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STUDY ON SELF-HEALING ASPHALT PAVEMENT WITH EMPHASIS ON REJUVENATION METHOD

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ABSTRACT: Asphalt is a widely used material to pave roads, parking lots, and other infrastructure that requires a smooth and level surface. However, it is susceptible to cracking due to prolonged exposure to sunlight and water infiltration. Once cracks form, they are exacerbated by the continuous stress of vehicular traffic, which can eventually lead to potholes and other surface defects, thereby disrupting smooth traffic flow. In recent decades, researchers have identified innovative self-healing methods for asphalt and proposed various strategies to enhance its self-repairing capabilities and extend its service life. This study focuses on three primary self-healing techniques for asphalt pavement design: nanoparticles, induction heating, and rejuvenation. Specifically, the study examines the effects of rejuvenating agents by incorporating sunflower oil microcapsules into stone mastic asphalt. The findings indicate that these microcapsules effectively heal cracks and improve the fatigue strength of asphalt pavements. Self-healing methods represent advanced approaches that leverage the inherent properties of asphalt to mitigate cracking and prolong the lifespan of pavement structures.

Keywords: Self-healing, Asphalt pavement, Induction heating, Rejuvenation, Nanoparticles

1. INTRODUCTION

Asphalt pavement is known for its ability to self-heal, meaning it can naturally repair minor cracks over time. This unique property of asphalt helps to extend the lifespan of roads and reduces maintenance costs. However, asphalt still deteriorates due to factors such as aging, oxidation, traffic loads, and harsh weather conditions. When cracks form and remain untreated, they grow, leading to potholes and expensive repairs. To address these issues, researchers have developed various self-healing techniques, with rejuvenation and heating methods being among the most promising.

Rejuvenation works by introducing healing agents into asphalt mixtures. These agents are often stored inside tiny capsules or fibers, which are released when cracks occur, restoring the flexibility and strength of the asphalt binder. Studies have shown that rejuvenators help slow down aging and improve the overall durability of asphalt pavements. For instance, in 2018, Tabakovic and Schlangen explored the use of healing capsules in stone mastic asphalt and found that they enhanced the material's resistance to cracking[1]. Similarly, bio-based rejuvenators, such as vegetable oils, could restore the chemical balance of aged asphalt, making it more flexible and resistant to damage [2].Heating methods, on the other hand, rely on external energy sources to repair cracks by softening the asphalt binder. Induction heating, a technique dating back to Michael Faraday's discoveries in the 1930s, uses steel fibers or other conductive materials mixed into the asphalt. When exposed to an electromagnetic field, these fibers generate heat, allowing the binder to reflow and close cracks. Induction heating significantly speeds up the self-healing process, but it requires precise distribution of metallic additives to ensure consistent results [3]. Moreover, microwave heating is a more accessible alternative that does not require special additives. Microwave energy can effectively restore asphalt properties, though further studies are needed to optimize this technique for widespread use [4].

Despite these advancements, there are still challenges in making self-healing asphalt practical and widely applicable. For this method to be helpful globally, we should ensure that rejuvenators and heating methods are performed consistently under different traffic and climate conditions. Some rejuvenators, for example, can make asphalt too soft, increasing the risk of rutting if not properly balanced. Additionally, while induction heating works well in controlled environments, its effectiveness on actual roads depends on factors such as material composition and heating efficiency. To address these concerns, researchers are looking for sustainable, cost-effective, and easy-to-implement solutions that can improve asphalt's self-healing properties without causing unintended side effects.

Beyond these self-healing approaches, there are other advanced research efforts in sustainable road construction. Studies have demonstrated the potential of recycled asphalt pavement material for ground strengthening and electric power generation, highlighting its dual role in infrastructure enhancement and energy production. Additionally, research on the scientific evolution of self-healing asphalt pavements has discovered innovative methods to improve road sustainability, making asphalt pavements more environmentally friendly [5-6].

This study explores the use of sunflower oil microcapsules as a rejuvenation agent in asphalt pavement. Sunflower oil is a bio-based material that has been identified as an environmentally friendly alternative to petroleum-based rejuvenators. Previous research has shown that vegetable oils can restore the flexibility of aged asphalt, but there is limited data on how sunflower oil performs when encapsulated and integrated into asphalt mixtures.

2. RESEARCH SIGNIFICANCE

This study has the potential to significantly extend the lifespan of road surfaces, minimize traffic disruptions associated with maintenance activities, and reduce maintenance costs. Additionally, it aims to lower the environmental impact of road infrastructure by mitigating premature aging of asphalt pavements and decreasing the reliance on natural resources for road network upkeep. Furthermore, the findings contribute to advancements in material science by promoting the development and application of self-healing materials across diverse industries.

3. MATERIALS AND METHODS

Testing was conducted at GAERTART CO., Ltd's research facilities in Japan, with invaluable support from Mr. Akira Nomoto, the laboratory head. A solution was prepared by mixing one teaspoon of sunflower oil with one teaspoon of sodium alginate in 200 ml of water in a beaker. In a separate beaker, a solution of calcium chloride was prepared by dissolving one teaspoon of calcium chloride in 200 ml of water. Using a syringe, the sunflower oil and sodium alginate solution was introduced into the calcium chloride solution in the form of droplets. This process resulted in the immediate formation of capsules, which were subsequently washed, dried, and stored for further use [7].

This experiment demonstrated that the inclusion of capsules in the asphalt mixture enhanced its rutting resistance and fatigue performance. It was noted that the number of loading cycles influenced the release of the healing agent under repeated stress. Al-Mansoori T., Norambuena-Contreras J., Micaelo R., and Garcia A. reported that at temperatures above 40°C, the healing performance of asphalt with and without self-healing agents was comparable, suggesting that capsule incorporation in high-temperature environments might be suboptimal. Garcia et al. conducted comprehensive studies on the healing properties of various asphalt types, including dense asphalt, SMA, and porous asphalt (PA). Their findings indicated that porous asphalt exhibited a slower release of healing agents, whereas denser mixes released them more rapidly.

The figure below illustrates the preparation process of the stone mastic asphalt (SMA) sample incorporating sunflower oil microcapsules. This figure provides a detailed overview of the steps involved in embedding the capsules into the SMA mixture, demonstrating the methodology used to assess the rejuvenating effects of the microcapsules on the asphalt's properties. Additionally, it highlights the uniform distribution of the capsules within the asphalt, ensuring their effective interaction with the material during the rejuvenation process. The materials used in the mixing process included stone mastic asphalt, sunflower oil microcapsules, bitumen, aggregates, and filler, which were combined in precise proportions to create a homogeneous mixture for testing.

Fig. 1 Preparation of stone mastic asphalt sample with capsules.

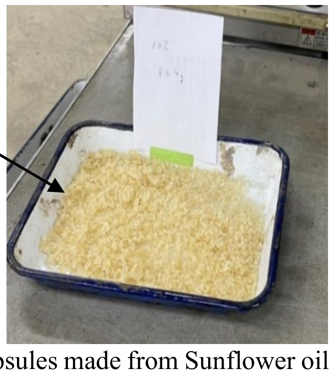

Fig. 2 Dried microcapsules made from Sunflower oil and sodium alginate.

The capsules were later incorporated into stone mastic asphalt (SMA) to evaluate their rejuvenating capacity. To prepare the SMA specimens, a mix of coarse aggregate (40/60), fine aggregate, and filler was used. The aggregates, with a density of 1.030 g/cm³, were dry-mixed for 2.5 minutes, after which bitumen was added and the mixture was wet-mixed for another 2.5 minutes. Finally, sunflower oil dried microcapsules were added, and the mixture was blended for an additional 2.5 minutes. This final mixture was poured into a steel mold to form specimens. A control sample without sunflower oil microcapsules was also prepared under identical conditions.Both the capsule-incorporated and control samples were cut into six specimens each and tested to compare their fatigue performance using impact testing and three-point bending fatigue tests. The distribution, durability, and strength of the capsules within the asphalt mixture were assessed to determine their effectiveness.Cracks were induced in the specimens, which were then conditioned at 30°C and 20°C to evaluate the healing capacity of the asphalt mixture. The healing effects were assessed at intervals of 5 hours, 120 hours (5th day), and 216 hours (9th day). It was observed that specimens containing capsules exhibited significant crack healing, whereas those without capsules showed no signs of healing. The healing process at 30°C was slower at the 5-hour mark but became faster and more pronounced by the 5th and 9th days. Similarly, healing occurred at 20°C, though it required slightly longer durations compared to 30°C.

3.1 Capsules Activation

Prior to evaluating the rejuvenating strength of the capsules, the stone mastic asphalt (SMA) specimens were pre-cracked using an impact test. Thin film plastic membranes were then inserted between the cracks of all six test specimens, including those with and without capsules. Subsequently, the specimens were placed inside a steel mold and conditioned in a temperature-controlled chamber at 20°C for two hours to activate the healing process.

Fig. 3 Activation of the healing Process

In this experiment, the activation method used for the microcapsules involved temperature conditioning. After inducing cracks in the stone mastic asphalt specimens using an impact test, the specimens were placed inside a steel mold and conditioned in a temperature-controlled chamber at 20°C. This temperature was maintained for two hours to allow the microcapsules to activate and release the healing agent. This method ensures the controlled activation of the microcapsules, enabling the healing agent to flow into the cracks and restore the structural integrity of the asphalt. By utilizing temperature-controlled conditions, the experiment simulated real-world environments where temperature fluctuations can trigger the release of the healing agent. The controlled activation of the microcapsules allows for the efficient and targeted repair of cracks, improving the long-term durability of the pavement.5.2 Specimen preparation for healing. After two hours of conditioning at 20°C in a temperature chamber, the plastic membranes were removed and the specimens were transferred respectively. These conditions were maintained for healing over a period of 5 hours to 9 days. This duration allowed the microcapsules to release the rejuvenator, which effectively wetted the crack surfaces, softened the aged bitumen, and facilitated the reconnection of the broken edges of the pavement, thereby preventing further damage [9].

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3.2 Evaluation of Healing Performance

The healing performance of the stone mastic asphalt (SMA) specimens was rigorously evaluated using a range of tests, including the indirect tensile strength test, dynamic modulus test, and fatigue test. These healed specimens were then compared to their unhealed counterparts to assess the efficacy of the microcapsules in facilitating the healing process. By incorporating microcapsules containing sunflower oil, the laboratory study aimed to demonstrate the potential of these capsules to restore the structural integrity of the SMA. The results provided valuable insights into the effectiveness of microcapsules in rejuvenating aged asphalt, potentially offering a sustainable solution to pavement maintenance and longevity [10].

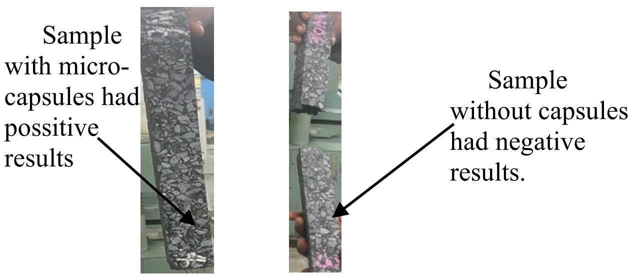

Fig. 4 Samples with capsules (W/C) healed cracks and samples without capsules.

Samples with capsules, which successfully healed their cracks, and those without capsules, which did not heal. The samples with capsules demonstrate how effective the capsules are in promoting crack healing, while the samples without capsules highlight the absence of this healing capability. This visual comparison further emphasizes the critical role of microcapsules in enhancing the self-healing performance of the materials [11-14].

3.3 Impact of Microcapsule Design and Temperature Variation on Self-Healing Efficiency

An essential aspect of self-healing asphalt technology is the design and functionality of the microcapsules themselves, which directly influence the healing efficiency and long-term performance of the asphalt mixture. While this study has demonstrated the potential benefits of incorporating sunflower oil-based microcapsules into Stone Mastic Asphalt (SMA), further exploration of the microcapsules' structural design and how they respond to different environmental conditions could provide critical insights for optimizing this technology.

3.4 Microcapsule Durability and Release Mechanism

One of the major factors affecting the efficacy of microcapsules is their durability under harsh conditions, such as high mixing temperatures and the mechanical stress during traffic loading. The physical stability of the capsules, particularly their ability to withstand the mixing and compaction processes without premature rupture, is crucial for their long-term functionality. Future research could focus on designing capsules with enhanced resistance to these conditions by modifying the encapsulation material or using alternative biopolymers. Additionally, studying the release mechanisms whether it is triggered by mechanical stress, temperature, or a combination of factors would offer valuable data for optimizing their use in different climates and road types.

3.5 Influence of Temperature on Healing Efficiency

The study showed that temperature plays a significant role in the healing capacity of the asphalt, with higher temperatures (30°C) accelerating the healing process compared to lower temperatures (20°C). However, as asphalt pavements are often subjected to wide temperature fluctuations, it is essential to understand how these microcapsules perform in both extreme heat and cold conditions. Research could investigate the impact of varying temperature cycles, including freeze-thaw conditions, on the healing efficiency of the microcapsules. Moreover, incorporating temperature-sensitive capsules that release healing agents at specific temperatures could offer targeted healing strategies based on regional climate conditions.

3.6 Long-Term Performance of Microcapsule-Modified Asphalt

While the short-term results of the current study show promising healing capabilities, the long-term performance and durability of microcapsule modified SMA need further evaluation. A critical concern is whether the continuous release of the healing agent could lead to over-saturation, which may compromise the mechanical properties of the asphalt over time. Additionally, the ability of the capsules to retain their functionality after multiple cycles of cracking and healing could be studied to understand their long-term impact on the asphalt's performance. Investigating the longevity of these microcapsules under real-world conditions such as prolonged exposure to UV light, moisture, and chemical degradation would help determine the sustainability and effectiveness of this self-healing technology.

3.7 Cost-Effectiveness and Scalability of Microcapsule Integration

The adoption of microcapsule-based self-healing asphalt depends on cost-effective production, seamless integration into asphalt mixes, and long-term economic benefits. Optimizing large-scale synthesis and ensuring compatibility with existing asphalt plants can reduce costs without compromising performance. Despite higher initial expenses, self-healing asphalt extends pavement lifespan, lowers maintenance costs, and reduces traffic disruptions. A life-cycle cost analysis, along with policy support and industry collaboration, can enhance scalability, making this technology a viable, sustainable solution for road infrastructure.

3.8 Healing Assessment

The healing effectiveness of the asphalt specimens was evaluated at three intervals: after 5 hours, 120 hours (on the 5th day), and 216 hours (on the 9th day). During these intervals, the specimens were checked for crack healing and their performance in terms of fatigue resistance and rutting resistance. The results of these tests allowed for a comparison of the healing abilities between the specimens with and without capsules.

4. RESULTS AND DISCUSSION

The results of this study highlight the significant role of sunflower oil-based microcapsules in enhancing the self-healing capabilities of Stone

Mastic Asphalt (SMA) road surfaces. During the initial 5-hour evaluation, one specimen with microcapsules and one without exhibited healing, suggesting that while microcapsules can enhance the early-stage healing process, their impact becomes more pronounced over time.

At the 120-hour mark, all specimens containing microcapsules at both 20°C and 30°C had fully healed, whereas only one specimen without microcapsules showed signs of healing. This finding indicates that the presence of microcapsules provides a consistent supply of the healing agent, enabling a more sustained and effective healing process. It also underscores the limitations of SMA surfaces without microcapsules, which rely solely on natural self-healing mechanisms that appear insufficient over extended periods.

By 216 hours, the disparity in healing performance between specimens with and without microcapsules became even more evident. All specimens with microcapsules demonstrated complete healing, while only two specimens without microcapsules, both at 30°C, showed any recovery. Notably, no healing occurred in specimens without microcapsules conditioned at 20°C. These findings affirm the critical importance of microcapsules in maintaining the self-healing capacity of SMA, especially under less favorable thermal conditions.

The study also found that higher temperatures, such as 30°C, were more conducive to healing over longer durations. This is likely due to the increased mobility of the healing agent at elevated temperatures, which enhances its ability to penetrate and repair cracks and voids in the SMA surface. However, the inability of specimens without microcapsules to heal effectively at the same temperature underscores the necessity of incorporating microcapsules for optimal performance.

Table 1 highlights the impact of microcapsules and temperature on SMA healing performance. At 20°C, all specimens with microcapsules fully healed (3/3), while none without microcapsules showed any recovery (0/3). Similarly, at 30°C, all specimens with microcapsules achieved healing, ranging from partial. Sunflower oil-based microcapsules promotes healing and performance at higher temperatures.

These findings suggest that both the presence of microcapsules and elevated temperatures play a crucial role in optimizing the self-healing capabilities of stone mastic asphalt. Sunflower oil-based microcapsules significantly enhance the self-healing ability of Stone Mastic Asphalt, especially over extended periods and at higher temperatures. While natural healing is limited, microcapsules provide a sustained supply of the healing agent, ensuring complete recovery even under less favorable conditions.

These findings collectively demonstrate that sunflower oil-based microcapsules significantly enhance the durability and self-healing properties of SMA road surfaces. The microcapsules ensure the availability of the healing agent over time, enabling effective and prolonged crack repair.

Table 1. Healing Results Summary

Condition	Healed Specimens	Not Healed Specimens
20°C with Capsules	Complete Healing (3/3	None (0/3)
20°C without Capsules	None (0/3)	No Healing (3/3)
30°C with Capsules	Partial to Complete (3/3)	None (0/3)
30°C without Capsules	None (0/3)	No Healing (3/3)

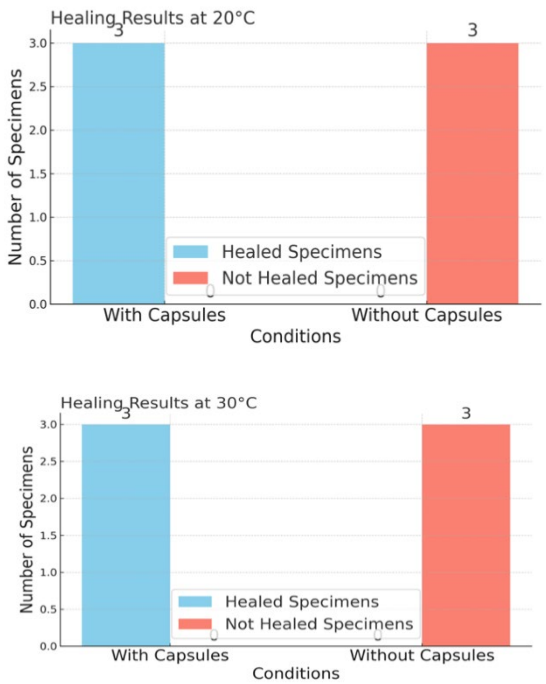

Fig. 5 Graph showing results at 20°C and 30°C.

This research not only underscores the practical potential of microcapsules to improve pavement longevity and safety but also identifies areas for further investigation, such as optimizing temperature conditions and exploring the long-term performance of microcapsule-modified SMA under varying environmental conditions.The table below shows the advantages and disadvantages of healing techniques of asphalt mixture.

Table 2. Study the advantages and disadvantages of asphalt self-healing techniques.

Techniques	Advantages	Disadvantages
Induction Heating	Rapid, Precise, Uniform, environment ally friendly, Efficient, Economical, and Effective	Energy Consumption, Skilled Labor, Limited Depth, Sensitivity to Moisture, Initial Investment,
Encapsulation	Durability, Enhanced Efficiency, Extended Service Life, Improved Material concordance,	High cost, Limited capacity, Risk of capsule breakage, Environmental issues,
Ionomers	Durability, Enhanced Crack Resistance.	Complex Application, High Cost.

5. CONCLUSIONS

This study provides a comprehensive evaluation of self-healing technologies in road construction, demonstrating the significant role of sunflower oil-based microcapsules in enhancing the durability of Stone Mastic Asphalt (SMA). By integrating microencapsulated rejuvenators and examining their effectiveness under different thermal conditions, this research highlights an innovative and sustainable approach to extending pavement lifespan and reducing maintenance costs.The results reveal that sunflower oil-based microcapsules significantly enhance the self-healing capacity of SMA, particularly over extended periods. While natural self-healing mechanisms in SMA were observed in some cases, the presence of microcapsules ensured a more reliable and sustained healing process. At the 120-hour mark, all specimens containing microcapsules had fully healed at both 20°C and 30°C, whereas only one specimen without microcapsules exhibited healing. By 216 hours, the disparity was even more pronounced complete healing was observed in all specimens with microcapsules, while specimens without microcapsules showed little to no recovery, particularly at lower temperatures. This underscores the critical role of microcapsules in providing a continuous supply of the healing agent, enhancing both short-term and long-term pavement performance.

Additionally, temperature played a crucial role in influencing the healing process. Higher temperatures (30°C) facilitated faster healing by increasing the fluidity and diffusion of the healing agent within the asphalt matrix. However, the ability of the microcapsules to induce healing even at 20°C over prolonged durations demonstrates their adaptability across various environmental conditions. The findings further confirm that SMA surfaces without microcapsules rely solely on natural healing mechanisms, which prove inadequate over time, especially under less favorable thermal conditions.

Beyond the benefits of microcapsules, the study also evaluates the potential of microwave heating as an alternative to traditional induction heating techniques. Unlike induction heating, which requires metallic additives, microwave heating provides a practical, energy-efficient solution for asphalt repair without additional conductive materials. The experimental results confirm its effectiveness in activating the healing process by softening the asphalt binder and accelerating crack closure.

While this study presents promising outcomes, challenges remain. The ability of microcapsules to withstand the high temperatures and pressures of asphalt mixing and compaction is a critical consideration for large-scale implementation. Additionally, ensuring their uniform dispersion within the SMA matrix remains a challenge due to its heterogeneous nature. Future research should focus on optimizing microcapsule design, improving dispersion techniques, and exploring alternative bio-based healing agents to enhance the efficiency and environmental sustainability of self-healing asphalt technologies.

In conclusion, this research demonstrates the substantial benefits of sunflower oil-based microcapsules in improving the self-healing performance of SMA, particularly under varying temperature conditions. The findings reinforce the viability of bio-based rejuvenators as an eco-friendly alternative to synthetic healing agents and establish microwave heating as a practical, scalable solution for pavement maintenance. By addressing existing challenges and optimizing these self-healing technologies, this study contributes to the development of more durable, cost-effective, and sustainable road infrastructure.For self-healing asphalt technologies to gain widespread adoption, it is essential to evaluate both their technical performance and economic feasibility. The integration of microcapsules into large-scale asphalt production must be cost-effective and scalable to ensure practical implementation in road infrastructure. A thorough cost-benefit analysis should consider not only the initial expenses of microcapsule synthesis and incorporation but also the long-term savings associated with reduced maintenance and extended pavement lifespan.Future research could focus on optimizing industrial-scale production methods for microcapsules to lower manufacturing costs while maintaining efficiency. Techniques such as spray drying, emulsification, or coacervationcould be explored to enhance production scalability.

Additionally, identifying alternative bio-based or waste-derived healing agents may further improve cost-effectiveness while maintaining sustainability.By addressing these economic and logistical aspects, future studies can refine self-healing asphalt technology, making it viable for large-scale application. Understanding the balance between production costs and long-term benefits will help governments, policymakers, and industry stakeholders make informed decisions about investing in microcapsule-enhanced asphalt. Ultimately, optimizing this technology can contribute to more durable, cost-efficient, and environmentally friendly road infrastructure.

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7. REFERENCES

[1] Yu, J., Lin, Z., Zou, G., Yu, H., Leng, Z., & Zhang, Y. Long-term performance of recycled asphalt mixtures containing high RAP and RAS. Journal of Road Engineering, vol. 4, 2024, pp. 36-53.

[2] Wei, K., Wu, Y., Cao, X., Yang, X., Tang, B., & Shan, B. Dual dynamic bonds approach for polyurethane recycling and self-healing of emulsified asphalt. The Science of the Total Environment, vol. 885, 2023, pp.1-13.

[3] Cavalli, M. C., Chen, D., Chen, Q., Chen, Y., Falchetto, A. C., Fang, M., Gu, H., Han, Z., He, Z., Hu, J., Huang, Y., Jiang, W., Li, X., Liu, C., Liu, P., Liu, Q., Lu, G., Ma, Y., Poulikakos, L., Zhu, W. Review of advanced road materials, structures, equipment, and detection technologies. Journal of Road Engineering, Vol. 3, Issue 4, 2023, pp.370-468.

[4] Garcia-Hernández. A., Salih S., Ruiz-Riancho I., Norambuena-Contreras J., Hudson-Griffiths R., and Gomez-Meijide B. Self-healing of reflective cracks in asphalt mixtures by the action of encapsulated agents, Construction and Building Materials, vol. 252, 2020, pp. 1-11.

[5] Shoji Yokohama. Experimental Study on Ground Strengthening and Electric Power Generation with Using Recycled Asphalt Pavement Material, International Journal of GEOMATE, vol. 22, Issue 89, 2022, pp. 40-46.

[6] Israil, M. Tumpu., Hamkah., Nursafanah Dzakiyah AlMakassari., Extraction Bitumen Buton Rock Asphalt as Solid Phase in Asphalt Emulsion Mixed: Stability, Flow, and Marshall Quotient. International Journal of GEOMATE, vol 28, Issue 125, 2025, pp. 11-18.

[7] Shiwen Bao., Quantao Liu., Hechuan Li., Lei Zhang, and Diego Maria. Barbieri Investigation of the Release and Self-Healing Properties of Calcium Alginate Capsules in Asphalt Concrete under Cyclic Compression Loading, vol.33, Issue 1, 2020, pp. 1-9.

[8] Nalbandian, Kevork Micael, Carpio, Manuel, Gonzalez, Alvaro. Analysis of the scientific evolution of self-healing asphalt pavements: Toward sustainable road materials, Journal of Cleaner Production, vol.293, 2021, 126107, ISN 0959-6526.

[9] Modulus Model Using Slag Materials and Reclaimed. Asphalt Pavement. International Journal of GEOMATE, vol.19, 2020 pp.1-7.

[10] Alpizar-Reyes, E., Concha, J. L., Martín-Martínez, F. J., & Norambuena-Contreras, J. Biobased Spore Microcapsules for Asphalt Self-Healing. ACS Applied Materials & Interfaces, vol. 14, 2022, pp. 31296-31311.

[11] Ali Behnood. Application of Rejuvenators to Improve the Rheological and Mechanical Properties of Asphalt Binders and Mixtures: A revie. Journal of Cleaner Production, vol.231, 2019, pp 171-181.

[12] Anupam, B.R., Umesh Chandra Sahoo., Mohamadtaqi Baqersad, and Hesham Ali., Al-Mansoori., T., Norambuena-Contreras., Micaelo J., R., and Garcia A., Self-healing of asphalt mastic by the action of polymeric capsules containing rejuvenators, Construction and Building Materials, vol. 161, 2018, pp. 330-339.

[13] Z., Hu, J., Huang, Y., Jiang, W., Li, X., Liu, C., Liu, P., Liu, Q., Lu, G., Ma, Y., Poulikakos, L., Zhu, W. Review of advanced Road Materials Equipment and Detection Technologies. Journal of Road Engineering, vol. 3, 2023, pp. 370-468.

[14] Sun., S. Wu, Q. Liu., J. Hu., Y. Yuan., and Q. Ye. Snow and Ice Melting Properties of Self-healing Asphalt Mixtures with Induction Heating and Microwave Heating, Applied Thermal Engineering, vol. 129, 2018, pp. 871-883.