Effect of High Temperature on Compressive Strength of Structural Lightweight and Normal Weight Concretes

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الخلاصة

يتضمن البحث دراسة تأثير درجات الحرارة العالية والتي تصل إلى 600 درجة مئوية على خرسانة إنشائية خفيفة الوزن و خرسانة اعتيادية الوزن . صـممت الخلطـة الخرسـانية الخفيفـة الـوزن تبعـا لـ ACI committee211-2-82 حيث كانت نسب الخلط ألحجميه 1:1.12:3.35 ونسبة الماء إلى الإسمنت الوزنيـة 0.5 ومحتوى الإسمنت 550 كغم/م3.نسب خلط الخرسانة الاعتيادية الوزنية كانـت 1:2:3 وبمحتـوى اسـمنت 400 كغم/م3 وبنفس نسبة الماء إلى الاسمنت. مقاومة الانضغاط للخرسانة الاعتيادية والإنشائية خفيفة الوزن بعمر 28 يوم 35.4 و 22.62 نت/ملم2 على التوالي.

أجريت فحوصات مقاومة الانضغاط الخرسانة الاعتيادية الوزن على مكعبات خرسانية بأبعاد100 ملم تحت درجـات الحرارة العالية 400,200,100 و 600 درجة مئوية وذلك برفع درجة حرارة الفرن إلى الدرجة المطلوبة ومن ثـم تعريض النماذج للحرارة لمدة 10 دقائق و فحصها مباشرة أما الخرسانة الخفيفة الوزن فقد فحصت وفق الطريقـة أعلاه إضافة إلى فحصها من خلال التعرض التدريجي للحرارة لحين الوصول إلى الدرجة المطلوبة بتجفيف وبـدون تجفيف لمعرفة مدى تأثير المحتوى الرطوبي .

أشارت النتائج إلى أن الخرسانة الإنشائية خفيفة الوزن أبدت فقدانا مشابها في مقاومة انضـغاطها عنـد التعـرض التدريجي للحرارة حيث كان الفقدان في مقاومة الانضغاط عند 600 درجة مئوية بعمر 28 يوم 30 % مقارنة بـ 28 % للخرسانة الاعتيادية الوزن. أما الأولى فقد أبدت فقدانا أعلى في مقاومة الانضغاط وفي كـل الـدرجات الحرارية عند التعرض المباشر لدرجات الحرارة العالية و بلغ أعظم فقدان 64.4 % عند 600 مئوي.كمـا كـان لتجفيف النماذج بالنسبة للخرسانة الخفيفة الوزن قبل التعرض للحرارة اثر كبير في تقليل الفقـدان فـي مقاومـة الانضغاط عند التعرض التدريجي للحرارة العالية.

Abstract:

This research studies the effect of high temperature which is reached to 600 °C on structural lightweight and normal weight concrete. Lightweight concrete mix designed according to ACI committee 211-2-82 with mix proportion 1:1.12 :3.35 by volume .The w\c ratio equal to 0.5 by weight and cement content 550 kg\m3. Mix proportions of normal weight concrete were 1:2:3 by weight with cement content 400 kg\m3 and same w\c. The design compressive strength at 28 days of normal weight concrete (NWC) and lightweight concrete (LWC) were 34.7 MPa and 22.62 MPa respectively. Compressive strength tests were performed on 100 mm cubes exposed to high temperature 100,200,400 and 600 °C. The normal weight concrete and light weight concrete test specimens were exposed to high temperature for 10 minute suddenly at the required degree. Moreover, light weight concrete test specimens tested after graduate exposure to high temperature reaching to the required degree with and without drying to examine the effect of moisture content.

The results indicated that the structural lightweight concrete exhibits approximately similar compressive strength loss compared to normal weight concrete up to 600 °C at 28 days in graduate exposure .The percentage of reduction on compressive strength was 30% in lightweight concrete compared to 28% in normal weight concrete at 600 °C .In sudden exposure to high temperature ,the opposite behavior was noticed .The percentage of reduction on compressive strength was 64.4% in lightweight concrete at 600°C . Drying of lightweight concrete specimens before graduate exposure to high temperatures significantly reduce the loss of compressive strength.

1- Introduction

Concrete is a low conductor which exhibits high resistance to temperature transients. However, extreme and rapid heating from fire can cause large volume changes due to thermal dilatation, shrinkage due to moisture migration, and eventual spalling due to high thermal stresses and pore pressure build-up. The large volume change produces stresses that result in microcracking and large fractures which may lead to structural failure. The extent of the concrete property variation due to high temperature depends on many internal and external parameters, such as concrete mix design, properties of the constituents, heating rate, cooling rate, maximum exposed temperature, etc[1]. In recent years progress has been made toward the development of rational methods for calculating the behavior of concrete structures subjected to fire or to other high-temperature exposure conditions.

The action of fire in concrete has been considered in different studies of structural analysis due to the reduction strength caused by high temperatures .

Malhotra (1956), Zoldners (1960), Davis (1967), Abrams (1971), Faiyadh (1989), Khoury (1992), and Noumowe et. al. (1994) had reported the effects of high temperature exposure on the properties of concrete. Several mechanisms have been identified for the deterioration of concrete due to high temperatures. These include decomposition of the calcium hydroxide into lime and water, expansion of lime on re-hydration, destruction of gel structure, phase transformation in some types of aggregate, and development of micro-cracks due to thermal incompatibility between cement paste matrix and aggregate phase. [2]

Degradation of mechanical properties of concrete due to short-term exposure to elevated temperature has been studied as early as the 1950s. Among the early studies were those of Abrams, Malhotra and Schneider . Results of these studies constituted the technical basis for the provisions and recommendations for determining concrete strength at elevated temperature in many existing codes. While these studies provided valuable information on concrete strength as a function of temperatures, almost all used specimens made with normal strength concrete (Fc ≤ 40 MPa). Thus, in light of the results of recent studies, which have shown that high-strength concrete (HSC) behavior at elevated temperature may be significantly different from that of NSC [3] .

As sited by Kodur [4] the results of fire tests Diederichs et al. 1995, Phan 1996, Kodur and Sultan 1998 have shown that there are well-defined differences between the properties of HSC and NSC at high temperatures. Further, concern has developed regarding the occurrence of explosive spalling when HSC is subjected to rapid heating, as in the case of a fire Diederichs et al. 1995 and Phan 1996.

2- Objective of the Research

This study has investigated the residual compressive strength of concrete subjected to high temperature .Various factors that may have contributed to the alteration of compressive strength in heated concrete have been identified .Two types of concrete were used in this study ,normal weight and light weight concrete .The main objective of this investigation was to study the effect of transient high temperature on compressive strength of lightweight concrete and compare the behavior with that of normal weight concrete. The test specimens were subjected to temperatures ranging from 100 to 600 °C and their behavior compared to that observed at room temperature.

3-<u>Effects of ingredients on behavior of concrete under high</u>

Temperatures

Reference [5] summarized the effect of ingredients on behavior of concrete under high temperatures as follow:-

CEMENT: Preliminary studies indicate that the amount of calcium hydroxide in concrete is of great importance in the resistance to high temperatures. Cements which release the least amounts of calcium hydroxide during hydration and hardening of the concrete are certainly to be favored. For this reason slag cement or Portland blast furnace slag cement are sometimes specified for this type of work.

AGGREGATES: Studies of concrete heated to high temperature indicate that the type of aggregate employed is critical. Nevertheless no standard specifications have been developed to define the aggregate properties desired for high temperature exposure. It seems obvious that aggregates with low coefficients of thermal expansion in the range of temperatures that the concrete is expected to experience would be preferable to those with high coefficients. Studies indicate that lightweight aggregates, especially those manufactured in high temperature kilns or furnaces, exhibit greater dimensional stability under heat.

WATER: The effect of quality of water used in concrete has not been studied in relation to performance of concrete under high temperatures. However it is assumed that the relationship would not extend beyond the effect of water quality on strength of the concrete at room temperature and therefore the plateau of strength from which reductions occur as the temperature is raised. The study reported in the August 1956 Magazine of Concrete Research indicated that the effect of temperature on the compressive strength is independent of the water/cement ratio within the range normally used in concrete.

4-<u>Factors affecting fire performance of concrete structures</u>

The factors related to spalling-damage in concrete structures can be summarized as follows [1] :-

Concrete strength: While it is difficult to specify the exact strength range, based on the available information, concrete strengths higher than 55 MPa are more susceptible to spalling and may result in lower fire resistance.

Moisture Content: The moisture content, expressed in terms of relative humidity, RH, influences the extent of spalling. Higher RH levels lead to greater regions of spalling. Fire-resistance tests on full scale HSC columns have shown that significant spalling occurs when the RH is higher than 80 percent. The time required to attain an acceptable RH level (below 75 percent) in HSC structural members is longer than that required for NSC structural members because of the low permeability of HSC.

Type of Aggregate: For the two commonly used aggregates, carbonate mineral aggregate (predominantly limestone) provides higher fire resistance and better spalling resistance than siliceous mineral aggregate (predominantly quartz). This is mainly because carbonate aggregate has a substantially higher heat capacity (specific heat), which is beneficial in preventing spalling.

Concrete Density: The extent of spalling of structural members made with lightweight aggregate is much greater than concrete made of normal-weight aggregate. This is mainly because lightweight aggregate contains more free moisture, which creates higher vapor pressure under fire exposures.

Fire Intensity: High heating rates are critical for the occurrence of spalling. Spalling of HSC is much more severe than NSC under the same heating rate.

Specimen Dimensions: The risk of explosive thermal spalling increases with increasing specimen size. This is due to the fact that the size is directly related to the heat and moisture transport through the structural member. Larger members can store more energy. Therefore, careful consideration must be given to the size of structural members when evaluating spalling; fire tests are often conducted on small-scale specimens, which may provide misleading non-conservative results.

Lateral Reinforcement: The spacing and configuration of ties have significant effects on the performance of HSC columns. Both closer tie spacing (at 0.75 times that required for NSC columns)

Load Intensity: A HSC structural member loaded in compression will spall to a greater degree than an unloaded member because the mechanical stress adds to the thermal stresses, 59-60

The compressive strength of concrete at high temperature is largely affected by the following factors: 1) Individual constituent of concrete, 2) Sealing/moisture condition, 3) Loading level during heating period, 4) Testing under 'hot' or 'cold residual' conditions, 5) Rate of heating or cooling, 6) Duration at constant temperature, 7) Time maintained in moist conditions after cooling before the test is carried out, and 8) Number of thermal cycles. With the growth of engineering structures, applications of structural lightweight concrete are increased day by day. Therefore, questions about the performance of structural lightweight concrete at high temperature need to examined. Influence of high temperature on characteristics of concrete is still toppical because properties of concrete aren't good known. Properties of concrete, especially compressive strength are major for design concrete and reinforced concrete. Strengthening of (concrete) structures has become more and more important due to the more rapidly changing demands on our buildings. To be able to predict the response of structures employing lightweight concrete after exposure to high temperature, it is essential that the strength properties of lightweight concrete subjected to high temperatures be clearly understood.

5- Experimental Work:

5-1 Materials

5-1-1 Cement

Sulfate resistance Portland cement produced by Turab alsbia company (Lebanese cement) was used throughout this study. Physical properties of used cement are listed in Table (1).The results are conformed to the Iraqi specification No.5 1984 [6].

Table (1) Physical properties of used cement .

Property	**Result**	**Limits of I.O.S No.5 1984**
Water cement ratio (standard cement paste)	0.36	----
Initial setting (Vicat) min.	110	≥ 45
Final setting (Vicat) hr:min	3:50	≤ 10
Fineness (Blaine method) cm2/gm	3190	≥ 2300
Soundness autoclave, %	0.18	≤ 0.8
Compressive strength (MPa) 3-day 7-day	 17.6 23.5	 ≥15 ≥23

5-1-2 Fine aggregate

A normal weight sand from Al_bokirbeet quarry of 4.75 mm maximum size was used for both lightweight and normal weight concrete. Specific gravity of sand was 2.65 with absorption 0.5%.The sulfate content as SO_3 % equal to 0.18% .Table(2) shows the grading of used fine aggregate .The grading was conformed to the limits of Iraqi specifications No.45 1984[7].

Table (2) Sieve analysis of fine aggregate

Sieve size mm	% passing	Limits of (I.O.S) NO.45\1984
4.75	100	90-100
2.36	92.1	85-100
1.18	82	75-100
0.6	64.8	60-79
0.3	21	12-40
0.15	7.15	0-10

5-1-3 Coarse lightweight and normal weight aggregates

A normal weight coarse aggregate from Al_Nibaai quarry of 9.5 mm maximum size and 2.6 specific gravity was used for producing normal weight concrete. Table (3) show the grading of used normal weight coarse aggregate. A crushed bricks were used as coarse lightweight aggregates in structural lightweight concrete .The bricks pieces which are considered as waste materials were crushed into smaller sizes by means of crusher machine .Table 4 and 5 show the grading and physical properties of coarse LWA respectively .The grading was confirmed to ASTM C330 [8] for structural LWA .The lightweight aggregate used in a saturated surface dry (SSD) condition recommended by ACI 211-2-82 [9] after submerged in water for 1 hour and spread in laboratory until obtaining saturated surface dry aggregates .

Table(3): Grading of normal coarse aggregate

Sieve size mm	Selected Grading	Limits of ASTM C330[8]
12.5	100	100
9.5	85	80-100
4.75	30	5-40
2.36	2.5	0-20
1.18	0	0-10

Table (4) Physical properties of lightweight aggregate

Sieve size mm	Test results	Limits of I.O.S No.45:1999[10]
14	100	100
10	96	95-100
5	15	0-25
2.36	2	0-5
1.18	0	0

Table (5) Grading of lightweight aggregate

Sieve size mm	Selected Grading	Limits of ASTM C330[8]
12.5	100	100
9.5	85	80-100
4.75	30	5-40
2.36	2.5	0-20
1.18	0	0-10

5-1-4 Water

Potable water was used in all mixes and curing.

5-2 Mixing of concrete

A pan mixer of 0.1% m3 capacity was used to mix the concrete ingredients .The mixer was firstly cleaned from the remaining lumps of concrete .The dry mixed ingredients were placed in the pan mixer and they were mixed for 2 minutes to ensure the homogeneity and to split the agglomerations of cement particle .The required quality of water was added to the mix and the whole constitutes were mixed for 3 minutes .

5-3 Preparation ,casting, curing and types of the test specimens

Steel molds of 100X100X100 mm were used for casting tested specimens .Before casting the molds were cleaned and oiled to avoid the adhesion of hardened concrete to the inside faces of molds. The fresh lightweight and normal weight concrete were placed inside the molds with approximately equal layers of 50 mm and consolidated by the mean of vibrating table for a sufficient period .Care was taken to avoid segregation of LWA because the lightest particles of LWA tend to float on the surface of concrete causing segregation of the mix consistent .After casting ,the concrete surface was leveled and covered with nylon sheets to prevent evaporation of water so as to avoid the plastic shrinkage cracks. On the second day the specimens were demolded ,marked and immersed in tap water until the test age.

6-4- Testing Program

6-4-1 Slump test

The test was performed for both lightweight and normal weight concretes according to ASTM C143a [11].

6-4-2 Fresh and hardened unit weights of lightweight concrete

The test was performed according to ASTM C 567-85 [12].

Note : The above tests in addition to compressive strength test at 28 days were conducted to achieve the requirements for SLWC in ASTM C330 [8]

6-4-3 Compressive strength test without exposure to high temperature

The test was conducted on 100 mm cube according to BS 1881 part 116 :1989 [13] .The test was performed at ages 7,14 and 28 days .The recorded value represents an average of three readings measured on three specimens.

6-4-3 Compressive strength test with exposure to high temperature

The test was performed at ages 14 and 28 days on same specimens .There are two types of exposure the first , by raising the kiln temperature to the elevated temperatures, then, the normal weight concrete and light weight concrete test specimens were exposed to high temperature for 10 minute suddenly. Second, lightweight concrete test specimens tested after graduated exposure to high temperature reaching to elevated temperatures with and without drying. The test was conducted immediately after the test specimens were extracted from the kiln.

7-1- <u>Results and Discussion</u>

7-1-1 Compressive strength test without exposure to high temperature

The results of compressive strength of SLWC and NWC at 7,14and 28 days are shown in Fig(1) .From these results the following notes are observed :

- The LWC is confirmed to the requirements of SLWC in ASTM C330 [8]where it had 22.62 MPa compressive strength and dry unit weight less than 1845 kg\m3 at 28days.

- SLWC and NWC, generally exhibited continuous strength gain .This is, generally, attributed to the continuous formation of hydration products during the curing period.

- The design compressive strength at 28 day of NWC and LWC were 34.7 MPa, 22.62 MPa respectively.

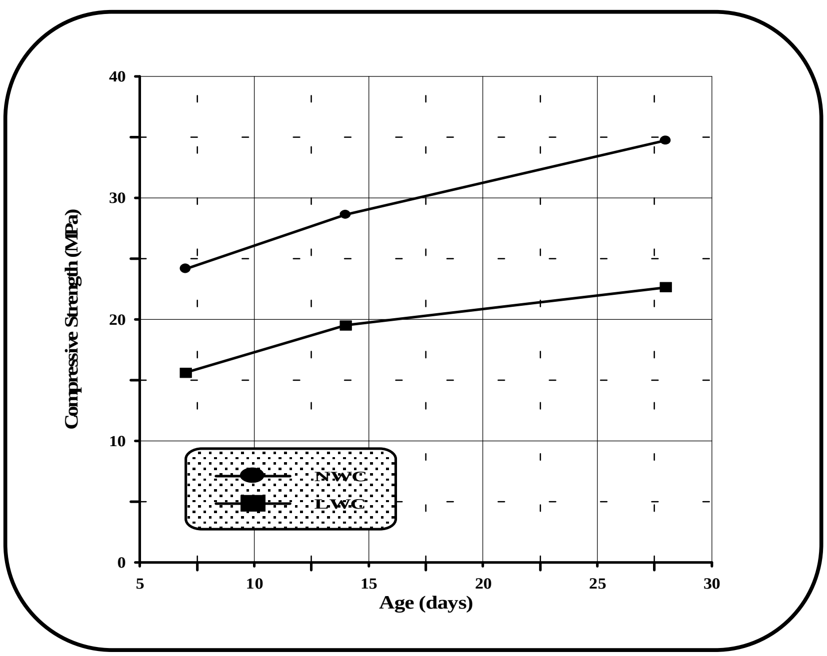

Fig. (1)Development of compressive strength of SLWC and NWC

7-1-2 Compressive strength test with exposure to high temperature

Fig (2) presents the relation between compressive strength and high temperatures of SLWC and NWC at 28 days. It is clear from the Fig. that there was, generally, continues loss of compressive strength with increasing of temperature .In sudden exposure to high temperatures, the compressive strength of NWC increased about 12.4% at 100 °C corresponding to the room temperature. The SLWC showed a 30 % loss of compressive strength corresponding to the compressive strength at room temperature, this may be attributed to the vapor pressure due to the ability of the lightweight aggregates to act like water reservoirs for vaporable water. The increased moisture content will have a negative influence on the fire resistance .Many researchers are stated several factors which are assumed to influence the sapling of the concrete during a fire. As sited by Lindgard and Hammer [14] , the main causes of spalling are suggested to be :-

- vapour pressure dependent on the moisture content and the permeability
- moisture glogging of capillary pores
- initial compressive stresses in the exposed layer.

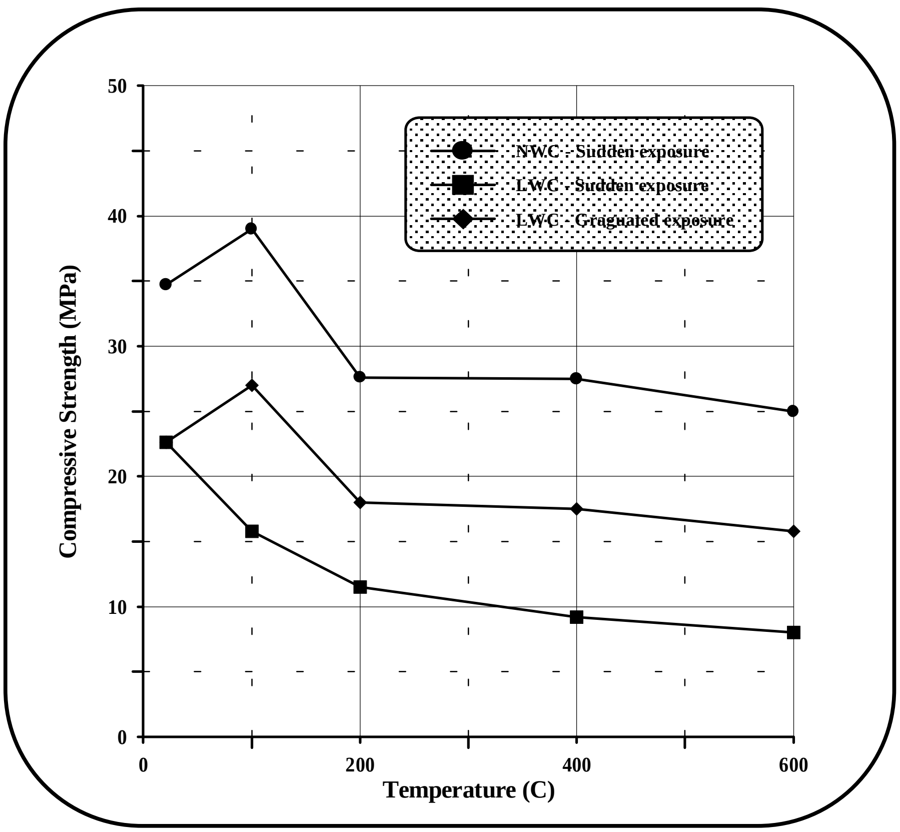

Fig. (2) Compressive strength-temperature relationships of SLWC and NWC under high temperature at 28 day

Compressive strength-temperature relationships of SLWC under graduated high temperature at 14 and 28 days are illustrated in Fig.3 .This Fig. shows the effect of high temperature on compressive strength of SLWC with the age. Its clearly that SLWC specimens showed higher percentage of reduction in compressive strength at 14 day corresponding to 28 day. The maximum percentages of reduction of compressive strength at 14 and 28 days were 50.2 % and 37.2 % respectively at 600 °C.

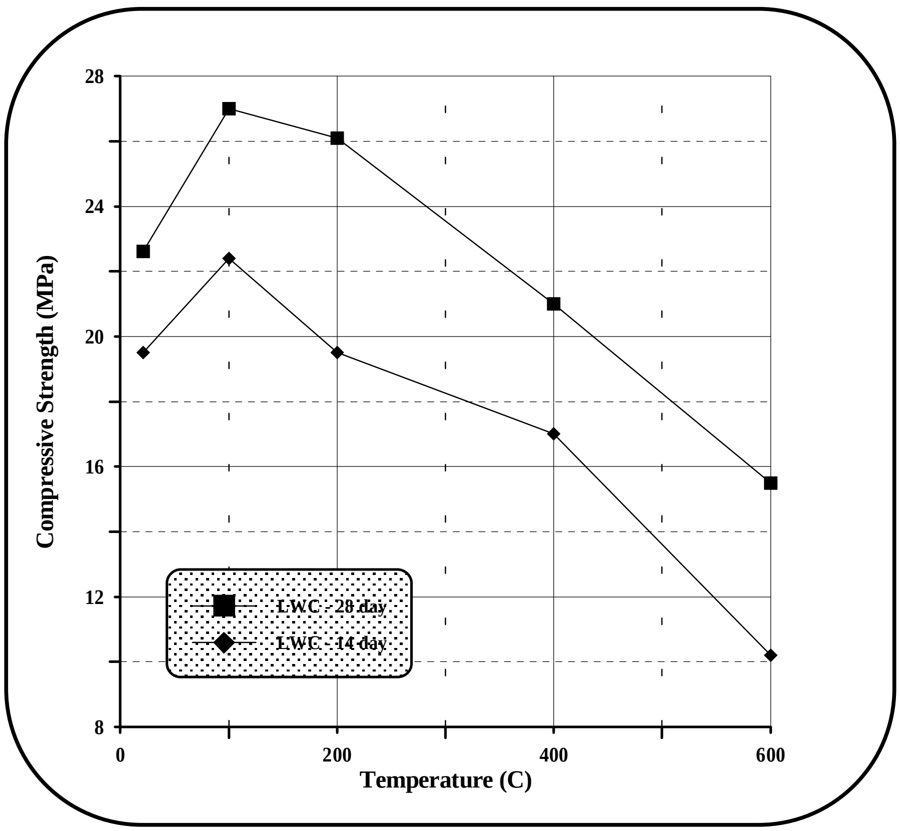

Fig. (3) Compressive strength-temperature relationships of SLWC under high temperature

Fig. 4 shows the effect of moisture content on Compressive strength-temperature relationships of SLWC at 28 days**.** It can be noticed that SLWC specimens without drying show significant reduction in compressive strength after 200 °C.This is mainly attributed to the vapor pressure due to the high moisture content. There are several theories explaining the spalling mechanisms, which may be classified in three categories: (a) pore pressure spalling, (b) thermal stress spalling, and (c) combined pore pressure and thermal stress spalling. High temperature causes the evaporation of free water near the concrete surface. The high vapor pressure in the surface layer drives the water vapor to diffuse in two opposite directions: to the surface and into the deeper part of the concrete specimen [1] .

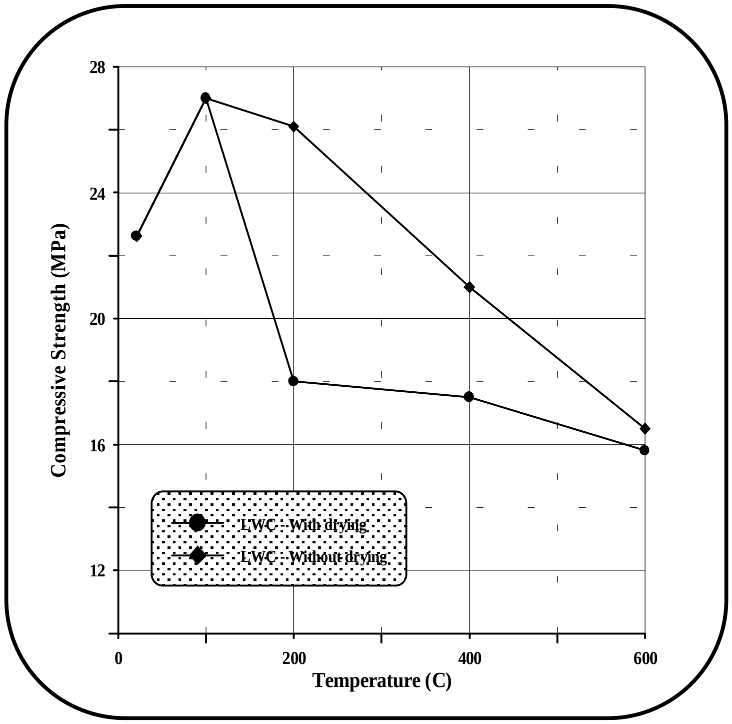

Fig. (4) Effect of moisture content on Compressive strength-temperature relationships of SLWC at 28 day

The relation between relative compressive strength (%) and high temperature is shown in Fig.5 **.** From this Fig., it appears that SLWC under graduate exposure to high temperature exhibits approximately the same behavior of NWC . If no spalling occurs, LWAC structures have potentially higher fire resistance than NWC structures, due to the lower heat conductivity of the LWAC [14]. In sudden exposure to high temperatures, the SLWC exhibits higher compressive strength loss corresponding to NWC at all degrees of high temperatures tested in present study.

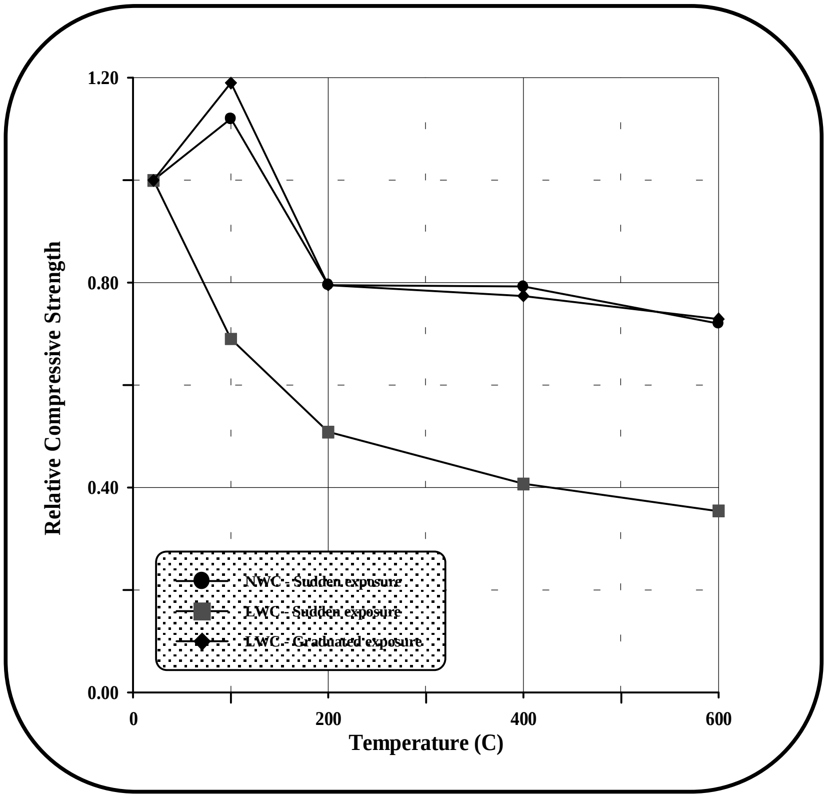

Fig. (5)Relative Compressive strength-temperature relationships of SLWC and NWC at 28 day

Conclusions

Based on the results of present study the following conclusions can be drawn :

1- The design compressive strength at 28 days of NWC and LWC were 34.7 MPa, 22.62 MPa respectively.

2- In sudden exposure to high temperatures, the compressive strength of NWC increased about 12.4% at 100 °C corresponding to the room temperature. The SLWC showed a 30 % loss of compressive strength corresponding to the room temperature. Moreover, the SLWC exhibits higher compressive strength loss with the increase of high temperatures corresponding to NWC.

3- In graduate exposure, the trend of SLWC to lose compressive strength similar to that of NWC. At 600 °C.SLWC compressive strength dropped to about 30% of the room temperature strength whereas the NWC showed a 28% loss of compressive strength.

4- At 600 °C , the maximum reduction in compressive strength of SLWC were 50.2 % and 37.2 % at 14 and 28 days respectively.

5- Drying of lightweight concrete specimens before graduate exposure to high temperature significantly reduce the loss of compressive strength .

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