Mapping the knowledge domains of fire-resilient underground construction materials through bibliometric analysis

Tong Zhang, Yi Shen, Chao Guo, Zhiguo Yan*

Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China

*Corresponding Author: yanzguo@tongji.edu.cn

Abstract. The fires in tunnel and shield structures are usually characterized by uneven temperature distribution, high thermal gradient and extreme maximum temperature. Cement and concrete composites, as typical construction materials for most underground structures, are vulnerable to elevated temperatures. With this consideration, the development of sustainable cement-based binders and incorporation of advanced minerals provide effective solutions to handle the fire-resistance problem. In this paper, the knowledge domains of scientific research on the fire-resilient construction materials are mapped by means of informetrics. To understand the research progress and current status, a total of 961 related papers published from 2000 to 2020 are retrieved from the Science Citation Index Expanded database. Through the bibliometric analysis of the co-citation of organizations, co-authorship of authors, and co-occurrence of keywords, the knowledge domains in the field of fire-resistant construction materials are visualized. The findings indicate that the research frontiers include the mechanical properties, durability, permeability, and spalling behaviour of concrete, as well as the incorporation of hybrid reinforcements and mineral admixtures to migrate the thermal damage.

1. Introduction

In the last decades, we have witnessed a booming development of the underground space, especially in China, coupling with the rapid growth of the total length of all tunnels and the number of super-long tunnels. However, owing to the closeness of the underground space, the uncontrolled burning in space posts a great threat to the safety of both human beings and shield structures. From the perspective of underground construction materials, there is no doubt that cement-based composites, i.e., cement paste, mortar, and concrete, are one of the most commonly-used construction binders. However, cementitious composites can experience serious thermal damage at elevated temperatures [1,2]. For example, high-strength concrete are vulnerable to explosive spalling when exposed to a fire [3,4]. In order to guarantee the fire safety of tunnels, passive fireproof solutions, e.g., laying fire-proof board and spraying fire-retardant coating, are applied to protect the underground structures from thermal damage [5]. Nevertheless, these passive methods may increase the extra load of structures, block the monitoring of the structural health, and bring in additional maintenance cost, e.g., regular repainting of the fire-retardant coating. With these considerations, the incorporations of mineral admixtures (e.g., fly ash, and blast furnace slag [6,7]) and reinforcements (e.g., hybrid steel [8,9] and polymer fibres [10,11]) in sustainable cement-based binders (e.g., geopolymers, and calcium aluminates [12,13]) provide active solutions to design fire-resilient underground construction materials.
Towards the development of resilient cities and underground space, the innovation of fire-resilient construction materials is one of the most fundamental researches. At present, the studies of fire safety in underground space have involved in combustion engineering [14,15], ventilation engineering [16,17], and emergency evacuation [18,19], etc. However, these researches only focus on various technical fields at the management level, and there is still lack of an overview from the perspective of material science. Considering that the research scope of the underground fire-resilient construction materials is relative wide, bibliometric analysis provides an effective way to visualize complex knowledge domains. In this paper, the method of mapping the knowledge domains is applied to analyze the current research progress in the field of fire-resilient construction materials, as well as to explore the research frontiers.

2. Data and methods

2.1. Data source

By selecting “high temperature” and “concrete” as two keywords in the title, a total of 961 documents published from 2000 to 2020 are retrieved from the SCIE (Science Citation Index Expanded) database of WOS (Web of Science) core collection platform. The keyword “underground space/structure” is not applied to limit the search scope, so that a wider research range can be presented in this paper. As listed in table 1, about 84.5% of the literature is “Articles” type, while the other types of publications include “Conference Papers”, “Review Articles”, “Editorial Materials”, “Books” and “Corrections”.

| Type            | Articles | Conference Papers | Review Articles | Editorial Materials | Books | Corrections |
|-----------------|----------|-------------------|-----------------|--------------------|-------|-------------|
| Number          | 812      | 122               | 7               | 13                 | 5     | 2           |

2.2. Tool and method

Bibliometrics is a discipline that takes the advantage of mathematical methods to statistically quantify the complex scientific research information (e.g., spatial distribution of the literature, co-authorship analysis, and research hotspots analysis) [20]. Through data collection, knowledge processing, and map drawing, bibliometric analysis can indicate the recent research progress and provide the scientific basis for management. By means of mapping the knowledge domains, a visualization software VOSviewer [21] is applied to carry out the bibliometric analysis of the retrieved 961 publications in this study.

3. Results and discussion

3.1. Spatial distribution of literature

Based on the retrieved 961 documents, figure 1(a) shows the cooperation networks of countries/regions. Each node in the figure represents a different country/region. The larger the node, the more the number of publications and the greater the influence of papers. The thickness of the connection lines means the cooperation strength between different countries/regions [20]. It is obvious that China has the highest number of publications (276), highest citations (3833), and strongest total link strength (41977). The United States has the second highest number of publications (128), which is less than half of the highest number, but shares a similar number of links (62) with China (65). Moreover, the color of the node also indicates the average year of the publications. Clearly, Singapore, Brazil, Malaysia, Iraq, and Saudi Arabia own more publications in the recent years, suggesting the stronger research capacity recently.

Figure 1(b) further displays the cooperation networks of main research institutions. According to the SCIE databases, authors from 910 organizations have published the retrieved 961 documents. Among the top 10 institutions in terms of the document volume, half is from China and the United States own two positions. Harbin Institute of Technology (China) has the highest number of papers (33) and the
strongest total link strength (12988), while Hanyang University (Korea) owns the highest average number of citations (52.58). Additionally, Nanyang University of Technology and Missouri University of Science and Technology have made great contributions to this filed in the last several years.

(a) Cooperation networks of countries/regions

(b) Cooperation networks of main research institutions
Figure 1. Spatial distribution of the retrieved publications.

3.2. Journal distribution of literature
Based on the bibliographic coupling analysis of the sources, the retrieved 961 documents are published by 359 different journals, covering the fields of structural engineering, material engineering, and environmental engineering. The cooperation networks of main research journals (with more than five papers) of the retrieved publications are presented in figure 2. Obviously, the “Construction and Building Materials” owns the highest number of publications (177) and strongest total link strength (28614), which may be attributed to the wide scope of received manuscripts and high number of total publications (2678 in the year of 2019). In contrast, “Cement and Concrete Research” performs the best in terms of the average number of citations (81.24), while its total number of publications only reaches 269 in the year of 2019. It is also interesting to find that although “Composite Part B” and “Fire Safety Journal” have relatively small volume of related publications (21 and 15, respectively), these two journals rank in the top three with the average number of citations being as high as 59.62 and 36.87, respectively.

Figure 2. Cooperation networks of main research journals of the retrieved publications.

3.3. Co-authorship analysis
The number of authors who have contributed to the retrieved 961 documents reaches up to 2933, while threshold of at least three publications yields only 178 records. Figure 3 displays the cooperation authors networks of the retrieved publications. Among the top five authors who have published highest number of papers, two of them are from China, while the others are from Singapore, Korea, and Czech, respectively. Wenzhong Zheng [22–25] from Harbin Institute of Technology (China) owns the highest number of papers (16), highest citations (292), and the strongest total link strength (21041). In addition, Harun Tanyildizi [26,27] from Firat University (Turkey) and Venkatesh Kodur [28–31] from Michigan State University (United States) show great influence in this field in terms of the average number of citations (36.00 and 30.71, respectively). When it comes to the year of publications,
it is also founded that Kanghai Tan [32–35] from Nanyang University of Technology, Xiuli Du [36,37] from Beijing University of Technology, and Nematzadeh Mahdi [38,39] from University of Mazandaran have made great contributions to the development of fire-resilient construction materials in the recent years.

3.4. Research hotspots and trends analysis

The number of keywords obtained from the WOS core database reaches as high as 3108, while only 270 words meet the requirement of at least five occurrences. Figure 4 plots the keywords co-occurrence networks of the retrieved 961 publications. The size of the nodes represents the frequency of occurrence of the keywords, the larger the node the more frequent the occurrence. The links between different nodes represent the connections between keywords, the wider the link suggests the stronger connections [20]. As marked in the co-occurrence network, there are five clusters of different node colours, which are further discussed in this section.

- **Cluster 1** (red): the red cluster mainly surrounds the keyword “high temperature”, and the keywords “durability” and “strength” occur frequently. More importantly, the incorporations of admixtures (i.e., silica fume and geopolymer) are highlighted in this cluster, which is a research trend to improve the mechanical properties of construction materials at elevated temperatures.

- **Cluster 2** (green): the expansions of the keyword “spalling” form the green cluster, and the keywords “fire” and “residual strength” occur frequently in this cluster, indicating that spalling behaviour of concrete at high temperatures is a hotspot in the related fields [3,35].

- **Cluster 3** (blue): the blue cluster mainly surrounds the keyword “compressive strength”, and hybrid fibres are highlighted in this cluster, including carbon, glass, polypropylene (PP), and steel fibres. This suggests that the addition of hybrid fibre reinforcements is an effective solution to mitigate the thermal damage of construction materials [32,40].

Figure 3. Cooperation authors networks of the retrieved publications.
Cluster 4 (yellow): the expansions of the keywords “mechanical properties” and “high performance concrete” form the yellow cluster, indicating that the mechanical properties and permeability of high-performance concrete at elevated temperatures attract more attentions.

Cluster 5 (purple): the purple cluster mainly surrounds the keyword “elevated temperatures”, and the keywords “flexural behaviour” and “toughness” occurs frequently in this cluster. This suggests that there are still needs to further investigate different aspects of mechanical behaviours of the construction materials when exposed to high temperatures.

Figure 4. Keywords co-occurrence network of the retrieved publications.

4. Conclusions
By means of the bibliometric analysis, this work maps the knowledge domains of fire-resilient underground construction materials based on the 961 publications retrieved from the WOS core database. The content involves the spatial distribution of literature, journal distribution of literature, co-authorship analysis, and keywords co-occurrence analysis. The main conclusions can be summarized as follows:

- China owns the highest volume of literature and strongest total link strength in the field of fire-resilient construction materials, indicating that the organizations and authors from China are the main capacities of research in this field. Moreover, authors from Singapore, Brazil, and Malaysia have shown great competitiveness in the recent years.

- Due to the wide scope of manuscripts and high volume of publications, “Construction and Building Materials” owns the highest number of publications, while “Cement and Concrete Research” performs the best in terms of the average number of citations. Moreover, “Composite Part B” and “Fire Safety Journal” also have great influence in this field with high-cited papers.

- Interestingly, the top five authors who have published highest number of papers are from four different countries, and there are close connections between different organizations,
suggested a relatively complete cooperation system in the field of fire-resistant construction materials.

- The research hotspots which need more future work include the mechanical properties (i.e., compressive strength, flexural behaviour, and toughness), durability, permeability, spalling behaviour, and incorporations of hybrid reinforcements (i.e., carbon, glass, PP, and steel fibres) and mineral admixtures (i.e., silica fume and fly ash) to migrate the thermal damage.

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