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# Experimental investigation and mechanism analysis of novel multi-self-healing behaviors of bitumen using microcapsules containing rejuvenator

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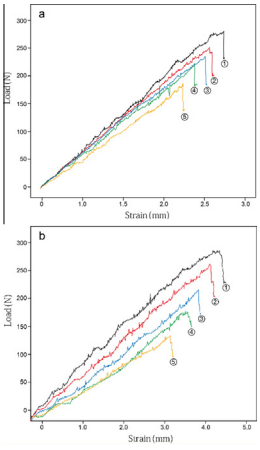
## HIGHLIGHTS

- The multi-self-healing ability of microcapsule/bitumen composite was found.
- This ability connects with the interface energy of microcrack.
- Microcapsules can break at various periods.
- This ability is a continuous adjustment of microstructure of bitumen.

## GRAPHICAL ABSTRACT

Load–strain curves of BOEF test under (a) 0 °C and (b) 25 °C for bitumen samples containing 2.0 wt.% microcapsule; self-healing cycles: ① first time, ② second time, ③ third time, ④ aged bitumen, and, ⑤ fourth time.

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## ABSTRACT

The aging problem of bitumen leads to pavement failure after years of usage. To improve its self-healing ability, it has been found that microencapsulated rejuvenator within bitumen may be an alternative approach. The aim of this paper is to investigate a novel multi-self-healing behavior of bitumen using microcapsules containing rejuvenator with different shell thickness and size distribution. The microcapsule sample was composed of three types of microcapsules with different mean size and shell thickness values. A modified beam on elastic foundation (BOEF) method was applied to investigate the mechanical properties of bitumen/microcapsule materials. The results show that these microcapsules were broken by microcracks under different conditions with a good normal distribution. The remaining microcapsules near the microcrack had the ability to leak rejuvenator later when another microcrack generated with even high crack tip strain. After loading–unloading cycles, the multi-self-healing ability of microcapsule/bitumen composite softened through of rejuvenator diffusion into bitumen. Properties of virgin and rejuvenated bitumen also confirmed that the aged bitumen had a multi-recovery ability due to

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the microcapsules containing rejuvenator. Both models of mechanical healing and physic–chemical healing were applied to analyze the mechanism of the multi-self-healing process. With a constant change and adjustment of microstructure, viscosity and thixotropy of bitumen, it possesses a healing ability numerous times over.



## 1. Introduction

The aging of bitumen leads to pavement failure after years of use. The stiffness of asphalt concrete increases while the relaxation capacity decreases, and the binder becomes more brittle, resulting in the development of microcracks and ultimately cracking of the interface between aggregates and binder [1]. The main cause of this phenomenon is the gradual increase of the asphaltene/maltene ratio in bitumen [2]. Meanwhile, governments invest heavily in the development of national road networks. In 2009, governments of the European Union invested 42% (€4.5 billion) of the EU transport network fund (€10.74 billion) in the development and maintenance of road networks [3]. In China, the government considers the development and maintenance of the road network to be critical to the growth and competitiveness of China's economy. Recent research highlights that the development of self-healing bitumen and its use in road paving could potentially double the road lifespan to between 40 and 80 years and could appreciably reduce road maintenance activity. In comparison with current maintenance practices, the use of self-healing bitumen can improve traffic flow, reduce demand for fresh aggregates, reduce $CO_2$ emissions and enhance road safety.

Bitumen can be classified as a self-healing material because it has the potential to restore its stiffness and strength by closing microcracks that occur when the pavement is subjected to traffic loads or high temperature. Properties relating to the autogenous healing ability of bitumen have been reported. The mechanism is that a crack repair in an asphalt pavement system depends on the wetting and inter-diffusion of material between the two faces of a microcrack such that the properties of the original material are regained [4]. The excellent durability of self-healing materials does not arise from the classical approach of minimizing damage but from the novel approach of designing materials with 'self-healing' capabilities. As in natural processes, the self-healing performance of an asphalt pavement can be improved; e.g., modifiers and additives can be introduced to the asphalt mix to improve the self-healing property. A review of the literature reveals that several methods have been applied to improve the self-healing of bitumen, including the addition of particles [5], the blending of polymers [6], heat induction [7], and the use of a rejuvenator [8].

The use of a rejuvenator is the only method that can restore the original properties of a pavement [9]. Rejuvenating agents have the ability to reconstitute the binder's chemical composition and consist of lubricating and extender oils containing a high proportion of maltene constituents [10]. However, it is difficult to use an oily rejuvenator effectively because the rejuvenator cannot penetrate the pavement surface easily [11]. An alternative approach that would overcome this problem might be the encapsulation of a rejuvenator within the bitumen. We previously reported a method of fabricating microcapsules containing rejuvenator using methanol-modified melamine–formaldehyde resin as the shell material [12]. These microcapsules have satisfactory thermal stability in bitumen and reliable mechanical properties in terms of withstanding the mixing process and temperature changes [13]. As shown in Fig. 1, the overall self-healing process of microcapsules/bitumen can be divided into four steps: (a) the generation of the microcrack, (b) the breaking of microcapsules, (c) the capillarity action and diffusion of the rejuvenator, and (d) the closure of the microcrack. It was demonstrated that the microcapsules were punctured by microcracks and leaked their oily liquid rejuvenator into the microcracks. With the help of capillarity, the rejuvenator filled the cracks with a movement speed mainly determined by the volume of microcapsules in the bitumen [14]. A diffusion phenomenon was also observed using a fluorescence microscope. We believe that this product is an environmentally friendly powder encapsulating suitable size rejuvenator for chemical engineering and construction engineering [15].

The self-healing or self-repair of a material or system is considered to be the ability of the material or system to substantially return to the initial or proper operating state or condition prior to exposure to a dynamic environment by making the necessary adjustments to restore to normality and/or the ability to resist the formation of irregularities and/or defects [16]. The main issue related to self-healing bitumen is the development of an asphalt

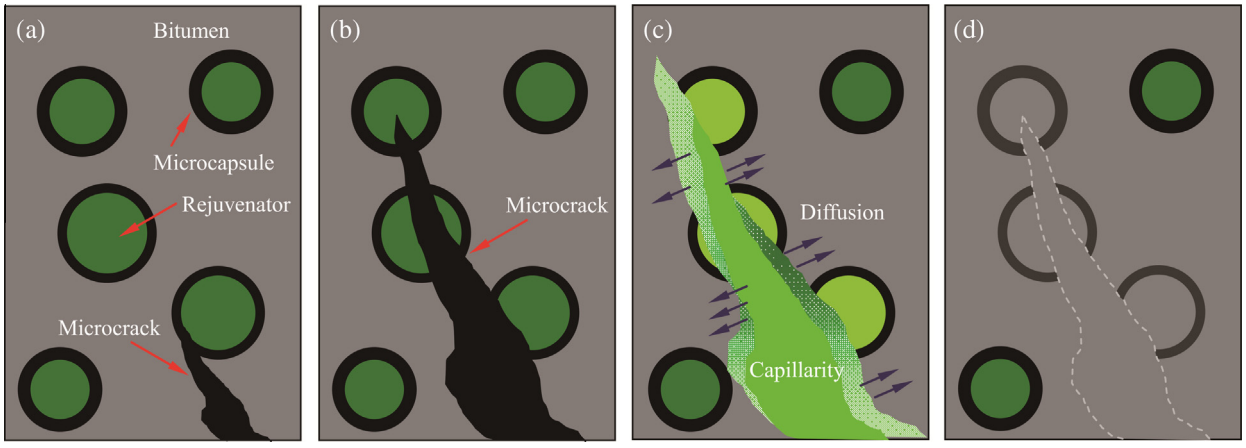


**Fig. 1.** Illustration of self-healing process of microcapsules/bitumen including four steps: (a) microcrack generation, (b) microcapsules broken, (c) capillarity and the diffusion behaviors of rejuvenator, and (d) microcrack closure.