

Thermal Performance Enhancement of Concrete through Activated Carbon Incorporation

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ABSTRACT

Concrete remains the most widely used construction material worldwide, motivating continuous efforts to improve its mechanical and thermal performance through the incorporation of functional additives. This study evaluates the effect of activated carbon microparticles, obtained from crushed charcoal, on the thermal behavior of hardened concrete while preserving its mechanical properties. Concrete mixtures were prepared using different water-to-additive proportions based on recommendations provided by CEMEX Mexico. Fresh-state performance was assessed through flowability and stability tests to verify mixture homogeneity, whereas compressive strength was determined in accordance with Mexican standards. Thermal diffusivity measurements were conducted on hardened specimens to evaluate the influence of activated carbon on heat transfer. The results showed that the incorporation of activated carbon produced a homogeneous mixture without segregation during casting or curing. The modified concrete exhibited an increase in compressive strength from 150 to 158 kg/cm² compared with the control mixture. In addition, the activated carbon enhanced the thermal diffusivity of the concrete, indicating a measurable modification of its thermal response. These findings demonstrate that activated carbon microparticles can be incorporated into conventional concrete without compromising its mechanical performance while improving its thermal characteristics, making this material a promising alternative for applications requiring enhanced thermal performance.

Keywords: Activated carbon, Compressive strength, Energy sustainability, Thermal diffusivity, Thermal properties.

1. INTRODUCTION

Concrete is one of the most widely used materials in the construction industry in Mexico due to its durability, versatility, and relatively low cost. Traditionally composed of Portland cement, sand, gravel, and water, concrete has been essential in infrastructure development. However, as building performance standards continue to evolve—particularly in terms of energy efficiency and environmental impact—so too has the need to improve concrete's properties beyond its basic structural capabilities.

Recent advancements in materials science have opened up new avenues for modifying concrete to enhance not just its mechanical strength but also its thermal and environmental performance. The use of additives and supplementary materials has become a common strategy for achieving these improvements, and more recently, nanotechnology has gained attention as a means to further refine concrete behavior at the microstructural level (López Yépez, Duran Herrera, & González Aviña, 2022; Manjunath & Narasimhan, 2020; Nwankwo, Bamigboye, Davies, & Michaels, 2020).

Despite significant progress in mechanical optimization, a notable gap remains in the development of concrete mixtures that also address thermal performance—particularly thermal diffusivity, which influences how heat moves through the material. This property is directly related to building energy efficiency and indoor comfort. While efforts have been made to reduce concrete's carbon footprint and improve durability using recycled

materials and advanced additives (Blazy, Blazy, & Drobiec, 2022; Gao et al., 2024; Zhao, Wang, & Yi, 2023) the potential for integrating thermal-enhancing materials remains underexplored.

To address these challenges, contemporary research has focused on three main vectors of improvement: thermal optimization, microstructural/nanotechnological reinforcement, and environmental sustainability through industrial and bio-waste valorization.

1.1. Thermal Optimization and Energy Storage in Cementitious Matrices

Improving the thermal efficiency of concrete without compromising its structural integrity requires innovative strategies for heat regulation and thermal resistance. A prominent approach involves the integration of Phase Change Materials (PCMs). Kim, Yun, Jin, and Kim (2025) demonstrated that carbon-reinforced cementitious composites containing microencapsulated and impregnated PCMs significantly enhance thermal energy storage and efficiency in buildings. Complementing this approach, Chin, Yang, Kong, Paul, and Wong (2020) evaluated lightweight concrete incorporating activated carbon as coarse aggregate, reporting a substantial reduction in thermal conductivity accompanied by favorable mechanical performance.

Beyond passive thermal management, active thermo-electric solutions have emerged for smart structural applications. Deng, Zhang, Zhang, He, and Li (2023) introduced a self-controlled temperature concrete using active electro-thermal strategies to regulate thermal variations directly within the matrix. Furthermore, the integration of nanomaterial modifications in alkali-activated concrete has proven successful in enhancing both impact resistance and high-temperature thermal stability under adverse thermal conditions (Raj R, Arulraj, N, Kanagaraj, & Stochino, 2025).

1.2. Microstructural Reinforcement, Polymers, Corrosion Mitigation and Sustainable Concrete

Extending structural lifespan and resisting physical damage are key priorities for next-generation concrete. Chemical and physical modifications at the microstructural level play a pivotal role in this domain. Bekturganova and Kolesnikova (2025) highlighted the significant impact of polymer additives on improving cohesion, impermeability, and overall mechanical performance. Fiber reinforcement also continues to play a vital role; Eid, Zaid, and Günel (2024) systematically reviewed fiber additives, demonstrating their capability to suppress microcracking, increase ductility, and improve energy absorption under mechanical loads.

Durability is further constrained by corrosion, particularly in reinforced concrete structures exposed to severe environmental degradation. Agboola et al. (2022) conducted a comprehensive review on corrosion-inhibiting admixtures, emphasizing their compatibility within cementitious matrices to mitigate chemical attack and extend service life.

The decarbonization of the construction sector requires replacing traditional energy-intensive materials with sustainable alternatives. High-strength concrete formulations increasingly rely on supplementary cementitious materials (SCMs). Amin, Abdelaziz, Agwa, and Abu El-Hassan (2022) evaluated various SCM combinations, detailing how microstructural densification enhances compressive strength and durability. Similarly, biomass ash has gained traction as a sustainable surrogate for fly ash; Olatoyan, Kareem, Adebajo, Olawale, and Alao (2023) reviewed its potential to replace traditional pozzolans, reducing carbon footprint while maintaining binder reactivity.

In parallel, circular economy principles drive the adoption of recycled aggregates in structural applications. Jagadeesh et al. (2024) reviewed the fresh and mechanical behaviors of high-strength concrete produced with recycled aggregates, concluding that proper mix designs can offset strength reductions. Finally, the synergy between biotechnology and nanotechnology has opened new possibilities; Abutu et al. (2025) demonstrated that nano-enhanced bio-additives markedly boost the mechanical and environmental performance of concrete, representing a promising path toward carbon-neutral construction materials.

Activated carbon, recognized for its high surface area and adsorption capacity, has recently been proposed as a novel additive in concrete. Although widely used in filtration and purification applications, its role in cementitious materials is still emerging, with limited studies examining its influence on thermal behavior. Preliminary research suggests it may offer benefits in regulating heat flow through concrete, which could reduce energy demand in buildings. However, empirical data on its performance—especially when derived from renewable sources like crushed charcoal—remains scarce.

This paper aims to evaluate how the addition of activated carbon microparticles affects the thermal properties of concrete and determine whether these improvements can be achieved without compromising the material's mechanical integrity. To achieve this, several concrete mixtures were prepared using different proportions of activated carbon, and comprehensive tests were conducted to assess their flowability, stability, and compressive strength. Additionally, thermal diffusivity was measured to assess the impact of the activated carbon on the concrete's heat management capabilities.

2. METHOD

2.1. Mix Preparation

A series of concrete mixtures were prepared using Portland cement, sand, gravel, and water, with the aim of achieving a compressive strength of 150 kg/cm². The mixtures were modified by adding varying percentages of activated carbon microparticles (0.1%, 0.5%, and 1.0% by weight). The activated carbon microparticles were sourced from crushed charcoal and incorporated into the concrete at different dosages.

Concrete samples were prepared manually with a uniform distribution, including the activated carbon microparticles, using a portable mixer at 60rpm. The activated carbon microparticles were added in three different concentrations—0.1%, 0.5%, and 1.0% by weight of the total dry mix— maintaining same proportions of the other compounds. The additives used in the mixtures were provided by CEMEX Mexico. The proportions of water and additional chemical additives were adjusted based on the specific requirements of each batch to ensure consistency across all samples. The concrete was prepared in full compliance with the Mexican standard NMX-C-155-ONNCCE to ensure the results were comparable and reliable.

2.2. Laboratory Test

Tests were conducted to assess the properties of the concrete mixtures. For each test, 10 samples were prepared and tested to ensure reliable and statistically significant results: The flowability and stability of each mixture were assessed by observing the ability of the concrete to flow and set evenly, with no signs of segregation. The consistency of the mixture was tested during the mixing and setting stages to evaluate how the inclusion of activated carbon microparticles affected the ease of handling and the uniformity of the mixture.

To evaluate the mechanical strength of the concrete, compressive strength tests were performed in accordance with the relevant Mexican standards. Each batch was tested on 10 samples, and the results were analyzed to determine how the addition of activated carbon impacted the concrete's ability to withstand stress. This test was critical in assessing the overall strength and performance of the mixtures.

The thermal diffusivity of the concrete mixtures was measured to evaluate how the addition of activated carbon affected the material's ability to conduct heat. A series of tests were carried out on 10 samples for each concentration of activated carbon, and the results were analyzed to determine whether the presence of activated carbon improved the thermal insulation properties of the concrete. This was a key focus of the study, as thermal performance plays an important role in the energy efficiency of buildings.

2.3. Mechanical Properties of the Concrete

The compressive strength of the concrete mixtures was evaluated with varying percentages of activated carbon microparticles and compared to the control mix (without additives). The results, as shown in Table 1, indicated a significant increase in compressive strength with the addition of activated carbon microparticles. The average compressive strength of the control mix (without any additives) was 150 kg/cm². However, with the incorporation of activated carbon microparticles at different percentages, the compressive strength improved as follows:

Table 1. Results of Compressive strength.

Activated Carbon (%)	Compressive Strength (kg/cm ²)
0.0 (No additive)	150 ± 0.09
0.1	153 ± 0.13
0.5	155 ± 0.11
1.0	158 ± 0.15

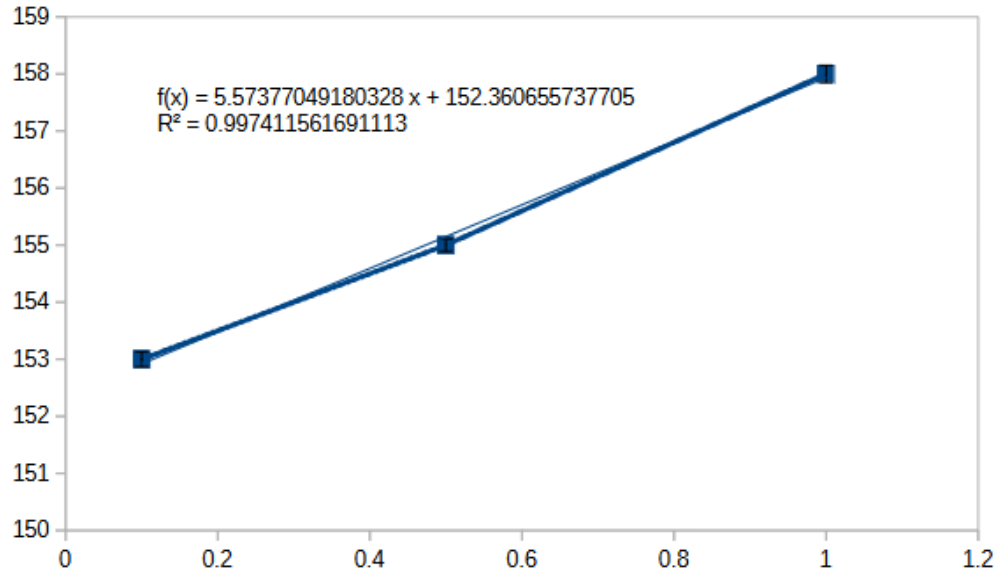


Figure 1. Compressive strength (y-axis) in kg/cm² according to %(Weight/Weight) of Activated Carbon dosed.

As shown in Table 1, the addition of activated carbon resulted in a progressive increase in compressive strength. Figure 1 shows the graphical results showing a correlation upper of 0.997. Specifically, with 1% of activated carbon, the compressive strength reached 158 kg/cm², an increase of 8 kg/cm² compared to the control mix. This indicates that activated carbon microparticles play a significant role in enhancing the mechanical strength of concrete. This improvement in strength can be attributed to the enhanced microstructure of the mixture, which likely increases the density of the concrete matrix, providing more resistance to compressive forces.

2.4. Thermal Properties

Figure 2 shows the equipment for the diffusivity test. Table 2 presents the thermal diffusivity values for each mixture, showing a decrease in diffusivity with the increase in activated carbon content showing how activated carbon affects the thermal diffusivity of the concrete. A lower thermal diffusivity suggests improved insulation properties, which is beneficial for energy efficiency in buildings.

Table 2. Thermal diffusivity values for each mixture.

Activated Carbon (%)	Thermal Diffusivity (x10 ⁻⁷ m ² /s)
0.0 (No additive)	4.5 ± 0.14
0.1	4.3 ± 0.12
0.5	4.0 ± 0.09
1.0	3.8 ± 0.16

As shown in Table 2 the thermal diffusivity of the mixtures progressively decreased as the percentage of activated carbon increased. The mixture with 1% activated carbon exhibited a 15% reduction in thermal diffusivity compared to the control mixture. This reduction suggests that the addition of activated carbon enhances the thermal insulating properties of the concrete, making it a more energy-efficient material. This is particularly important for buildings, as it could reduce the need for artificial heating and cooling, thus improving overall energy performance and sustainability.



Figure 2. Diffusivity test (Left) and mechanical test (Right).

2.5. Flowability and Stability of the Mixture

The flowability and stability of the mixtures were also evaluated. The results indicated that the addition of activated carbon microparticles did not negatively affect the workability of the concrete. In fact, the mixtures remained stable and homogeneous during the mixing and setting processes, with no signs of segregation or issues with uniformity. The flowability and stability were observed in the following manner.

- 0.0 (No additive) Good flowability and stability, no segregation.
- 0.1% Good flowability and stability, no segregation.
- 0.5% Good flowability and stability, no segregation.
- 1.0% Excellent flowability and stability, no segregation.

As shown, all mixtures, including the one with 1% activated carbon, exhibited good flowability and stability throughout the process. There was no segregation, and the mixtures maintained their homogeneity during setting and curing. This is a crucial result, as it indicates that the incorporation of activated carbon does not compromise the concrete's workability or the quality of the final product. This is particularly important in practical applications, as it ensures that the concrete will perform well during mixing, pouring, and curing.

2.6. Impact on Sustainability and Energy Efficiency

The improvements in thermal diffusivity have significant implications for the sustainability and energy efficiency of buildings. Concrete with better thermal insulation properties can reduce the reliance on artificial heating and cooling systems, leading to lower energy consumption and greater overall environmental sustainability. Furthermore, the use of crushed charcoal as a source of activated carbon offers an eco-friendly alternative, as it is a renewable and biodegradable material. This aligns the research with the growing trend of using more sustainable materials in construction.

The incorporation of activated carbon microparticles into the concrete mixture offers not only improvements in mechanical and thermal properties but also significant implications for sustainability, energy efficiency, and the reduction of the environmental impact of concrete production. As the construction industry seeks more sustainable materials, activated carbon provides a promising solution, both in terms of material efficiency and energy performance.

2.7. Energy Efficiency and Thermal Insulation

The reduction in thermal diffusivity (as discussed in section 2) translates into improved thermal insulation properties, which can have a direct impact on the energy efficiency of buildings. Concrete with better thermal

insulation reduces the need for artificial heating and cooling systems. This can significantly decrease energy consumption over the life cycle of a building.

From the results in Table 2, the mixture with 1% activated carbon exhibited a 15% reduction in thermal diffusivity, which suggests enhanced thermal insulation. Let's assume that this improvement in thermal properties leads to a 10% reduction in heating and cooling energy demand for buildings made with this concrete, based on the improved insulation efficiency.

For a typical residential building, the energy consumption for heating and cooling can account for 40% of the total energy use. By taking the average annual energy consumption for a residential building to be around 15,000 kWh, the energy savings from using concrete with activated carbon could be approximately: This reduction in energy demand would result in an annual energy saving of 1,500 kWh per building. If applied to multiple buildings, the energy savings could be substantial, contributing to the overall reduction in greenhouse gas emissions associated with energy production.

2.7.1. Reduction in Cement Use

Concrete production is responsible for a significant portion of global CO₂ emissions, primarily due to the energy-intensive production of cement. In this study, the use of activated carbon not only enhances the thermal properties of the concrete but may also lead to potential savings in cement use, contributing to a reduction in CO₂ emissions.

The addition of activated carbon may allow for a reduction in the total amount of cement used, without compromising the concrete's strength or performance. According to some studies, replacing a small percentage of cement with sustainable materials such as activated carbon (or other supplementary cementitious materials like fly ash or slag) can reduce the cement content by up to 10%.

In our case, if 5% of the cement in a concrete mixture could be replaced with activated carbon microparticles, it is estimated the potential reduction in cement use: Assuming that the cement content of a typical concrete mix is 300 kg per cubic meter (a common figure for standard mixes), a 5% reduction would mean a savings of 15 kg. This reduction in cement not only reduces the demand for cement production but also lowers the associated CO₂ emissions. According to estimates, cement production emits approximately 0.9 kg of CO₂ per kilogram of cement produced. Thus, the CO₂ savings per cubic meter of concrete can be calculated following a value of 13.5kg CO₂ per cubic meter.

2.8. Cumulative Impact on Sustainability

Using a concrete mixture modified with 1% activated carbon can lead to estimated energy savings of 1,500 kWh per building each year due to improved thermal efficiency; additionally, incorporating 5% activated carbon microparticles allows for a reduction of 15 kg of cement per cubic meter of concrete, which translates to a CO₂ emission reduction of approximately 13.5 kg per cubic meter—assuming 0.9 kg of CO₂ per kilogram of cement—and for a project using 1,000 m³ of concrete, this results in total cement savings of 15,000 kg, equivalent to around 13.5 metric tons of CO₂ avoided.

3. CONCLUSION

The addition of activated carbon microparticles obtained from crushed charcoal can significantly enhance the thermal properties of concrete without compromising its mechanical strength. The results suggest that this additive holds great potential as a viable option for developing more efficient and sustainable construction materials, opening new opportunities for innovation in the construction industry. The improvement in thermal diffusivity can contribute to greater comfort in buildings, creating a more energy-efficient environment and helping to reduce reliance on heating and cooling systems. This not only has implications for indoor comfort but also for optimizing operational costs in buildings.

Beyond the positive effects on mechanical strength, the study revealed substantial improvements in the thermal properties of concrete, particularly in thermal diffusivity, which is a key indicator of how heat is transferred through materials. The mixtures with activated carbon showed a notable reduction in this property, suggesting that concrete enhanced with this additive may provide better thermal insulation compared to conventional concrete. This improvement could not only increase energy efficiency in buildings but also lead to significant

reductions in heating and cooling costs, making it an attractive solution for constructing more sustainable and energy-efficient buildings.

It is essential to continue exploring and developing new materials and additives in the construction industry, as this paves the way for creating more functional and adaptable materials to meet contemporary needs. The incorporation of activated carbon into concrete represents a promising avenue for enhancing its properties, aligning with global trends toward greater sustainability and energy efficiency in construction. While the results obtained so far are very positive, further long-term studies are recommended to evaluate the impact of activated carbon on other critical concrete properties, such as compressive strength, durability, and behavior under extreme weather conditions, to ensure its viability for large-scale applications in construction.

The implications for the construction industry are significant, suggesting that the use of activated carbon could not only improve the thermal and mechanical properties of concrete but also serve as an effective strategy for creating concrete with enhanced sustainability. Future research should explore different additive proportions and assess their impact on a wider range of concrete properties, aiming to optimize performance and ensure that it remains economically viable and technologically advanced. The use of activated carbon in concrete is not only beneficial for improving its thermal and mechanical properties but also for reducing the environmental footprint of construction projects. The savings in cement usage associated with the incorporation of this additive have a direct impact on reducing carbon emissions generated during concrete production. Moreover, the improvement in thermal efficiency can lead to long-term energy savings in buildings, reducing overall energy consumption and making them more sustainable and eco-friendlier.

Furthermore, the use of activated carbon derived from renewable resources, such as crushed charcoal, provides an environmentally friendly alternative to traditional concrete additives. Activated carbon is biodegradable and renewable, making it a promising path toward more sustainable construction materials. This approach aligns with global construction trends to reduce reliance on non-renewable resources and minimize environmental impacts, helping foster a more sustainable built environment.

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TRANSPARENCY

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

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