Substituting aggregates with hot braised steel slag (HBSS) to improve the self-healing properties of asphalt mixtures for sustainable pavement

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Introduction

Environmental pollution and resource shortages are the two most urgent issues in our society. Pavement construction needs mega amounts of aggregates, which could reduce the natural resource and burden on the environment. Hence, finding a substitution for pavement aggregates is crucial. According to the World Steel Association report, the steel industry currently generates significant waste, with approximately a hundred million tons of steel slag annually. However, less than 30% of the slags were recycled and reused [1]. Consequently, environmental issues, including heavy metal pollution, land occupation, soil pollution, and water pollution, are generated, also due to their low utilization rate [2]. Therefore, many researchers attempted to use recycled steel slag in pavement construction [3]. Asphalt pavement is the most common form of roadway; however, it is prone to cracking under environmental and loading conditions. In recent years, microwave maintenance technology has been proposed to repair cracks in asphalt pavements effectively. Natural aggregates have limited wave absorption properties, while steel slag exhibits excellent wave absorption properties, which can be used for self-healing asphalt pavement. Therefore, replacing natural aggregates with steel slag and applying microwave heating (MH) technology show the potential of saving natural resources, reducing environmental pressure, repairing pavement cracks, and extending the pavement life cycle. This work aims to evaluate the self-healing properties of asphalt mixtures containing steel slag and recommend the optimum steel slag content based on healing properties, thermal characteristics, and road performance.

Materials and methods

In this research, the Open Graded Friction Course (OGFC) structure was used together with different hot braised steel slag (HBSS) content to evaluate the effect of steel slag on self-healing properties. HBSS shows a better microwave-absorbing ability compared to other metallic wastes. The 4.75–9.5 mm of limestone was replaced with 0%, 20%, 40%, 60%, 80%, and 100% contents of steel slag in volume, respectively, marked as SS0, SS20, SS40, SS60, SS80, and SS100. The characteristics of the aggregates and steel slag were analyzed using SEM and X-RD. Then, the healing index (HI) was defined as the strength recovery rate via semi-circular bending tests to confirm the optimal steel slag replacement content of conventional aggregate. In previous studies, this method has been validated in assessing the self-healing capabilities of asphalt mixtures. The asphalt mixtures with macro cracks (wider than 1mm) were heated using a microwave oven. An infrared camera was adopted to monitor the temperature during heating. Finally, high-temperature stability, low-temperature crack resistance, and water stability were evaluated based on the standards. The optimum steel slag content was determined in consideration of balancing these properties. The complete cracking-healing-evaluation process is reported in Fig. 1.

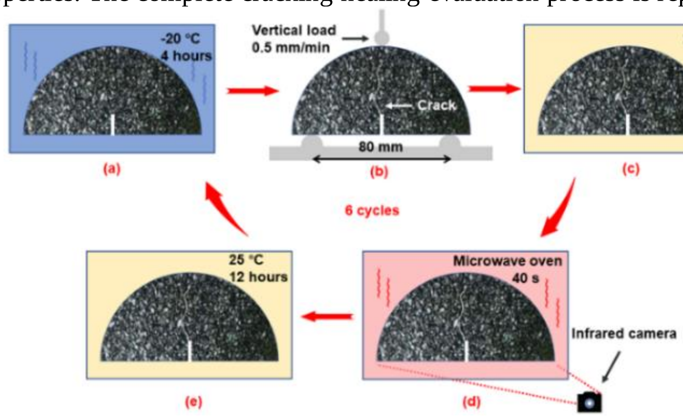

Fig.1 Cracking-healing: (a)cryogenic insulation; (b)loading; (c)drying; (d)microwave heating; (e)self-healing.

Results

The microstructures of steel slag and aggregates were magnified 1000X in Fig. 2(a). Blue and yellow represent areas with and without pores. Steel slag has a porous structure, while limestones have fewer pores. This difference in characteristics causes the steel slag to have a better environment for reflecting microwaves, resulting in a better MH capacity. In addition, steel slag contains multiple metallic oxides, while limestone contains one substance ($CaCo_3$). Generally, materials containing more metal elements are considered the better absorbing materials. In summary, the steel slag with better MH properties is feasible as the wave-absorbing material. Fig. 2(b) indicates that all specimens exhibited better healing capacity than SS0 due to the steel slag's better MH capacity. The healing index (HI) of the SS20, SS40, SS60, SS80, and SS100 is 86.7%, 86.6%, 84.3%, 92.8%, and 78.5% in the initial cycle, respectively, which is 1.3, 1.3, 1.3, 1.4, and 1.2

times than that of SS0. In which SS80 performed the best healing properties. The initial HI of SS80 reached 92.8%, while it decreased to 66.5% in the last cycle. If HI lower than 50% is considered the threshold value, self-healing of pavement is no longer recommended; only SS80 shows the potential of self-healing functions after five cycles. The HI of SS0 dropped below 50% after two cycles, while SS20, SS40, etc., could undergo 4, 4, 4, 5, and 4 cycles. This trend indicated that steel slag could significantly improve self-healing properties and prolong the pavement life. Although SS100 shows a better healing performance than SS0, its heating rate is so fast that the asphalt mixtures may be overheated, leading to aged mixtures. Fig. 2(b) demonstrated parts of thermal images of the specimens when cracking-healing tests were conducted at the end of the first cycle. The darker colors (blue) indicate lower temperatures, and the bright colors (red) indicate higher temperatures. It can be observed that the temperature rise is not uniform; the temperature rises in specific areas are relatively fast. This behavior is because these areas contain steel slag, which can transfer heat to the surrounding area more efficiently. Therefore, the temperature is transmitted around the center of the steel slag; this hot area expands, and the temperatures of the surrounding areas increase to different degrees. The thermal images of SS0 exhibited the best heating uniformity (less temperature gradient), owing to the composition of the asphalt mixture with the same aggregate. However, the HI of SS0 was too low to satisfy healing properties. The thermal images of SS40 and SS80 have one and two heating points, but the impact is so small that it rarely causes overheating issues. From the thermal images of SS100, it can reach above 140 °C after 40 s. The mixtures become overheated and soft at a too-high temperature. HL was defined as the ratio of effective healing areas (between softening point and 90 °C) to total areas. SS80 and SS100 increased rapidly; their HL was 63.7% and 46.4% after heating. However, the HL of SS100 began to decrease after 30 s. This is because the bituminous mixtures overheated after 30 s. Fig. 2(c) shows the dynamic stability (DS), maximum bending strain (εB), and TSR of asphalt mixtures. Steel slag could improve the high-temperature stability of pavement. SS0 has a DS of 4656 times/min, and the values of SS20 to SS100 are 1.30, 1.50, 1.61, 1.36, and 1.15 times SS0. The high density and strength of steel slag can increase the inlay of aggregates and thus improve the resistance to deformation. However, when steel slag content is too much, their porous structure will absorb more asphalt, thus declining the adhesion between aggregates. Consequently, the high-temperature stability of pavement is reduced. A higher εB indicates a better crack resistance. The εB shows a linearly decreasing trend with the growth of content (from 4175 με to 2780 με). This phenomenon can be explained by the lower adhesion between aggregates resulting from the adsorption of asphalt by steel slag. The TSR curve has the same trend as the DS curve. The TSR increased from 87.1% of SS0 to the peak value (92.3%) of SS40. Then it decreased to 84.6% of SS100. When there is more steel slag, water stability is reduced because of the expansion of free f-CaO and f-MgO.

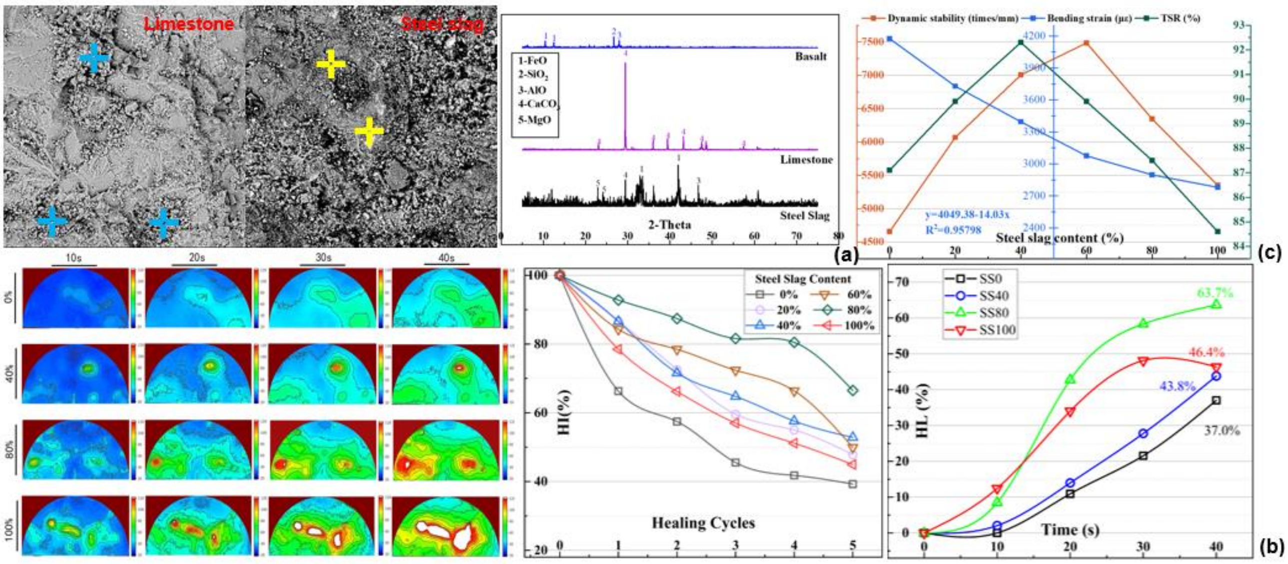

Fig. 2 (a)structure and chemical composition; (b)HI, HL, and thermal images; (c)Road performance

Conclusions

Steel slag could increase the microwave-heating properties of asphalt mixtures, as a result in improving self-healing properties. However, high steel slag content may cause overheating problems. Using steel slag enhanced the high-temperature and water stability while deteriorating the low-temperature crack resistance. An 80% steel slag content is recommended as the optimal replacement for aggregates for self-healing purposes. Because it not only has the best healing properties without overheating problems but also meets road performance requirements.

References

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