Using Sustainable Biochar to Lower the Detrimental Effects of Fire in Concrete

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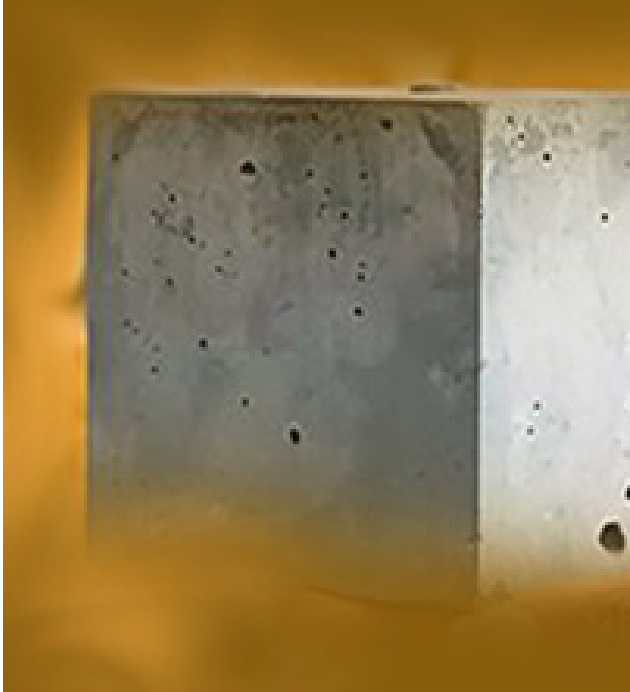
2023:7



This report constitutes a final working manuscript for the headlined project. The official project report, to which reference should be made, can be found on the LTU´s website

”Using Sustainable Biochar to Lower the Detrimental Effects of Fire in Concrete”

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Using Sustainable Biochar to Lower the Detrimental Effects of Fire in Concrete

Final Report for Project number: 322-003

Funded Application to Brandforsk, 2023

By: Oisik Das and Rhoda Afriyie Mensah (LTU)

Summary:
This project sought to investigate the potential of biochar, specifically produced at temperatures exceeding 700 °C, to enhance the fire resistance and sustainability of concrete structures. The hypothesis rested on the unique properties of high-temperature biochar, including its intricate microporous structure, which was anticipated to facilitate moisture escape and mitigate the risk of crack formation during exposure to high temperatures. Biochar's non-combustible and thermally stable nature was also expected to provide an additional layer of protection against heat-induced damage in concrete. Although the project fulfilled the sustainability aspect regarding the replacement of cement, which consequently reduces the carbon footprint, the experimental results did not substantiate the initial hypothesis, revealing that while the morphologies of biochar-added concrete and control concrete were similar, biochar's influence on the fire behaviour of concrete was limited. Despite this, the study yielded valuable insights, demonstrating that concrete can safely incorporate up to 20 wt.% biochar as a substitute for aggregates, maintaining structural integrity after fire exposure up to 600 °C. Moreover, the replacement of up to 20 wt.% of cement with biochar was shown to allow for safe structural performance up to 200 °C. The study highlighted a CO_2 reduction ranging from 10.6 % to 21 % as the biochar percentage increased from 10 wt.% to 20 wt.% as a replacement to cement, emphasising biochar's promising role in sustainable construction practices. Therefore, biochar in concrete can help the construction industry to be a role model for sustainability in the future. In the future, in-depth research is warranted to comprehend the fundamental effect of biochar on the fire behaviour of concrete at a microscopic level.

Keywords: Biochar Concrete; Elevated temperatures; Mechanical Properties.

1. Background:

Concrete, an indispensable material in modern construction, is ubiquitously employed across the globe for its remarkable durability, versatility, and strength [1]–[3]. The extensive use of concrete can be attributed to its robustness, affordability, and ability to withstand a wide range of environmental stresses [4]. However, despite its resilience in many aspects, concrete possesses a vulnerability that becomes alarmingly apparent when subjected to fire. While concrete is not flammable per se, exposure to high temperatures during fire outbreaks can have catastrophic consequences, leading to loss of strength, stiffness, spalling, and, consequently, a severe reduction in its load-bearing capacity [5]. Furthermore, traditional concrete production heavily relies on cement, a major contributor to the construction industry's environmental impact, accounting for 40 % of the global carbon footprint [6]. As the second most widely used material globally, the concrete market saw substantial growth, with a 12 % compound annual growth rate in 2021, and is expected to reach approximately USD 442 billion by the end of 2023 [7]. This growth further exacerbates carbon emissions. To align with the United Nations Sustainability Development Goals, both the construction industry, in general, and the concrete sector, specifically, must take swift action to mitigate emissions associated with cement manufacturing. Strategies include exploring alternative binders, carbon capture, and utilisation, and the use of blended cement to reduce the environmental footprint of concrete production [8], [9]. This dual challenge of fire vulnerability and environmental impact necessitates a paradigm shift in the way concrete is produced, which has brought about the incorporation of recyclable and renewable materials in lieu of conventional binders and aggregates.

In 2018, Sweden had a substantial food waste issue, amounting to 133 kg per capita, totalling 133 million kg based on the population at the time. This problem has persisted, with the current population of Sweden in 2022 at around 10.5 million. To address this, the government has set a target to reduce food waste by 20 % per capita in the next three years [10]. Leveraging these food wastes for novel materials could significantly alleviate the environmental impact. With this context, there is a pressing need to identify a renewable additive that can enhance the fire-safety of concrete, while also reducing its carbon footprint and promoting waste utilisation.

Biochar, a carbonaceous material obtained from the pyrolysis of organic waste, offers a promising solution that potentially could mitigate the adverse effects of fire in concrete [11], [12]. Biochar is not only renowned for its excellent fire-safe properties but is also a sustainable alternative due to its environmentally friendly production process [13]. The incorporation of biochar into concrete presents several notable benefits, as was posited by several previous studies. It contributes to improved thermal insulation properties in concrete, making structures more energy-efficient and resilient to temperature fluctuations [14]. Additionally, the utilisation of biochar in concrete formulations can help mitigate CO_2 emissions and reduce natural resource depletion, aligning with the goals of sustainable and eco-friendly construction practices [7], [14], [15]. While there may be trade-offs in terms of compressive strength, biochar's positive impacts on carbonation resistance, chloride ion penetration resistance, and cement hydration make it a valuable additive for enhancing the overall performance and longevity of concrete structures.

It is reported that biochar when produced at temperatures exceeding 700 °C, possesses a range of unique properties that can be effectively harnessed to enhance the fire resistance and sustainability of composites [16]. Its inherent porosity, characterised by a vast network of interconnected micropores, will serve as an essential feature in this context [17]. These pores could provide multiple pathways for trapped moisture within the concrete to escape, thereby potentially mitigating the risk of crack formation during exposure to high temperatures due to the volumetric expansion of water vapor. Furthermore, biochar's non-combustible and thermally stable nature (up to 50 kW/m^2 heat flux corresponding to 750 – 800 °C) could act as a robust heat shield within the concrete, offering an added layer of protection against heat-induced damage. In this context, it was hypothesised that this combination of properties 'could' make biochar a promising additive for improving the fire resistance of concrete structures while promoting sustainability in construction practices.

The current study is designed to investigate the hypothesis that incorporating fine biochar (100 – 200 µm) derived from waste wood and coarse biochar (1.5 – 3.5 mm) from food waste (fruit pits) through pyrolysis can enhance the fire resistance and sustainability of concrete. This will be achieved by replacing various percentages (0, 10, 15, and 20 % by weight) of cement and aggregates in concrete with biochar. The biochar-concrete samples will undergo comprehensive testing, including evaluations of compressive and tensile strength, and modulus of elasticity under normal room temperature conditions and after exposure to fire.

To simulate fire exposure, the samples will be subjected to direct flame in a controlled furnace, following the ISO-834 standard curve. The temperatures chosen for removal from the furnace, namely 200, 600, and 1000 °C, correspond to different stages of enclosure fire scenarios—growth, flashover, and fully-developed fire. Post-fire testing will determine if the inclusion of biochar preserves the mechanical properties of the concrete, and the optimal biochar loading amount that retains the highest value will be identified.

This research has the potential to catalyse the development of a new generation of concrete with a significantly reduced carbon footprint with a fire behaviour that is akin to a standard concrete. Furthermore, the use of biochar in concrete promotes circularity by valorising food waste and logging residues through recycling. The study's beneficiaries extend to concrete suppliers, the construction industry, property owners, and society as a whole, as it enables the continued use of concrete as a construction material with enhanced sustainability and without any detrimental effect on the fire safety of concrete, contributing to safer and more environmentally friendly building practices.

2. Experiments:

2.1. Materials:

For this research, the following materials were used: 1) regular Portland cement, which contains fly ash, limestone, and has a clinker ratio of 80 %; 2) 0-8 mm fine aggregate and 8-16 mm coarse aggregate were used for both the cement and aggregate replacement batches; 3) the fluid medium was Master Glenium 592; 4) fine biochar powder (ca. 100 – 200 µm) and coarse biochar aggregates of size ranging from 1.5 to 3.5 mm was supplied by Novocarbo GmbH, Hamburg, Germany. The fine biochar was produced from the pyrolysis of logging waste containing about 90 % softwood and 10 % hardwood whereas the coarse biochar pieces were a result of fruit pit pyrolysis. The raw materials used as feedstock for biochar are organic wastes, which promote sustainability and waste valorisation.

2.2. Methods:

2.2.1. Biochar characterisation:

When biochar is used as a constituent in concrete, its density, particle size, and porosity are the important factors that can influence the properties of the concrete. The density of the biochar samples was determined using pycnometer (AccuPyc II 1340). Two different methods were used to determine the particle size distribution. The particle size distribution of fine biochar was determined using the instrument Mastersizer 3000- Malvern Panalytical, which uses the diffraction laser scattering method for measurement. High-quality photographic images of coarse biochar with the scale were taken and processed in the ImageJ software to measure the particle size distribution [18]. Figure 1 depicts one of the photographic images used for the analysis.

Figure 1: Photographic picture used for the Image J analysis of coarse biochar.

The tea bag method [19] was used to determine the water absorption of the two biochars. The tea bag was made from filter paper, and a known weight of biochar was filled and sealed inside. During the experiment, extra precautions were taken to prevent biochar leakage. The biochar-filled tea bag was then immersed in a beaker containing distilled water. To prevent carbonation of the liquid due to CO_2 absorption from the air, the beaker was tightly wrapped with aluminium foil. The tea bag was then removed at specific time intervals (1, 5, 15, 30, 45, 60, 90, 130, 150, 180, 240, and 1440 min), the surface water on the tea bag was gently wiped out with tissue paper, and the weight gain was measured using a weighing scale. Simultaneously, the empty tea bag water absorption was measured with the same method. Three samples were tested, and average values were considered. Water absorption of the biochar particles was calculated using the following equation [19],

Water absorption of biochar (g/g) = $(M_2-M_1)/M_0$

Where, M_2 is the mass gain of tea bag containing biochar, M_1 is the mass gain of an empty tea bag and M_0 is the mass of biochar added.

2.2.2. Nanoindentation:

The hardness and reduced modulus of the specimens were determined through nanoindentation, employing a Hysitron TI-950 tribo-indenter equipped with a three-sided diamond Berkovich tip. To prepare the samples, they were first embedded in epoxy resin and allowed to cure for 12 h. Subsequently, the samples were meticulously ground and polished to achieve smooth surfaces. A standard quasi-static load function was applied during the testing process, involving a total of 12 indents, with a maximum load of 10 µN being applied to relatively flat sample regions identified using an optical microscope with a 20x objective magnification. Hardness and reduced modulus values were then computed based on the load-displacement data, following the methods outlined in a prior research study [11].

2.2.3. Cone calorimeter tests:

To evaluate the reaction-to-fire properties of the two biochars, including parameters like peak heat release rate (PHRR), time to ignition (TTI), and total heat release (THR), a TCC 918 cone calorimeter manufactured by Netzsch Analyzing & Testing was utilised. During the testing process, the samples were subjected to a heat flux of 35 kW/m^2. The test was conducted following the ISO 5660–1:2015 standard [20], ensuring standardised and consistent measurement conditions.

2.3. Material preparation and casting of concrete:

Three batches were cast for each type of concrete (aggregate and cement replacement) including a reference with no biochar. For the concrete samples, 10, 15, and 20 wt.% of the cement and fine aggregates were replaced with fine and coarse biochar, respectively, as shown in the recipe presented in Table 1. The materials required for the batches were weighed with an accuracy of 0.01 kg. The humidity of the fine aggregate was considered to adjust the water-cement ratio before they were uniformly mixed in a concrete mixer. The water-cement ratio for the batches was 0.32.

The casting was performed as follows: the dry ingredients were placed in the mixer with the fine aggregate in the bottom, then cement, fine biochar/coarse biochar (depending on the batch being prepared), and lastly the 8-16 mm aggregate. The dry ingredients were mixed for 1 min before the water was added together with 80 % of the fluid medium and then it was mixed for about 2 mins. When the concrete stiffened, the rest of the fluid medium was added and mixed for about one more minute. A slump test was conducted according to EN 12350–2 for each batch to assess the workability of the concrete. After testing, the concrete was placed in cube-shaped and cylindrical moulds, covered with plastics, and left to dry for 24 h. The cubic samples were demoulded, cured for 28 days underwater, and kept in a humidity chamber set at 23 °C.

Table 1: Concrete recipe

Aggregate Replacement Recipe				
Ingredient	0 wt.%	10 wt.%	15 wt.%	20 wt.%
Unit	(kg)	(kg)	(kg)	(kg)
Biochar	0	3.8	6.2	8.3
Cement	15	15	16.5	16.5
Fine aggregate	37.6	33.9	35.2	33.1
Coarse aggregate	16.1	16.1	17.7	17.7
Water	4.8	5.8	6.8	6.8
Master glenium	0.08	0.09	0.17	0.2
Cement Replacement Recipe				
Ingredients	10 wt.%	15 wt.%	20 wt.%	
Biochar	1.6	2.4	3.2	
Cement	14.6	13.8	12.9	
Fine aggregate	40.6	40.6	40.6	
Coarse aggregate	17.4	17.4	17.4	
Water	6.2	7.2	7.2	
Master glenium	0.1135	0.2	0.2	

Note: 0 wt% cement replaced sample had the same recipe as the 0 wt% aggregate replaced sample.

2.4. Characterisation of concrete:

2.4.1. Compression Tests:

Five cube-shaped specimens measuring 100 mm on each side underwent compression testing in accordance with EN 12390–3 standards. A 2015 Toni Technik machine was used to conduct the tests at a testing speed of roughly 10 kN/s. Precise measurements of the length, width, and height of each specimen were taken using an electronic vernier calliper with an accuracy of 0.01 mm. Additionally, the weight of each sample was recorded to estimate its density.

2.4.2. Tensile Splitting Testing:

Tensile splitting tests were conducted on cylindrical specimens from each concrete batch, each measuring 200 × 100 mm. The tests employed a 2015 Toni Technik apparatus equipped with a tensile splitting jig, and they followed the Swedish standard for testing hardened concrete, SS-EN 12390:2009, with a splitting force rate of 1.70 kN/s. Similar to the compression test, the dimensions (length and diameter) and weight of each sample were measured to calculate cylinder density.

2.4.3. Fire tests:

In the fire testing phase, the specimens were placed inside a furnace, following the ISO-834 standard fire curve. However, the experiments were intentionally halted at three specific temperature points: 200, 600, and 1000 °C. These temperatures correspond to critical stages of fire development within an enclosure, representing fire growth, flashover, and fully developed fire conditions.

A time-sensitive test was also conducted in the furnace with the intention of exposing the concrete to the standard fire curve for 30, 60, and 90 mins. After the fire tests, the specimens underwent additional testing to assess the impact of fire exposure on concrete mechanical and microscopic properties. This included both compression and tensile strength testing and electron microscopy to determine how exposure to high temperatures influenced the characteristics of the concrete samples.

2.4.4. Scanning Electron Microscopy (SEM):

For the analysis of the samples, an FEI Magellan 400 field emission XHR-SEM instrument was employed. The SEM was operated at an accelerated voltage of 3 kV with a current of 6.3 A.

3. Limitations of the project:

The project was a one-year work wherein the research team endeavoured to comprehend changes in mechanical properties of biochar-added sustainable concrete when exposed to the standard fire curve. The fire behaviour of concrete is very complex involving thermal penetration based on conductivity, specific heat, and density of the material; spalling sensitivity that changes with sample size and when a sample is reinforced (or not reinforced); and the rate of heat front progression that might affect a concrete sample's compressive strength. The project was too limited to investigate all these aforementioned factors and thus, the project experiments were designed to only investigate the effect of fire exposure on 1 dm^3 (cubes) and 1.6 dm^3 (cylinders) unloaded biochar-added sustainable concrete having a specific mix recipe. Thus, the current project was more akin to an ad-hoc object test that gives an overview of the changes in mechanical properties after biochar-added concrete was subjected to a standard ISO-834 fire curve. The comparisons were made with the same 'type' and 'dimension' of unloaded samples (i.e., standard concrete) that did not have any biochar. Future studies will attempt to gain insight into the effect of biochar in altering the thermal conductivity of concrete and spalling sensitivity with loaded concrete slabs.

4. Results and Discussion:

4.1. Biochar properties:

4.1.1. Density and Water absorption capacity:

In general, the true density of the biochar varies between 1.5 and 2 g/cm^3, and the density test results of the current investigation were similar to this. Fine biochar had a density of 1.9 g/cm^3 and coarse biochar had a density of 1.58 g/cm^3. For comparison, the density range for fly ash, which is used to replace cement in concrete, is 1 – 2.5 g/cm^3 [21]. Figure 2 shows the particle size distribution for both biochars. The fine biochar was in the size range of 100 to 400 µm with 200 µm as the dominant particle size. This is similar to the particle size of the fine biochar (< 0.5 mm) used in the work of Edeh et al.[22]. The average particle size of the coarse biochar was 2.95 mm, which is within the standard sizes of coarse biochar (> 2 mm, ranging between 2.71 and 5.37 mm) shown in the work of Trifunovic et al. [23]. Figure 3 reveals the water absorption capacity of both the biochars as a function of time. The coarse biochar absorbed less water than the fine biochar, however, after 30 min of immersion, both biochars show saturation in water absorption. The fine biochar had relatively more water absorption than the coarse counterpart because water molecules cling to finer particles more tightly than coarser particles owing to the higher surface area of the fine particles (i.e., increased surface tension). Additionally, the coarse biochar has larger pores and airspaces that facilitate the outward drainage of absorbed water. However, the micro pores in the fine biochar hold the water, thus increasing the water absorption capacity of fine biochar. The water absorption capacity of the fine biochar is confirmed in the work of Gupta et al. [24] where fine biochar particles with sizes ranging from 5 to 200 µm had a water absorption of 2.50 ± 0.20 g/g. In addition, Maljaee et al. [25] stated emphatically that grinding biochar to fine particles increases the water retention capacity due to the large surface area, hence, it can be inferred that fine biochar particles could have higher water absorption capacity than the coarse ones.

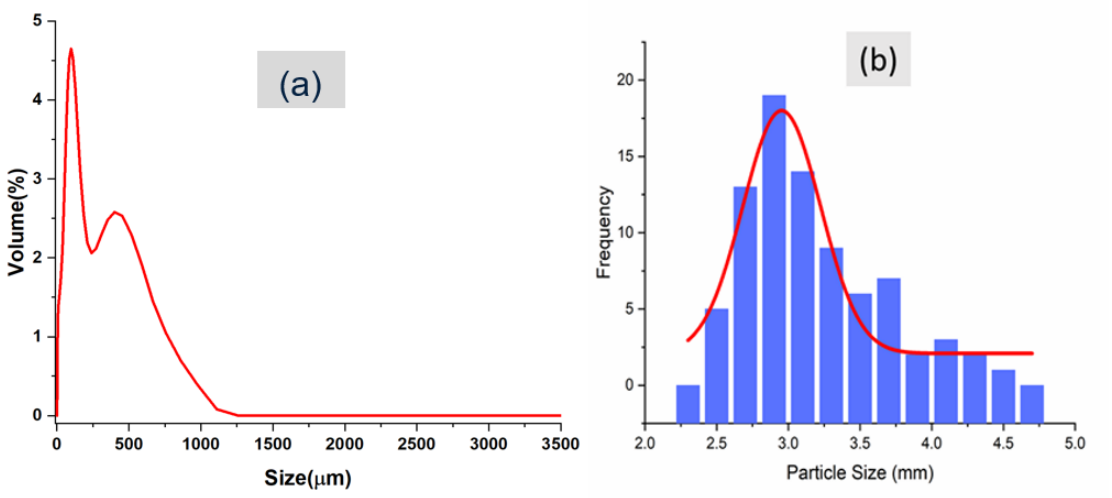


Figure 2: Particle size distribution of biochar, (a) fine biochar and (b) coarse biochar.

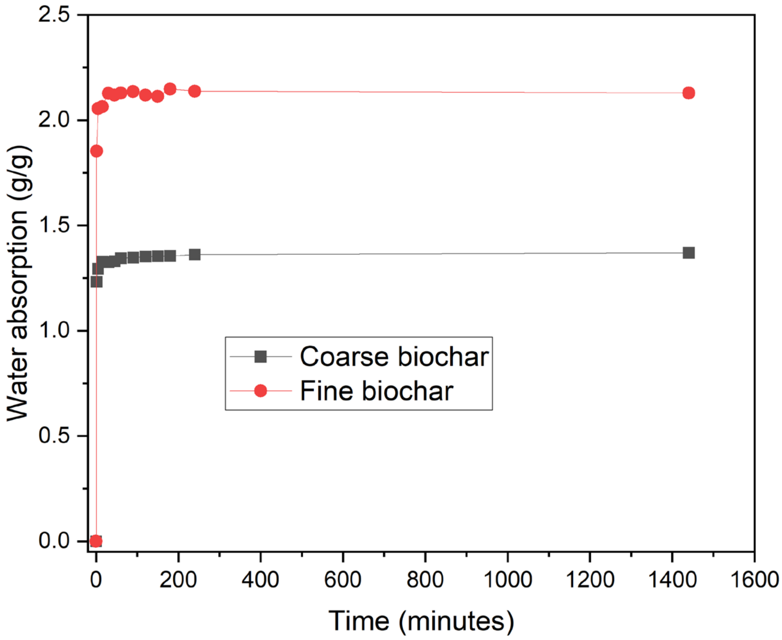


Figure 3: Water absorption capacity of the two biochar types investigated.

4.1.2. Nanoindentation:

For the nanoindentation experiments, the force exerted on the indenter and the displacement of the indenter into the material were continuously measured throughout the test. This data has been used to develop the load-displacement curve shown in Figure 4 and the resulting data, as shown in Table 2. Young's modulus was calculated from the reduced modulus, as specified by Das et al. [12]. It is seen from the results that the indentation response on both biochars is less plastic and more elastic due to the presence of C–C covalent bonds [11], [26]. The coarse biochar is slightly softer than the fine biochar. The nanoindentation results also show that fine biochar has a higher Young's modulus compared to coarse biochar. This means that fine biochar is more resistant to both plastic and elastic deformation at the nanoscale, indicating that it has better mechanical properties in terms of stiffness and resistance to deformation. However, it's important to note that the values provided are specific to the nanoscale and may vary depending on factors like production methods and the specific source of the biochar. These properties can be important when considering the suitability of biochar for various applications.

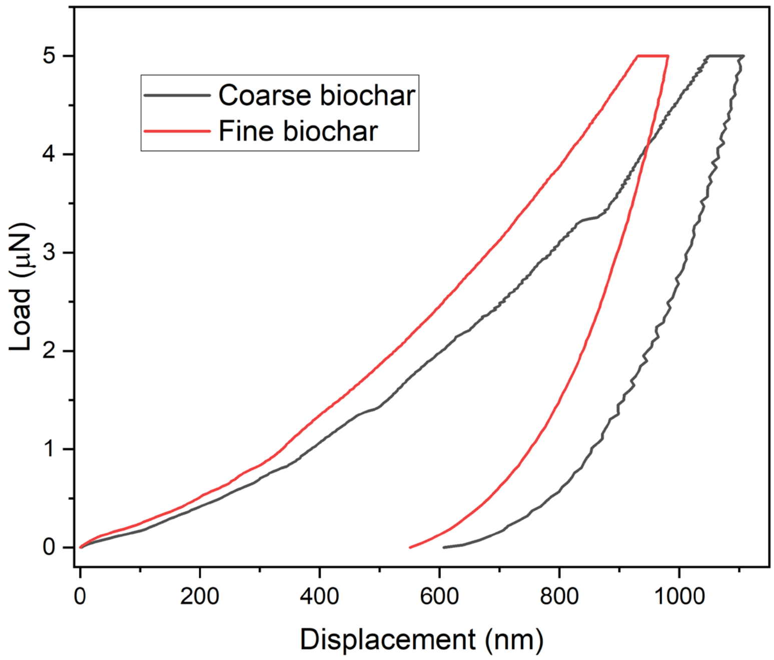


Figure 4: Load-displacement curves of the fine and coarse biochar.

Table 2: Mechanical properties of the fine and coarse biochar.

Sample	Hardness (Gpa)	Young's Modulus (Gpa)
Fine Biochar	0.28 ± 0.03	5.1 ± 0.3
Coarse Biochar	0.22 ± 0.04	3.37 ± 0.4

4.1.3. Reaction-to-fire properties of biochars:

The fine and coarse biochars were exposed to irradiation in the cone calorimeter to record their reaction-to-fire properties, Table 3 and Figure 5. The cone calorimeter results indicate that the coarse biochar exhibited ca. 38% higher peak heat release rate (PHRR) compared to the fine biochar, with values of 37.3 kW/m² and 27.04 kW/m², respectively. The coarse biochar also reached its peak heat release rate significantly faster, taking 49 % less time than the fine biochar, with time to PHRR values of 379 s and 771 s, respectively. Although the coarse biochar released slightly more total energy (29.5 MJ/mg) compared to the fine biochar (28.1 MJ/mg), both materials did not ignite during the test (TTI = No ignition), suggesting they possess fire-resistant characteristics at the employed heat flux of 35 kW/m^2

Table 3: Reaction-to-fire properties of the respective biochars

Parameters	*Coarse Biochar*	*Fine Biochar*
PHRR (kW/m^2)	37.3±5	27.04±3
THR (MJ/mg)	29.5±1	28.1±1.5
Time to PHRR (s)	379±15	771±30
TTI (s)	No ignition	No ignition

Note: peak heat release rate = PHRR, total heat release = THR, time to ignition = TTI

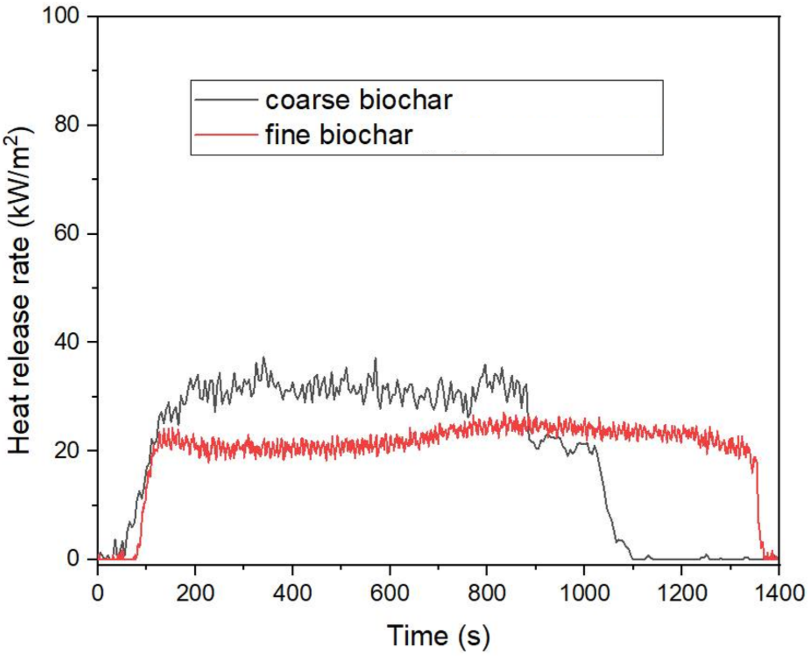


Figure 5: Plot of heat release rate versus time for the fine and coarse biochar.

4.2. Physical properties of concrete after fire tests:

After subjecting concrete samples to different temperatures, distinct observations were recorded. At 200 ℃ (Figure 6a), no notable changes were observed. At 600 °C, as shown in Figure 6b, significant cracks emerged due to the loss of the cement's binding capability. This loss occurred as water evaporated from the C-S-H (calcium-silicate-hydrate) structure, resulting in crack formation and surface flaking. This temperature also triggered the dehydration of the components within the cement paste, especially affecting the C-S-H structure, and caused the dissociation of calcium hydroxide ($Ca(OH)_2$) [27]. This dissociation process gave rise to the formation of calcium oxide (CaO) and water, contributing to alterations in the concrete's structural integrity and appearance [28]. At 1000 ℃ (Figure 6c), noticeable colour alterations occurred, primarily caused by the oxidation of iron present in the fine and coarse aggregates [29].

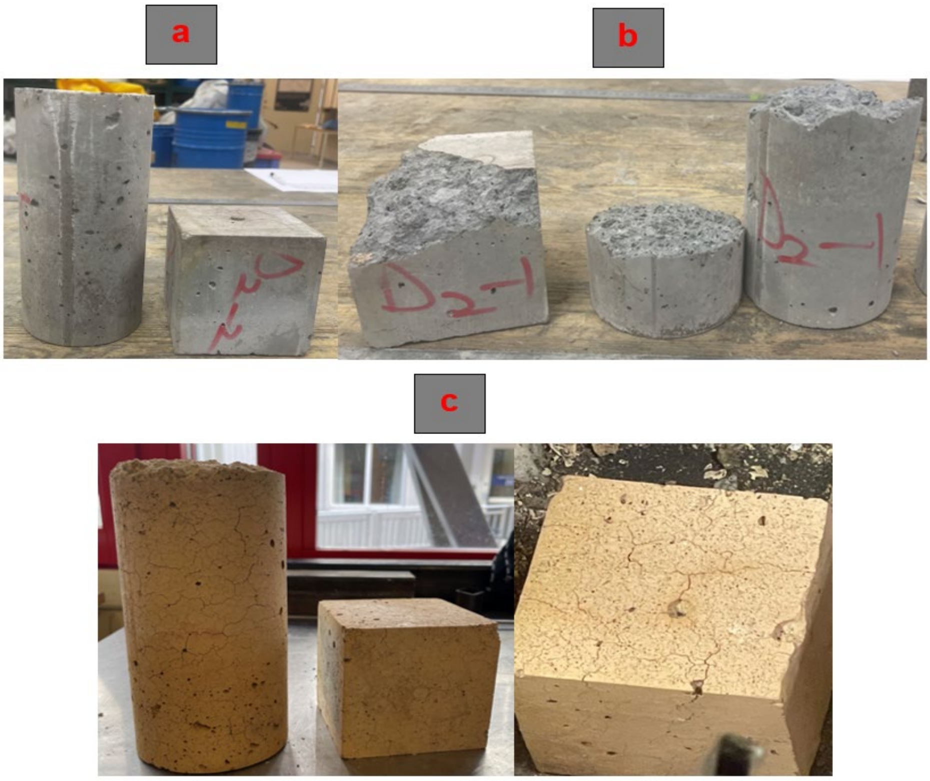


Figure 6: Concrete samples exposed to a) 200 °C b) 600 °C c) 1000 °C

4.3. Mechanical properties of concrete before and after fire exposure:

4.3.1. Cement replacement samples:

The compressive, tensile splitting strength, and modulus of elasticity of the control sample and the cement replacement samples exposed to 200, 600, and 1000 °C are presented in Figure 7. It is seen that the partial replacement of cement with biochar in concrete had notable effects on its properties. Reducing the cement content led to a decrease in the binding ability, resulting in lower compressive strength, tensile splitting strength, and increased stiffness of the concrete. At 200 °C, a modest increase in both compressive strength and modulus was observed with the 10 wt.% and 15 wt.% replacement, with improvements of 6.5 % and 4.2 %, respectively, while the 20 wt.% replacement showed a 7 % increase for both parameters. The increase in compressive strength can be attributed to the accelerated hydration process, which is a result of the additional energy supplied at 200 °C [28], [30].

However, at 600 °C, these benefits diminished, with a 10 wt.% replacement causing a 6.1 % decrease in compressive strength and a 4.4 % decrease in modulus, and the 20 wt.% replacement resulting in a 7.2 % reduction in both compressive strength and modulus. At 1000 °C, the negative impact of biochar replacement became more pronounced, with substantial decreases in compressive strength and modulus observed, particularly at higher replacement percentages. The tensile splitting tests also followed a similar trend. There was a consistent decrease in tensile strength as the temperature increased. This reduction in tensile strength can be attributed to the thermal stresses and degradation of the material's structural integrity at elevated temperatures.

Furthermore, the study found that the variation in biochar content did not result in statistically significant differences in the loss of tensile strength with increasing temperature. This suggests that the replacement of cement with this specific wood-based biochar in this recipe, within the tested range, did not significantly impact the material's response to temperature-induced tensile stress. Additionally, it was noted that all concrete cylinders, regardless of the biochar content, experienced thermal cracking at the highest temperature tested, 1000 °C. This observation is consistent with the well-known effect of extreme heat on concrete, causing thermal expansion and ultimately leading to cracking.

Notably, it was found, with this particular recipe used, that concrete with up to 15 % fine biochar replacing cement could withstand temperatures of 600 °C, which may be crucial in fire resistance applications, possibly corresponding to the flashover temperature. These findings underscore the importance of carefully considering the proportion of biochar replacement in concrete for desired structural and thermal performance.

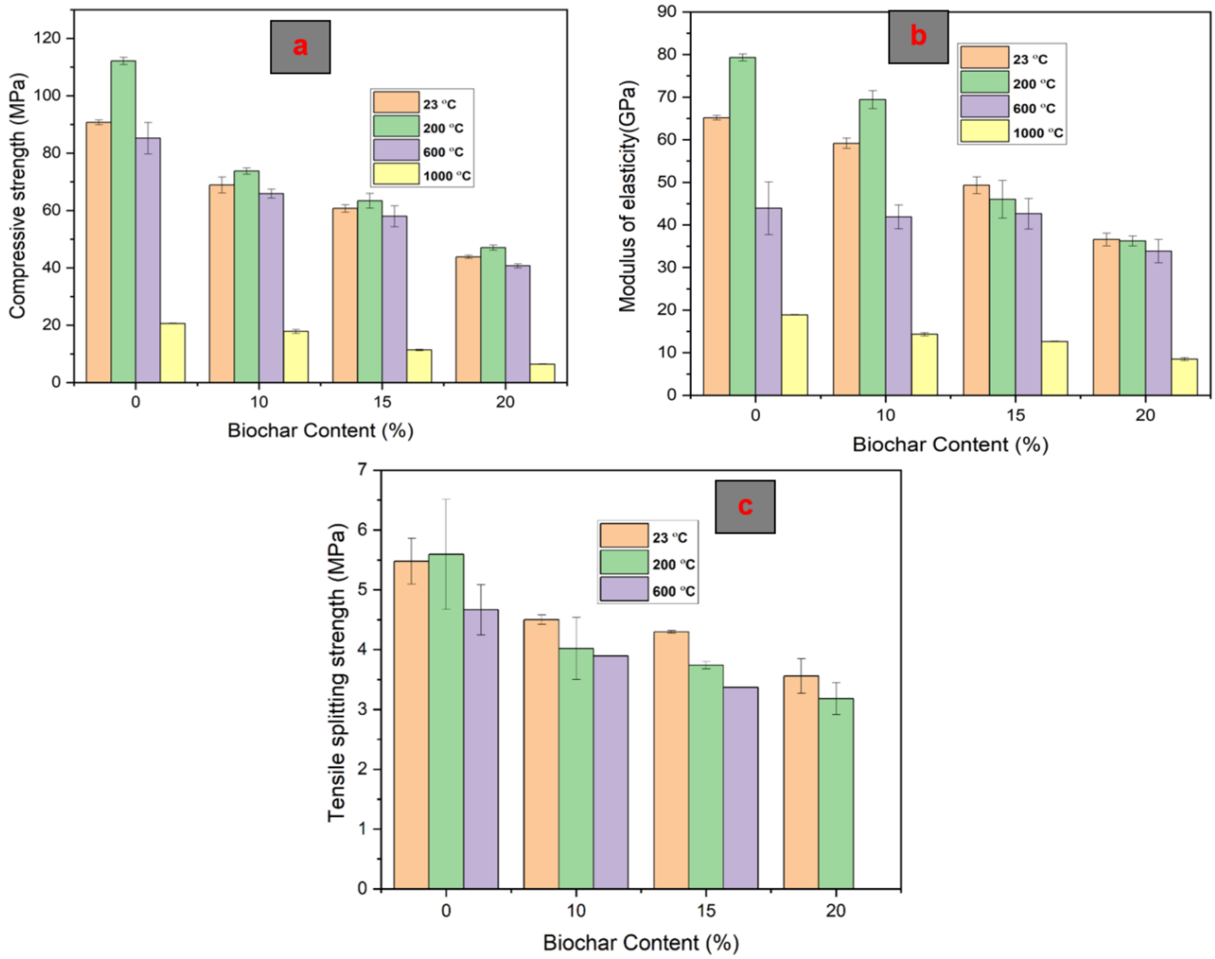


Figure 7: Mechanical properties of the control and cement replacement samples exposed to 200, 600, and 1000 °C. a) compressive strength b) modulus of elasticity c) tensile splitting strength.

4.3.2. Aggregate replacement samples:

Figure 8 shows the mechanical properties of the aggregate replacement samples before and after exposure to temperature. In this study, the replacement of fine aggregate in concrete with coarse biochar, having an average size of 2.5 mm, resulted in distinct observations regarding compressive strength and modulus. At 200 °C, a notable increase in both compressive strength and modulus was observed, with a 24 % and 19 % enhancement for 0 wt.% and 10 wt.% biochar replacement, while the 15 wt.% and 20 wt.% replacement led to slight decreases of 7 % and 1 % in the compressive strength and modulus, respectively. At 600 °C, there were generally minor reductions in compressive strength and modulus for all replacement percentages, ranging from

1.3 % to 15 %. However, at the highest temperature of 1000 °C, a substantial decrease in both compressive strength and modulus was observed across the board, with losses of 77 % to 90 % for different replacement levels. Notably, in the tensile splitting test, tensile strength consistently decreased with rising temperatures, with the most significant tensile strength loss observed in the 20 wt.% biochar replacement samples. Additionally, all concrete samples experienced thermal cracking at 1000 °C. It is worth highlighting that, overall, the reduction in strength and modulus was more pronounced in the cement replacement samples than in the aggregate replacement samples.

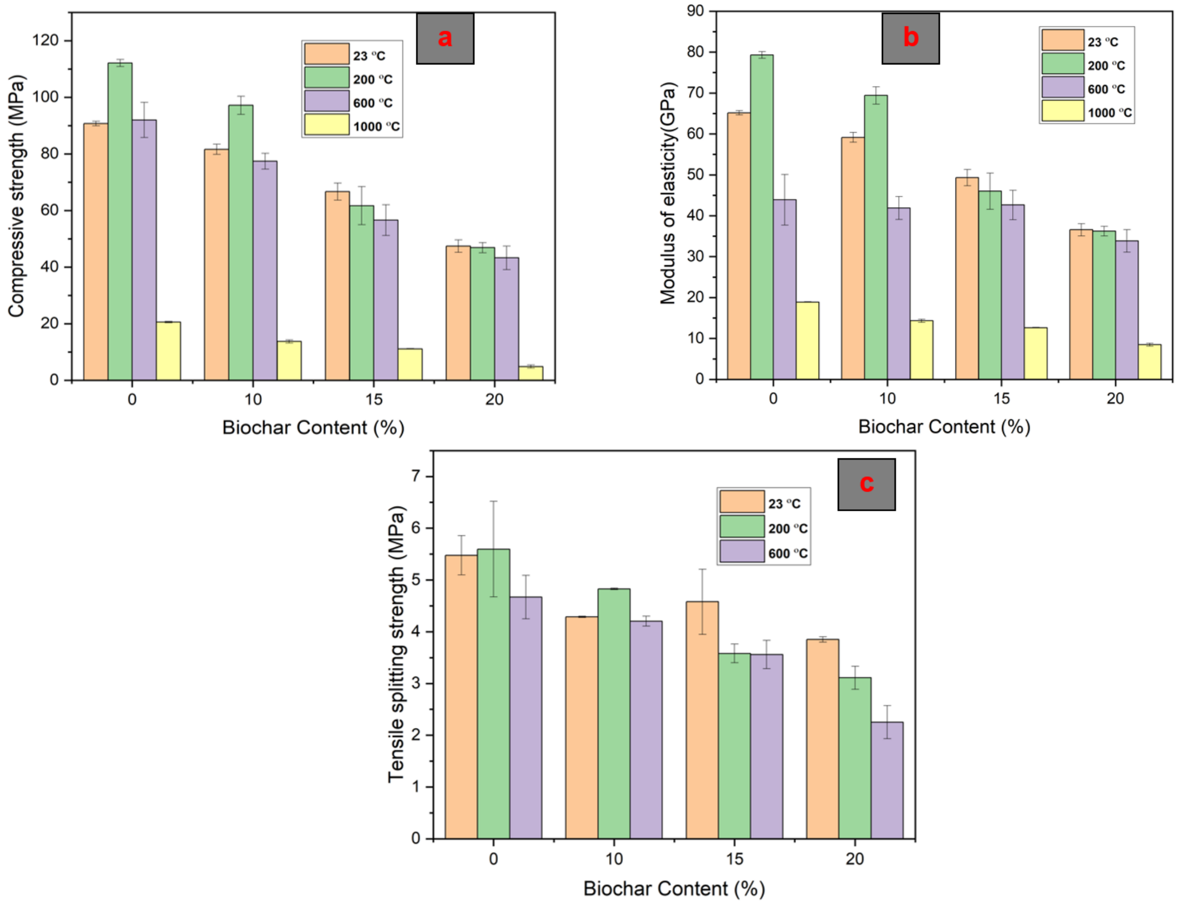


Figure 8: Mechanical properties of the control and aggregate replacement samples exposed to 200, 600, and 1000 °C. a) compressive strength b) modulus of elasticity c) tensile splitting strength.

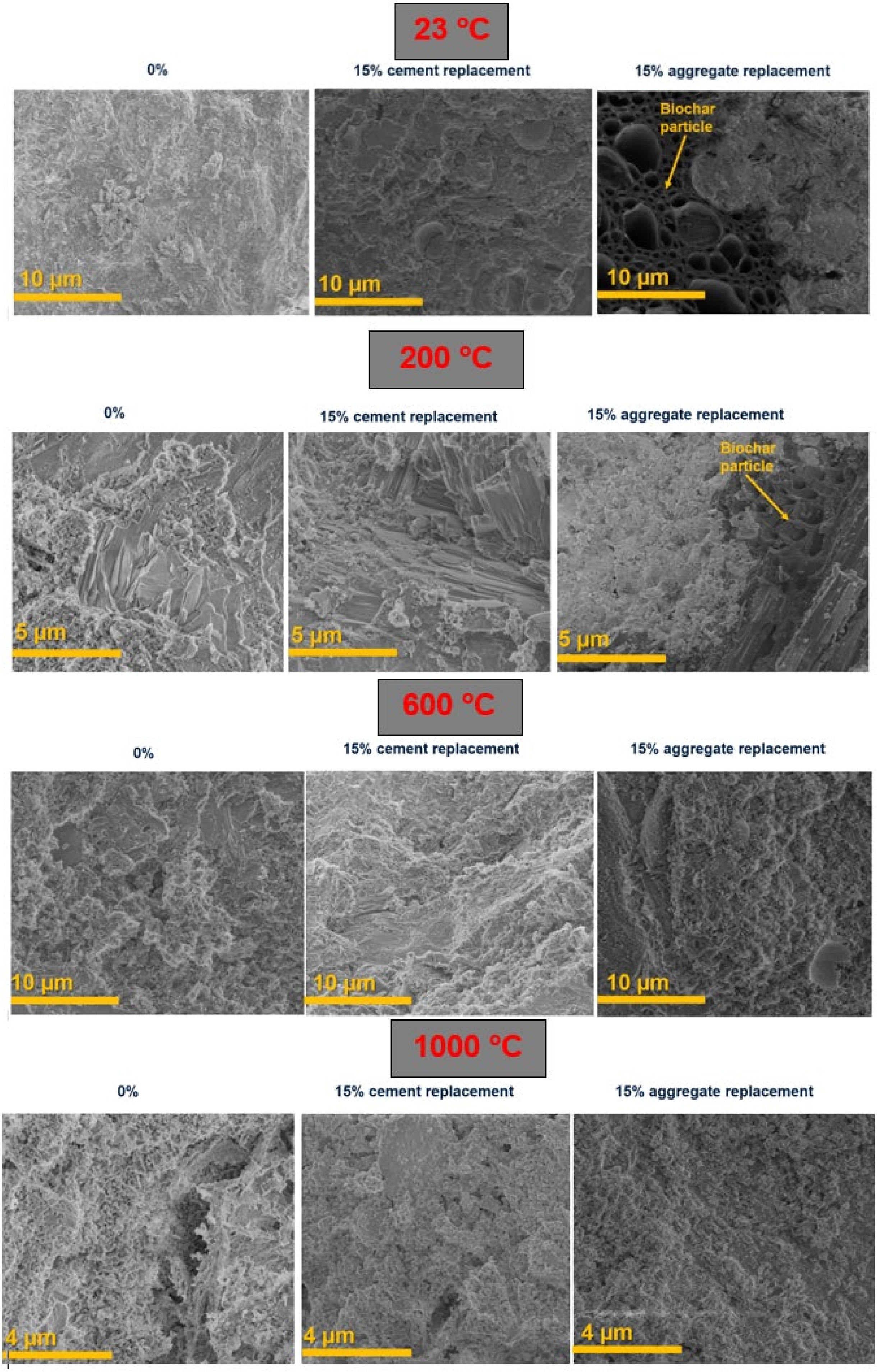
The comparison of mechanical properties between the control concrete and biochar-added concrete revealed an interesting finding. Specifically, the concrete with a 15 wt.% biochar loading exhibited tensile and compressive strength, as well as modulus, that were either similar or statistically indistinguishable from those of the 0 wt.% and 10 wt.% biochar concrete samples. As a result, based on the outcomes of this study, the 15 wt.% biochar loading has been identified as the optimal and most promising biochar content. This selection has the potential to contribute to the development of environmentally friendly concrete structures.

4.4. Scanning electron microscopy:

In the SEM analysis of concrete samples with 15 wt.% biochar and the reference concrete with no biochar (0 wt.%), several observations were made (see Figure 9). At room temperature (approximately 23 °C), the morphology of the reference concrete (0 wt.%) and the samples with 15 wt.% biochar replacement appeared similar. However, in the biochar-added samples used for aggregate replacement, the presence of larger biochar particles was evident, distinguishing them from the cement-replaced samples.

Upon exposure to 200 °C, there was no significant change observed in the morphology. The biochar particles in the aggregate-replaced samples remained visibly unaltered compared, indicating the resilience of the biochar structure under moderate heat.
At 600 °C, as the temperature increased, the visibility of calcium hydroxide crystals diminished in all the samples, which was indicative of the thermal decomposition of this component. However, the overall morphology of both the standard concrete and the biochar-added concrete still exhibited similarities, suggesting that the introduction of biochar did not dramatically alter the material's response to this temperature range.

A significant transformation in the morphology was observed at 1000 °C for all the concrete samples. Notably, the calcium oxide (CaO) was decomposed, forming calcium salts in 'globule-like structures,' as reported in the literature [28], [31]. This transformation indicated the severe thermal stress experienced by the concrete at this extreme temperature, leading to the alteration of its structural characteristics.



23 °C
0%
15% cement replacement
15% aggregate replacement
Biochar particle
10 µm
10 µm
10 µm
200 °C
0%
15% cement replacement
15% aggregate replacement
Biochar particle
5 µm
5 µm
5 µm
600 °C
0%
15% cement replacement
15% aggregate replacement
10 µm
10 µm
10 µm
1000 °C
0%
15% cement replacement
15% aggregate replacement
4 µm
4 µm
4 µm

Figure 9: SEM micrographs of 0 wt% and 15 wt% biochar-added concrete exposed to 23, 200, 600, and 1000 ºC.

5. Thermal cracking potential of biochar concrete:

An assessment focusing on the thermal cracking potential of concrete samples with and without biochar, specifically comparing the reference concrete with biochar-added variants was conducted. At 200 ºC, no thermal cracking was observed in any of the samples, irrespective of biochar presence. However, at 600 ºC, a significant divergence became apparent. The concrete samples with biochar replacing cement experienced thermal cracking, possibly attributed to the lower cement content, which indicates reduced binding ability. In contrast, the concrete samples with biochar replacing aggregates remained intact at this temperature. As the temperature increased to 1000 ºC, thermal cracking was evident across all the samples, including the reference concrete without biochar. Consequently, it can be deduced that, in the specific recipe examined in this study, the presence of biochar in the concrete had no significant influence when used as an aggregate replacement. However, replacing cement with biochar appeared to diminish the material's heat-shielding capacity. These findings provide valuable insights into the nuances of biochar's impact on concrete properties, shedding light on the importance of ingredient replacement choices in fire resistance considerations.

Fire	Thermal Cracking Potential						
	0%	10%		15%		20%	20%
		Cement Replacement	Aggregate Replacement	Cement Replacement	Aggregate Replacement	Cement Replacement	Aggregate Replacement
Small Fire (200 ºC) 	✓	✓	✓	✓	✓	✓	✓
Flashover Fire (600 ºC) 	✓	✗	✓	✗	✓	✗	✓
Fully Developed Fire (1000 ºC) 	✗	✗	✗	✗	✗	✗	✗

✓ No thermal cracking ✗ Thermal cracking

Figure 10: Comparison of the thermal cracking potential of reference and biochar added concrete.

A time-sensitive test was conducted in the furnace with the intention of exposing the concrete to the standard fire curve for 30, 60, and 90 mins. 15 wt% cement replaced samples were chosen for this experiment. However, after 30 mins, the temperature in the furnace rose up to 715 ℃, which caused the samples to crack under thermal load. Hence, no further test was done using this set-up because exposing the samples to longer time would have yielded the same result as 30 mins exposure.

6. Sustainability of biochar added concrete:

Numerous studies have consistently highlighted a concerning fact: the production of one metric tonne of cement results in the release of an equivalent amount of carbon dioxide into the atmosphere [7]. To combat this alarming carbon footprint, researchers have been exploring methods to reduce cement usage in concrete by partially substituting it with eco-friendly materials like biochar [7]. Biochar, produced from organic waste with significantly lower energy requirements, presents an attractive option for achieving sustainability in concrete production. This project investigates the effects of replacing cement with biochar at varying levels, 10 , 15, and 20 wt.%. Table 5 quantifies the reductions in CO_2 emissions achieved through these substitutions. Partially replacing cement and fine aggregates in concrete with biochar, as presented in this project report, aligns with several United Nations Sustainable Development Goals (SDGs), contributing to global sustainability efforts. It directly advances SDG 13 - Climate Action by offering a solution to reduce carbon emissions through the substitution of cement with biochar, significantly lowering the carbon footprint in the construction industry. Additionally, it contributes to SDG 9 - Industry, Innovation, and Infrastructure by endorsing innovative, eco-friendly materials like biochar in concrete production, thereby promoting sustainable infrastructure development, resource efficiency, and environmentally resilient construction practices. Furthermore, this research aligns with SDG 12 - Responsible Consumption and Production by reducing the environmental impact of cement production. It encourages responsible resource management and fosters a greener and more sustainable future for the construction industry and, by extension, the planet by advocating for sustainable production processes and materials.

Table 5: Quantity of CO_2 reduction with the addition of biochar in this project

Percentage of Biochar	CO_2 produced/reduced	Percentage of CO_2 reduction
0 wt.%	Produced 0.015 tonne	0 %
10 wt.%	Reduced by 0.0016 tonne	10.67 %
15 wt.%	Reduced by 0.0024 tonne	16 %
20 wt.%	Reduced by 0.0032 tonne	21.33 %

From Table 5, it is evident that the inclusion of biochar in concrete mixtures leads to a significant reduction in CO_2 emissions during production. As the percentage of biochar increases, the CO_2 reduction becomes more pronounced. When no biochar is added (0 wt.%), the production of concrete generates 0.015 tonnes of CO_2. However, by incorporating 10 wt.% biochar, the CO_2 emissions are reduced by 10.67 %. This reduction becomes even more substantial with 15 wt.% and 20 wt.% biochar additions, resulting in CO_2 reductions of 16 % and 21.33 %, respectively. These findings underscore the effectiveness of biochar in mitigating the carbon footprint of concrete production, demonstrating its potential as a sustainable and eco-friendly alternative in the construction industry.

7. Conclusions:

The project was grounded in the hypothesis that biochar, produced at temperatures exceeding 700 °C, possessed unique properties that could enhance the fire resistance and sustainability of concrete structures. It was postulated that biochar's inherent porosity, characterised by an extensive network of interconnected micropores, might facilitate moisture escape, potentially mitigating the risk of crack formation during exposure to high temperatures. Additionally, biochar's non-combustible and thermally stable nature (up to a heat flux of 50 kW/m^2) could act as a heat shield, providing added protection against heat-induced damage. However, the project's findings revealed that while the morphologies of the concrete samples with and without biochar were similar, biochar did not substantively impact the fire behaviour of the concrete. The hypothesis, therefore, was not supported by the experimental results. Nevertheless, the project yielded valuable insights, demonstrating that up to 20 wt.% of aggregates can be replaced with coarse biochar, following this recipe, while maintaining the structural integrity of concrete after fire exposure until 600 °C. Additionally, replacing up to 20 wt.% of the cement with biochar allows for safe structures up to 200 °C. Incorporating biochar in concrete mixtures offers a progressively effective means of reducing CO_2 emissions in construction. From this study, as the percentage of biochar increased from 10 wt.% to 20 wt.%, the corresponding reduction in CO_2 emissions rose from 10.6 % to 21 %, respectively, showcasing the promising potential of biochar as a sustainable and environmentally-friendly solution for the construction industry. These findings provide guidance for optimising the use of biochar in concrete, shedding light on its potential benefits and limitations in the context of fire resistance and structural safety.

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