrium moisture and weight previous to heating. Then, they were placed into the oven without preload and were submitted to the selected heating regime up to reach a maximum of six temperatures until a thermal steady state was achieved: 100, 200, 400, 600, 800 and 965 °C. Oven was heated according to the time–temperature schedule of ASTM E 119-00 [12]. Afterwards, all the specimens were maintained in the oven for slow cooling down for 30 min. Before testing, G#1 series were allowed to cool in the desiccators to room temperature to avoid contact with the atmosphere and further up take of humidity. In G#2 series, load was applied to the hot specimen at a prescribed rate until failure occurs. G#3 and G#4 series were quenched in water at 22–23 °C for 30 s. In G#3 series load was applied right after the quenching when the material was wet. After the prescribed quenching time in water, G#4 series were kept in the etuve at 60 ± 5 °C for 24 h and later they were replaced into the desiccator until the equilibrium moisture content is reached prior to testing.

The dimensions of the specimens were 50 × 50 × 50 mm and 40 × 40 × 160 mm. Each data point reflects the three test results. The weights of the specimens were measured by the scale of electronic PRECISA 4000C, which has a 10 kg capacity and 0.01 gr. precision. Ultrasound pulse velocity was determined by the CNS Electronic Ltd. PUNDIT non-destructive ultrasound equipment. The mechanical tests were done by the Amsler Type 6DB7F120 Hydraulic test equipment with capacity of 6–60 kN and by the Losenhausenwerk Hydraulic test equipment with capacity of 20–200 kN. NUVE MF100 oven was used to obtain high temperatures with the maximum capacity of 1000 °C and 1 °C precision and Hereaus etuve was used for drying water-quenched specimens with maximum capacity of 300 °C and ±5 °C precision.

The detailed sample compositions were coded using the format (# # # – *X* – *X*). The first coding group indicates the effective temperature (°C) the specimen submitted. The second letter shows the cooling type of the specimen which is (A) for air-cooled (G#1, G#2) samples and (W) for water quenched (G#3, G#4) samples. The third letter shows the condition of the sample when the load was applied. It is coded as (R), (H), (W) and (D) to indicate room temperature, hot, wet and dry conditions respectively. As an example, 400-A-R indicates the code of a specimen fired at 400 °C, air cooled and tested at room temperature.

While, volume, unit weight, ultrasound velocity, Young's Modulus of Elasticity (MoE) tests were done only on G#1 series; compressive and splitting strength tests were applied to all the series from G#1 to G#4. Splitting test results of G3 series were found not applicable to evaluate.

3. Results and discussion

The test results of the volume, unit weight, ultrasound velocity, and MoE of G#1 series before and after heating are given in Table 2 and the average compressive and splitting strength test results of G#1, G#2, G#3 and G#4 series are given in Table 3.

3.1. Effect of high temperatures on volume and unit weight

Relative changes observed in volume, length, weight and unit weight of the material as function of applied temperature is given in Fig. 1. The linear thermal expansion coefficient of aerated concrete is $\alpha = 8 \times 10^{-6}$ m/m °C. Accordingly, material expands initially, but shrinks relatively more than its original size depending on the applied temperature. The trend of the relational line is adjacent to the calculated theoretical values of linear and volumetric thermal expansion of the material until 200 °C which are also shown in the same figure. Dimensional changes directly affect the volume of the material. It gradually decreases between

Table 2
Volume, unit weight, ultrasound velocity and MoE of G#1 series

Series G#1	Volume (cm^3)			Unit weight (g/cm^3)			Ultrasound velocity (km/s)			MoE (kN/mm^2)		
	Before	After	%	Before	After	%	Before	After	%	Before	After	%
20-A-R	123.6	123.6	1.00	0.69	0.69	1.00	1.86	1.86	1.00	2.36	2.36	1.00
100-A-R	136.1	137.3	1.01	0.56	0.55	0.98	2.05	2.08	1.01	2.37	2.40	1.01
200-A-R	135.1	135.8	1.01	0.57	0.55	0.96	1.99	1.90	0.95	2.28	1.98	0.87
400-A-R	135.8	131.6	0.97	0.57	0.55	0.95	2.00	1.67	0.84	2.29	1.54	0.67
600-A-R	133.8	128.9	0.96	0.59	0.55	0.93	1.96	1.46	0.74	2.27	1.17	0.51
800-A-R	134.1	127.6	0.95	0.59	0.53	0.90	1.97	1.01	0.51	2.39	0.55	0.23
965-A-R	134.3	124.0	0.92	0.59	0.55	0.93	2.05	1.00	0.49	2.47	0.55	0.22

400 and 800 °C. Between 200 and 400 °C and above 800 °C the decrease is relatively sharp. The capillary micro cracks occur in the material between 225 and 450 °C could be the reason of this dimensional change. Another sharp decrease seen approximately between 800 and 925 °C is probably due to the sintering reaction starts in the material [11]. Thus, if the material will be quenched by water during the fire, it is apparent that it will shrink because of rapid cooling and will damage due to the formation of strong crack propagation. Using the material with compatible flexible mortars would be advised when it is intended to be used above 800 °C.

Figs. 2 and 3 give the relative changes in volume and unit weight of the material as function of elevated temperatures together with the same properties of gypsum paste and mortars which are known to have good fire resistance for comparison [13]. Although the trends of relative volume lines are similar, it is 0.92 for G#1 and around 0.65 for gypsum paste and mortars at 965 °C. Thus, aerated concrete can be well accepted as a dimensionally stable material especially up to 800 °C. Parallel to the changes in volume, unit weight of aerated concrete decreases approximately 10% depending on the elevated temperatures and is relatively smaller than gypsum based paste and mortars. This value is important for the evaluation of MoE of the material.

3.2. Effect of high temperatures on the young's modulus of elasticity

Fig. 4 shows the variation of ultrasound velocity as function of elevated temperatures. Equilibrium moisture content of aerated concrete depending on the relative humidity of the test environment is generally below 3.5% by volume of the dry material and is released at approximately 100 °C. A slight increase observed at 100 °C is due to the evaporation of free water. From 200 °C up to 800 °C the values gradually decrease, and remain almost same upwards. Between 300 °C and 500 °C water of crystallization removes from the material and free calcium hydroxide decomposes into calcium oxide. From this temperature level upwards shrinkage occurs depending on the dehydration of $Ca(OH)_2$. In fact, at this temperature range mortars like Portland cements which contain significant amount of free Ca $(OH)_2$ are influenced more than the mortars which complete carbonation process [14]. $CaCO_3$ exists in the structure of aerated concrete is more resistant to high temperatures than $Ca(OH)_2$, Fig. 4 also gives the two reference diagrams of normal weight concrete (NWC) quenched and non-quenched [15]. The ultrasound velocity of quenched concrete is relatively lower than none quenched one. Calcium oxide which is wetted by quenching transforms into calcium hydroxide again and concrete expands. These changes in volume may increase the cracks in the structure. It should also be considered that specimens of G#1 series were cooled in air and the values of ultrasound velocity were proportionally higher than the values that would be achieved if the material was quenched. Additionally, aerated concrete does not contain coarse aggregate and has lower thermal conductivity than NWC which may relatively decrease the effect of quenching on the structure of the material. This subject will be discussed in the following sections.

Effect of high temperatures on MoE of G#1 series is given in Table 2 and Fig. 5. Like the values obtained for ultrasound velocity and unit weight, MoE values also decrease gradually between 100 and 800 °C which could be the result of gradual increase of micro cracks in the structure of the material. 800 °C can be accepted as the approximate temperature where sintering reaction starts. Relative MoE values of NWC [14] and gypsum composites [13] obtained from the related literature are also given in Fig. 5 in order to make a comparison. MoE values of concrete which reflects the variation until 400 °C are almost parallel with G#1. Gypsum paste gives its physically bonded water at 100 °C, hereafter particularly at 200 °C, chemically bonded water is released and the material dehydrates until 400 °C. MoE of gypsum mortar also decrease at 400 °C, but above 400 to 800 °C, since the mortar has already been dehydrated, no more significant change takes place in the properties of mortar.

3.3. Effect of high temperatures on the compressive strength

Relative Compressive strength values of G#1 and G#2 series as function of elevated temperatures are given in Table 3 and Fig. 6. Although values of ultrasound velocity and MoE slightly increase at 100 °C, and have descending values until 800 °C, compressive strengths of G#1 and G#2 series increase at 200 °C and decrease apparently only after 600 °C. Chemical structure of the aerated concrete starts to break down between 225 and 450 °C where first capillary cracks were observed. These cracks do not have significant affect on the compressive strength of the material, but above 500 °C the amount of the cracks develop parallel to the increase of temperature and the material becomes weaker. Maximum compressive strength is found at approximately 200 °C for G#1 series and 400 °C for G#2 series which were tested hot. Starting from approximately 400 °C up to 800 °C compressive strength of the material is gradually lost, but above 800 °C severe lost is seen due to the sintering reaction starts to occur in the structure.

In Fig. 6 relative values of compressive strengths of G#1 and G#2 series are compared with the relative compressive strengths given in [11] for aerated concrete (Type G4). As seen in the figure, three series behave almost similarly and values fall lower than their initial values approximately at 800 °C. Relative compressive strength test results given in previous literature related to hot and cool tested NWC [14] and gypsum mortars [13] were added to the Fig. 6 as well. They are both descending distinctly as the temperature rise. Compressive strengths of the cool tested concrete are higher and relatively stable than the test results of hot tested concrete which decrease steeply particularly right after 600 °C. These results support the results achieved in our research. The compressive strengths of gypsum pastes and lightweight gypsum mortars have also similar tendencies. Like the evaluations on MoE, gypsum mortars lose approximately 80% of their compressive strength at 200 °C due to the dehydration of the matrix phase.

Table 3
Compressive and Splitting Strength test results

Series	Applied temperature (°C)	Test temperature (°C)	Compressive strength (N/mm^2)	Normalized values (comp)	Splitting strength (N/mm^2)	Normalized values (splitt)	Series	Temperature before quenching (°C)	Temperature after quenching (°C)	Test temperature (°C)	Compressive strength (N/mm^2)	Normalized values (comp)	Splitting strength (N/mm^2)	Normalized values (spltt)
G#1-							G#3-							
20-A-R	21	21	3.29	1.00	0.71	1.00	20-W-W	21	21	21	3.93	1.00	–	–
100-A-R	100	21	3.48	1.06	0.90	1.27	100-W-W	109	33	39	4.17	1.06	–	–
200-A-R	200	21	3.70	1.12	0.55	0.77	200-W-W	179	40	50	3.25	0.83	–	–
400-A-R	400	21	3.43	1.04	0.39	0.55	400-W-W	303	45	56	3.00	0.76	–	–
600-A-R	600	21	3.66	1.11	0.50	0.70	600-W-W	503	63	77	2.42	0.62	–	–
800-A-R	800	21	3.18	0.97	0.29	0.41	800-W-W	675	71	81	2.20	0.56	–	–
965-A-R	965	21	2.12	0.64	0.19	0.27	965-W-W	791	64	77	1.47	0.37	–	–
G#2-							G#4-							
20-A-H	21	21	3.29	1.00	0.71	1.00	20-W-D	21	21	21	3.29	1.00	0.71	1.00
100-A-H	100	110	3.55	1.08	0.45	0.63	100-W-D	99	32	21	3.12	0.95	0.61	0.86
200-A-H	200	197	4.40	1.34	0.34	0.48	200-W-D	167	39	21	4.21	1.28	0.54	0.76
400-A-H	400	385	5.41	1.64	0.40	0.56	400-W-D	336	48	21	3.07	0.93	0.29	0.40
600-A-H	600	543	3.63	1.10	0.37	0.52	600-W-D	457	59	21	3.23	0.98	0.29	0.40
800-A-H	800	756	3.33	1.01	0.36	0.51	800-W-D	570	66	21	2.99	0.91	0.31	0.44
965-A-H	965	768	2.01	0.61	0.18	0.25	965-W-D	738	62	21	2.43	0.74	0.17	0.24

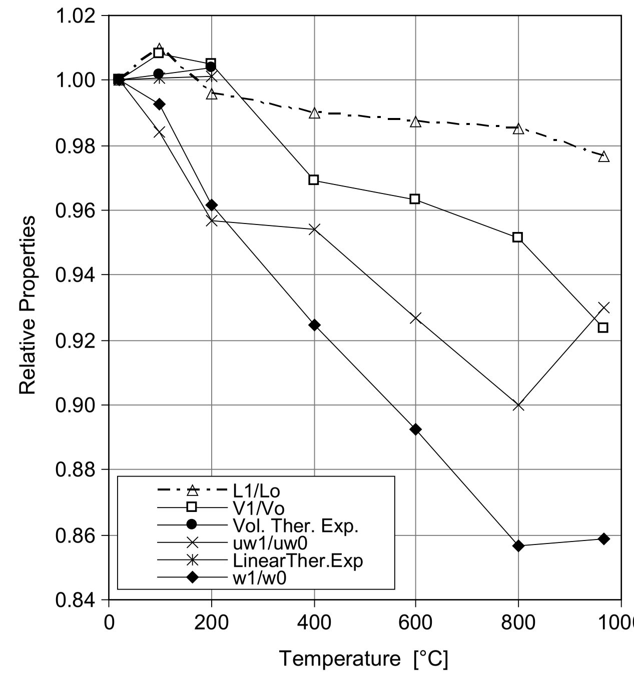

Fig. 1. Relative length (L_1/L_0), volume (V_1/V_0), weight (w_1/w_0) and unit weight (uw_1/uw_0) of G#1 series as function of elevated temperatures and relative values of thermal expansions.

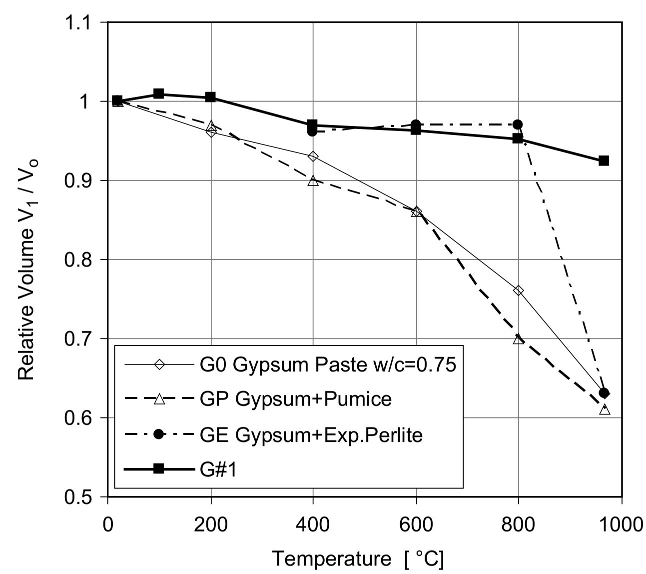

Fig. 2. Relative volume of G#1 series and gypsum paste (G0) and different lightweight gypsum mortars with pumice (GP) and expanded perlite (GE) as function of elevated temperatures [13].

3.4. Effect of high temperatures on the splitting strength

The splitting strengths of G#1 and G#2 series as function of high temperatures are given in Fig. 7. There is an approximate relationship between compressive strength and flexural and tensile strength of aerated concrete [14]. It is assumed that tensile strength is 1/6 and flexural strength is 1/5 of its compressive strength. In order to make an evaluation on the general mechanical behaviour of the material under tensile stress theoretical tensile and flexural strengths that were calculated with the measured compressive strength values of G#1 are also added to

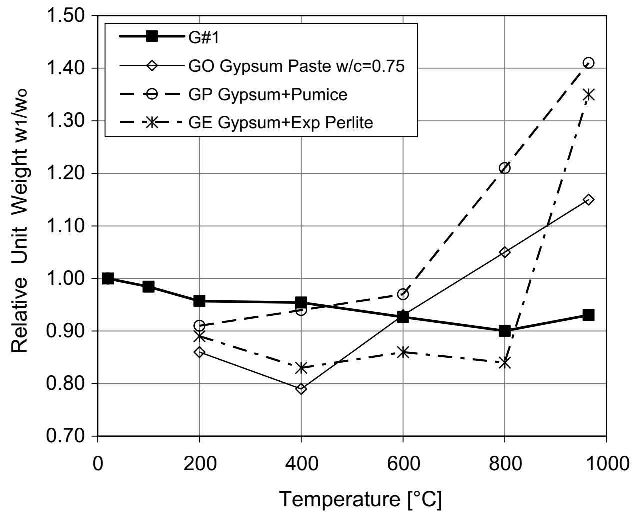

Fig. 3. Relative unit weights of G#1 series and gypsum paste (G0) and different lightweight gypsum mortars with pumice (GP) and expanded perlite (GE) as function of elevated temperatures [13].

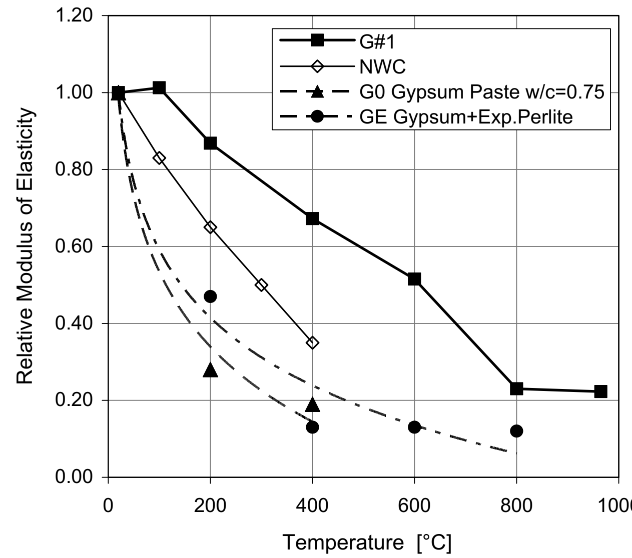

Fig. 5. Relative values of MoE for G#1 series, NWC [14], gypsum paste (G0) and gypsum mortar with expanded perlite (GE) [13] as function of elevated temperatures.

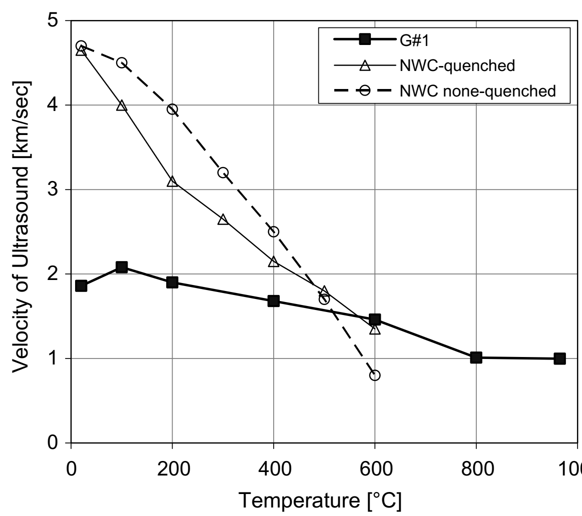

Fig. 4. Ultrasound velocity of (G#1) series and NWC quenched and none quenched as function of elevated temperatures [15].

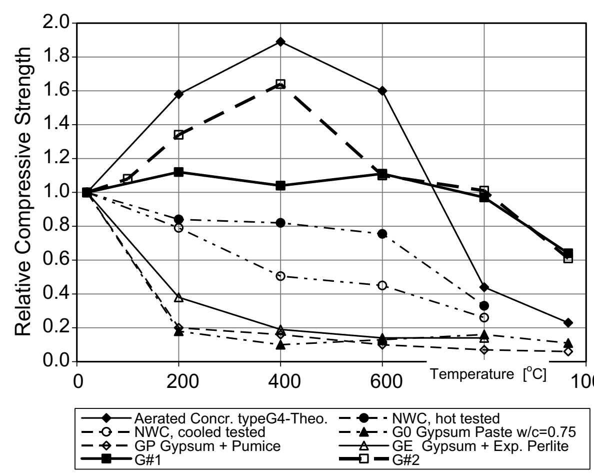

Fig. 6. Relative compressive strengths of G#1 and G#2 series, aerated concrete (Type G4) [11] hot and cool tested NWC [14], gypsum paste (G0) and different lightweight gypsum mortars with pumice (GP) and expanded perlite (GE) as function of elevated temperatures [13].

Fig. 7. Tensile, splitting and flexural strengths of the material vary in similar trend as function of elevated temperatures. Except a weak increase at 100 °C for G#1 series, the splitting strengths of both series drop at 200 °C and by 400 °C lose 45% of their initial strength. Above 600 °C the rate of the fall is high and ends with 25% of their initial strength at 965 °C. This variation can also be followed from the relative values of the test results given in Fig. 8. In spite of a distinct increase in compressive strengths of both series at 200 °C, the parallel behavior in splitting strength can only be seen in G#1 series at 100 °C. At 400 °C while the compressive strength of G#1 does not reach the expected level, the splitting strength of G#2 at 100 °C is obviously lower than expected. The results are not thought to be generalized because of these unexpected variations. For both of the series, at 965 °C, splitting strengths drop 75% and compressive strengths drop%35 lower than their initial strength. Accordingly, the splitting strength of the material is more sensitive to the structural changes occur in the material than compressive strength under high temperature effect. Fig. 8 gives the relative values obtained from previous literature for cool tested NWC as well [14,16]. Relative compressive and splitting values of concrete are identical and have constant decreasing slope as the temperature rises. Generally, results are different but confirm the values obtained for aerated concrete at 400 °C.

In the previous section, relationship between the compressive strength and ultrasound velocity of the material was mentioned. As a general evaluation, the relative values of the four basic properties of G#1 which were measured under same testing conditions as function of temperature rise are given altogether in Fig. 9. Relative values of compressive and splitting strengths of G#2 are also added to the same figure. Test results in real and relative values are given in Table 2 and Table 3.

The four different properties of G#1 increase at 100 °C. Splitting strength gain is the highest and is about 27%. The increase in relative values of MoE and compressive strength is adjacent and relatively in lower level than splitting strength. The known relationship between these properties as function of strain ratio should be examined in the future studies. By 200 °C, except relative

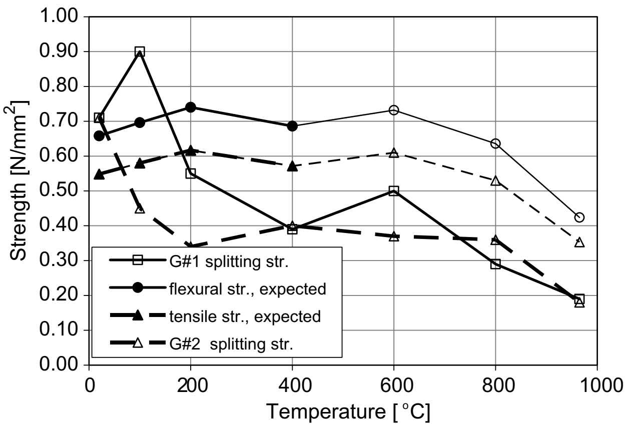

Fig. 7. Splitting Strengths of G#1 and G#2 series and theoretical values of Tensile and Flexural Strengths of G#1 as function of elevated temperatures.

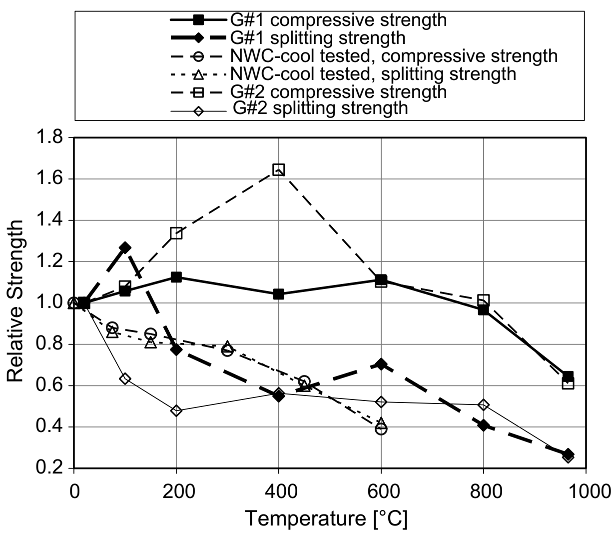

Fig. 8. Relative values of compressive and splitting strengths of G#1 and G#2 series and cool tested NWC [14] [16] as function of elevated temperatures.

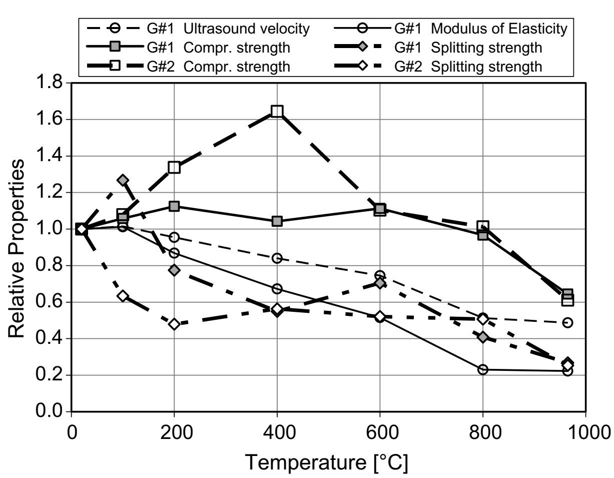

Fig. 9. Relative properties of Ultrasound Velocity, MoE, of G#1 and Compressive and Splitting Strengths of G#1 and G#2 as function of elevated temperatures.

increase of the compressive strength, all other properties change to decrease. Capillary cracks occur in the structure of the material can be accepted as the reason why MoE and compressive strength do not change directly proportional. Hence, if the relationship among various mechanical properties is to be looked for, more accurate findings can be achieved by testing the material at 100 °C. Besides, MoE and splitting strengths reflect the effect of high temperature better than compressive strength.

3.5. Effect of quenching on the mechanical strength

The residual strength of the material changes also according to the cooling conditions. Generally water is used for quenching in fire. Instantaneous temperature change by means of water quenching gives rise to develop stress concentrations in the material. Besides, aerated concrete being porous, there is a strong interaction between water, water vapour and the porous system which may affect the strength of the material. As such, the strength of the concrete is higher when it is cooled in air than in water [15]. Under this section of the study, the effect of quenching on the mechanical properties of the material is investigated after high temperature exposure. Hence, the wet and dry strength of the material after quenching are both taken into consideration.

Time dependent cooling of the specimens taken out of the oven is investigated at first in order to examine the effect of cooling conditions on the strength of the material. For this aim, G4 type of aerated concrete tested in the context of this research, G2 type of aerated concrete which has higher porosity ratio and lower density (0.31–0.5 g/cm^3) and NWC [14] were brought into comparison.

Figs. 10 and 11 show that the cooling trend of all the materials is approximately same depending on time. But, there is an inverse relationship between density and cooling rate of the material. G2 type of aerated concrete cools faster than the NWC. Because density of the later is greater than G2 and its higher thermal storage capacity keeps the heat for a longer time. Another inverse relationship obtained from the same figure is between fire temperature and cooling rate. Cooling rate of the specimens exposed 965 °C is faster than the specimens exposed to 600 and 400 °C. These results can be complementary especially for G#2 series which were tested hot. In G#2 series, load was applied at approximately 38% lower degree than 965 °C for G#2–965, 23% lower degree than 600 °C for G#2–600 and 15% lower degree than 400 °C for G#2–400 series, respectively. The sharp temperature change before and after quenching of G#4–965 series can be followed in the same figure as well. These results are also valid for G#3–965 series which were

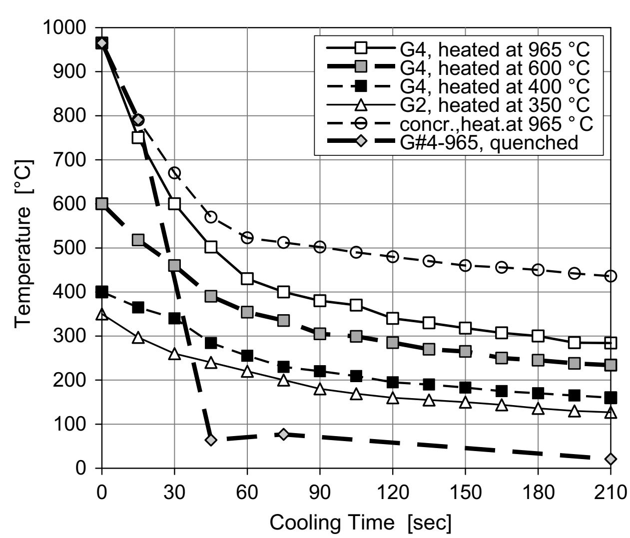

Fig. 10. Cooling temperatures of different samples as function of cooling time. Materials: aerated concrete Type G4, Type G2 and NWC [14].

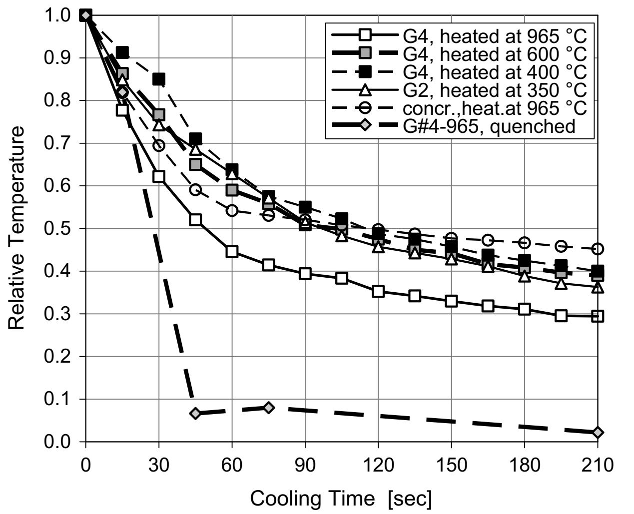

Fig. 11. Relative cooling temperatures of different samples as function of cooling time. Materials: aerated concrete Type G4, Type G2 and NWC [14].

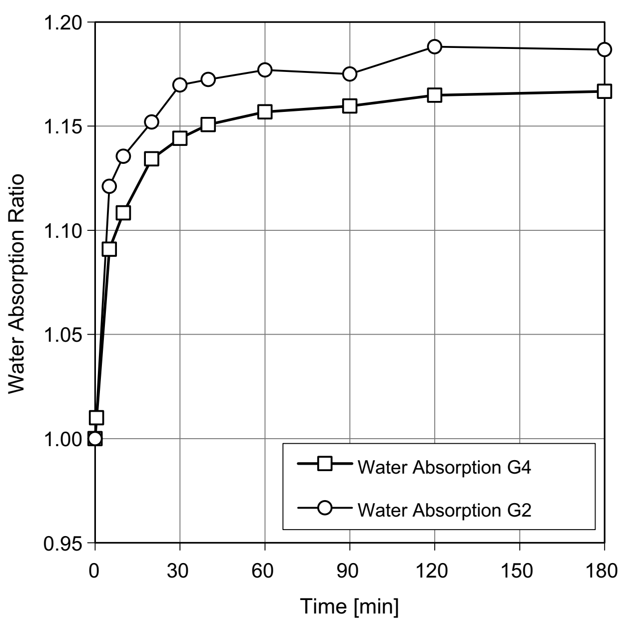

Fig. 12. Water absorption ratio of aerated concrete (Type G4 and Type G2) as function of soaking time.

tested wet immediately after they were quenched for 30 s. The test temperature of the material is approximately 40% less than the fire temperature after quenching.

The rate of the water absorption depending on time is also to be considered prior to the evaluation of the effect of quenching on the mechanical properties of the material. Fig. 12 gives the water absorption rate of the two types of aerated concrete (G2 and G4) as function of time [11]. Although water absorption ratios of both series vary in a similar trend as function of time, the results obtained from the experiments for G4 type is relatively smaller than G2 type as expected. The water absorption ratio is approximately 17% by weight at the first 3 h, and 1% at the first 30 s. But it should be taken into account that the specimens of that experiment were not exposed to the high temperatures previously. If the specimens are quenched after exposed to high temperatures, especially proceeding from 400 °C, the surface cracks disseminate and gradually deepen from the effect of the thermal stress. This effect apparently increases the water absorption ratio of the material especially at the first 30 s as shown in Fig. 13. The influence of the quenching on the strength of the material is relatively greater than expected under these conditions.

Fig. 14 and Table 3 give the relative strengths of all the series. Hot tested G#2 series have the highest compressive strength in the range of 200–600 °C, especially at 400 °C. Between 200 and 800 °C, the results of the two dry tested series G#1 and G#4 change parallel to each other. Water quenched series G#3 and G#4 have lower strength values than the other series which were not quenched. This could be the result of the thermal stress applied to the material as mentioned above. G#3 series is more vulnerable to the stress loaded which indicates that wet strength of the material is lower than the dry strength. Besides, as the temperature rises the strength of the G#3 is getting decreased and finally at 925 °C it can only bear 37% of its initial strength.

Relative splitting strengths of all the series are close to each other especially above 400 °C. It was unable to reach applicable results for G#3 series. The relative splitting strengths of G#1 and G#4 series are higher than G#2 series up to 250 °C. Hot tested G#2 series which has the highest compressive strength at this temperature range apparently brittle than the others as expected. Besides, like the values achieved from the compressive strength tests, water quenching decrease the splitting strength of the material as well. Above 100 °C the relative values of dry tested G#1 and G#4 series decrease sharply until 400 °C. The micro cracks occur approximately between 225 °C and 400 °C do not have significant affect on the compressive strength of the material, but splitting strength which indicates the tensile strength of the material is more sensitive to structural cracks and the reason of the sharp decrease until 400 °C could be these cracks occurred in the material. From 400 °C up to 800 °C, no significant change was determined in the splitting strengths. This indicates that there is no residual crack formation above 400 °C to 740 °C where sintering reaction starts to develop in the material [11]. Hence, above 800 °C, the effect of the sintering and the excess temperature, decrease the splitting strength of the material approximately 75% lower than its initial strength.

Fig. 13. Thickness of the absorbed water by G#3 after fire exposure: (a) 400-W-W: 6 mm (b) 600-W-W: 8 mm and (c) 800-W-W: 12 mm.

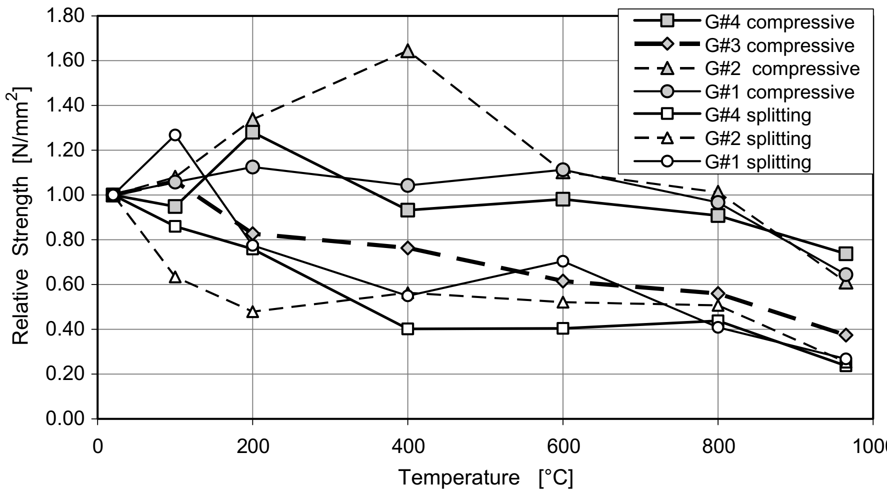

Fig. 14. Relative compressive and splitting strengths of all the series as function of elevated temperatures.

4. Conclusion

This research focused on the effect of the high temperatures and cooling regimes on the mechanical properties of aerated concrete. The unstressed residual strength is found by testing the G#1 series after the high temperature. G#2 series were tested for accessing the strength of aerated concrete during high temperatures In order to find the quenching effect on the residual properties of the material after the high temperature G#3 and G#4 series were tested. The following conclusions may be drawn:

(1) After fire exposure, the volume of the aerated concrete increases at first due to the thermal expansion of the material, it increasingly shrinks depending on the rising temperature level. Both the unit weight and the volume of the material decrease approximately 10% at the examined temperature range. The volumetric stability of the aerated concrete is a significant performance requirement in terms of its use in fire safety applications. MoE of the aerated concrete increases 1% due to the loss of moisture at approximately 100 °C and gradually decreases as the temperature is elevated to 800 °C and remains constant until 965 °C. The reason of the decrease in MoE, especially approximately above 200 °C, is mainly the result of gradual increase of micro cracks developing in the structure of the material.

(2) Dry-tested materials without regarding their cooling conditions have almost similar performance as the temperature is elevated. A slight increase is observed at 200 °C due to the release of physically bounded water, between 200 and 400 °C chemical decomposition of the structure takes place and first capillary micro cracks are observed. Material is able to sustain compressive stress until 600 °C. Between 600 °C and 800 °C strength is gradually lost due to the propagation of the cracks. However, sintering reaction developing approximately at 800 °C causes a sharp change in the structure and got the material lost 40% of its strength in the observed temperature range. Hot tested aerated concrete has relatively higher strength values between 200 and 600 °C.

(3) Water quenching reduces the compressive strength of the material. However, wet strength right after the quenching is lower than the dry strength. Thermal stress occurred by water quenching right after the high temperature exposure increases the surface cracks and water absorption ratio of the material with a subsequent loss in the strength. Besides, strength of the material gradually decreases as the temperature rises. While the wet strength of the material is approximately 35% of its initial strength, it is 75% when it is dry at 965 °C.

(4) As a result, based on the evaluations done in the context of this research, it can be concluded that if quenching effect would be disregarded, high temperature does not have a considerable effect on the strength of the material at approximately 700–800 °C. Above this level, the strength of the material is distinctively influenced. Splitting strength and MoE can give more accurate results regarding the micro structure of the material.

On the other hand, this material is generally used in a construction jointly with various mortars and in various details. So, fire effect is to be considered not just only on the material itself but on the building assemblies and the elements where aerated concrete is used as a whole. The results obtained in this study should be supported by the future studies which will define the temperature dependent stress/strain curves by considering the effect of quenching on the material properties. The influence of quenching on the reinforcing materials of reinforced aerated concrete elements would be an input to achieve a comprehensive result.

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