International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Annales de Chimie - Science des Matériaux
Vol. 48, No. 4, August, 2024, pp. 467-479
Journal homepage: http://iieta.org/journals/acsm

Mapping Publications of Cracks Monitoring in Concrete Structures: Bibliometric and Scientometric Review in 2013-2023

Kharisma Wira Nindhita, Ahmad Zaki*, Guntur Nugroho

Magister of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Bantul 55183, Indonesia

Corresponding Author Email: ahmad.zaki@umy.ac.id

https://doi.org/10.18280/acsm.480404

Received: 11 January 2024
Revised: 12 June 2024
Accepted: 17 July 2024
Available online: 30 August 2024

Keywords:
bibliometric, concrete, crack, monitoring, scientometric, VOS Viewer

ABSTRACT

In recent years, various monitoring methods for concrete structures have been widely researched and applied. However, there are still many research gaps found in related research due to the absence of comprehensive research that maps this research trend. This research presents a comprehensive bibliometric and scientometric analysis regarding "Monitoring Cracks in Concrete Structures" by Scopus over the last decade (2013-2023) with the help of VOS viewer software. From the results of the analysis, it was found that the research trend was increasing with research developments led by China and the USA. The results of the network visualization analysis also show 7 clusters or hotspots for research development, one of which is the concrete damage detection method. In the future, collaboration and integration of monitoring systems based on IoT, deep learning, and CNN can be further developed, so that the data produced is more real-time and accurate.

1. INTRODUCTION

Concrete is a popular material used in the field of infrastructure construction, be it buildings, bridges, roads, drainage channels, dams and coastal buildings [1, 2]. The use of concrete materials always increases from year to year globally [3]. In 2019 concrete use increased from 2.8 to 4.08 billion tons [4]. Meanwhile, the type of concrete structure that is most widely used today is the type of reinforced concrete which is more practical, but is able to withstand compression and bending [5]. However, steel reinforcement also has a weakness for corrosion which can reduce the strength and service life of the structure, as well as increase the cost of maintenance and repair of the structure [1, 6-8].

Apart from that, damage to concrete, especially cracks, both small and large, due to overload or weather can also cause further damage to the concrete, such as corrosion [9, 10]. The accumulation of corrosion or rust products in the reinforcement can peel off the concrete cover, causing structural failure [11-14]. Therefore, to mitigate and prevent more severe cracks, it is necessary to carry out a real-time monitoring process. So, concrete can be handled as early as possible to save costs and repair labor [1, 15, 16].

Remembering that the monitoring process in concrete buildings is very important for the engineering aspect. So, in recent years various monitoring methods on concrete structures have been widely researched and applied. Such as research related to the use of Non-Destructive Test (NDT) methods in the form of wave emissions [17], one of which is Acoustic Emission (AE) [6, 16, 18] and Electromechanical Impedance (EMI) [19] for monitoring concrete damage due to cracks. and corrosion. Then AE research was collaborated with Machine Learning which was used to detect crack types [20]. In further research, the process of monitoring crack types was also collaborated with image processing [21], one of which was the Unmanned Aerial Visual (UAV) method [22] and the creation of semi-automatic 3D maps on large structures [23], then processed using Network techniques. Convolutional Neural (CNN) [24]. Not only monitoring research on old structures, but real-time monitoring processes are also applied to the concrete curing process regarding strains and temperatures [25]. Of the various existing studies, most of them still focus on the laboratory scale, so the results obtained are sometimes less significant when applied in the field. Apart from that, most monitoring processes still use conventional methods, namely checking the location directly using tools, then the data is processed first to determine the type or level of damage, as well as appropriate repair methods. From these problems, of course research gaps are still found regarding the topic of monitoring cracks in concrete structures. So, further research is needed regarding the collaboration process between monitoring methods, data processing processes, and suggestions for appropriate types of improvements.

The research mapping process to find or analyze research gaps in a study can easily be carried out using bibliometric and scientometric methods. The bibliometric method can assist the process of analyzing scientific output related to document trends each year, type of document, country of origin, the most relevant publications, the most influential publications, and also the origin of the most productive documents publishing publications in the field of monitoring cracks in concrete structures. This method has been widely applied to analyze trends in various research fields such as health [26-29], environment and disaster [30-32], materials and energy [33-36], education [37-41], and processing engineering. data monitoring [42-45]. Apart from that, in more advanced analysis methods, bibliometric methods are often associated with scientometric methods which are able to analyze and map the evolution of knowledge from large datasets [26]. The scientometric analysis process is an interactive identical visualization of complex analytical data structures for statistics and interactive visual exploration [29, 30], with the help of one of the software tools, namely VOS Viewer. This software can be used as a visualization and mapping facility for research collaboration networks in various scientific literature [46, 47].

Therefore, this research aims to illustrate the visual relationship between publication connections, keywords, researchers, research countries, and study trends related to monitoring cracks in concrete structures using bibliometric [48] and scientometric [38] methods in the last decade (2013-2023). It is hoped that this research can provide a new perspective or research gap for further in-depth and collaborative research on equipment, data processing methods, and crack monitoring systems in concrete structures. So that the existence of a monitoring system for concrete structures can develop following technological trends and have more sophisticated capabilities and accurate results.

2. RESEARCH SCOPE AND SIGNIFICANCE

In this research, the mapping process will focus on monitoring cracks in concrete structures with the scope of research and research significance including:

a. Trends in the development of concrete crack monitoring tools and systems in a broader scope because most research focuses more on concrete behavior and data processing methods.
b. This research includes various studies that have existed over the last decade (2013-2023) related to methods, equipment, data processing and the process of monitoring cracks in concrete.
c. This research also attempts to visualize the network relationship between keywords, researchers, research countries, and study trends related to monitoring cracks in concrete structures.
d. This research not only seeks to conduct a comprehensive bibliometric and scientometric review regarding research development trends in the last decade. However, it also provides a new perspective or research gap related to future research on equipment, data processing methods, and crack monitoring systems in concrete structures.

3. RESEARCH METHOD

3.1 Data mining method

Research data collection was carried out by extracting publication data from the Scopus database. The code entered in the Scopus database is (TITTLE-ABS-KEY (monitoring AND cracks AND on AND concrete AND structure)). With "TITLE-ABS-KEY" which means article title, abstract, and keywords which function as a document search sorter in Scopus [26]. Data searches were limited to publications from the last decade, namely between 2013-2023. The search subject area is also limited to the Engineering field only. Meanwhile, document type, language, country, and document source are not limited. Restrictions on certain time periods and engineering fields are intended to further specify research and adapt to current technological developments. From the results of these restrictions, search results of 1,191 documents were obtained for further analysis regarding publication trends and relationships between documents using bibliometric and scientometric analysis methods.

3.2 Bibliometrics analysis method

Bibliometric analysis is a combination of quantitative and qualitative methods that also adopt statistical and mathematical methods [28, 31]. The bibliometric method is one of the most widely used methods to determine the development of certain sciences with various research objects such as publication trends, authors, topics, and others [34, 35, 49]. In this research, the bibliometric analysis method is used to sort large collections of literature and also analyze research development trends in certain fields [32, 47, 49, 50]. In this step, the Scopus database is analyzed regarding the development of document trends each year, document type, country of origin, the most relevant publications, the most influential publications, and the origin of documents that are most productive in publishing publications in the field of monitoring cracks in concrete structures. The data analysis and visualization process use the Microsoft Excel application as a processing tool.

The process of analyzing document trends each year will provide an overview of the development and number of concrete crack monitoring publications in the last decade, as well as the potential for development in the number in the future. Analysis of the classification of document types will greatly help readers regarding the diversity of types of documents that are often published and the depth of the types of research. The territory network analysis serves to show which countries are currently intensively conducting research related to monitoring concrete cracks. The most relevant publication analysis functions to show search results from the Scopus database that best match the search keywords. The analysis of the most influential publications serves to show which publications are the basic reference for various other studies related to monitoring cracks in concrete. Meanwhile, the analysis of publishers shows which publishers have productivity and play a role in spreading the field of concrete crack monitoring. Apart from that, it can also be known that further research can be developed in the future.

3.3 Scientometric analysis method

The scientometric analysis method is a quantitative analysis method for understanding trends or patterns that emerge in the knowledge structure of a research field [29]. Scientometric analysis is able to measure how big the impact of research is from the results of the relationship between research subjects, and is able to map the evolution of knowledge from large-scale datasets [26]. The process of scientometric analysis is identical to the mapping of data from scientific literature to the interactive visualization of complex data structures for statistical analysis and interactive visual exploration [29, 30].

In this research, VOS viewer software was used to assist the scientometric analysis process [37, 51]. This software is widely used for quantitative analysis to produce results in a way that is well-organized, meaningful, and easy to understand [43]. VOS Viewer software can also be used as a visualization and mapping facility for research collaboration networks in various research fields to analyze the intellectual landscape of various scientific literature [33, 46, 47].

Scientometric analysis with Vos Viewer software this time will focus on: (1) co-word analysis; (2) co-author analysis; and (3) cluster analysis. Co-word analysis includes an explanation of identifying the frequency of occurrence of keywords and research topics related to monitoring concrete cracks, as well as research developments [40]. Co-Author's analysis includes a collaboration network between authors, so that the writing patterns and partnerships that underlie research related to concrete crack monitoring can be identified [52]. Meanwhile, clustering analysis includes interpretation of keyword networks as well as relationships between keywords related to various concrete crack monitoring research [27, 30]. Meanwhile, the analysis techniques and settings used in the Vos Viewer software are shown in Table 1. From this table, the keyword mapping results produced 292 keywords from the limitation of words appearing at least 10 times. This limitation aims to further specify the level of relationship between keywords in the documents being analyzed. Meanwhile, the author mapping results resulted in 169 authors from the limitation of the appearance of a minimum of 4 documents. This limitation is intended to filter documents published by authors who specialize in that field.

Table 1. VOS viewer limitation method

Assessment	Consideration	
	Keywords	Authors
Analysis type	Co-occurrence	Co-authorship
Counting method	Full counting	
Units of analysis	All keywords	All Authors
Minimum occurrence	10 times	4 documents
Result outcomes	292 keywords	169 authors

4. RESULT AND DISCUSSION

Research and publications related to monitoring cracks in concrete structures have developed quite a lot from year to year. From the results of 1,191 documents found in the Scopus database search, several scientific mappings analyze can be described based on the number of documents per year, type of document, country of origin of the author, and occurrence of keywords. Co-authorship analysis can determine collaboration patterns between countries and institutions. In this section, the analysis aspects described are: (4.1) Annual publication trend analysis; (4.2) Territory network analysis; (4.3) Co-authorship analysis; (4.4) Most contributing documents and sources; (4.5) Document type distribution; and (4.6) Keyword clustering and hotspots.

4.1 Annual publication trend analysis

From the results of the Scopus database extraction, 1,191 documents were obtained for monitoring cracks in concrete in the Engineering sector in the period 2013-2023. Figure 1 shows the number of published documents indexed by Scopus. From the results of data processing, it can be seen that the number of publications in 2013 tended to be low and stagnant until 2020. However, the number of publications increased quite drastically when entered 2021, but the number of publications fell again in 2022. Meanwhile at the end of 2023 it was recorded that the number of publications related to monitoring cracks in concrete structures reached its highest point compared to previous years with175 documents.

From the analysis results, the trend of publications related to monitoring cracks in concrete structures has tended to increase in the last decade. This increase in the number of publications can be made possible by the increasing development of technology in monitoring building structures [53]. Moreover, concrete structures are the type of building that is most widely used throughout the world and susceptible to damage, even structural failure if they experience cracks [54].

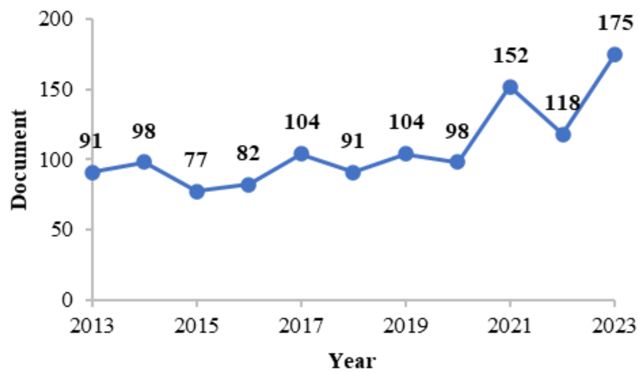

Figure 1. Annual publication trend

From the results of data analysis on related keywords, several publications with the most relevance were obtained with all the keywords entered in the Scopus database search source as shown in Table 2. From the total data, there were 5 publications with the most relevance, with the publication title in first place, namely "Identification and monitoring of concrete cracks based on optical frequency domain reflectometry technique" by Wu et al. [55] with the number of citations being 5.

Table 2. The most relevance publications

No.	Title	Authors	Year	Citations
1	Identification and monitoring of concrete cracks based on optical frequency domain reflectometry technique	Wu et al. [55]	2019	5
2	Experimental study on PPP-BOTDA-based monitoring approach of concrete structure crack	Su et al. [56]	2021	9
3	The monitoring method for crack damage of concrete structures based on piezoceramics transducers	Zhang [57]	2014	2
4	Research on performance of smart concrete materials and self-monitoring of cracks in beam members	Li et al. [58]	2023	1
5	Monitoring methods of crack behavior in hydraulic concrete structure based on crack mouth opening displacement (CMOD)	Huo et al. [59]	2014	1

Table 3. The newest publication

No.	Title	Authors
1	Analysis of Geometric Characteristics of Cracks and Delamination in Aerated Concrete Products Using Convolutional Neural Networks	Razveeva et al. [60]
2	Image-based Concrete Cracks Identification under Complex Background with Lightweight Convolutional Neural Network	Meng et al. [24]
3	Damage localization using acoustic emission sensors via convolutional neural network and continuous wavelet transform	Vy et al. [61]
4	Structural assessment of the pedestrian bridge accessing Civita di Bagnoregio, Italy	Buffarini et al. [62]
5	In-situ nonlinear ultrasonic technique for monitoring damage in ultra-high performance fibre reinforced concrete (UHPFRC) during direct tensile test	Yin et al. [63]

Meanwhile, from the 5 publications with the most relevance in Table 2, it can be seen that the publication entitled "Experimental study on PPP-BOTDA-based monitoring approach of concrete structure crack" by Su et al. [57] obtained the highest citations, namely 9 citations. From Table 2, the relevance of publications with the keywords entered is more directed at methods and equipment that are often used in monitoring cracks in concrete structures.

If the most relevant publications with keywords that have a span of more than 10 years refer to equipment and research methods for monitoring concrete cracks. So, in Table 3 which shows the latest publications, which were published in 2023, are more directed towards the integration of real-time monitoring systems by collaborating using the development of digital Convolutional Neural Network (CNN) technology. This is reflected in the first ranking of the latest publication entitled "Analysis of Geometric Characteristics of Cracks and Delamination in Aerated Concrete Products Using Convolutional Neural Networks" by Razveeva et al. [60].

4.2 Territory network analysis

In the last decade, China has been the country that has published the most research in the field of monitoring cracks in concrete structures. Based in Figure 2, the distribution of the number of research publication documents for the top 15 countries in related fields, China contributed the largest number of publications with 330 documents. Then followed by the USA and India with 184 and 78 documents respectively, as the largest contributors of documents in related fields. Meanwhile, Germany, Canada, UK, Australia, Italy, Japan, Belgium, France, Spain, South Korea, Malaysia, and Poland are also developing research in the field of monitoring cracks in concrete structures. Meanwhile, Figure 3 shows the distribution network and linkages between countries in the development of knowledge related to monitoring cracks in concrete structures developed by 84 countries. From this figure the strongest cross-country author collaboration relationships are owned by China (17 links) and the USA (29 links) which is also reflected in the number of documents produced by these two countries. China and the USA also collaborate with many other countries, so they have wide and large network coverage. Meanwhile, the United Kingdom (UK) (27 links) which contributed 54 documents, has a higher level of international collaboration than India (12 links) which is ranked 3rd in contributing the most documents. However, from the visualization results in Figure 3, there are still countries that are not yet connected in international collaboration but have started to develop research in related fields.

So, from the results of this analysis and visualization of countries that have participated in the development of research on monitoring cracks in concrete structures, there are still large opportunities to establish international research collaborations and exchange new ideas between countries on a broader scale. Thus, research related to monitoring cracks in concrete structures can be more developed and accurate.

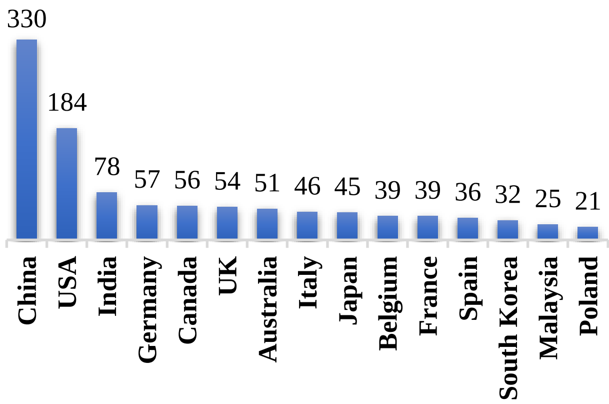

Figure 2. Territory participant

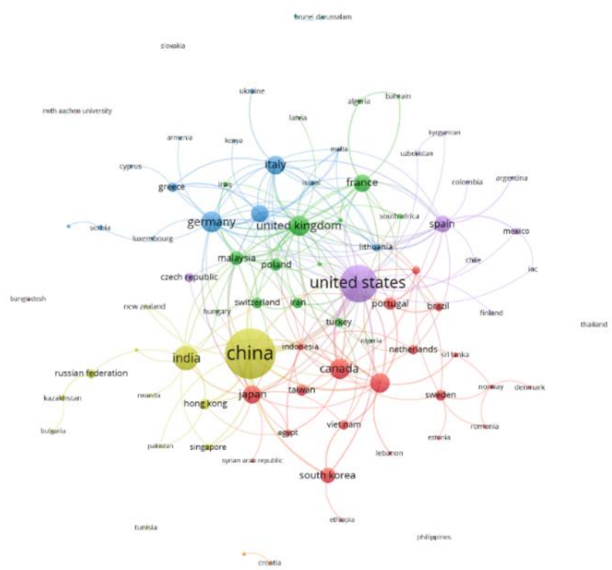

Figure 3. Country distribution and network

4.3 Co-authorship analysis

The results of the analysis of the authorship network related to monitoring cracks in concrete structures in the last decade are shown in Figure 4. From the visualization results of the authorship mapping, the names of the authors are dominated by Chinese people in the red cluster. This is of course in line with the existence of the largest number of publications coming from China. However, the distribution of the network from the red cluster which is dominated by Chinese people has not yet widely reached all clusters, because collaboration between researchers is still limited to national collaboration or in the same country, as is also the case in other clusters.

Meanwhile, Figure 5 shows a visualization of the affiliate network or organization from the author mapping results. From the visualization results, the network linkages between affiliates are still not evenly connected. Only few affiliates are connected and form their own cluster. This shows that the level of collaboration between researchers is still relatively low, because it is possible that researchers have still collaborated with the same researchers in recent years. So, from the results of this visualization, it is hoped that in future research, researchers can further expand international connections and collaboration in related research fields which can encourage the development of concrete structure crack monitoring system technology to become more sophisticated and accurate.

4.4 Most contributing documents and sources

Based on the results of analysis of 1,191 documents in the field of monitoring cracks in concrete structures, there are the top 10 most productive journals in the last decade related to this field. It can be seen in Figure 6 that the distribution of documents from the top 10 journals is, Construction and Building Materials (52 documents), Proceedings of SPIE (50 documents), Lecture Notes in Civil Engineering (47 documents), Engineering Structures (37 documents), Sensors Switzerland (36 documents), Applied Mechanics and Materials (31 documents), Structural Health Monitoring (31 documents), Advanced Materials Research (28 documents), Sensors (20 documents), and Smart Materials and Structures (18 documents). Of the top 10 journals, the “Construction and Building Materials” journal occupies the highest position as the document source that contributes most to the research field of crack monitoring in concrete structures. Moreover, the “Construction and Building Materials” journal is one of the well-known journals with the publisher Elsevier which is the owner of the Scopus database.

However, the results of the analysis of the highest number of citations, the first place with 687 citations was obtained by Dung and Anh [64] with the publication title "Autonomous concrete crack detection using deep fully convolutional neural network" from the journal "Automation in Construction". Even though the highest number of publications was obtained by the journal "Construction and Building Materials", one of its publications is still in third place with a total of 439 citations and the publication title "Comparison of deep convolutional neural networks and edge detectors for image-based crack detection in concrete” by Dorafshan et al. [65].

From the results of the analysis in Table 4, the trend in research development in the field of monitoring cracks in concrete structures is more towards developing damage detection, especially cracks in real time and automatically. Apart from that, the use of sensors and Unmanned Aerial Vehicles (UAV) combined with deep learning systems has also been increasingly developed in recent years, considering the increasing development of the digital world and the enormous number of citations in related research.

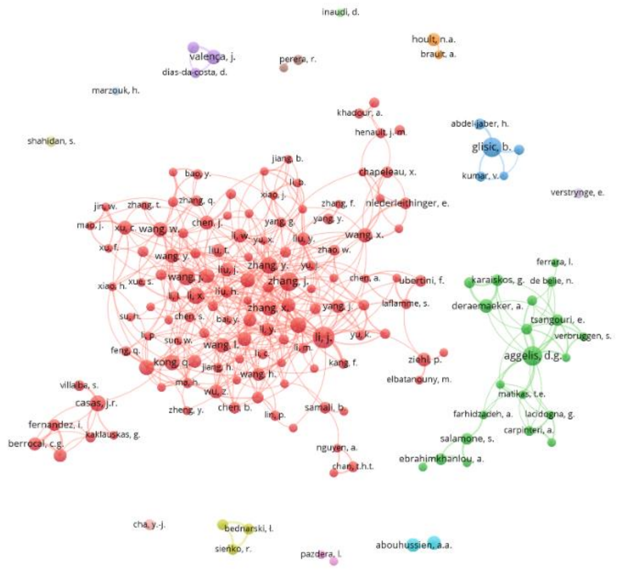

Figure 4. Co-authorship network

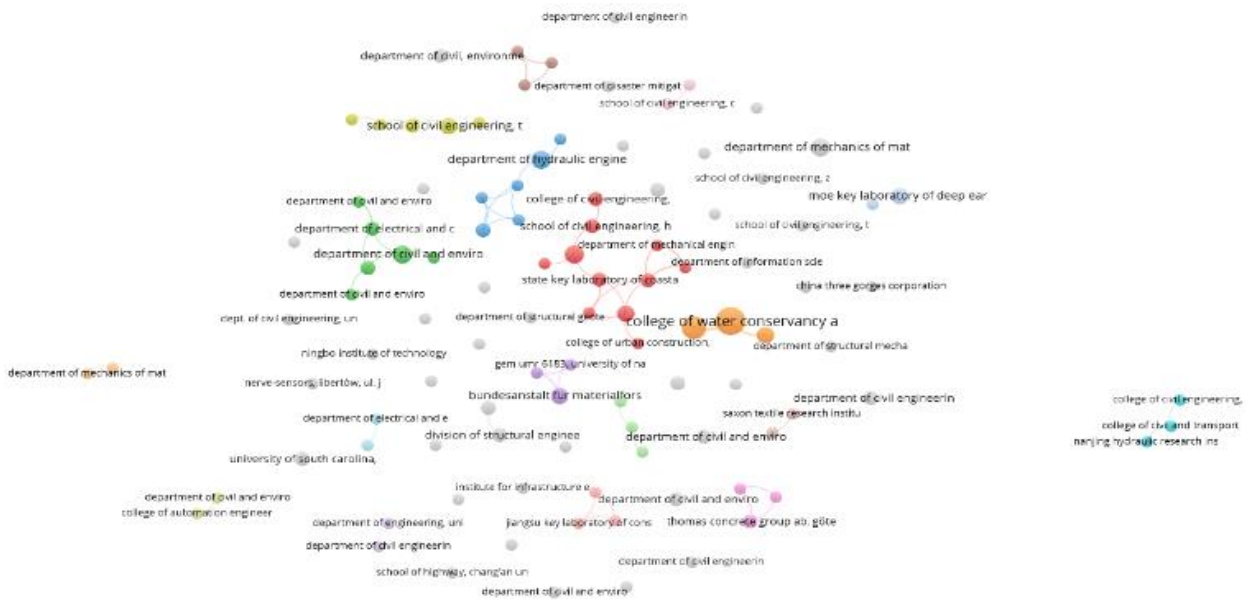

Figure 5. Affiliation distribution and network

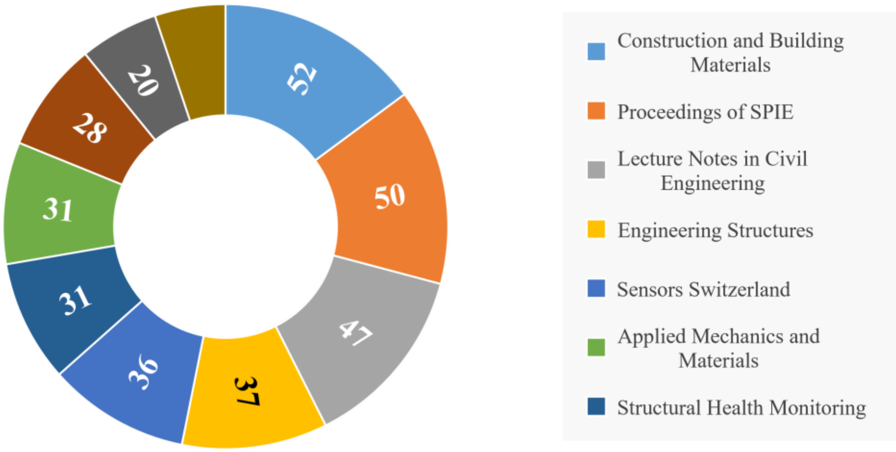

Figure 6. Most contributing document sources

Table 4. The most impactful document

No.	Title	Authors	Source	Year	Citations
1	Autonomous concrete crack detection using deep fully convolutional neural network	Dung and Anh [64]	Automation in Construction	2019	687
2	Intrinsic self-sensing concrete and structures: A review	Han et al. [66]	Journal of the International Measurement Confederation	2015	513
3	Comparison of deep convolutional neural networks and edge detectors for image-based crack detection in concrete	Dorafshan et al. [65]	Construction and Building Materials	2018	439
4	Automated crack detection on concrete bridges	Prasanna et al. [67]	IEEE Transactions on Automation Science and Engineering	2016	320
5	Investigations on scalable fabrication procedures for self-sensing carbon nanotube cement-matrix composites for SHM applications	D'Alessandro et al. [68]	Cement and Concrete Composites	2016	256

4.5 Document type distribution

Of all the types of documents contained in the Scopus database related to monitoring cracks in concrete structures, there are 5 types of documents that discuss related topics. Document types are divided into articles, conference papers, conference reviews, book chapters, and reviews. It can be seen in Figure 7 that the largest distribution is in the article document type which occupies 60% or 711 documents. Furthermore, the conference paper document type occupies 29% or 344 documents, conference review accounts for 6% or 71 documents, book chapters account for 4% or 44 documents, and reviews account for 1% or 18 documents.

From the various types of documents, it can be seen that articles occupy the highest distribution of document types, this is possible because most of the research related to monitoring cracks in concrete structures is the result of field tests using tools and then the data is processed, thereby obtaining a conclusion regarding the condition of the structure being studied. Likewise, in the conference paper document type, it is possible for research to focus more on the results of field studies using new methods or real case studies that produce conclusions about the condition of a structure.

Meanwhile, conference review, book chapter and review document types are more likely to discuss theory, elaboration of new formulas, or even a summary of developments in methods and technology for monitoring cracks in concrete structures. Thus, the research trend related to monitoring cracks in concrete structures is dominated by the type of research articles that are more detailed regarding the actual results of experiments and assessments in the field.

Figure 7. Document type distribution

4.6 Keyword clustering and hotspots

In various research fields, the main essence of each discussion is illustrated by the keywords used. Figure 8 shows a visualization of the distribution and connections between keywords in research in the field of monitoring cracks in concrete structures. From 1,191 documents analyzed using VOS Viewer software, overall visualization results were obtained regarding keywords that often appear or are used by researchers. Various dots have different sizes and colors. The larger the dot size, the greater the frequency of appearance of the word in each document. Meanwhile, the difference in color at each point better describes the division of research types based on clusters formed from the VOS viewer software.

It can be seen in Figure 8 that several words have a point size that is larger than other points, such as cracks, reinforced concrete, concrete beams and girders, structural health monitoring, concretes, crack detection, acoustic emissions, damage detection, prestressed concrete, and corrosion. All of these keywords form a cluster and network that is interconnected with each other. There are 7 clusters with 7 different colors which are described in points 4.5.1 to 4.5.7 below.

4.6.1 Cluster 1 (red cluster)

Based on the visualization in Figure 8, the first cluster is marked in red and the keyword “cracks “is a word that is often used in research on monitoring cracks in concrete structures. The keyword "cracks" is the main keyword in this field of research because the focus of this research is on cracks in the concrete structure that will be studied. The keyword "cracks" has a frequency of appearance of 404 times with connections to other words of 259 links. The keyword "cracks" also has a connection with big keywords from each cluster such as "reinforced concrete", "structural health monitoring", "concretes", "damage detection", "prestressed concrete", "acoustic emissions", and "corrosion".

From the results of the analysis of the mapping in Figure 8, the results obtained are that cluster 1 or cluster red which has the big keyword "Cracks", better describes the mechanical properties of the structure studied. This relationship is illustrated between the keyword "Cracks" and keywords that indicate factors in the occurrence of a crack such as "ductility", "deformation", "fracture", "fatigue", "failure", "tensile", and others. So, red cluster or cluster 1 describes the mechanical properties factors that cause cracks in concrete structures.

4.6.2 Cluster 2 (green cluster)

Figure 8 shows the clustering network for the main keyword reinforced concrete which is marked in green. The second cluster is dominated by the keyword "reinforced concrete" with a total of 343 occurrences and 253 links, followed by the keyword "concrete beams and girders" with 200 occurrences and 239 links. This cluster is also connected to other large clusters such as the keywords "cracks", "structural health monitoring", and others.

The results of the analysis of the green cluster in Figure 8 show that this cluster is more directed towards the use of fiber as an additional ingredient in concrete mixtures which is known to increase the ability of concrete to withstand loads and help reduce damage to concrete, especially cracks. In this cluster, it can also be seen that the crack monitoring tool that is often used in concrete structures is in the form of a sensor or fiber optic sensor. Meanwhile, the main keyword, namely "reinforced concrete", shows that most of the research focuses on reinforced concrete structures which are the type of structure most widely used in this era. So, in this cluster, the type of keyword that is highlighted is the use of additional materials in the form of fiber to increase the ability of concrete to resist damage, one of which is cracking.

4.6.3 Cluster 3 (blue cluster)

Figure 8 shows the clustering network marked in blue. The third cluster is dominated by the keywords "Structural health monitoring", "Concretes", "Concrete construction", "Concrete building", and "Crack detection". In this cluster, there is a strong connection between keywords, so that the number of word occurrences and total links for several large keywords in this cluster are not too different. Table 5 shows the number of keywords with the highest occurrences and links in this cluster.

From the results of the analysis of the blue cluster in Figure 8, it shows that the keyword "structural health monitoring" is the main keyword in this cluster. In this cluster, the relationship between keywords is more directed at processing and data retrieval methods for detecting damage to concrete structures. Data collection methods for damage detection include "visual inspection" and "Unmanned Aerial Vehicle (UAV)". Then the data processing method resulting from structural monitoring can use machine learning, deep learning, automation, deep neural networks, and image processing. So, in this cluster it can be seen that the type of keyword that will be highlighted is the method of collecting and processing data for detecting damage to concrete structures.

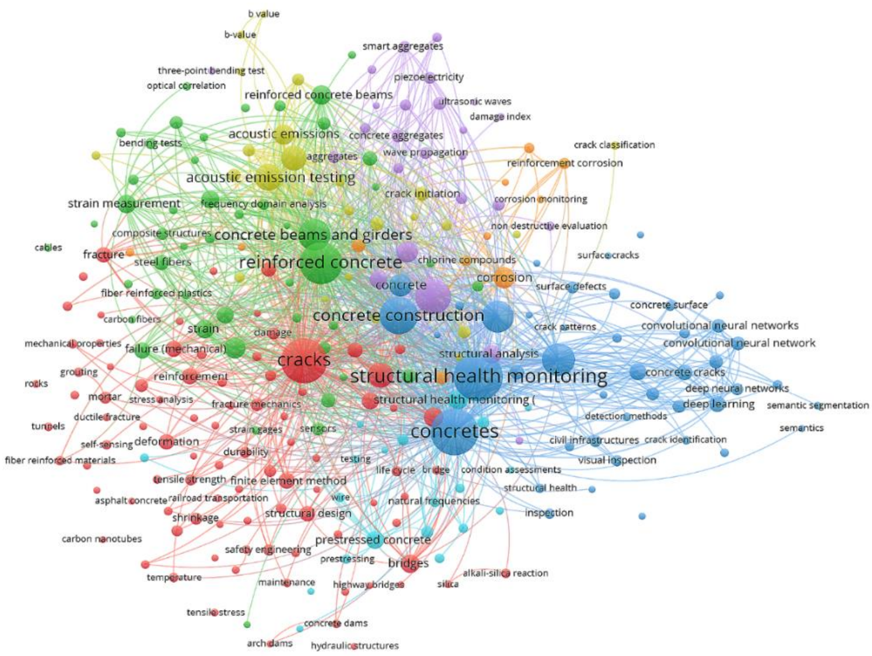

Figure 8. Visualization of keyword network and distribution

Table 5. Blue cluster links and occurrences

Keyword	Occurrences	Links
Structural health monitoring	456	257
Concretes	434	258
Concrete construction	272	258
Concrete building	202	243
Crack detection	213	235

4.6.4 Cluster 4 (yellow cluster)

The 4th cluster is marked in yellow as shown in Figure 8. This cluster shows the dominance of the keyword by the word "Acoustic emission" which is a type of Non-Destructive Test (NDT) that has been very popular in the last few years until now. The keyword "acoustic emissions" has a frequency of 123 occurrences and a total of 189 links. Meanwhile, the keyword "Acoustic emissions testing" has 146 occurrences and 204 links.

In this cluster, the relationship between keywords refers more to the method that is often used in crack testing of concrete structures, namely the use of acoustic emission. Acoustic emissions will be closely related to research that leads to the detection of damage to structures, especially reinforced concrete, and also corrosion. Thus, this cluster emphasizes the acoustic emission method as one of the popular methods used to detect damage to concrete structures.

4.6.5 Cluster 5 (purple cluster)

Based on Figure 8, this 5th cluster is shown in purple which is dominated by the words "Damage detection" and "Nondestructive examinations". With the frequency of appearance of the keyword "damage detection" 240 occurrences and 247 links. Meanwhile, the keyword, "Nondestructive examination" has 90 occurrences and 191 links. Where the keyword "damage detection" is very closely related to the keyword "structural health monitoring" (cluster 2) which refers to methods for detecting and processing data on damage to concrete building structures. Meanwhile, the keyword "Nondestructive examination" is more closely related to the keyword "Cracks" (cluster 1), which means the purpose of non-destructive testing is to check for damage, especially cracks in building structures.

The results of the analysis of the internal relationships between keywords in the purple cluster are as shown in Figure 8, which tends to lead to the type of damage detection tool for concrete structures. This type of detection tool refers more to Non-Destructive Test (NDT) equipment such as the use of ultrasonic waves, piezoelectricity, transducers, elastic waves, and coda waves. So, in this cluster, it can be seen that the keyword highlighted is the type of damage detection tool in concrete structures.

4.6.6 Cluster 6 (ocean blue cluster)

The color distribution in the 6th cluster is shown in ocean blue as shown in Figure 8. The most dominant keyword is the word "Prestressed concrete" with 62 occurrences and 158 links. The keyword "prestressed concrete" has a close relationship with the keyword "concrete beams and girders" (cluster 2). This is possible because most concrete beam and girder construction uses prestressed concrete structures.

Apart from that, the internal relationship between keywords in cluster 6 focuses more on the properties and behaviour of prestressed concrete structures such as stiffness, prestressing, vibration and post-tension concrete. The application of prestressed concrete is closely related to the structure of concrete bridges, also composite beams and girders. So, in this cluster the keywords are more prominent in field structures which are often used as research objects in monitoring cracks or damage to concrete structures.

4.6.7 Cluster 7 (orange cluster)

In the 7th cluster, the grouping is shown in orange as can be seen in Figure 8. The most dominant keyword is the word "Corrosion" with 86 occurrences and 169 links. This keyword is very closely related to the keywords "Reinforced concrete" (cluster 2), "concretes" (cluster 3), and "cracks" (cluster 1). This is possible because the main factor of corrosion in reinforced concrete is caused by cracks which can accelerate the rate of corrosion in concrete reinforcement.

Apart from that, the internal relationship in this cluster also shows that corrosion has several other factors that cause damage to reinforced concrete to become more severe, namely the presence of chloride diffusion which can increase the corrosion rate of reinforced concrete structures. In this cluster, there is also the keyword "repair" which indicates that research related to monitoring cracks in concrete structures does not only focus on structural behaviour, detection tools, and processing methods but can also be linked to further treatment of structural damage that may have occurred. So, in this cluster, the keyword is more prominent in one type of damage that arises due to cracks in reinforced concrete structures, namely corrosion.

5. CHALLENGE, PERSPECTIVE, AND FUTURE DIRECTION

Various methods for monitoring concrete cracks have developed greatly in the last decade. It can be seen from the related research trend that it is towards increasing every year. In its development, the process of monitoring concrete cracks has been widely applied both on a laboratory and field scale. So, the limitations, potential applications and further research related to monitoring cracks in concrete can be summarized as follows:

5.1 Non-destructive test method

Various methods for monitoring concrete cracks initially used visual assessment methods, which were later developed using Non-Destructive Test (NDT) methods. The NDT method has been widely researched and used in the process of monitoring concrete cracks [69]. These various studies include NDT using Acoustic Emission (AE) [70-75], ultrasonic wave [63, 76, 77], electromechanical impedance [19], Impact Echo (IE) [78], Ground Penetrating Radar (GPR) [79], and others. The monitoring method used is not limited to normal concrete, but also begins to research the characteristics of geopolymer concrete, the influence of environmental conditions, corrosion and self-healing concrete. Apart from that, in the monitoring process on a larger scale, monitoring processes have begun to be developed using Unmanned Aerial Vehicle (UAV) or drone technology [21-23, 80]. So the monitoring process can be carried out on a large scale with image-based output. However, the monitoring process still requires scheduled maintenance which is less efficient in time and energy. So there is still a need for integration with other technologies to improve the automation system and the accuracy of monitoring concrete cracks.

5.2 Automation and efficiency of concrete crack monitoring

Apart from the development of conventional NDT methods, the use of sensors as a concrete monitoring development is also starting to be widely developed [81]. Various monitoring of concrete cracks such as the use of fiber optic sensors [44, 82, 83], piezosensor [84], and wireless sensors [85, 86]. Apart from that, the use of sensors in the process of monitoring concrete cracks also supports the real-time detection process, so that damage to concrete can be immediately detected. Apart from that, there are technological developments such as the Internet of Things (IoT) [45] and Artificial Intelligence (AI) such as Machine Learning [87, 20], Deep Learning (DL) [80, 88], Arificial Neural Network (ANN) [42], and Convolutional Neural Network (CNN) [53] can be integrated into a concrete monitoring system to process input data from the field. This integration process is also intended to improve the damage detection automation process, data processing efficiency, and increase detection accuracy.

5.3 Automatic labeling and repair optimization

Currently, the process of monitoring damage to concrete is still done manually, so it takes a lot of time and energy. Meanwhile, automatic crack monitoring and analysis processes are still rarely implemented. Therefore, in the future there is a need to develop technology related to automatic detection processes accompanied by automatic labeling processes for various types of concrete cracks based on AI. The automatic labeling process will be very useful in making decisions about the type of repair for concrete damage. In further research, database technology can also be developed that can provide recommendations for repairing concrete damage automatically from the results of processing types of concrete damage labeling. However, this technology still needs to be studied by relating various factors, such as environmental conditions, weather, structural materials, ease of access to repairs, level of damage, time, repair costs, and various other factors that greatly influence the strength of the structure.

5.4 Central database monitoring detection

In the development of advanced research, when all damage monitoring components have been tested in the laboratory and field, a central database can be created regarding various types of cracks and suggestions for appropriate repairs. This database will be very useful for the process of monitoring infrastructure that is considered vital or important, thereby minimizing excessive damage to infrastructure. However, the creation of this database still requires in-depth study and collaboration of various components both across fields and countries. This is also related to the need for input of large amounts of data with various environmental conditions and effects that can have fatal consequences on infrastructure. Apart from that, various track records of previous damage can be used as a reference for repairing other infrastructure that has experienced similar types of damage.

6. CONCLUSION

This research presents a comprehensive bibliometric and scientometric analysis of the development of "Monitoring Cracks in Concrete Structures" published by Scopus over the last decade (2013-2023). Research includes analysis of document trends each year, keyword networks, author networks, affiliate networks, country networks, sources, types of documents, the most impactful documents, and mapping of emerging technologies. The scientometric method with the help of VOS viewer software is applied to analyze and visualize the relationship between keywords, authors, countries, and institutions/organizations affiliated with the author. From the 1,191 documents analyzed, the following conclusions can be drawn:

1. The publication trend tends to increase from year to year, although it cannot be said to be a stable trend. With the latest research trends that focus more on methods and equipment that are often used in monitoring cracks in concrete structures, as well as the integration of real-time monitoring systems by collaborating using the development of digital Convolutional Neural Network (CNN) technology.
2. There are 84 countries developing research on monitoring cracks in concrete structures, with China and the USA as the most productive countries in publications. The mapping results produce a visualization that there is still low collaboration between affiliates or countries. Thus, opportunities to establish international research collaborations on a wider scope are still wide open for the development of more up-to-date and accurate tools, methods and monitoring systems.
3. The results of the analysis show that the distribution of document types is dominated by articles at 60%. The most productive and contributing document source is the journal "Construction and Building Materials". Apart from that, the 3 publications with the most citations also came from this journal.
4. From the results of the network visualization analysis, 7 research clusters or hotspots were formed in the field of monitoring cracks in concrete structures, namely mechanical properties of concrete, added materials in the form of fiber, data collection and processing methods, detection methods using acoustic emissions, types of digital detection tools, structure of the research object, and concrete corrosion.
5. In future research related to monitoring cracks in concrete structures, it can be further developed by expanding the use of NDT-based detection or monitoring tools and the use of ultrasonic waves. Apart from that, data processing methods and monitoring systems can be collaborated with the integration of the Internet of Things (IoT), deep learning, and Convolutional Neural Network (CNN), so that the resulting data is more real-time and accurate. From the development of existing methods and equipment, it is hoped that it can also develop in accordance with technological developments, and be easy to apply to field structures such as bridges, buildings, etc.

REFERENCE

[1] Yip, B.F., Haniffah, M.R.M., Kasiman, E.H., Abidin, A.R.Z. (2022). Research progress on microbial self-healing concrete. Jurnal Teknologi, 84(3): 25-45. https://doi.org/10.11113/jurnalteknologi.v84.17895

[2] Nindhita, K.W., Zaki, A., Zeyad, A.M. (2024). Effect of Bacillus Subtilis Bacteria on the mechanical properties of corroded self-healing concrete. Frattura ed Integrita

Strutturale, 18(68): 140-158. https://doi.org/10.3221/IGF-ESIS.68.09
[3] Venkatesh, C., Chand, M.S.R., Nerella, R. (2019). A state of the art on red mud as a substitutional cementitious material. Annales de Chimie: Science des Materiaux, 43(2): 99-103. https://doi.org/10.18280/acsm.430206
[4] Akhtar, J.N., Khan, R.A., Khan, R.A., Akhtar, M.N., Nejem, J.K. (2022). Influence of natural zeolite and mineral additive on bacterial self-healing concrete: A review. Civil Engineering Journal, 8(5): 1069-1085. https://doi.org/10.28991/CEJ-2022-08-05-015.
[5] Prayuda, H., Soebandono, B., Cahyati, M.D., and Monika, F. (2020). Repairing of flexural cracks on reinforced self-healing concrete beam using bacillus subtillis bacteria. International Journal of Integrated Engineering, 12(4): 300-309. https://doi.org/10.3390/s150819069
[6] Zaki, A., Chai, H.K., Aggelis, D.G., Alver, N. (2015). Non-destructive evaluation for corrosion monitoring in concrete: A review and capability of acoustic emission technique. Sensors (Basel), 15(8): 19069-19101. https://doi.org/10.3390/s150819069.
[7] Ramón, J.E., Castillo, Á., Martínez, I. (2021). On-site corrosion monitoring experience in concrete structures: Potential improvements on the current-controlled polarization resistance method. Materiales de Construcción, 71(344): 265-276. https://doi.org/10.3989/mc.2021.11221
[8] Zaki, A., Megat Johari, M.A., Wan Hussin, W.M.A., Jusman, Y. (2018). Experimental assessment of rebar corrosion in concrete slab using ground penetrating radar (GPR). International Journal of Corrosion, 1-10. https://doi.org/10.1155/2018/5389829.
[9] Nindhita, K.W., Zaki, A. (2023). State of the art: Correlation self-healing agent and corrosion on concrete. In The Third International Conference of Construction, Infrastructure, and Materials (ICCIM 2023), Tarumanagara, Indonesia. https://doi.org/10.1051/e3sconf/202342905034
[10] Belhadj, A.H.M., Tenza-Abril, A.J., Mahi, A. (2023). Assessment of the durability against a chemical attack of Fiber-Reinforced Lightweight Pouzzolanic Concrete under the effect of temperature. Annales de Chimie - Science des Matériaux, 47(1): 25-33. https://doi.org/10.18280/acsm.470104
[11] Gao, Y., Suryanto, B., Chai, H.K., Forde, M.C. (2021). Evaluating the effect of corrosion on shear-critical RC beams by integrated NDT. Developments in the Built Environment, 7: 100050-100063. https://doi.org/10.1016/j.dibe.2021.100050.
[12] Astuti, P., Kamarulzaman, K., Hamada, H. (2021). non-destructive investigation of a 44-year-old RC structure exposed to actual marine tidal environments using electrochemical methods. International Journal of Integrated Engineering, 13(3): 148-157. https://doi.org/10.30880/ijie.2021.13.03.018
[13] Li, W., Wu, M., Shi, T., Yang, P., Pan, Z., Liu, W., Liu, J., Yang, X. (2022). Experimental investigation of the relationship between surface crack of concrete cover and corrosion degree of steel bar using fractal theory. Fractal and Fractional, 6(6): 325-340. https://doi.org/10.3390/fractalfract6060325
[14] Shevtsov, D., Cao, N.L., Nguyen, V.C., Nong, Q.Q., Le, H.Q., Nguyen, D.A., Zartsyn, I., Kozaderov, O. (2022). Progress in sensors for monitoring reinforcement corrosion in reinforced concrete structures-A review. Sensors (Basel), 22(9): 3421. https://doi.org/10.3390/s22093421
[15] Mirshahmohammad, M., Rahmani, H., Maleki-Kakelar, M., Bahari, A. (2022). Effect of sustained service loads on the self-healing and corrosion of bacterial concretes. Construction and Building Materials, 322: 126423-126438. https://doi.org/10.1016/j.conbuildmat.2022.126423
[16] Zaki, A., Chai, H.K., Behnia, A., Aggelis, D.G., Tan, J.Y., Ibrahim, Z. (2017). Monitoring fracture of steel corroded reinforced concrete members under flexure by acoustic emission technique. Construction and Building Materials, 136: 609-618. https://doi.org/10.1016/j.conbuildmat.2016.11.079
[17] Lei, D., Yang, L., Xu, W., Zhang, P., Huang, Z. (2017). Experimental study on alarming of concrete micro-crack initiation based on wavelet packet analysis. Construction and Building Materials, 149: 716-723. https://doi.org/10.1016/j.conbuildmat.2017.05.159
[18] Shahidan, S., Zuki, S.S.M., Jamaluddin, N. (2016). Damage grading system for severity assessment on concrete structure. Case Studies in Construction Materials, 5: 79-86. https://doi.org/10.1016/j.cscm.2016.09.001
[19] Kaur, H., Singla, S. (2022). Non-Destructive testing to detect multiple cracks in reinforced concrete beam using electromechanical impedance technique. Materials Today: Proceedings, 65: 1193-1199. https://doi.org/10.1016/j.matpr.2022.04.175
[20] Zhang, T., Mahdi, M., Issa, M., Xu, C., Ozevin, D. (2023). Experimental study on monitoring damage progression of Basalt-FRP Reinforced concrete slabs using acoustic emission and machine learning. Sensors, 23(20): 8356. https://doi.org/10.3390/s23208356
[21] Mousa, M.A., Yussof, M.M., Udi, U.J., Nazri, F.M., Kamarudin, M.K., Parke, G.A.R., Assi, L.N., Ghahari, S.A. (2021). Application of digital image correlation in structural health monitoring of bridge infrastructures: A review. Infrastructures, 6(12): 176. https://doi.org/10.3390/infrastructures6120176
[22] Kim, H., Lee, J., Ahn, E., Cho, S., Shin, M., Sim, S.H. (2017). Concrete crack identification using a UAV incorporating hybrid image processing. Sensors, 17(9): 2052. https://doi.org/10.3390/s17092052
[23] Merkle, D., Solass, J., Schmitt, A., Rosin, J., Reiterer, A., Stolz, A. (2023). Semi-automatic 3D crack map generation and width evaluation for structural monitoring of reinforced concrete structures. Journal of Information Technology in Construction, 28: 774-805. https://doi.org/10.36680/j.itcon.2023.040
[24] Meng, Q., Hu, L., Wan, D., Li, M., Wu, H., Qi, X., Tian, Y. (2023). Image-based concrete cracks identification under complex background with lightweight convolutional neural network. KSCE Journal of Civil Engineering, 27(12): 5231-5242. https://doi.org/10.1007/s12205-023-0923-1
[25] Jo, H.J., Park, D.Y., Kim, K.W., Ahn, T.J. (2023). Real-time monitoring of concrete curing using fiber Bragg grating sensors: Strain and temperature measurement. Sensors and Actuators A: Physical, 362: 114650. https://doi.org/10.1016/j.sna.2023.114650

[26] Zhong, B., Wu, H., Li, H., Sepasgozar, S., Luo, H., He, L. (2019). A scientometric analysis and critical review of construction related ontology research. Automation in Construction, 101: 17-31. https://doi.org/10.1016/j.autcon.2018.12.013

[27] Kocak, M., García-Zorita, C., Marugán-Lázaro, S., Çakır, M.P., Sanz-Casado, E. (2019). Mapping and clustering analysis on neuroscience literature in Turkey: A bibliometric analysis from 2000 to 2017. Scientometrics, 121(3): 1339-1366. https://doi.org/10.1007/s11192-019-03259-w

[28] Arshad, M., Qamar, A.M., Missen, M.M.S., Lodhi, A.A., Prasath, V.B.S. (2023). Global trends and collaborations in dengue virus research: A Scientometric and bibliometric overview (1872-2019). International Journal of Design & Nature and Ecodynamics, 18(6): 1539-1548. https://doi.org/10.18280/ijdne.180630

[29] Chen, C., Hu, Z., Liu, S., Tseng, H. (2012). Emerging trends in regenerative medicine: A scientometric analysis in CiteSpace. Expert Opinion on Biological Therapy, 12(5): 593-608. https://doi.org/10.1517/14712598.2012.674507

[30] Olawumi, T.O., Chan, D.W.M. (2018). A scientometric review of global research on sustainability and sustainable development. Journal of Cleaner Production, 183: 231-250. https://doi.org/10.1016/j.jclepro.2018.02.162

[31] Du, H., Li, B., Brown, M.A., Mao, G., Rameezdeen, R., Chen, H. (2015). Expanding and shifting trends in carbon market research: A quantitative bibliometric study. Journal of Cleaner Production, 103: 104-111. https://doi.org/10.1016/j.jclepro.2014.05.094

[32] Jiang, Y., Ritchie, B.W., Benckendorff, P. (2017). Bibliometric visualisation: An application in tourism crisis and disaster management research. Current Issues in Tourism, 22(16): 1925-1957. https://doi.org/10.1080/13683500.2017.1408574

[33] Jiménez-Islas, D., Pérez-Romero, M.E., Del Río-Rama, M.D.L.C., Flores-Romero, M.B. (2022). Mapping research trends in publications related to bio-jet fuel: A scientometric review. International Journal of Design & Nature and Ecodynamics, 17(1): 1-8. https://doi.org/10.18280/ijdne.170101

[34] Mao, G., Liu, X., Du, H., Zuo, J., Wang, L. (2015). Way forward for alternative energy research: A bibliometric analysis during 1994–2013. Renewable and Sustainable Energy Reviews, 48: 276-286. https://doi.org/10.1016/j.rser.2015.03.094

[35] Mao, G., Zou, H., Chen, G., Du, H., Zuo, J. (2015). Past, current and future of biomass energy research: A bibliometric analysis. Renewable and Sustainable Energy Reviews, 52: 1823-1833. https://doi.org/10.1016/j.rser.2015.07.141

[36] Chang, X., Zhang, R., Xiao, Y., Chen, X., Zhang, X., Liu, G. (2020). Mapping of publications on asphalt pavement and bitumen materials: A bibliometric review. Construction and Building Materials, 234: 117370. https://doi.org/10.1016/j.conbuildmat.2019.117370

[37] Orduña-Malea, E., Costas, R. (2021). Link-based approach to study scientific software usage: The case of VOSviewer. Scientometrics, 126(9): 8153-8186. https://doi.org/10.1007/s11192-021-04082-y

[38] Mingers, J., Leydesdorff, L. (2015). A review of theory and practice in scientometrics. European Journal of Operational Research, 246(1): 1-19. https://doi.org/10.1016/j.ejor.2015.04.002

[39] Moral-Muñoz, J.A., Herrera-Viedma, E., Santisteban-Espejo, A., Cobo, M.J. (2020). Software tools for conducting bibliometric analysis in science: An up-to-date review. El Profesional de la Información, 29(1). https://doi.org/10.3145/epi.2020.ene.03

[40] Chen, X., Chen, J., Wu, D., Xie, Y., Li, J. (2016). Mapping the research trends by co-word analysis based on keywords from funded project. Procedia Computer Science, 91: 547-555. https://doi.org/10.1016/j.procs.2016.07.140.

[41] Su, H.N., Lee, P.C. (2010). Mapping knowledge structure by keyword co-occurrence: A first look at journal papers in Technology Foresight. Scientometrics, 85(1): 65-79. https://doi.org/10.1007/s11192-010-0259-8

[42] Abdul Shahid, M.D., Mohd Hashim, M.H., Mohd Fadzil, N., Ahmad Rushdi, M.H., Al-Fakih, A., Muda, M.F. (2023). A bibliometric analysis on the relevancies of artificial neural networks (ANN) techniques in offshore engineering. Cogent Engineering, 10(1). https://doi.org/10.1080/23311916.2023.2241729

[43] Ali, L., Alnajjar, F., Khan, W., Serhani, M.A., Al Jassmi, H. (2022). Bibliometric analysis and review of deep learning-based crack detection literature published between 2010 and 2022. Buildings, 12(4). https://doi.org/10.3390/buildings12040432

[44] Mahbubi, K., Zaki, A., Nugroho, G. (2024). Bibliometric and scientometric trends in structural health monitoring using fiber-optic sensors: A comprehensive review. Journal of Civil and Hydraulic Engineering, 2(1): 51-64. https://doi.org/10.56578/jche020104.

[45] Rahita, A.C., Zaki, A., Nugroho, G., Yadi, S. (2024). Internet of Things (IoT) in structural health monitoring: A decade of research trends. Instrumentation Mesure Métrologie, 23(2): 123-139. https://doi.org/10.18280/i2m.230205

[46] Chou, J.S., Pham, A.D. (2013). Enhanced artificial intelligence for ensemble approach to predicting high performance concrete compressive strength. Construction and Building Materials, 49: 554-563. https://doi.org/10.1016/j.conbuildmat.2013.08.078

[47] Kazemi, R. (2023). Artificial intelligence techniques in advanced concrete technology: A comprehensive survey on 10 years research trend. Engineering Reports, 5(9): e12676. https://doi.org/10.1002/eng2.12676

[48] Otávio José de, O., Fabio Francisco da, S., Fernando, J., Luis César Ferreira Motta, B., Thaís Vieira, N. (2019). Bibliometric method for mapping the state-of-the-art and identifying research gaps and trends in literature: An essential instrument to support the development of scientific projects. In Scientometrics Recent Advances, IntechOpen: Rijeka. https://doi.org/10.5772/intechopen.85856

[49] Wang, Y., Lai, N., Zuo, J., Chen, G., Du, H. (2016). Characteristics and trends of research on waste-to-energy incineration: A bibliometric analysis, 1999-2015. Renewable and Sustainable Energy Reviews, 66: 95-104. https://doi.org/10.1016/j.rser.2016.07.006

[50] Sekhar, R., Sharma, D., and Shah, P. (2021). State of the Art in metal matrix composites research: A bibliometric analysis. Applied System Innovation, 4(4): 86. https://doi.org/10.3390/asi4040086

[51] Oyewola, D.O., Dada, E.G. (2022). Exploring machine learning: A scientometrics approach using bibliometrix and VOSviewer. SN Applied Sciences, 4(5): 143. https://doi.org/10.1007/s42452-022-05027-7

[52] Daud, A., Ahmad, M., Malik, M., Che, D. (2015). Using machine learning techniques for rising star prediction in co-author network. Scientometrics, 102: 1687-1711. https://doi.org/10.1007/s11192-014-1455-8

[53] Alaloul, W.S., Qureshi, A.H., Musarat, M.A., Saad, S. (2021). Evolution of close-range detection and data acquisition technologies towards automation in construction progress monitoring. Journal of Building Engineering, 43: 102877. https://doi.org/10.1016/j.jobe.2021.102877

[54] Safiuddin, M., Kaish, A.B.M.A., Woon, C.O., Raman, S.N. (2018). Early-age cracking in concrete: Causes, consequences. Remedial Measures, and Recommendations, Applied Sciences, 8(10): 1730. https://doi.org/10.3390/app8101730

[55] Wu, J.H., Hao, L., Peng, Y., Na, J. (2019). Identification and monitoring of concrete cracks based on optical frequency domain reflectometry technique. Laser and Optoelectronics Progress, 56(24). https://doi.org/10.3788/LOP56.241201

[56] Su, H., Wen, Z., Li, P. (2021). Experimental study on PPP-BOTDA-based monitoring approach of concrete structure crack. Optical Fiber Technology, 65: 102590. https://doi.org/10.1016/j.yofte.2021.102590

[57] Zhang, H. (2014). The monitoring method for crack damage of concrete structures based on piezoceramics transducers. Applied Mechanics and Materials, 578-579: 1134-1137. https://doi.org/10.4028/www.scientific.net/AMM.578-579.1134

[58] Li, J., Chen, L., Hu, G., Guo, J., Wang, Z., Lu, W., Luo, J., Fan, X., Zhu, Y., Wang, X., Zhu, W. (2023). Research on performance of smart concrete materials and self-monitoring of cracks in beam members. Materials Today Communications, 35: 105775. https://doi.org/10.1016/j.mtcomm.2023.105775

[59] Huo, Z.Y., Qian, G.X., Zheng, D.J. (2014). Monitoring methods of crack behavior in hydraulic concrete structure based on crack mouth opening displacement (CMOD). Open Civil Engineering Journal, 8(1): 225-231. https://doi.org/10.2174/1874149501408010225

[60] Razveeva, I., Kozhakin, A., Beskopylny, A.N., Stel'makh, S.A., Shcherban', E.M., Artamonov, S., Pembek, A., Dingrodiya, H. (2023). Analysis of geometric characteristics of cracks and delamination in aerated concrete products using convolutional neural networks. Buildings, 13(12). https://doi.org/10.3390/buildings13123014

[61] Vy, V., Lee, Y., Bak, J., Park, S., Park, S., Yoon, H. (2023). Damage localization using acoustic emission sensors via convolutional neural network and continuous wavelet transform. Mechanical Systems and Signal Processing, 204: 110831. https://doi.org/10.1016/j.ymssp.2023.110831

[62] Buffarini, G., Clemente, P., Giovinazzi, S., Ormando, C., Scafati, F. (2023). Structural assessment of the pedestrian bridge accessing Civita di Bagnoregio, Italy. Journal of Civil Structural Health Monitoring, 13(8): 1499-1516. https://doi.org/10.1007/s13349-022-00628-7

[63] Yin, T., Ng, C.T., Chen, L., Kotousov, A. (2023). In-situ nonlinear ultrasonic technique for monitoring damage in ultra-high performance fibre reinforced concrete (UHPFRC) during direct tensile test. Measurement: Journal of the International Measurement Confederation, 222: 113587. https://doi.org/10.1016/j.measurement.2023.113587

[64] Dung, C.V., Anh, L.D. (2019). Autonomous concrete crack detection using deep fully convolutional neural network. Automation in Construction, 99: 52-58. https://doi.org/10.1016/j.autcon.2018.11.028.

[65] Dorafshan, S., Thomas, R.J., Maguire, M. (2018). Comparison of deep convolutional neural networks and edge detectors for image-based crack detection in concrete, Construction and Building Materials, 186: 1031-1045. https://doi.org/10.1016/j.conbuildmat.2018.08.011

[66] Han, B., Ding, S., Yu, X. (2015). Intrinsic self-sensing concrete and structures: A review. Measurement: Journal of the International Measurement Confederation, 59: 110-128. https://doi.org/10.1016/j.measurement.2014.09.048

[67] Prasanna, P., Dana, K.J., Gucunski, N., Basily, B.B., La, H.M., Lim, R.S., Parvardeh, H. (2016). Automated crack detection on concrete bridges. IEEE Transactions on Automation Science and Engineering, 13(2): 591-599. https://doi.org/10.1109/TASE.2014.2354314

[68] D'Alessandro, A., Rallini, M., Ubertini, F., Materazzi, A.L., Kenny, J.M. (2016). Investigations on scalable fabrication procedures for self-sensing carbon nanotube cement-matrix composites for SHM applications. Cement and Concrete Composites, 65: 200-213. https://doi.org/10.1016/j.cemconcomp.2015.11.001

[69] Domaneschi, M., Niccolini, G., Lacidogna, G., Cimellaro, G.P. (2020). Nondestructive monitoring techniques for crack detection and localization in RC elements. Applied Sciences, 10(9): 3248. https://doi.org/10.3390/app10093248

[70] Abouhussien, A.A., Hassan, A.A.A. (2016). the use of acoustic emission intensity analysis for the assessment of cover crack growth in corroded concrete structures. Journal of Nondestructive Evaluation, 35(3). https://doi.org/10.1007/s10921-016-0369-1

[71] Barat, V., Marchenkov, A., Ivanov, V., Bardakov, V., Elizarov, S., Machikhin, A. (2021). Empirical approach to defect detection probability by acoustic emission testing. Applied Sciences, 11(20). https://doi.org/10.3390/app11209429

[72] Bu, J., Guo, Z., Zhang, J., Zhang, Y. (2023). Experimental study on the damage mechanism of reinforced concrete beams based on acoustic emission technique. Applied Sciences, 13(16). https://doi.org/10.3390/app13169207.

[73] Zaki, A., Tan, J.Y., Chai, H.K., Aggelis, D.G. (2015). Assessment of corrosion damage using acoustic emission technique under load testing. In Proceedings of the 7th Asia Pacific Young Researchers and Graduates Symposium, Kuala Lumpur, Malaysia, pp. 20-21.

[74] Zaki, A., Ibrahim, Z. (2023). Secondary AE analysis of pre-corroded concrete beam. In Lecture Notes in Civil Engineering, pp 243-255. https://doi.org/10.1007/978-981-16-9348-9_22

[75] Zeng, H., Hartell, J.A., Soliman, M. (2020). Damage evaluation of prestressed beams under cyclic loading based on acoustic emission monitoring. Construction and

Building Materials, 255: 119235. https://doi.org/10.1016/j.conbuildmat.2020.119235
[76] Zaki, A., Sunaryo, D.N.Y., Afanda, R. (2023). Corrosion analysis on reinforced concrete using ultrasonic pulse velocity. In 2023 International Workshop on Artificial Intelligence and Image Processing (IWAIIP), Yogyakarta, Indonesia, pp. 139-144. https://doi.org/10.1109/IWAIIP58158.2023.10462858
[77] Ahmed, S., Kopsaftopoulos, F. (2023). Active sensing ultrasonic guided wave-based damage diagnosis via stochastic stationary time-series models. Structural Health Monitoring, 23(4): 2559-2595. https://doi.org/10.1177/14759217231201975
[78] Yoon, Y.G., Kim, C.M., Oh, T.K. (2022). A study on the applicability of the impact-echo test using semi-supervised learning based on dynamic preconditions. Sensors, 22(15): 5484. https://doi.org/10.3390/s22155484
[79] Zaki, A., Megat Johari, M.A., Wan Hussin, W.M.A., Jusman, Y. (2018). Experimental assessment of rebar corrosion in concrete slab using ground penetrating radar (GPR). International Journal of Corrosion, 2018: 1-10. https://doi.org/10.1155/2018/5389829.
[80] Kang, D., Cha, Y.J. (2018). Autonomous UAVs for structural health monitoring using deep learning and an ultrasonic beacon system with Geo-tagging. Computer-Aided Civil and Infrastructure Engineering, 33(10): 885-902. https://doi.org/10.1111/mice.12375
[81] Chang, Q., Yang, W.X., Gao, H.M., Meng, Y. (2021). A research on fatigue crack growth monitoring based on multi-sensor and data fusion. Structural Health Monitoring, 20(3): 848-860. https://doi.org/10.1177/1475921719865727
[82] Chakraborty, J., Katunin, A., Klikowicz, P., Salamak, M. (2019). Early crack detection of reinforced concrete structure using embedded sensors. Sensors, 19(18): 3879. https://doi.org/10.3390/s19183879
[83] Liu, Y., Bao, Y. (2023). Automatic interpretation of strain distributions measured from distributed fiber optic sensors for crack monitoring. Measurement, 211: 112629. https://doi.org/10.1016/j.measurement.2023.112629
[84] Maheshwari, M., Annamdas, V.G., Pang, J.H., Asundi, A., Tjin, S.C. (2017). Crack monitoring using multiple smart materials; fiber-optic sensors & piezo sensors. International Journal of Smart and Nano Materials, 8(1): 41-55. https://doi.org/10.1080/19475411.2017.1298220
[85] Sofi, A., Regita, J.J., Rane, B., Lau, H.H. (2022). Structural health monitoring using wireless smart sensor network–An overview. Mechanical Systems and Signal Processing, 163: 108113. https://doi.org/10.1016/j.ymssp.2021.108113
[86] Zhang, J., Sunny, A.I., Zhang, G., Tian, G. (2018). Feature extraction for robust crack monitoring using passive wireless RFID antenna sensors, IEEE Sensors Journal, 18(15): 6273-6280. https://doi.org/10.1109/jsen.2018.2844564
[87] amli, M., Kwan, W.H., Abas, N.F. (2013). Strength and durability of coconut-fiber-reinforced concrete in aggressive environments. Construction and Building Materials, 38: 554-566. https://doi.org/10.1016/j.conbuildmat.2012.09.002
[88] Belloni, V., Sjölander, A., Ravanelli, R., Crespi, M., Nascetti, A. (2020). Tack project: Tunnel and bridge automatic crack monitoring using deep learning and photogrammetry. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 43: 741-745. https://doi.org/10.5194/isprs-archives-XLIII-B4-2020-741-2020