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Self-Healing Concrete: A Bibliometric Analysis

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Abstract **–** Research on self-healing concrete has thrived in recent years. This study aims to map the evolution of self-healing concrete among the different research constituents, reveal the trends, and identify the key contributors, research themes, and critical publication outlets and topics in the field. Bibliometrix R software package was utilized to conduct a bibliometric analysis on a total of 1,402 publications written by 2,880 authors and published between 1974 to 2021. These publications were retrieved from the Scopus database. Performance analysis revealed that 86% of the publications were journal articles and papers published in conference proceedings. Citations and keywords analysis showed that review articles were the most cited papers, and research on utilizing bacteria in self-healing concrete was the most trending topic. High collaboration rates among top-cited and most productive countries, authors, and universities were reported using science mapping. The findings of this study highlight the need for future work focused on real-life applications, optimization of self-healing mechanisms, rheological properties, and microstructure characteristics of self-healing concrete.

Keywords**:** Self-healing concrete, Bibliometric analysis, Bibliometrix, Performance analysis, Science mapping.

1. Introduction

Concrete has been one of the most extensively used building materials, owing to its unique mechanical and durability properties. Even with its superior performance, concrete has inveterate weaknesses, including relatively low tensile strength and ductility, making it prone to cracking [1]. Cracks can develop at any stage of the concrete service life. Even though cracks might not affect the strength of concrete at an early age, their formation and propagation expose the steel reinforcement and reduce the long-term durability and serviceability. This facilitates the ingress of undissolved particles of undesirable fluids and gases through the concrete [2]. The development and propagation of such cracks can be either alleviated or reduced once detected by various techniques [3-6]. Typically, manual repairs are used to address crack formation. However, these methods are primarily inefficient, costly, do not last more than 10-15 years, and require external interference [7]. Accordingly, past research has examined different efficient and cost-effective means to repair the concrete with minimal interference. As a result, concrete that could repair or heal itself, i.e., self-healing concrete, was devised.

Self-healing concrete can repair microcracks without any external action or human involvement [1]. Self-healing techniques are promising approaches for the rehabilitation of microcracks in concrete [8]. Two different approaches to self-healing in concrete are available, including autogenous and autonomous self-healing. Autogenous self-healing of concrete is a phenomenon where cracks are closed through the reaction of unhydrated cement particles with moisture in the air to form crystalline materials [8], [9], [10]. While this method seems promising, the quantity of self-healing products resulting from the continuous hydration of cement is limited and may not sufficiently seal cracks in concrete [11]. Conversely, autonomous self-healing depends on the addition of engineered materials to the concrete to repair or seal larger cracks. Past research has highlighted an improvement in the ability of concrete to self-heal using this technique [12]. Several autonomous self-healing approaches have been investigated, such as electrodeposition technology [13], embedding shape memory alloy (SMA) [7], capsules [15], vascular technology [17], and bacteria utilization [18].

Research on self-healing concrete has increased in recent years. This has led to the collection and analysis of such work in the form of state-of-the-art review articles [18]. Indeed, several review articles covered self-healing concrete. While some examined the subject from a comprehensive perspective [7], others investigated specific topics [2], [7], [8], [19]. However, most of these reviews are incapable of being replicated. Also, the process of selecting the papers, which are typically limited to the topic, is not described sufficiently. To overcome these shortcomings, the use of bibliometric analysis has become more prevalent in different disciplines. Unlike other techniques, bibliometric analysis provides more structured, reliable, and objective-based evaluation to a large body of information, help in inferring trends over time, identify researched themes, identify shifts in the boundaries of the disciplines, pinpoint the most prolific scholars and institutions, and, ultimately, present an overall view of the conducted research [18], [20]. However, such an approach has not been applied to the field of self-healing concrete yet.

This paper aims to map the evolution and research trends in self-healing concrete by utilizing bibliometric analysis of the relevant literature. It determines the key contributors, research themes, and critical publication outlets and topics to collectively analyze the findings and identify the gaps in the literature for future studies.

2. Methods

2.1. Aims of the Bibliometric Analysis

A bibliometric analysis is first defined by a precise aim. Determining the aim will aid in selecting the best bibliometric analysis technique and, subsequently, choosing the proper data format required [21]. The aim of this study relates to the retrospection of the performance analysis and science mapping of the self-healing research field. In terms of performance analysis, it identifies the productivity of the research elements, including authors, countries, journals, etc. Furthermore, science mapping reveals the bibliometric structure that encompasses the interaction between the different aspects of research contributing to the intellectual and social systems.

2.2. Bibliometric Analysis Technique

To perform a proper bibliometric analysis, a suitable bibliometric technique should be chosen. Many tools and software packages capable of performing a single procedure or both at the same time are available, such as “CiteSpace”, “CitNetExplorer”, “VOSviewer”, and “Bibliometrix”. Bibliometrix is an open-source tool developed by Aria and Cuccurullo [18]. Unlike the other software solutions, it provides a rapid analysis and establishes data matrices for both performance analysis and science mapping of the bibliographic collection. In this study, the latest version of Bibliometrix R package was used through a web-based app, Biblioshiny [22].

2.3. Data Collection Tables and Figures

In bibliometric analysis, data collection is usually divided into three stages, including data retrieval, data loading and converting, and data cleaning [18]. In the first stage, the bibliographic information was extracted from Scopus, as it is one of the largest databases for academic abstracts and citations and covers nearly 50 million pieces of literature published since 1823 [21], [23]. Data retrieval resulted in obtaining 1402 articles written in English and published between 1974 and 2021. These articles were obtained by searching the Scopus database for the keywords “self-healing concrete”, “autogenous”, and “autonomous”. In the second stage, the data was loaded and converted into a suitable format for the employed bibliometric tool. The database utilized in this analysis was in BibTeX format, as it was supported by the “Bibliometrix” R package. In the final stage, a quality assurance measure was applied, as the quality of the results depended on that of the data. Duplicate and misspelled words were checked in the retrieved database using Microsoft Excel. Initial inspection of the database showed that such errors did not exist.

2.4. Bibliometric Analysis Run and Results Reporting

The command “biblioshiny ()” (Fig. 1) opened a web browser and granted access to the Biblioshiny application, where the obtained bibliographic databases were uploaded. Subsequently, the analysis was conducted, and the results were reported, as shown in the following section.

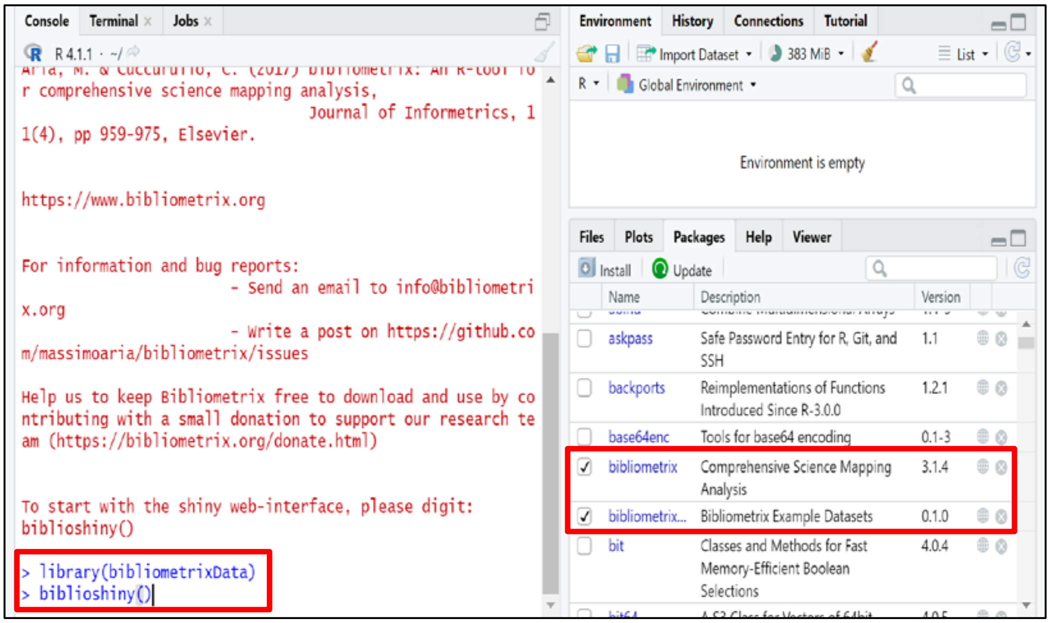


Fig. 1: RStudio console with the loaded “Bibliometrix” R package and the command “biblioshiny()”.

3. Results and Discussion

3.1. Performance Analysis

Bibliometric performance analysis encompasses descriptive metrics related to the publication, citation, frequency, and trends (or “hot topics”) of a scientific field. As shown in Table 1, a total of 1,402 studies on self-healing concrete were retrieved from Scopus across 462 sources (journals, books, etc.) between 1974 and 2021 and were written by 2,880 authors. This is associated with an average of 4.49 publications per year and a collaboration index of 2.2. Most of these studies were published as journal articles and in conference proceedings (60% and 26%, respectively). Fig. 2 provides insights into the evolution of interest in self-healing concrete. Very few sources were published between 1974 and 2006, after which the number of articles has gradually increased.

Table 1: Data on the extracted publications.

Description	Time span 1974 – 2021
Sources (Journals, Books, etc)	462
Documents	1402
Average publication per year	4.49
Average citations per document	20.21
Authors	2880
Authors of single-authored documents	75
Authors of multi-authored documents	2805
Collaboration index*	2.2

*Total number of authors of multi-authored articles divided by the total number of multi-authored articles.

Table 2 presents the top 10 contributing countries, authors, relevant affiliations, and journals to scientific publications on self-healing concrete. It can be noted that the productivity of one research constituent did not represent the other. For instance, in terms of scientific production, the most productive country is China, whereas, in relevant affiliation, the ranking was not led by a Chinese institution. Instead, Ghent University was the most prolific institution, with 197 publications, followed by the Delft University of Technology with 103 publications. This is because the country is associated with the corresponding author only, while the affiliations are those of the complete list of authors. A three-field plot, presented in Fig. 3, between countries (AU_CO), authors (AU), and affiliation (AU_UN) also confirmed this finding. Furthermore, most articles were published in top-tier journals with impact factors ranging from 2.1 to 10.9 and conference proceedings. The scope of these journals covered civil engineering construction and materials.

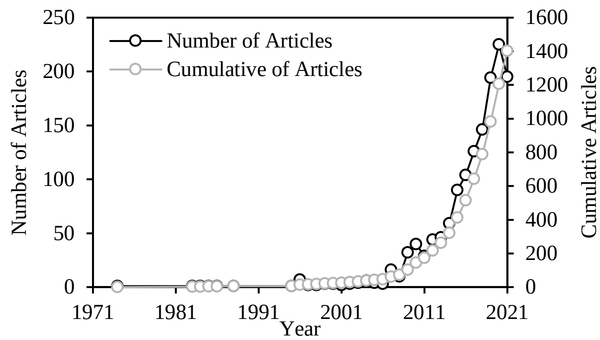


Fig. 2: Annual scientific production between 1974 and 2021.

Table 2: Top ten productive countries, productive authors, relevant affiliation, and frequent journals.

R	Country	N.P	Author	N.P	Universities/Insitutes	N.P	Frequent Journal	N.P
1	China	203	De Belie N	105	Ghent University, Belgium	197	Construction and Building Materials	189
2	USA	105	Van Tittelboom	43	Delft University of Technology, Netherlands	103	Materials	65
3	India	91	Ferrara L	41	Tongji University, China	74	Cement and Concrete Composites	53
4	Belgium	85	Schlangen E	41	Southeast University, China	70	IOP Conference Series	34
5	Netherlands	58	Xing F	37	Shenzhen University, China	54	Journal of Materials in Civil Engineering	30
6	UK	58	Jonkers H	34	Politecnico Di Milano, Italy	44	Materials Today: Proceedings	26
7	Korea	50	Wang X	28	Universiti Teknologi Malaysia, Malaysia	27	Cement and Concrete Research	25
8	Italy	38	Snoeck D	27	Wuhan University of Technology, China	26	Lecture Notes in Civil Engineering	25
9	Canada	29	Al-Tabbaa A	23	University of Cambridge, UK	25	RILEM Bookseries	21
10	Germany	27	Gruyaert E	22	Hanyang University, South Korea	21	Journal of Advanced Concrete Technology	18

R = Rank; N.P = Number of publications.

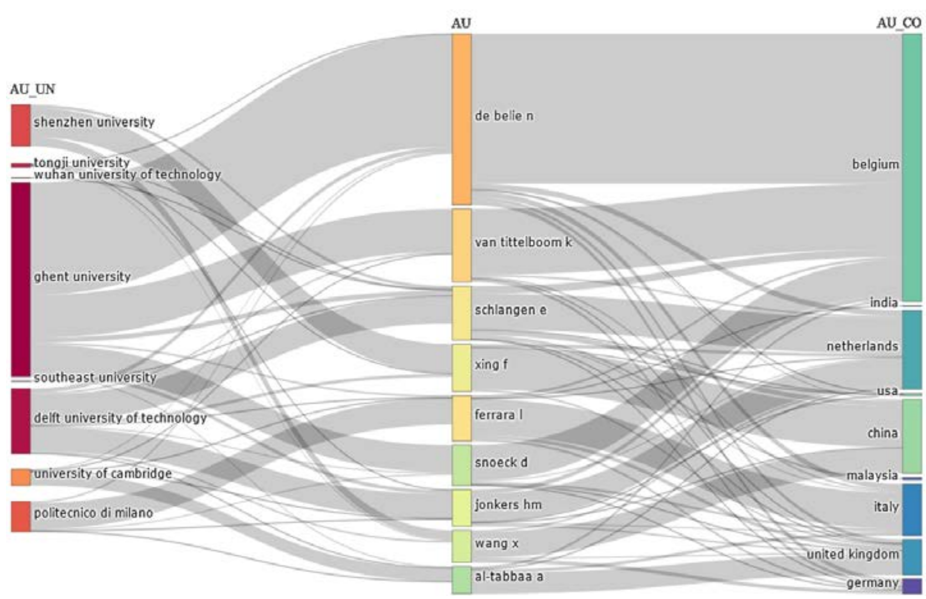


Fig. 3: Three-field plot analysis of countries (AU_CO), authors (AU), and affiliation (AU_UN).

Information related to the citations of these publications was drawn from the results obtained from Biblioshiny. The most cited documents identified after the bibliographic search are shown in Table 3. The number of the total citations ranged from 232 to 722, with most documents being review articles. The high number of citations for review articles is owed to their use as a base for future research. Furthermore, five of the top ten documents were related to the self-healing of concrete using bacteria, i.e., microbially induced carbonate precipitation. This indicates that researchers have been utilizing naturally existing materials rather than manufactured products in the self-healing of concrete.

To explore the trends (or "hot topics") in self-healing concrete, the top 20 keywords along with their frequency (Freq.) were summarized in Table 4. This analysis identifies the focus or areas of interest relevant to self-healing concrete and whether this focus shifted over time. The dominant words, excluding concrete, self-healing materials, and self-healing, were cracks, calcium carbonate, bacteria, compressive strength, durability, and repair. Based on this finding, most research seems to have examined the compressive strength and durability performance of self-healing concrete that sealed cracks using bacteria or microbially induced calcium carbonate precipitation.

Table 3: Top ten most cited papers.

R	Paper Title	Citations
1	Microbial carbonate precipitation in construction materials: A review [24]	722
2	Self-Healing Materials [25]	718
3	Water Permeability and Autogenous Healing of Cracks in Concrete [26]	591
4	Application of bacteria as self-healing agent for the development of sustainable concrete [27]	656
5	Quantification of crack-healing in novel bacteria-based self-healing concrete [8]	498
6	Self-Healing in Cementitious Materials—A Review [29]	426
7	Self-healing concrete by use of microencapsulated bacterial spores [15]	393
8	Permeability and self-healing of cracked concrete as a function of temperature and crack width [30]	369
9	Use of silica gel or polyurethane immobilized bacteria for self-healing concrete [31]	358
10	Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent [32]	232

R = Rank

Table 4: Top twenty frequent keywords in literature.

Frequent Keywords											
R	Keyword	Freq.	R	Keyword	Freq.	R	Keyword	Freq.	R	Keyword	Freq.
1	Concretes	558	6	Self-healing concrete	223	11	Durability	151	16	Cementitious materials	118
2	Self-healing materials	526	7	Bacteria	216	12	Cements	146	17	Scanning electron microscopy	114
3	Self-healing	461	8	Compressive strength	205	13	Mortar	146	18	Bacteriology	102
4	Cracks	409	9	Self-healing concretes	187	14	Calcite	125	19	Concrete construction	95
5	Calcium carbonate	290	10	Repair	167	15	Reinforced concrete	120	20	Chlorine compounds	89

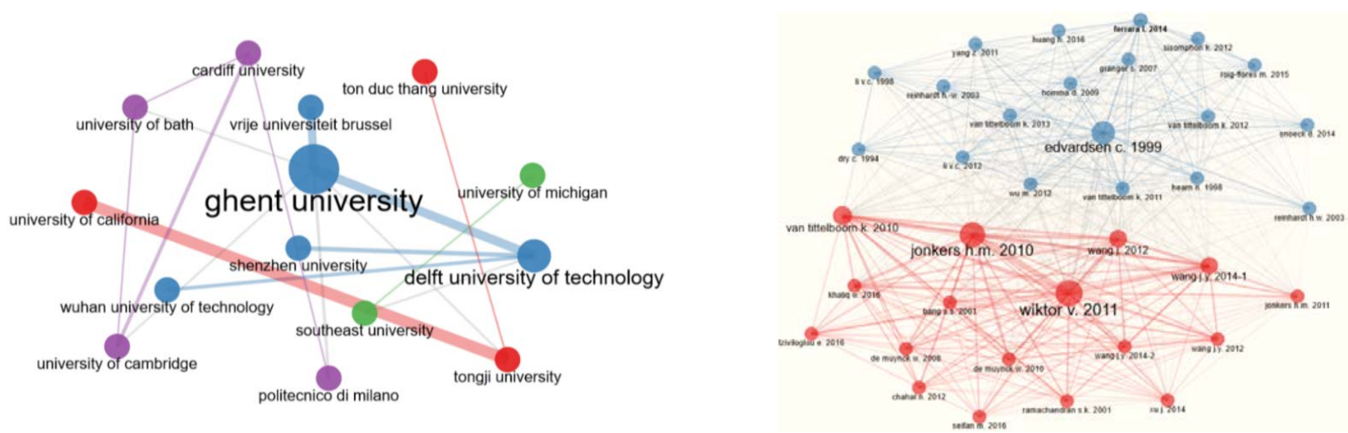
R = Rank; Freq. = Frequency.

To examine the trends during the overall investigated period (1974 – 2021), the articles were divided into periods, 1974-2000, 2001-2010, and 2011-2021. In the period 1974-2000, keywords such as cracks, degradation, strength, durability, bridges, and reinforced concrete were commonly used. This shows that the main research topics involved the repair of cracks in bridges and reinforced concrete to maintain strength and durability performance. Also, the electric field effect, which evolved into electrodeposition technology, an autonomous self-healing technique, was investigated during this period. In the following period of 2000-2010, the term "self-healing concrete" was introduced. Studies also focused on bacteriology, bacteria, cracks, and calcium carbonate. This shows that the use of bacteria to induce calcium carbonate precipitation as a form of repair or self-healing of concrete began to receive major attention. In the final period 2011-2021, still, research was conducted in the field of self-healing concrete using bacteria but with more emphasis on its mechanical and durability properties and microstructure. Real-life applications of self-healing concrete were not well represented in the keywords. This shows that research on the performance of self-healing concrete in real-life applications is lacking. Also, terms relating to the rheological properties and optimization of self-healing mechanisms are not clearly identified. Microstructure techniques other than scanning electron microscopy could be used to understand the post-repair changes. Thus, further research in these areas should be carried out.

3.2. Science Mapping

Science mapping examines the relationships relevant to the intellectual interactions and structural connections the research constituents. The collaboration network among countries is presented in Fig. 4. It can be seen that are made between countries located within the same geographical area, e.g., Europe, and those across different continents and speaking different native languages, e.g., USA and China. In fact, these two countries have more cross-country collaborations than any of the others identified in the present work, providing an explanation for their high number of publications (105 and 203, respectively). Furthermore, the university-based collaboration network in Fig. 5(a) corroborates this finding, where the highest number of collaborations exist between the University of California in the USA and Tongji University in China. Another major collaboration is noted between Ghent University, Belgium and Delft University of Technology, Netherlands, with 197 and 103 publications, respectively. This is supported by the author collaboration network of Fig. 5(b), which displays extensive collaborations among authors from these two universities.

Fig. 4: Country collaboration map.



(a) (b)

Fig. 5: Collaboration network among (a) universities and (b) authors.

4. Conclusions

Self-healing concrete has received growing attention in the past few years. With the escalating number of publications, accumulating knowledge has become more complicated. Using bibliometric analysis, this study mapped the evolution of interest in self-healing concrete among the different research constituents in addition to revealing research trends and identify the key contributors, research themes, and critical publication outlets and topics. Performance analysis revealed that most publications were journal articles (60%) and papers published in conference proceedings (26%). The most productive universities were Ghent University, Belgium and Delft University of

Technology, Netherlands. The data also showed that research on self-healing concrete surged after the year 2000, with review papers being the most cited. Citation and keywords analysis revealed that research on utilizing bacteria in self-healing concrete was the most trending topic. The relationship between research constituents highlighted high collaboration rates between countries regardless of geographic location and top publishing universities and authors. Furthermore, the findings of this study highlight the need for studies examining the applications and performance of self-healing concrete in real-life scenarios. The rheological properties, optimization of self-healing mechanisms, and utilization of microstructure evaluation techniques should also be investigated in future studies.

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