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Effect of High Elevated Temperature on the Behavior of Concrete Containing Slag and Nano Clay

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Abstract Fires have the capacity to result in significant harm to both people and their belongings. Concrete is a primary structural material extensively utilized in construction because of its strength, durability, and ease of production, but its fire resistance is its most distinctive advantage over other construction materials. Yet, using cement in construction is gradually gaining global influence because of the increasing rate of carbon dioxide (CO_2) emission and global warming caused by it. So, in a trial to find a partial replacement for cement, this paper investigated how elevated temperatures affect compressive strength in slag and nano-modified concrete mixtures. Concrete mixtures, containing nanoclay replacing 0.3%, 0.5%, and 0.8% of cement by weight, and slag replacing 50% of cement by weight, were examined for compressive strength change in fixed temperatures fluctuating between 25 ℃ and 700 ℃ for 2 hours. Results showed that in the mixtures including NC and slag the compressive strength increased up to 300 ℃ and improved the compressive strength by 40%, 54%, and 44% respectively when exposed to 700 ℃ for 2 hours. Using NC and slag to the concrete mix leads to improvement in the compressive, tensile and flexural strength when compared to the control mix.

Keywords Concrete, Nanoclay (NC), Slag, Compressive Strength, Elevated Temperature, Mass Loss

1. Introduction

Concrete is extensively utilized as a fundamental material in the building sector because of its notable features regarding fire resistance, durability and compressive strength. Concrete is a mixture of materials that exhibits fast changes in its properties resulting from high-temperature exposure. The concrete structures' ability to endure and survive extreme temperatures is regarded as a crucial determinant of their longevity and performance throughout time.

Concrete is widely regarded as a highly effective material for resisting fire in construction. However, on high-temperature exposure, the cement paste's chemical structure and the aggregates' physical characteristics undergo changes, causing a deterioration in the concrete mechanical and physical characteristics [1-4]. Elevated temperatures result in loss of mass, decrease in mechanical qualities, and decrease in durability.

Many researchers have examined the characteristics of concrete including ordinary Portland cement (OPC) and have subjected it to high temperatures. They noticed that the concrete compressive strength reduced by approximately 20% and 70% once exposed to elevated temperatures of 400 ℃ and 800 ℃ respectively. Concrete fire resistance is evaluated using testing methodologies specified in ASTM-E119 [5]. Dehydration, namely the liberation of chemically bonded water from calcium silicate hydrate (C-S-H), becomes notable once temperature exceeds 110 ℃ [1].

Calcium hydroxide, a crucial ingredient in cement mortar, undergoes dissociation at approximately 530 ℃, leading to the concrete contraction [2]. The decrease of the concrete compressive strength was notably greater in samples subjected to a temperature of 600 ℃. At a temperature of 800 ℃, the breakdown of C–S–H gels and $Ca(OH)_2$ led to complete disintegration of the concrete [3]. According to Yonggui et al. [6], the concrete compressive strength declined by 40% to 60% when exposed to temperatures ranging from 400 to 600 ℃. Additionally, the weight of the concrete decreased dramatically with increasing temperature. The decrease occurred gradually till reaching a temperature of 800 ℃ [4].

Cement production has a substantial contribution to emissions of carbon dioxide [7], due to its extensive utilization globally [8]. The construction material business requires cement approximately 4.65 billion tons annually on a global scale, resulting in the production of CO_2 approximately 4 billion tons [9]. This adds up to 7% of the overall human-caused impact [10]. Increased utilization of supplementary cementitious materials (SCM) will greatly diminish carbon dioxide emissions. Hence, there is an increased emphasis on finding novel cement replacements.

Mineral admixtures are commonly utilized as additives in concrete to develop the overall material performance. The use of nanoparticles as a strengthening ingredient in concrete has garnered significant attention due to recent technological breakthroughs. The unique chemical and physical characteristics of nanoparticles may improve the qualities of cement-based materials at the nano and microscale, developing overall performance. Nanoparticles exhibit reactivity according to their diminutive size of particles and substantial surface area. This reactivity serves to bolster the transition layer between mixed cement mortar, resulting in reduced permeability and heightened strength [11]. Furthermore, nanoparticles possess significant potential in augmenting the concrete fire [12].

Nanoparticles, which are fundamental units of nanomaterials, have been demonstrated to augment the concrete lifespan and durability. Nano Metakaolin, nano silica, nano titanium oxide, nano alumina, and carbon nanotubes are advanced nanomaterials that showed compelling proof of developing the concrete performance. This improvement contributes to construction of infrastructure and facilitates long-term monitoring [13]. The presence of NS and NC in concrete causes a decline in permeability, an increase in strength, and a denser microstructure forms [14-16].

Adding NC to concrete will increase the compressive strength [13] because of the high pozzolanic reactivity of NC particles. The needle action mechanism may be achieved by NC particles due to their long structure with tilted edges [16]. Although extensive study was conducted to determine the ideal amount of NC for improving the mechanical characteristics of self-compacting concrete (SCC), the ideal NC amount remains conflicting. Researchers have found that replacing 0.75 - 1 % of cement weight with NC significantly enhances the concrete mechanical properties. However, Hosseini, P., et al. and Hakamy, A. et al. [17, 18] found that incorporating 6-7.5% nano-clay into concrete can enhance the mechanical characteristics. In addition [19, 20], researchers discovered that substituting 10% of the cement with NC resulted in a significant enhancement of 46.8% in tensile strength and 63.1% in compressive strength in comparison with the standard mixture [21]. Substituting 5% cement with NC results in the maximum levels of compressive and flexural strengths, as indicated by reference [16]. The NC particles' rapid reactivity with free lime throughout hydration is due to the particles' tiny size, amorphous structure, and wide surface area. A secondary C-S-H gel is created as a result of this reaction, filling the capillary holes in the SCC matrix. If proportion of non-compacted material in concrete surpasses the ideal ratio, Concrete's compressive strength decreases as a result. The compressive strength decreases when substituting 10% of the cement in the control specimen [16]. The possible reason for this is that inadequate dispersion of NC particles hindered the cement hydration process and caused the clustering of NC particles surrounding the cement particles, causing the formation of weak regions in the matrix itself [17, 22]. Alomayri [23] discovered that the geopolymer pastes compressive strength strengthened with basalt fiber and 3% nano-$CaCO_3$ (NCC) was 17.2% better than the compressive strength of the standard paste. That development might be linked to the ability of suitable nanoparticles to obstruct the small and extremely small empty spaces, additionally the efficiency of NCC to speed the geopolymerization process. Researchers [24] found that the NCC and NS-infused ultra-high performance concrete's (UHPC) mechanical properties increased as the amount of nanoparticles increased. However, the properties decreased when the nanoparticle content exceeded 1% and 3.2% respectively. An enhancement in nanoparticle concentrations will result in losses in flexural and compression strength. This can be due to a higher volume of capillary gaps and trapped air, in addition to a poorer interface between fibers and matrix.

The addition of NC and NS as cement replacements in concrete enhanced concrete mechanical properties at high temperatures as high as 200 ℃ [25]. The mechanical properties of concrete degrade when temperature exceeds 300 ℃ [26, 27]. According to Nadeem et al. [28], a temperature of 400 ℃ might be considered the essential threshold for a transformation in concrete properties. Concrete with NS and NC is cost-effective and exhibits excellent performance because of the gradual degradation of traditional concrete under extremely circumstances. In contrast, the fire resistance and resilience to high temperatures of nano-concrete determine its durability [29]. Multiple studies have discovered that the decline in non-concrete materials is not uniform when exposed to different high temperatures. There were no notable differences in the impact of mechanical characteristics at high temperatures between NC and NS, as stated in reference [29].

Another approach to address the issue of cement is the efficient employment of waste materials, such as industrial byproducts, as substitutes for cement [30]. One of the products is slag, which is a waste material that is generated during the pyro-metallurgical processing of Ferro-nickel [31-35]

The incorporation of Crepidula fornicate shells and Ferronickel slags in cement, replacing up to 30% of the cement content, lacks a noticeable impact on its workability in its fresh form. Nevertheless, when the inclusion exceeds 30%, a minor decrease in workability is noticed. The decline in workability is caused by the absorption of water of these compounds, which have a large specific surface area [36].

Studies have shown that the usage of Ground granulated blast furnace slag (GGBFS) has been noticed to ameliorate many concrete performance attributes [37-40]. GGBFS offers improved durability, including a high level of resistance to chloride penetration, defense against alkali-silica reactions, and protection against sulfate assault. By incorporating GGBFS as an alternative to OPC, the concrete durability and strength can be improved. This is achieved by generating a more compact structure, resulting in an extended lifespan for concrete constructions [37]. The quantity of GGBFS is inversely proportional to both the coefficients of diffusion and chloride ion permeability. Nevertheless, as the quantity of Ground granulated blast furnace slag replacement has been increased, the resistance to carbonation decreased, as indicated by previous research [38]. GGBFS can significantly decrease the diameters of pores and the total volume of pores [39].

The findings indicate that the extent of corrosion on the surface is influenced by the quantity of GGBFS substitution, and the concrete with a higher proportion of GGBFS exhibits enhanced resistance to steel corrosion. Substituting GGBFS may reduce the initial concrete strength, even so it can enhance the subsequent strength and enhance durability and microscopic structure of the material [41].

The blast-furnace slag (BFS) concrete specimens were subjected to high temperatures between 200 and 800 ℃. The findings indicate that adding BFS did not have a significant impact on weight loss [42, 43]. The after-concrete compressive strength that includes BFS is analogous to OPC concrete [44]. Nevertheless, the performance of concrete that includes BFS was inferior to OPC concrete when the temperature reached beyond 400 ℃ [42]. The concrete mass loss, dynamic modulus of elasticity, and compressive strength including non-GGBFS were measured after being subjected to a temperature of 800 ℃. The findings indicate that ultrasonic pulse velocity and the residual compressive strengths were less than the OPC concrete [43].

Nevertheless, there are only few literary works that discuss the effect of high temperature on the concrete characteristics that contains GGBFS. Researchers investigated the mechanical characteristics of GGBFS concrete when subjected to 100 ℃ [45].

Temperatures are between 200 and 350 degrees Celsius. The findings indicated that the mechanical characteristics of the concrete did not see a substantial decline at a temperature approaching 100 ℃. At a temperature approaching 200 ℃, the decrease in mass was negligible. After being subjected to a temperature of 350 ℃, the splitting tensile strength, modulus of elasticity, and compressive strength decreased by around 40% of their initial values [46].

Fire resistance refers to the capacity of concrete to allow structural elements to endure fire or provide protection against it. This encompasses the ability to withstand fire or to maintain a certain structural function, or both. The increase in temperature results in a reduction in concrete strength, potentially compromising its structural integrity. The rate of strength reduction is influenced by several elements, including the temperature increase of the fire, the insulating qualities of concrete, the heating rate, the dehydration of C–S–H gel, and the thermal incompatibility between aggregates and cement paste [47]. Fire testing methods assess the fire-resistant characteristics of concrete. The predominant and nationally recognized testing protocol is the one established by ASTM-E119. The impact of fire on concrete reinforced with natural pozzolans has not been thoroughly examined. Researchers and prior research exhibit divergent views on the alterations in the properties of concrete, specifically within the temperature range of 100–250 ℃. It is widely recognized that temperatures over 300 ℃ result in a decline in mechanical characteristics [48–49]. This study aims to provide researchers with enhanced insights into the behavior of concrete under varying heat exposure settings, both with and without the incorporation of nano and slag additions.

2. Materials and Methods

2.1. Experimental Work

This research investigates to study concrete compressive strength as it is the most significant factor of concrete mechanical characteristics. The specimens of concrete were prepared as follows: 0.3%, 0.5% and 0.8% of cement weight were replaced with NC and 50% with slag, Tests were conducted on the specimens to evaluate the compressive strengths at various curing times 7, 28, 56 and 90 days. These mixtures were molded in cubes (100*100*100 mm) for 1 day at room temperature and then demolded to be put in curing water for the previously mentioned periods. The main purpose here is to study the impact of high temperatures (100, 300, 500 and 700 ℃) for 2 hours. After reaching these temperatures, the specimens were cooled by two methods: 1- The furnace was stopped and left to cool down naturally avoiding the consequences of a temperature gradient on the concrete mechanical characteristics. 2- The specimens were removed and allowed to cool down at ambient temperature immediately after turning the furnace off.

2.2. Material Properties

This section provides an elaborate account of the materials employed in this investigation. The materials are: Aggregates, cement, NC, slag and superplasticizer as shown in Figure 1.

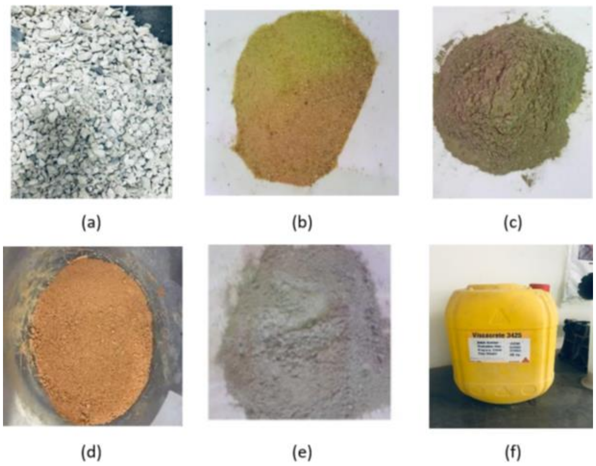


Figure 1. Coarse Aggregates (a), Fine Aggregates, (b) Cement, (c) Nano-clay (d), Slag, (e) and Superplasticizer (f)

2.2.1. Coarse Aggregates

The size of basalt used in this research is 1 with 2.7 specific gravity, 1.48 t/m^3 bulk density, an absorption rate of 0.79 and a crushing value force of 15.2%.

2.2.2. Fine Aggregates

Sand with 2.6 specific gravity, bulk density: 1.7 t/m^3, absorption rate: 1.63 and fineness modulus: 2.25 was used in this experimental work.

2.2.3. Cement

Ordinary Portland cement (CEMI 42.5 N) that conforms to ASTM C150 [50]. The specific surface area and specific gravity were 35 m^2/gm and 3.15, respectively. The chemical properties of cement are shown in Table 1.

Table 1. The cement chemical composition

Oxide composition	Mass %
SiO_2	19.78
Al_2O_3	5.98
Fe_2O_3	2.85
CaO	63.26
MgO	1.99
SO_3	2.12
K_2O	1.3
Na_2O	1.02
Loss on Ignition	1.68

The characteristics of the utilized cement were chosen according to ASTM C188 [51], ASTM C187 [52] and ASTM C191 [53].

2.2.4. Nano-clay (NC Kaolina)

The nano used is a light brown powder with specific gravity: 2.53 and specific surface area: 11,435 cm^2 /gm [54]. And chemical properties are given in Table 2.

Table 2. The chemical properties of CN

Oxide composition	Mass %
SiO_2	61.33
Al_2O_3	18.79
Fe_2O_3	6.08
CaO	0.69
MgO	0.43
SO_3	0.53
K_2O	0.52
Na_2O	0.48
Loss on Ignition	9.06

XRD Analysis:

The XRD analysis (Figure 2) shows that the nano-clay has a high amount of amorphous phase, reactive silica, and metakaolinte. The low amount of mullite and kaolinite indicates a more reactive and amorphous nature of the nano-clay.

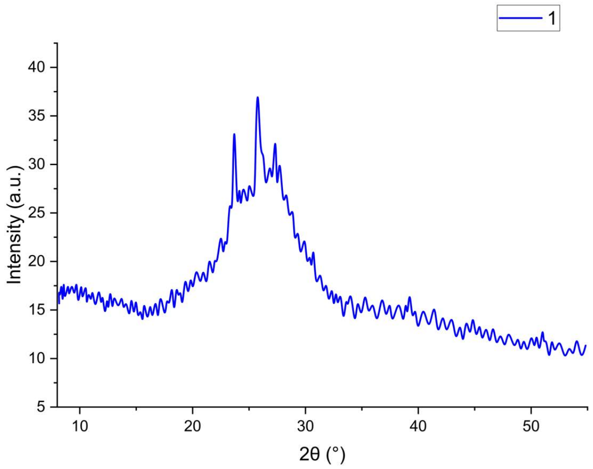


Figure 2. XRD of NC-Kaolin

2.2.5. Slag

The slag used is a white powder with specific gravity: 2.85, 0.15 µm particle size, 19450 m^2/kg fineness modulus and 146 m^2 /gm specific surface area [55]. Chemical properties are given in Table 3.

Table 3. The slag chemical composition

Oxide composition	Mass %
SiO_2	34.37
Al_2O_3	14.04
Fe_2O_3	0.76
CaO	39.66
MgO	7.24
SO_3	1.82
K_2O	0.37
Na_2O	0.22
Loss on Ignition	0.97

XRD Analysis:

The glassy slag is primarily composed of amorphous phases, which account for 69.65% of the material. The low amount of crystalline quartz (1.95%) suggests a highly reactive nature of the slag as shown in Figure 3.

Potential Benefits:

The combination of the high specific gravity, large specific surface area, favorable chemical composition and mineralogy of the nano-clay suggests that it may be a functional replacement or supplementary material for cement in concrete applications. The improved packing, increased surface area for interaction, and potential chemical reactivity can enhance mechanical properties, durability, and overall performance of the concrete. This enhanced reactivity, combined with the other favorable physical properties, indicates the potential for the nano-clay and glassy slag to improve the overall performance and concrete durability when used as a cement substitute or supplement. However, as mentioned earlier, further testing and optimization of the mix design would be necessary to fully evaluate the effectiveness of the nano-clay in concrete applications.

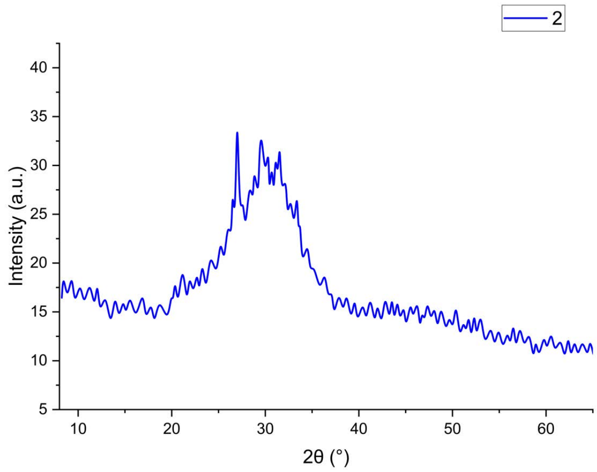


Figure 3. XRD of Slag

2.2.6. Superplasticizer

Namely Sika ViscoCrete_3425, was used to improve the workability of the material. It satisfies requirements of ASTM C494 [56] Type F and has a 1.08 specific gravity.

2.3. Concrete Mix Design

To accomplish the goals of this study, four specific concrete mixtures were made and examined, molded 3 beams, 3 cylinders and 120 cubes “3 cubes for each time and heat”. Table 4 presents the comprehensive design of all the mixes. The investigation of the hybrid mix was motivated by the distinct properties of each material. Prior research has found that NC might be categorized as a filler substance that enhances the density and concrete durability by reducing the void ratio [8]. However, the low absorption of water and smooth surface structure encourage particle movement during mixing, which counteracts the hydration properties of the cementitious system. During the initial phase, the poor reactivity of slag cement slows down the hydration process. This phenomenon results in a "diluting" effect as the water to cement ratio (w/c ratio) increases, resulting in a decrease in strength and a suppression of the temperature increase attributed to the release of heat during hydration. During the later stage, a second pozzolanic reaction occurs, causing depletion of calcium hydroxide and compaction of the solidified paste. This ends up in an improvement in the compressive strength and intensifies autogenous shrinkage strain resulting from better pore structure and the increased reduction of moisture [9]. Therefore, the combination of Slag and Nano clay can provide an intermediate interface between both materials. Figures 4 and 5 describe the process of preparing and water-curing specimens.

Table 4. Mix proportions (kg/m^3)

Mix	Cement	Water	Sand	Coarse	Slag	NC	Superplasticizer
CSN0 (Control)	450	157.5	625	1125	0	0	4.5
CSN1 (0.3% NC)	223.65	157.5	625	1125	225	1.35	2.24
CSN2 (0.5% NC)	222.75	157.5	625	1125	225	2.25	2.23
CSN3 (0.8% NC)	221.4	157.5	625	1125	225	3.60	2.21

Figure 4. Specimens after casting and curing

Figure 5. Curing of the specimens in water

3. Results

3.1. Compressive Strength

The results of the compressive strength test after various temperatures exposure for 2 hours (100 ℃, 300 ℃, 500 ℃, and 700 ℃) and ages (7, 28, 56, and 90 days) are shown in Table 5 for the "Cooling method (1) in furnace" and in Table 6 for the "Cooling method (2) in air".

The test results are provided for the control mixture and the three concrete mixtures including NC and slag materials (CSN1, CSN2, and CSN3).

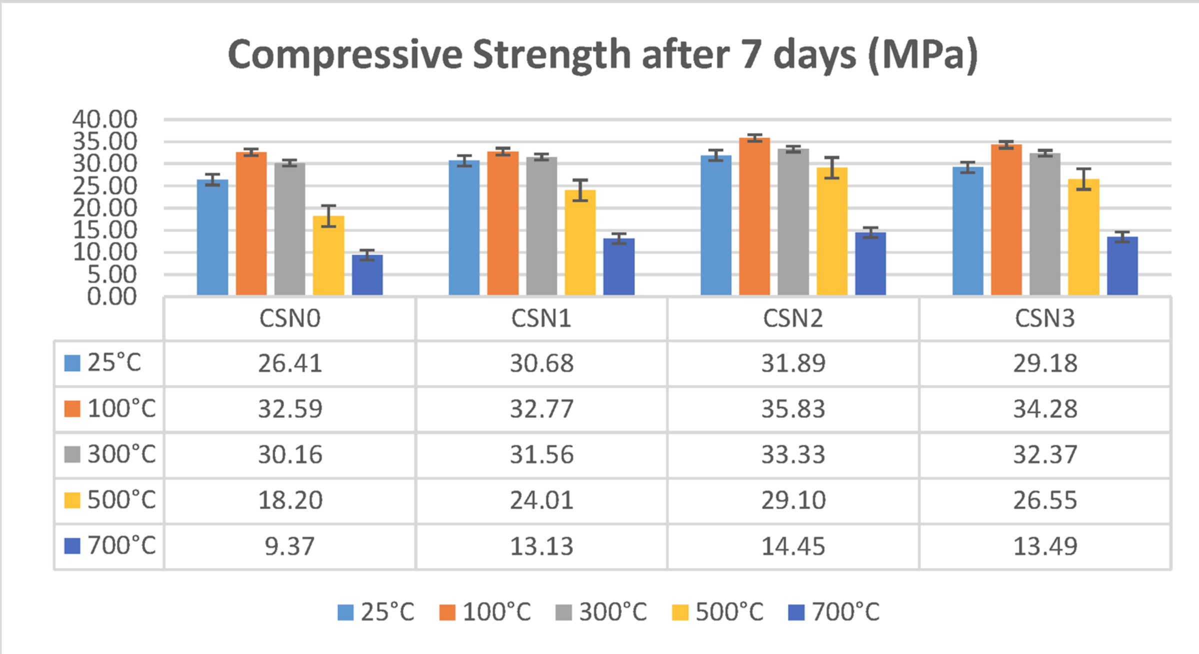
Figures 6-9 and 10-13 illustrate the results of the compressive strength test graphically for the two cooling methods.

Table 5. The compressive strength after diverse temperatures exposure (N/mm^2)

Cooling method (1) in furnace					
Temperature	Age	CSN0	CSN1	CSN2	CSN3
25 ℃	7	26.41	30.68	31.89	29.18
	28	33.86	39.84	41.42	37.90
	56	34.72	40.64	42.25	38.66
	90	36.43	41.73	43.38	39.70
100 ℃	7	32.59	32.77	35.83	34.28
	28	42.32	42.56	46.53	44.52
	56	43.17	43.41	47.46	45.41
	90	44.64	45.54	49.88	47.99
300 ℃	7	30.16	31.56	33.33	32.37
	28	39.16	40.99	43.29	42.04
	56	39.95	41.81	44.16	42.88
	90	41.02	42.93	45.34	44.03
500 ℃	7	18.20	24.01	29.10	26.55
	28	23.64	31.18	37.79	34.49
	56	24.11	31.81	38.55	35.18
	90	24.76	32.66	39.58	36.12
700 ℃	7	9.37	13.13	14.45	13.49
	28	12.17	17.05	18.77	17.52
	56	12.42	17.39	19.15	17.87
	90	12.75	17.86	19.66	18.35

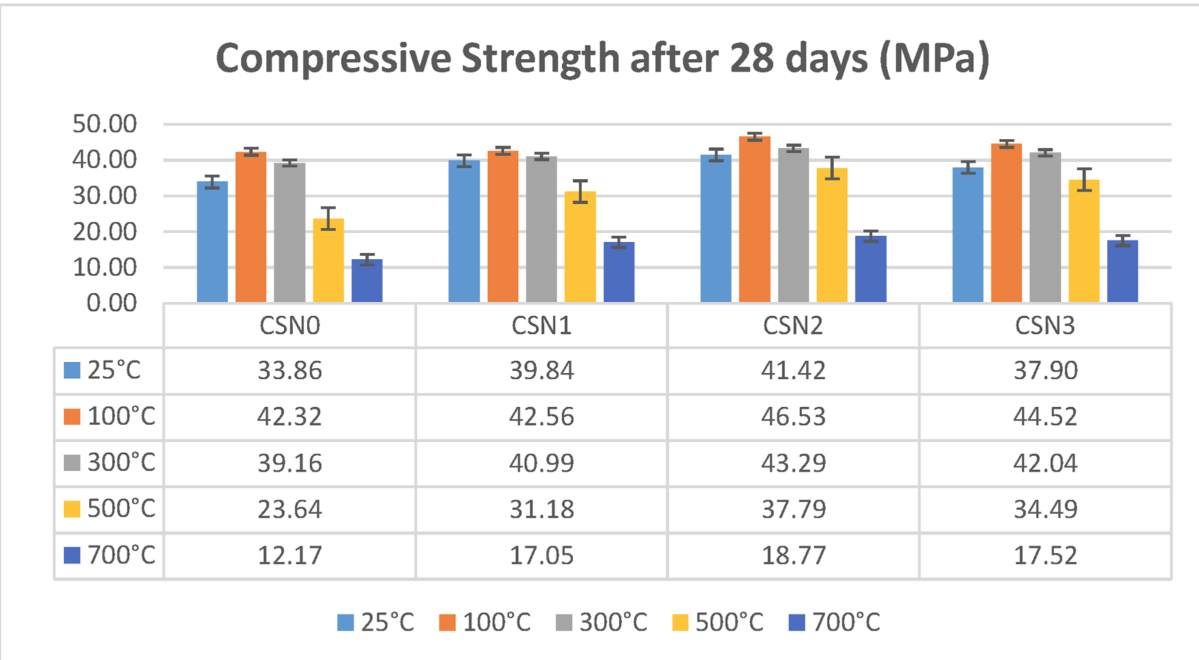
Table 6. The compressive strength after diverse temperatures exposure (N/mm^2)

Cooling method (2) in air					
Temperatures	Age	CSN0	CSN1	CSN2	CSN3
25 ℃	7	26.4	30.7	31.9	29.2
	28	33.9	39.8	41.4	37.9
	56	34.7	40.6	42.2	38.7
	90	36.4	41.7	43.4	39.7
100 ℃	7	22.8	27.9	31.5	27.4
	28	29.6	37.0	40.5	37.4
	56	30.2	37.8	41.3	36.3
	90	31.2	39.6	42.4	38.4
300 ℃	7	21.1	27.5	29.0	25.9
	28	27.4	35.7	37.7	33.6
	56	28.0	36.4	38.4	34.3
	90	28.7	37.3	39.4	35.2
500 ℃	7	12.7	20.9	25.3	23.1
	28	16.5	27.1	32.9	30.0
	56	16.9	27.7	33.5	30.6
	90	17.3	28.4	34.4	31.4
700 ℃	7	6.6	11.4	12.6	11.7
	28	8.5	14.8	16.3	15.2
	56	8.7	15.1	16.7	15.5
	90	8.9	15.5	17.1	16.0



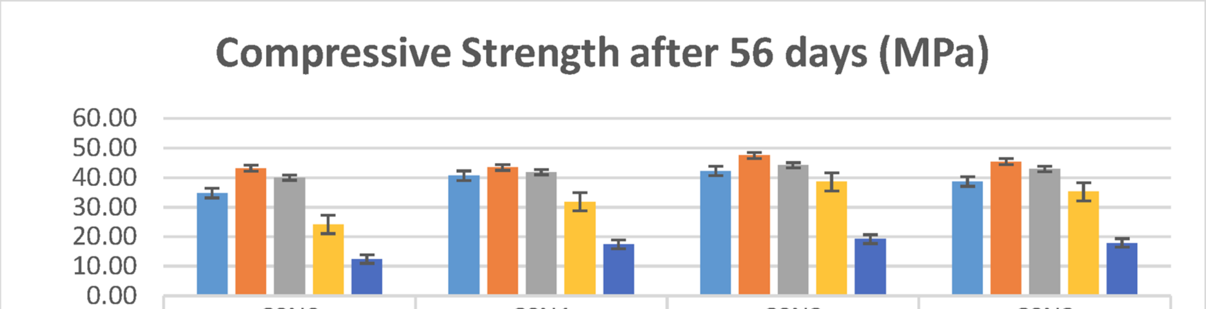
	CSN0	CSN1	CSN2	CSN3
25°C	26.41	30.68	31.89	29.18
100°C	32.59	32.77	35.83	34.28
300°C	30.16	31.56	33.33	32.37
500°C	18.20	24.01	29.10	26.55
700°C	9.37	13.13	14.45	13.49

Figure 6. The compressive strength after diverse temperatures exposure at age 7 days



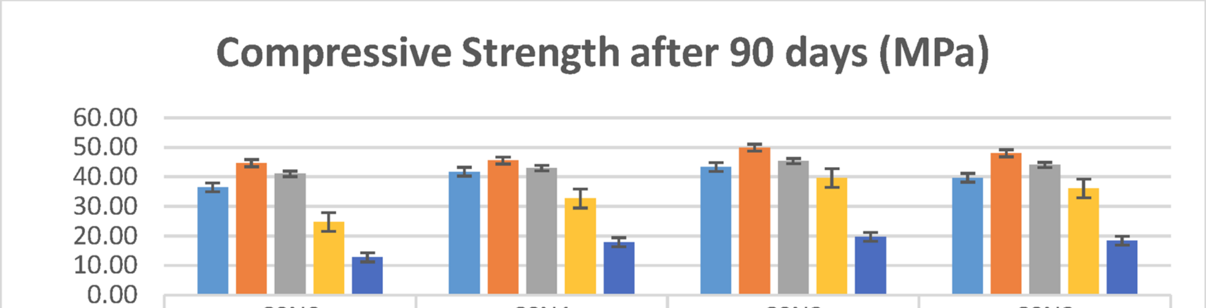
	CSN0	CSN1	CSN2	CSN3
25°C	33.86	39.84	41.42	37.90
100°C	42.32	42.56	46.53	44.52
300°C	39.16	40.99	43.29	42.04
500°C	23.64	31.18	37.79	34.49
700°C	12.17	17.05	18.77	17.52

Figure 7. The compressive strength after diverse temperatures exposure at age 28 days



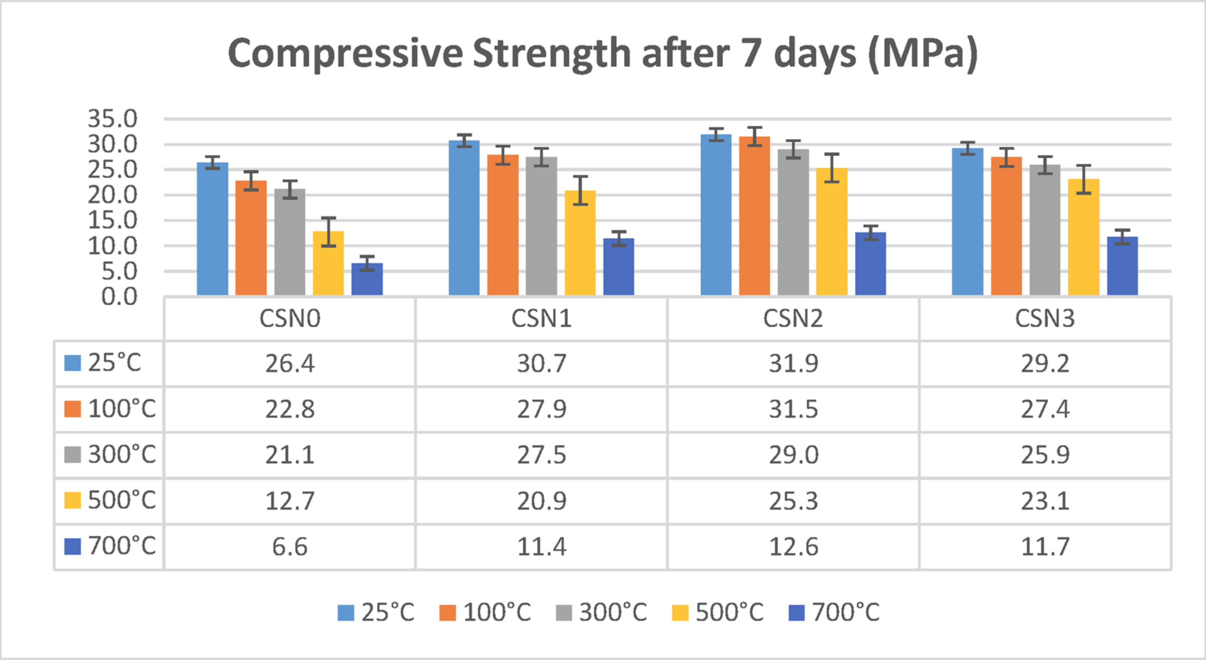
	CSN0	CSN1	CSN2	CSN3
25°C	34.72	40.64	42.25	38.66
100°C	43.17	43.41	47.46	45.41
300°C	39.95	41.81	44.16	42.88
500°C	24.11	31.81	38.55	35.18
700°C	12.42	17.39	19.15	17.87

Figure 8. The compressive strength after diverse temperatures exposure at age 56 days



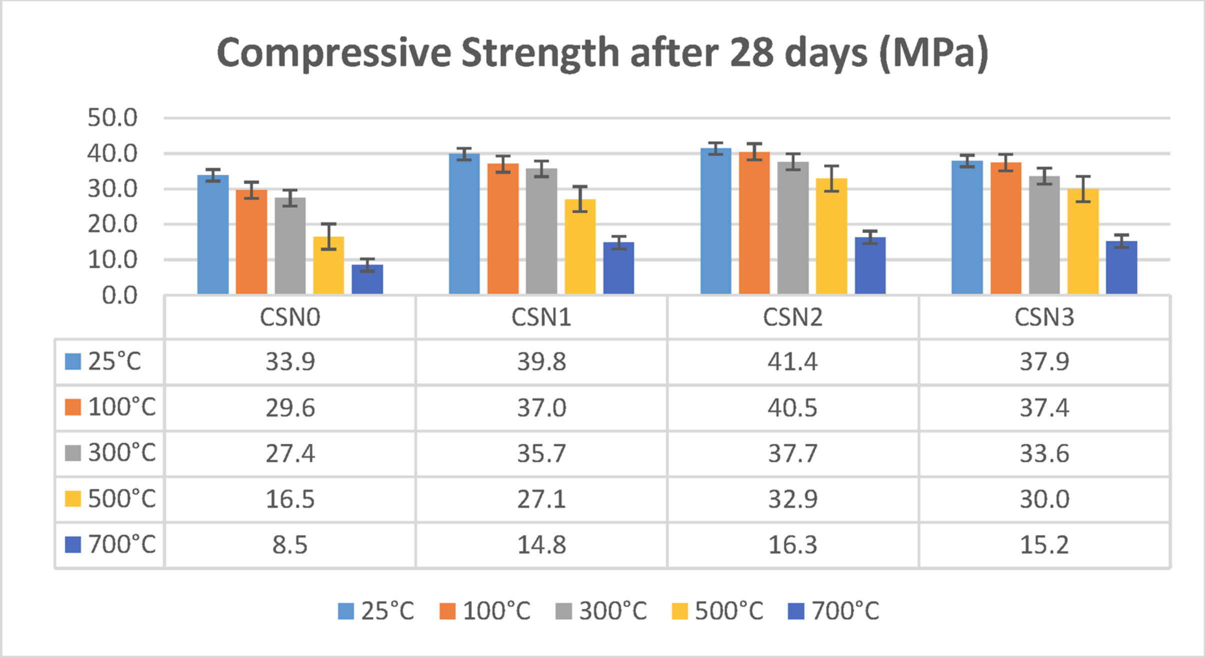
	CSN0	CSN1	CSN2	CSN3
25°C	36.43	41.73	43.38	39.70
100°C	44.64	45.54	49.88	47.99
300°C	41.02	42.93	45.34	44.03
500°C	24.76	32.66	39.58	36.12
700°C	12.75	17.86	19.66	18.35

Figure 9. The compressive strength after diverse temperatures exposure at age 90 days



	CSN0	CSN1	CSN2	CSN3
25°C	26.4	30.7	31.9	29.2
100°C	22.8	27.9	31.5	27.4
300°C	21.1	27.5	29.0	25.9
500°C	12.7	20.9	25.3	23.1
700°C	6.6	11.4	12.6	11.7

Figure 10. The compressive strength after diverse temperatures exposure at age 7 days



	CSN0	CSN1	CSN2	CSN3
25°C	33.9	39.8	41.4	37.9
100°C	29.6	37.0	40.5	37.4
300°C	27.4	35.7	37.7	33.6
500°C	16.5	27.1	32.9	30.0
700°C	8.5	14.8	16.3	15.2

Figure 11. The compressive strength after diverse temperatures exposure at age 28 days

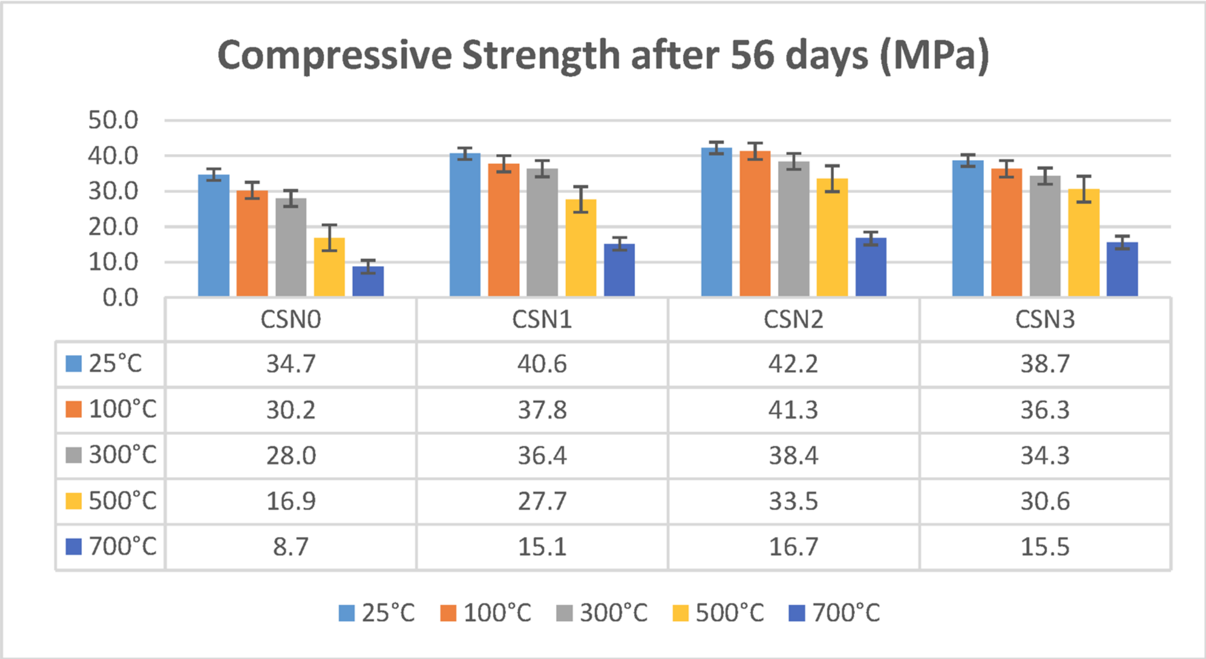


Figure 12. The compressive strength after diverse temperatures exposure at age 28 days

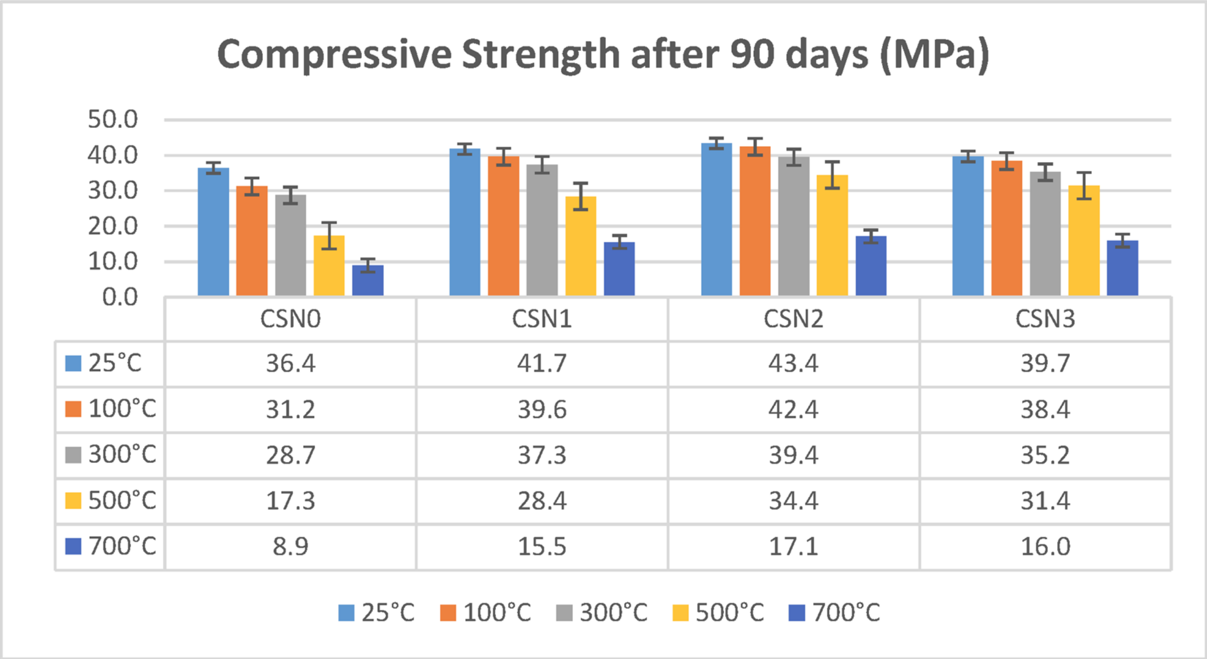


Figure 13. The compressive strength after diverse temperatures exposure at age 90 days

Research results show that the nano and slag materials improve the concrete compressive strength in comparison with control mix, with the optimum ratio being 0.5% nano-cement (CSN2) [10, 11].

3.2. Mass Loss

Mass reduction can impact both the resistance against fire and the total concrete strength. Exposure to high temperatures can lead to mass loss, resulting in spalling of the concrete elements. This can have a detrimental impact on the rigidity of the element, particularly if the core and reinforcing steel are exposed.

Tables 7 and 8, as well as Figures 14 and 15, show the values and ratios of mass loss of all concrete mixtures at various temperatures, respectively [25].

Table 7. Mass of concrete at different temperatures (Kg)

Temperature	CSN0	CSN1	CSN2	CSN3
25 ℃	2536	2538	2554	2574
100 ℃	2482	2497	2502	2522
300 ℃	2315	2352	2426	2422
500 ℃	2253	2284	2324	2322
700 ℃	2047	2235	2286	2216

Table 8. Mass loss as a percentage for concrete at different temperatures

Temperature	CSN0	CSN1	CSN2	CSN3
100 ℃	2.13%	1.62%	2.04%	2.02%
300 ℃	8.71%	7.33%	5.01%	5.91%
500 ℃	11.16%	10.01%	9.01%	9.79%
700 ℃	19.28%	11.94%	10.50%	13.91%

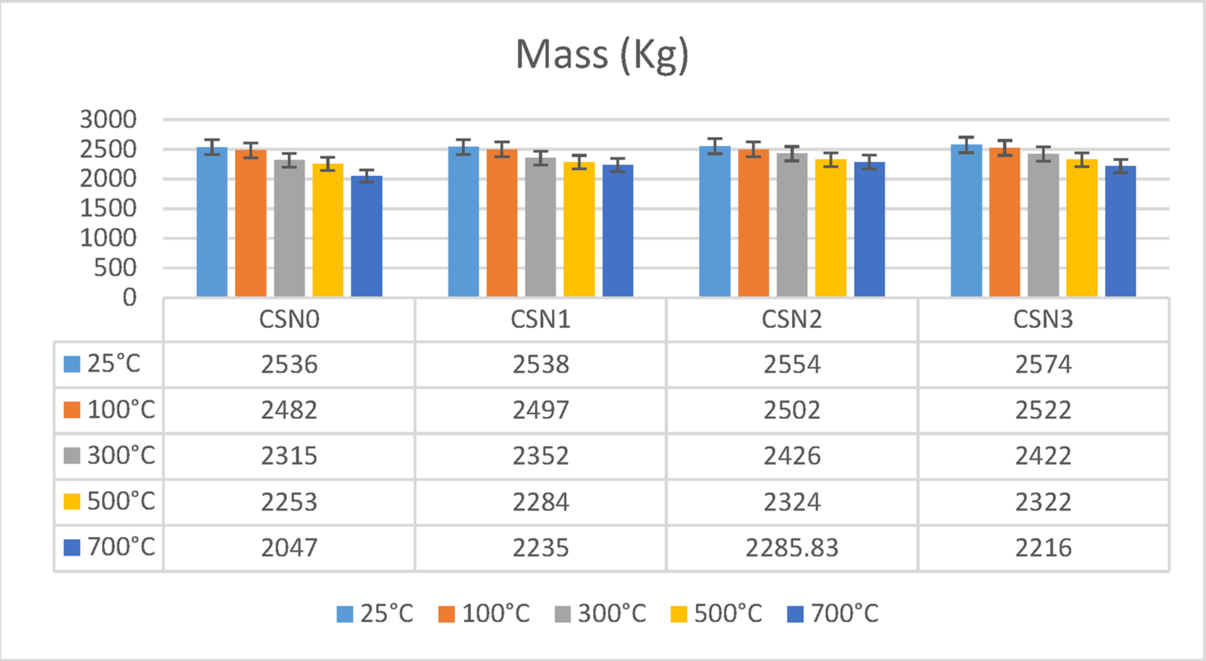
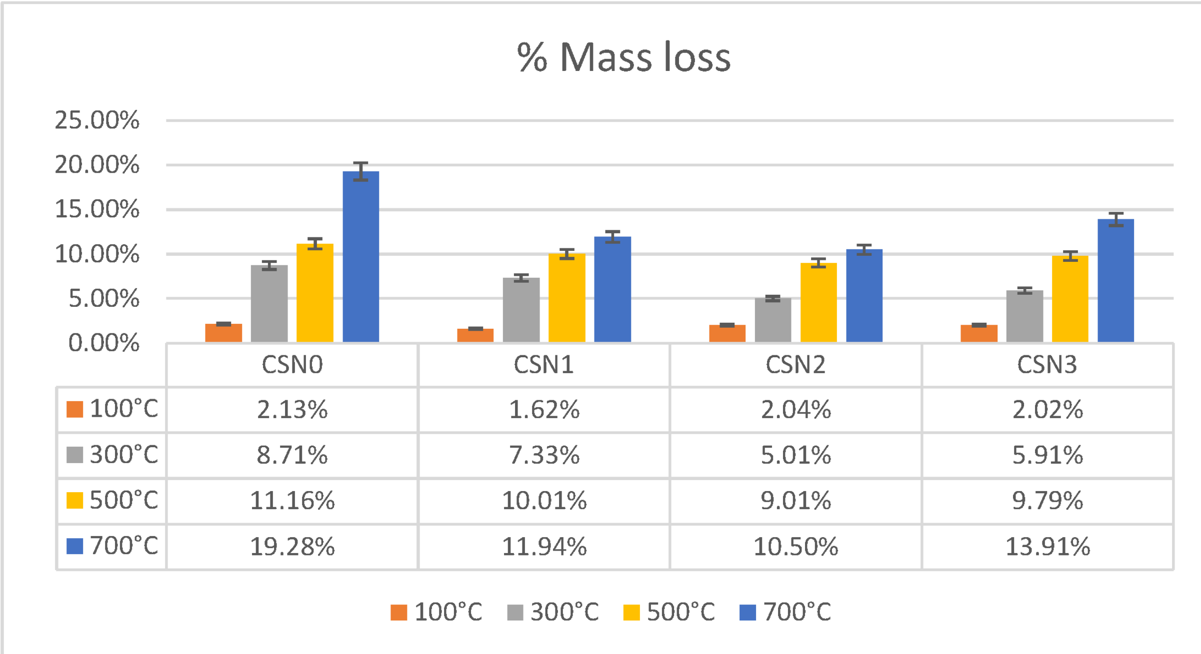


Figure 14. Mass of concrete at different temperatures



	CSN0	CSN1	CSN2	CSN3
100°C	2.13%	1.62%	2.04%	2.02%
300°C	8.71%	7.33%	5.01%	5.91%
500°C	11.16%	10.01%	9.01%	9.79%
700°C	19.28%	11.94%	10.50%	13.91%

Figure 15. Mass loss as a percentage for concrete at different temperatures

Figures 16, 17, and 18 display the failure of the cubes, cylinders, and beams and Figures 19 and 20 show the shape of the cube surface after exposing it to 700 ℃ for 2 hours.

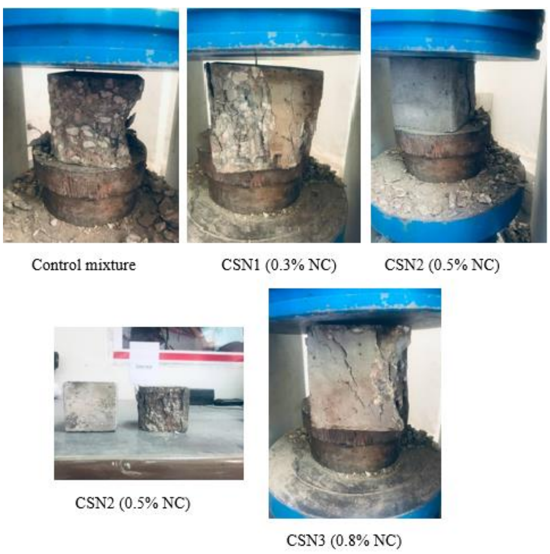


Figure 16. Mechanisms of failure of the cubes

Figure 17. Shape of cube surface after exposure to 700 ℃ for 2 hours (cooling in furnace)

Figure 18. Shape of cube surface after exposure to 700 ℃ for 2 hours (cooling in air)

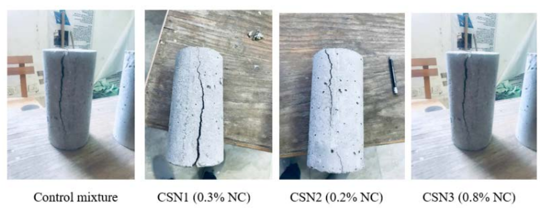


Figure 19. Mechanisms of failure of the cylinders

Control mixture Nano mixture

Figure 20. Mechanisms of failure of the beams

4. Discussion

4.1. Compressive Strength

There are two distinct stages of behavior observed:

- Up to 300°C, the compressive strength increases but the specimens with nano and slag additives show a more prominent increase compared to the control.
- Above 300°C, the control mix experiences a sharp decline in strength, while the nano and slag modified specimens exhibit a more gradual reduction.

This increase is due to the hydrothermal interaction of nanoparticle materials resulting from the temperature rise and the release of free lime during the hydration process. Furthermore, nanoparticles initiate pozzolanic processes that generate extra hydration products, hence enhancing the strength of concrete. At elevated temperatures, the thermal impact may induce water migration, while external moisture supply for dehydration is inadequate. Internal stress, together with micro and macro fractures, arises from the heterogeneous volume dilatations of components and the accumulation of vapor within the pores. Consequently, at elevated temperatures, particularly over 200 ℃, the noted reduction in compressive strength of blended concrete incorporating nanomaterials may result from internal thermal stress induced around pores, leading to the formation of microcracks [57].

Referring to Tables 5 and 6, the difference in strength between the two cooling methods (furnace vs. air) is notable, with the air-cooled specimens showing a greater decrease in strength. This is caused by the evaporation of chemically bound water, resulting in conversion of CSH to CaO inside the composite. This leads to a deterioration in the chemical bonds between the binder and filler components, ultimately leading to a deterioration in compressive strength [12].

In summary, the data and analysis indicate that the use of NC and slag materials can boost the concrete high-temperature resistance and compressive strength, with the optimum performance observed at the 0.5% nano-cement replacement level.

4.2. Mass Loss

Mass loss can impact the fire resistance and overall integrity of the structural component. Thermal effects from high temperature exposure can lead to mass loss and spalling of concrete elements, resulting in a detrimental impact on the stiffness of the element, particularly if the core and reinforcing steel are exposed.

The results demonstrate a significant improvement in mixtures that contain Nano additions with various concentrations in their composition [25].

5. Conclusions

The purpose of the study was to investigate the effects of adding pozzolanic materials like NC and slag as partial substitutes for cement in concrete mixtures. The main focus was on evaluating the impact on the concrete's compressive, tensile, and flexural strength, especially when subjected to high temperatures. The experimental study's findings lead to the following conclusion:

1. Nanotechnology and its effects on engineering, civil especially, are considered a promising and broad field for study and research to improve the criteria of concrete.
2. The pozzolanic materials like NC and slag – considered as filler materials – can be utilized as partial substitutes for cement which is regarded as one of the most important causes of CO_2 emission. So, it will decrease this emission in addition to improving the concrete mechanical and physical characteristics.
3. Using NC and slag to the concrete mix leads to improvement in the compressive, tensile and flexural strength when compared to the control mix.
4. Replacing 50 % of cement weight with slag in all mixtures and 0.3%, 0.5% and 0.8% of cement weight with NC cause an improvement in the compressive strength by 12%, 22%, and 18% respectively, in ambient temperature.
5. It became apparent that in the mixtures including NC and slag the compressive strength increased up to 300°C followed by a decline at higher temperatures. However, the decrease was less significant in comparison with the control mix.
6. Exposing the concrete to high temperatures up to 700°C for 2 hours causes a 64% decline in compressive strength which can lead to construction failure and loss of lives. So we did our research to enhance the concrete resistance against high temperatures e.g. fires. Therefore, we recommend doing more research in that specific domain.
7. Substituting 50 % of cement weight with slag in all mixtures and 0.3%, 0.5% and 0.8% of the cement weight with NC improved the compressive strength by 40%, 54%, and 44% respectively when exposed to 700°C for 2 hours.
8. According to our experiments, the optimum percentage of NC addition is 0.5%.
9. The usage of slag and NC also caused an observed enhancement in the concrete mass loss.

Conflicts of Interest

The authors declare that there is no conflict of interest.

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