Journal of Management and Sustainability; Vol. 15, No. 1; 2025
ISSN 1925-4725 E-ISSN 1925-4733
Published by Canadian Center of Science and Education

Asphalt Pavement Materials Management to Reduce Urban Heat Island Effetcs: A Review

Felipe Santos[1], Emilia Kohlman Rabbani[1] & Daniel Matos[2]

[1] Politechnic School of Pernambuco, University of Pernambuco, Recife, Pernambuco, Brazil

[2] Federal University of Mato Grosso do Sul, Campo Grande, Mato Grosso do Sul, Brazil

Correspondence: Felipe Santos, Politechnic School of Pernambuco, University of Pernambuco, Rua Benfica, 455 – Madalena - 50720-001, Recife, Pernambuco, Brazil.

Received: November 8, 2024 Accepted: January 9, 2025 Online Published: February 14, 2025

doi:10.5539/jms.v15n1p51 URL: https://doi.org/10.5539/jms.v15n1p51

Abstract

Urban pavements, typically constructed with asphaltic materials, significantly contribute to forming urban heat islands. Consequently, there is an urgent need to explore bituminous material solutions that mitigate thermal discomfort and address issues related to the mechanical properties of pavements, thereby enhancing their durability and service life. This study aims to analyze asphalt mixtures employed to reduce the temperature of flexible pavements through a comprehensive literature review. Reviewed 241 articles from two international databases and included 49 in the final analysis after applying selection criteria. The findings highlight the effectiveness of various materials and methods in providing thermal insulation and storage, refracting solar radiation, and achieving energy transmission through incorporation into asphalt mixtures. Among these, fiberglass, polyethylene glycol, and hollow microspheres yielded the most promising results. Despite the demonstrated efficacy of recent studies in temperature mitigation, the review underscores the critical need for durability control methods to ensure large-scale applicability.

Additionally, comprehensive laboratory analyses are necessary, considering not only high temperatures but also the physicochemical interactions that may accelerate the degradation of the asphalt binder. Identifying and implementing innovative practices and materials to optimize pavement management and mitigate thermal effects is essential. Applying these findings can guide the development of future pavement designs and interventions, helping to reduce the effects of urban heat islands and ensure more durable and sustainable structures better suited to meet urban populations' needs.

Keywords: flexible pavement, asphaltic materials, thermal reduction.

1. Introduction

Carbon emissions generated by human economic activity are warming the planet, affecting temperatures globally in prolonged and geographically diverse ways. Global warming is a persistent worldwide phenomenon with uneven local economic impacts (Cruz & Rossi-Hansberg, 2023). As a result, urban heat islands have emerged in urban areas experiencing higher temperatures than surrounding regions because of heat absorption and retention by urban materials, lack of vegetation, and intensified human activity. Elevated temperatures can lead to thermal discomfort for city dwellers, increased air pollution, and higher energy consumption due to excessive use of cooling systems (Ren et al., 2021).

Climate change has already affected approximately 9% of the global population, meaning that over 600 million people live outside the temperature range historically associated with high human population density. Projections suggested that if current policies lead to a global temperature increase of 2.7°C by the end of the century, between 22% and 39% of the population may face even more extreme temperatures. These figures underscore the need for more effective policies to mitigate the social impacts of climate change and address climate-related inequalities (Lenton et al., 2023).

One factor contributing to urban heat islands is the expansion of impervious surfaces in cities, particularly pavements, which increase surface runoff and reduce vegetation. The demand for urban transportation further exacerbates these effects, intensifying the need for urban roads. Research shows that using cool materials to reduce thermal absorption can help mitigate thermal effects in urban environments (Hayes et al., 2022). These materials reflect more solar radiation and absorb less heat, lowering surface temperatures and alleviating some impacts of heat islands.

Pavement management is crucial for optimizing the environmental performance of transport infrastructure and achieving sustainability goals. A vital aspect of this management is evaluating pavement's environmental impact from a life-cycle perspective, including the extraction, production, transport, construction, operation, maintenance, rehabilitation, and end-of-life phases of materials (Chong et al., 2023). In the materials context, the asphalt mixtures widely used for paving consist of layers, with the top layer being particularly affected by thermal variations. Rising temperatures can compromise the pavement's load-bearing capacity, resulting in the development of cracks and structural degradation due to the aging of the asphalt binder (Ktari et al., 2022).

Identifying innovative practices and materials to optimize pavement management and mitigate thermal effects is essential. This study explores existing literature to evaluate the effectiveness of various materials and techniques in the thermal management of pavements. The goal is to identify successful cases to guide future pavement designs and interventions in existing structures, considering local thermal specificities. By doing so, the study seeks to reduce the effects of urban heat islands and ensure more durable structures suited to urban populations' needs.

Although many studies focus on the dynamic life cycle of pavements and cool pavements, only some have developed methodologies to identify materials that can reduce thermal effects in urban areas when used on flexible pavements or their surfaces. It includes understanding their functionality and evaluating the thermal and mechanical properties influencing their service life. Therefore, this study aims to fill that gap by identifying and applying materials with the potential to reduce thermal effects in flexible pavements while enhancing their longevity and performance.

2. Method

This study employs a Systematic Literature Review, guided by the PRISMA method (Page et al., 2021), to examine existing scientific publications on asphalt mixtures used in flexible pavements with the potential to reduce their temperature. The review includes collecting bibliometric information and detailed descriptions of the materials and their characteristics. The methodology consists of two main stages: conducting a bibliometric review and performing a descriptive data analysis.

2.1 Bibliometric Review

The bibliometric review extracts scientific publications from the Engineering Village and Web of Science databases, selected for their relevance to the field of Civil Engineering and the number of available titles for consultation. Search publications using a search string generated from combinations of keywords related to the proposed topic, such as flexible pavement, asphalt mixtures, and temperature reduction.

Several exclusion criteria were established to filter the publications found in the databases, such as duplicate articles, studies focusing on low temperatures, and those not addressing materials for asphalt mixtures. The search was limited by specific parameters, focusing on English-language journal articles published over the past 10 years. Table 1 outlines the research protocol.

Table 1. Research protocol

Elements	Definition
Research guiding questions	What is the relationship between pavement performance and thermal comfort in urban areas? What countries have been investigating the problem of heat island effects associated with flexible pavements? Is this a current topic with a growing trend? What asphalt materials are used in flexible pavements to mitigate the effects of temperature? How can these materials be used to reduce the temperature of these pavements? What mechanisms of temperature control are used in flexible pavements?
Search terms	Asphalt pavement, bituminous pavement, flexible pavement, asphalt, asphaltic materials, asphalt mixtures, bituminous materials, temperature reduction, temperature control, thermal control, and thermal effects.
Databases	Engineering Village, Web of Science
General string	("asphalt pavement" or "bituminous pavement") AND ("temperature control" or "thermal insulation" or "heating temperature" or "temperature reduction" or "asphalt pavement temperature")
Limitations	Articles in English from the last 10 years
Exclusion criteria – EC	EC1: Articles addressing low temperatures; EC2: Articles that do not focus on temperature analysis; EC3: Articles that do not address materials for asphalt mixtures; EC4: Articles addressing temperature in the manufacturing process; EC5: Articles addressing numerical models; EC6: Duplicate articles; EC7: Literature review articles or not published in journals; EC8: Articles not accessible.

The database search yielded 324 articles. Excluded 83 due to duplication, 175 based on the established exclusion criteria, and 17 after a full-text analysis, leaving 49 articles in this review (Appendix A). Figure 1 presents the PRISMA flow diagram detailing the number of articles excluded and included in the review.

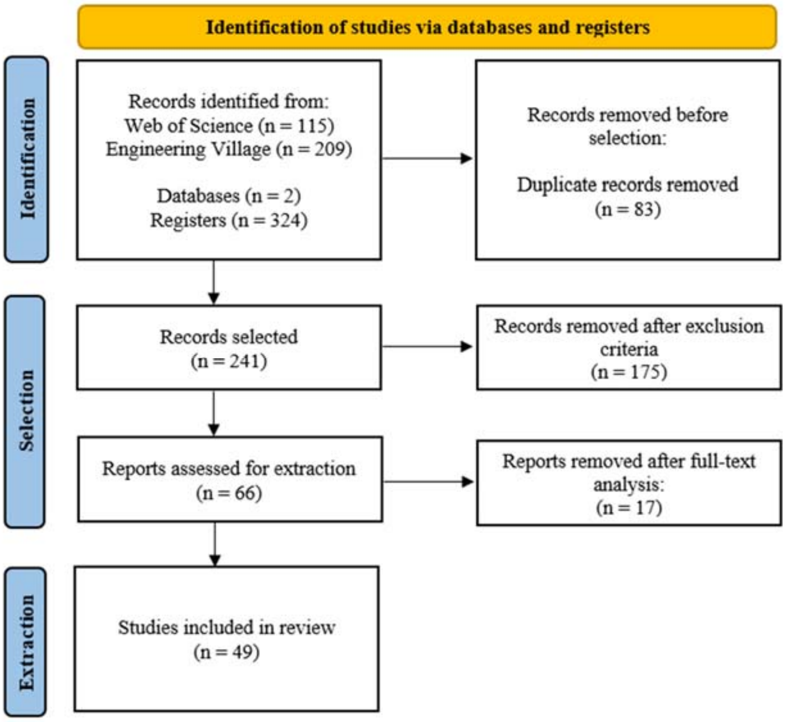

Figure 1. PRISMA flow diagram (adapted by Page et al., 2021)

2.2 Descriptive Analysis

After identifying the articles aligned with the established criteria and performing a descriptive analysis of the collected research, the key findings relevant to the research questions are summarized and cataloged. This analysis includes a timeline of publication trends, identification of the countries with the highest volume of studies in this field, examination of various materials utilized for reducing pavement temperatures, exploration of temperature control mechanisms, and review of the methods used for temperature testing and analysis.

3. Results

3.1 Global Overview of Publications

The results provided a comprehensive understanding of the research development, including the publication years and the countries with the most publications, which is key to grasping the topic's current context.

The temporal analysis of the articles in the review reveals that 2023 had the highest number of publications, totaling 12. 2020 has seven publications, while 2018, 2019, 2021, 2022, and 2024 have four articles. Despite limiting the review to the last 10 years, the analysis observes a growing trend in the topic over the past decade. This trend is evident as 2023, the last full year of the bibliometric review, saw the highest number of articles, surpassing the second-highest year, 2020, by 71%. Figure 2 illustrates the temporal evolution of the publications.

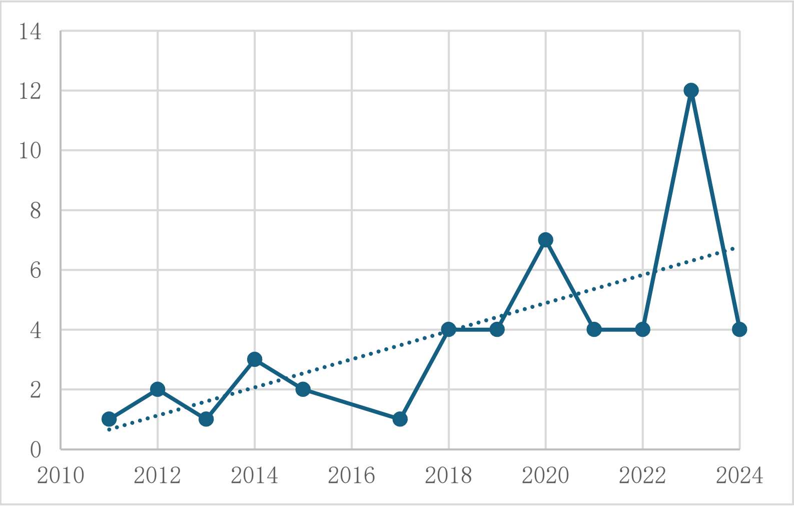

Figure 2. Timeline analysis of publication

Regarding publications by country, 54 authorships were identified, with approximately 79% originating from China, the country with the highest representation. The United States also stood out, contributing five authorships. Figure 3 presents the list of countries with publications on the subject.

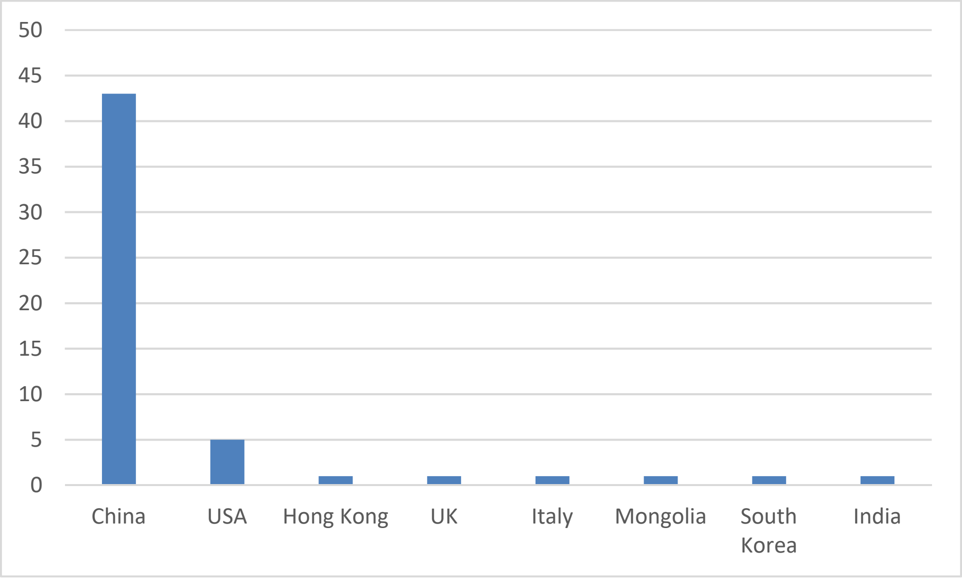

Figure 3. Publication by countries

3.2 Asphalt Mixtures Characterization

The descriptive analysis provided information regarding the materials used to reduce the temperature of asphalt pavements and the temperature control mechanisms and thermal analysis methods employed in the studies. Regarding the types of materials and asphalt mixtures examined in the research, Hot Mix Asphalt (HMA) emerged as the most used, representing approximately 43% of the total, followed by Asphalt Cement (AC) with 22%, Stone Matrix Asphalt (SMA) with 20%, and seal coat with 14% (Figure 4).

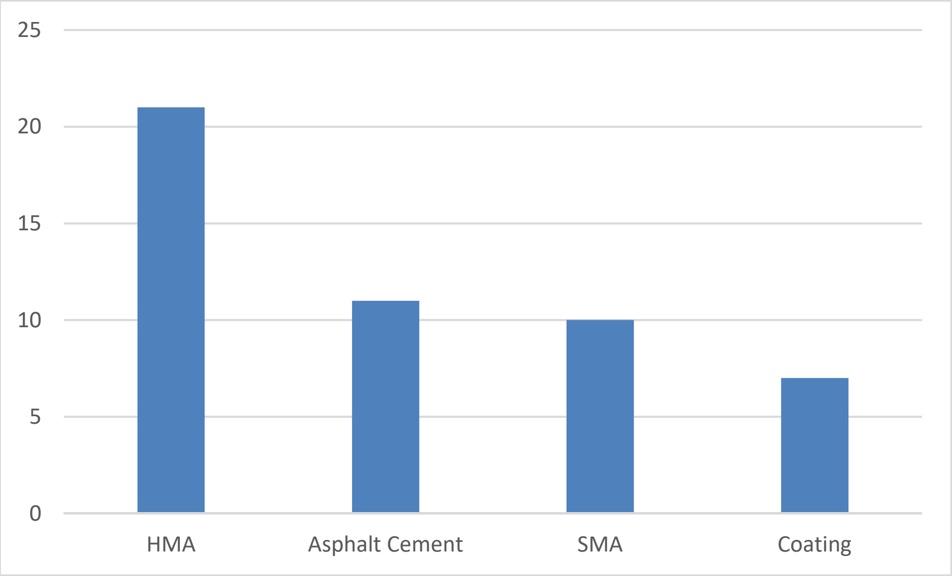

Figure 4. Type of asphaltic materials and mixtures analyzed

Researchers identified five distinct groups of temperature control mechanisms in pavements. The most common mechanism was thermal insulation, achieved by adding different materials, accounting for approximately 42% of the studies. Solar radiation reflection followed, along with thermal regulation, thermal conductivity, and heat absorption, as shown in Figure 5.

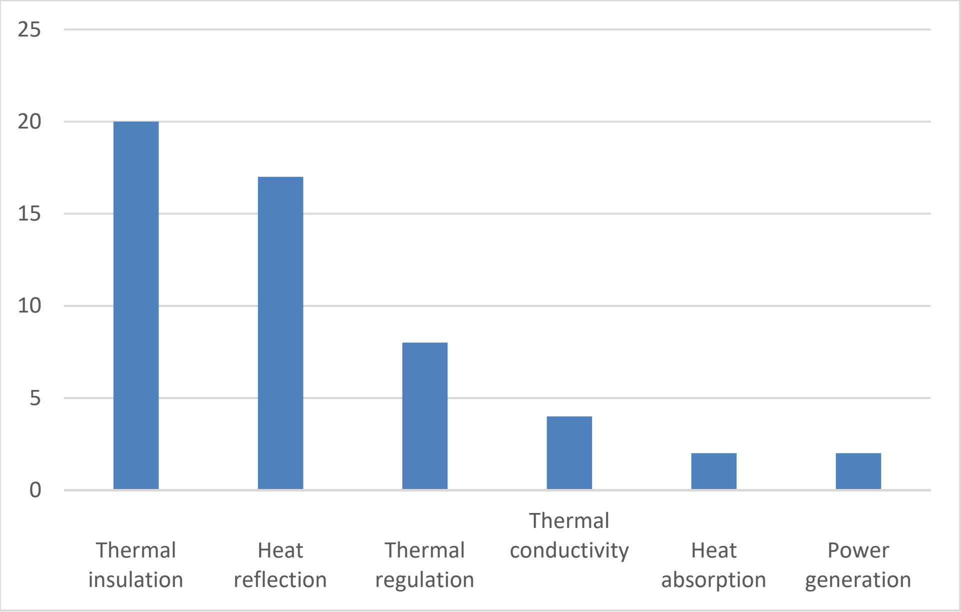

Figure 5. Mechanisms of temperature control in pavements

As for the tests conducted in the studies to analyze the thermal characteristics of pavements, the majority employed experimental temperature simulation tests using sun lamps, totaling 21 articles. Differential Scanning Calorimetry for AC was the second most common method, featured in 14 studies, followed by thermal evaluations using ovens and thermometers in 10 studies, and five studies that conducted measurements in controlled environments and the field, as illustrated in Figure 6.

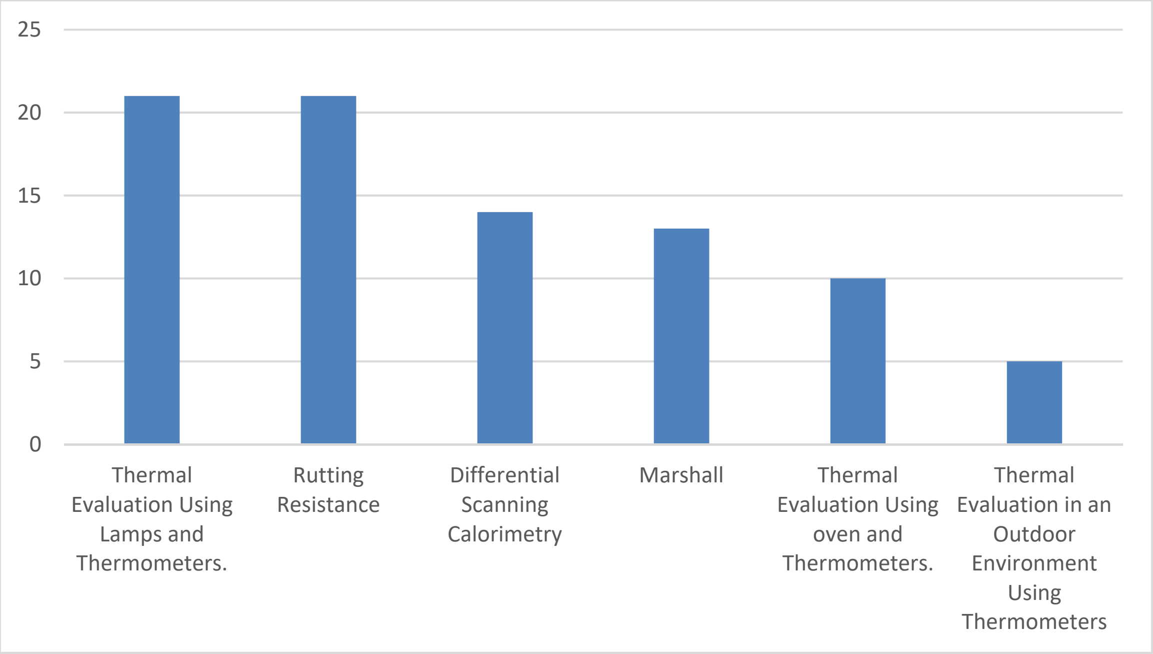

Figure 6. Type of tests conducted

Researchers frequently studied Phase Change Materials (PCMs), featuring in 19 studies. They explored thermochromic additives in 14 publications and included fly ash in 6. They also investigated other materials, such as hollow glass microspheres in 5 studies, graphite in 4, and ceramics in 2. Additionally, researchers observed several materials as additives or aggregates in individual studies, including steel slag, cellulose fiber, ceramic fiber, glass wool, steel fiber, air voids, vermiculite, and steel rods. Figure 7 illustrates the variety of materials used across the analyzed studies.

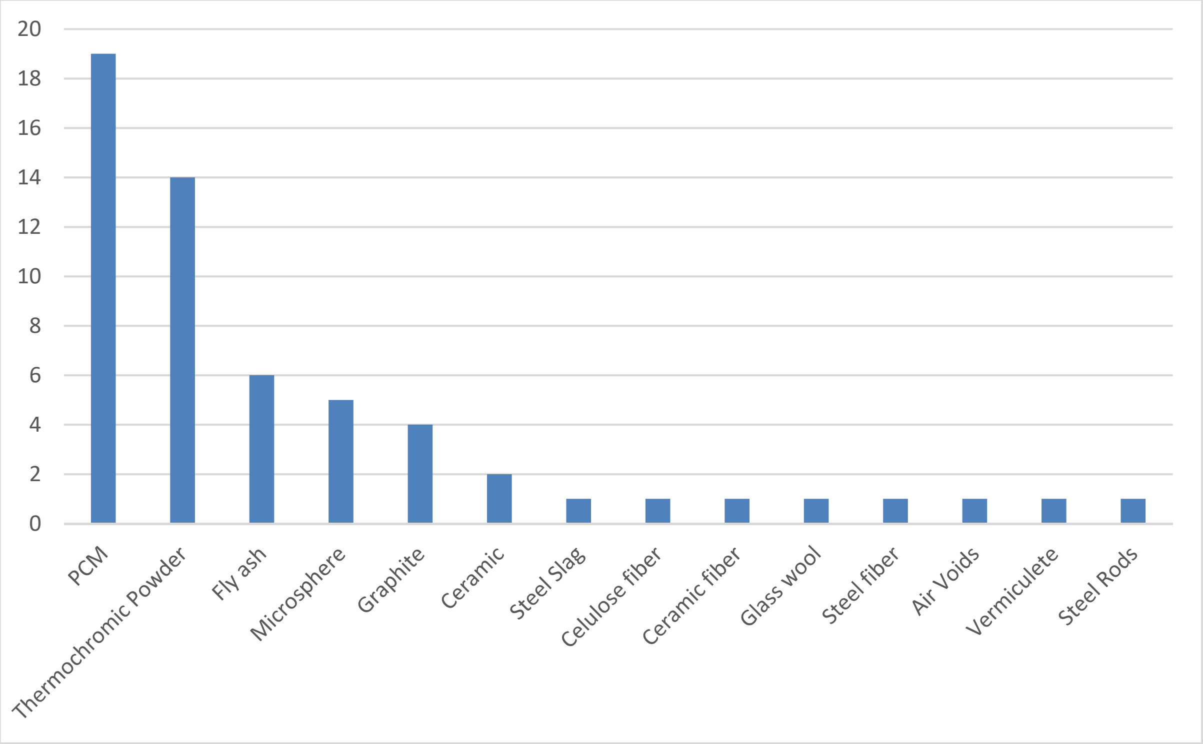

Figure 7. Type of materials

3.3 Temperature Reduction Efficiency

The reviewed studies revealed variability in the temperature reduction efficiency of different materials. Across all studies, the mean temperature reduction was 5.50°C, with a standard deviation of 2.70°C. Microspheres presented the highest average reduction (6.40°C), followed by thermochromic powders (5.60°C) and Phase Change Materials (PCMs) (5.32°C). Fly ash and graphite exhibited lower averages, with reductions of 4.59°C and 4.30°C, respectively. Figure 8 illustrates the thermochromic powders (Bo et al., 2021) on the left and PCMs (Ding et al., 2024) on the right.

Figure 8. Illustration of the thermochromic powders and Phase Change Materials

Researchers also observed maximum and minimum reductions in temperature. Jiang et al. (2020) reported a maximum reduction of 13.2°C using thermochromic powder, while Chen and Ma (2012) recorded a reduction of 9.5°C with the same material. Conversely, Wang et al. (2021) reported a minimum reduction of 0.5°C, also using thermochromic powder. Table 2 summarizes the mean temperature reductions and standard deviations for this review's most frequently studied materials, providing a comparative overview of their performance.

Table 2. Temperature Reduction Efficiency of Various Materials

Material	Mean (ºC)	Standard Deviation
All Studies	5,50	2,70
Fly Ash	4,59	2,63
Graphite	4,30	3,03
Microsphere	6,40	2,12
PCM	5,32	1,97
Thermochromic Powder	5,60	2,80

4. Discussion

The results indicate that the topic is timely and shows a growth trend in the coming years. The worsening global climate situation likely necessitates more effective measures to counter urban temperature increases. The analysis also shows that countries such as China and the United States have increasingly invested in this type of research over the years. Additionally, other European and Asian regions have been exploring this topic. This diversification of countries may relate to creating international sustainability agendas, such as the Sustainable Development Goals (SDGs) of the 2030 Agenda, which provide comprehensive guidelines for addressing environmental challenges and promoting sustainable development (United Nations, 2015).

Pavements are among the significant contributors to urban heat islands (Xu et al., 2021), particularly flexible pavements, which are the most used type. Asphalt cement was the most used among the materials discussed in the research. This material, composed of petroleum-derived hydrocarbons, is semisolid at room temperature, with its viscosity decreasing as it heats up, reducing its resistance (Jwaida et al., 2024). It produces asphalt concrete, such as Hot Mix Asphalt (HMA) and Stone Matrix Asphalt (SMA). HMA is the traditional process for constructing asphalt pavements, involving a mixture of heated aggregates and asphalt cement. SMA, also identified in the research, is a gap-graded dense asphalt mixture that requires more durable aggregates, higher asphalt content, and typically a modified asphalt binder and fibers to increase its resistance and durability (Zhang et al., 2020).

The study identified several approaches for controlling the thermal impact on flexible pavements, making thermal conditions more manageable. The most notable mechanisms were solar reflection, thermal insulation, thermal regulation, thermal conductivity, and heat absorption. Solar reflection aims to increase the amount of solar radiation reflected by the pavement surface, preventing heat absorption. Materials with high reflectance, such as light-colored surfaces or reflective additives, are commonly used to achieve this effect, as seen in Cao (2011), who used high reflective fillers to reduce pavement temperature. Thermal insulation prevents heat transfer between pavement layers, keeping the surface layer cool and protecting the underlying structure. Materials with low thermal conductivity, such as microspheres or porous materials, achieve this effect by creating an effective thermal barrier (Chen, 2019; Cao et al., 2023; Ding et al., 2024). Thermal regulation seeks to maintain stable temperatures by absorbing heat during the day and releasing it slowly at night. This mechanism helps smooth daily thermal fluctuations, particularly in urban environments with significant temperature variations (Wang et al., 2023; Liu et al., 2024; Wei et al., 2022). Thermal conductivity refers to the ability of a material to transfer heat from one area to another. Materials with high thermal conductivity, such as metals, can be used to dissipate heat into deeper pavement layers or to facilitate heat exchange with the external environment, accelerating surface cooling (Du et al., 2021; Gong et al., 2022; Yinfei, 2021). Heat absorption relates to the material's capacity to absorb and store heat during the day, preventing the pavement surface temperature from rising excessively. Materials with high specific heat capacity are more efficient, storing significant amounts of heat without causing large temperature increases (Zhang et al., 2023; Yinfei et al., 2018).

Researchers conduct thermal analysis of pavements using various methodologies chosen according to the specific research objectives and characteristics of the materials analyzed. Usual methods include thermal evaluation with lamps and thermometers, differential scanning calorimetry (DSC), and thermal conductivity tests. They often use thermal evaluation with lamps and thermometers to simulate solar exposure and measure temperature variations in asphalt mixtures, such as HMA and SMA, under controlled conditions. This approach allows observation of the surface response of pavements to heating (Obando et al., 2023; Chen et al., 2012; Yi et al., 2019). Researchers primarily apply DSC to analyze the thermal behavior of the asphalt binder, providing data on thermal transitions and the material's resistance to temperature variations. They use thermal conductivity tests to assess a material's ability to conduct heat, which is critical for studying heat dissipation properties in asphalt mixtures and understanding heat propagation through the pavement (Bo et al., 2021; Liu et al., 2024; Huang et al., 2023).

Among the mixtures analyzed, Phase Change Materials (PCM) stood out. According to Pan et al. (2020), PCMs can store or release thermal energy through phase changes to stabilize temperature fluctuations. Thermochromic additives, also identified in the study, alter the pavement's color and are used as fillers in final pavement layers, reducing solar radiation absorption through partial light reflection (Li et al., 2020). PCMs, such as diatomite with ethylene glycol and microencapsulated PCM, were frequently used for thermal regulation. Additionally, materials such as fly ash, fiberglass, cellulose fibers, and microspheres effectively reduced thermal susceptibility and improved asphalt mixtures' mechanical properties. However, despite their favorable mechanical properties, metallic materials did not meet expectations in mitigating temperature effects. The increased thermal conductivity from incorporating such materials can accelerate heat buildup in pavements (Yinfei et al., 2014). Another critical factor observed was the influence of air void indices on the thermal insulation of samples, highlighting their importance in understanding the thermal dynamics of mixtures. These findings offer key considerations for optimizing asphalt formulations to reduce temperatures in flexible pavement layers (Li et al., 2013). Furthermore, materials with high thermal conductivity, such as graphite, steel rods, and metal fibers, improved the mechanical resistance of pavements (Du et al., 2015; Du et al., 2018), but in some cases, increased pavement temperatures, as noted by Fu et al. (2023).

The urban heat island phenomenon also intensifies issues such as asphalt binder softening, resulting in high maintenance costs. Improving the mechanical resistance of pavements through innovative mixtures that promote thermal control reduces maintenance frequency and enhances resource efficiency. This improvement allows for investments in additional infrastructure and fosters more sustainable and resilient urban environments. Implementing techniques to mitigate urban heat island effects strengthens cities' resilience to climate change by reducing heat absorption and improving thermal comfort. These strategies not only alleviate the immediate impacts of urban heat but also prepare cities to withstand extreme climate conditions in the future (United Nations, 2015; Shamsaei et al., 2022).

5. Conclusion

This study aimed to analyze asphalt mixtures used in flexible pavements with the potential to reduce their temperature, considering that heat affects their load-bearing capacity and lifespan. The literature review conducted in this work identified materials that enhance the thermal efficiency of pavements and their practical applications. It assists in selecting the most suitable methods and implementing preventive measures to ensure road quality, safety, and durability. Furthermore, the results have the potential to support the development of new criteria for the design and performance of bituminous coatings, ensuring their quality, safety, and efficiency.

The reviewed studies demonstrate the effectiveness of various material selection criteria and asphalt layers utilized by researchers over the past decade, particularly regarding temperature mitigation and its effects on pavement performance. However, durability control methods for the samples remain necessary to facilitate the large-scale applicability of these innovations.

For future research, it is recommended that laboratory analyses of the mixtures and their performance, including durability testing through specific assessments, be conducted. This is essential, as physicochemical interactions, in addition to high temperatures, can accelerate oxidation and, consequently, the aging of the asphalt binder.

Acknowledgments

The authors thank the Universidade de Pernambuco and the Universidade Federal de Mato Grosso do Sul for their support in developing this research.

Funding: This research was funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior grant number 001, by the Programa de Fortalecimento Academico - PFA of the University of Pernambuco through APQ for the research Group Safe and Sustainable Development - DESS, and by Escola Politécnica da Universidade de Pernambuco (POLI/UPE) through the stricto sensu grant.

References

Anupam, B. R., Sahoo, U. C., & Rath, P. (2023). Effect of two organic phase change materials on the thermal performance of asphalt pavements. *International Journal of Pavement Engineering*, *24*(1). https://doi.org/10.1080/10298436.2023.2215900

Betancourt-Jimenez, D., Montoya, M., Haddock, J., Youngblood, J. P., & Martinez, C. J. (2022). Regulating asphalt pavement temperature using microencapsulated phase change materials (PCMs). *Construction and Building Materials*, 350. https://doi.org/10.1016/j.conbuildmat.2022.128924

Bo, W., Liu, J., Peng, W., & Yu, B. (2021). Properties and Characterization of Temperature-Responsive Asphalt by Using Thermochromic Powder. ASTM International, Journal of Testing and Evaluation, 49(5), 3646-3664. https://doi.org/10.1520/JTE20200276

Cao, C., Hu, X., Wan, J., Wu, S., Gan, W., & Zhang, Y. (2023). Enhanced Thermal Insulation of Steel Slag Based on Ultrathin Friction Course with Ceramic Fiber. *Journal of Materials in Civil Engineering*, *35*(10), 04023374. https://doi.org/10.1061/JMCEE7.MTENG-15983

Cao, X., Tang, B., Zhu, H., Zhang, A., & Chen, S. (2011). Cooling Principle Analyses and Performance Evaluation of Heat-Reflective Coating for Asphalt Pavement. *Journal of Materials in Civil Engineering*, *23*(7), 1067–1075. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000256

Chen, M., Wan, L., & Lin, J. (2012). Effect of Phase-Change Materials on Thermal and Mechanical Properties of Asphalt Mixtures. *ASTM International, Journal of Testing and Evaluation*, *40*(5), 746–753. https://doi.org/10.1520/JTE20120091

Chen, Q., Wang, C., Fu, H., & Zhang, L. (2018). Durability evaluation of road cooling coating. *Construction and Building Materials*, *190*, 13–23. https://doi.org/10.1016/j.conbuildmat.2018.09.071

Chen, Y., Hu, K., & Cao, S. (2019). Thermal Performance of Novel Multilayer Cool Coatings for Asphalt Pavements. *Materials*, *12*, 1903. https://doi.org/10.3390/ma12121903

Chen, Z., & Ma, D. (2012). Effectiveness of Solar Heat Reflective Coatings in Reducing Asphalt Concrete Temperature. *ASTM International, Journal of Testing and Evaluation*, *40*(5), 740–745. https://doi.org/10.1520/JTE20120069

Chen, Z., Zhang, H., Yang, X., Leng, Z., & Tang, Y. (2024). Cooling efficiency of thermochromic asphalt pavement material and its contribution to field performance enhancement of asphalt mixture. *Construction and Building Materials*, *411*, 134562. https://doi.org/10.1016/j.conbuildmat.2023.134562

Cheng, C., Liu, J., Gong, F., Fu, Y., Cheng, X., & Qiao, J. (2023). Performance and evaluation models for different structural types of asphalt mixture using shape-stabilized phase change material. *Construction and Building Materials*, *383*, 131411. https://doi.org/10.1016/j.conbuildmat.2023.131411

Chong, D., Wang, N., Su, S., & Li, L. (2023). Global warming impact assessment of asphalt pavement by integrating temporal aspects: A dynamic life cycle assessment perspective. *Transportation Research Part D: Transport and Environment*, *117*, 103663. https://doi.org/10.1016/j.trd.2023.103663

Cruz, J.-L., & Rossi-Hansberg, E. (2024). The economic geography of global warming. *The Review of Economic Studies*, *91*(2), 899–939. https://doi.org/10.1093/restud/rdad042

Ding, T., Wei, S., Ren, X., Guo, M., & Yu, D. (2024). Multiscale evaluation on temperature adjusting performance and road performance of asphalt mixture containing dual phase change materials. *Construction and Building Materials*, *417*, 135302. https://doi.org/10.1016/j.conbuildmat.2024.135302

Dong, Z., Zhang, J., Sun, G., Yang, D., & Wang, J. (2024). Morphology changes of polymer solid-solid phase change material in high-viscosity modified asphalt (HVMA) and its influence on the properties of HVMA. *Materials Today Communications*, *39*, 109098. https://doi.org/10.1016/j.mtcomm.2024.109098

Du, Y., Dai, M., Deng, H., Deng, D., Wei, T., & Li, W. (2020). Evaluation of thermal and anti-rutting behaviors of thermal resistance asphalt pavement with glass microsphere. *Construction and Building Materials*, *263*, 120609. https://doi.org/10.1016/j.conbuildmat.2020.120609

Du, Y., Shi, Q., & Wang, S. (2014). Highly oriented heat-induced structure of asphalt pavement for reducing pavement temperature. *Energy and Buildings*, *85*, 23–31. https://doi.org/10.1016/j.enbuild.2014.09.035

Du, Y., Shi, Q., & Wang, S. (2015). Bidirectional heat induced structure of asphalt pavement for reducing pavement temperature. *Applied Thermal Engineering*, *75*, 298–306. https://doi.org/10.1016/j.applthermaleng.2014.10.011

Du, Y., Wang, S., & Zhang, J. (2015). Cooling asphalt pavement by a highly oriented heat conduction structure. *Energy and Buildings*, *102*, 187–196. https://doi.org/10.1016/j.enbuild.2015.05.020

Du, Y., Xu, L., Deng, H., Deng, D., Wu, H., & Liu, W. (2020). Evaluation of thermal behavior and high-temperature performances of asphalt mixture containing fly ash cenosphere. *Construction and Building Materials*, *245*, 118429. https://doi.org/10.1016/j.conbuildmat.2020.118429

Gong, X., Liu, W., & Ying, H. (2022). Phase Change Heat-induced Structure of Asphalt Pavement for Reducing the Pavement Temperature. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, *46*, 1655–1668. https://doi.org/10.1007/s40996-021-00670-3

Guo, T., Wang, C., Yang, X., & Sun, X. (2017). Development and performance of sand fog seal with cooling and air purification effects. *Construction and Building Materials*, *141*, 608–618. https://doi.org/10.1016/j.conbuildmat.2017.03.003

Hayes, A. T., Jandaghian, Z., Lacasse, M. A., Gaur, A., Lu, H., Laouadi, A., … Wang, L. (2022). Nature-based solutions (NBSs) to mitigate urban heat island (UHI) effects in Canadian cities. *Buildings*, *12*, 925. https://doi.org/10.3390/buildings12070925

Hu, J., Wanasekara, N., & Yu, X. (Bill). (2014). Thermal Properties of Thermochromic Asphalt Binders by Modulated Differential Scanning Calorimetry. *Transportation Research Record*, *2444*(1), 142–150. https://doi.org/10.3141/2444-16

Huang, Q., Qian, Z., Hu, J., & Zheng, D. (2020). Evaluation of Stone Mastic Asphalt Containing Ceramic Waste Aggregate for Cooling Asphalt Pavement. *Materials*, *13*(13), 2964. https://doi.org/10.3390/ma13132964

Huang, Z., Wei, J., Fu, Q., Zhou, Y., Lei, M., Pan, Z., & Zhang, X. (2023). Preparation and Experimental Study of Phase Change Materials for Asphalt Pavement. *Materials*, *16*, 6002. https://doi.org/10.3390/ma16176002

Huo, D., Hou, D., Zhang, S., Gao, W., Yu, C., Jia, L., … Guo, M. (2023). Study of Pavement Performance and Temperature Regulation Capacity of Asphalt Binders Modified with Dual-Phase-Change Materials. *Buildings*, *13*(11), 2702. https://doi.org/10.3390/buildings13112702

Jiang, H., Wang, S., & Wang, G. (2022). Establish directional heat induced structure based on a grouting compound gradient thermal conductivity method. *Construction and Building Materials*, *325*, 126610. https://doi.org/10.1016/j.conbuildmat.2022.126610

Jiang, W., Xiao, J., Yuan, D., Lu, H., Xu, S., & Huang, Y. (2018). Design and experiment of thermoelectric asphalt pavements with power-generation and temperature-reduction functions. *Energy and Buildings*, *169*, 39–47. https://doi.org/10.1016/j.enbuild.2018.03.049

Jiang, Y., Deng, C., Chen, Z., & Tian, Y. (2018). Evaluation of the cooling effect and anti-rutting performance of thermally resistant and heat-reflective pavement. *International Journal of Pavement Engineering*, *21*(4), 447–456. https://doi.org/10.1080/10298436.2018.1483506

Jiao, W., Sha, A., Zhang, J., Jia, M., Jiang, W., & Hu, L. (2023). Design and properties of polyurethane solid–solid phase-change granular temperature regulation asphalt mixtures. *Solar Energy*, *253*, 47–57. https://doi.org/10.1016/j.solener.2023.02.008

Jwaida, Z., Dulaimi, A., Bahrami, A., Mydin, M. A., Özkılıç, Y., Ramadhansyah Jaya, R., & Wang, Y. (2024). Analytical Review on Potential Use of Waste Engine Oil in Asphalt and Pavement Engineering. *Case Studies in Construction Materials*, *20*. https://doi.org/10.1016/j.cscm.2024.e02930

Kong, L., Xu, L., Du, Y., Jin, J., Loprencipe, G., & Moretti, L. (2023). Use of Hybrid Mineral Filler with High Emissivity in Asphalt Mixture for Cooling Road Pavements. *Materials*, *16*(1), 175. https://doi.org/10.3390/ma16010175

Ktari, R., Saint-Laurent, D., Hornych, P., Hammoum, F., Marsac, P., & Nguyen, M. L. (2020). Effect of climate on asphalt pavement performance using two mechanistic-empirical methods. *International Journal of Pavement Engineering*, *23*(5), 1433–1458. https://doi.org/10.1080/10298436.2020.1806276

Lenton, T. M., Xu, C., Abrams, J. F., et al. (2023). Quantifying the human cost of global warming. *Nature Sustainability*, *6*, 1237–1247. https://doi.org/10.1038/s41893-023-01132-6

Li, H., Harvey, J., & Jones, D. (2013). Cooling Effect of Permeable Asphalt Pavement under Dry and Wet Conditions. *Transportation Research Record*, *2372*(1), 97–107. https://doi.org/10.3141/2372-11

Li, Q., Hu, T., Luo, S., Gao, L., Wang, C., & Guan, Y. (2020). Evaluation of cooling effect and pavement performance for thermochromic material modified asphalt mixtures under solar radiation. *Construction and Building Materials*, *261*, 120589. https://doi.org/10.1016/j.conbuildmat.2020.120589

Ma, B., Chen, S.-S., Wei, K., Liu, F.-W., & Zhou, X.-Y. (2019). Analysis of thermoregulation indices on microencapsulated phase change materials for asphalt pavement. *Construction and Building Materials*, *208*, 402–412. https://doi.org/10.1016/j.conbuildmat.2019.03.014

Mrema, A. H., Noh, S.-H., Kwon, O.-S., & Lee, J.-J. (2020). Performance of Glass Wool Fibers in Asphalt Concrete Mixtures. *Materials*, *13*(21), 4699. https://doi.org/10.3390/ma13214699

Obando, C. J., Karam, J. J., Medina, J. R., & Kaloush, K. E. (2023). Thermal Properties of Asphalt Pavements Modified with a Lightweight Silica-Based Composite. *Journal of Materials in Civil Engineering*, *35*(8), 04023218. https://doi.org/10.1061/JMCEE7.MTENG-15190

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, *372*, 71. https://doi.org/10.1136/bmj.n71

Pan, J., Xing, H., Liu, G., Wang, Y., & Liu, X. (2020). Characterization of thermal properties of bituminous mastic containing different fillers to be used in the cool pavement. *Construction and Building Materials*, *265*, 120362. https://doi.org/10.1016/j.conbuildmat.2020.120362

Ren, T., Zhou, W., & Wang, J. (2021). Beyond intensity of urban heat island effect: A continental scale analysis on land surface temperature in major Chinese cities. *Science of The Total Environment*, *791*, 148334. https://doi.org/10.1016/j.scitotenv.2021.148334

Si, W., Zhou, X., Ma, B., Li, N., Ren, J., & Chang, Y. (2015). The mechanism of different thermoregulation types of composite shape-stabilized phase change materials used in asphalt pavement. *Construction and Building Materials*, *98*, 547–558. https://doi.org/10.1016/j.conbuildmat.2015.08.038

Wang, H.-R., Wang, Y.-M., Qi, M.-L., Wang, Q.-L., Li, X., Zhu, X.-X., … Liu, Z.-M. (2021). PEG/diatomite modified Asphalt Mixture with Self-Regulating temperature property. *Case Studies in Construction Materials*, *15*, e00585. https://doi.org/10.1016/j.cscm.2021.e00585

Wang, J., Zhang, Z., Guo, D., Xu, C., & Zhang, K. (2018). Study on Cooling Effect and Pavement Performance of Thermal-Resistant Asphalt Mixture. *Advances in Materials Science and Engineering*, *2018*, Article ID 6107656, 11 pages. https://doi.org/10.1155/2018/6107656

Wang, K., Cheng, J., Zhu, Y., Wang, X., & Li, X. (2021). Experimental research on the performance of the thermal-reflective coatings with liquid silicone rubber for pavement applications. *e-Polymers*, *21*(1), 453–465. https://doi.org/10.1515/epoly-2021-0046

Wang, X., Chen, H., Kuang, D., & Wu, S. (2023). Temperature regulation and rheological properties assessment of asphalt binders modified with paraffin/SiO2 micro-encapsulated phase change materials. *Construction and Building Materials*, *368*, 130377. https://doi.org/10.1016/j.conbuildmat.2023.130377

Wang, X., Ma, B., Xiao, Y., Wei, K., Wang, L., Si, W., … Xu, J. (2023). Road performance and thermal-insulation effect in construction of asphalt mixture containing phase-change thermal-insulation agent. *Construction and Building Materials*, *377*, 131117. https://doi.org/10.1016/j.conbuildmat.2023.131117

Wei, K., Liu, Z., Wang, L., Ma, B., Fan, Y., Shi, J., & Cheng, P. (2022). Preparation of polyurethane solid-solid low-temperature PCMs granular asphalt mixes and study of phase change temperature control behavior. *Solar Energy*, *231*, 149–157. https://doi.org/10.1016/j.solener.2021.11.056

Xu, L., Wang, J., Xiao, F., EI-Badawy, S., & Awed, A. (2021). Potential strategies to mitigate the heat island impacts of highway pavement on megacities with considerations of energy uses. *Applied Energy*, *281*, 116077. https://doi.org/10.1016/j.apenergy.2020.116077

Yi, Y., Jiang, Y., Li, Q., Deng, C., Ji, X., & Xue, J. (2019). Development of Super Road Heat-Reflective Coating and Its Field Application. *Coatings*, *9*(12), 802. https://doi.org/10.3390/coatings9120802

Yinfei, D., Wang, J., & Chen, J. (2021). Cooling asphalt pavement by increasing thermal conductivity of steel fiber asphalt mixture. *Solar Energy*, *217*, 308–316. https://doi.org/10.1016/j.solener.2021.02.030

Yinfei, D., Zheng, H., Chen, J., & Liu, W. (2018). A novel strategy of inducing solar absorption and accelerating heat release for cooling asphalt pavement. *Solar Energy*, *159*, 125–133. https://doi.org/10.1016/j.solener.2017.10.086

Yuan, D., Jiang, W., Xiao, J., Ling, X., Zhang, Y., & Lu, R. (2023). Experimental study on the temperature-regulating function of road thermoelectric generator system. *Journal of Cleaner Production*, *384*, 135586. https://doi.org/10.1016/j.jclepro.2022.135586

Zhang, L., Ding, P., Si, W., Kang, X., Zhang, H., & Gu, Q. (2023). Study on the Photothermal Performance of a “Thermal Shielding” Coating Using Tungsten Bronze as Functional Material for Asphalt Pavement. *Materials*, *16*(22), 7150. https://doi.org/10.3390/ma16227150

Zhang, Z., Luo, Y., Huang, S., & Zhang, K. (2017). Evaluation of temperature reduction and pavement performance of floating beads asphalt mixture. *International Journal of Pavement Engineering*, *20*(3), 349–356. https://doi.org/10.1080/10298436.2017.1293267

Zhang, Z., Sha, A., Liu, X., Luan, B., Gao, J., Jiang, W., & Ma, F. (2020). State-of-the-art of porous asphalt pavement: Experience and considerations of mixture design. *Construction and Building Materials*, *262*, 119998. https://doi.org/10.1016/j.conbuildmat.2020.119998

Copyrights