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RESEARCH ARTICLE

Microcapsule-enabled self-healing concrete: A bibliometric analysis

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ABSTRACT With the development of self-healing technology, the overall properties of the microcapsule-enabled self-healing concrete have taken a giant leap. In this research, a detailed assessment of current research on the microcapsule-enabled self-healing concrete is conducted, together with bibliometric analysis. In the bibliometric analysis, various indicators are considered. The current state of progress regarding self-healing concrete is assessed, and an analysis of the temporal distribution of documents, organizations and countries of literature is conducted. Later, a discussion of the citations is analyzed. The research summarizes the improvements of microcapsule-enabled self-healing cementitious composites and provides a concise background overview.

KEYWORDS microcapsule, self-healing concrete, bibliographic analysis

1 Introduction

Large underground shopping centers, tunnels under rivers, subway systems, and other constructions have a 100-year designed service life. It is necessary to develop sustainable concrete that will assist in extending the service life of concrete structures and make concrete more resilient and repairable. Self-healing cementitious materials have drawn the attention of an increasing number of academics recently. Concrete has a natural ability to cure itself [1]. However, once concrete starts to crack, it may take some time for the cracks to close due to such autogenous healing. In addition, auto-healing is restricted to tiny cracks and only works when there is water, making it challenging to predict behavior.

Figure 1 represents self-healing concrete that can spontaneously heal cracks. By means of healing agents added into the concrete mixture, such as fibers or capsules, self-healing concrete imitates how animal bodily wounds heal naturally [2–4]. When fibers or capsules break as a result of cracks, the healing agent inside spreads to fill the holes. Concrete's low tensile strength makes cracks impossible to avoid [5,6]. The concrete is less durable as a result of these fissures [1]. Microcracks in the concrete can cause damage, and gases and liquids that seep into the concrete can corrode the internal steel bars [7]. Because of this, it is crucial to address fractures early in order to stop their propagation. The sustainability, environmental friendliness, and service life of concrete structures can all be improved by self-repairing of fractures.

Several concrete self-healing techniques have been put forward by international experts [1,3,5,7]. They may consist of capsule-based self-healing techniques [8–12], glass tube-based self-healing techniques [13], electrochemical deposition self-healing techniques [14–20], microbial self-healing techniques [21], or shape memory alloy-based techniques [22]. As a specific example, Mihashi et al. [23] used urea-formaldehyde microcapsules and gelatin microcapsules. Another technique is to use an air-hardening curing ingredient that is distributed through glass pipes [13]. A healing agent is provided through the pipe, which is exposed to the atmosphere at one end. Further chemicals can be injected through the open end to patch up significant cracks. In addition, the impact of electrochemical deposition on various concrete

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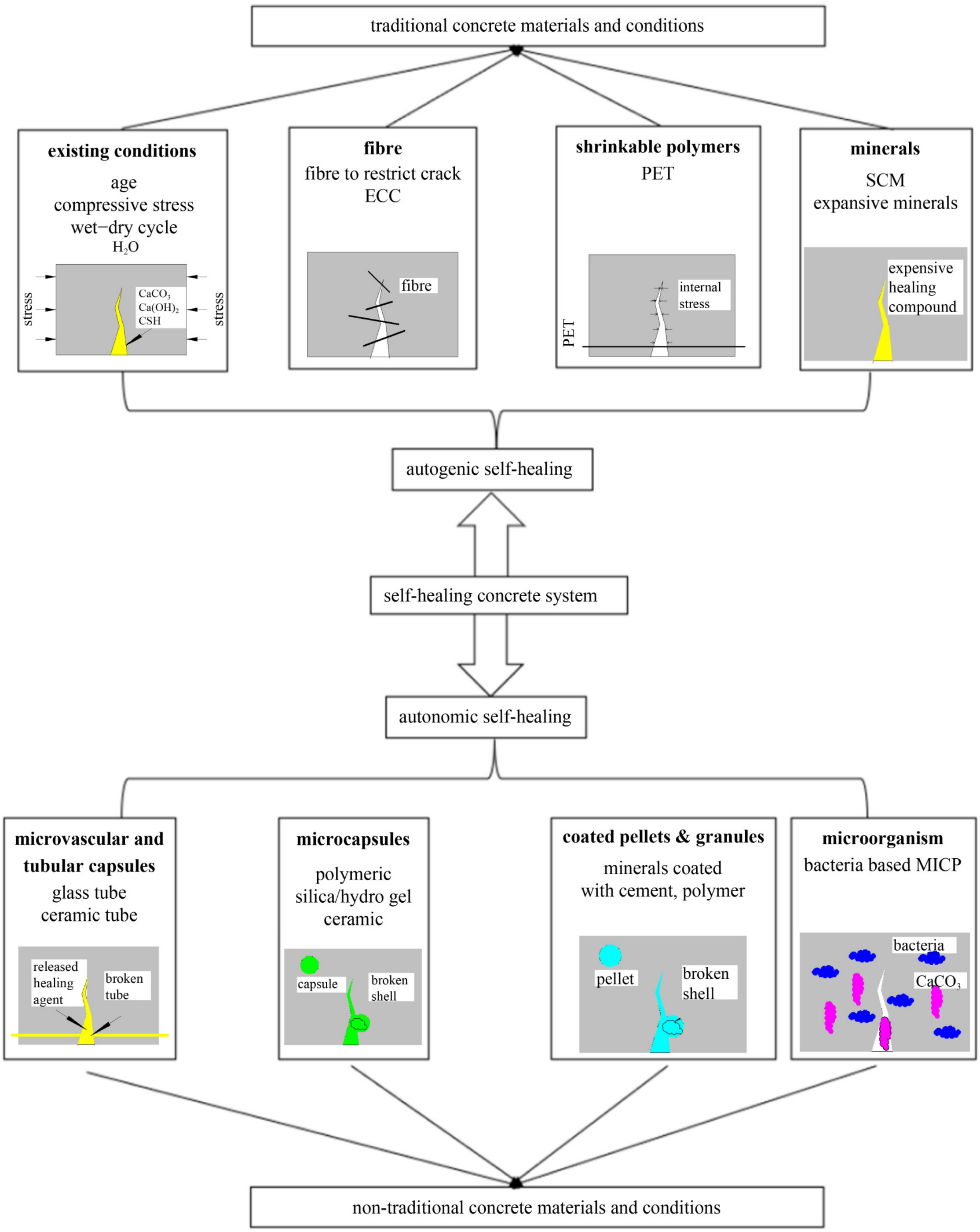

Fig. 1 Self-healing concrete system.

properties has been studied [14]. Whether bacteria can work as self-healing agents in concrete has also been investigated, whereby bacterial spores can be used as healing agents [21]. It has been claimed that self-repairing concrete using highly elastic shape memory alloy as reinforcement can assist in sealing gaps and in repairing emergency damage [22].

Based on published papers, the field of library and information science, known as bibliometrics, can describe, assess, and forecast the current state and future course of science and technology. Bibliometric analysis can systematically examine the progress of research on self-healing concrete, based on papers published in the Web of Science (WoS) Database. It can visualize the abstract literature data by creating relevant literature knowledge maps, and can use bibliometrics and applied statistical methods to examine the citations of pertinent papers to fully comprehend the research trend.

This study analyzed the self-healing concrete's mechanism, influencing variables, and evaluation. The self-healing concrete is the basis of a multidisciplinary topic combining civil engineering, mechanics, chemistry, microbiology, material science, etc. For scholars and others to comprehend the possible applications of microencapsulated self-healing concrete, this study outlines the research development process and can serve as a reference for future research.

2 Data and methodology

2.1 Data sources

The WoS offers statistics on, among other things, the number of publications per year and the nations where papers have been published. In Section 3, the search term “self-healing concrete” is used, for the period from 1995 to 2022, and 1718 valid papers are accessed. The data analysis in Section 3 illustrates that microcapsule self-healing concrete is a research hotspot within the wider field of the self-healing concrete. In Section 4, the search term is “self-healing concrete + microcapsules”, and 213 effective papers are assessed, from the period 1995 to 2022.

2.2 Bibliometric method

Globally, the amount of data are growing rapidly along with information technology. Big Data analysis is used in a variety of disciplines to assess the limits of current research. A tool for evaluating published literature that is based on quantitative and statistical techniques is called a literature analysis. Bibliometric investigations can identify self-healing concrete’s essential characteristics, using temporal analysis based on the WoS.

Using data available from the database and the VOSviewer software, bibliometric mapping is carried out based on earlier studies [24,25]. The VOSviewer uses the database to create a map of co-occurrence terms, taking into account keywords appearing in both the titles and abstracts. The software uses a “binary counting” method to extract the terms by simply identifying those terms. When redundant and unnecessary terms are removed, only the terms related to the research are retained. The software creates maps after arranging the keywords into groups based on their links, considering a term’s relationships and frequency of occurrence.

Based on the methods of bibliometrics and applied statistics, the 1718 documents retrieved are used to establish the database of the self-healing concrete, and data from the source journals are extracted for statistical analysis. Institution analysis, country analysis, co-citation analysis of keywords, citation analysis and research frontier analysis are carried out, and the frontier hotspots and potential problems of self-healing concrete research are visually analyzed. The selection of relevant evaluation indicators is described as follows.

1) Development trend. The number of papers, to a certain extent, represents the attention and importance of a research field. By creating citation analysis reported in the WoS, the number of published papers and the frequency of citations can be obtained. Through time series distribution analysis of these data, we can infer the developmental history of self-healing concrete. From the statistics of the literature, we can analyze the main disciplines within the field of research.

2) Scientific research ability of institutions. The number of papers which are published by various institutions is also considered. The papers retrieved in the WoS can be used to identify the organization that is investigating the microcapsule-enabled self-healing concrete. By drawing the common knowledge map of the organizations, it is possible to obtain the number of papers published, the number of citations, and so on, of the research institutions in the field of the self-healing concrete, to analyze the scientific research ability of institutions.

3) Scientific research ability of nations. Documents retrieved from the WoS can be used to analyze the scientific research of nations that are investigating microcapsule-enabled self-healing concrete. By drawing the map of the common knowledge of the nations, it is possible to obtain the parameters such as the number of published papers and the number of citations in each country.

4) Research hotspots and topics. Keywords are highly condensed contents of the research, and can be used to calculate the analysis indicators of research hotspots through high-frequency co-occurrence analysis. Through the analysis of the time distribution of keywords, the frontier fields and development trends can be determined.

3 Self-healing concrete

3.1 Analysis of the temporal distribution of documents

According to the WoS Core Collection Database, there are 305813 papers about concrete and 9119 papers concerning concrete healing at the time of writing (date). There are 1718 papers about self-healing concrete, with 40578 citations. Hundreds of articles are purely numerical studies, and more than 1000 papers are entirely experimental. The specific distribution is displayed in Fig. 2.

It can be concluded that the number of publications and the frequency of citations of the self-healing concrete research increase from 1995 to 2021. There are two major stages in the research on self-healing concrete: steady growth and rapid growth. Steady growth stage (1995–2006): the number of published papers in this stage fluctuates at the beginning, and the number is low. Then it continues to increase, with small inter-annual differences. Rapid growth stage (2007–2021): the

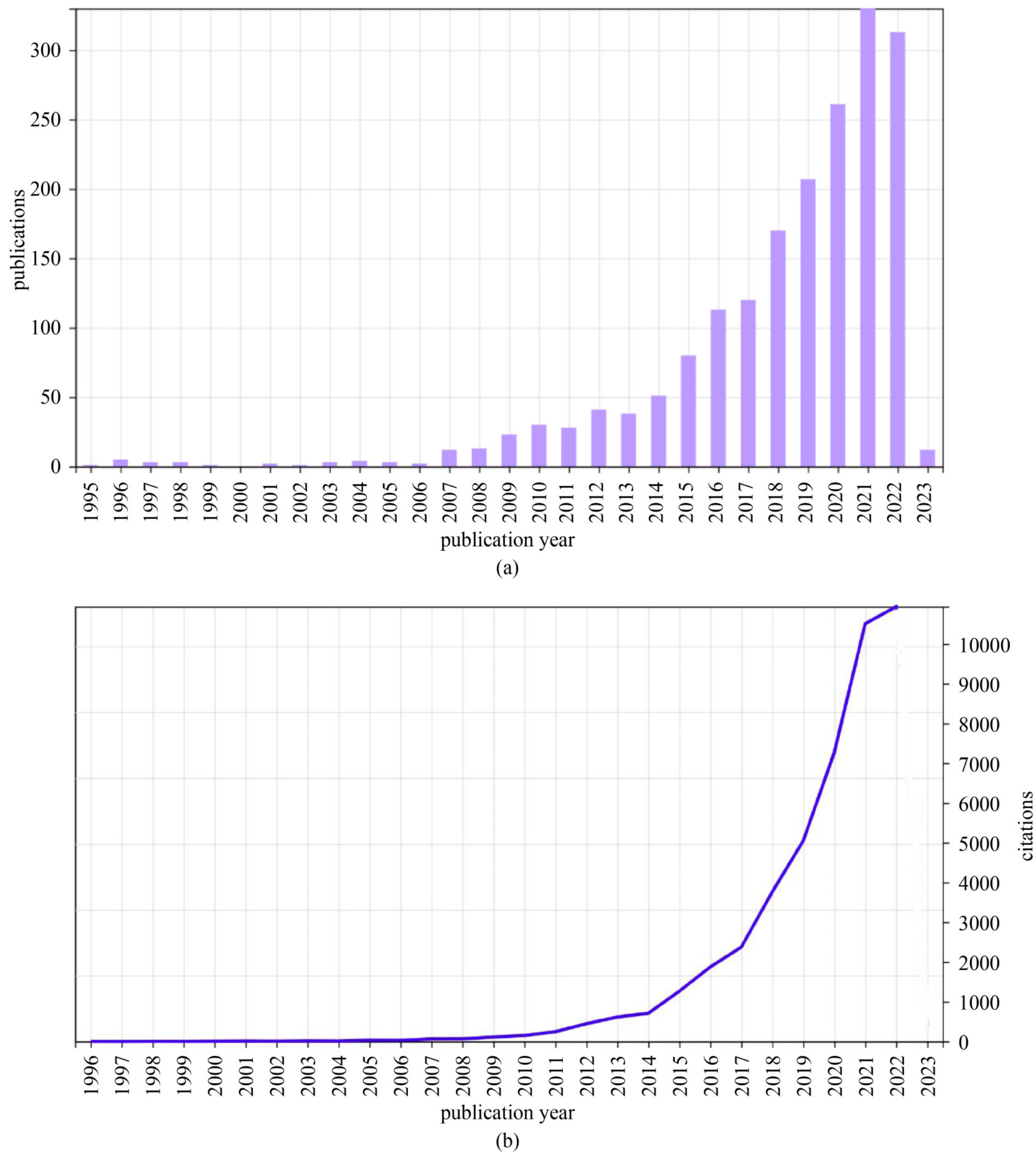

Fig. 2 Distribution of published papers and citations of the self-healing concrete: (a) number of published papers on the self-healing concrete; (b) citation frequency of the self-healing concrete research.

increase in the number of published papers in this stage is significantly higher than that in the first stage, with the separation point of the stages at 2007. The number of published papers reaches its peak in 2021, indicating that the research on the self-healing concrete has attracted more and more attention from scholars.

In Fig. 3, a statistical study of the journals which focus on self-healing concrete is presented. The vertical axis shows the number of papers published on self-healing concrete in each journal, while the horizontal axis represents various journals. *Construction and Building Materials* (CBM) ranks first, with 366 papers. Second place goes to *Materials*, with 115 papers on the self-healing concrete. *Cement and Concrete Composites* (CCC) ranks third, with 113 papers on the self-healing concrete. *Cement and Concrete Research* (CCR) ranks fourth, with 53 papers on the self-healing concrete. Fifth-placed is *Journal of Materials in Civil Engineering*, which publishes 45 papers on the self-healing concrete. *Journal of Building Engineering* ranks sixth, which has published 31 papers on the self-healing concrete. It can be concluded that numerous articles about self-healing concrete study have appeared in prestigious SCI journals.

In Fig. 4, statistical analysis of the disciplines related to the self-healing concrete is exhibited. The graph shows that the published journals with the papers on self-healing concrete mainly involve material science (56%), construction technology (49%), civil engineering (41%), composite materials (10%), applied physics (9%), physical chemistry (8%), condensed matter physics (7%), environmental science (4%), green sustainable science and technology (4%), mechanics (3%), chemistry (3%), etc. From the above analysis, the research of the self-healing concrete has been addressed by a wide range of scientists, and the research has obvious interdisciplinary characteristics.

3.2 Analysis of keywords in the literature

Analysis of keywords and snapshots of some areas, according to time series, can allow inference of the research direction, trend changes and research characteristics of the research field. Analysis of the basic information of 1718 papers and merge synonyms can produce a map of keywords, as exhibited in Fig. 5.

There are 4827 keywords in the literature, of which 20 appear more than 100 times. By analyzing the map of the keywords, one can see that concrete, self-healing, permeability, bacteria, performance, behavior, cracks, strength, durability, cementitious materials, hydration, fly ash, mechanical properties, and microcapsules have high frequency, it can be seen that that these keywords appear frequently and represent the research focus of the self-healing concrete. Specifically, the keywords bacteria, permeability, performance, behavior, cracks, strength, durability, hydration, mechanical properties, compressive strength, fly ash and microcapsules appear 277, 274, 249, 239, 211, 197, 191, 146, 145, 143, 131, and 106 times, respectively. From the keywords, it can be seen that the two main research methods regarding self-healing concrete are microbial self-healing concrete and the microcapsule self-healing concrete. At present, permeability, mechanical properties, and durability are the key criteria used to assess self-healing concrete.

Based on the network maps of literature keywords, the literature is clustered and analyzed. The clustering results are displayed in Fig. 6.

Five clusters can be seen in Fig. 6. These five study categories can be used to group together studies on self-healing concrete: self-healing concrete using mineral additions, microcapsule self-healing, microbial self-healing, autogenic self-healing and theoretical models on the self-healing concrete.

The results of analysis of keyword emergence are shown in Fig. 7. The keywords with high intensity are emerging hot topics in this research field. Further analysis shows that the words with the highest emergent strength are mechanical properties, calcium carbonate deposition, and repairing agents, indicating that from 2017 to 2022, the research on self-healing concrete has been largely about the microcapsule self-healing method and the microbial self-healing method.

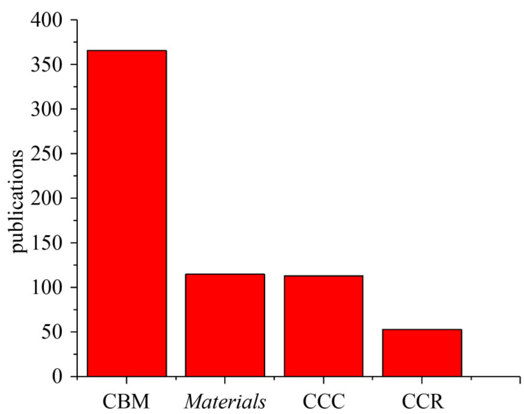

Fig. 3 Papers about self-healing concrete that have been published in different journals.

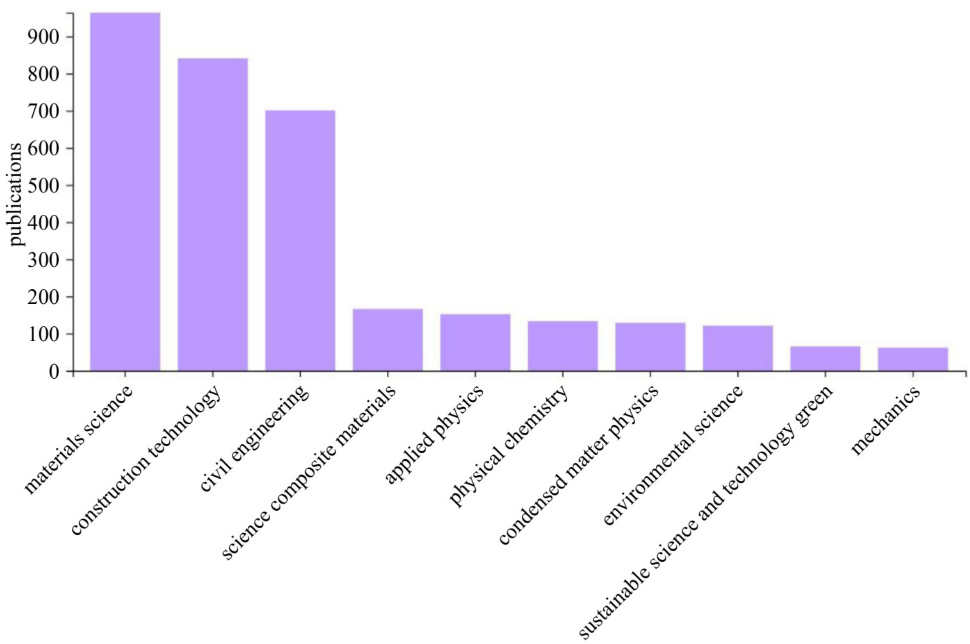

Fig. 4 Discipline related to self-healing concrete.

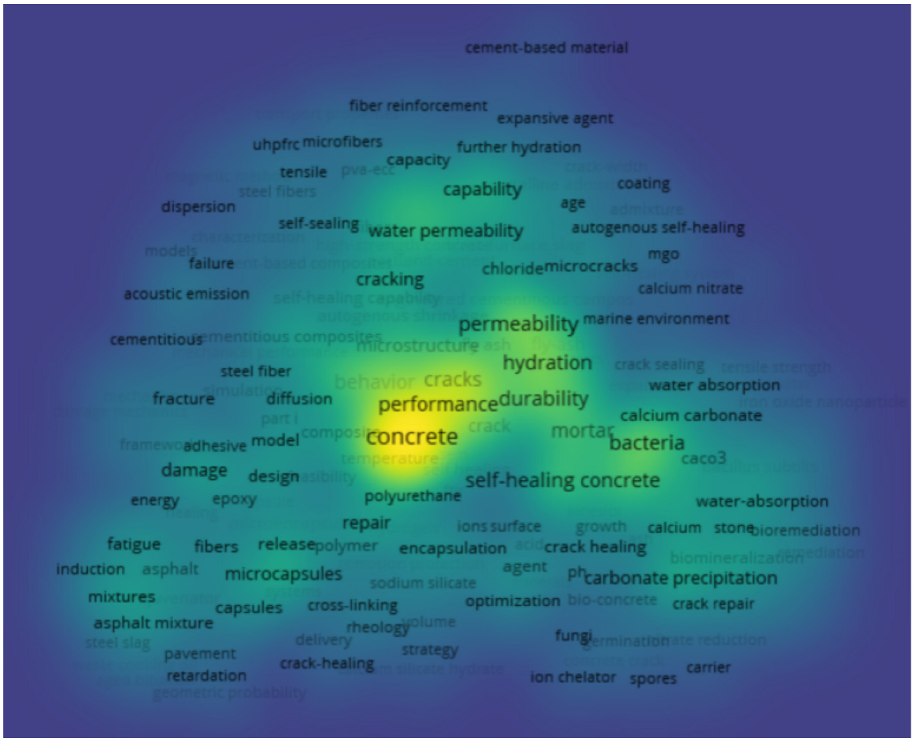

Fig. 5 Knowledge map of keywords. The color means the frequency of keywords.

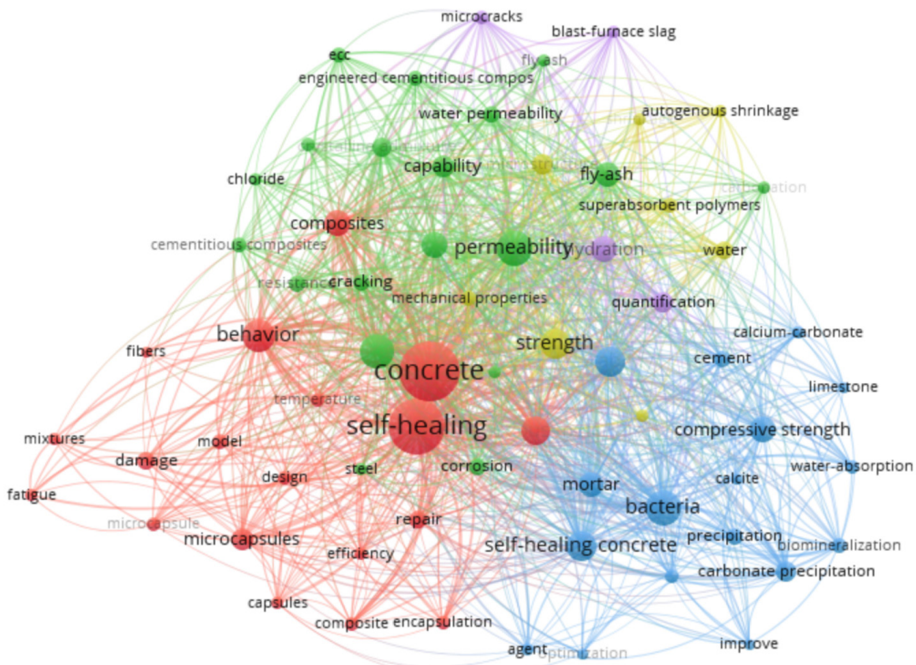

Fig. 6 Clustering knowledge map of keywords.

4 Microcapsule-enabled self-healing concrete

4.1 Analysis of papers

From the research outlined in Section 3, microcapsule self-healing concrete is one of the main research hotspots in this field. Here, the microcapsule self-healing concrete is investigated by bibliometric methods. According to the WoS, the number of published papers on the microcapsule self-healing concrete is 213, with 5008 citations. The specific distribution is exhibited in Fig. 8.

Figure 8 presents the number of papers and the frequency of citations about microencapsulated

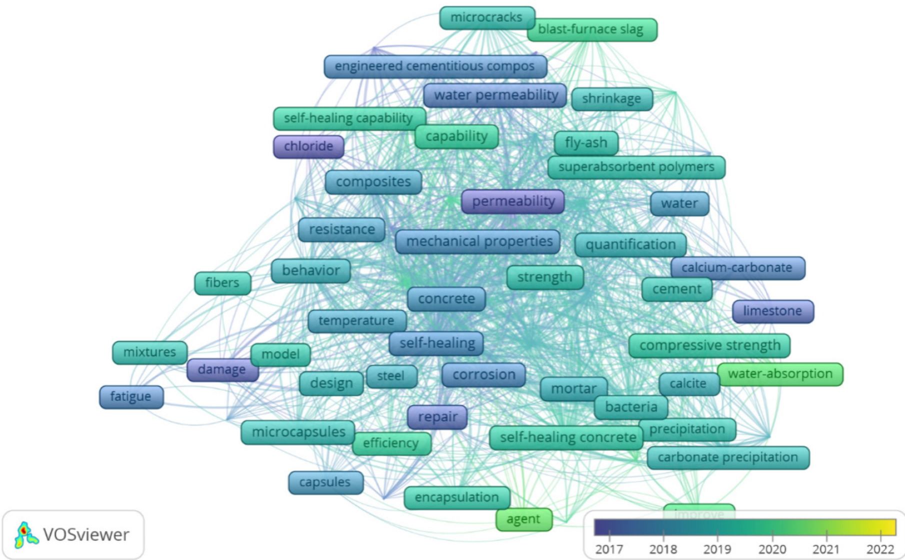

Fig. 7 Sequence diagram of keywords.

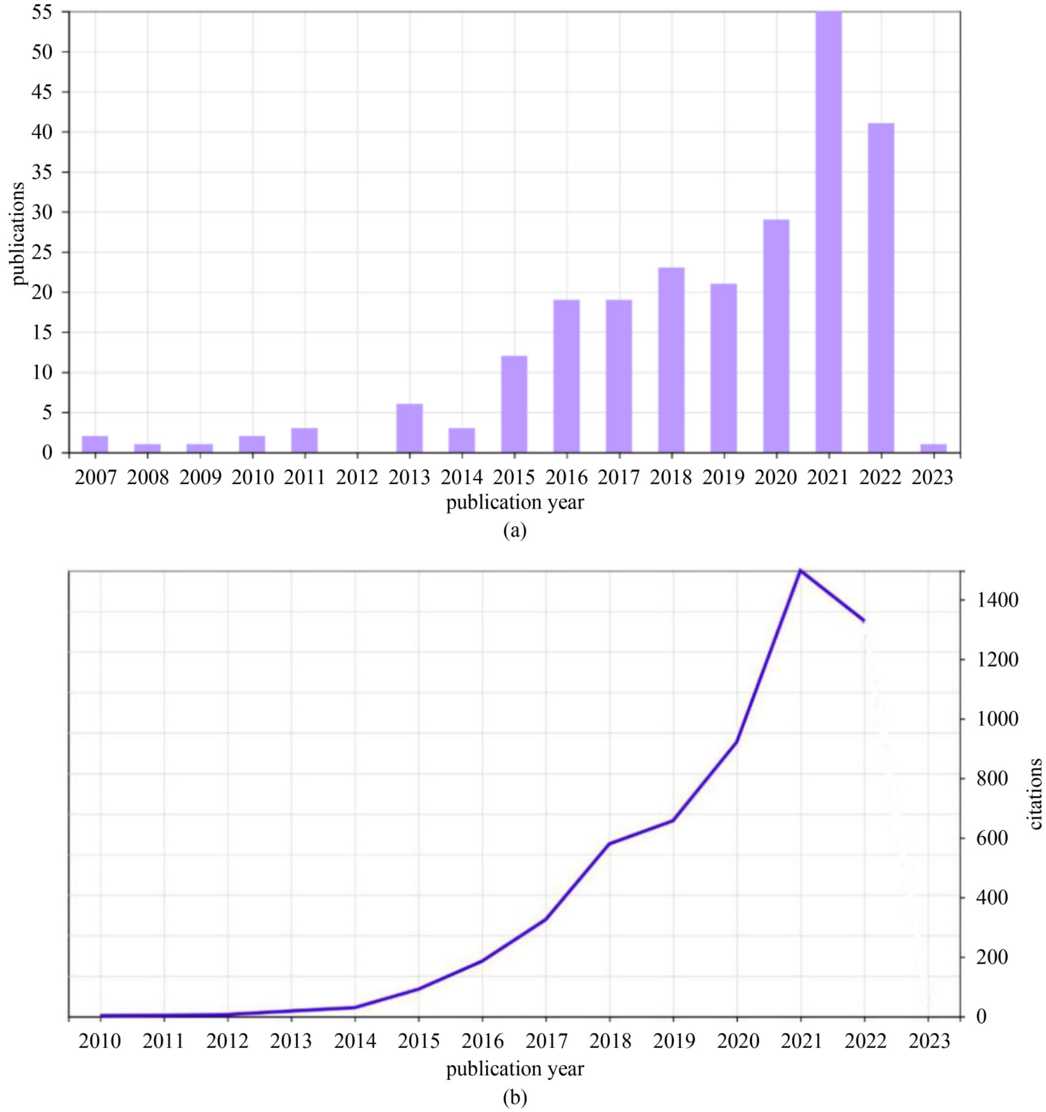

Fig. 8 Distribution of papers and citations of the microcapsule self-healing concrete: (a) number of published papers on the microencapsulated self-healing concrete; (b) citations of the microencapsulated self-healing concrete.

self-healing concrete, indicating that research on microencapsulated self-healing concrete is steadily advancing. The research on the microencapsulated self-healing concrete is divided into two development stages: steady growth and rapid growth. Steady growth stage (2007–2014): the number of papers in this stage fluctuates at the beginning, and the number is low. Then it continues to increase, with small inter-annual differences. Rapid growth stage (2015–2021): The growth of the number of papers in this stage is significantly higher than that in the first stage, with the stage separation point being 2015. The number of published papers reaches its peak in 2021, with 54 articles, indicating that scholars are interested in research on microencapsulated self-healing concrete. From 2007 to 2021, the citation frequency of literature shows a significant growing tendency, and the number of citations reaches its peak of 1488 in 2021. The above analysis suggests that the research on the microencapsulated self-healing concrete has attracted increasing attention from scholars and has a good future research prospect.

The statistical analysis of published journals is shown in Fig. 9. CBM ranks first, which has published 63 papers on the microencapsulated self-healing concrete. The second is Materials, which has published 17 papers on the microencapsulated self-healing concrete. The third is the *Journal of Materials in Civil Engineering*, which publishes 13 papers on the microencapsulated self-healing concrete. The fourth is CCC, which has published 12 papers on the microencapsulated self-healing concrete, and the fifth is *Journal of Cleaner Production*, which has published 6 papers. The sixth place is the *International Journal of Damage Mechanics*, which has published 5 papers. The seventh place is *Applied Sciences*, which has published 4 papers on the microencapsulated self-healing concrete. Polymers ranked eighth, and publishes 4 papers on the microencapsulated self-healing concrete. *Smart Materials and Structures* ranks ninth, and has published four papers. The tenth is *Transportation Research Record*, which has published 4 papers. It can be seen from the above analysis that the research on the microencapsulated self-healing concrete has been widely reported by SCI journals, and has a good research prospect.

In Fig. 10, a statistical analysis of the disciplines is displayed. From the figure, the journals that publish papers on the microencapsulated self-healing concrete mainly involve material science (63%), construction technology (47%), civil engineering (46%), applied physics (11%), physical chemistry (9%), condensed matter physics (8%), composite material science (7%), applied chemistry (5%), mechanics (5%), and polymer science (5%). From the above analysis, the research on microencapsulated self-healing concrete has involved many scholars from different disciplines, and the research has clear interdisciplinary characteristics.

4.2 Analysis of organizations

To further understand the research status and actual contribution of research institutions on microcapsule-enabled self-healing concrete, the number of published

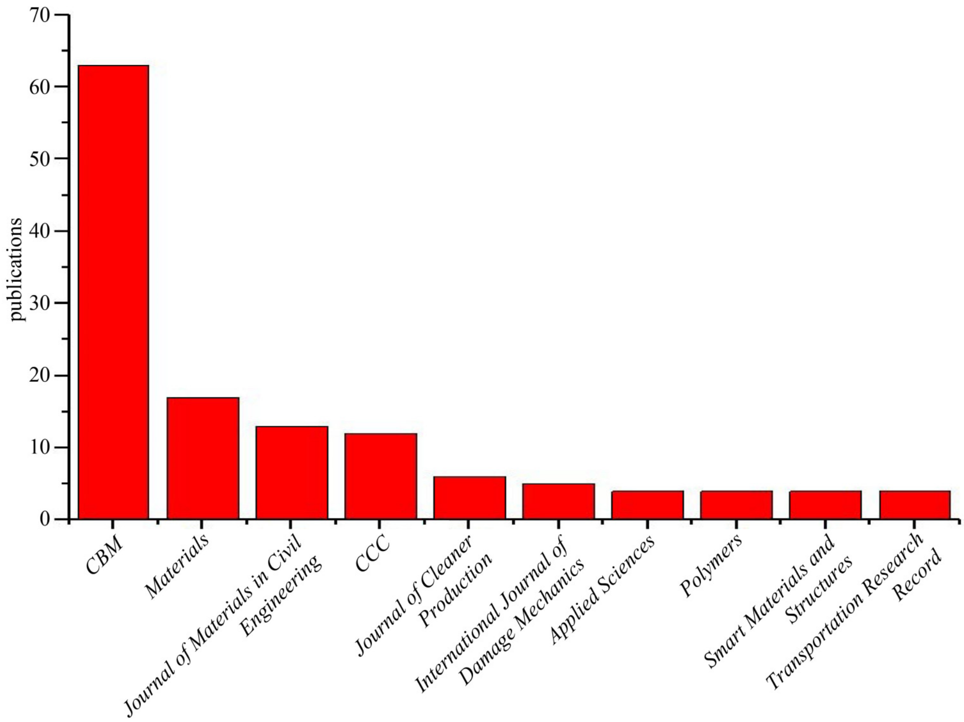

Fig. 9 Published journals on the microencapsulated self-healing concrete.

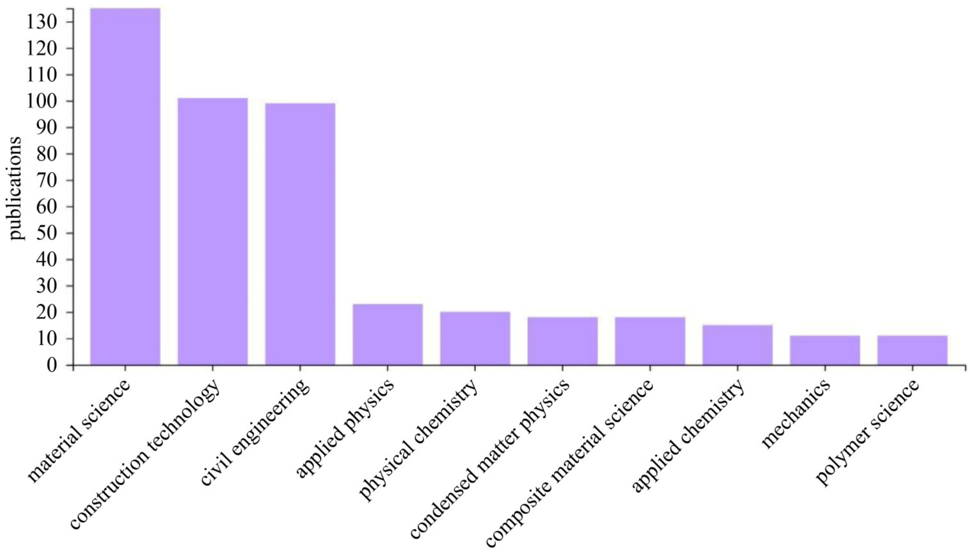

Fig. 10 Disciplines related to the microencapsulated self-healing concrete.

papers by each institution is counted. With 213 documents as the basic source of information, the period is selected from 1995 to 2022. Considering that the segmented processing of document data are more conducive to improving the accuracy of statistics, the time slice is set to 1 year; that is, it is divided into 28 periods for analysis. The number of papers published by different institutions is displayed in Fig. 11.

From Fig. 11, the research on the microencapsulated self-healing concrete involves 186 institutions in the WoS core collection database, of which 21 institutions have published more than 4 papers, and the institutions are mainly universities. Shenzhen University, plays an important role in the research field, and has published 46 papers on microencapsulated self-healing concrete. Tongji University ranks second, and has published 20 papers on the microencapsulated self-healing concrete. Louisiana State University ranks third, and has published 17 papers on microencapsulated self-healing concrete. Beijing University of Science and Technology ranks fourth, and has published 13 papers. Delft University of Technology ranks fifth, and has published 12 papers. Wuhan University of Technology ranks sixth, and has published 11 papers. Harbin Institute of Technology ranks seventh, and has published 9 papers in this field. The University of California, Los Angeles ranks eighth, and has published eight papers on the microencapsulated self-healing concrete. The Transportation Research Center of Louisiana in the USA ranks ninth, and has published seven papers. Qatar University ranks tenth, and has published 6 papers on the microencapsulated self-healing concrete. The agencies are distributed all over the world.

The time sequence of papers published by different institutions has been analyzed. In the past decade, Shenzhen University, Tongji University, Delft University, Louisiana State University and other institutions have been active in the research of the microencapsulated

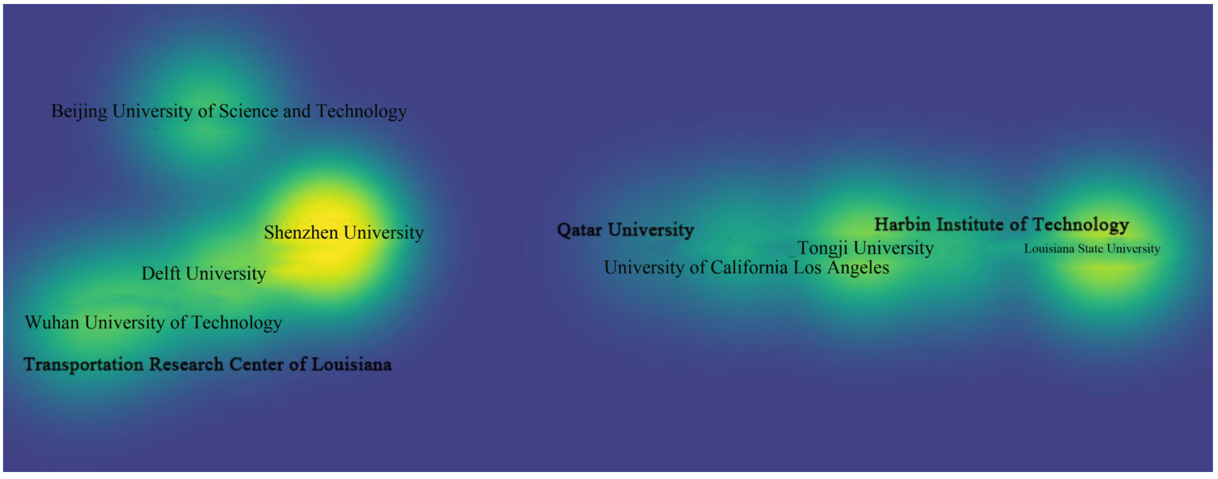

Fig. 11 Distribution density of the organizations studying the microcapsule self-healing concrete. The color means the frequency.

self-healing concrete. Among them, Virginia University of Technology, Beijing University of Science and Technology, Wuhan University of Technology, The University of California Los Angeles, and other institutions, have made outstanding achievements in the field of the microencapsulated self-healing concrete in the past two years.

4.3 Analysis of countries

To further understand the research status and actual contributions of various countries in the field of microencapsulated self-healing concrete, the number of papers published on the microencapsulated self-healing concrete in various countries is counted. With 213 papers as the basic information, the time is selected from 1995 to 2022. The publication of papers in various countries is exhibited in Fig. 12.

The research on the microencapsulated self-healing concrete involves 37 countries in the WoS core set database. Among them, China in this field plays a pivotal role, and 115 papers on microencapsulated self-healing concrete have been published. The USA ranks second, with 39 papers in the field. The UK ranks third, and has published 23 articles. The Netherlands ranks fourth, with 12 papers. Germany ranks fifth, with 9 papers. South Korea ranks sixth, and has published 9 papers on microencapsulated self-healing concrete. Chile ranks seventh, with 8 papers on. Spain ranks eighth, and has published 8 papers. Qatar ranks ninth, and has published 6 papers. India ranks tenth, and has published 6 papers.

Figure 13 shows the time sequence of papers published by different countries, indicating that China, the UK, Pakistan, Iran, and Malaysia have made outstanding achievements in the field recently.

4.4 Analysis of keywords in the literature

The research direction, trend and characteristics of the microencapsulated self-healing concrete can be inferred by analyzing the keywords and capturing snapshots of some aspects of the time series. The basic information of 213 papers is analyzed by keywords, and the map of keywords is obtained after merging synonyms, as displayed in Fig. 14.

There are 917 keywords in the literature, of which 78 appear more than 5 times. By analyzing the maps of the keywords, some nodes of keywords are large, such as concrete, self-healing, permeability, composites, microencapsulation, bacteria, performance, behavior, cracks, strength, durability, damage, model, cementitious materials, urea-formaldehyde resin microcapsules, mechanical

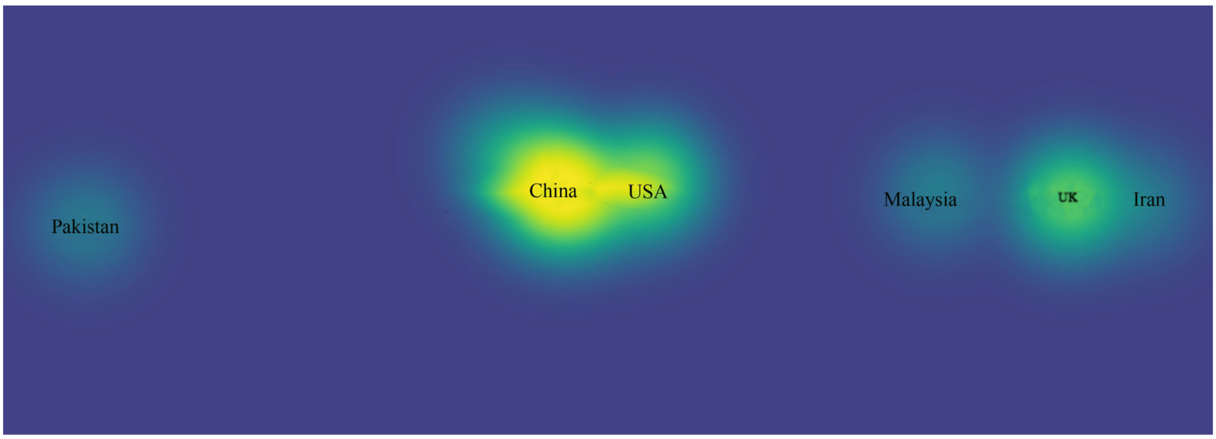

Fig. 12 Distribution density of the papers on the microcapsule self-healing concrete from different countries. Color means frequency.

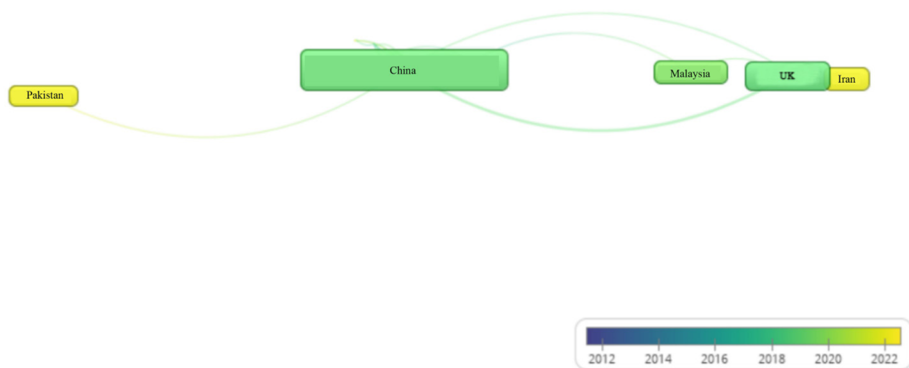

Fig. 13 Temporal distribution of papers published by different countries on the microencapsulated self-healing concrete.

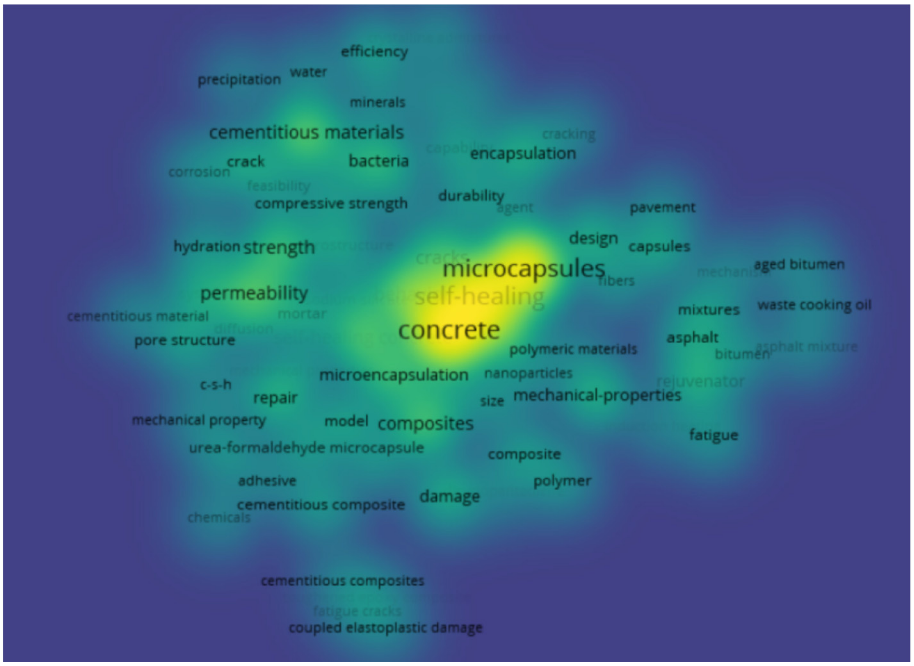

Fig. 14 Knowledge map of the keywords on the microencapsulated self-healing concrete. Color means frequency.

properties, sodium silicate, polymer, epoxy, polyurethane, and dicyclopentadiene (DCPD), which indicates that the frequency of these keywords is high. At present, polyurethane, sodium silicate, DCPD, bacteria and epoxy resin are mainly used as repairing agents for self-healing concrete. The healing agents are encapsulated by shell materials in the microcapsules. Shell materials of microcapsules are made of polymer materials like urea-formaldehyde resin. Microcapsules are mainly used for repairing cracks, improving concrete strength and other mechanical properties, and reducing concrete permeability. A large number of papers have paid attention to both experimental and theoretical aspects. At present, the main indices for evaluating the microcapsule self-healing concrete are permeability, mechanical properties and durability.

Based on the network maps of literature co-citation, cluster analysis is carried out on the keywords of the literature, and the clustering results are depicted in Fig. 15.

Figure 15 illustrates that six clusters are obtained by clustering. Therefore, according to the keywords from the literature, the research of the microcapsule self-healing concrete can be divided into six research categories: microcapsule self-healing asphalt concrete, microbial microcapsule self-healing concrete, autogenous microcapsule self-healing concrete, preparation of microcapsules, performance evaluation of microcapsule self-healing concrete, and theoretical models of self-healing concrete.

Figure 16 shows the keywords with high highlight intensity that are emerging hot topics in this research field. Further analysis shows that the keywords with the highest emergent strength are bacteria and mechanical properties, which indicates that from 2017 to 2022, the research of the microencapsulated self-healing concrete is more about adding microbial microcapsules to concrete. In general, from 2017 to 2022, research of microencapsulated self-healing concrete is varied.

4.5 Citation analysis

4.5.1 Analysis of citations of different papers

To further understand the research status and influence in the field of microencapsulated self-healing concrete, the citations of each paper on microencapsulated self-healing concrete are counted. With 213 papers as the basic information source, the time period is selected from 1995 to 2022. The time slice is set as one year; that is, it is divided into 28 periods for analysis. The citations of different papers are obtained.

77 papers on the microencapsulated self-healing concrete have been cited more than 20 times in the WoS core collection database. Next, we analyze the highly cited literature to obtain the current research focus.

The paper of Wang et al. [26] has been cited 408 times. Bacterial spores were enclosed in self-healing concrete in this investigation using microcapsules. The first thing that was investigated was the activity of spores on mortar samples. The findings revealed that samples containing biological microcapsules had a better healing rate than those without bacteria. The largest crack that the bacterial series sample could repair was 970 μm wide. The total water permeability of the bacterial specimens was around ten times lower than in the case of non-bacterial specimens.

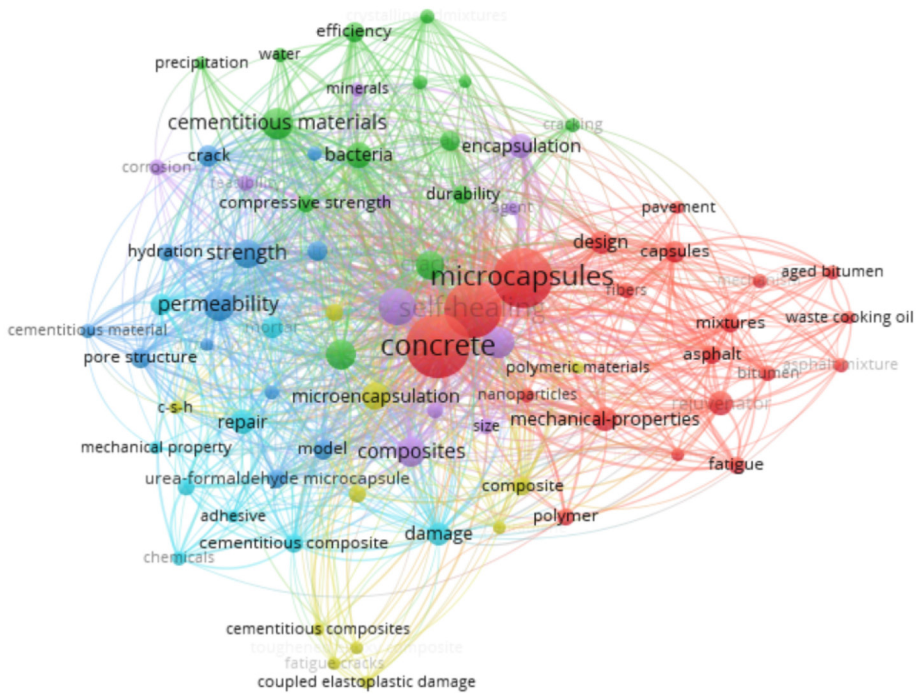

Fig. 15 Clustering knowledge map of keywords.

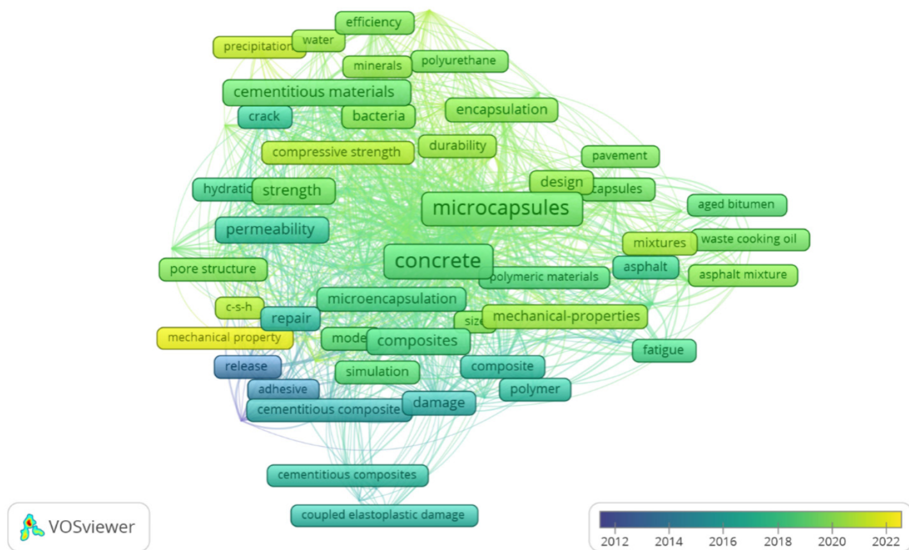

Fig. 16 Keywords sequence diagram of papers on microcapsule self-healing concrete.

The paper of Yang et al. [27] has been cited 181 times. In this research, an oil core and silica gel shell microcapsule design were used. Triethylborane and methyl methacrylate monomer were chosen as the system's catalyst and healing agent, respectively. Interfacial self-assembly and the sol-gel reaction were used to microencapsulate them.

The paper of Li et al. [28] has been cited 171 times. To develop self-healing capability, divinylbenzene microcapsules were added to cement slurry in this work. At the beginning, mechanical tests on the injured specimen were used to gauge the self-healing. On the effectiveness of healing, the impacts of microcapsule content, curing environments, and degree of injury were examined. The findings demonstrated that self-healing concrete containing capsules can be healed. Surfactant-produced voids, however, had an impact on the strength. The absorbability reduced as the healing agent repaired the fracture.

The paper of Song et al. [29] has been cited 132 times. The methacryloxypropyl-terminated polydimethylsiloxane were microencapsulated. The agitation rate could be used to regulate the microcapsules' mean diameter and size distribution. As microcapsules ruptured, the healing substance was released and filled the wound. The system could self-heal, according to research on the permeability of water and the entry of chloride ions.

The paper of Dong et al. [30] has been cited 95 times. It described a new chemical self-healing method for cement-based composites using microcapsule technology. The releasing behavior was the study's main topic. The results of the work demonstrated that the wall thickness of the microcapsule controlled the rate of release of corrosion inhibitors coated with polystyrene resin. The pH level also had an impact on how quickly the corrosion inhibitor released.

The paper of Lv et al. [31] has been cited 90 times. This research described a novel polymer microcapsule with DCPD acting as the self-healing agent and phenolic resin as the shell. In situ polymerization was used to create PF/DCPD microcapsules. The outcomes demonstrated that both in simulated pore solutions and actual cement environments, the manufactured microcapsules had good durability. To monitor the condition and fracture behavior of microcapsules within a cement slurry matrix, X-ray computed tomography was used.

The paper of Dong et al. [32] has been cited 81 times. Here, epoxy resin was adopted for crack recovery of cementitious materials. The microcapsules that were produced had extraordinary thermal stability, good size, and great surface texture. The rate of fracture healing ranged from 20.7% to 45.59%, proving the self-healing effect. Moreover, the rates of impermeability and compressive strength recovery were about 13% and 19.8%, respectively.

The paper of Sun et al. [33] has been cited 80 times. The most recent studies on self-healing mechanisms, models, and characterization of asphalt and asphalt concrete pavement were thoroughly covered in that study. Models for potential self-healing pathways were suggested. The factors influencing the capacity for self-healing were also covered. Induction heating and microencapsulation self-healing technology were the final two external self-healing technologies that were suggested for pavement repair.

The paper of Wang et al. [34] has been cited 78 times. This study looked at how cement-based composites implanted with organic microcapsules recovered in terms of strength and impermeability. Organic microcapsules and catalysts were combined with cement, sand, and water to create mortar samples. The strength was enhanced by up to 9% after adding a modest proportion of microcapsules, and then decreased with the addition of more microcapsules. The healing effect was investigated using mechanical tests and chloride ion penetration tests. The number of microcapsules had a nearly linear relationship with the final level of recovery.

The paper of Giannaros et al. [35] has been cited 74 times. In that investigation, the cement sample was supplemented with liquid and solid forms of microencapsulated sodium silicate. Sodium silicate and calcium hydroxide combined to generate hydrated calcium silicate gel, which was used to fill fissures. According to the strength growth between 28 and 56 d, it was shown that adding microcapsules hindered cement's ability to build compressive strength.

Based on the analysis of the above articles, the current research is mainly focused on the preparation of different microcapsules. The influence of different materials is considered.

4.5.2 Analysis of citations of different countries

To further understand the research status and influence of microencapsulated self-healing concrete, the citations of papers in each country are counted. With 213 papers as the basic information, the time is selected from 1995 to 2022. The time slice is set as one year, that is, it is divided into 28 periods for analysis. The citation of papers of different countries is shown in Fig. 17.

Research on microencapsulated self-healing concrete has been cited more than 5 times in the WoS core set database in each of 13 different countries. China has the highest number of citations, with 2231 citations. The second is the USA, which has 918 citations. The third is the UK, with 851 citations. The fourth is the Netherlands, which has 689 citations. The fifth is Belgium, with 442. The sixth is Chile, with 309. The seventh is South Korea, with 226. The eighth is Malaysia, with 203. The ninth is Spain, with 163. The tenth is Qatar, with 131.

Figure 18 shows the time sequence of the cited papers on microencapsulated self-healing concrete in various countries. The technology on the microencapsulated self-healing concrete is advanced in China, Germany, the UK, Belgium, the Netherlands, and South Korea in the past decade based on the core set database of WoS. In the past three years, India and Australia have made outstanding achievements in research on microencapsulated self-healing concrete.

4.5.3 Analysis of citations of different organizations

To further understand the research status and influence regarding microencapsulated self-healing concrete, the citations of the microencapsulated self-healing concrete of each institution are counted. With 213 documents as the basic information, the time is selected from 1995 to 2022.

There are 15 institutions that have been cited more than 5 times in the WoS core set database on research of microencapsulated self-healing concrete. Shenzhen University, has the highest number of citations, with 1120 citations. The second is Tongji University, which has been cited 735 times. The third is Delft University of

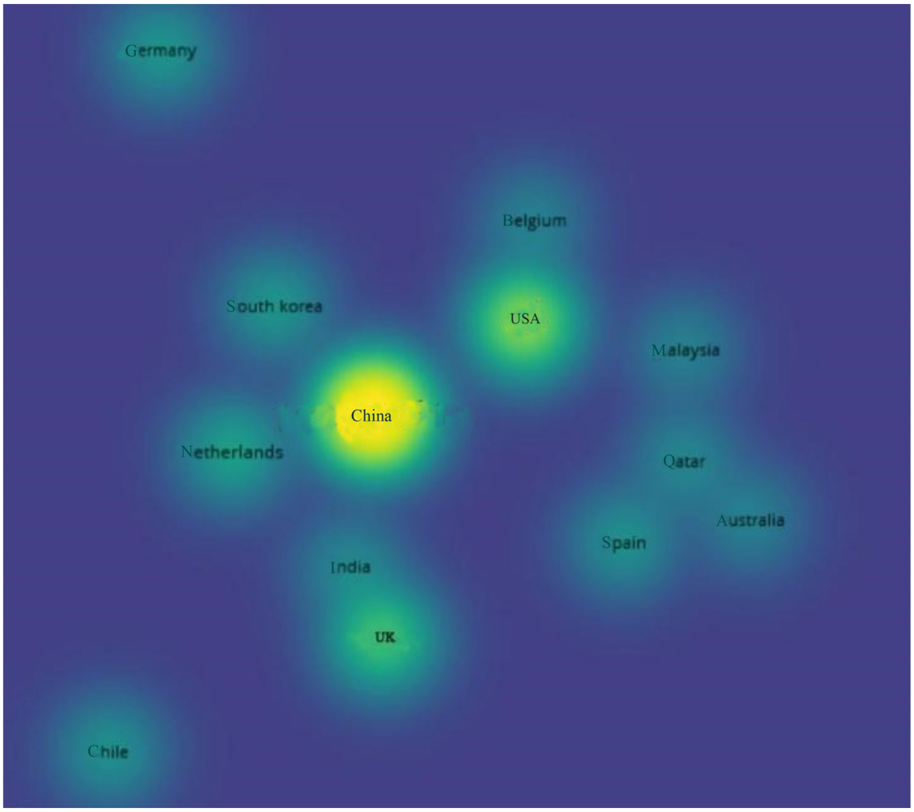

Fig. 17 Citation of different countries on the microencapsulated self-healing concrete. Color means frequency.

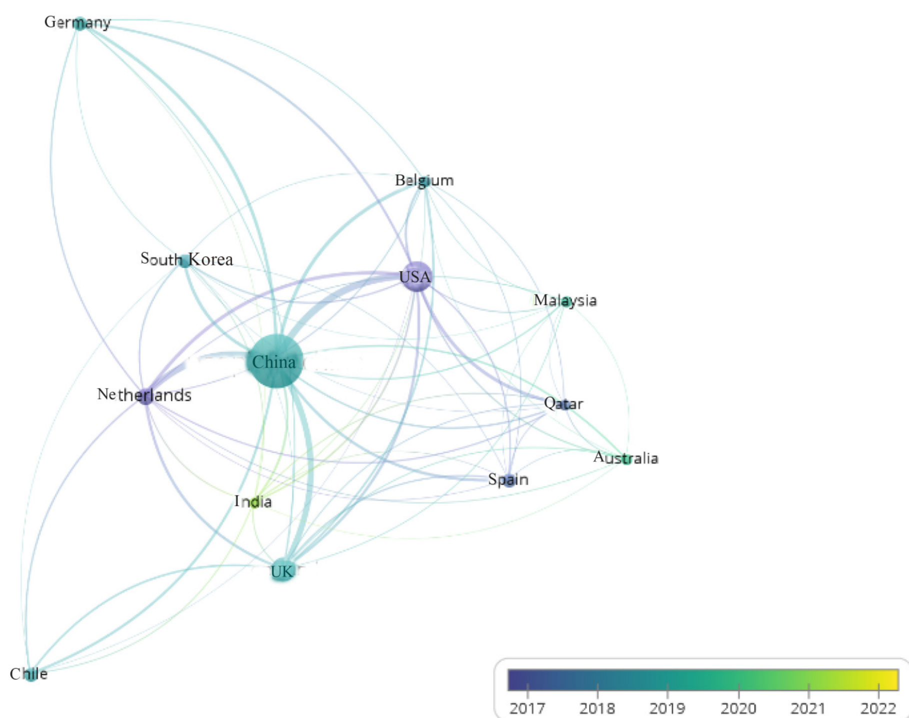

Fig. 18 Citation time of papers on the microencapsulated self-healing concrete in different countries.

Technology, which has been cited 689 times. The fourth is Cambridge University, which has been cited 525 times. The fifth is Louisiana State University, which has been cited 337 times. Sixth, Biobio University of Chile is cited 300 times. The seventh is the University of California, Los Angeles, which has been cited 194 times. The eighth is Qatar University, which has been cited 131 times. The ninth is Wuhan University of Technology, which has been cited 93 times. Based on the above analysis, we can find that Tongji University, Shenzhen University, and Wuhan University of Technology are developing rapidly in the field of the microencapsulated self-healing concrete.

Figure 19 shows the time sequence of the cited papers of different institutions on the microcapsule self-healing concrete. In the past ten years, Shenzhen University, Tongji University, Delft University, Cambridge University, Louisiana State University, Biobio University, University of California, Los Angeles, Qatar University, and Wuhan University of Technology have specific prominence in research of microencapsulated self-healing concrete. In the past three years, Beijing University of Technology, Wuhan University of Technology, Nanchang University, Harbin University of Technology, and Shandong University of Science and Technology have performed well in research on microencapsulated self-healing concrete.

4.5.4 Analysis of co-cited papers

Analysis of co-cited papers on the microencapsulated self-healing concrete is analyzed here. In the 213 papers, there are 5765 co-citations, where 27 papers appear more than 20 times. Through analysis of the key nodes of the maps, it can be seen that there are two large nodes (i.e, [3, 36]), which suggests that these two articles have the greatest impact on the research field.

4.6 Experiments and modeling of microcapsule self-healing concrete

There are many powerful numerical approaches that deal with modeling of self-healing concrete. Cracking behavior has been investigated, including by meshfree methods [37,38], by peridynamics [39,40], by the discrete element methods [41], by fracture mechanics [42], by extended isogeometric analysis [43], by the smooth extended finite element method [44], by the phantom node method [45], by Monte Carlo methods [46] and by molecular dynamics [47], etc.

In the various studies, many different characterization methods have been used to evaluate the healing effect, including bending tests [48], uniaxial tensile tests [49], compression tests [50], splitting tests [51], water absorption tests [52], nanoindentation tests [53], ultrasonic pulse velocity tests [54], acoustic emission tests [55], coda wave interferometry [56], resonant frequency tests [57], gas permeability tests [58], electrical resistivity tests [59], optical microscope tests [60], SEM [34], spectroscopy and thermos analysis [61], X-ray diffraction [62], Fourier transform infrared spectroscopy [63], thermogravimetric analysis [32], X-ray computed tomography [64], neutron radiography/tomography [65], etc. Based on the above-mentioned methods, different evaluation indexes have been applied to estimate the healing effect; these include compressive strength, first cracking strength, flexural strength, tensile strength, tensile ductility, tensile stiffness, interface bonding strength, microhardness, ultrasonic pulse velocity, acoustic emission, electrical resistivity, visualization and imaging, etc.

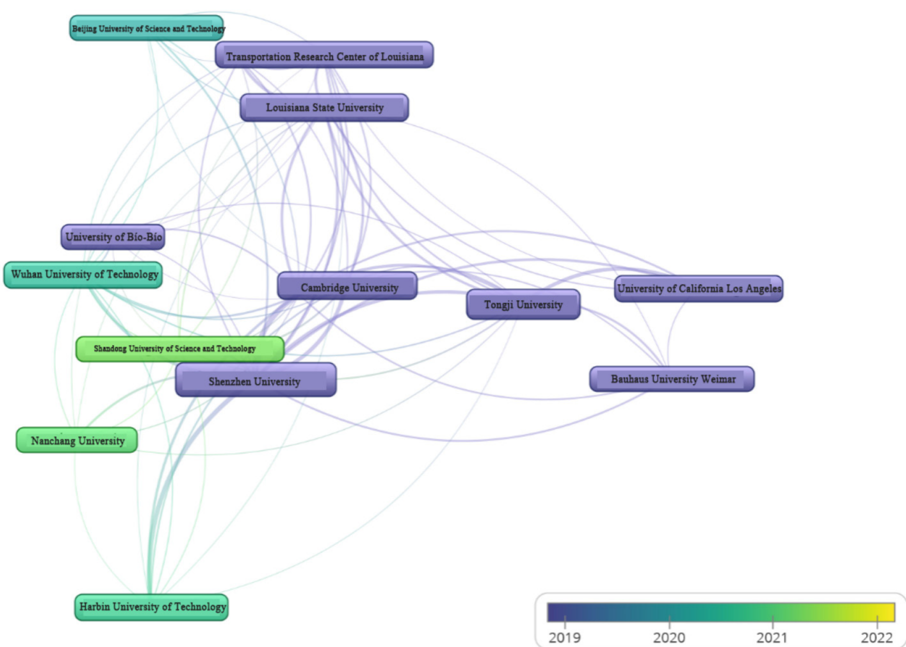

Fig. 19 Citation time of different organizations on research on microencapsulated self-healing concrete.

4.7 Disadvantages and challenges of the microcapsule self-healing concrete

The utilization of microcapsule self-healing techniques for repairing cementitious materials is currently the subject of an increasing quantity of research, and its promise in the engineering area has been established. Although major advances in the study of various self-healing techniques have been made, there is still a long way to go before technical applications can be made. Based on the research of authors [8–11,66,67] and the results of other researchers, there are still many problems facing microcapsule self-healing concrete. Relative component proportions of concrete are significantly changed by the usage of microcapsules. The volume fraction of microcapsules is important. The workability and the strength of the self-healing concrete are also dramatically impacted. Some microcapsules alter the structure’s endurance. Microcapsules are composed of healing agents and shell materials. Because the healing agents’ content is so low when microcapsules are utilized, only a few cracks may be healed. The most dependable encapsulation technology is incompatible with the most efficient healing agent. It is important to investigate the reliability of long-term protection as well as the survival rate following agitation since some microcapsules will break during agitation. It is unclear whether healing agents are helpful over the long run. It is important to assess the healing agent’s effectiveness after multiple loads. The healing agents’ long-term toxicity needs to be examined. Water supplies can get contaminated when concrete structures are nearby. The polymer is easy to fail after it has solidified, which detracts from the mechanical characteristics of the healed concrete. Some restorative substances having beneficial effects on the body cannot be encapsulated.

It is determined that there is room for improvement of microencapsulated self-healing concrete, and the following research can be carried out, particularly on the following aspects.

1) The effectiveness of encapsulating technologies for repeated and long-term uses is not well studied. Results vary because of various shell materials of microcapsules and environmental factors.

2) For use in actual engineering applications, stable, resilient, inexpensive, and easily mass-produced microcapsules are required.

3) It should be investigated to see if encapsulation techniques permit dangerous ions to flow through the outer layer of concrete, accelerate steel corrosion, and promote the growth of cracks, which in turn accelerates the structure’s deterioration.

4) To get the greatest results, the ideal encapsulation strategy should be chosen for a particular application.

5) New shell materials of microcapsules should be investigated.

6) New healing agents should be studied.

7) New healing mechanisms should be explored.

8) The effect of microcapsules on the resilience of cementitious materials should be investigated.

9) It is important to research the interface between the healing products and the concrete, because it impacts the healing product’s stability under mechanical or environmental stress.

10) To achieve the best outcomes, the most appropriate agents should be used in various situations.

11) Other methods may be used together to enhance the self-healing effect of microcapsule self-healing concrete, like using electric fields [68].

5 Conclusions

A new technique promising in extending the service life of concrete, ensuring the security of concrete structures, and lowering maintenance costs is the use of self-healing concrete. Here, the microcapsule-enabled self-healing concrete is studied using bibliometric methods. The main conclusions of the study are summarized as follows.

1) Since 2007, researchers have gradually paid more attention to the research of the self-healing concrete. The number of published papers and citations has increased significantly. The journals which publish papers on the self-healing concrete are mainly concentrated in materials science, civil engineering, applied physics, physical chemistry, biotechnology, showing the characteristics of an interdisciplinary area of study. It is expected that the research enthusiasm for the self-healing concrete will continue to grow in the future. The research institutions are mostly colleges and universities, and the research teams are relatively scattered. The research on the self-healing concrete has been widely reported by many journals.

2) Microcapsule self-healing concrete is a research hotspot within the field of self-healing concrete. At present, microcapsule self-healing concrete mainly uses polyurethane, sodium silicate, DCPD, bacteria and epoxy resin as repairing agents. Polymer materials such as urea-formaldehyde resin are used as shell materials of microcapsules, mainly for repairing cracks, improving concrete strength and other mechanical properties, and reducing concrete permeability. Scholars have paid attention to both experimental and theoretical models. At present, the main indices of evaluating the microcapsule self-healing concrete are permeability, mechanical properties and durability. According to the citations, research on microencapsulated self-healing concrete can be divided into three clusters: microencapsulated concrete containing microorganisms, microencapsulated self-healing concrete containing chemical healing agents, and theoretical models of the microencapsulated self-healing concrete.

3) At present, the research on the microencapsulated self-healing concrete at Shenzhen University, Tongji University, Louisiana State University, Cambridge University, and Delft University share a leading position.

4) China, the USA, the UK, the Netherlands, and Germany have made the most prominent contributions to the research field of the microencapsulated self-healing concrete.

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Conflict of Interests The authors declare that they have no conflict of interest.

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