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Effects of elevated temperature on compressive strength and weight loss of the light-weight concrete with silica fume and superplasticizer

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Abstract

In this study, structural light-weight concretes produced by Pumice (LWC) and concretes with normal-weight aggregate (NWC) were investigated. Compressive strength and weight loss of the concretes were determined after being exposed to high temperatures (20, 100, 400, 800, 1000 °C). To achieve these objectives, 12 different types of concrete mixtures were produced. In producing the mixtures, silica fume (SF) was used to replace the Portland cement in the ratios of 0%, 5% and 10% by weight. Half of the mixtures were obtained by adding superplasticizers (SP) to the above mixtures in the ratio of 2% by weight. In conclusion; unit weight of LWC was 23% lower than that of NWC. The LWC containing 2% SP could retain 38% of the initial compressive strength. Rate of deterioration was higher in NWC when compared to LWC. The loss of compressive strengths increased depending on the ratio of using SF at about 800 °C and over.

Keywords: Light-weight concrete; Pumice; High temperature; Silica fume

1. Introduction

It is a well-known fact that coefficient of thermal expansion values of concrete ingredients (cement paste and aggregates) are different from each other. Therefore, temperature changes in concrete cause differential volume changes in the ingredients, and these results in cracking and lower durability. This concept is known as the ‘‘thermal inconsistency of the ingredients’’ [1–3].

Neville [4] pointed out that at temperatures approximately above 430 °C, concretes with siliceous aggregates show significant strength loss when compared to those with light-weight aggregates. At 600 °C, concrete can loose half of its strength. Above 800 °C, loss of the bound water in the hydrates may cause a strength loss of even 80%, which may lead to the failure of a structure. In this case, the difference between the strength loss in normal-weight concretes (NWC) and light-weight concretes (LWC) ceases.

In another research [5], fire resistance of light-weight concretes having 500–1600 kg/m^3 unit weight was investigated and it was found that an increase in unit weight resulted in reductions in the fire resistance of the concretes. Previous studies showed that increasing moisture content increases the coefficient of thermal conductivity of concretes up to 100 °C, but decreases it at higher temperatures.

Turker et al. [6] investigated the micro-structure and strength of the concretes exposed to fire. In this study, mortars containing ordinary portland cement and three aggregate types were subjected to 100, 250, 500, 700 and 850 °C for 4 h. Unlike the mortars with quartz and limestone, at high temperatures, cracking was observed in the aggregate itself for the mortars with pumice instead of crack propagation at the interface. Therefore, it was concluded that the interface was strong when pumice was used [6].

Hammer [2] compared the data obtained from the high-strength light-weight and normal-weight concretes containing 0–5% silica fume (SF) which were exposed to

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20, 100, 200, 300 and 450 °C with the data of the concretes which were not exposed to high temperatures. It was found that at 450 °C, NWC containing 0% SF showed the best performance but the behavior of the others was similar to each other. At 600 °C, LWC with 5% SF and NWC without SF were similar to each other and they showed the best performance by a strength loss of 48% relative to the control concrete exposed to 20 °C. When the concrete temperatures were 200–300 °C, reductions in compressive strength were 25–35%.

According to Kong et al. [7] and Abeles and Bardhan-Roy [8], concretes containing light-weight aggregate preserve their strength up to nearly 500 °C. It was stated that the residual strength of LWC after fire decreases linearly from 100% to 40% as a result of increasing the temperature from 500 to 800 °C.

Hammer [9] reported that during the hydrocarbon fires, light-weight aggregate concretes experience greater spalling when compared to normal-weight concretes. There are three main reasons for this when the LWC and NWC are compared [10,11]:

- Permeability and vapor pressure depending on the moisture content.
- Moisture in the capillary pores (glogging moisture).
- Initial compressive strength of the spalling layer.

In this study, the compressive strengths and weight losses of the LWC containing pumice aggregate, SF and superplasticizer (SP) at high temperatures were investigated in comparison to NWC.

2. Experimental study

2.1. Materials

NWC were produced with crushed aggregate from Ankara-Elmadag (Turkey) district. Maximum aggregate size was 16 mm. The density and water absorption capacity of the 0–4 mm aggregate group were 2570 kg/m^3 and 2.73%, respectively. These values were 2700 kg/m^3 and 0.55% for 4–16 mm aggregate group. In concrete mix proportioning, aggregates were composed of 55% sand (0–4 mm) and 45% gravel (4–16 mm).

The light-weight aggregate (pumice) in LWC production was obtained from Isparta-Golcuk (Turkey) in three groups: 0–4, 4–8 and 8–16 mm. The specific gravities of these sizes were 2.09, 1.75 and 1.50, respectively. The pumice aggregate was graded to fit the limitations given in ASTM C 330 [12].

The cement used was an ordinary portland cement (PC) with a specific gravity of 3.15, Blaine fineness of 3350 cm^2/g, initial setting time of 150 min and final setting time of 196 min. The 7-day and 28-day compressive strengths of PC were 41.3 and 51.2 MPa, respectively.

SF used in the concrete production was obtained from Antalya Etimine Electro-Ferrochrome Plant, Turkey.

Chemical compositions of the pumice aggregate, PC and SF are shown in Table 1.

Municipal tap water was used as mixing water. A Type F superplasticizer (SP) conforming to ASTM C 494 was used to improve the workability.

2.2. Experimental programme

Concretes were produced with a 75 dm^3 capacity mixer. Mix proportioning of the LWC was made according to ACI 211.2 [13] standard. In naming the concrete mixes, the type of the concrete (N for NWC and L for LWC) was followed by the SF incorporation amount (5 for 5% and 10 for 10%) and finally by the SP content (0 for 0% and 2 for 2%). For example, L-10-2 denotes the LWC with 10% SF and 2% SP.

To determine the effects of high temperatures on concrete properties, prismatic specimens (100 × 100 × 500 mm) were produced. The specimens were cured in lime saturated water for 28 days [14,15]. Then, they were stored in the laboratory at 20 ± 2 °C and 60 ± 5% relative humidity until 90 days. Core specimens with 50 mm diameter and 100 mm length were drilled from the prismatic specimens and the drilled specimens were exposed to 100, 400, 800 and 1000 °C by using a SFL Advanced High Temperature & Environmental Systems furnace having a heating capacity of 2000 °C at a rate of 5 °C/min. Five specimens were used for each temperature and they were allowed to cool with a rate of 2 °C/min to room temperature in a desiccator. After cooling, tests were performed to determine their mass changes and compressive strengths. Unit weight of the concrete was also determined. The data obtained were compared with the results obtained for the control specimens which were stored at 20 ± 2 °C in the laboratory.

To determine the weight changes, the specimens were weighed prior to heating (w_i) and after cooling (w_s) with an accuracy of 0.01 g. The changes (W) were expressed as percentages of the initial weights by using

Table 1
Chemical compositions of the PC, SF and pumice aggregate

Composition (%)	PC	SF	Pumice
CaO	63.98	0.44	4.60
SiO_2	20.64	80.9	59.0
Al_2O_3	5.06	0.34	16.6
Fe_2O_3	3.14	0.55	4.80
MgO	1.20	5.23	1.80
SO_3	2.38	–	0.40
K_2O	0.8	4.50	5.40
Na_2O	0.31	0.35	5.20
Cl	0.035	0.13	–
Loss on ignition	1.72	2.70	1.60
Insoluble residue	0.46	–	–
C_3S[a]	52.48		
C_2S[a]	19.63		
C_3A[a]	8.02		
C_4AF[a]	9.15		

[a] Main compounds of the PC were calculated according to Bouge's equations.

$$W = \frac{w_i - w_s}{w_i} \times 100 \quad (1)$$

From the data obtained, mass changes of the NWC and LWC were investigated.

3. Results and discussion

3.1. Fresh concrete properties

Mix proportions and some fresh properties of the NWC are given in Table 2. The slump was tried to be kept constant at 7 ± 2 cm. Since use of superplasticizer increased the slump by approximately 2 cm, water contents of the mixes were reduced accordingly. As seen from the table, water/binder ratio of the NWC was between 0.42 and 0.58.

Mix proportions and some fresh properties of the LWC are shown Table 3. As seen, water/binder ratio of the LWC was between 0.43 and 0.47. Use of superplasticizer decreased the slump by approximately 2 cm, water contents of the mixes were reduced accordingly. The mix designs are based upon an estimated active water demand. That portion absorbed by the aggregate is not considered for determining yield since it has no volumetric effect. Due to the absorbed condition this water is not available to affect the cement paste. Therefore, as noted in ASTM C 125 (Concrete and Concrete Aggregates), absorbed water is not considered when calculating the water–cement ratio. The considered water amount is net weight of water which is the amount that is absorbed by the pumice subtracted from the total amount of water.

Tables 2 and 3 show that water requirement of both NWC and LWC increased when SF was used. Very fine spherical SF particles improve the grading of the binder by filling the gaps between the relatively coarser cement particles and increase the free water amount. Despite this beneficial effect, the high surface area of SF particles to be wetted causes high water requirement and lower durability [16,17]. In these cases, use of SP enabled to reach the desired slump with much lower water contents, as seen from both Tables 2 and 3. Unit weights of both NWC and LWC decreased slightly with the use of admixtures.

3.2. Hardened concrete properties

3.2.1. Physical properties

Some of the physical properties of the hardened concretes after 28 days are given in Table 4.

The concretes containing SP resulted in higher unit weights when compared to those without SP. Similar to the results obtained for fresh states, use of SF slightly decreased the unit weights. Therefore, highest unit weights were obtained for the concretes containing 2% SP and no SF.

When absorption capacities are considered, it is seen that use of SP in NWC resulted in lower values when compared to control mix (N-0-0). On the other hand, for LWC mixes, the concretes containing SP and SF had generally higher absorption capacities when compared to control mix. When SF content is kept constant, the absorption capacities of both NWC and LWC decreased by the use of SP. This can be attributed to the lower w/c when SP was used.

The comparison of the unit weights of NWC and LWC show that even the heaviest LWC (1722 kg/m^3) was 23% lighter than the lightest NWC (2248 kg/m^3).

Table 2
Mix proportions (for 1/m^3) and some fresh properties of the NWC

Concrete	Cement (kg)	Water (kg)	Paste/aggregate	w/b	Aggregate (kg)		SP (kg)	SF (kg)	Slump (cm)	Fresh unit weight (kg/m^3)
					0–4 mm	4–16 mm				
N-0-0	386	205	0.22	0.53	788	962	–	–	5.50	2367
N-0-2	386	174	0.22	0.45	788	962	7.72	–	7.70	2385
N-5-0	367	214	0.22	0.55	783	957	–	19.32	10.9	2347
N-5-2	367	164	0.22	0.42	788	962	7.72	19.30	9.80	2365
N-10-0	347	224	0.22	0.58	782	957	–	38.67	10.2	2325
N-10-2	348	164	0.22	0.42	788	962	7.73	38.62	9.20	2342

Table 3
Mix proportions (for 1/m^3) and some fresh properties of the LWC

Concrete	Cement (kg)	Water (kg)	Paste/aggregate	w/b	Aggregate (kg)			SP (kg)	SF (kg)	Slump (cm)	Fresh unit weight (kg/m^3)
					0–4 mm	4–8 mm	8–16 mm				
L-0-0	430	199	0.32	0.46	730	550	52	–	–	8.4	1809
L-0-2	430	187	0.32	0.43	730	550	52	8.6	–	6.4	1840
L-5-0	408.5	202	0.32	0.47	729	549	52	–	21.50	7.2	1792
L-5-2	408.5	189	0.32	0.44	729	549	52	8.6	21.51	7.1	1811
L-10-0	387	202	0.32	0.47	729	549	52	–	43	6.8	1772
L-10-2	387	188	0.32	0.44	730	550	52	8.6	43	6.2	1787

Table 4
Some physical properties of the hardened concretes

Concrete	Unit weight (kg/m^3)	Water absorption capacity (%)
N-0-0	2297	5.82
N-0-2	2325	5.13
N-5-0	2273	4.63
N-5-2	2302	4.27
N-10-0	2248	5.06
N-10-2	2277	2.84
L-0-0	1678	5.90
L-0-2	1722	5.83
L-5-0	1665	6.42
L-5-2	1711	5.97
L-10-0	1656	8.25
L-10-2	1696	8.11

3.2.2. Weight loss after exposure to high temperatures

The furnace used in this study to determine the properties of the specimens exposed to high temperatures reached 1000 °C in 200 min. The weight losses (in percent) of the NWC and LWC with increasing temperatures are given in Fig. 1a and b, respectively.

Highest weight losses were observed in N-10-0 for NWC and in L-5-2 for LWC. Similar to the results of a research by Akoz et al. [18] in which mortars with and without SF were exposed to high temperatures, the concretes containing SF showed higher weight losses when compared to the control concretes. The comparison of Fig. 1a and b reveal that the weight losses for NWC were higher than LWC. However, the most significant difference between these figures was their shapes: after 800 °C, the weight loss of NWC increases with an increasing rate whereas the weight loss of LWC increases with a decreasing rate. These results show that the performance of LWC were better than NWC when weight loss is considered.

The difference between the strength loss in normal-weight concretes (NWC) and light-weight concretes (LWC) was not observed until 100 °C. The weight loss of aggregates is different exposed to high temperatures. At temperatures above 400 °C, both of the concretes (NWC and LWC) show significant weight loss. From this temperature, behavior of NWC and LWC differs from each other. The rate of weight loss of NWC increases where as the rate of weight loss of LWC decreases until 1000 °C, which leads to the failure of specimen structure. This can be attributed to the mineral structure of the LWA. This is probably caused by the fact that less evaporation of water in C–S–H structure of LWC. Less relative weight loss of the LWC may be due to lower heat conductivity property of the pumice structure. The diffusion of heat into the LWC specimen core is less than the NWC may also be the cause of less loss. Coefficient of thermal expansion of NWA is higher than LWA. Use of silica fume in LWC increased the weight loss compared to LWC without additives. This may be due to reaction of $Ca(OH)_2$ with silica fume and by hydration C–S–H are built. The capillary pores and micro-pores of LWA are filled and denser cement paste is formed.

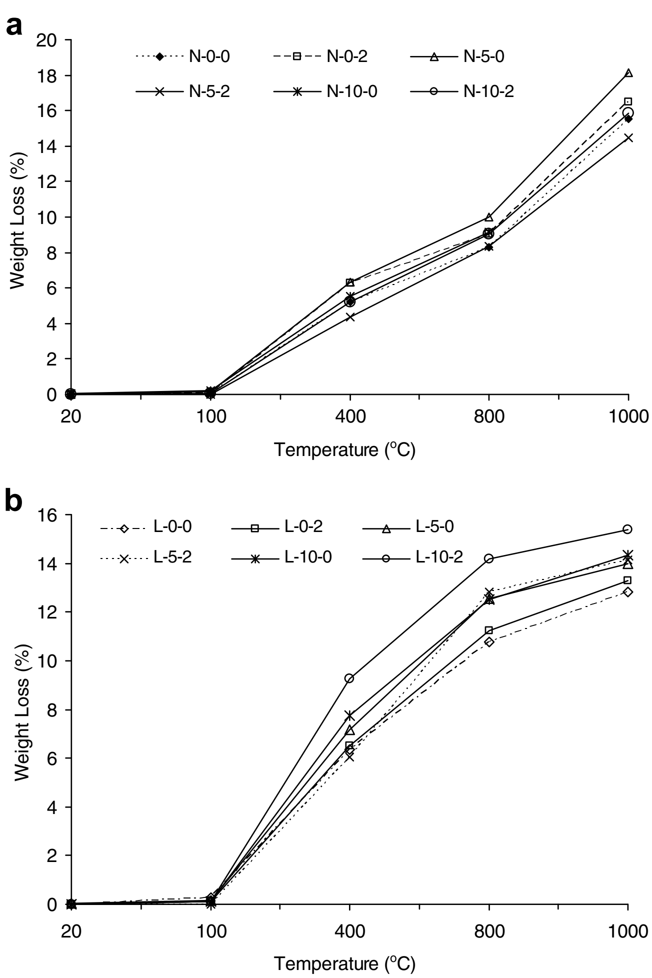

Fig. 1. Weight Losses of (a) NWC and (b) LWC.

3.2.3. Change in strength after exposure to high temperatures

Strengths of the NWC specimens exposed to high temperatures are given in Table 5. Relative strengths – in percent – at a given temperature with respect to the strengths of the same concrete at 20 °C are also included in this table.

Table 5 shows that at all temperatures, relative strengths with respect to 20 °C were highest in control concretes. In other words, the strength losses of other concretes were very close or higher when compared to control concrete. Maximum strength loss at 400 °C was observed in N-0-2 specimens and it was 42%. Nevertheless, the compressive strength of this type of concrete (32.10 MPa) was still higher than that of control mix (29.16 MPa). Similar to the results obtained for weight losses at 800 and 1000 °C, relative strengths decreased as the SF content increased. This behavior was noted also by other researchers [18–21].

In the same way, the compressive strengths at 1000 °C were lowest again for the concretes containing highest amount of SF (N-10-0 and N-10-2). In a research by Yuzer et al. [22], the strength of the concretes with 10% SF started to decrease beyond 100 °C and lost 50% of its initial

Table 5
Strengths of the NWC specimens

Concrete	t (°C)	f_c (MPa)	Relative strength (%)	SD (MPa)
N-0-0	20	36.36	100	1.55
	100	41.94	115	2.73
	400	29.16	80	2.98
	800	5.89	16	1.11
	1000	1.56	4	0.21
N-0-2	20	55.08	100	3.57
	100	52.23	95	2.34
	400	32.10	58	2.24
	800	6.98	13	0.77
	1000	1.58	3	0.08
N-5-0	20	43.31	100	2.53
	100	42.55	98	0.56
	400	31.54	73	2.93
	800	3.82	9	0.60
	1000	0.87	2	0.05
N-5-2	20	58.60	100	3.41
	100	49.40	84	2.34
	400	46.03	79	0.64
	800	5.77	7	0.68
	1000	2.56	1	0.38
N-10-0	20	30.55	100	1.15
	100	27.13	89	2.44
	400	20.06	66	1.82
	800	0.90	3	0.03
	1000	0.00	0	0.00
N-10-2	20	53.38	100	0.88
	100	52.00	97	1.20
	400	41.99	79	1.66
	800	4.03	8	0.65
	1000	0.00	0	0.00

Table 6
Strengths of the LWC specimens

Concrete	t (°C)	f_c (MPa)	Relative strength (%)	SD (MPa)
L-0-0	20	18.51	100	1.49
	100	18.24	99	0.41
	400	14.57	79	1.56
	800	5.20	28	0.31
	1000	0.00	0	0.00
L-0-2	20	17.41	100	1.41
	100	17.53	101	1.20
	400	17.07	98	0.08
	800	6.62	38	1.18
	1000	0.00	0	0.00
L-5-0	20	16.64	100	0.15
	100	17.26	104	1.93
	400	16.15	97	2.49
	800	5.45	33	0.66
	1000	0.54	3	0.04
L-5-2	20	22.59	100	1.28
	100	18.37	81	1.08
	400	19.33	86	1.06
	800	4.70	21	0.74
	1000	0.56	2	0.04
L-10-0	20	19.41	100	0.57
	100	14.52	75	0.73
	400	7.52	39	0.17
	800	3.03	16	0.20
	1000	0.00	0	0.00
L-10-2	20	22.47	100	2.21
	100	22.37	100	1.05
	400	20.43	91	0.98
	800	4.48	20	0.31
	1000	0.00	0	0.00

strength at 600 °C. The N-10-0 and N-10-2 concretes did not carry any load at all due to the severe deterioration that they had experienced. Visual inspection of the specimens showed that there was disintegration of approximately 1 mm thick pieces from the aggregate surfaces. Especially for 1000 °C, the mortar phases cracked severely and lost their binding properties. In some specimens, cracks were observed also in the coarse aggregate–mortar interface. Moreover, the specimens which were exposed to 1000 °C could not keep their cylindrical shapes.

The compressive strengths and relative strengths with respect to 20 °C for LWC are given in Table 6. As seen from this table, the concretes (except L-10-0 and L-0-0) were not affected by the increase of temperature up to 400 °C. These results were consistent with the findings of other researchers [8,9] who found that strength of LWC did not change significantly up to 500 °C. The strengths of these two concretes decreased considerably (>20%) at 400 °C.

The L-10-2 coded specimens preserved the strength value, obtained at 20 °C temperature, upto 400 °C, but the same specimens presented almost the lowest value at 800 °C temperature environment. The similar result obtained by Hammer [9] for the 5% SF added LWC at 600 °C which has given the best behavior with respect to NWC at 20 °C.

Fig. 2 and Table 7 were prepared to compare the behaviors of NWC and LWC. Fig. 2 shows that both concrete types showed a similar response to the temperature rise. After making a peak at 100 °C, the strengths decreased beyond 100 °C. The rate of decrease was very fast between 400 and 800 °C for both NWC and LWC. The lowest strengths were observed in the concretes containing 10% SF and no SP (N-10-0 and L-10-0). Generally, the compressive strengths and relative strengths at 800°C (Table 7) decreased with increasing SF content. Although the strengths of NWC at 400 °C were higher than those of LWC even at 20 °C, the strengths of the NWC and LWC containing same amount of SF and SP were comparable to each other at 800 °C. However, relative strengths of LWC were higher than NWC for any combination of the admixtures. In other words, LWC showed less strength losses than NWC. Strength losses were 62–74% for LWC, and 74–97% for NWC. The higher resistance of the LWC at 800 °C can be explained by the lower coefficient of thermal expansion of LWC. Tables 5 and 6 show that neither of the concretes could have a considerable strength at 1000 °C.

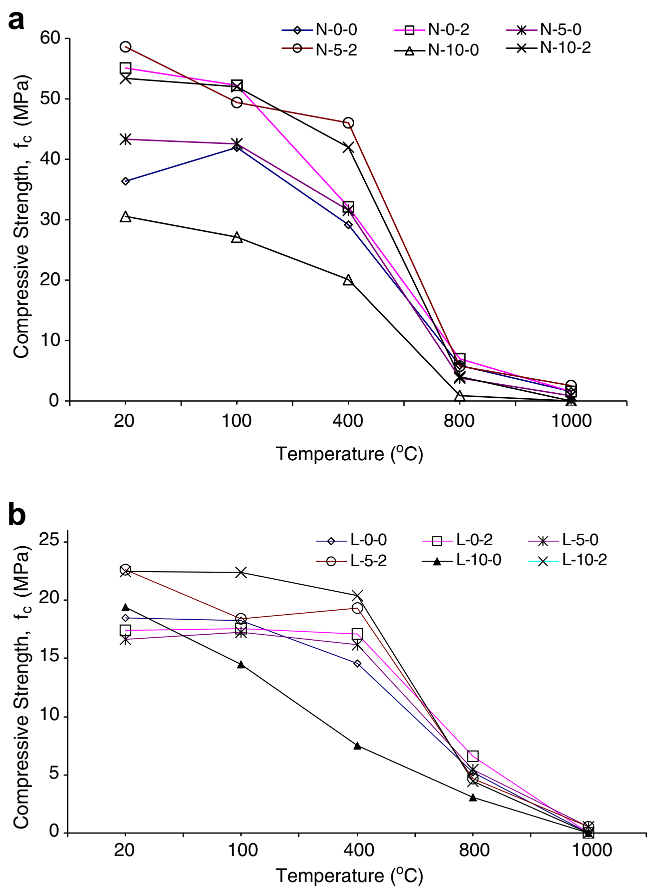

Fig. 2. Strengths of (a) NWC and (b) LWC.

Table 7
Strengths and relative strengths at 800 °C

Admixtures (%)		f_c (MPa)		Relative strength (%)	
SF	SP	NWC	LWC	NWC	LWC
0	0	5.9	5.2	16	28
5	0	3.82	5.5	9	33
10	0	0.9	3.0	3	16
0	2	7.0	6.6	13	38
5	2	5.8	4.7	7	21
10	2	4.0	4.5	8	20

Reduction in the compressive strength of both of the concrete exposed to beyond 400 °C is quite rapid. Decomposition of LWC and NWC beyond 800 °C at the surface and beyond 1000 °C at the core results in deterioration of concretes. If the temperature is found to have reached beyond 400 °C in a concrete, a detailed survey should be carried out to determine its behavior especially for the NWC.

4. Conclusions

1. Use of SF increased the water requirement and decreased unit weight slightly. The concretes containing higher SF amounts had generally higher weight losses and strength losses and lower strengths.
2. The behaviors of NWC and LWC were similar to each other when exposed to high temperatures. However, NWC showed higher strength losses than LWC.
3. Rate of deterioration was higher in NWC when compared to LWC.
4. Neither LWC nor NWC could withstand 1000 °C.

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