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Review Article

Self-healing of microcapsule-based materials for highway construction: A review

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HIGHLIGHTS

- Auto-recovery in inner and invisible cracks is achieved by microcapsules.
- The technique improves the strength and impermeability of cracked materials.
- Self-healing brings composites a chance to interact with environment.
- The practical significance of self-healing in highway projects is discussed.

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ABSTRACT

Maintaining the health and reliability of civil facilities is of strategic importance. In highway engineering, pavement cracking impairs the road service and travel comfort level, while structure cracking can cause catastrophic damage. Microcapsule-based self-healing materials offer solutions to auto-recovery micro-cracks and maintain structural health. Such solution has become available by laboratory synthesis and proved effective in addressing the cracking problem during long-term mechanical, thermal, and hydraulic conditions. However, full-scale applications of this technique are not prevalent, showing its potential limitations in highway engineering. Crack healing in highways is a big topic, therefore, this review has two insertion points. (1) We focus on the cracking issues on two specific materials: asphalt and concrete, which account for the vast majority of all the materials used in pavement and structures in highways. (2) Instead of the laboratory studies, we pay more attention to the practical applications, the meaning of healing performance, and the adverse effects of microcapsules to the main structural components (i.e., tunnel lining, bridge piers and beams) and pavement in highways. The practical significance of self-healing materials in highway projects was discussed from the three aspects: strength, durability, and stress redistribution. The difficulty in applying this new technique is also discussed from economic perspective. For future-proofing, a material evaluation system that fits the load condition is required. The self-healing technique brings...
1. Introduction

The cracking of structures and facilities is a traditional problem in highway engineering, but it has not been addressed thoroughly. The cracks including tiny ones are existing in almost all highways with different extents (Das and Siddagangaiah, 2022; Gardner et al., 2018). Cracks cause a wide variety of problems in many components of highways. These cracked components can be pavements (asphalt and concrete) or some structural parts such as concrete bridge beams and tunnel linings. The cracks are likely to form large-scale networks without reasonable treatment. For pavements, the cracking impairs its service life and driving comfort. For structural parts, cracks are more dangerous. Once a main structure part fails, for example, the bridge columns, the consequence can be catastrophic. The pavements merely bear the vehicle loads. For structural components of bridges, material self-weight should also be considered. The vehicle loads and material self-weight are both assessable. However, in tunnels, lining structure is subject to rock pressure and hydraulic erosion in addition to vehicle loads and material self-weight. Due to the inherent complexity of geotechnical mediums, rock pressure is changeable sometimes and difficult to predict, and the hydraulic erosion is hard to deter. These cracks should be dealt to avoid further hazards. Some typical crack disaster forms existing in highways are shown in Fig. 1.

Many countries have paid amounts of money to maintain and repair their infrastructures. In the U.S., maintaining highways due to corrosion costs approximately $4 billion (Torgal-Pacheco, 2015), in Australia nearly $550 million per year (Chen et al., 2004). In the U.K., about £50 billion is allocated for it per year (HM Treasury, 2016). China paid ¥37.18 billion on road maintenance in 2019 (Ministry of Transport of the People’s Republic of China, 2020). It is estimated that the cost of concrete production ranges from $65/m³ to $80/m³ while the crack repair and structure maintenance cost approximately $147/m³ (Taylor, 1986). Moreover, the durability of repaired structures remains a significant problem after 5 years, 20% of these facilities would fail, climbing to 55% after 10 years (Tilly and Jacobs, 2007). The main method of repairing cracks in practical projects at presents is to fill the visible cracks with cement mortar or asphalt materials. It still faces two problems: (i) the performance of the structure can only recover to the level of the original structure at most, therefore, the cracks will arise again provided that the external environment and load remain unchanged; and (ii) only the visible cracks on the surface can be repaired, whereas the inner and micro cracks abound in structures. To inhibit further stress concentration, offset a certain degree of tensile stress, and prevent further crack expansion, the crack repairs should be timely when the components are under continuous loading (Xu et al., 2022).

Asphalt and concrete are the main and likely-to-crack building materials in highway engineering. Asphalt is widely used as pavement materials because of its low tire noise, high skid-wear resistance, and renewable utilization. Concrete is used in pavements of most tunnels because mixing asphalt needs high temperature and causes noxious fumes, which are difficult to dissipate in tunnels. Also, concrete is used as the main building material in highway support structures such as tunnel linings, retaining walls, and beams. In short, asphalt and concrete account for the vast majority of all the materials used in pavement and structures in highways. Therefore, the crack-repair technology is mainly aimed at asphalt and concrete in highway engineering. Enjoying the advances in multifunctional materials, many studies have focused on how to prevent the cracking of building materials such as asphalt.
and concrete under the complex effects of force, temperature and water penetration (Cui et al., 2021; Cui and Wang, 2021). The conventional approach is to embed some reinforcing components like fibers or a certain number of compounds in concrete or asphalt to improve the ability of materials to prevent cracking (Cui et al., 2020a, b). Another method is called self-healing, which means incorporating some healing agents into building materials so that the materials can be healed automatically when tiny cracks appear, providing intriguing solutions to the long-term crack prevention (Li and Hao, 2022; Schreiberova et al., 2019; Tabakovic et al., 2019; Tanyildizi et al., 2022; Wan et al., 2022). Among these self-healing techniques, encapsulating rejuvenating agents into building materials is regarded as a refreshing method (Bekas et al., 2016; Blaiszik et al., 2010; Liu et al., 2021; Mauldin and Kessler, 2010; Zhu et al., 2015). The microcapsules can be distributed throughout the asphalt or concrete (Xu et al., 2018a, b), and keep the healing agents inside. The microcapsules will break and release the rejuvenator when cracks approach them (Ilyaei et al., 2021).

However, most of the studies on microcapsule-based materials only involved lab-scale tests instead of practical applications. There have been enough review research summarizing the healing enhancement by adding micro-encapsulated healing agent into asphalt, and most of them are concentrated on laboratory environment. Because of the situation of current review research, instead of the laboratory studies, this review pays more attention to the practical applications, the meaning of healing performance, and microcapsules’ adverse effects to the main structural components (i.e., tunnel lining, bridge piers and beams) and pavement in highways. The highlighted part is a new perspective as a refreshing method of negative charge. Two positively charged calcium ions ($\text{Ca}^{2+}$) are combined with two different alginate chains at the molecular level, the self-healing process is related to links and combinations of ions. Taking calcium alginate microcapsules (CA), which use segmented alginate fibers as a carrier to wrap repair agents (Li et al., 2021), as an example, when sodium alginate dissolves in the solution, it releases sodium ions ($\text{Na}^+$), so that the alginate chain carries a unit of negative charge. Two positively charged calcium ions ($\text{Ca}^{2+}$) are combined with two different alginate chains at

2. Self-healing materials

2.1. Microcapsule-based asphalt

The fundamental self-healing mechanism of microcapsule-based materials are (i) growing cracks break capsules and (ii) rejuvenator is released into cracks to repair. More specifically, capsules containing the rejuvenating agent are embedded in building materials. When cracks arise and grow, the incorporated microcapsules near the cracks break subject to the mechanical effect of the crack-tip stress. Subsequently, the rejuvenator inside the microcapsules is released into the cracks through capillary permeation to realize automatic repairing (Kanu et al., 2019; Li et al., 2018; Zhu et al., 2013). It is highly likely that the early-stage cracks can be completely healed by the released rejuvenator, hence preventing further crack propagation and structure failure (Xu et al., 2018a, b). Fig. 2 shows the self-healing process through microcapsules. It should be noted that the self-healing process in Fig. 2 is originally for polymer coatings (Cho et al., 2009). It is used here to show the general self-healing process with the microcapsules, not specifically for asphalt or cementitious mixture.

At the molecular level, the self-healing process is related to links and combinations of ions. Taking calcium alginate microcapsules (CA), which use segmented alginate fibers as a carrier to wrap repair agents (Li et al., 2021), as an example, when sodium alginate dissolves in the solution, it releases sodium ions ($\text{Na}^+$), so that the alginate chain carries a unit of negative charge. Two positively charged calcium ions ($\text{Ca}^{2+}$) are combined with two different alginate chains at

![Fig. 2 – The self-healing process generated by microcapsules (Cho et al., 2009).](image)
the same time to cross-link and solidify the solution, thereby wrapping the repair agent in it (Gu et al., 2004; Hia et al., 2018). Fig. 3 shows the reaction between sodium alginate and calcium. Fig. 4 shows the microscopic healing process. In Fig. 4(a), the cracks in the asphalt made the capsules rupture, and the wrapped rejuvenator flowed out. The cracks were then filled by capillary action. After 30 min, the cracks were recovered (Fig. 4(b)).

The qualities of microcapsules are controlled by their preparation process and conditions. First, to meet the practical paving environment, the microcapsules need to keep stable under temperature of construction mixing and compaction. Second, the shell of microcapsules should have moderate strength. If the strength is insufficient, cracks may occur during the mixing process of the asphalt mixture, which will affect the subsequent use of the microcapsules. If the strength is too high, the crack may avoid the capsule and continue to develop, the microcapsule does not crack, the encapsulated repair agent cannot flow out in time, and the repair effect of the crack is greatly reduced (Zaremotekhases et al., 2020). In order to ensure that the above requirements of microcapsules can be met, it is necessary to control the size, shell thickness and core/shell ratio of microcapsules. In preparing the microcapsules, there are many affecting factors, mainly including the dripping acceleration, stirring speed, terminal pH and terminal reaction temperature. The specific test conditions vary depending on the type of microcapsule. Table 1 illustrates the required preparation conditions of four typical types of microcapsule: alginate microcapsules (CA), methanol-melamine-formaldehyde microcapsules (MMF), urea-formaldehyde prepolymer microcapsules (UF), and melamine-urea-formaldehyde microcapsules (MUF).

Table 2 sums up current laboratory studies on the above four typical types of microcapsules. First of all, we can see that their thermal stabilities are all qualified for asphalt mixture mixing and paving. The weight loss is not obvious or can be ignored when the temperature is lower than the limit. The capsules can withstand the temperature during construction without premature cracks. However, the stiffness modulus of asphalt mixture might decrease with a certain number of microcapsules. One possible reason for this adverse effect is that compared to the aggregate particles and bitumen, the capsule is lower in stiffness at room temperature. This effect can be magnified by the size and quantity of the capsules. We also need to be careful that the addition of microcapsules will change the quality of asphalt. For example, the ductility index is unqualified after adding excessive microcapsules in the asphalt mixture. Another adverse effect is that the healing rate of microcapsule-based asphalt is sometimes lower than the original repair rate. The reason may be that the preparation of that asphalt sample introduces some defects and reduces the ductility. In general, the self-healing effects of asphalt are improved by microcapsules in many aspects including strength, penetration, softening point, viscosity, modulus, etc. Two remarkable self-healing behaviors are (i) the self-
healing can be multiple rounds, and (ii) the fatigue life is increased dramatically.

2.2. Microcapsule-based concrete

Similar to encapsulation-based asphalt, these micro capsules used in concrete serve as rejuvenator agent through breaking the shell and releasing the healing agent when inner cracks spread to the capsules (Gilford et al., 2014; Sun et al., 2021; Xue et al., 2019). The fundamental difference between the two self-healing materials lies in the way that their healing agent acts interact with corresponding building materials. In general, capsules for cementitious composites are classified mainly according to their core materials. Many kinds of materials have been used as the core, such as catalysts, adhesives, and organic solvents. In order to achieve wide application in practical engineering, low cost and mass production are necessary. The most common core materials for microcapsule-based self-healing concrete are as follows: epoxy resin (EP), sodium silicate, toluene-diisocyanate (TDI), polyurethane (PU) and acrylic acid. The physical properties of the core material should be considered when matching with the core material. Specifically, when the lipophilic material is selected as the core, the hydrophilic material should be selected as the shell; when the water-soluble material is selected as the core, the water-insoluble synthetic polymer material should be selected as the shell. Besides, the shell material is required not to react with the core material. Common shell materials are: natural materials, semi-synthetic materials, synthetic materials, and inorganic materials, shown in Table 3. The preparation process of microcapsules for cementitious materials is similar to that of asphalt microcapsules, but neither of them has reached the level of mass-production. The most commonly used preparation method for microcapsules in the laboratory is in-situ polymerization, which can be generally divided into four steps, as shown in Fig. 5.

The concrete embedded with these different types of microcapsules has been tested to obtain the following performance: physical properties of the microcapsules, self-healing efficiency, and microstructure of the specimens. These characteristics are important for the mechanical properties of the structure. Some crucial test results for different forms of microcapsule-based materials are summarized in Table 4. The information given in the table can facilitate the selection of the capsules suitable for practical service environment. With different types of shells, the particle sizes of microcapsules are different, among which most sizes are μm-level. Smaller particles indicate that microcapsules can be distributed in cement matrix more uniformly. Researchers are not paying as much attention to the thermal stability of microcapsules used in concrete as in asphalt, because the mixing temperature of concrete is very low (5°C–35°C), hence the thermal stability of concrete-targeted microcapsules is not important. The most significant indicator, self-healing efficiency, has received an inspiring achievement. Here, the healing efficiency η is defined as follows.
### Table 3 – The common shell materials of microcapsules.

<table>
<thead>
<tr>
<th>Shell category</th>
<th>Material</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural material</td>
<td>Bone gelatin, gelatin, gum arabic, agar gel, starch, protein, ammino acid, alginate, maltose, fat, lecithin, et al.</td>
<td>Advantages: nontoxic, easy to form membrane, biocompatible, degradable, cost-effective Disadvantages: poor mechanical performance, raw material is unstable</td>
</tr>
<tr>
<td>Semi-synthetic material</td>
<td>Carboxymethyl-cellulose, methylcellulose, ethylcellulose, cellulose acetate-phthalate, nitrocellulose, et al.</td>
<td>Advantages: low toxicity, high viscosity, solubility increases after salinization Disadvantages: easy to hydrolyze, unstable with high temperature or acid, short shelf-life</td>
</tr>
<tr>
<td>Synthetic material</td>
<td>Polyamine, polyamide, polyelefin, polyether, polyester, polyurea, polyurethane, polyvinyl alcohol, epoxies, urea-formaldehyde, phenolic resin, acrylic resin, polysiloxane, et al.</td>
<td>Advantages: easy to form membrane, stable, good mechanical performance which can be customized Disadvantages: high cost, less biocompatible</td>
</tr>
<tr>
<td>Inorganic material</td>
<td>Calcium silicate, calcium sulphate, silicon dioxide, aluminium oxide, clay, et al.</td>
<td>Difficult to form membrane</td>
</tr>
</tbody>
</table>

### Table 4 – Characteristics of typical forms of microcapsules from laboratory tests (Beglarigale et al., 2018; Dong et al., 2013; Du et al., 2019, 2020; Lyu et al., 2020; Mostavi et al., 2015; Sidiq et al., 2019, 2020; Wang et al., 2013, 2019; Xue et al., 2019).

<table>
<thead>
<tr>
<th>Core category</th>
<th>Size</th>
<th>Thermal stability</th>
<th>Self-healing efficiency</th>
<th>Negative impacts on strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP</td>
<td>Normal distribution with a mean diameter of about 160 μm</td>
<td>Stable below 250 °C</td>
<td>Compressive strength: 25% on 28 d (with 10% microcapsules)</td>
<td>20% (with 10% microcapsules)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Impermeability: 24% on 28 d (with 10% microcapsules)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Impermeability: over 20% on 3 d (with 6% microcapsules)</td>
<td></td>
</tr>
<tr>
<td>TDI</td>
<td>30–300 μm (600 rpm); 6–80 μm (1000 rpm)</td>
<td>Stable at 120 °C</td>
<td>Compressive strength: about 30% on 28 d (with 3.0%–4.5% microcapsules)</td>
<td>7.5% (with 4.5% microcapsules)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Crack healing (width less than 0.4 mm): fully reserved after 6 h</td>
<td>22.5% (with 6% microcapsules)</td>
</tr>
<tr>
<td>Sodium silicate</td>
<td>With a large range of 80–800 μm</td>
<td>10% mass loss at 80 °C</td>
<td>Compressive strength: about 30% on 7 d, and 50% on 56 d (with 2.5%–5.0% microcapsules)</td>
<td>20% (with 5% microcapsules)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Stiffness: over 15% on 7 d, and 30% on 56 d (with 2.5%–5.0% microcapsules)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Porosity: about 50% on 14 d, and 80% on 56 d (with 2.5%–5.0% microcapsules)</td>
<td></td>
</tr>
<tr>
<td>PU</td>
<td>–</td>
<td>–</td>
<td>Flexural strength: 15%</td>
<td>–</td>
</tr>
<tr>
<td>Acrylic acid</td>
<td>–</td>
<td>–</td>
<td>Flexural strength: 21.3%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Impermeability: 83.33%</td>
<td></td>
</tr>
</tbody>
</table>
where \( \alpha_{\text{healed}} \) and \( \alpha_{\text{healed}} \) are test indicators for the healed specimen, \( \alpha_{\text{cracked}} \) and \( \beta_{\text{cracked}} \) are test indicators for the cracked specimen, and \( \alpha_{\text{initial}} \) and \( \beta_{\text{initial}} \) are the same indicators for the original specimen. Regarding failure and durability of materials, \( \alpha \) is usually selected as compressive strength, flexural strength or stiffness, while \( \beta \) is chloride diffusion coefficient or porosity.

The efficiency (calculated by the equation) of more than 20% has been obtained, and sometimes the efficiency can be up to 50% (Jin et al., 2012; Kirkby et al., 2009; Kosarli et al., 2021; Nji and Li, 2010). The healing covers multiple aspects of performance, such as compressive strength and stiffness. In addition, the impermeability is particularly recovered well. Hence, the new material can probably be used in karst, underwater, and submarine environment, where erosion or penetration is rather serious. The cracking-induced damage has been completely cured in many tests. It is worth noting that the efficiency is time-dependent. It will increase significantly over time within 50 d and then keep stable.

Besides these advantages, the phenomenon that the incorporation of microcapsules could cause a negative impact on the mechanical strength of concrete was reported in many studies. Since the concrete is generally used in the support structure, the strength indicators such as compressive and flexural strength is of valuable significance to facility health (Fang et al., 2020; Wen et al., 2020; Zhou et al., 2019). By contrast, the asphalt, only used in pavements, is not as strength-dependent as concrete. To address the problem of strength reduction, some special supplements have been developed which can compensate for the adverse effects induced by the microcapsules if adding them into the raw mixture of concrete. Also, the amount of the microcapsules needs to be balanced to avoid the extreme reduction of mechanical properties.

### 3. Full-scale applications

#### 3.1. Microcapsule-based asphalt

The microcapsule-based self-healing technology for asphalt has been successfully applied in Fenghai Road, Shanghai, China in November 2016 (Tongji University, 2016). The particle size of the capsules is about 100 \( \mu \)m (Fig. 6). This application is an important practice of self-healing technology of microcapsule asphalt. It is a large-scale practice with a test area of hundreds of square meters. The life-time of road and the influence of microcapsules on the mechanical performance of pavements need further observations. In addition, another example, the long-life self-healing test roads in Tianjin and Handan which employed microcapsule-based asphalt have proved effective in January 2017. Both test roads are 50 m in length. The average particle size of the microcapsules is 50–100 \( \mu \)m, and the density is 0.2–0.3 g/cm\(^3\). The data of road morphology image, road cracks, average temperature, precipitation and volume of traffic were collected to measure the aging extent of the asphalt specimens sampled from pavements, and to observe the microform of encapsulation-based asphalt. It was found that when the volume ratio of microcapsules is 0.05–0.10, the healing effect is considerable; the life-time of asphalt pavements can be extended by 60%–70% by this new form of self-healing technique. This healing effect was obtained according to the 24-month observations and monitoring, and the data was collected once a month. However, these detailed data and results are not disclosed yet.

#### 3.2. Microcapsule-based concrete

The self-healing concrete has been applied in Qianhai Tunnel, a smart tunnel in Shenzhen, China, as shown in Fig. 7 (Wang et al., 2019). Concrete was used as the main material in the tunnel. It is constructed near the Lingdingyang Estuary where the moist atmosphere could considerably heighten the probability of ingress of corrosive ions, which would
aggravate the material cracking. Hence the epoxy resin (EP) self-healing concrete was applied in this project. The urea-formaldehyde resin was used as the shell and epoxy resin E-51 as the healing agent. The curing agent MC120D, used for the reaction with the healing agent (epoxy resin E-51), was obtained from Guangzhou Kawai Electronic Materials Ltd. Company (Guangzhou, China). 10% microcapsules and 5% curing agent by weight of the total binders was added in the self-healing materials. Prior to casting the concrete, the microcapsules, curing agent, and fresh concrete were equably mixed by continuous mechanical stirring. The following five aspects of the capsule-based self-healing materials were studied in advance in the laboratory: (i) physical properties of the microcapsules, (ii) concrete cube compressive strength, (iii) chloride migration coefficient, (iv) long-term shrinkage, and (v) microstructure of the specimens. The tests show that the microcapsule-based technique substantially boosted the automatic healing behavior of the materials after cracking. In addition, the impermeability of concrete was also markedly improved. However, about 20%–30% reduction of the compressive strength was observed which was caused by the addition of these microcapsules because they changed the microstructure of the original material. For concrete structures, which are mainly used to bear pressure, this reduction seems to be fatal, but it is actually permitted in actual projects. Some supplements like steel fibers can be added to compensate. Based on the results, the self-healing concrete was then used as the support material in the tunnel. Through strain monitoring and experimental observations, the behavior of the structural elements (concrete slabs) precast by using EP microcapsule concrete was studied.

The microcapsules do not influence the strain performance of concrete in practical engineering. The A group (measurement points P1, P2, P3) contained no microcapsules, while B group (measurement points P4, P5, P6) contained 10% microcapsules. It can be found in Fig. 8 that except for the sensors destroyed due to the in-situ disturbance and P1 of which the horizontal strain was extremely low, the two groups showed similar quantity and development trends of strain. All the points showed relatively low shrinkage strain and it was within –350–100 με. There were not significant changes, therefore, the change of local structure quality was consistent with the normal state. The result shows that the self-healing concrete will not impair the mechanical performance of original structures. Further monitoring indicated that the surface properties of the concrete between the two groups were not significantly different. There was no obvious healing action in the surfaces with the addition of microcapsules during the four-month observations (Fig. 9). The laboratory tests had proved that the microcapsules indeed have significant healing effects on cracked concrete (Hager et al., 2016; Kahar et al., 2021; Qi et al., 2011; Szmechtyk et al., 2018; Wang et al., 2010). Evaluating the self-healing materials cannot only rely on the surface characteristics, because the crack healing inside the structure, which is the core of structure performance, will not be reflected transparently.

Another developed self-healing system has been implemented in a concrete retaining wall, which is the first successful attempt to employ microcapsule-based self-healing concrete on site in the UK (Al-Tabbaa et al., 2019). This on-site research was conducted from October 2015 to May
2016. A retaining wall panel (1.8 m tall, 1 m wide and 150 mm thick) was cast using concrete encapsulated with sodium silicate, and for comparison purposes, a control panel without microcapsules was together set. The uniqueness of the in-situ research is reflected in the full-scale application of the self-healing system compared with some local applications. In this study, the self-healing indicators consist of air permeability, crack depth and microscopic crack width. The walls were loaded on purpose to generate cracks after 35 d curing and then reloaded, after which, the walls were continuously monitored to attain their healing behavior for six months.

Different monitoring methods were implemented: digital image correlation (DIC) technique was used to measure wall displacements and corresponding strains; air permeability were measured at different points on the surface of the walls using a field permeability tester; linear variable differential transformers (LVDTs) were employed to monitor lateral wall displacements; demountable mechanical strain gauge (DEMEC) pips were installed near the LVDTs to measure crack opening; a handheld digital microscope was used to record the micro images along the crack length spanning the panel width. The field situation and measurement arrangement are shown in Fig. 10.
The results showed that although the addition of capsules (8% by volume) was found to cause a slight negative impact on the mechanical strength, the self-healing wall showed higher healing rate in permeability and crack size, validating the full-scale practicability of the self-healing technique encapsulating sodium silicate. Specifically, the permeability received a significant recovery that the permeability coefficient decreased by 50% with six-month healing after cracking (Fig. 11(a)). From Fig. 11(b) and (c), the crack was quickly cured in the microcapsule concrete compared with control panel, but higher air temperature caused a negative effect on crack healing. In overall, with the addition of microcapsules, the mechanical performance of structure materials was transparently improved. A 25% recovery of the concrete strength was also attained in their study. While the microcapsule concrete has proved able to resist complex pressure, the difference in healing effects between in-situ applications and laboratory-scale tests deserves further studies.

4. Discussions

4.1. Strength reduce

The asphalt is always used for pavements instead of structures, so 10% strength/modulus reduce is unobvious. In addition, the pavements are under vehicle load which is dynamic and different from the static load condition in most tests. Hence the current laboratory research might improperly estimate the strength loss caused by microcapsules. Many studies show that cement and concrete are sensitive to strain rate. Their strength and deformation characteristics will change greatly with strain rate (Chen et al., 2013). Bischoff and Perry (1991) have summarized the relationship between compressive strength and strain rate of concrete under different strain rates. The dynamic compressive strength of concrete increases with strain rates, and the increase degree is significant when the strain rate reaches a certain threshold. This result has been validated in many studies (Caverzan et al., 2016; Donze et al., 1999; Ye et al., 2019; Zhou and Hao, 2008). For microcapsule composites used in pavements or other components under dynamic load, it is more reasonable to incorporate strain rates in variables when evaluating its strength, so as to simulate the vehicle load on the road (Chowdhury et al., 2015).

The strength comes to the first when evaluating the materials used in structures (Dong et al., 2013). That indicates the strength weaken induced by the adding of microcapsules may be unacceptable. The concrete used in bridge structures and tunnel lining is usually C30 of which the compressive strength is 30 MPa. As shown in Table 4, the encapsulation will bring roughly 20% strength reduce (related to the
content of microcapsules), which means the loss can be up to 6 MPa when using the C30 concrete. In practical applications, compared with the microcapsule composites, steel fiber reinforced concrete is more often used for structures, which improves various kinds of material strength. Strength is regarded as more important than crack self-repair in structural components.

However, it is worth considering that if the reduction of material strength caused by microcapsules is really fatal to all structures. At least for tunnels, the answer is probably negative. Fig. 12 shows the typical stress-strain characteristics of surrounding rock, as well as stress-time characteristics. After tunnel excavation, the elastic energy of surrounding rock will be released instantly and strain $\varepsilon_1$ will be produced. Set concrete lining at this time ($t_1$). The early strength of shotcrete widely used in mountain tunnel construction is low. Assume that $t_2$ is the time when the material reaches the design strength. At this time ($t_2$), the strain of surrounding rock is $\varepsilon_2$. If $\varepsilon_2$ is within the elastic range, the concrete is relatively safe after reaching the design strength because the tunnel lining often adopts a large safety factor (generally more than 2). The strength of the structure is completely enough to resist the load of surrounding rock, even though microcapsules decrease the ultimate strength slightly. Obviously, for certain geological and engineering conditions, $\varepsilon_2$ is related to the duration ($t_2 - t_1$): the earlier the concrete reaches the design strength, the smaller the corresponding surrounding rock strain. On the other hand, $\varepsilon_2$ is also related to the stiffness of concrete during hardening (from $t_1$ to $t_2$). If the lining stiffness is not enough to restrict the deformation, the surrounding rock will be deformed rapidly and become elastoplastic or even plastic.

In addition, in the process of concrete hardening, if the material strength is not enough to resist the stress caused by deformation, the lining will be directly damaged. According to the above analysis, the decisive factors for tunnel structural safety are the strength, stiffness characteristics and duration of concrete hardening stage. The addition of microcapsules only reduces the ultimate strength of the material after complete hardening, and hardly affects the hardening characteristics of the material (strength, stiffness and hardening time in hardening period). In conclusion, because the structural design safety factor of tunnels is large, and microcapsules do not affect the material hardening characteristics, the strength reduction caused by microcapsules is acceptable in tunnel linings.

It is still worth mentioning that microcapsules improve the tensile strength of concrete. Its different effects on tensile and compressive strength can be explained from the micro perspective of material properties. According to Section 2.2, the common particle size of microcapsules is 200–400 μm (Blaiszik et al., 2009; Celestine et al., 2015; Wang et al., 2014a). Based on the classification of pores in building materials (Wang et al., 2018), the sizes of microcapsules belong to harmful pores, which have a negative effect on the compressive strength of concrete. Although the compressive...
strength of microcapsule is smaller than that of cement-based material and cannot bear higher load, its tensile flexibility is stronger (Wang et al., 2017). Concrete is recognized as a brittle material. When microcapsules are uniformly added into concrete, its overall fracture toughness of concrete is improved, which enhances the resistance to fatigue crack propagation. This improvement can decrease crack growth rates and increased cyclic stress intensity for the onset of unstable fatigue-crack growth. In some cases, tensile strength and flexural strength might be smaller with microcapsules depending on their bond strength with the matrix.

The strength reduction caused by microcapsules is possible to solve. As the result in Section 2, the self-healing ability and strength can be balanced to avoid some extreme situation, which can be achieved by adjusting the microcapsule content and particle size (Milla et al., 2017; Rule et al., 2007; Wang et al., 2021). The diameter of microcapsules as small as 300 nm has been realized through sonication and stabilization procedures (Blaiszik et al., 2009). The microcapsules will even increase compressive strength of materials sometimes. This is because these building materials are with different mixture particle sizes and there exist pores which can be filled by a suitable content of microcapsules. Since the strength of the structure is still regarded as very important, the microcapsule content can be adjusted to maintain the strength reduction rate at about 10%, which is acceptable for most structures (Jiang et al., 2021). Moreover, the loss of strength can be compensated by other methods, such as adding steel fibers (Ferrara, 2019; HasaniNasab et al., 2019), memory alloy or directly using high-strength concrete if budget allows (Arce et al., 2019; Bonilla et al., 2018; Bundur et al., 2017; Davies et al., 2021; Shirzad et al., 2019; Wang et al., 2014b; Xia et al., 2021). An example is the multi-responsive composite fiber proposed for bitumen self-healing, which combined the advantages of two methods namely electromagnetic/microwave heating and microcapsules (Shu et al., 2019).

### 4.2 Durability improvement

Durability is related to the service life of roads. The longer design life requires higher durability. According to the policies of different countries in the world, the service life of asphalt pavements is 10–20 years, the service life of concrete pavements is about 30 years, and the service life of main structure is generally 50 years. These regulations imply three meanings. (1) The durability requirement of the main structure is higher, due to the higher risk after its damage. (2) The pavements are more prone to cracks and gradually damage. (3) The durability of asphalt is lower than that of concrete. Compared with the main structures such as tunnel lining and piers, the renovation of pavements is frequent (Hager et al., 2016). According to the test results, there is no doubt that the durability of microcapsule self-healing composites will be significantly improved (Bao et al., 2019). Therefore, it seems that microcapsules should be added to pavement materials, especially asphalt. Microcapsule-based self-healing asphalt has received more achievement on life-time increase. The remarkable improvement of life-time by microcapsules has been observed in a laboratory test (Sun et al., 2018a) and practical application in Section 3.1. In addition, multiple-round healing was realized in (Su et al., 2016), which also enhances the fatigue life of pavements. On the contrary, there is not a focus on the life-time increase of cement concrete. Even so, the life of concrete has also been improved theoretically. This is because this self-healing technique markedly improves the impermeability of concrete. For highway operational environment, the concrete is sometimes subject to hydraulic erosion, for example, bridge piers. Chloride migration influences its lifetime. Therefore, the durability of concrete is also improved by microcapsules theoretically.

However, in practice, the life-extension effect in practical applications of this technology is still unclear. The tests in Sections 2 and 3 are usually observed without loads or under static loads after the sample is damaged, but in real condition, the pavement or structure will continue to bear the load after the crack occurs, and the stress concentration will occur at the crack. By current test process, it is difficult to estimate the self-repair ability and life improvement of materials. An example is the tunnel case in Section 3.2, where the crack healing effects of the concrete slabs are similar, no matter if microcapsules are added. Thus, the repair effect of microcapsules may be very limited when the structure is continuously under load. In highway engineering, the pavement and bridge beams will continue to be subjected to vehicle dynamic load, and the tunnel lining will also continue to be subjected to large surrounding rock pressure. In order to test the actual healing effect of microcapsule composites in laboratory, it is necessary to apply the corresponding simulated loads after the sample is cracked. With these loads, the crack may not be completely self-repaired, and its healing effect will certainly be affected. Different from current healing-effect evaluation focusing on strength, stiffness, and permeability coefficient of materials, a practical evaluation method is to test the contribution of microcapsules to material durability under real loads. The process is: (1) preparing the samples with/without microcapsules; (2) defining the damage; (3) loading on the samples and start timing; (4) stop timing when the sample damages; and (5) comparing the test time of the samples with/without microcapsules, thereafter obtaining the improvement of material durability by microcapsules. It should be noted that damage does not mean that cracks begin to appear, but that the materials have failed to meet the requirements of project operation. The material may be still capable of service with cracks.

### 4.3 The effect on stress redistribution

The redistribution of stress would happen when the load, geometry or mechanical properties of structure change. For the structure under load, the crack will affect the internal stress distribution and produce stress concentration in the crack area. The effect of cracking and recovery on stress redistribution has been analyzed in one of our previous studies (Xu et al., 2022). Taking tunnel engineering as an example, a local numerical model of crack area is established. The small-scale lining structure is selected from...
the whole structure, and the boundary conditions of stress and displacement are set. The process from intact structure to cracking and then to repair is analyzed. During this period, the stratum stress keeps released. The stress variation near the crack with/without repair were compared. As a simple model, its result is also applicable to other types of facilities like bridges and buildings. Non-repair simulation has four stages: (1) intact state (stress release to 70%), (2) cracking, (3) stress release to 85%, and (4) stress release to 100%. The repair simulation has five stages: (1) intact state (stress release to 70%), (2) cracking, (3) crack filling, (4) stress release to 85%, and (5) stress release to 100%. The development of the maximum and minimum vertical stress in the crack area with stages is drawn in Fig. 13. During the whole process, the stress redistribution is consistently in progress because the rock pressure release is long-term. The crack initiation and healing would both influence the redistribution process.

The stress is distributed evenly and only compressive stress can be observed in the intact lining block in vertical direction. Cracking brings an obvious stress concentration around the crack. The vertical tensile stress appears at the upper and lower edges of the crack, and the compressive stress inside the crack increases heavily, most of which reaches more than 400 kPa, and 600 kPa locally. After the crack repair, the stress distribution does not receive a positive response, because at stage 2, the structure has reached a new balance with the crack. The crack filling will not recover the cracking-induced deformation. After stage 3, the ground stress is still being released. With stress release, the stress around the crack is different under the two conditions. When the crack is cured, the tensile stress is eliminated with stress release. Since tensile strength of concrete is only 1/10 of the compressive strength, it is the main cause of cracks and crack propagation. Continuous stress release does not cause further stress concentration around the crack. Therefore, when the cracked components are subject to changing loads, for example, the pavements and bridge beams, in-time repair is important to alleviate further stress concentration and crack propagation.

4.4. Economic perspective

The economic necessity of microcapsule-based self-healing is not proved yet. Even though the microcapsule-based self-healing technique can decrease the long-term maintenance expenditures, its initial construction investment is undoubtedly higher than that of normal materials. Considering the time value of money, the opportunity cost of microcapsule-based materials is not necessarily lower. In addition, higher initial construction investment is not conducive to competitive bidding. At present, the highway investor and the constructor are mainly separated. When a microcapsule-based technique is not obligated (this is the usual situation at present), the constructor needs to use normal materials to keep a lower quoted price to win the bid. After winning the bid, because the maintenance expenditures are usually paid by the investor, the constructor is not encouraged to use this self-healing technology. On the other hand, if a microcapsule-based technique is obligated in the construction contract, it would be risky for the investor because this new technique would increase the initial construction costs while it is hard to predict the later maintenance expenditures of microcapsule-based components. To this end, we suggest to try new investment modes. For instance, the constructor can be responsible for the maintenance, so as to encourage the constructor to try this self-healing technique, and control its on-site construction quality to assure the self-healing effects.

5. Conclusions and future research prospects

5.1. Conclusions

Self-healing is a new idea to prevent cracks, which has been realized through the encapsulation. This paper discussed...
microcapsule-based self-healing asphalt and concrete used in highway projects. The main conclusions are as follows.

1. Laboratory studies confirmed the feasibility of microcapsule-based self-healing system. The cracking-induced damage can be recovered automatically, which covers different aspects of properties: mechanical strength, impermeability, and stiffness. With the microcapsules, the improvement of healing rate is more than 20%.

2. The microcapsule-based self-healing technology cuts both ways. To take advantage of the self-healing technique and lighten the adverse influence of the microcapsules, it is necessary to make the amount and particle size of the microcapsules reasonable, indicating that a balance should be struck between the healing rate and mechanical strength.

3. Microcapsule-based self-healing asphalt and concrete have been applied successfully. The life-time of asphalt pavements is supposed to be extended by 60%–70%. The self-healing concrete was used as tunnel linings and retaining walls, where the permeability and crack depth received significant recoveries.

4. Both positive and negative effects of microcapsule-based concrete and asphalt should be considered in specific application scenarios. In highway engineering, the time-independent compressive strength reduction caused by the addition of microcapsules is acceptable in tunnel lining: The increase of durability should be taken into account. The self-healing is important to deter structures from gradually long-term stress redistribution.

5.2 Knowledge gap and future research opportunities

The knowledge gap in research of microcapsules exists in theory, laboratory test, and on-site construction, which also shows the future research opportunities.

1. In theory aspect, the strength of capsules needs further research. It should be accurately calculated to avoid capsule breaking during mixing and paving, but allow capsules to break when inner cracks are initiated. The range of appropriate strength can be studied. Another more complex problem is that the capsule strength, i.e. the shell thickness and size should be different when incorporated into building materials. Different strengths is the key to the self-healing ability for numerous times. The capsules with different shell thickness and size are supposed to be broken in different healing rounds. It is still unknown that how to determine the distribution of capsule strength to achieve higher healing rate. The capsule size and shell thickness need to be determined comprehensively since they will influence other indicators of materials.

2. In laboratory research aspect, a standard test process and evaluation system are still lacking. Both in the process of damage and healing, the materials should be under the experimental conditions corresponding to their real service environment. For instance, all materials and structures do need to heal under continuous loading, because the cracked components are still under various loads like vehicles, self-weight, and soil pressure during healing. The mechanical and permeability tests are currently used as fundamental methods to study the self-healing performance of the microcapsule-based materials. Standard indicators and evaluation criteria are still required, which can help to assess and then select an appropriate form of self-healing concrete or asphalt for practical applications in an efficient and reliable way.

3. In on-site construction aspect, many aspects should be improved to enable the wider use of microcapsules in pavements. Proper construction should prevent or decrease the capsule damages, considering compaction could rupture microcapsules, especially in soft matrices at high temperatures. The incorporation of microcapsules could need to change the aggregate gradation, especially at mastic level. In addition, the shape of aggregates could affect the interlock and thus the activation sensitivity of microcapsules etc. To assure the self-healing effects of microcapsule-incorporated materials, an on-site construction standard is required. Finally, non-destructive monitoring for structures can help to provide a clear display of self-healing effects. A systematic and convenient monitoring method is needed. People’s confidence in using this new technique will be greatly improved if the healing effects can be well detected and described.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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