

Thermal spalling in NSC: experimental studies and findings

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ABSTRACT

Concrete is a fundamental material in modern construction, but it faces significant durability problems under extreme thermal conditions, which can lead to structural failures. This study addresses the phenomenon of thermal spalling in Normal Strength Concrete (NSC), focusing on how high temperatures affect its structure through experimental investigations. It identifies the key factors influencing spalling, including heating regimes, concrete mix design, and the role of thermo-chemical reactions. To gain insights into this process, a series of controlled experiments was carried out on three types of NSC mixtures, with the samples heated to temperatures of 600°C, 900°C, and 1200°C. Additionally, Scanning Electron Microscopy (SEM) was utilized to study the changes in microstructure in NSC under high temperature conditions. The experiments demonstrated explosive spalling at 610 °C, and deterioration in the concrete at temperatures surpassing 700°C, where there was notable release of chemically bonded water, resulting in structural weakening. The results indicate that at 900 °C the concrete showed signs of porosity, micro-cracks, and the breakdown of hydration components, like calcium hydroxide and calcium silicate hydrate (CSH), and the aggregates spalled. Moreover, at 1050 °C the aggregates near the heated surface were melted. These microstructural alterations were more pronounced at 1200°C, leading to a substantial loss in material integrity. The findings suggested that the extent of spalling and reduction in strength were influenced by variables like heating speed, temperature variations, and release of chemically bonded water within the concrete matrix. The SEM findings underscore the critical impact of high-temperature exposure on the microstructure of NSC, contributing to a deeper understanding of thermo-chemical spalling mechanisms and their implications for structural durability. Despite the progress made, this study requires further research on large-scale structural elements and prestressed or restrained concrete specimens to develop comprehensive predictive models.

KEYWORDS

Thermal spalling, Normal Strength Concrete, High-temperature exposure, Concrete heating regimes, Furnace temperatures

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1. Introduction

Concrete is a popular building material well-known for its strength, adaptability, and longevity [1-3]. Concrete, an essential material in modern construction, faces various durability challenges, especially under extreme thermal conditions [4,5]. A sharp thermal gradient between the outer core and concrete surface can form when subjected to high temperatures, which can cause internal tensions and differential expansion. Internal stress is exacerbated further by the simultaneous generation of pore pressure by the decomposition of hydrated products and the evaporation of free water [1,3]. Thermal spalling is a critical phenomenon where concrete surfaces disintegrate due to rapid temperature changes, leading to potential structural failures [6,7]. The performance of concrete-based structures in fire is generally reliable; however, concrete's complex composition leads to significant property changes when exposed to high temperatures [8,9]. Fire exposure impacts the durability of the concrete matrix by decreasing its essential properties, mainly due to irreversible physical and chemical changes, which affect residual strength, durability, and spalling—the forcible ejection of material from the heated surface of a concrete member [8,10-12]. Explosive spalling is a major threat to fire safety and fire resistance of reinforced concrete

structures [10,13,14]. Both perpendicular tensile and compressive stresses form as the concrete's exterior temperature rises, with the former developing parallel to the heated surface. The concrete spalls off even though these variance stresses are greater than its tensile strength [15]. Two primary causes of explosive spalling are the non-uniform application of thermal loads and vapor pressure accumulation in the pores [16,17]. The occurrence can seriously jeopardize the integrity of reinforced concrete structures due to the reduction of the cross-sectional area of the structural elements and even lead to the direct exposure of reinforcing bars to flames. The literature shows that various parameters influence the occurrence of fire spalling, such as heating rate, specimen geometry and boundary conditions, concrete grade, and external loads [18]. Understanding the physics behind this phenomenon is crucial for predicting spalling and advancing protective measures. Factors such as water loss, subsequent cracking, coarsening of the microstructure, dissolution of hydrates, decomposition of aggregates, and increased permeability significantly affect the mechanical properties and permeability of concrete [9,10,19]. The combined effects of external loading and thermal stress play a key role in triggering spalling conditions, with experimental results indicating that compressive loading markedly increases spalling propensity and severity [18-20]. The non-uniform distribution of thermal stresses and the accumulation of vapour pressure in the pores are two main reasons for explosive spalling [6,7,16,17]. Current codes of practice only recommend protective measures against thermo-hygral spalling [10]. Though considerable information has been gathered on both phenomena, there remains a need for more systematic studies of the effects of thermal exposures. The response of entire concrete structures to realistic fires presents greater challenges due to the interactions of structural elements, the impact of complex small-scale phenomena at full scale, and the spatial and temporal variations in exposures, including the cooling phase of the fire. Moreover, there is still a severe lack of data from real structures for validation, though valuable insights may also be gained from studying the performance of concrete structures in real fires [8,9]. Previous research has extensively studied the individual effects of thermal stresses on concrete. Studies by [21-24] have highlighted the impact of high temperatures on concrete's mechanical properties and microstructure. Similarly, investigations by [25], have elucidated the chemical degradation processes affecting concrete in hazardous environments. However, the combined effects of thermal and chemical stresses, leading to thermo-chemical spalling, have received relatively less attention. Advancements in experimental techniques and modeling approaches have facilitated a deeper understanding of thermo-chemical spalling. For instance, [1] developed a comprehensive model incorporating thermo-hygral and chemical interactions to predict spalling in concrete exposed to fire. Their findings underscore the importance of considering multi-physical interactions to accurately predict spalling behavior. Similarly, experiments conducted by [7,13] have demonstrated the critical role of moisture content and heating rate in influencing spalling severity. Future predictive tools aiming to assess the spalling risk and determine the spalling extent should consider all types of spalling and their interactions [10]. However, to properly understand the durability performance of fire-exposed concrete structures constructed with sustainable concretes, substantial work is required in this domain [11]. Furthermore, advanced numerical models should be established to better understand the fire safety of reinforced concrete structures [13,14]. This article delves into experimental studies and findings related to thermal spalling in NSC, providing a comprehensive understanding of its causes, effects, and mitigation strategies. It compiles both conflicting and common views from previous research on thermo-hygral and thermo-chemical concrete spalling. Thermo-chemical spalling, which is the topic discussed in this research, specifically refers to the spalling caused by the synergistic effects of thermal and chemical stresses. This type of spalling poses significant risks to structures exposed to high temperatures and aggressive chemical environments, such as tunnels, industrial facilities, and buildings subjected to fire incidents. The primary mechanisms driving thermo-chemical spalling include thermal gradients and chemical water removal from cement paste within the concrete matrix. Based on analyses of these contradictory and concordant test results, the mechanisms of occurrence and criteria for forecasting this type of spalling are established. It has been observed that spalling can occur within different temperature ranges. By conducting a series of controlled laboratory experiments, we seek to identify the key factors influencing thermo-hygral and thermo-chemical spalling to enhance the resilience of concrete structures and fill this knowledge gap. Despite these advancements, there remains a need for further research, particularly full-scale structural members to elucidate the intricate mechanisms underlying thermo-hygral, thermo-mechanical, and thermo-chemical spalling in NSC. In the following sections, we will detail the experimental methodology, present the results of our investigations, and discuss the implications of our findings for the design and maintenance of concrete structures exposed to extreme environments. Through this research, we hope to contribute to the development of more durable and reliable construction materials capable of withstanding the combined challenges of thermal and chemical stresses.

1.1. Understanding Thermal Spalling

Research indicates that thermal spalling occurs due to a combination of pore pressure, thermal stress, and mechanical damage. When concrete heats, trapped moisture turns into steam, increasing the internal pressure and causing explosive spalling if this pressure exceeds the material's tensile capacity [6,10,26]. Thermal spalling manifests when concrete is

subjected to sudden, intense heat, leading to internal pressures that surpass the material's tensile strength. The rapid temperature rise results in water vaporization within the concrete, creating high internal steam pressures. Furthermore, thermal gradients within the concrete cause differential expansion, further stressing the material [27]. Understanding the fundamental mechanisms of thermal spalling is essential for anticipating and mitigating this undesirable phenomenon. These mechanisms can be explained primarily by either thermal stress or pore pressure accumulation. Over the past few decades, scholarly discussions have focused on the relative significance of these two mechanisms. According to the governing mechanisms, there are three forms of thermal spalling: thermo-hygral, thermo-mechanical, and thermo-chemical spalling [10]. Thermo-hygral spalling is caused by moisture blockage and pore pressure increase within heated concrete, typically occurring at temperatures between 220 °C and 320 °C [28]. Thermo-mechanical spalling results from heat-induced thermal stress combined with applied stress, usually occurring within the 430 °C to 660 °C range [10,28]. Thermo-chemical spalling is associated with the rehydration of calcium oxide and the breakdown of hydrated products and calcite, typically happening at temperatures above 700 °C [28]. Some compressive strains and perpendicular tensile stresses form in the concrete as its exterior temperature rises, parallel to the heated surface's surface. When the variance stresses surpass the concrete's tensile strength, the concrete spalls off [15]. Additionally, other factors contributing to concrete matrix cracking include rising temperatures, the chemical breakdown of hydrates, variations in cement paste shrinkage, thermal fluctuations, and coarse aggregate expansion. At high temperatures, the thermal and elastic inconsistencies between aggregates and the cementitious matrix further degrade the concrete, exacerbating these detrimental processes [19].

2. 2. Thermal spalling experimentation studies

The behavior of NSC under heat stress has been studied experimentally in some research. Usually, these investigations comprise:

2.1. Test-subject variables

NSC samples are made using 5 mixture designs to maintain uniformity throughout tests. To fulfill this objective, the experimental program consisted of 48 test specimens (18 for thermo-hygral spalling and 30 for thermo-chemical spalling). All the specimens were 200 x 200 x 200 mm concrete blocks. There was no difference in the control specimen's mixture percentage or curing condition. The variables were compared with the remaining specimens' results to examine their effects on thermo-chemical spalling. To investigate the impact of the following factors on explosive spalling (thermo-hygral spalling), 3 mixture designs were utilized and the outcomes were compared with the remaining specimens: NSC, mixture II ($S = 175$ mm), mixture III ($S = 150$ mm), and mixture IV ($S = 100$ mm) have the following w/cm ratios: 0.46, 0.46 and 0.43. Rates of heating: 300°C–2.5°C/min and higher than 300°C–5°C/min. Curing conditions include a 28-day immersion in water followed by a 90-day air drying period. Table 1 displays the test specimens' respective test matrices and important parameters. According to [29], and prior studies on thermal spalling, and the parameters and circumstances of high-temperature testing, NSC specimens experience spalling between 375 °C and 425 °C. All 5 mixture designs were utilized and two heating regimes 900 °C and 1200 °C were chosen for the test series based on these results to clearly investigate thermo-chemical spalling. To do this, all the samples were dried totally of any remaining free water in the concrete by being held in an oven set at 105 °C for 72 hours before the fire test. Then, with maximum temperatures of 900 °C and 1200 °C, the high temperature test was run.

2.2. Materials samples

All samples of NSC were made using ASTM Type II Portland cement, two types of crushed coarse aggregate (19 mm and 10 mm nominal maximum size) with a fineness modulus (FM) of 4.94, and fine aggregate made of natural sand (FM) of 3.83. Table 1 compiles fresh and hardened concrete's properties and combination ratios. Superplasticizers have been added to concrete in amounts of 0.6 and 0.8%, respectively, to lower the free water content and achieve the appropriate water-to-cement ratio for mixing designs Mix I and Mix V.

Table 1. Properties of both fresh and hardened concrete, test matrix, and concrete mixture amounts

Materials and properties	Mixtures	Mixtures	Mixtures	Mixtures	Mixtures
Materials and properties	Mix I	Mix II	Mix III	Mix IV	Mix V
Cement (kg/m ³)	400	400	400	400	400
Water (kg/m ³)	160	184	184	172	160
Normal aggregate max size 19 mm (kg/m ³)	359.1	343.8	347.8	354	359.1

Normal aggregate max size 10 mm (kg/m ³)	448.8	430	434.7	442.5	448.8
Normal sand SSD (kg/m ³)	964.4	945.5	934.2	950.8	964.4
Air content, %	1.5	1.5	1.5	1.5	1.5
Specimen No (control)	6 (2)	10 (2)	10 (2)	10 (2)	6 (2)
slump, mm	200	175	150	100	25
w/c	0.4	0.46	0.46	0.43	0.4
Superplasticizer, %	0.8	-	-	-	0.6
Compressive strength, Mpa	47	36	40	44	59
Weight, Kg	18.56	18.16	18.53	18.67	18.75
Max. furnace temperature, °C	900	900	900	900	900
Max. furnace temperature, °C	1200	1200	1200	1200	1200
curing condition	28 days Submerged & up to 90 days Air dried	28 days Submerged & up to 90 days Air dried	28 days Submerged & up to 90 days Air dried	28 days Submerged & up to 90 days Air dried	28 days Submerged & up to 90 days Air dried
Heating rate	Up to 300°C 2.5 °C/min More than 300°C 2.5-5°C/min	Up to 300°C 2.5 °C/min More than 300°C 2.5-5°C/min	Up to 300°C 2.5 °C/min More than 300°C 2.5-5°C/min	Up to 300°C 2.5 °C/min More than 300°C 2.5-5°C/min	Up to 300°C 2.5 °C/min More than 300°C 2.5-5°C/min

2.3. Heating Procedures

Samples are heated under controlled conditions to replicate high-temperature exposure or actual fire situations. It has been found in earlier research that, when specimens were heated to target temperatures of 350°C and 650°C at a rate of 5°C/min, most explosive spalling incidents can be occurred. The temperatures shown above are furnace settings; the actual temperature of the concrete is much lower. Based on these findings, two heating regimes were selected for the test series to study thermo-hygral spalling In Figure 1. It has been shown that the first regime sets a maximum furnace air temperature of 600°C, while the second sets it at 900°C. Also, two heating regimens were chosen for the test series based on these results to investigate thermo-chemical spalling, Figure 2. Furnace temperature maximums in the first and second regimes are 900°C and 1200°C, respectively. According to Fig. 1, the heating rates are "up to 300°C - 2.5°C/min and above 300°C - 2.5 - 5°C/min."

2.4. Test Configuration and Instrumentation

A 10 mm diameter by 100 mm deep hole was drilled into the outside face of each concrete block, across from the face that would be exposed to high temperatures, to detect the inside temperature. A metallic probe measuring 500 mm in length and 6 mm in diameter was attached to a TM-902C type K contact thermometer. The probe's tip contains the temperature sensor. Only one side of the specimens was heated by convection in a programmable electric furnace equipped with a type S thermocouple, used for the tests. This furnace can test four concrete blocks at once. The configuration produced a one-way heat flow through the specimens, from the heated face to the back face, simulating the one-way heating situation that one side of a concrete column, wall, or other structure would experience. The four sides of the specimens were covered with a fireproof blanket to minimize side effects on the concrete blocks, prevent energy waste, and lower the furnace's internal temperature. An overview of a standard test setup with four specimens outside the furnace is shown in Figure 3.

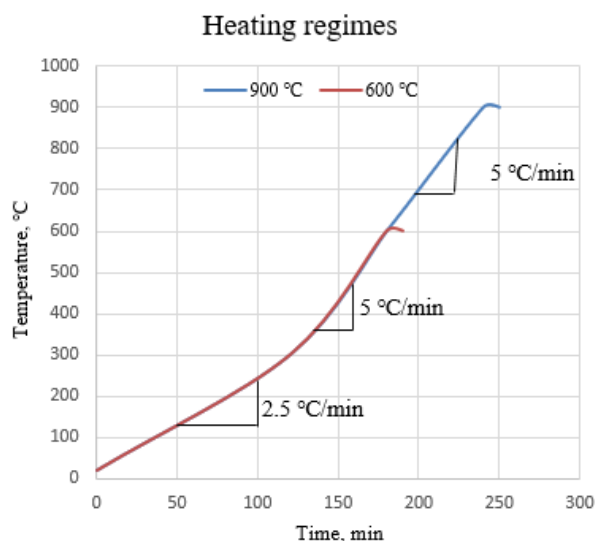


Figure 1. Temperature-time curve before testing for maximum 600 °C and 900 °C high temperature

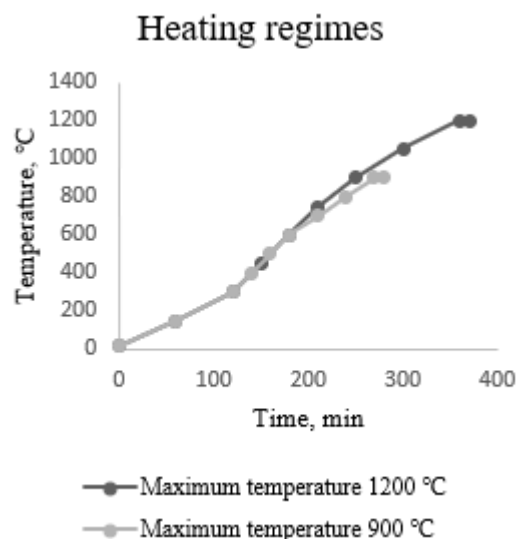


Figure 2. Temperature-time curve before testing for maximum 1200 °C high temperature



Figure 3. Typical configuration for testing



Figure 4. Chemical water release

3. Results and Discussion

3.1. General

Heating concrete causes its aggregates to expand and the surrounding cement paste to contract, weakening the bond between them. This mismatch in thermal strains leads to cracking, which can be a major cause of concrete damage [2]. Heating cement paste causes water loss through evaporation, with free water evaporating first, followed by capillary and physically bound water, and finally chemically bound water within cement hydrates. The mechanical strength of cement paste is greatly influenced by chemical bonds and cohesive forces in calcium silicate hydrate (C-S-H) gel sheets, with about half of the strength due to these cohesive forces [30]. In moist, sealed conditions, heated cement paste can undergo internal autoclaving, where moisture converts to vapor, causing chemical and physical changes that may strengthen the paste [31]. The extent of these changes depends on cement composition, calcium-to-silicon ratio, fine particle content, and temperature and pressure. When heating cement paste with a calcium-to-silicon ratio near 1.5 above 100 °C, it forms porous and weak calcium silicate forms, while higher temperatures (150-200°C) produce tobermorite, xonolite, and hillebrandite silicates [32]. Neutron diffraction studies show that ettringite decomposes before C-S-H gel, which dehydrates gradually. Dehydration at standard drying temperatures (105 °C) partially compromises the cement paste structure. At 500-550 °C, portlandite rapidly decomposes into calcium oxide and water vapor, increasing calcium oxide levels and reducing the effectiveness of Portland cement components after cooling [32]. The dehydration of C-S-H gel increases porosity, with initial

heating causing slight expansion followed by significant shrinkage, leading to increased total pore volume and average pore size [2,31,33,34]. Aggregates, making up 70–80% of concrete's volume, play a crucial role in its thermal behavior. "Thermal stability of aggregates" refers to their ability to maintain performance at high temperatures, as assessed by dilatometric, thermogravimetric, and differential thermal tests. Ideal aggregates for high temperatures should exhibit low thermal strain and minimal residual strains, with no weight loss or thermal reaction indicated by DTA and TGA curves. Thermal strains in aggregates depend on their mineral composition, with different minerals exhibiting unique thermal expansion properties. For example, quartz aggregates undergo a β - α inversion at 574°C, causing a notable volumetric increase. Carbonate stones like limestone and dolomite are stable up to 600°C but decompose into CaO and CO₂ above 700°C. The CaO can rehydrate upon cooling, leading to significant expansion. Polymineralic stones may suffer from inter-crystalline stresses due to thermal incompatibility, causing disintegration. Further heating leads to aggregate melting, with temperatures varying by composition: most igneous rocks melt above 1000°C, granites at 1210–1250°C, and basalts at 1050°C, often accompanied by gas release and expansion [35]. The results of this research regarding the microstructure performance of cement paste and aggregate against high temperatures show confirmation of previous studies.

3.2. High Temperature and thermo-chemical Spalling Characteristics

As mentioned in sections 2.1 and 2.4, a furnace was used to test 12 samples in the initial phase of the fire analysis. To guarantee uniformity, the furnace was kept at the targeted maximum temperature for ten minutes after it had reached it. Considering the device's limits in the lab, controlled, gradual cooling was taken into consideration. In research conducted by [36] it was described that severe temperature gradients and increased pore pressures brought on by rapid heating typically result in more noticeable spalling and larger losses in residual strength. On the other hand, slow heating lessens the severity of spalling by enabling a more uniform temperature distribution. It has been reported by [29,37] that in normal-weight concretes, thermal spalling tends to occur when the surface temperature falls within the range of 375°C to 425°C. But, at 600°C, none of the samples spalled. Moreover, at 680°C, samples Mix-II and Mix-III began to spall when heated from 610°C to 680°C, during which time there were fifteen faint explosions loud. The delay in the timing and temperature at which spalling occurs is influenced by factors such as the rate of temperature increase, the amount of free water in the concrete, the interconnected pores that allow this water to evaporate, and the thermal gradient. In this test, one side of the samples was exposed to high temperatures, while five others allowed free water to escape, affecting the spalling process. When the free water temperature of such interior surfaces approaches the boiling point of water, which is approximately 100 °C, considerable water vapor pressure is produced in a short time, causing explosive spalling of concrete blocks near high-temperature surfaces. In 20 minutes following a 3-hour fire exposure, there were 15 audible sounds of concrete spalling during the test. Two samples have lost up to 45% of their volume, and one has lost up to 30%. Thus, it may be said that the temperature-exposed surface of concrete is where spalling begins, and the immediately beneath the spalling surface develops into a new surface that is subjected to high temperatures and undergoes spalling accordingly. Up until the high temperature persists and the concrete is destroyed, this conversion of the lower surface into a new surface exposed to high temperatures is constant.

Explosive spalling, which is defined by the abrupt, violent delamination and total fragmentation of a 60 mm to 90 mm thick concrete layer on the heated surface, happened as predicted in specimens Mix-II, Mix-III, and its duplicate. A significant amount of energy was released simultaneously with the spalling, propelling the broken pieces of concrete while maintaining the 110 mm to 140 mm thick section of the specimen intact. This rapid and dramatic destruction is in line with the theory that explosive spalling in NSC is caused by an increase in interior pore pressure. Upon heating, all specimens that withstood spalling developed visible fissures and underwent color changes. The specimen after spalling is depicted in Figure 5, alongside a specimen that withstood spalling. Figures 6 and 7 depict the time-temperature curves at which the specimens exhibited resistance to spalling and spalled, respectively. Resistance to spalling can be increased by modifying the concrete mix design to include aggregates with advantageous thermal characteristics and adding fibers to increase tensile strength.

Figure 5. Image of spalled concrete blocks next to withstood spalling blocks

As stated in sections 2.1 and 2.4, 20 samples were subjected to a furnace in the second phase of this fire test. The samples were dried totally of any free water in the concrete by being stored for 72 hours at 105 °C; nonetheless, in every sample, the release of chemical water was seen at a temperature between 700 and 800 °C Figure 4.

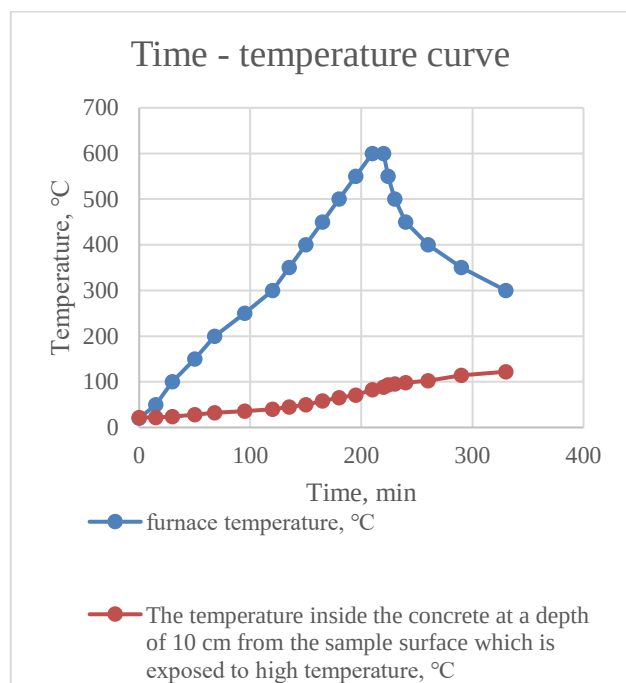


Figure 6. Time-temperature curve of the furnace and internal concrete blocks following exposure to a maximum temperature of 600°C.

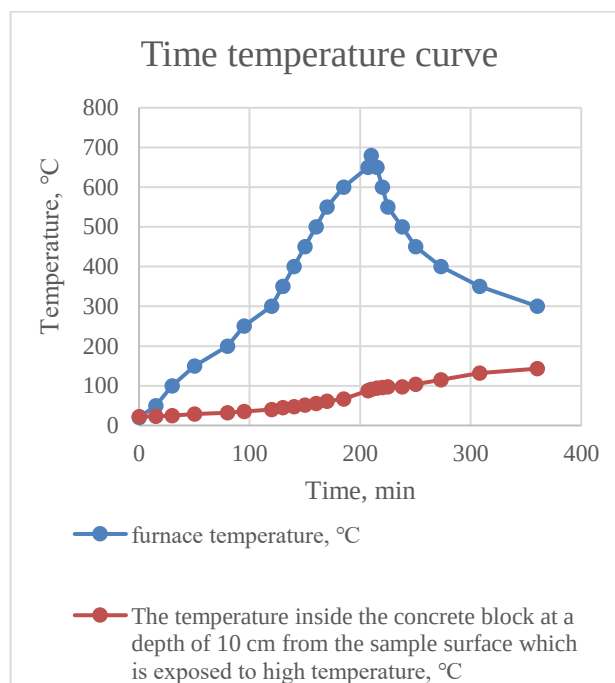


Figure 7. Time-temperature curve of the furnace and internal concrete blocks after spalling occurred at 680°C.

As depicted in Figure 8 on the surface subjected to high temperatures, visual cracks, colour changes to greyish white, visual expansion, and aggregate spalling (Figure 8. x) can be seen at 900 °C. Since thermo-chemical spalling happens silently, explosive spalling cannot be heard, but some aggregates do spall as well because of the release of chemical water and the very porous surface that results from temperature exposure. Additionally, this problem suggests that thermo-chemical spalling is occurring. Furthermore, the Van der Waals force beneath aggregate and cement paste vanished around 1200 degrees due to the total elimination of chemical water, causing significant spalling. The microstructure of the concrete matrix entirely vanished and the concrete transformed into primary components, or aggregates, at a depth of 40 to 50 mm from the surface exposed to the high temperature of all 5 Mixtures of concrete blocks. This process is known as thermo-chemical spalling. On the concrete surface shown in Figures 8. m, g at 1200 °C and u, v, w at 1050 °C, the aggregates that were near the hot surface melted and became crushed. The samples' surface also started to become yellowish. The hypothesis that a rise in chemical water release in NSC is the source of thermo-chemical spalling is supported by this striking distraction. The maximum temperatures of the furnace, which were 900 °C and 1200 °C, respectively, are depicted in the time-temperature curves in Figures 9 and 10. The temperature inside the concrete exposed to high temperatures 10 cm below the surface reached 180 °C and 248 °C, respectively, when the furnace's maximum temperature reached 900 °C and 1200 °C. Additionally, during the cooling phase, the temperature inside the concrete increased to 303 °C when the furnace's temperature dropped from 1200 °C to 900 °C, and to 332 °C when the furnace's temperature dropped from 900 °C to 350 °C. It may even reach 400 °C. Figure 5 presents the time-temperature curve for the furnace and internal concrete blocks immediately following exposure to an oven at 105°C, reaching a maximum temperature of 900 °C. Figure 10 displays the time-temperature curve for the furnace and internal concrete blocks after 72 hours of conditioning in the oven at 105°C, followed by 24 hours of storage at ambient temperature, with a maximum temperature of 900°C. Figure 11 depicts the time-temperature curve for the furnace and internal concrete blocks at a maximum temperature of 1200°C, with the cooling phase recorded after 24 hours.



Figure 8: Performance of concrete blocks against maximum high temperature. Mix I to Mix V (c, d, g, h, k, l, o, p, s, and t) and x – explosive spalling of aggregates for Mix III at max. 900 °C. u, v, w – melting of aggregates for Mix II, Mix III, and Mix IV at 1050 °C. Mix I to Mix V (a, b, e, f, i, j, m, n, q, and r) at max. 1200 °C.

Figure 12 illustrates the time-temperature curve for the furnace and internal concrete blocks at a maximum temperature of 1200°C. The investigation's findings in this instance make it abundantly evident that temperatures over 200 °C harm concrete's microstructure. In this study, the samples were not loaded and were subjected to high temperatures on one side. In actuality, when concrete structures are loaded, more than one side of them—particularly columns—are exposed to fire. Stated differently, concrete buildings are vulnerable to damage during a fire, hence precautions must be taken to lower potential dangers. The amount of residual compressive strength lost is determined by the speed and duration of the heating process. Severe temperature gradients and greater pore pressures brought on by rapid heating are typically the source of

more evident spalling and significant losses in residual strength. On the other hand, slow heating lessens the severity of spalling by enabling a more uniform temperature distribution [38]. It is possible to enhance resistance to spalling by incorporating particles with advantageous thermal properties into the concrete mix design and by adding fibers to increase tensile strength.

3.3. Residual Compressive Strength and Weight Loss

Testing materials while they are "hot" is done to see how they respond to fire; testing materials after they have cooled down is done to see how they function after a fire. There are fewer residual mechanical characteristics as a result of the extra pressures brought on by cooling when cooling occurs quickly. A 44% volume increase and the formation of cracks result from the rehydration of CaO, which is produced by the disintegration of portlandite and/or calcium carbonate. It follows that the absorption of moisture during cooling may increase damage. A gradual loss in compressive strength can be caused by several things, including the dehydration of C-S-H gel, the breakdown of portlandite, and discrepancies in the deformations of expanding aggregates and decreasing cement paste. Temperature-induced thermal spalling causes a considerable reduction in the residual compressive strength of NSC. The concrete matrix is weakened due to the dehydration of cement paste, the coarsening of the microstructure, and the breakdown of calcium hydroxide, which is the cause of this strength loss.

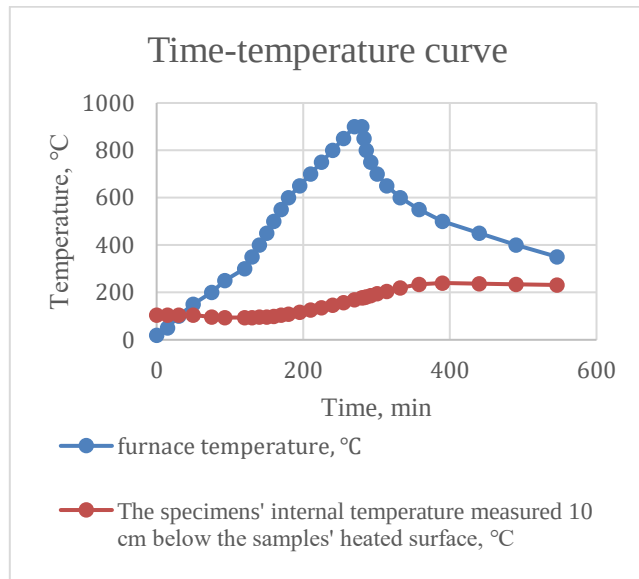


Figure 9. The time-temperature curve of the furnace and internal concrete blocks immediately after the oven at 105 °C and a maximum temperature of 900°C

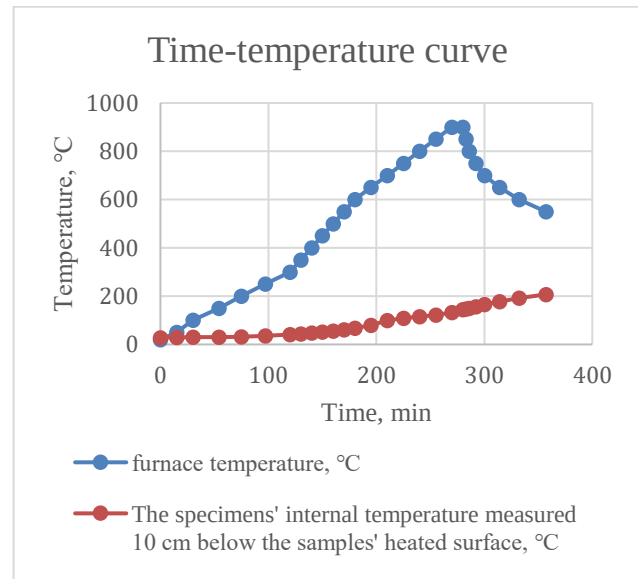


Figure 10. The time-temperature curve of the furnace and internal concrete blocks After 72 hours in the oven at 105 °C and 24 hours of storage at ambient temperature and a maximum temperature of 900°C

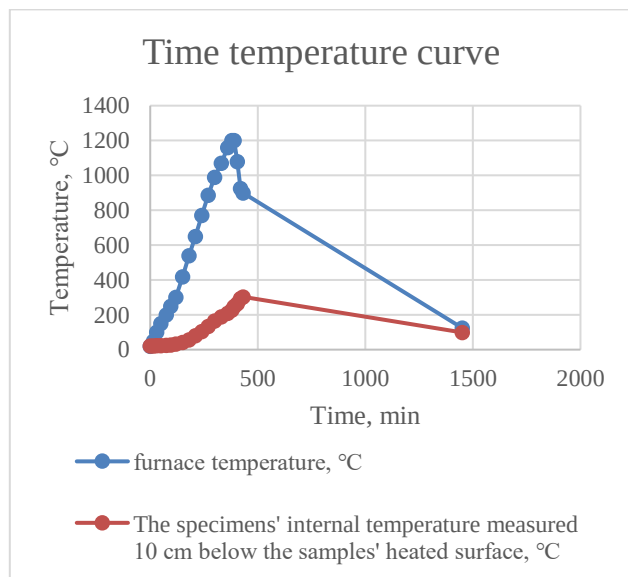


Figure 11. The time-temperature curve of the furnace and internal concrete blocks at a maximum temperature of 1200°C. The cooling phase was recorded after 24 hours

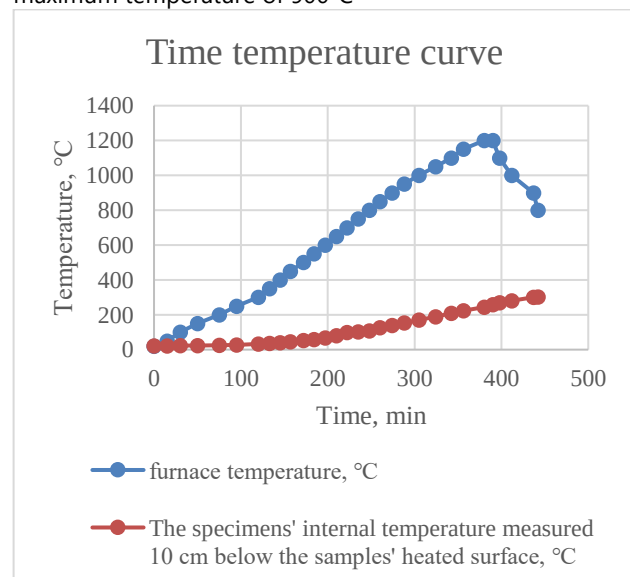


Figure 12. The time-temperature curve of the furnace and internal concrete blocks at a maximum temperature of 1200°C

Figure 13. demonstrates that the residual compressive strength (RCS) decreased for every sample. At a maximum temperature of 900 °C, Mix V specimens displayed the lowest RCS of 13.6%, while Mix II specimens displayed the greatest RCS of 22.3%. On the other hand, Mix I has the lowest RCS of 38.3%, and Mix II and III have the greatest RCS of 50% at the maximum temperature of 1200 °C. How much residual compressive strength is lost depends in large part on how quickly and how long the heating process takes. Studies conducted through experimentation have demonstrated that when concrete is heated to a high temperature, it experiences more severe spalling and a larger decrease in its residual compressive strength. The accelerated propagation of damage is caused by the combined effects of mechanical and thermal stresses [36]. The intricacy of thermal spalling and its noteworthy influence on the residual compressive strength of concrete with normal strength are evidenced by these studies. Gaining an understanding of these elements is essential to enhancing structural integrity and fire safety in building procedures. The weight loss of NSC following maximum high temperatures of 900 °C and 1200 °C is shown in Figure 14. At a maximum temperature of 900 °C, the effects of increased temperature tests on NSC weight loss are larger than those at 1200 °C. The weight losses for the mixtures of Mix I, Mix II, Mix III, Mix IV, and Mix V specimens were 8.1%, 5.5%, 7.6%, 6.9%, and 4.8%, respectively, after the maximum high temperature of 900 °C. The weight losses for Mix I, Mix II, Mix III, Mix IV, and Mix V specimen mixtures were, in order, 14.5%, 14.3%, 14.6%, 15.0%, and 11.7% after a maximum high temperature of 1200 °C.

3.4. SEM Test Results

Figures 15 and 16 display SEM images and results comparing the residual compressive strength of the samples. This test aimed to observe the microstructure for comparative purposes and to provide a clearer explanation of previous test results. The microstructure of the cement paste varies in all samples, influenced by the distance from the high-temperature exposed surface and the temperature profile across the sample's cross-section, regardless of spalling occurrence. The width of cracks has increased, and the cement paste near the high-temperature surface has become more porous. SEM images of the cement paste exposed to high temperatures up to 5 cm from the heated surface are shown in Figure 15, which demonstrate images captured 5 cm away from the heated surface, revealing greater porosity and wider cracks in the concrete's microstructure.

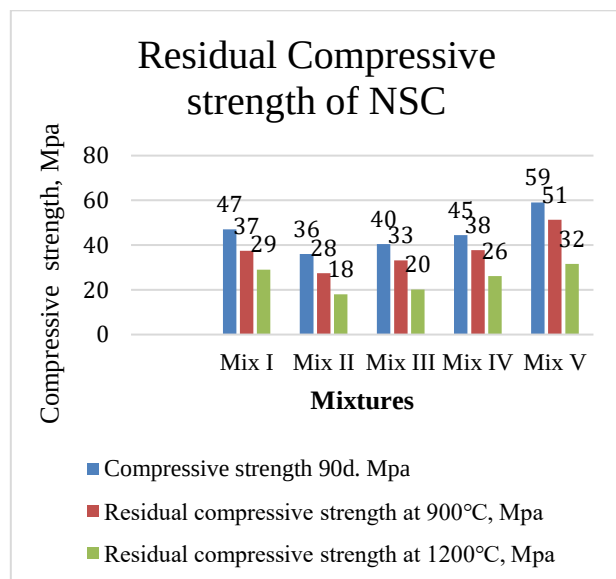


Figure 13. Residual compressive strength of NSC blocks after high-temperature exposure

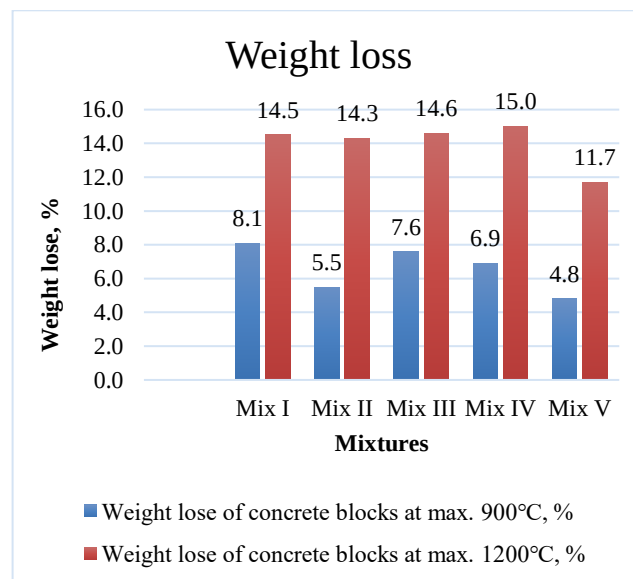


Figure 14. Weight loss of NSC blocks after high-temperature exposure

However, Figure 16 shows images captured 10 cm away from the heated surface, still depicting the cement paste's dense microstructure. Figures 17 through 21 display SEM images and results comparing the residual compressive strength of the samples, where t , is the maximum high furnace temperature at the exposed face of specimens and d , is the depth inside the concrete blocks from the surface of the sample exposed to high temperature. This test aimed to observe the microstructure for comparative purposes and to provide a clearer explanation of previous test results. SEM test samples for the maximum furnace temperature of 900 °C were done from the depth of 5 and 10 cm of concrete blocks, and for the maximum furnace temperature of 1200 °C, they were only done from the depth of 10 cm. Since the microstructure of the cement matrix of the samples that were exposed to the maximum temperature of 1200 °C was destroyed by more than 80%

at a depth of 5 cm, sampling for the SEM test was not done. The microstructure of the cement paste varies in all samples, influenced by the distance from the high-temperature exposed surface and the temperature profile across the sample's cross-section, regardless of thermo-chemical spalling occurrence in all mixtures. The width of cracks has increased, and the cement paste near the high-temperature surface has become more porous. SEM images of the cement paste exposed to high temperatures up to 5 cm from the heated surface reveal greater porosity and wider cracks in the concrete's microstructure. However, images captured 10 cm away from the heated surface, still depict a dense microstructure of the cement paste. Moreover, from the comparison of images a and b of Figures 11 to 15, it can be seen that the microstructure of concrete blocks is more damaged at a depth of 10 cm from the surface of temperature 1200 °C than at a depth of 10 cm from the surface of temperature 900 °C. This shows the confirmation of other tests in this report. A study [39] reported similar microcracking patterns and pore structure changes in NSC exposed to high temperatures, identifying critical temperature thresholds where significant microstructural damage occurs. They noted that the microstructure exhibited significant cracking and pore enlargement at temperatures of approximately 450°C and higher, aligning with the observations in this study.

4.4.Mitigation Strategies

Based on the experimental findings, several strategies have been proposed to mitigate thermal spalling in NSC: 1. Reducing the initial moisture content in concrete and ensuring proper curing methods can minimize the risk of spalling. Techniques such as pre-drying and the use of hydrophobic admixtures have shown promise in experimental studies. 2. Applying thermal barriers or insulation materials to concrete surfaces can help reduce the thermal gradients and prevent rapid heating. Fire-resistant coatings and intumescent paints are commonly used for this purpose. 3. Adjusting the mix design of concrete to include aggregates with favorable thermal properties and incorporating fibers to enhance tensile strength can improve resistance to spalling.

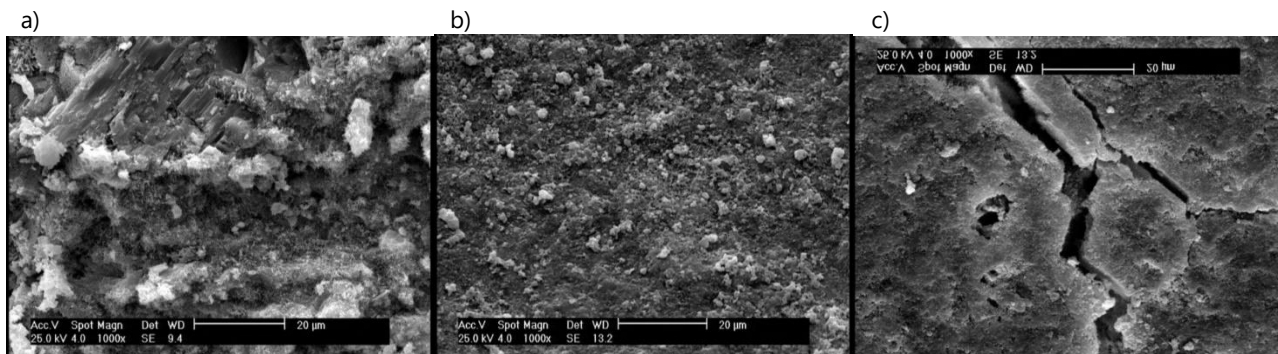


Figure 15. SEM image of a specimen's section located 5 cm from the heated surface at a maximum 680 °C high temperature for Mix II. And Mix III. a) resisted spalling; the cement paste has been cracked and porous; b) experienced spalling; the porosity of cement paste is lower; c) experienced spalling; the width of the cracks has increased

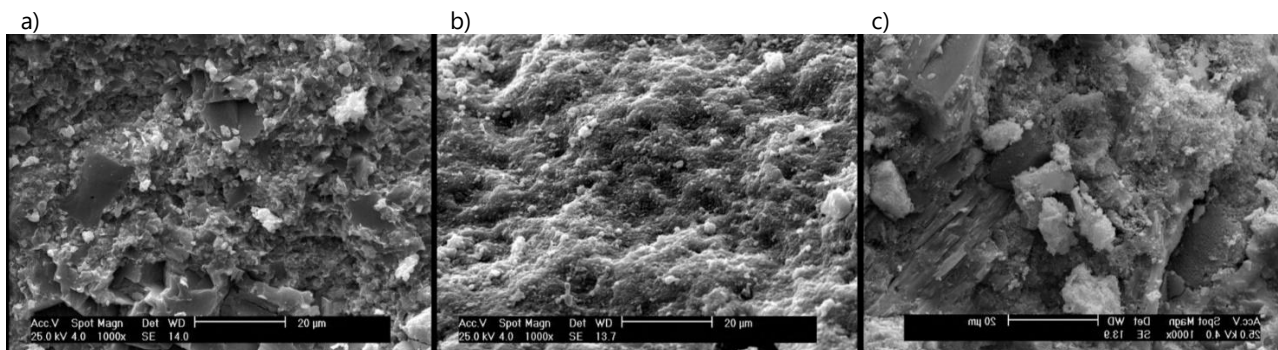


Figure 16. SEM image of a specimen's section located 10 cm from the heated surface at a maximum 680 °C high temperature for Mix II. And Mix III. a) resisted spalling; the cement paste has fewer and smaller fractures; b) experienced spalling; the porosity of cement paste is lower; c) experienced spalling; low porosity and small cracks

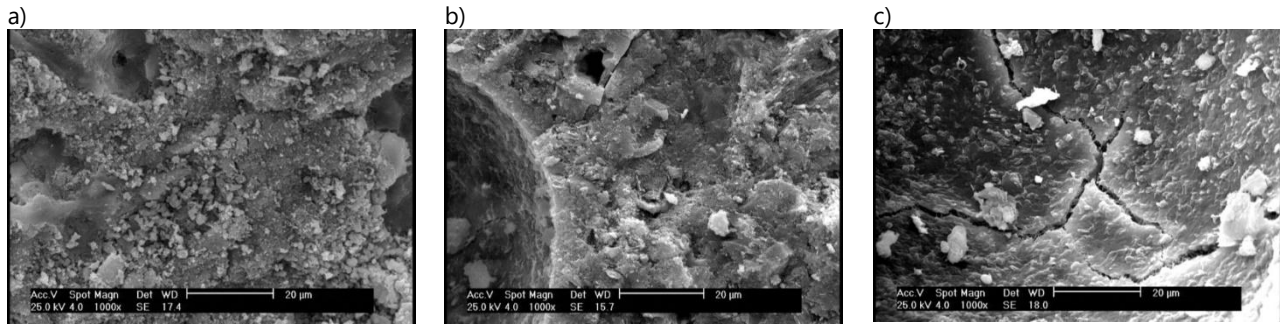


Figure 17. SEM image for Mix I. a) $t = 1200\text{ }^{\circ}\text{C}$, $d = 10\text{ cm}$; b) $t = 900\text{ }^{\circ}\text{C}$, $d = 10\text{ cm}$; c) $t = 900\text{ }^{\circ}\text{C}$, $d = 5\text{ cm}$

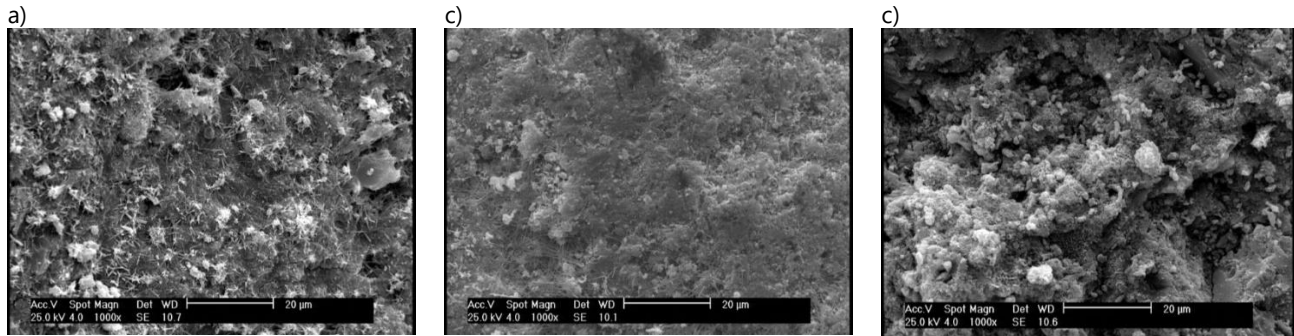


Figure 18. SEM image for Mix II. a) $t = 1200\text{ }^{\circ}\text{C}$, $d = 10\text{ cm}$; b) $t = 900\text{ }^{\circ}\text{C}$, $d = 10\text{ cm}$; c) $t = 900\text{ }^{\circ}\text{C}$, $d = 5\text{ cm}$

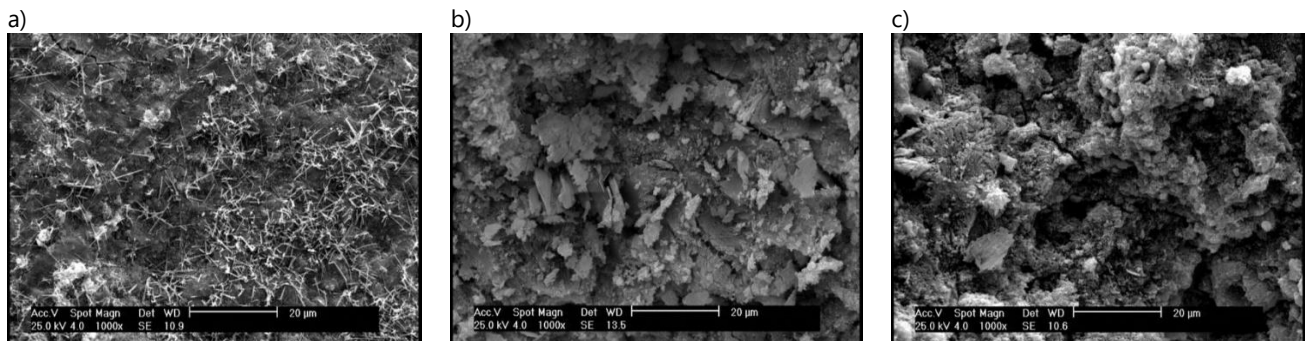


Figure 19. SEM image for Mix III. a) $t = 1200\text{ }^{\circ}\text{C}$, $d = 10\text{ cm}$; b) $t = 900\text{ }^{\circ}\text{C}$, $d = 10\text{ cm}$; c) $t = 900\text{ }^{\circ}\text{C}$, $d = 5\text{ cm}$

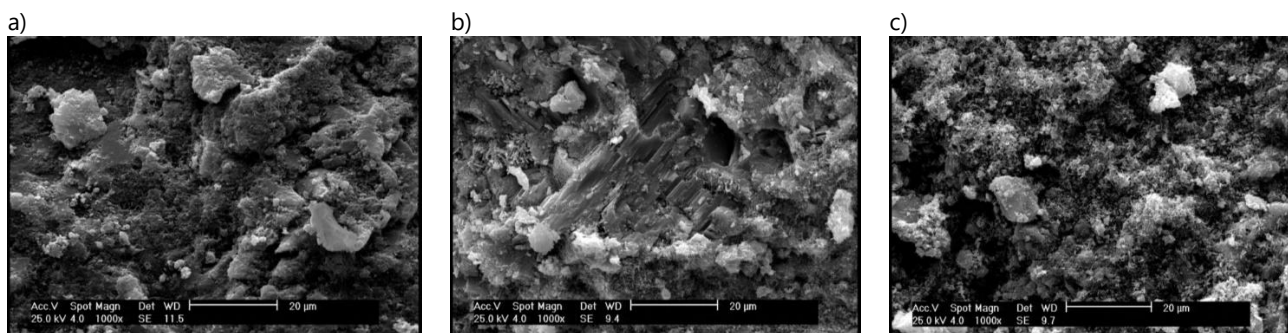


Figure 20. SEM image for Mix IV. a) $t = 1200\text{ }^{\circ}\text{C}$, $d = 10\text{ cm}$; b) $t = 900\text{ }^{\circ}\text{C}$, $d = 10\text{ cm}$; c) $t = 900\text{ }^{\circ}\text{C}$, $d = 5\text{ cm}$

a) b) c)

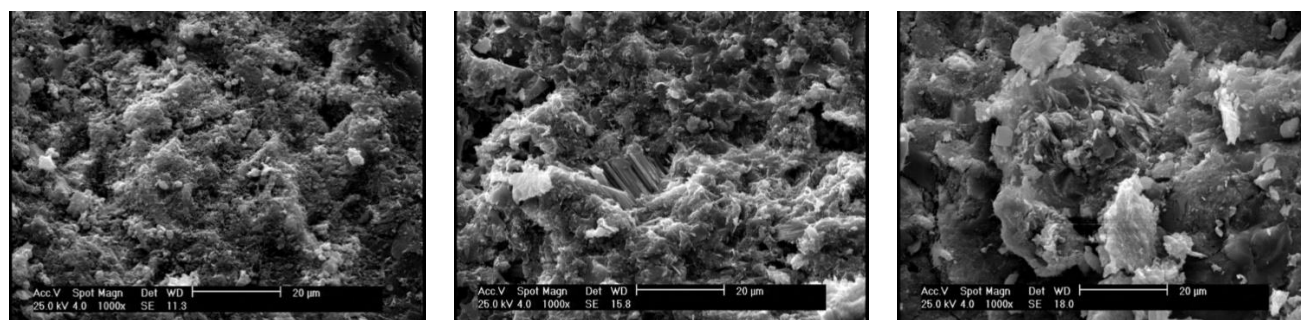


Figure 21. SEM image for Mix V. a) $t = 1200\text{ }^{\circ}\text{C}$, $d = 10\text{ cm}$; b) $t = 900\text{ }^{\circ}\text{C}$, $d = 10\text{ cm}$; c) $t = 900\text{ }^{\circ}\text{C}$, $d = 5\text{ cm}$

5. Conclusion

This study examines the mechanisms, factors, and mitigation measures of thermal spalling, specifically thermo-hygral and thermo-chemical spalling, in NSC (NSC). According to experimental findings, pore pressure and thermal stress buildup inside the concrete matrix are the primary causes of thermal spalling, and mechanical stress exacerbates the severity of spalling even more. The study determines crucial variables that lead to spalling and the ensuing deterioration of the structural integrity through a series of carefully monitored laboratory tests.

These results emphasize the role of chemical reactions and temperature gradients in causing spalling, especially at temperatures higher than 700°C , which causes microstructure degradation and uniform chemical water release. Our research verified that the occurrence of spalling takes place at a specific temperature range, usually above 610°C , and that the damage varies depending on the heating rate and composition of the concrete. The quick creation of high-water vapor pressure that happens when the interior surfaces' free water temperature rises over the water's boiling point, which is approximately 100°C , results in the explosive spalling of concrete blocks close to these surfaces. During this test, 15 instances of concrete spalling were heard within 20 minutes after a 3-hour fire exposure. Two samples lost up to 45% of their volume, and one lost up to 30%. Spalling begins at the temperature-exposed surface of the concrete, and as this surface spalls, the underlying layer becomes exposed to high temperatures and undergoes spalling as well. This process continues if the high temperature persists, leading to the progressive destruction of the concrete. For instance, five of the concrete blocks' faces were exposed to normal temperature, while one face was subjected to a high temperature.

The findings also showed that exposure to high temperatures causes a significant drop in residual compressive strength, which is caused by the cement matrix's deterioration and increased porosity. Experiments have indicated that the degree of spalling, the amount of residual compressive strength lost, and the weight reduction are significantly influenced by the heating rates, the highest temperature at which the material is exposed, and the properties of the inherent materials. The results indicate that at $900\text{ }^{\circ}\text{C}$ the aggregates spalling happened and at $1050\text{ }^{\circ}\text{C}$ the aggregates near to heated surface were milted. Significant thermo-chemical spalling, strength, and weight losses were specifically noted in NSC by the study, with the most consequences occurring at temperatures of 1200°C . These results were validated by scanning electron microscopy (SEM) examination, which showed higher structural damage—such as wider cracks and increased porosity—near the heated surface. In line with the documented spalling behavior, these microstructural alterations highlight the key temperature range at which considerable damage happens. By highlighting the significant effects of high temperatures on NSC microstructure, the SEM results advance our knowledge of thermo-chemical spalling mechanisms and how they affect structural durability.

The study suggests mitigation methods such as using specific aggregate types, hydrophobic admixtures, proper curing techniques, thermal barriers, insulating materials, and mix design modifications with fibers and materials with optimal thermal properties. These methods aim to improve the design of concrete mixes and fire-resistant components, enhancing the durability and safety of structures in extreme conditions. Future research should focus on developing predictive models and new materials resistant to thermal and chemical stresses. Understanding thermo-chemical spalling better will help develop a more durable infrastructure for modern construction sites. The study acknowledges the need for further investigation, particularly on full-scale structural components and pressurized or constrained concrete specimens, to create comprehensive predictive models and enhance the resilience and fire safety of reinforced concrete constructions.

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