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Fire Endurance of Cellular Lightweight Concrete

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ABSTRACT

During their service life, structures may be subjected to several damage causes. Fire damage is considered one among of the excepted causes. Moreover, as material properties can change dramatically due to exposure to high temperature associated with fire, investigating their performance under fire is so important to assure the structure safety when subjected to fire.
Concrete shows generally better fire resisting characteristics when compared to the other construction materials due to its relatively low thermal conductivity, high heat capacity and slower strength degradation with temperature. On the other hand, cellular lightweight concrete (CLC) is considered one the novel types of concrete which is suitable and preferable for several construction applications due to its numerous advantages including thermal properties, lightweight, …etc.
The lack of the existing data about the fire endurance of CLC material led to the need of the current experimental investigation. So, this study is designed to investigate the performance of CLC mixtures with different densities under fire with several temperature levels as well as different duration of exposure. After exposure to high rise temperature, the residual compressive properties were investigated. The results revealed that the CLC mixtures show better residual compressive properties compared with those for traditional Portland cement concrete mixtures. Moreover, CLC mixtures with lower densities showed better residual compressive properties compared to mixtures with higher density values.

Keywords: Cellular lightweight concrete, fire endurance, thermal properties, residual strength, damage.

Introduction

Cellular lightweight concrete (CLC) is also called foamed concrete is a lightweight material consisting mainly of Portland cement paste or cement matrix (mortar) with a uniformly distributed pore structure produced by mechanically introducing air voids in the form of small bubbles created from a mixture of foam agent occupying a total volume of at least 20%. Mixture design of such type of concrete is flexible as it may be designed to give any target value for the density that is commonly ranged between 400 and1600 kg/m3 [1]. This kind of concrete is recognized for its enhanced characteristics. In its fresh state has a high flowability that makes it capable of filling the restricted and irregular sections. It can be also successfully pumped over significant heights and distances. On the other hand, CLC possesses several attractive hardened mechanical as well as physical properties. Lightweight density as well as excellent thermal insulation are examples of the advanced and benefit properties of such type of concrete [2]. Low density can help in reducing structural own weight, foundation size, labor, transportation as well as operating costs [3]

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Due to its properties, CLC is considered an economic solution in fabrication of lightweight large scale construction materials and components like structural members, partitions, filling grades and road embankment due to its easy production process from manufacturing plants to final position of applications [4, 5]. Moreover, it enhances the fire resistance, thermal conductivity and sound absorbance due to its textural surface and micro-structural cells [3]. The compressive strength of CLC was found to have a direct relationship with the density where a reduction in unit weight exponentially and adversely affects the compressive strength. .moreover, rate of foam agent, water to cement ratio, filler type and grading of particles, curing method, cement – filler ratio and characteristics of additional ingredients and their distribution are the factors that may affect the compressive strength of CLC [3,6].
The splitting tensile strength of CLC is lower than that of normal concrete. The splitting tensile strength as a ration of the compressive strength was reported for CLC as 0.2 to 0.4 which is higher compared with that for traditional concrete (0.08: 0.11) [3]. CLC durability may be defined as the ability of its resistance to withstand any external interface that may influence or cause deterioration and reduce the serviceability of CLC life span. The durability of CLC was studied in term of permeability that is the measure of the water to flow under pressure in a saturated porous medium [7]. For CLC, the water absorption is relatively higher than other types of concrete [8]. CLC show higher acoustic insulation resistance compared to traditional concrete due to its cell like structures [9].

Exposure to fire may be considered as a combination of the influence of fire flame as well as exposure to accompanying elevated heat temperature. As the CLC is not burnable material, so the influence of elevated heat temperature on both physical as well as the mechanical properties may be considered as the effect of fire on CLC. In this domain, limited studies were conducted to investigate the fire as one of the most severe condition that structures may be subjected to [10]. Fire performance of material is influenced by the characteristics of the material's thermal properties, mechanical properties, deformation properties and special characteristics of material in fire. Thermal properties influence the heat transfer in the structural element, whereas mechanical properties influence the strength and stiffness variation. Deformation properties together with mechanical properties influence the extent deformation and strains in the structural member [11]. The mechanical properties of CLC with various densities in elevated temperatures were investigated [12]. They have measured compressive strength, modulus of elasticity, compressive stress-strain relationship and flexural bending strength of foamed concrete with densities 650 kg/m^3 and 1000 kg/m^3. All the tests were conducted increasing the load while keeping the specimen at a constant elevated temperature (100 °C, 200 °C, 300 °C, up to 600 °C) and it was found that the compressive strength of foamed concrete decreases with temperature. However, up to 200 °C, foamed concrete is in a position to maintain 94% of original unheated strength. Whereas, at 400 °C. 75% and at 600 °C, only 40% of original strength was retained. Moreover, modulus of elasticity at 200 °C, 400 °C and 600 °C was respectively 75%, 40% and 25% of the original value [12].

Fire resistance of structural members is generally evaluated through standard fire tests [13]. However, due to high cost and time consumption for fire tests, numerical approaches and finite element modeling has been identified as an effective method of evaluating fire performance of structures [10]. These numerical models are developed considering the material properties at elevated temperatures. In the light of the above, it is clear that there is a need for identifying both of physical as well as the mechanical properties of CLC. This of course enables understanding the performance of such material when it is being subjected to fire. Data required for modeling such material under fire can also be collected. So this study aims at evaluating the residual performance of CLC after being exposed to different of fire levels as well as fire durations.

2. Research significance

As exposure of CLC to fire may influence of its performance where it is employed, this investigation intended to investigate and evaluate its physical and mechanical properties as affected by different levels of temperature and exposure durations. This enables safely proper implementation as well as modeling of such material in the corresponding situations.

3. Experimental program

3.1 Materials

3.1.1 Cement

Portland cement CEM I of grade 42.5 N was used in this investigation. 85 and 260 minutes were the initial and final setting times, respectively. The used cement is complied with the requirements of the Egyptian standard specifications ESS (4756-1/2013).

3.1.2. Filler

Fine quartz with specific gravity of 2.6 was used in this study. The grading of the used quartz is shown in Fig. (1).

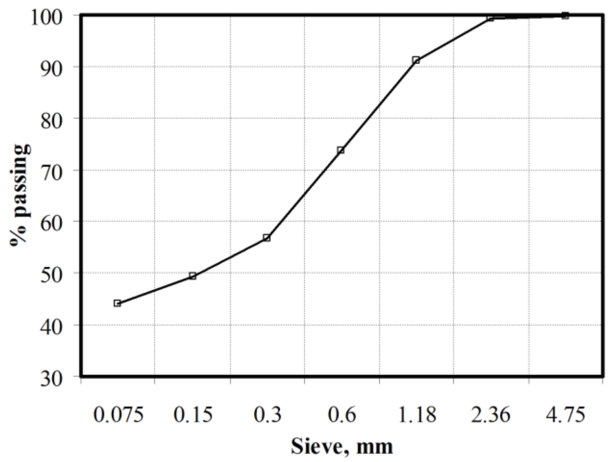

Fig. (1): Grading curve for the used filler

3.1.3. Water

Clean water from water supplier tap was used in this study for both mixing and curing CLC mixtures and samples.

3.1.4. Foam

A protein foaming agent with 1.07 g/cm^3 density at 20 °C in liquid state was used in this study. The foaming agent was diluted in water with a ratio of 1:40 by water volume to produce foam agent solution by passing it through a foam generator. The foam density needed to reach a range between 60 to 80 g/L before being mixed with other materials.

3.1.5. Fibers

Polypropylene of fiber of 670 aspect ratio, 18 microns diameter, 500 MPa tensile strength, 0.9 specific gravity and 165°C melting point (as per the data sheet of the product) with volume fraction of 0.05% was used.

3.2. Design of mixtures

Five CLC mixtures were proportioned with approaching the target of different densities. Each mix composed of solid part as well as the void part that is generated using foam agent. The solid part in this study composed of Portland cement (CEM I 42.5 N), filler (quartz) as well as water with weight ratios of 2:1:1. The constituents are given in Table (1).

3.2. Mixing, curing and testing

The materials to be charged into the mixing drum of the used mechanical mixer. The materials include cement, quartz and water are mixed for three minutes to achieve a homogonous mixture. Then the prepared foam to be pumped into the drum mixture until reaching the required volume as pre-designed mix. The mixing process continued until reaching a homogonous mixture. After that, the fresh unit weight was evaluated and then the mixture was cast in the proper forms. The cast CLC mixtures were cured by covering and keeping them moist for 28 days. After 28 days, cylindrical specimens of 100mm diameter and 200mm height were extracted using core cutting machine and were left for air drying. The corresponding specimens for each mix were weighted to determine unit weight and then they were subjected to elevated heat temperature of 200, 400 and 600°C for periods of 1 and 2 hours as per the parametric study. Moreover, the specimens were left for air cooling and then they were evaluated for the loss of weight and then for the residual compressive properties. The furnace used as well as the rate of heating used are presented in Figs. (2) and (3), respectively. The compressive test was conducted to evaluate the compressive behavior of the investigated mixtures according to ASTM C469. Test setup for compressive testing is presented in Fig.(4).

Table (1): Design proportions of the CLC mixtures

Mix No.	Wet density kg/m^3	Air dry density kg/m^3	Constituents*		
			Cement m^3/kg	Filler kg/m^3	Water kg/m^3
M1	**515**	**400**	**275.5**	**128.75**	**128.75**
M2	**626**	**500**	**313**	**156.5.**	**156.5**
M3	**737**	**600**	**368.5**	**184.25**	**184.25**
M4	**849**	**700**	**424.5**	**212.25**	**212.25**
M5	**960**	**800**	**480**	**240**	**240**

* The given materials compose the solid part and the rest is foam bubbles.

Fig. (2): An automatic electric furnace

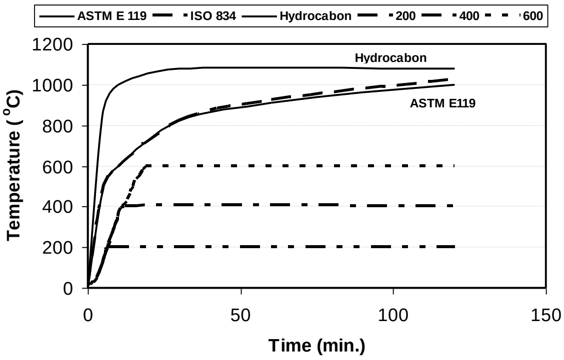

Fig. (3): Rates of the applied fire

a- layout for compressive test

b- CLC specimen

Fig. (4): Compressive test setup

4. Results and discussions

4.1. Physical properties

The effect of the elevated heat temperature was evaluated as a percentage of the residual unit weight a ratio. The residual unit weight is the balanced density to the initial one. The results are given in Table (2) and are presented on Fig. (5). It can be simply noticed that the unit weight reduced with the influence of elevated temperature. The reduction in the density firstly refers to the loss of pore water. Moreover, dehydration of the calcium hydroxide is essentially zero up to about 400°C and it increases most rapidly around 535°C and becomes complete at about 600°C [14] which is accompanied by much loss of unit weight. The gradual reduction in unit weight reached its heights value (0.85) with 2 hrs of exposure to 600 °C. Moreover, the residual unit weight is inversely proportional to the initial density as shown in Fig. (5). Fig. (6) shows the pore distribution inside CLC mixtures by the effect of the used foam agent (as per the target density). The total volume of the pores as well as its distribution plays an important role in the duty of such type of concrete. As increasing the total volume of the introduced bubbles with a uniformly distributed sizes, produces more stable mixtures as evaluated by the residual density.

Table (2): Results of the investigated CLC mixtures

Mix		M1	M2	M3	M4	M5
20°C	Unit weight, kg/m^3	800	700	600	500	400
	F_c MPa	2.88	2.54	1.8	0.83	0.54
	E_c MPa	1522.2	1173	978.9	528.4	366.08
200°C (1 hr.)	Residual unit weight%	0.94	0.942	0.95	0.97	0.98
	F_c MPa	2.95	2.92	2.1	1.03	0.79
	E_c MPa	1879.3	1357.8	1176	638.6	516.7
200°C (2 hr.)	Residual unit weight%	0.93	0.918	0.925	0.94	0.98
	F_c MPa	2.85	3.08	2.32	0.94	0.71
	E_c MPa	1382.4	1339.8	1067.2	564	461.5
400°C (1 hr.)	Residual unit weight%	0.924	0.925	0.93	0.95	0.94
	F_c MPa	2.32	2.49	2.05	0.84	0.64
	E_c MPa	1273.2	1140.4	1096.7	519.12	406.4
400°C (2 hr.)	Residual unit weight%	0.91	0.905	0.874	0.9	0.92
	F_c MPa	2.21	2.56	1.9	0.81	0.61
	E_c MPa	1177.9	1126.4	845.5	511.9	384.3
600°C (1 hr.)	Residual unit weight%	0.86	0.856	0.85	0.88	0.94
	F_c MPa	1.95	2.1	1.71	0.8	0.59
	E_c MPa	810.5	955.5	899.5	520	376.4
600°C (2 hr.)	Residual unit weight%	0.856	0.85	0.85	0.86	0.89
	F_c MPa	1.87	1.53	1.4	0.75	0.576
	E_c MPa	672.9	688,5	613.2	468.8	361.7

F_c = compressive strength MPa, E_c = Elastic modulus MPa

4.2. Mechanical properties

The response of the investigated CLC mixtures in compression at room temperature (20°C) is presented in Fig.(7). The relationship between compressive stress and the compressive strain takes a trend of a direct proportional in first stage (straight line) which indicates an elastic behavior. After reaching the ultimate stress, a descending behavior was recorded for the investigated specimens. The rate of the loss of stiffness depended mainly on the grade of the tested specimen. Lower grades show relatively higher degree of ductility. On the other hand specimens of higher grade (M1) show relatively to some what low ductility when compared to

other mixes. Generally the stress-strain relationships for the investigated CLC mixes proved the high level of dutility for such type of concrete. Moreover, the final failure pattern happened by compressibility and no crushing was observed due to its cell like structure.
The compressive strengths of the investigated mixtures are 2.88, 2.54, 1.8, 0.83 and 0.54 MPa for M_1, M_2, M_3, M_4 and M_5, respectively. It is clear that there a direct proportional relationship between the compressive strength and the unit weight as shown in Figs. (8 and 9).

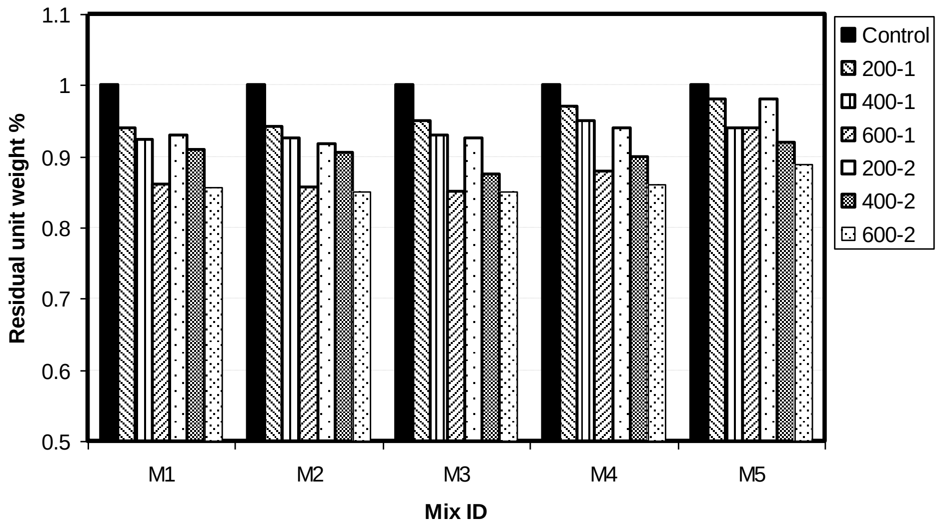

Fig. (5): Residual density ratio versus mix code after exposure

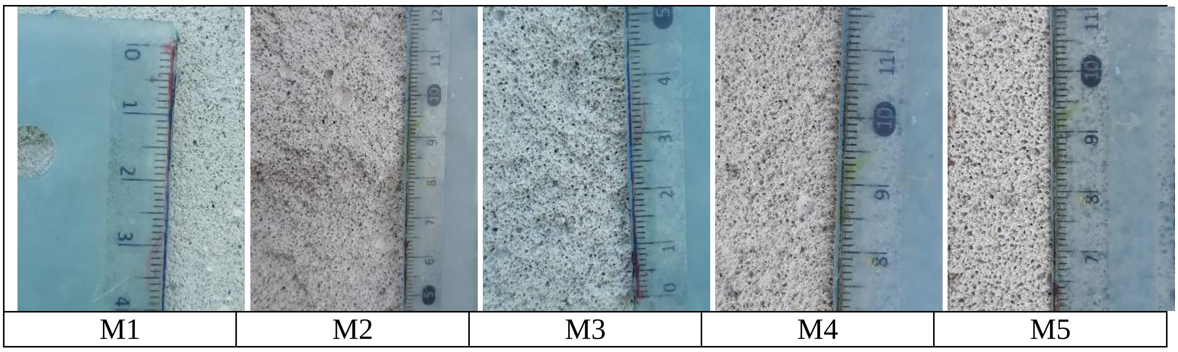

Fig. (6): Distribution of pores in cross section of the investigated CLC mixes

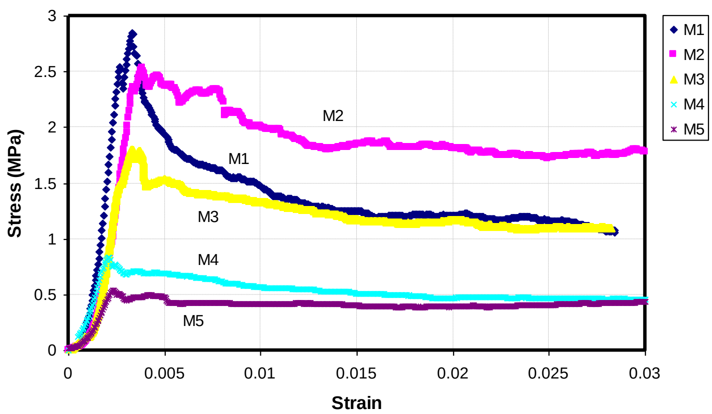

Fig.(7): Stress- strain under compression for the CLC mixes before exposure to fire

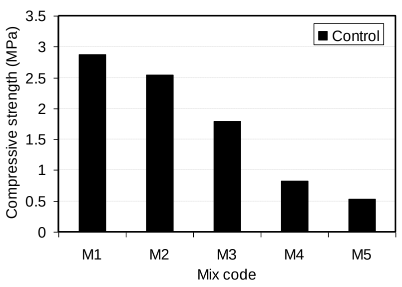

Fig. (8): Relationship between mix code and the compressive strength

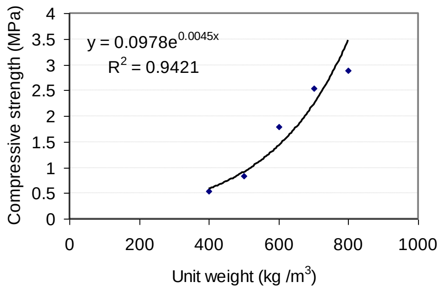

Fig. (9): Compressive strength versus unit weight for the investigated mixes

The mechanical properties of the investigated mixes as affected by exposure to different elevated temperature levels as well as different exposure periods are presented in Figs. (10 to 13). The influence of elevated temperature for one hour on stress- strain relationship for M_2 as an example is presented in Fig. (10). Up to 200°C, the specimens seemed to be more stiff due to the excess hydration of the rest cement particles at its inner parts approaching relatively higher strength values at 200°C. After approaching such strength, a relatively steep degradation was recorded (200-1) this may be due to loss of reinforcing action provided by fiber as they melt at 165 °C. Whereas, specimens exposed to temperature level higher than 200°C (400 and 600°C) showed small losses of compressive strength as well as reduction of the ductility due to the absence of the reinforcing action. Moreover, considering the extending of the exposure time into two hours, the stress-strain relationships of the conducted specimens was affected as stated before for one hour but with different level as shown in Fig, (11).

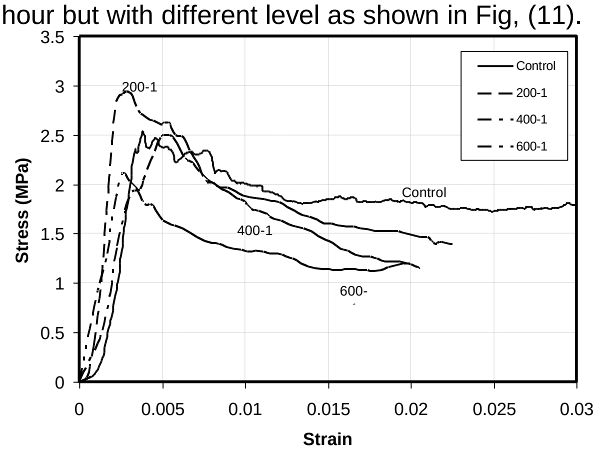

Fig.(10) : Stress – stain relationship for CLC after exposed to fire for 1 hr. (M_2)

To evaluate the fire endurance of the investigated CLC specimens, both of the residual compressive strength as well as the residual elastic modulus of elasticity of the investigated mixtures are calculated and plotted on Figs. (12 and 13). The residual compressive strength is the ratio between the compressive strength after exposure and the corresponding one at room temperature (20°C).

The residual compressive strength values for the conducted mixtures are presented in Table (2) and in Fig. (12). It is clear that the residual compressive strength reduces with the increase of the exposure time as well as the temperature level.

The residual compressive strength ranges between 0.94 and 0.856 for M1 when it is exposed to 200°C for one hour and 600°C, respectively. On the other hand, the values for M2 range between 0.94 and 0.85 for the same exposure conditions, respectively. Moreover, for M3, the residual compressive strengths are 0.95 and 0.85 for the extreme exposure conditions, respectively. 0.97 and 0.86 are the residual compressive strengths for M4 for extreme exposure conditions, respectively. Whereas, for M5, the residual compressive strengths are 0.98 and 0.89 for the extreme exposure conditions, respectively

The residual compressive strength approaches about 0.85 for the investigated CLC mixtures compared to about (0.4 to 0.5) for Portland cement concrete with siliceous and limestone aggregate at 600° C [15]. Moreover, the elastic modulus of the investigated CLC mixtures was evaluated after exposure to different levels of temperatures as well as different durations of exposure to fire. The values for the elastic modulus of elasticity are calculated and compared. It is noted that the same trend recorded previously for the residual compressive strength with the influence of the exposure factors is also noticed for the elastic modulus of elasticity (Ec) as given in Table (2) and Fig. (13). For M1, Ec values are 1522.2 (at 20°C) and 1879.3, 1273.2, 810.5 MPa for one hour (at 200, 400, 600°C) and 1382.4, 1177.9, 672.9 MPa for two hours (at 200, 400, 600°C), respectively. It is clear that an increase in the modulus of elasticity was recorded when M1 was exposed to 200°C whereas, after that the stiffness reduced. The same trend was recorded with other conducted mixtures as shown in Fig. (13). Generally, CLC mixtures of relatively lower strength show higher residual elastic modus values (M5) compared with the mixes having a relatively higher strength grade (M1). The residual elastic modulus of elasticity is above 0.77 for the investigated mixes compared to about 0.35 for traditional Portland cement concrete at 400°C [15].

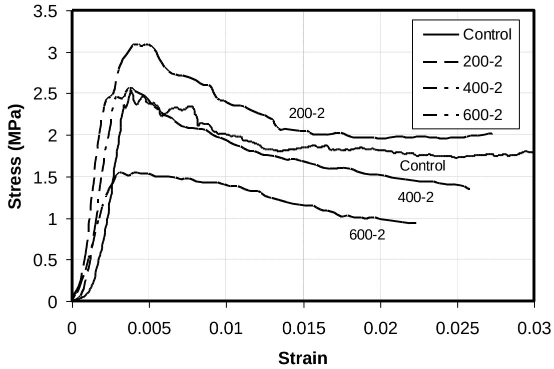

Fig.(11): Stress–stain relationship for CLC after exposed to fire for 2 hrs. (M_2)

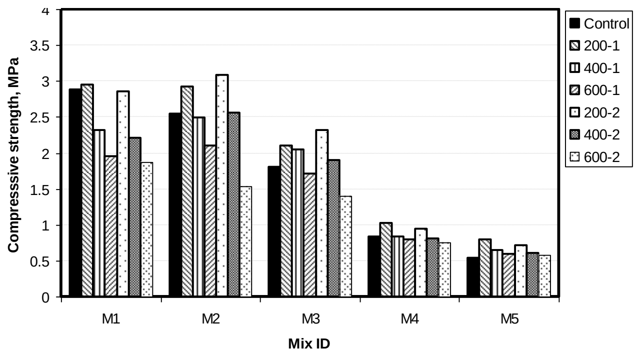

Fig. (12): Compressive strength versus mix code after exposure to elevated temperature

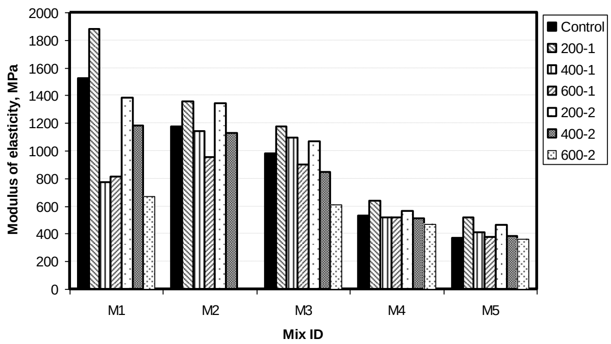

Fig. (13): Modulus of elasticity versus mix code after exposure to elevated temperature

5. Conclusions and recommendations

This study was intended to investigate the fire endurance of five different CLC mixtures with different densities after being exposed to different levels of temperatures as well as for different periods of exposure. Based on the current experimental study, the following conclusions can be extracted;

- Cellular lightweight concrete (CLC) material can be produced with the target unit weight and consequently the mechanical properties will be a function of its density. Moreover such type of concrete show high level of ductility.
- The mechanical properties of CLC enhanced remarkably when it is exposed to high rise temperature up to 200°C due to the hydration of the rest cement particles at its inner part.
- Due to its cellular structure nature, CLC shows high level of fire endurance as measured by residual compressive strength. The residual compressive strength approaches 0.85 compared with 0.4 for traditional Portland cement concrete after exposure to 600°C for two hours.
- CLC show enhanced performance after exposure to fire as evaluated by elastic modulus of elasticity as the residual of 0.77 is achieved for this type of concrete compared to 0.35 for traditional Portland cement concrete after exposure to 400°C for two hours.
- As the unit weight reduces, the fire endurance of such type of concrete enhanced remarkably as evaluated by the loss of unit weight, residual compressive strength, residual elastic modulus of elasticity and ductility.

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References

[1] Md Azree Othuman Mydin and Y.C. Wang, (2012), "Mechanical properties of foamed concrete exposed to high temperatures", Construction and Building Materials 26, 638–654.

[2] T. Richard, J. Dobogai, T. Gerhardt, and W. Young, (1975), " Cellular concrete - A potential load-bearing insulation for cryogenic applications?", IEEE Transactions on Magnetics (Volume: 11, Issue: 2, pp. 500 – 503.

[3] Y.H. MugahedAmran, NimaFarzadnia and A.A.Abang Ali, (2015), " Properties and applications of foamed concrete; a review", Construction and Building Materials, Volume 101, Part 1, 30, Pages 990-1005.

[4] K.Ramamurthy, E.K.Kunhanandan Nambiar and G.Indu Siva Ranjani,(2009), "A classification of studies on properties of foam concrete", Cement and Concrete Composites, Volume 31, Issue 6, Pages 388-396.

[5] Alexander Tarasov, Elsabé Kearsley, A.S. Kolomatskiy and Derek Mostert,(2010), " Heat evolution due to cement hydration in foamed concrete", Magazine of Concrete Research 62(12):895 – 906.

[6] R. C. Valore, Jr. (1954)," Cellular Concretes Part 2 Physical Properties", ACI J. proc. 50 (6), pp. 817-836.

[7] B. B. Sabir, S. Wild and M. O'Farrell, (1998), "A water sorptivity test for mortar and concrete", Materials and Structures Vol. 31, pp 568-574.

[8] L. COX and S. VAN DIJK, (2002), " Foam Concrete: A Different Kind of Mix", the Concrete Society, Volume: 36, Number: 2, pp. 54-55.

[9] N.Narayanan and K.Ramamurthy, (2000), " Structure and properties of aerated concrete: a review", Cement and Concrete Composites, Volume 22, Issue 5, Pages 321-329.

[10] Venkatesh Kodur,(2014), "Properties of Concrete at Elevated Temperatures", ISRN Civil Engineering, Hindawi Publishing Corporation, Volume 2014, Article ID 468510, 15 pages.

[11] Dwaikatand MB, Kodur VKR (2010), "Fire induced spalling in high strength concrete beams", Fire Technol 46(1):251–274

[12] Mydin M, Wang Y (2011)" Mechanical properties of foamed concrete exposed to high temperatures", Constr Build Mater 26(1):638–654

[13] Standard test methods for fire tests of building construction and materials (2008) ASTM E119-08b, ASTM International, West Conshohocken, PA, USA.

[14] Harmathy T. Z., (1970) “Thermal Properties of Concrete at Elevated Temperatures,” J. of Materials 5, 47–74.

[15] M. S. Shetty, (2013), Concrete Technology (Theory and Practice), s. chand & company pvt. ltd.