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The Post-fire Behavior of Lightweight Structural Concrete is Improved by Nano-SiO_2 and Steel Fibers

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ABSTRACT

The primary goal of the engineering design of building is to reduce the weight of the structure and its resistance to fires and earthquakes because fires are inevitable. Hence, the direction of this study was to use lightweight concrete because of its unique advantages in weight loss and fire resistance due to its thermal insulation property. It was also intended to enhance the strength and behavior of this concrete at high temperatures. For this purpose, four mixing designs samples without fibers and nano-SiO_2, samples with different proportions of nano-SiO_2, samples with different proportions of fibers, and samples with both fibers and nano- SiO_2 together were prepared. The results showed damage to samples free of nano-SiO_2 and fibers, changing their color, reducing their resistance and reducing their weight. But adding nano-SiO_2 fibers or using them together leads to improving the properties of concrete at all temperatures. Due to nano- SiO_2, its pozzolanic interactions improve the microstructure, and the fibers prevent cracks in concrete. This study also dealt with the effect of changing the size of the samples on the compressive strength, and the results showed an increase in the resistance of the samples with small sizes, and resulted factors for converting the resistance of non-standard samples into a standard.

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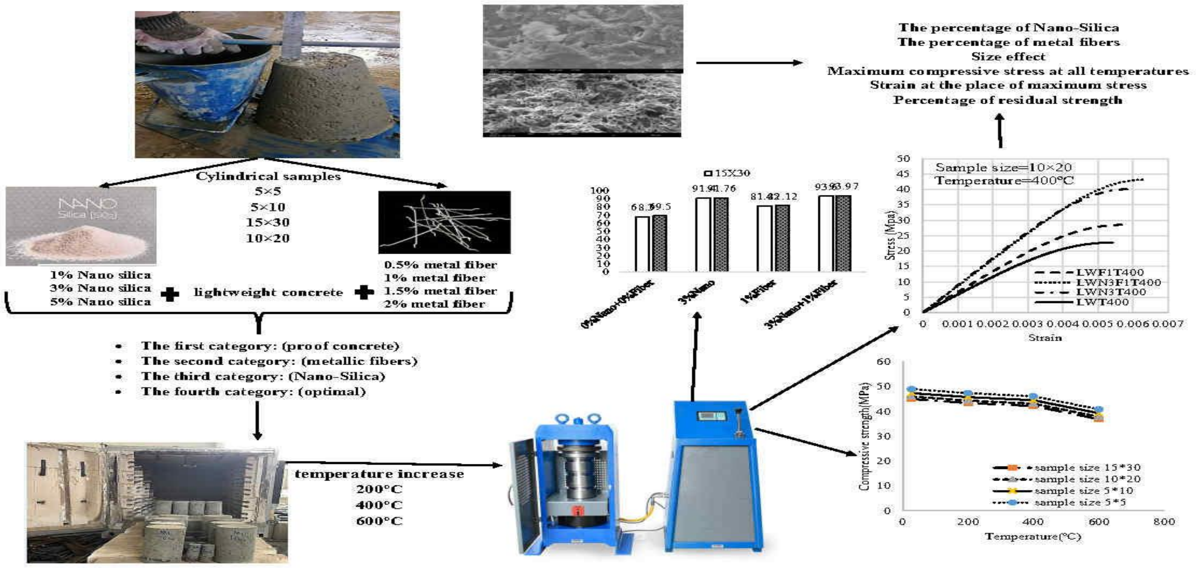
Graphical Abstract



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1. INTRODUCTION

Concrete is the most widely used material in construction worldwide due to its ease of use and low cost. Its compressive strength is one of the most significant reasons for accepting this material. The concrete used in this study is lightweight concrete (LWC), as its use by engineers has increased in recent years because the heavy structure and traditional materials will have many consequences for the structure. If the weight is less, it will increase the structure's safety and resistance to fire and earthquakes without affecting its strength. It entered the application of LWC after the production and manufacture of light concrete in the early twentieth century in 1917, after which many lightweight concrete buildings and bridges were built in the world, including the largest concrete building with 52 floors and a height of 215 meters in Houston, Texas, the Park Plaza Hotel building. It is among the buildings constructed between 1920 and 1930. The 42-story building in Chicago, the TWA terminal at New York Airport in 1960, Dulles Airport in Washington in 1962, a church in Norway in 1965, a bridge in Wiesbaden, Germany, in 1966, and a water bridge in Rotterdam, Netherlands, in 1968. This type of bridge was built in the Netherlands, England, Italy, and Scotland in the 1970s and 1980s, along with other buildings where it was used for LWC. FIP has published some significant lightweight concrete projects, demonstrating their astronomical use. Also, LWC significantly reduces construction costs, which can be examined in two aspects:

1. Reducing the dead load on the building: This factor decreases the cost of the skeleton and the foundation. Note: Reducing the building's dead load will reduce damage during an earthquake or fire.
2. Saving energy consumption: Due to the ease of cutting and drilling this type of concrete, we will witness a decrease in the cost of operating the facility, and during the operation of the building, due to the insulation of the building structure, there will be a significant decrease in the cost.

Also, LWC has other benefits. The volume of waste in this type of concrete is less than ordinary concrete, as the issue of the environment and its pollution has been taken into account recently, and natural materials that do not destroy the environment are of particular interest attention. Destroying LWC requires less energy than standard concrete because smaller machines can be used. In addition, because this type of concrete contains air, the volume of waste during demolition is smaller than normal concrete. Thus, using LWC spread due to its essential advantages, such as lightness, thermal insulation, reduced production and transportation costs, and sufficient earthquake resistance. Lightweight concrete can withstand high temperatures and fire due to its low thermal conductivity and specific heat. Considering all the previous advantages of LWC, specifications for this type of concrete and how to improve these properties under certain conditions have been studied. In fact, LWC is known for its potential ability to withstand high temperatures and fire due to its low thermal conductivity and specific heat. However, this does not mean high temperatures do not affect LWC. Elevated temperatures may lead to severe discoloration, a change in concrete compressive strength, a reduction in weight and modulus of elasticity, and a change in concrete appearance [1]. One of the significant problems with LWC applications in industry and structures at high temperatures is that the favorable properties of concrete are reduced at high temperatures.

Nistratov et al. [2] used the regeneration of fibers made from waste composites and found that the minimum temperature to destroy the carbon plastic matrix is 410 °C and that adding 1% of the fibers led to their growth of 37% due to their high density and low porosity. In his study, Moosaei et al. [3] improved the ductility of light aggregate concrete by integrating hybrid steel and polypropylene fibers. He found a significant increase in compressive ductility and the ability to absorb energy.

Toric et al. [4] have investigated the mechanical properties of LWC after exposure to high temperatures. Concrete samples in four concrete mixtures were heated to 600 °C and subjected to various tests after 90 days. The results indicate that the compressive strength has decreased by 20%. Poon et al. [5] indicated that high temperatures weakened concrete's compressive strength and hardness.

Considering that LWC has lower strength due to the lower specific weight of this type of concrete, researchers have always tried to improve its mechanical properties by adding admixtures. They also have improved properties at elevated temperatures. These additives are steel fiber and nano-SiO_2. Wang et al. [6] studied lightweight concrete (SFLWC). They used two types of concrete with steel fibers and steel fibers with knurled ends and wrinkled shapes. The results showed that the higher the temperature, the higher the axial peak.

The strain significantly increased while the axial compressive strength and modulus of elasticity decreased. Concrete hardness rises at lower temperatures and decreases at higher temperatures. However, steel fibers can enhance the material's ability to absorb energy as well as its specific and residual durability. Mohammadi and Bagheripour [7] studied the engineering properties of self-compressing lightweight concrete (SCLWC) after adding fibers to it and found that the compressive strength was improved by adding 1% fine steel fibers. Goaiz et al. [8], Mohammed and Kadhim [9] showed that adding fiber increased compressive strength. A study by Varghese et al. [10] showed that carbon fiber-reinforced concrete samples had better residual shear strength than others. Combining carbon and basalt fibers into concrete reduced microcracking in samples exposed to elevated temperatures. Some researchers stated that the fibers do not have a noticeable effect on the compressive strength of concrete [11-13]. According to literature, it can be said that the use of fiber cannot provide a complete improvement in LWC. Düğenci et al. [14] have stated in their research that the compressive strength and modulus of elasticity of concrete-containing fibers decrease significantly with increasing temperature. Lau and Anson [15] showed that steel fibers increase resilience to heat and cracking. Among the additions that attracted researchers' interest in improving the behavior of concrete and making the microstructure dense and homogeneous at high temperatures is nano-SiO_2 due to its interaction with calcium oxide produced through the decomposition of cement hydrates at high temperatures.

According to literture [16, 17], adding nanomaterials such as alcofine and replacing it with cement can improve compressive strength and reduce environmental pollution.

Bastami et al. [18] investigated changes in concrete's compressive and tensile strengths due to heat modification with nano-SiO_2. This study tested six samples with different percentages of nano-SiO_2 and two without nano-SiO_2. After making the samples, they were heated to 400, 600, and 800 degrees Celsius. The results showed that adding nano-SiO_2 increased compressive and tensile strengths and permeability, flaking, and mass loss. Horszczaruk et al. [19]studied the effect of high temperatures on the performance of concrete containing nano-SiO_2. In this research, concrete with 5% different nano-SiO_2 and three edge temperatures of 200 °C was made and tested. The analysis of mass loss, bending, and compressive strength and observation with SEM was done for samples. Based on the results, an ideal nano- SiO_2 content improved the thermal resistance. Brzozowsk et al. [20] found that nanoparticles enhanced the behavior of concrete at high temperatures in cement mortar containing quartz and magnetite aggregates. Researchers [21-24] found that adding 4% of nano-SiO_2 by replacing it with cement improved compressive strength, and whenever it exceeded 4%, its positive effect decreased. Ahmadi et al. [25] found in their study that adding nano- SiO_2 as an alternative to cement 1, 3, and 5% improves the microstructure of cement and increases its compressive strength.

The purpose of this study was to design a mixture of nano- SiO_2 and fibers to improve the behavior of LWC after fire exposure. For this purpose, four mixing designs with nine groups of samples were made. Designing the first mixing for control samples and designing the second mixing with different weight ratios 1%, 3% and 5% nano- SiO_2 by replacing it with the weight of cement and subtracting the third mixing for different volume ratios of 0.5, 1, 1.5 and 2% fibers. The results showed that the best percentage for nano- SiO_2 is 3%, and the optimal percentage for fiber is 1%. Thus, a composite fourth mixing design consisting of 3% nano-SiO_2 and 1% steel fibers was made. After that, the samples were exposed to different temperatures of 200, 400, and 600 °C, and a comparison was made between them and the control samples. These groups contain samples of different sizes (10×20, 15×30, 5×10 and 5×5 cm). The purpose of the difference in the size of the samples was to show the effect of size on compressive strength. The results showed that the smaller the size of the sample, the greater the compressive strength.

2. MATERIALS AND METHODS

This section describes the quality and quantity of materials used to prepare concrete samples.

2. 1. Materials

2. 1. 1. Aggregates The lightweight aggregate in this study is Light Weight Expanded Clay Compound (LECA). Figure 1 shows the LECA model used in this research. Specific gravity and water absorption tests were also performed on the samples. The maximum LECA size is limited to 12 mm. The maximum amount of these samples was determined using the sieve analysis test according to "ASTM C330" [26]. Also, the mechanical and physical parameters of the LECA assemblies are presented in Table 1. Sand with a maximum grain size of 4.75 mm was used as a fine aggregate according to ASTM C33 [27]. Figure 2 shows the results of the sieve analysis test performed on fine sand and silica.

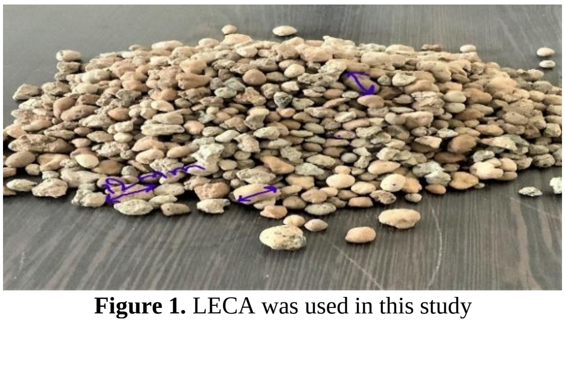


Figure 1. LECA was used in this study

Portland cement type 2 was used in this investigation. Based on the manufacturer's information, its chemical, physical, and mechanical properties are summarized in Table 2. This Portland cement type produces moderate heat due to its reaction with water. In addition to that, it has balanced resistance to salts, sulfates, and chlorides. Also, this cement is suitable for pouring concrete in hot weather. This cement may not be used in facilities subject to sulfate attacks. Less heat is produced due to the slow reaction of cement with water, so this type of cement can be used in relatively large constructions, such as massive and large-sized foundations.

TABLE 1. A LECA aggregate's mechanical and physical characteristics

Elements	**Na_2O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**SO_3**
wL%	0.376	2.163	4.141	19.298	0.116
Elements	**Cl**	**K_2O**	**CaO**	**TiO_2**	**MnO**
wL%	0.011	0.808	58.95	0.221	0.1
Elements	**Fe_2O_3**	**Ni**	**Cu**	**Zn**	**Rb**
wL%	2.982	0.009	0.006	0.01	0.003
Elements	**Sr**	**Bn**	**LOl**		
wL%	0.025	0.086	6.47		

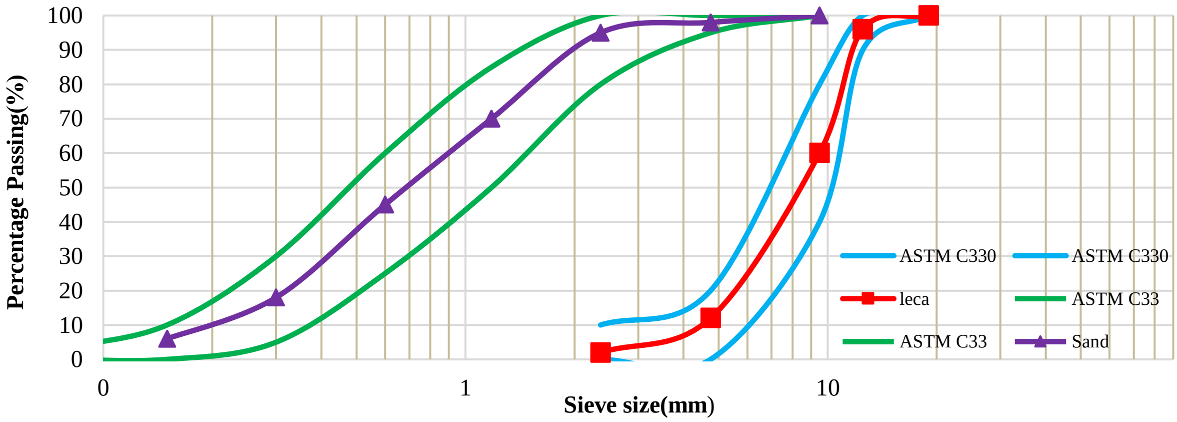


Figure 2. The sieve analysis test of coarse and fine aggregates was used in this research

TABLE 2. Characteristics of the cement used in this research

Elements	**Na_2O**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**SO_3**
wL%	1.735	16.353	63.259	0.201	0.331
Elements	**Cl**	**K_2O**	**CaO**	**TiO_2**	**MnO**
wL%	0.098	3.114	4.159	0.532	0.112
Elements	**Fe_2O_3**	**Ni**	**Cu**	**Zn**	**Rb**
wL%	5.566	0.006	0.006	0.015	0.009
Elements	**Sr**	**Zr**	**Ba**	**Pb**	**LOl**
wL%	0.043	0.017	0.047	0.014	0.5
Elements	**MgO**	**Cr**			
wL%	3.869	0.014			

The third-generation superplasticizer based on carboxylate is an Abadgaran Construction Chemical Industries product.

This study relied on Nano Sadra's nano-SiO_2 [28]. White in color, with 99% pure nano-SiO_2 powder has a particle size of 11-13 nm. The microstructure has been verified using a transmission electron microscope (TEM) and X-ray diffraction (XRD) images. A transmission electron microscope (TEM) is a high-resolution, ultra-magnification instrument for the structural characterization of materials. XRD analysis, or X-ray powder diffraction analysis, another name for X-ray spectroscopy, is a technology used to learn about the chemical makeup and crystal structure of the natural and artificial objects without destroying them. X-ray patterns are like fingerprints in that they can identify specific crystal structures. The TEM photo with different resolutions (a) 0.1 nm, (b) 150 nm, (c) 40 nm, (d) 300 nm and X-ray XRD diagram are presented in Figures 3 and 4. TEM device model: EM10C-100KV device, Zeiss, Germany, was used in our work.

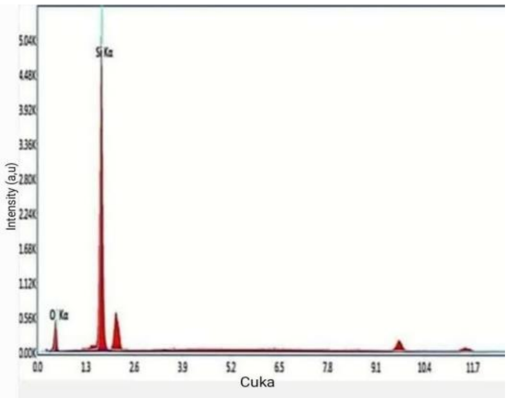
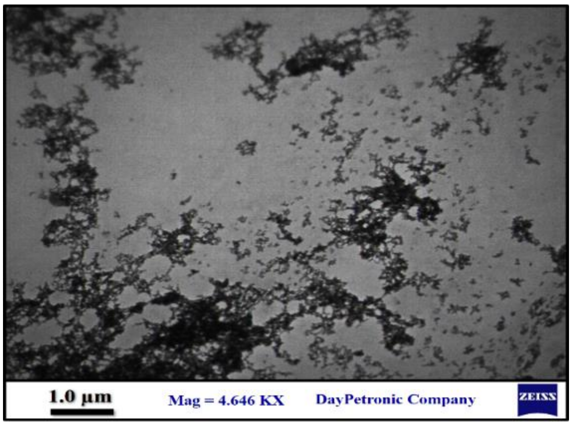
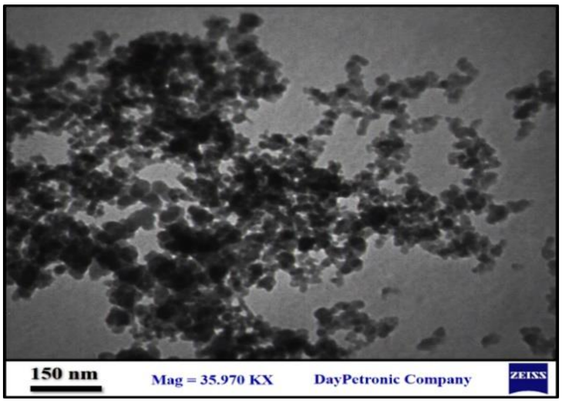


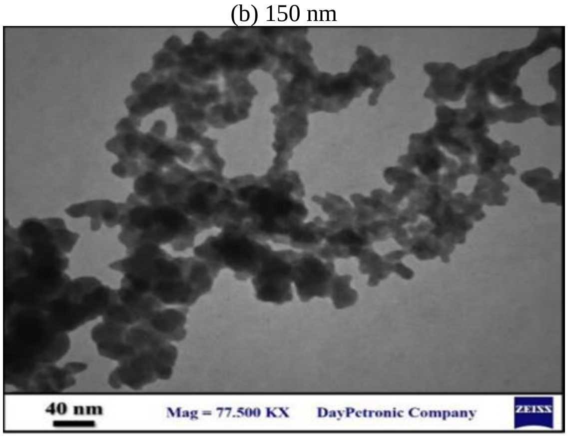
Figure 3. The XRD chart of nano-SiO_2



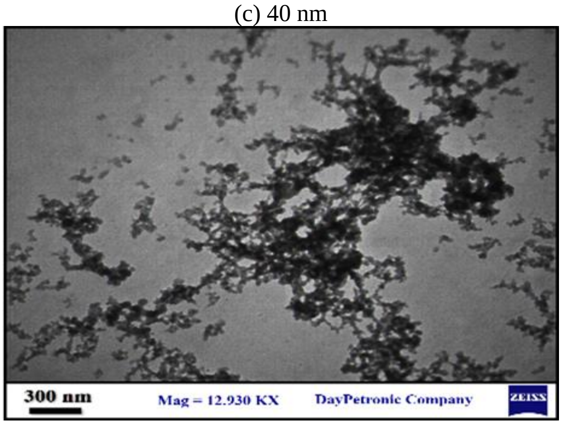
(a) 0.1 nm



(b) 150 nm



(c) 40 nm



(d) 300 nm

Figure 4. TEM image of nano-SiO_2 at different accuracies

Among different types of fibers, steel fibers are often applied for construction purposes and improve concrete properties more effectively than other fibers [30]. Steel fibers with short and discrete lengths are available in lengths of up to 80 mm and cross-sectional areas ranging from 0.1 to 1.5 mm^2 [29]. Ki Mix Company supplied the steel fibers used in this study. It has a straight shape with a hooked end. Table 3 displays information about steel fiber properties. Figure 5 shows the shape of the steel fibers used in this study.

TABLE 3. The mechanical and physical properties of steel fibers are presented.

Tensile strength (MPa)	L/D	Diameter (mm)	Length (mm)	cross-section shape	Appearance
1200	62.5	0.8	5	circle	straight

Figure 5. The shape of the fibers with knotted ends used

2. 2. Concrete Mixture In this study, the mixing design in the standard "ACI 211.2" [30] was used in making preliminary samples, and then the design was modified several times until a mixing design with a suitable slamb between 50 and 80 mm was obtained. The LWC mixing technique per cubic meter used in this study is shown in Table 4.

The nano- SiO_2 weight ratio is added by replacing it with the cement weight. Three percentages were used in this study: 1, 3 and 5% nano- SiO_2.

To distribute nano- SiO_2 powder uniformly, it is mixed well with cement for 2 minutes until a homogeneous mixture is obtained for use as a concrete admixture. All dry materials are combined in a mixer for two minutes, and then water containing plasticizers is gradually added to the mixture. Then, in a mixture containing fibers, steel fibers are added to the mixture. After the materials are completely mixed in the mixer, the fresh concrete is poured in three layers into the required molds arranged in advance. Concrete mixtures are compacted on a vibrating table. Molds were opened after 24 hours. Mold samples were taken and cured by covering them with nylon and a damp cloth for 28 days, as shown in Figure 6. Then they were exposed to free air. Ninety days after being prepared, some samples were put in the oven for thermal testing. Some samples were heated to 200 °C, 400 °C, and 600 °C, while others were stored at 25 °C at room temperature. Twelve samples were made for each mixing plant and temperature. Three samples were made with cylindrical molds of different dimensions (15×30, 10×20, 5×10, and 5×5 cm) to observe the effect of size. Table 5 also shows the number of samples and tests performed on them. Table 6 represents the subtraction admixture characteristics of the samples.

TABLE 4. The LWC mixing plan used in this research

Cement (kg/m^3)	Coarse aggregate (Leca) (kg/m^3)	Fine aggregate (sand) (kg/m^3)	Water to cement ratio	Superplasticizer percentage	28 days' compressive strength f_c (MPA)	Specific Weight ɣ (kg/m^3)
450	350	850	0.38	1%	30	1910

TABLE 5. Number of samples

Experiment	Sample dimension (cm)	Sample shape	Number of samples
Compressive strength and modulus of elasticity	10×20	Cylindrical	108
Compressive strength and modulus of elasticity	15×30	Cylindrical	48
Compressive strength	5×10	Cylindrical	48
Compressive strength	5×5	Cylindrical	96

TABLE 6. LWC mixture plan

	Nano-SiO_2 (%)(weight percentage of cement)	steel fibers (%)Volume percent	Plan
1	-	-	The first category (control samples)
2	-	0.5	The second category (metallic fibers)
3	-	1	
4	-	1.5	
5	-	2	
6	1	-	The third category (Nano-SiO_2)
7	3	-	
8	5	-	
9	3	1	The fourth category (optimal)

Figure 6. Samples under occurring

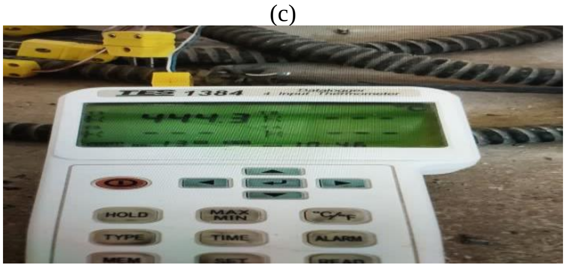
2. 3. Expose the Samples to Temperature The samples were heated for 48 hours, or 2880 minutes, at 100 °C before the temperature required for surface drying was reached. This method may help prevent cracking in the samples at high temperatures [31]. After that, the samples were heated to 200, 400, and 600°C. The electronic oven is set through the control panel at 5 degrees per minute. When the samples are heated inside the furnace, the oven temperature is set to the required degree. The oven temperature it reaches is known through the furnace side keyboard. In order to measure the temperature, samples must arrive, which is done with a digital thermometer attached to a wire outside the furnace. This wire was carefully placed inside the concrete paste inside a cube mold with 100 x 100 x 100 mm dimensions. We enter the mold with the rest of the samples when the samples are heated. The other end of the wire protrudes through a small hole in the oven side, on the outside, to connect to the thermometer in Figure 7 (a) the samples after exposure to temperatures, (b) the arrangement of the samples to enter the oven, (c) the thermometer to measure the temperature of the sample. This can be seen in the graphs obtained from the digital thermometer in Figure 8, showing the temperature change inside the sample and in the furnace. (A) samples after exposure to temperature 200°C, (b) samples after exposure to temperature 400°C, (c) samples after exposure to temperature 600°C.

2. 3. Test Procedure Three studies were conducted for this research. Firstly, to study the effect of steel fibers and nano-SiO_2 on the compressive strength and modulus of elasticity of light structural concrete and to find the optimal ratio of steel fibers and nano-SiO_2. Secondly, to examine the effect of temperature on concrete compressive strength, and finally, to examine the effect of concrete sample size on compressive strength.

(a)

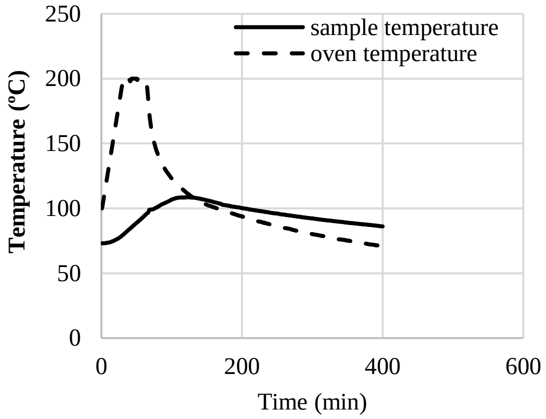
(b)

(c)

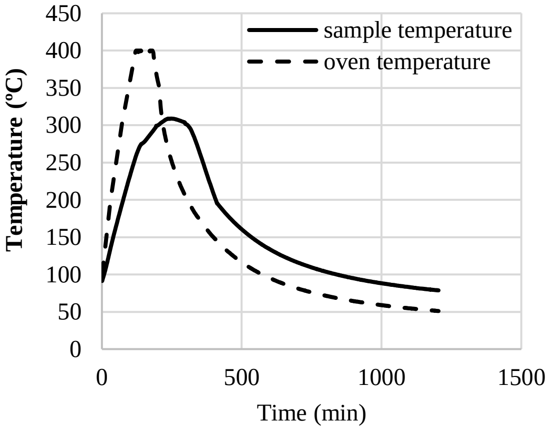


(d)

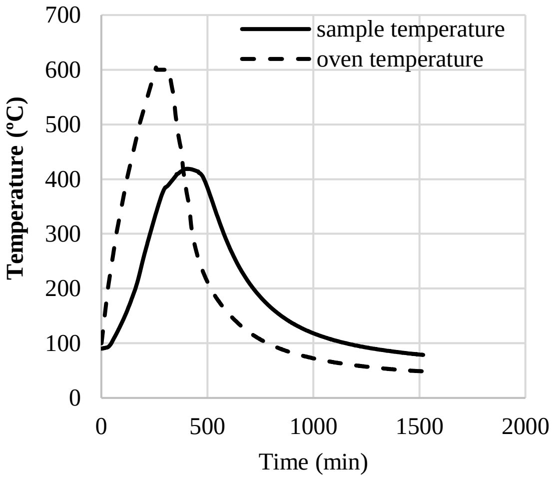
Figure 7. Samples in the electrical furnace



(a) Temperature=200ºC



(b) Temperature=400ºC



(c) Temperature=600ºC

Figure 8. The graphs of the temperature increment on the samples

2. 4. Mechanical Experiment

Samples were prepared for various tests based on a predetermined mixing plan and method, including thermal and mechanical loading. The uniaxial compression test, (μ, modulus of elasticity) test, and compressive stress-strain curve were used in this study to check the mechanical properties of the samples. The compressive strength test was performed according to the ASTM C39 standard [32]. The samples' elastic modulus was determined based on the ASTM C469 standard [33]. This study used an instrument with a capacity of 2000 kN and an accuracy of 1 kN to measure stress-strain curves (Figure 9). This test was performed according to the ASTM C617 standard [34].

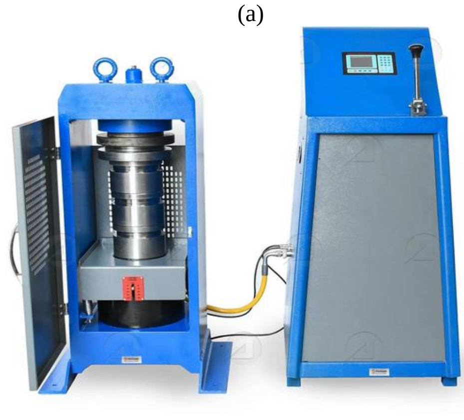
3. RESULTS AND DISCUSSION

In the results section, investigate the behavior of LWC containing nano- SiO_2, fibers, or both at different temperatures by knowing the compressive strength, elastic modulus, stress-strain curve, and the effect of the different sizes of the samples on the compressive strength.

3. 1. Effect of Nano-SiO_2 and Steel Fibers on LWC Compressive Strength at Room Temperature

The compressive strength results for different steel fibers and nano-SiO_2 proportions in LWC for all sample sizes can be seen in Tables 7 and 8 and Figures 10 to 13.

(a)



(b)

Figure 9. (a) Pressure Test Machine; (b) Test Setup

TABLE 7. The compressive strength (MPa) at 25°C for 15×30 and 5×10

Size sample(cm)	Control	3%Nano	1%Fiber	3%Nano+1%Fiber
15×30	32.6	43	34.5	45
5×10	33.9	44.9	35.8	47.4

TABLE 8. The compressive strength at 25°C for 10×20 and 5×5

Size sample (cm)	Control	1% Nano	3% Nano	5% Nano	0.5% Fiber	1% Fiber	1.5% Fiber	2% Fiber	3% Nano+1% Fiber
10×20	33.1	36.6	43.8	41.2	34.5	34.9	34.1	33.8	46
5×5	34.7	38.3	46	43.2		37.8	36.5	36	49

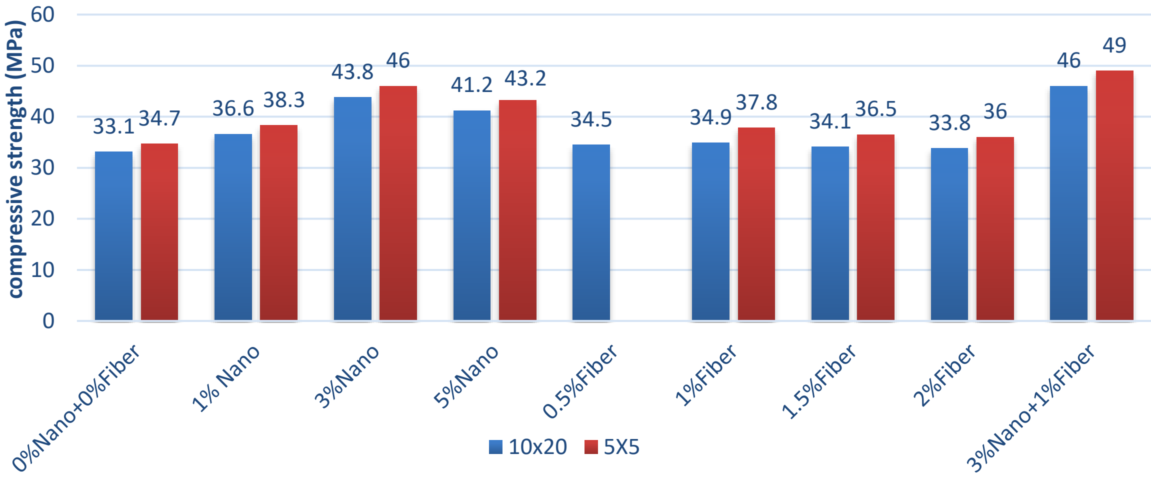


Figure 10. The compressive strength at 25ºC for 10×20cm and 5×5cm size samples

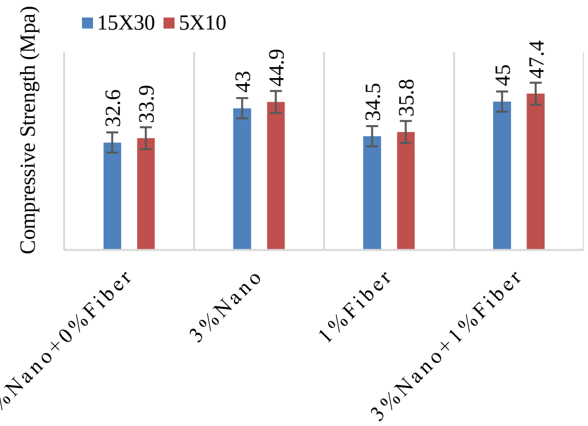


Figure 11. The compressive strength at 25ºC for 15×30cm and 5×10cm size samples

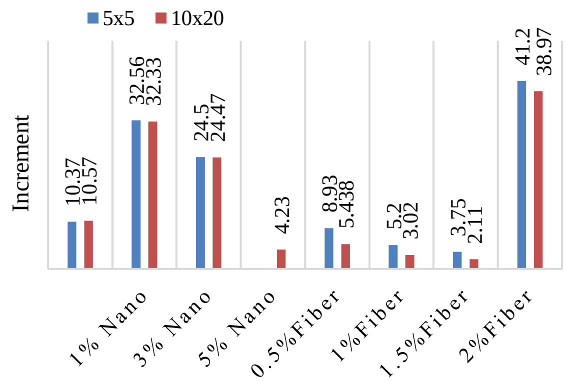


Figure 12. Differences from control samples at 25ºC (%)

To select the most suitable nano- SiO_2 and the highest fiber ratio, 10 × 20 cm molds were used. The largest percentage of nano- SiO_2, as shown in the results, is 3%, and the highest percentage of fiber is 1%. The positive effect of nano- SiO_2 decreases when the ratio exceeds 3%. This can be explained by the fact that a certain amount of calcium hydroxide crystals were produced

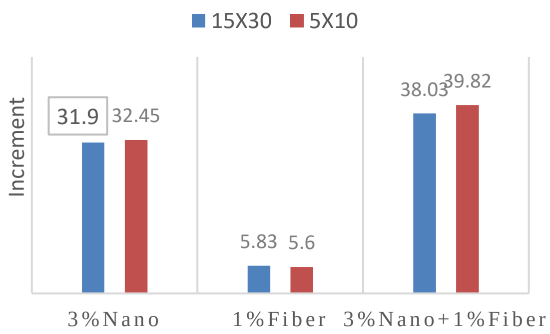


Figure 13. Differences from control samples at 25ºC (%)

during the interaction of water with cement, which reacts with nano- SiO_2 which from this fusion produces a gel (hydra silicate calcium). When more nano- SiO_2 than required is added, it reacts with calcium hydroxide, and the excess nano- SiO_2 is precipitated and replaced by the spent cement, which reduces the strength of the cement paste and reduces the adhesion between the aggregate and the cement paste. The reason why nanoparticles cause an increase in compressive strength can be explained as follows: The reaction between cement and water, known as the pozzolanic reaction, leads to the formation of vast amounts of calcium hydroxide crystals. $Ca(OH)_2$, a hexagonal crystal present in the transition zone between the cement paste matrix and the aggregate, breaks concrete's strength. Because of nano-SiO_2 has a high specific surface area, it is highly reactive and reacts rapidly with $Ca(OH)_2$ to form a calcium silicate gel. As a result of the pozzolanic reaction, the size, and concentration of calcium hydroxide crystals are reduced, and a dense, high-strength H-S-C gel (calcium silicate hydrate) is produced, which fills the voids in the transition zone to enhance the strength and durability of concrete, known as micro-filling. The average diameter of H-S-C gel particles is about 10 nm. Therefore, filling the existing pores creates a denser and homogeneous viscous paste matrix, as previously shown by other researchers [35]. However, we note from the results that adding 2% of the fibers reduces the compressive strength because the fibers prevent cracks growth. Its principal function is to repair cracks, leading to a decrease in compressive strength. Also, we noted from the results that the highest compressive strength was in the compain mixture design, as it increased by 39%. The reason for this increase is that by adding nano- SiO_2 to the mixture containing fibers, the strength of the concrete increases due to an increase in density of the mixture and the increase in the contact surface between the fibers and the cement paste.

3. 2. Mechanical Properties of LWC at High Temperatures

Figure 14 shows the compressive strength of all sample sizes of LWC at 200ºC, 400ºC, and 600ºC, as well as control samples.

As shown in the above figure, the compression strength decreases with increasing temperature in all sample sizes, and this is because heat damages the load-bearing mechanical structure of concrete, and the mechanical properties of concrete change permanently. Figure 15 compares changes in compressive strength after heat exposure for samples of three different sizes.

Figure 15 reveals that as concrete's temperature rises, particularly between 400ºC and 600ºC, the material's compressive strength decreases dramatically. The values of the percentage weight loss of the samples due to heat are presented in comparing form in Figure 16.

As shown in Figure 16, with the increase in temperature experienced by the sample and an increase in the duration of exposure to the appointed temperature, the weight loss of the samples increases. This weight loss is related to the amount of water in the concrete structure, the decomposition of calcium hydroxide into quicklime and water, the evaporation of

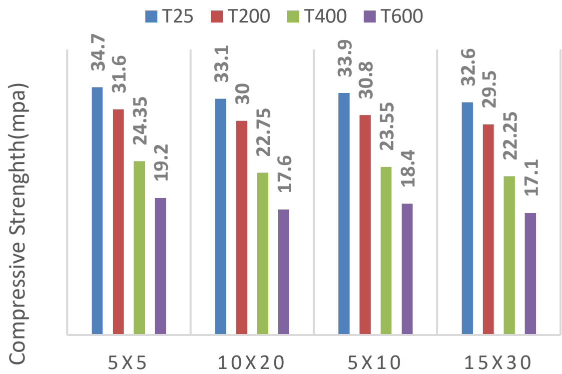


Figure 14. LWC compressive strength at high temperatures

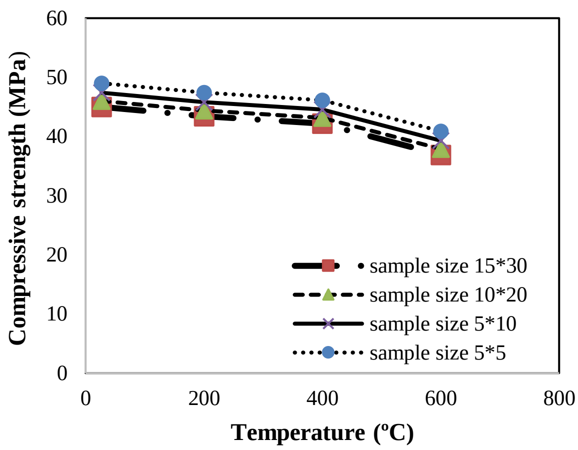


Figure 15. LWC compressive strength exposed to high temperatures

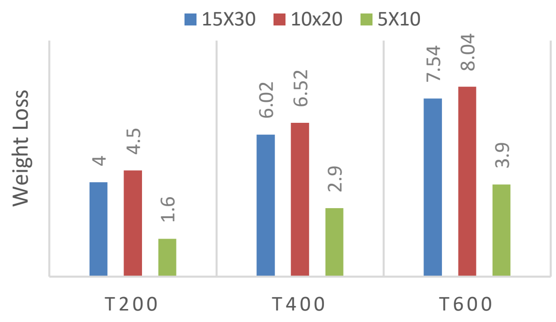


Figure 16. Weight loss percentage (%) of LWC due to high temperature

produced water, the separation of surface absorption water from CSH layers, and the decomposition of aggregates. All of these phenomena become more intense as temperatures and heating times increased. This result has been confirmed in the literature [21, 26]. Figure 17 shows residual compressive strength following exposure to high temperatures for different sample sizes compared to control samples.

The 600°C temperature had a significant effect on the residual compressive strength of the concrete. Figure 17 shows that lightweight concrete compressive strength decreased with temperature increase. It can also be seen that the smaller the sample size, the greater its residual resistance.

3. 3. Effect of Temperature on LWC Containing Nano-SiO_2 and Fibers

Tables 9 and 10 and Figure 18 show the compressive strength, weight loss, and residual compressive strength of all sample sizes at 200ºC, 400ºC, and 600ºC.

The results showed the state of deterioration of the samples and the weight reduction when the temperature rose to 600. However, the nano- SiO_2 and the fibers helped somewhat in improving the resistance at the temperature of 600. We note that the effectiveness of the nano- SiO_2 decreased at high temperatures and became similar to the behavior of the fibers because, before the temperature rise, the nanoparticles improved the microstructure. After the high temperature here, the fibers played like a bridge in preventing cracks. Also, we notice that at high temperatures, the concrete color changed and became pinkish, as shown in Figure 19.
As shown in the figures, the lack of fibers and nano-SiO_2 in the sample indicates the amount of crack. The wear due to compressive load and failure at the place where the load is applied is very high. By adding 1% steel fiber, this amount of failure is greatly reduced.

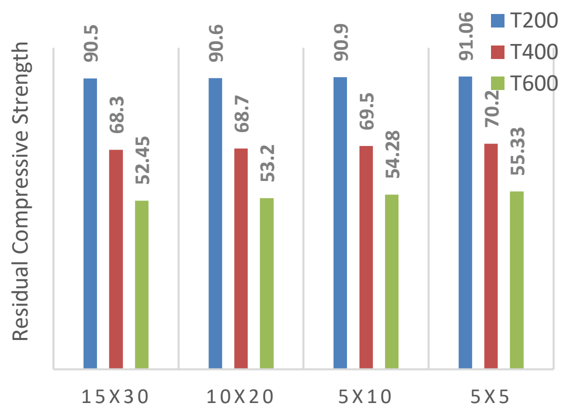


Figure 17. Residual compressive strength after high-temperature exposure

TABLE 9. Residual compressive strength and weight loss of LWC containing nano-SiO_2 and fibers at high temperatures for 15×30 and 5×10 samples

Parameter	temp	Size sample (cm)	0%Nano+0%Fiber	3%Nano	1%Fiber	3%Nano+1%Fiber
Residual %	T200	15×30	90.5	96.3	94.5	96.4
		5×10	90.9	96.4	94.7	96.6
	T400	15×30	68.3	91.4	81.45	93.6
		5×10	69.5	91.76	82.12	93.97
	T600	15×30	52.45	73.56	65.5	82
		5×10	54.28	74.7	66.76	82.91
Weight loss%	T200	15×30	4	2.9	3.5	2.5
		5×10	1.6	1.28	1.46	1.06
	T400	15×30	6.02	5.33	4.6	4.2
		5×10	2.9	2.5	2.7	2.1
	T600	15×30	7.54	7.16	6.6	6.2
		5×10	3.9	3.5	3.6	3.2

TABLE 10. Residual compressive strength and weight loss of LWC containing nano-SiO_2 and fibers at high temperatures for 10×20 and 5×5 samples

Parameter	temp	Size sample (cm)	0% Nano+ 0% Fiber	1% Nano	3% Nano	5% Nano	1% Fiber	1.5% Fiber	2% Fiber	3% Nano+ 1% Fiber
Residual %	T200	10×20	90.6	93.7	96.3	94.9	94.6	94.95	95.3	96.5
		5×5	91.06	93.9	96.5	95.1	94.9	95.3	95.6	96.7
	T400	10×20	68.7	88.5	91.6	84.3	81.7	82.1	82.25	93.8
		5×5	70.2	89.03	91.96	85.02	83.07	83.29	83.33	94.16
	T600	10×20	53.2	66.78	74.04	68.62	65.9	66.57	66.57	82.4
		5×5	55.33	68.25	75.28	69.9	68.57	70.96	68.61	83.47
Weight loss%	T200	10×20	4.5	3.8	3.3	2.9	4	4.1	4.3	3
	T400	10×20	6.52	5.9	5.73	5.4	5.1	5.25	5.6	4.7
	T600	10×20	8.04	7.7	7.56	7.2	7.1	7.5	7.8	6.7

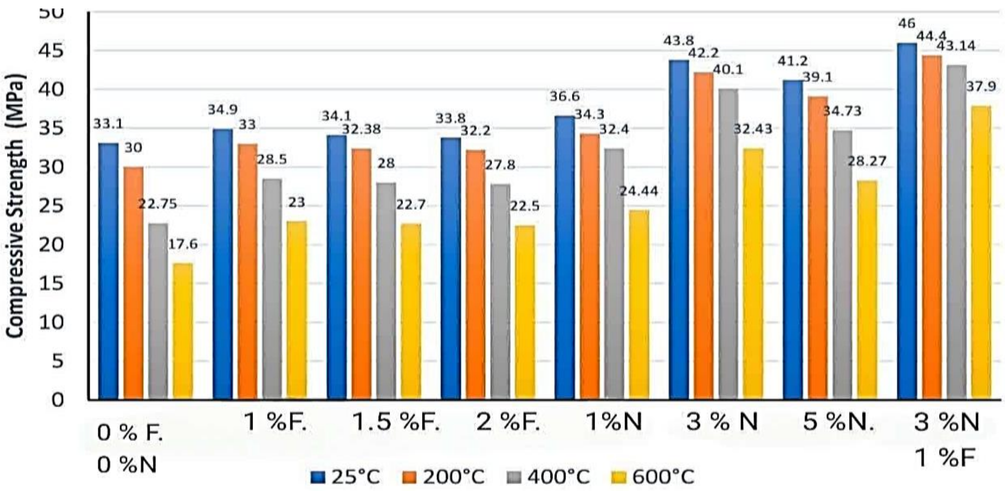


Figure 18. Compressive strength of samples at different temperatures

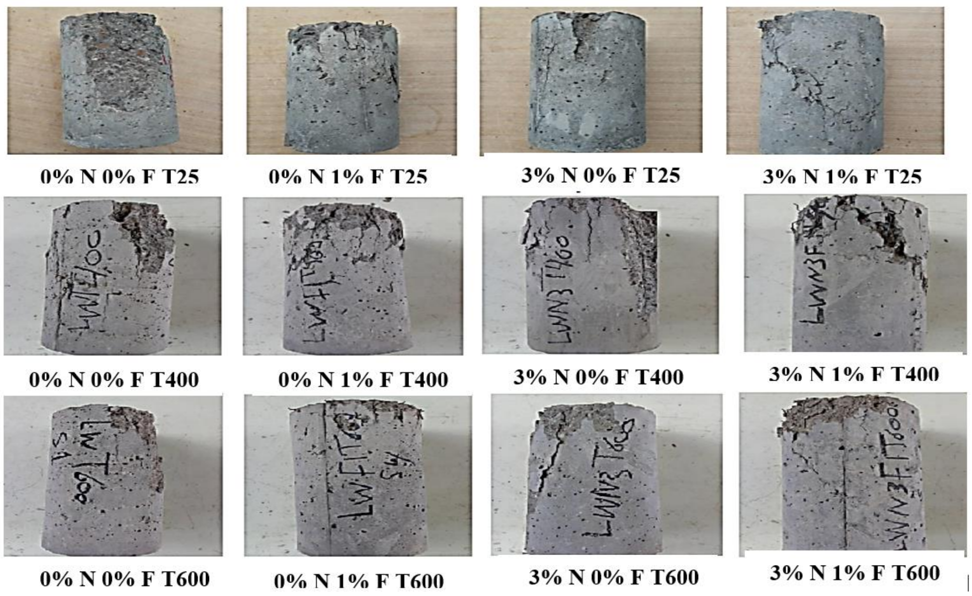


Figure 19. Pictures of samples' compression test

In the sample with nano- SiO_2, the failure rate is lower compared to the control sample, and the most satisfactory results are related to the sample with 1% of fibers.and 3% silica nanoparticle is that the amount of local corrosion and damage in the sample is greatly reduced, and a small prevalence was found in the sample. According to the figures, the process obtained at 400 ºC is similar to that at 25 ºC.

Furthermore, compared with the 25 ºC samples, only the damage rate of the samples increased, and the resistance also decreased. According to the figures, the orientation obtained at 600 ºC is similar to the directions at 25 and 400 ºC. Moreover, only the damage rate of the samples increased compared to 25 and 400 ºC, and the resistance also decreased. The method of cracking and damage to the samples with fibers and samples has separate nano- SiO_2, and the presence of this material affects the crack pattern in the parts.

3. 4. Modulus of Elasticity The elasticity modulus elasticity was calculated according to Equation (1):

$$E = [(S_2 - S_1) / (\varepsilon_2 - 0.000050)] \quad (1)$$

{Where (E) is the modulus of elasticity in MPa, (S_2) is the stress corresponding to 40% of the ultimate load, (S_1) is the stress corresponding to the longitudinal strain of 50 millionths in MPa, and (ε_2) is the longitudinal strain produced by stress S_2.}

According to Figure 20 and Table 11, the effect of nano-SiO_2 and steel fibers on the modulus of elasticity of LWC has been investigated in all mix designs.

Results show that the modulus of elasticity of LWC increases when the amount of nano-SiO_2 and steel fibers increases. In general, by adding 1% steel fibers and 3% nano-SiO_2, the most significant impact on improving concrete's modulus of elasticity has been observed.

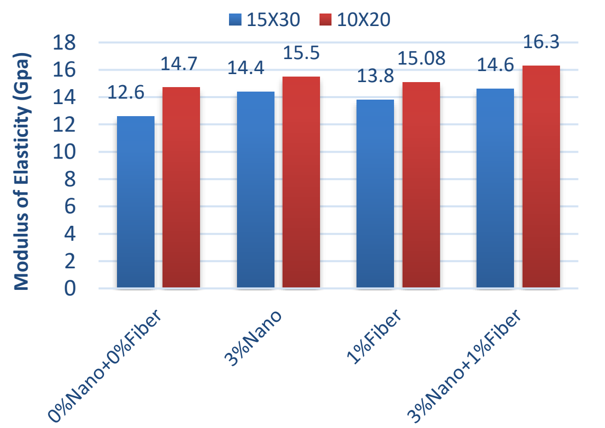


Figure 20. Comparison of the modulus of elasticity (GPa) of all concrete specimens

TABLE 11. The modulus of elasticity (GPa) of all concrete specimens

Sample Size	Temperature (ºC)	0% Nano+ 0% Fiber	3% Nano	1% Fiber	3% Nano+ 1% Fiber
15×30	25	12.6	14.4	13.8	14.6
10×20	25	14.7	15.5	15.08	16.3
15×30	200	9.8	11.09	9.41	11.3
10×20	200	10	12.03	11.07	12.7
15×30	400	5.66	8.3	6.3	8.5
10×20	400	6.1	8.9	7.13	9.1
15×30	600	3.26	5.3	4.11	5.6
10×20	600	3.5	5.4	4	5.7

Other studies [36] corroborate this finding. The elasticity of concrete's constituent materials, most notably cement paste, affects the concrete's modulus of elasticity. Therefore, the elasticity modulus improves by adding nano-SiO_2. This is also linked to reduced porosity in cement paste and enhanced compressive strength. Denser concrete results from increasing its elasticity modulus. The findings of other researchers [37] corroborate this. In general, when the compressive strength increases, the modulus of elasticity also increases, and when the porosity in the cement paste is reduced by adding nano-SiO_2 and metal fibers, the modulus of elasticity increases.

3. 5. Compressive Stress-strain Relationship between LWC and Strain at Peak Strength Figures 21 and 22 show that adding steel fibers and nano-SiO_2 to LWC changes its behavior after maximum compressive stress, making the compressive stress-strain curve tangent less steep.

The maximum stress-strain curve was observed by adding 1% fiber and 3% nano- SiO_2 for all sample sizes. The increase in the modulus of elasticity with the

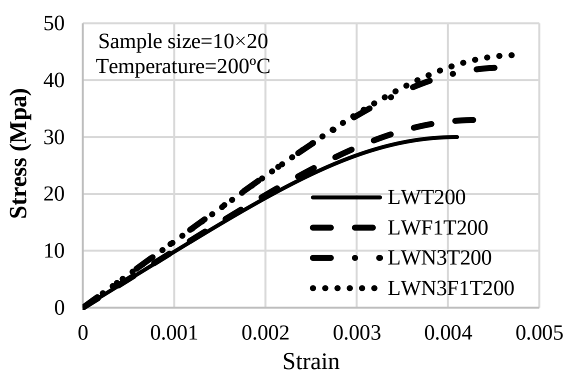
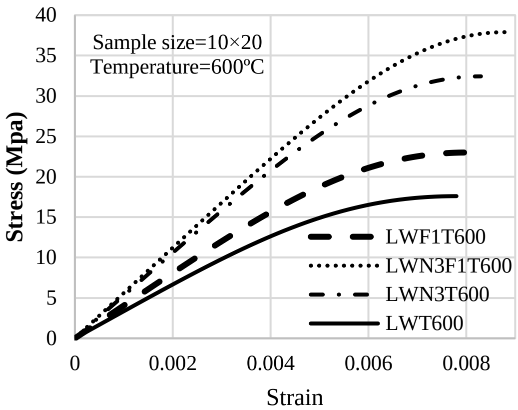
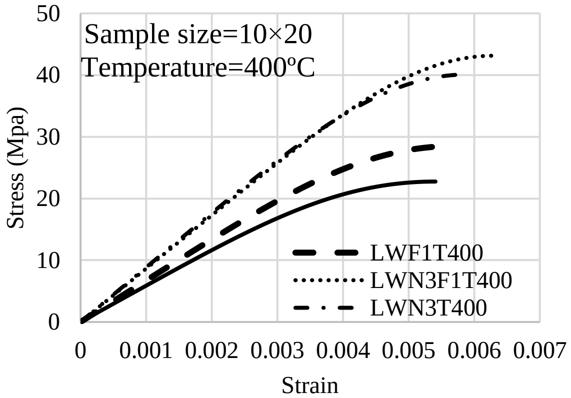
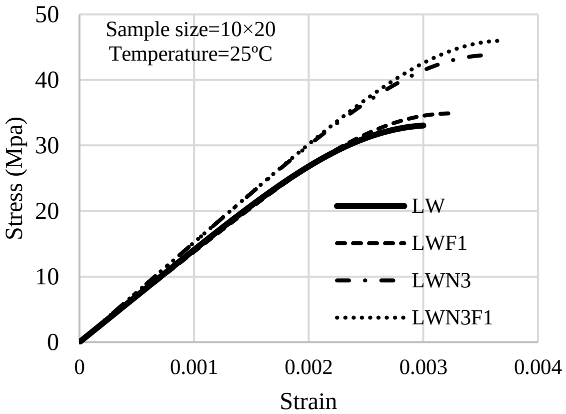
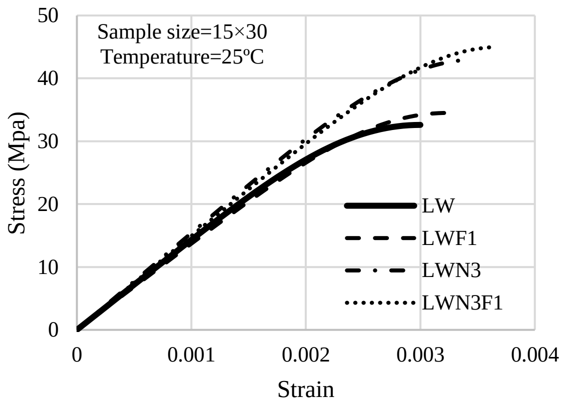


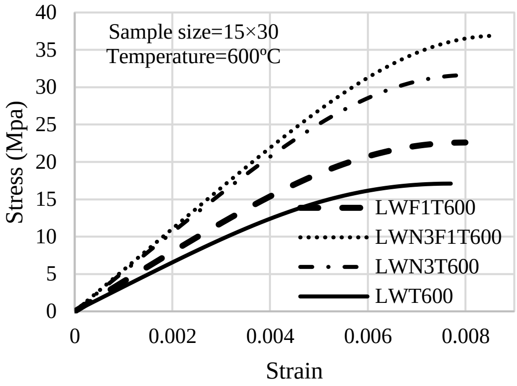
Figure 21. The stress-strain diagram of 10x20 cm samples for all LWC mix designs

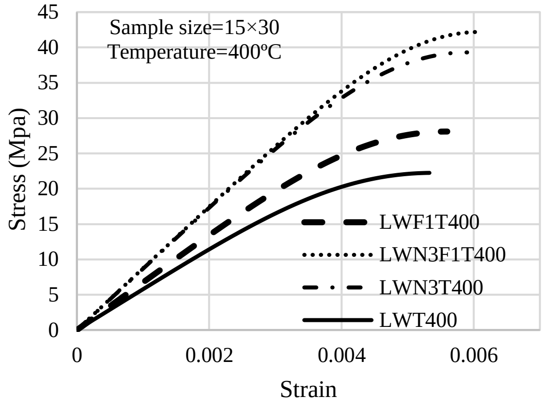












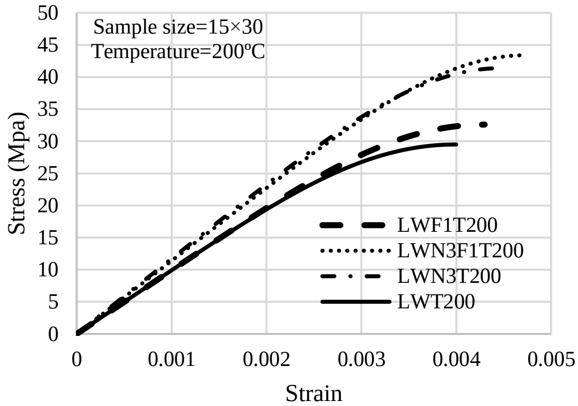


Figure 22. The stress-strain diagram of 15x30 cm samples for all LWC mix designs

increase in nano- SiO_2, which is associated with a decrease in the porosity of the cement paste and an increase in compressive strength, is evident. Due to the denser concrete composition, hardness increases the modulus of elasticity. The results of other studies confirmed with reported data in literature [24, 38]. Nanoparticles and fibers improve concrete's elasticity modulus. Figures 21 and 22 show the peak stress curves in the nano- SiO_2-containing samples.

3. 6. SEM Images of LWC Samples In Figures 23 and 24, images prepared by SEM are shown. Figure 23 shows a concrete structure without nano-SiO_2 and steel fiber, and Figure 24 shows concrete in the presence of 3% nano-SiO_2.

As shown in the figures above, the microstructure of concrete containing nano-SiO_2 has been significantly improved and is more uniform than regular concrete. Large, clustered calcium hydroxide crystals can be seen in the control sample when no nano-SiO_2 is present. However, in the sample with nano-SiO_2, the calcium hydroxide crystals reacted with the silica to produce a very resistant H-S-C gel with a very dense, compact structure. In this way, using nano-SiO_2 in concrete significantly improves its microstructure, increases the cement matrix density, and strengthens the transition zone between the aggregate and the cement paste. Figure 24 shows the structure of concrete without nano-SiO_2 and steel fiber at a temperature of 600ºC and Figure 25 shows concrete in the presence of 3% nano-SiO_2 at the same temperature of 600ºC.

It is evident from the images obtained from the SEM test that applying high heat to concrete has caused fundamental changes in the microstructure of concrete and the cement paste matrix. The effects of temperature on concrete can be attributed to the non-hydration of cement paste, increase in porosity, decrease in available moisture, thermal expansion, change in pore pressure, decrease in strength, and thermal cracking caused by incompatibility, creep, and thermal separation. The microstructure of induced concrete is greatly affected and structurally weakened when ordinary concrete images are taken at high temperatures. According to the pictures, the creation of a tree structure, the presence of numerous capillary pores caused by the evaporation of the water in the capillary spaces in the hydrated calcium silicate gel (H-S-C), and the decrease in the amount of hydrated H-S-C gel in the dark areas are evident, which indicates the weakness in the concrete microstructure after applying high temperature to the concrete.

Additionally, in 2018, Wang et al. [24] investigated the effect of nano-SiO_2 on the compressive strength and shrinkage of LWC made from artificial aggregates and found similar outcomes.

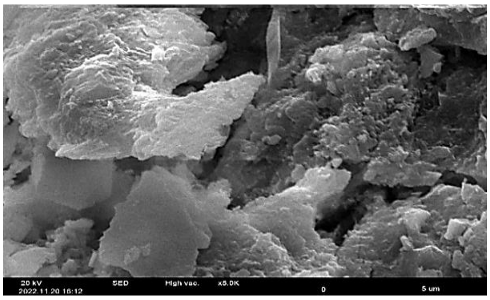


Figure 23. SEM picture of an LWC sample at 25ºC

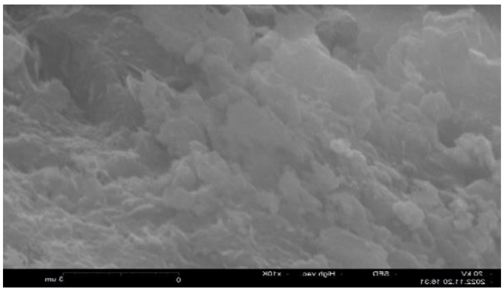


Figure 24. SEM image of a LWC sample containing 3% nano-SiO_2 at 25ºC

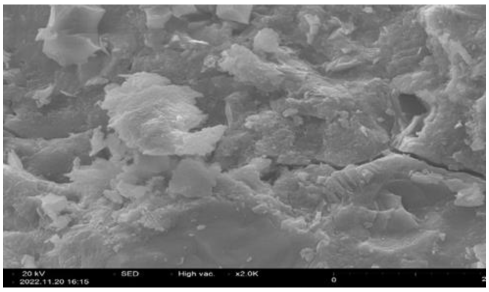


Figure 25. SEM picture of an LWC sample at 600ºC

3. 7. Effect of Sample Size on Mechanical Properties An analysis of the effect of sample size on compressive strength is shown in Figures 26-30.

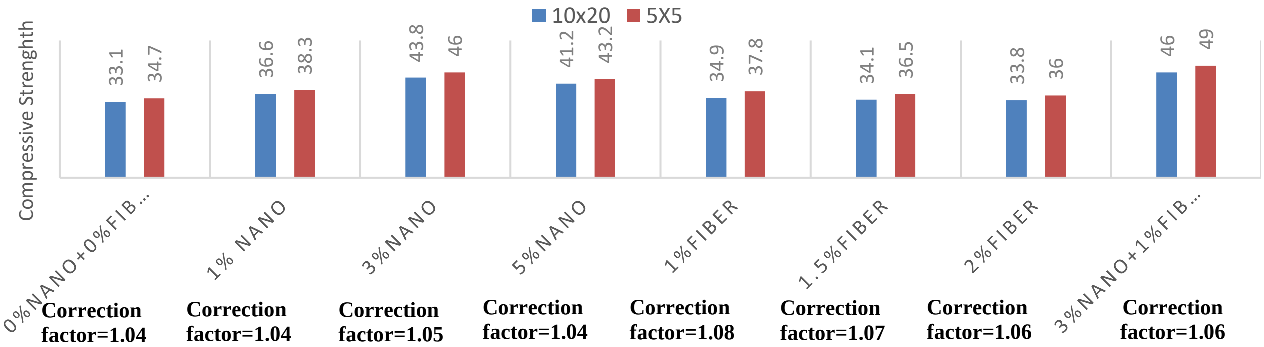


Figure 26. The effect of sample size on compressive strength at 25ºC

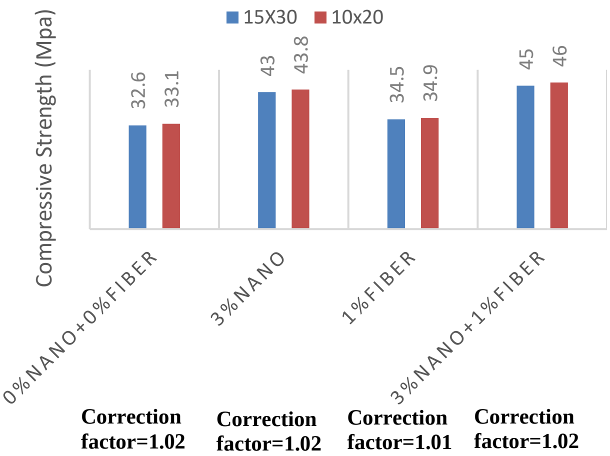


Figure 27. The effect of sample size with dimensions 15x30 cm and 10x20 cm

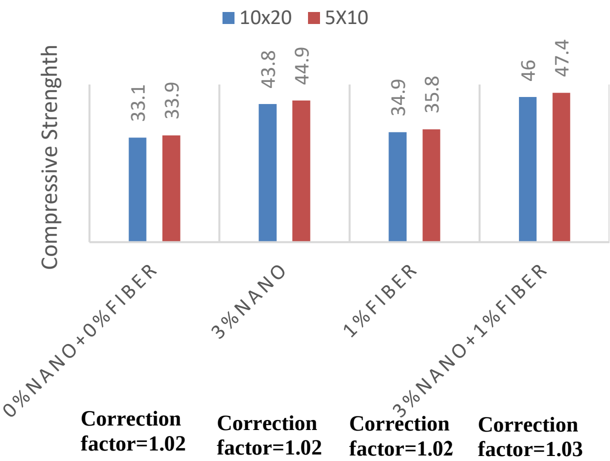


Figure 28. The effect of sample size with dimensions 5x10 cm and 10x20 cm

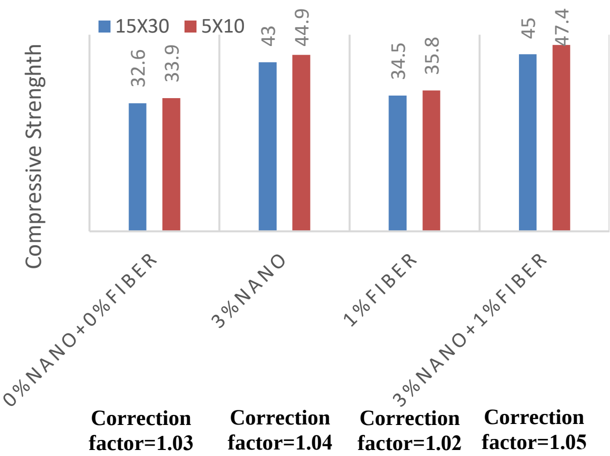


Figure 29. The effect of sample size with dimensions 15×30 and 5×10

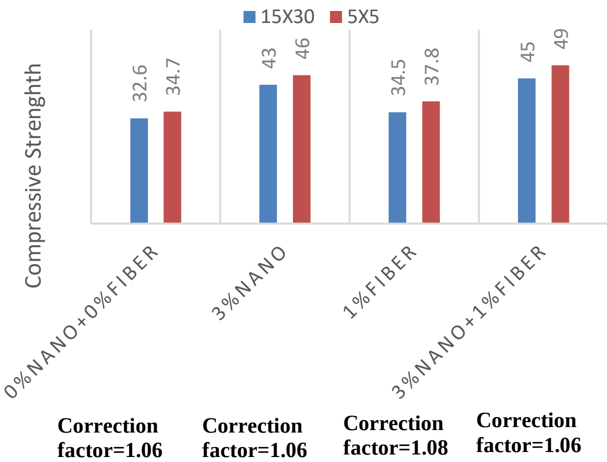


Figure 30. The effect of sample size with dimensions 15×30 cm and 5×5 cm

The effect of sample size is clearly seen in the results, as shown in the above figures. By reducing the dimensions and volume of the sample, the compressive strength increases. From the results it can be seen that the factors extracted by multiplying them by the resistance of the non-standard samples,the resistance of the standard sample is obtained according to the standard specifications [39].

4. CONCLUSIONS

This paper studied LWC behavior after exposure to high temperatures. It also examined its behavior when nano-SiO_2 fibers, fibers, or both are added at high temperatures. This study also examined the effect of changing the sample dimensions on the compressive strength of the samples. For this, four mixing designs were made with nine groups, each containing sufficient samples of different sizes. The samples were exposed to temperatures of 200, 400, and 600 ºC. Then their behavior was verified by analyzing the curves of compressive strength, pressure, strain, modulus of elasticity, and residual strength. The results were as follows:

- The ultimate compressive strength was observed when 3% nano-SiO_2 or 1% steel fibers were added to the mixture separately, with an average increase in compressive strength of 32.33% and 4.23%, respectively. Thus a composite mixture of 3% nano-SiO_2 and 1% fibers was made.
- When samples were exposed to high temperatures, their compressive strength and weight decreased. This is not preferred in concrete used in construction. The fibers' ability to stop the cracks' formation and the nano-SiO_2's ability to reaction

pozzolanic and form a gel that helps fill the pores in weak areas in the concrete contributed to limiting this behavior.

- The composite mixture of nano-sio2 and fibers had the best behavior to retain the residual strength of the samples (ratio of high heat resistance to ambient temperature resistance) after exposure to high temperatures, the residual compressive strength values for the composite mixture were (96.5%, 93.8%, and 82.4%) at exposure to a temperature of 200, 400, and 600, respectively.
- In the results obtained from the stress-strain curves, we notice increased stress and peak tension in designs containing nano-SiO_2 material. During this period, fine cracks have not appeared yet. For this reason, we note that the effectiveness of the fibers is low, and the effectiveness of nano-SiO_2 is higher because the fibers in the temperature act as a bridge to prevent cracks and nano-SiO_2 improve the microstructure in a period before exposure to temperatures.
- The effect of different sample sizes on the results was investigated. When the sample size decreased, the resistivity value increased. A comparison was made between standard and non-standard samples, and appropriate factors were extracted to convert them into standard samples.

This was a preliminary study of LWC behavior with nano- SiO_2 and fibers under static loads. It is suggested to study its behavior with nano- SiO_2 fibers under dynamic loads and with different strain rates to know the endurance of this type of concrete under earthquakes or explosions. It is also proposed to study its behavior by adding other types of fibers.

5. ACKNOWLEDGMENTS

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Persian Abstract

چکیده

هدف اولیه در طراحی مهندسی ساختمان، کاهش وزن سازه و افزایش مقاومت آن در برابر آتش سوزی و زلزله است زیرا در سازه ها، آتش سوزی اجتناب ناپذیر است. در این مقاله از بتن سبک به دلیل مزایای ویژه آن بخصوص کاهش وزن و افزایش مقاومت در دماهای بالا به دلیل خاصیت عایق حرارتی آن استفاده شده است. همچنین با افزودن نانو سیلیس یا الیاف فلزی یا هر دو به بتن سبک، به بررسی رفتار بتن سبک پرداخته شده است. برای این منظور در چهار دسته کلی طرح اختلاط بتن ارائه شده است: نمونه های بدون الیاف و نانو سیلیس، نمونه هایی با درصدهای مختلف نانوسیلیس ونمونه هایی با در صد های مختلف الیاف فلزی و نمونه‌هایی با الیاف و نانوسیلیس با هم. نتایج نشان داد که در دماهای بالابه نمونه‌های بدون نانو سیلیس و الیاف فلزی آسیب وارد شده است. تغییر رنگ، کاهش مقاومت فشاری و کاهش وزن نمونه ها بدلیل آسیب بتن در دماهای بالا بوده است. با افزودن نانو سیلیس و الیاف فلزی، خواص بتن را در تمام دماها بهبود یافته است، زیرا واکنش پوزولانی نانو سیلیس، ساختار بتن را بهبود می بخشد و الیاف فلزی از ایجاد ترک در بتن جلوگیری می کند. این مطالعه همچنین به بررسی تاثیر تغییر ابعاد نمونه ها بر روی مقاومت فشاری پرداخته است و نتایج نشان دهنده افزایش مقاومت نمونه های با اندازه کوچکتر است.