INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 17 No. 7 (2025) 189-198
https://publisher.uthm.edu.my/ojs/index.php/ijie

Post-Thermal Performance of Concrete Containing 60% of Slag

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DOI: https://doi.org/10.30880/ijie.2025.17.07.019

Article Info

Received: 29 April 2025
Accepted: 12 September 2025
Available online: 31 December 2025

Keywords

Slag, porosity, mass loss, elastic modulus, compressive strength

Abstract

Post-thermal performances of concrete have been studied extensively, as it is crucial to determine whether the structure can be used after a fire event; however, concrete properties can always be improved. One of the innovations introduced in concrete mixtures is the replacement of cement with industrial waste materials, such as slag. Concrete containing slag is already established in the construction industry. However, there is limited information regarding the post-thermal performance of concrete containing slag up to a 60% replacement. Hence, this study aims to investigate the post-thermal performance of concrete containing 60% slag replacement at ambient temperature and after exposure to elevated temperatures of 200°C and 500°C for one hour. Therefore, the properties of hardened concrete were determined. Three batches of 100 mm × 100 mm × 100 mm cubes specimens containing 0% (normal concrete, NC) and 60% slag replacement (concrete containing slag, CCS) were tested under compressive strength test. It was found that the compressive strength of CCS is 34.4 MPa, which is lower than that of NC, which achieved 40.6 MPa with 0.85 difference ratio. The residual compressive strength of CCS is 32.6 MPa, while NC has 47.4 MPa, with 0.69 difference ratio. The residual compressive strength decreases gradually with an increasing temperature exposure up to 500°C. A similar trend also occurs on modulus of elasticity (MOE); CCS has a decrease of elastic modulus compared to NC. In contrast for 200°C temperature exposure, CCS shows an increment about 19 on MOE value. However, both NC and CCS maintain a residual compressive strength exceeding 30 MPa, which remains within the acceptable target range. It can be concluded that slag can give an acceptable potential for the future in construction industry.

1. Introduction

The use of green and high-performance materials is one of the most effective ways to achieve sustainable development in the field of Civil Engineering. Among all the construction materials, concrete is the most popular [1], which consists mainly of several traditional components: ordinary Portland cement (OPC), natural aggregate, water and chemical additives (such as superplasticiser).

One innovation made to conventional concrete was concrete containing slag (CCS), which was high slag blast furnace cement. Slag is one of the waste by-products from the steelmaking industry but has potential for the concrete industry due to its specific physical and chemical properties [2], [3]. Stated that during the pyrometallurgical production of copper, 2.2 to 3 tons of copper slag are generated for every ton of copper produced [4]. The presence of slag in concrete mixtures as a replacement is a cost-effective method in increasing the strength and behaviour of concrete [5]. Two benefits arise from replacing cement with slag: first, it helps manage waste in landfills, and second, it reduces the amount of cement used. This thereby lowers the amount of CO^2 produced during cement manufacture [6]. According to Gopalakrishnan et al. [7], using copper slag as an admixture in concrete is the most effective method of managing waste by-products. It has been established that individuals living near landfill slag are exposed to toxic elements, and there is a risk of enrichment for poisonous elements in plants and animals, which can ultimately harm human health, either directly or indirectly [8]. Slag can pose a significant environmental issue if not properly and efficiently disposed.

This indicates that the practice of including slag in concrete mix has a positive effect while minimising waste by-products from the steel industry. An investigation has been conducted into the development of sustainable ultra-high-performance concrete containing ground granulated blast-furnace slag (GGBS) and glass powder (GP). Tran et al. [9] stated that a combination of 20% GP and 5% GGBS appears to be an ideal ratio in terms of concrete strength. According to Ayim-Mensah et al. [10], a maximum of 40% replacement of GGBS was found to achieve great compressive strength at ambient temperature. However, some studies obtained significantly different slag contents. As examples, Yazici et al. [11] achieved optimum compressive strength with 20% slag replacement, while Oner & Akyuz [12] found that 50% and 55% slag replacement can also yield optimum compressive strength.

The effect of steel slag on the strength, workability, and durability of concrete at ambient temperatures has been investigated extensively. However, there has been limited research on the behaviour of concrete containing slag at and upon exposure to elevated temperatures. In the context of thermally damaged concrete, the pozzolanic reaction of ground granulated blast-furnace slag (GGBFS) can help in densifying the microstructure, potentially offsetting some of the strength loss due to thermal exposure. A study investigated the impact of incorporating 40% GGBFS and 20% fly ash on the properties of concrete subjected to thermal damage at temperature elevations of 200, 400, 600, and 800 °C. Although the primary focus was on durability, the inclusion of GGBFS was also found to influence the compressive strength of the concrete [13]. The study suggests that the combined use of GGBFS and fly ash enhances the residual properties of concrete after exposure to high temperatures, contributing to improvements in both durability and compressive strength. In summary, incorporating GGBFS into concrete mixtures can enhance compressive strength—particularly in the long term—and improve the performance of thermally damaged concrete.

GGBFS is known to enhance the ultimate compressive strength of concrete. Its slower hydration process leads to the development of a more refined microstructure, resulting in increased strength over time [3], [9], [10], 14]. However, the rate of early-age strength gain is typically slower compared to ordinary Portland cement concrete. The specific effects on compressive strength depend on various factors, including the replacement level of GGBFS, curing conditions, and the presence of other supplementary cementitious materials such as fly ash. Hence, this study aims to investigate the effect of elevated temperatures on the behaviour of concrete containing 60% slag as a cement replacement.

2. Methodology

2.1 Materials

Ordinary Portland Cement (OPC) Type CEM I 42.5 MPa was used in this study, as it is the most common cement type and performs well in stabilization works. The concrete mixes were prepared using OPC together with natural aggregates, where crushed granite with a maximum size of 10 mm served as coarse aggregate and natural river sand was used as fine aggregate; the coarse aggregate was sourced from Quarry Rock Kajang Sdn. Bhd. Additionally, 60% of the cement content in the mix was replaced with high slag blast furnace cement supplied by Slag Cement Sdn. Bhd. as shown in Fig. 1. Ground granulated blast furnace slag (GGBFS), a by-product of the steel manufacturing process, possesses latent hydraulic properties that enhance long-term strength and durability. The slag used in this study had a typical specific gravity of approximately 2.90–3.00, which contributes to its suitability as a supplementary cementitious material. Its inclusion aims to evaluate its effectiveness as a sustainable cement replacement under elevated temperature conditions.

2.2 Mix Design

The concrete grade 30 was prepared by using the concrete mix design form. Furthermore, the slump test use in the 60 to 180 mm and the max aggregate size was 10mm of crushed coarse aggregate. The free-water content ratio that use in this concrete 0.52. From the calculation the result of concrete grade 30 design was shown in Table 1.

Fig. 1 *High slag blast furnace cement*

Table 1 *Design mix*

Samples	Cement (kg/m³)	Slag (kg/m³)	Water (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)
NC	445	0	205	710	985
CCS	178	267	205	710	985

2.3 Samples Preparation

A total of 36 samples (18 cubes and 18 cylinders) were prepared for residual compressive strength and modulus of elasticity testing as shown in Fig. 2. For the cubic specimens, 18 cubes measuring 100 × 100 × 100 mm were prepared, consisting of 9 samples of normal concrete (NC) and 9 samples of concrete containing slag (CCS), both designed at a concrete grade of 30 MPa. For the cylindrical specimens, 18 cylinders measuring 100 × 200 mm were cast, again comprising 9 NC and 9 CCS samples. All specimens were exposed to three different temperatures, 27°C (ambient), 200°C, and 500°C, for a duration of 1 hour after reaching the target temperature, before undergoing compressive strength and modulus of elasticity testing. Table 2 presents the details of the samples used in this study.


(a) **(b)**

Fig. 2 *Experimental sample of (a) Cubic; and (b) cylindrical shapes*

Table 2 *Details of specimens*

Specimens	Percentage of OPC (%)	Percentage of Slag (%)	Temperature Exposure (°C)
NC27	100	0	27
CCS27	40	60	27
NC200	100	0	200
CCS200	40	60	200
NC500	100	0	500
CCS500	40	60	500

2.4 Experimental Set-up

2.4.1 Thermal Exposure

The compressive strength and modulus of elasticity (MOE) testing at elevated temperature were conducted for 27 specimens with 2 different shapes (cube and cylinder) at up to 200 °C and 500°C. This test was conducted to determine the residual compressive strength and modulus of elasticity of normal concrete and concrete containing 60% slag as cement replacement. The samples were exposed to transient elevated temperature for one hour duration once the furnace reached required temperature. Fig. 3 shows the time-temperature curve for the ISO 834 and ASTM E119 standards [15]

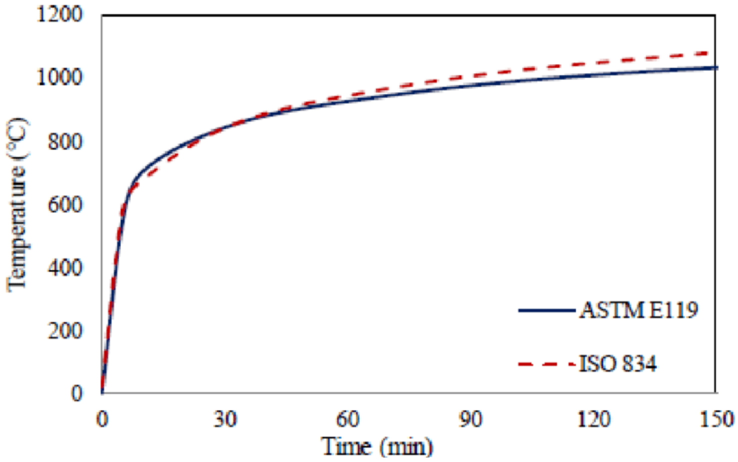


Fig. 3 *Temperature-time curve for ISO 834 and ASTM E119 [15]*

2.4.2 Compressive Test

The compressive strength test was carried out for a total of 18 samples with dimension of 100 x 100 x 100 mm (9 samples each for NC and CCS). This test was done to determine the concrete behaviour under applied load by using universal testing machine as shown in Fig. 4. The capacity of machine used is about 2000 kN with a load control rate of 3.0 kN/s. All the specimens were tested after 28 days of curing process. Three results were obtained to calculate the average compressive strength for all batches of concrete, including NC and CCS at various temperatures.

Fig. 4 *Compressive testing machine*

2.4.3 Modulus of Elasticity

A computer-based data collection system was used to record all data from the strain gauges that were installed at the centre of the specimens. The type of strain gauge used was KC-70-120-A1-11L1M2R, with a length of 67 mm, and the temperature coefficient of the gage factor was +0.015%/°C. A total of 36 strain gauges were used for the 18-cylinder specimens, with each specimen requiring two strain gauges for horizontal and vertical displacements as shown in Fig. 5. All of the samples will be compress by using three cycle concepts in order to determine the modulus of elasticity of the concrete. For the first and second cycle, the samples were compress up to one third of its ultimate compressive strength. Then, it will be compress up to ultimate compressive strength in the last cycle.

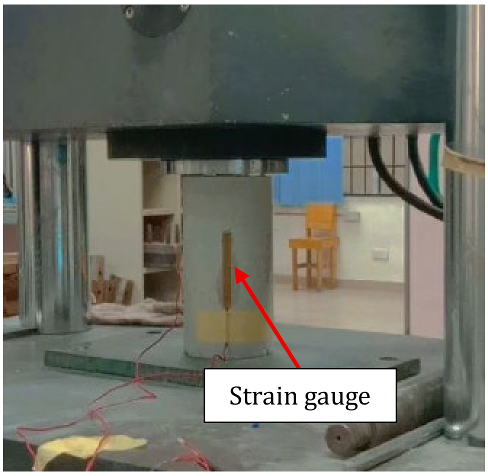


Fig. 5 *Testing modulus of elasticity*

3. Results and Discussion

3.1 Porosity at Ambient Temperature

Fig. 6 illustrates the porosity values for the Normal Concrete (NC) and Cement–Slag Concrete (CCS) specimens. The NC sample recorded a porosity of 0.32%, whereas the CCS specimen exhibited a lower porosity of 0.25%. This reduction in porosity for CCS indicates that the incorporation of slag contributes to a denser and more refined microstructure. The latent hydraulic properties of slag promote additional formation of calcium–silicate–hydrate (C–S–H) gel, which fills voids within the matrix and reduces pore connectivity. In contrast, NC, which relies solely on OPC hydration, develops a comparatively more porous structure. Overall, the lower porosity in CCS demonstrates improved compactness and enhanced durability potential due to the beneficial microstructural development provided by slag.

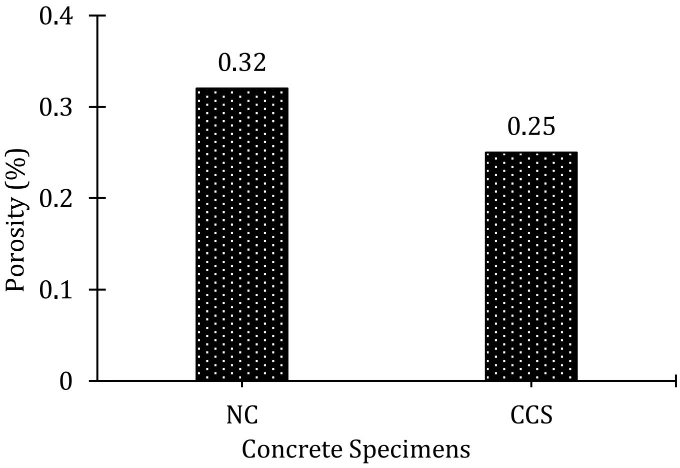


Fig. 6 *Porosity of concrete specimens*

3.2 Mass Loss

The mass of concrete specimens was measured at 28 days of curing age. Fig. 7 illustrates the mass loss of the concrete specimens at various temperatures. Due to high temperature exposure, the mass loss on NC200 reaches 0.75%, which is slightly higher than that of CCS200, which has a mass loss of only 0.63%. On the other hand, the mass loss on CCS500 was even greater at 7.49%, whereas CCS500 had a mass loss of 6.74%. Since the concrete specimens are exposed to heat, the concrete's moisture content evaporates, causing the specimens' mass to decrease due to the temperature's impact. It indicates that the temperature increases will have an impact on mass, which will increase evaporation and cause concrete to lose weight.

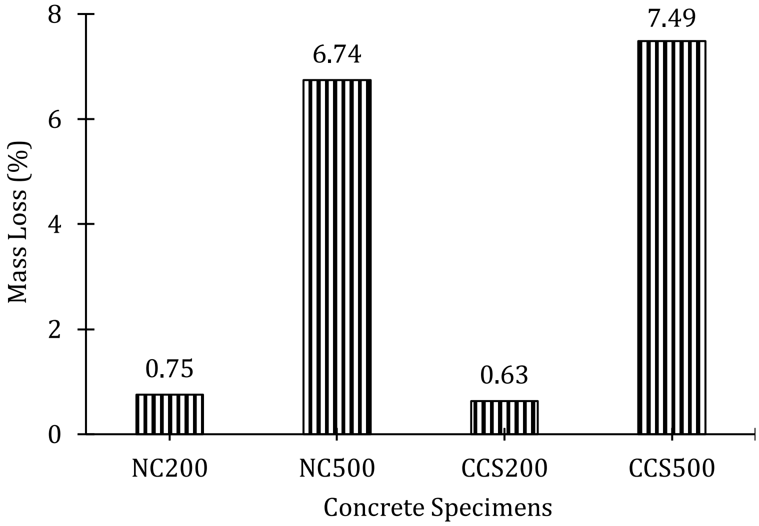


Fig. 7 *Mass Loss of concrete specimens after elevated temperature exposure*

3.3 Colour Change

The observation revealed that the colour changes on the concrete specimens occurred as a result of the data collected before and after the specimens were exposed to fire. Fig. 8 shows the physical change at temperatures of 200°C and 500°C for NC and CCS, respectively. At 200°C, spalling occurred at CCS, whereas there was very slight spalling at NC. At 500°C, the specimens' colouration completely changed to a whitish grey, and practically the whole surface began to spall. It is mostly caused by pore pressure. Pore pressure spalling is typically associated with thermal-hygral activity within the overheated concrete. Pore pressure increases gradually in the micropores due to heat transmission and moisture displacement.

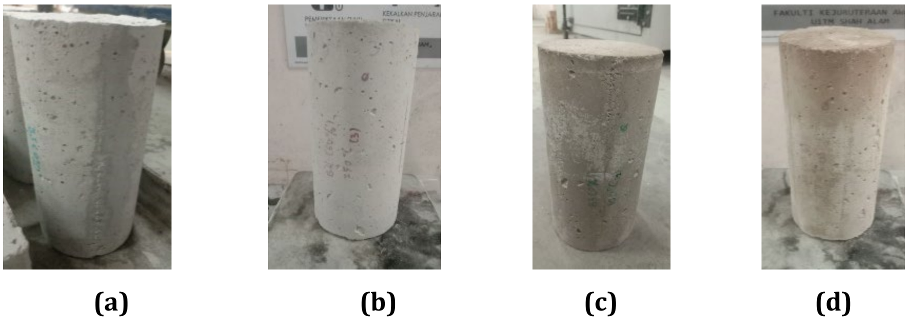

(a) (b) (c) (d)

Fig. 8 *Concrete specimens after exposure to heat – (a) NC200; (b) CCS200; (c) NC500; and (d) CCS500*

3.4 Residual Compressive Strength

Fig. 9 illustrates the 28-day compressive strength of NC and CSS at ambient temperature (27°C) and other varying temperatures (200°C and 500°C). At ambient temperature, NC achieves a compressive strength of 40.6 MPa, which is significantly higher than that recorded on CSS. The compressive strength of CSS is only 34.4 MPa. This represents a reduction of approximately 15.3% in strength for CSS compared to NC. The lower strength of CSS can be attributed to the effects of the substitution material used, which may alter the hydration process or weaken the microstructure and bonding within the concrete matrix. Factors such as the chemical composition, particle size, or reactivity of the substitution material could influence this performance disparity. Additionally, the ambient curing conditions might interact differently with the properties of the substitution material, further contributing to the reduced strength. Despite this reduction, CSS may still be suitable for non-structural or less demanding applications, particularly if the substitution offers environmental or economic advantages, such as the reuse of industrial waste or reduced costs. Further investigation into the properties and behaviour of the substitution material is essential to optimise its performance and broaden its potential applications.

For CCS200, the residual compressive strength at 200°C is 94.5% of its initial strength of 34.5 MPa, representing a reduction of 1.9 MPa. When exposed to a moderate temperature of 200°C, NC exhibits a significant increase in strength, peaking at 47.4 MPa, which is a 16.7% improvement. This can be attributed to the densification of the concrete matrix and the loss of free moisture. In contrast, CCS shows a slight decrease in strength to 32.6 MPa, indicating a sensitivity to moderate heat, possibly due to the behaviour of supplementary cementitious materials.

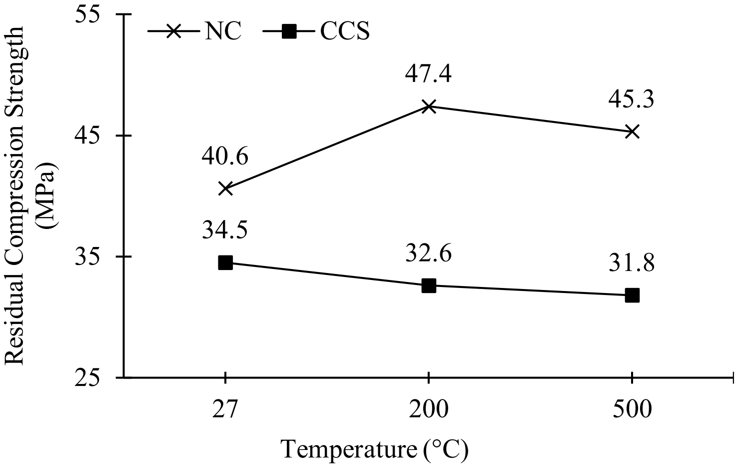


Fig. 9 *Residual compressive strength of NC and CSS at elevated temperature*

At 500°C, NC500 has a greater residual compressive strength than CCS500. However, both NC and CCS experience a decline in compressive strength. NC reduces slightly to 45.3 MPa, which remains above its original strength at ambient temperature. This reduction can be attributed to thermal degradation and microcracking within the concrete matrix. On the other hand, CCS exhibits a further decline to 31.8 MPa, highlighting its greater vulnerability to elevated temperatures. Across all tested temperatures, NC consistently demonstrates higher residual compressive strength than CCS. The sharper decline in compressive strength of CCS at elevated temperatures highlights the potential limitations of supplementary cementitious materials in high-temperature applications.

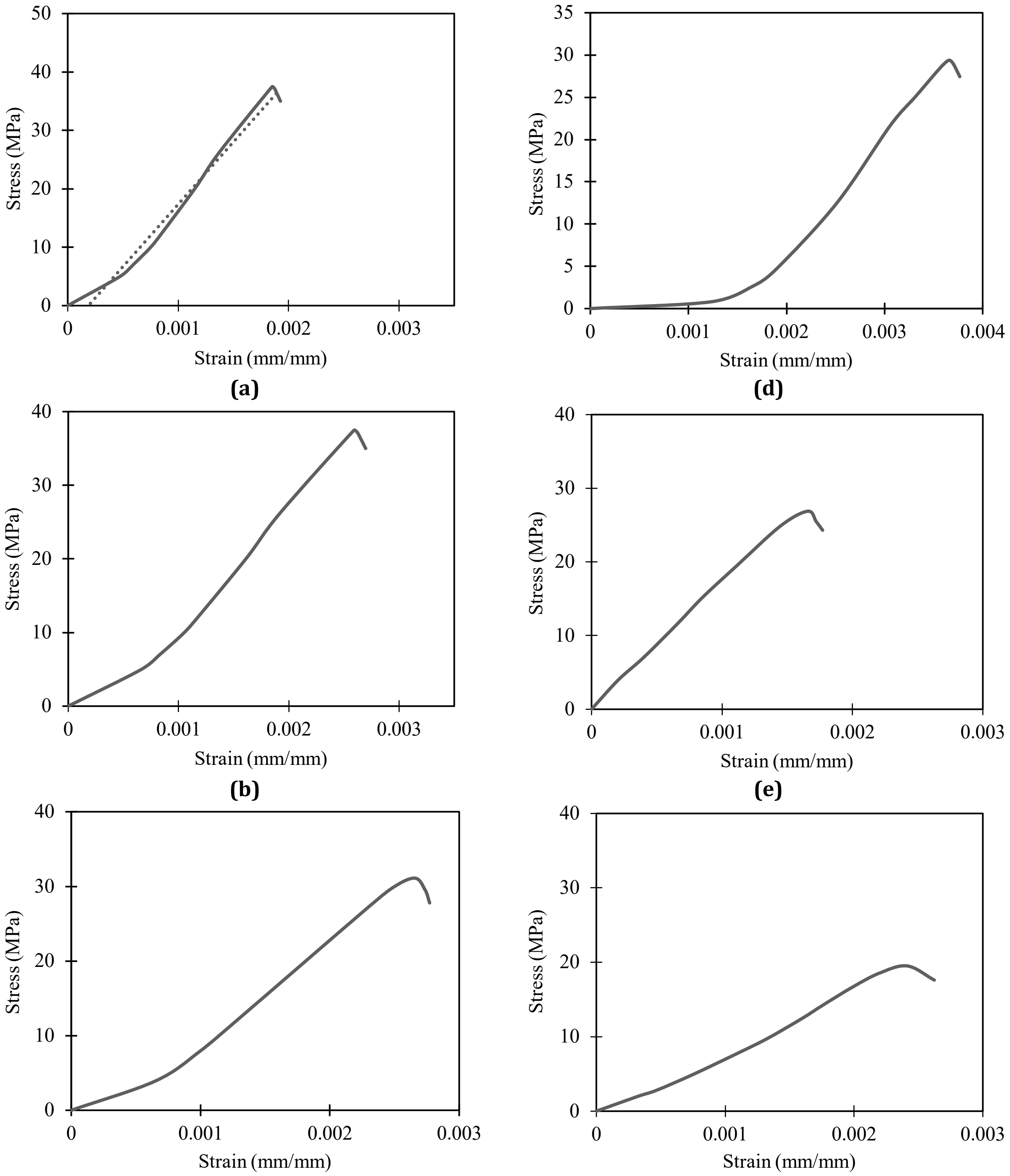
Overall, NC shows better resilience under thermal stress, while CCS may require further modifications to improve its performance in such conditions. High-slag blast furnace cement is a siliceous pozzolanic material. As the amount of slag decreases, the pozzolanic activity rises. The strength of a given partial replacement of cement depends on the particle size of the slag, which affects its pozzolanic activity. This demonstrates that the 60% replacement of slag was too high and resulted in a decrease in compression strength. It can be concluded that, even at 500°C, both NC and CCS maintain a residual compressive strength exceeding 30 MPa, which remains within the acceptable target range.

3.5 Elastic Modulus

The stress-strain curves for NC at 27°C, 200°C, and 500°C are shown in Fig. 10(a) to Fig. 10(c). Calculating the slope of stress to strain allowed the determination of the modulus of elasticity (MOE). For NC, the results indicate that MOE increased by approximately 19.0 GPa at 200°C, but decreased by around 14.8 GPa at 500°C. The stress-strain curves for CCS at 27°C, 200 °C, and 500 °C are shown in Fig. 10(d) to Fig. 10(f). The results for CCS demonstrate that MOE increases by approximately 16.8 GPa at 200°C, but then decreases to 9.2 GPa at 500°C. A comparison of E-value at various temperatures shows that NC has a greater value than CCS. The tabular data of MOE can be referred in Table 3.

MOE is a critical parameter in assessing the stiffness and deformation resistance of concrete. Based on Table 3, different concrete mixtures exhibit varying MOE values, reflecting their mechanical performance under different temperature exposures. NC27, representing normal concrete at 27°C, exhibits the highest MOE at 23.6 GPa. Meanwhile, NC200 and NC500, which were exposed to 200°C and 500°C, display lower values of 19.0 GPa and 14.8 GPa, respectively. This indicates that as the exposure temperature increases, the stiffness of NC decreases, likely due to thermal damage affecting the concrete microstructure. In comparison, CCS with 60% replacement exhibits a different trend. At 27°C, CCS27 has a MOE of 14.1 GPa, which is significantly lower than NC27. This suggests that slag replacement reduces the initial stiffness of concrete. However, at 200°C, CCS200 achieves a higher MOE of 16.8 GPa, indicating a slight improvement in stiffness, possibly due to enhanced pozzolanic reactions at moderate temperatures. In contrast, at 500°C, CCS500 experiences a significant reduction, with an MOE of 9.2 GPa, the lowest among all mixtures. This suggests that high-temperature exposure weakens CCS more than NC, likely due to thermal degradation of the slag-induced cementitious matrix.

The ratio of differences provides further insights into the relative stiffness changes. NC200 and NC500 have ratios of 0.81 and 0.63, respectively, compared to NC27, confirming the loss of stiffness with increasing temperature. Among CCS mixtures, CCS27 serves as a reference (1.00), while CCS200 has a ratio of 1.19, indicating an improvement at 200°C. However, CCS500 has a much lower ratio of 0.65, confirming a significant decline in stiffness at 500°C. This suggests that CCS exhibit temporary stiffness gains at moderate temperatures but suffers severe stiffness reduction at elevated temperatures compared to NC.



(a) **(d)**

(b) **(e)**

(c) **(f)**

Fig. 7 *Modulus of elasticity of (a) NC27; (b) NC200; (c) NC500; (d) CCS27; (e) CCS200; and (f) CCS500*

Several factors contribute to these variations in MOE. The material composition, particularly the 60% slag replacement, influences stiffness by altering the hydration and microstructural properties of the concrete. Temperature exposure can have a significant impact on the mechanical performance of concrete containing pozzolans, such as slag, fly ash, and rice husk ash. As temperature exposure potentially activates a pozzolanic reaction in the concrete [16]. This is because alkali activation involves the release of heat as a by-product, similar to the heat dissipated during the hydration of OPC. However, higher temperatures, starting at 500°C, can cause microcracking, pore expansion, and loss of cohesion in the cement paste. Stated that the dissociation of $Ca(OH)_2$

at temperatures ranging from 300°C to 400°C led to massive and sudden creep, typically causing failure at temperatures above 600°C [17]. Additionally, the dissociation of $CaCO_3$ at 700°C contributes to ceramic binding, while complete water loss occurs at 800°C and melting takes place at temperatures ranging from 1200°C to 1350°C. In fact, it found that $Ca(OH)_2$ dehydrated between 500°C and 600°C [18].

Table 3 *Modulus of elasticity*

Concrete	Modulus of Elasticity (GPa)	Ratio of Differences
NC27	23.6	1.00
NC200	19	0.81
NC500	14.8	0.63
CCS27	14.1	1.00
CCS200	16.8	1.19
CCS500	9.2	0.65

Overall, the results indicate that concrete containing 60% slag exhibits different behaviour under thermal exposure compared to normal concrete. While CCS may experience slight improvements in stiffness at moderate temperatures (200°C), this type of concrete suffers greater stiffness losses at high temperatures (500°C). This suggests that CCS may be suitable for applications with moderate heat exposure, but further investigation is required for high-temperature environments. Future studies should focus on optimising slag replacement levels, improving high-temperature resistance, and evaluating long-term durability to enhance the structural performance of CCS under thermal conditions.

Due to the replacement usage of high-slag blast furnace cement, which comprises calcium oxide (CaO) and magnesium oxide (MgO), the mechanical strength of slag powder has been improved. CaO hydrolyses at a rate that is higher than MgO. In a chemical reaction known as hydrolysis, water is typically used to dissolve the chemical bonds that separate two different substances. However, the outcome of this experiment reveals a decline in strength when comparing concrete with and without slag.

4. Conclusion

There were several conclusions based on this study:

- The porosity findings show that NC with grade 30 at ambient temperatures is more porous than CCS at 0.25% after 28 days, indicating that the additive concrete slag is less porous than a normal mixing of concrete.
- However, after one hour of exposure to fire, concrete containing slag becomes less strong in terms of compression strength compared to NC, but remains the grade remain above 30 MPa at 28 days of curing.
- The decreasing modulus of elasticity for both NC and CCS indicates that the slag is contributing to reducing the elastic modulus at post-fire performance.
- The cylindrical compressive strength is also impacted by temperature, with CCS losing the most strength compared to NC.
- The additive concrete with 60 % replacement slag improves the concrete's durability, enhancing porosity.

Acknowledgement

The authors would like to extend our gratitude to the Faculty of Civil Engineering at Universiti Teknologi MARA for providing the necessary platform and facilities for this research. The authors would like to thank the Ministry of Higher Education Malaysia for providing the financial support under the grant FRGS-EC/1/2024/TK06/UITM/02/20.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Qurratuaini Khidir, Nurizaty Zuhan, Oh Chai Lian;* ***data collection:*** *Qurratuaini Khidir;* ***analysis and interpretation of results:*** *Nurizaty Zuhan, Qurratuaini Khidir, Bishir Kado;* ***draft manuscript preparation:*** *Nurizaty Zuhan. Qurratuaini Khidir, Nadiah Sa'ari. All authors reviewed the results and approved the final version of the manuscript.*

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