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Frost durability of cementitious materials: What's next?

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ABSTRACT

Frost durability, a critical parameter for concrete, especially in harsh exposure regions, has been extensively researched, with almost four thousand papers published since the 1970s. However, a systematic mapping of this research is yet to be explored. This paper presents a novel approach based on Natural Language Processing (NLP) and machine learning to semi-automatically analyze the existing literature on frost durability of cementitious materials. The aim is to identify research gaps and provide insights for future work, offering a comprehensive understanding of the freeze and thaw (FT) research area. Data sets containing academic abstracts on FT tests have been created, and the identified articles are topically structured using a latent Dirichlet allocation (LDA) topic modeling approach. The publication volume associated with each topic over time has been quantified, providing an overview of the research landscape. The results show that NLP and t-SNE effectively review large volumes of technical text data, identifying 12 dominant themes in FT research, such as mechanical properties and material composition. Over recent decades, there has been a shift from focusing on structural performance to emerging topics like cracking and Supplementary Cementitious Materials (SCMs). Additionally, t-SNE and K-means clustering revealed four main clusters, suggesting future research should focus on the FT durability of eco-friendly materials, accelerated testing, and enhanced FT durability materials. These findings not only facilitate the identification of gaps and opportunities for future work but also have practical implications for developing more durable and sustainable concrete.

1. Introduction

Concrete's freeze-thaw (FT) durability is critical to its long-term performance, especially in cold climates. FT cycles significantly reduce the performance of concrete structures [1]. FT damage primarily occurs due to the freezing of pore solution within the concrete. Water in the pores freezes as the temperature drops, increasing volume and internal pressure. This pressure causes microcracks and degradation of the concrete matrix. Most damage occurs between 0°C and −10°C, as more pore solution freezes within this temperature range [2]. FT cycles induce mechanical degradation, including compressive, tensile, and flexural strength reductions caused by the formation of microcracks, increased porosity, and changes in pore structure, further compromising the material's integrity [3]. The potential risks of climate change, such as more severe and frequent FT cycles, cause concern. Projections for regions like Finland

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suggest more precipitation and FT cycles, particularly affecting south-facing facades, which are more exposed to climatic stress [4]. In addition, concrete structures often face combined deterioration mechanisms, such as FT damage, chloride ingress, and carbonation, further affecting durability [5] and accelerating the degradation process. Adding air-entraining agents, fibers, and other additives can significantly improve concrete's FT resistance. Fibers increase structural integrity and reduce crack propagation. Optimized mix designs, including SCMs, also enhance concrete durability [6]. Concrete is an evolving material, and despite intense research, several problems remain unresolved, such as optimizing the durability of novel cementitious composites, understanding their long-term performance under varying environmental conditions, and improving resistance to combined degradation processes.

Concrete production contributes to the global carbon footprint, accounting for approximately 8 % of all anthropogenic emissions. This includes substantial emissions of nitrogen oxides, sulfur oxides, and particulate matter, which, together with CO_2, lead to climate and health damage [7]. The need for low-carbon alternatives in concrete production is therefore urgent. Efforts to mitigate concrete emissions include using biofuels, alternative raw materials, and carbon capture technologies in Portland cement (PC) production [8] as well as blending PC with SCMs. Life cycle assessments of concrete structures highlight the importance of considering production emissions and in-service durability. Concrete mixes with lower CO_2 emissions should also ensure adequate performance in FT conditions to maximize their overall environmental benefits [9]. Changes in the research focus on greener concrete alternatives led to extensive research on FT resistance of novel types of cementitious binders. Since the 1970s, nearly 4000 papers on concrete's FT durability have been published, resulting in a vast amount of data. This review aims to analyze trends in the FT durability of concrete over the past decades using Natural Language Processing (NLP) and topic modeling techniques, highlighting developments and shifts in research focus. The paper employs Latent Dirichlet Allocation (LDA) to analyze a corpus of literature on FT, identifying existing gaps and underrepresented topics within the field. Following the topic identification, t-distributed Stochastic Neighbor Embedding (t-SNE) and K-means clustering techniques are applied to categorize the topics into four clusters. These clusters are subsequently examined in detail, allowing for a discussion of the current research landscape. Finally, a research outlook is formulated based on the cluster analysis, highlighting key areas for future investigation within the domain of concrete FT durability.

2. Research significance

The novelty of this research lies in its unique approach, utilizing NLP methodologies to analyze a large corpus of literature on concrete frost durability. NLP allows for quantitative analysis of large text corpora using machine learning techniques [10]. In NLP, frequency, distribution, and context are analyzed using a basic element called a unigram, i.e., a word.

Topic modeling, a method in NLP, categorizes and structures academic literature into distinct themes [11]. This technique allows for a clearer understanding of the various research areas and their development over time and offers a quantitative analysis of research trends [12]. Latent Dirichlet Allocation (LDA), which relies on Bayesian probabilistic modeling, is among the most commonly used topic models [13]. LDA is an unsupervised method that treats each document as a blend of topics, where each topic consists of a collection of words. This approach uses a "bag of words" model, disregarding the sequence of words [14]. Statistically, LDA represents a probability distribution over words and identifies topics by evaluating word co-occurrences in the corpus [15]. For more detailed information on LDA, refer to resources such as [13]. Topic modeling and text-mining have been used in fields like medicine [16,17], finance [18-20] or engineering [12,21,22]. Bayesian probabilistic topic models like LDA are highly efficient, easy to use and interpret, flexible, and computationally efficient since they rely on few parameters [23]. Other topic modeling techniques include algebraic models such as Non-negative Matrix Factorization [24,25] or deep learning-based models such as Bidirectional Encoder Representations from Transformers (BERT) [26]. A comprehensive review of topic modeling methods is presented in [23,27]. Despite the vast amount of data available in the literature, NLP techniques are rarely applied in the field of building materials (e.g., [28,29]).

Table 1
Selected recent review papers, including cementitious materials' FT aspects.

Review area	Subtopic	Ref.
FT mechanisms	Possible enhancements	[45,46]
	Coupled with other actions	[39,40]
	Cryogenic FT cycles	[47,48]
	Models	[49,50]
Material-related	Geopolymers	[30,31]
	Foam concrete	[51]
	Micro- and nanoparticles	[52]
	Ground granulated blast furnace slag	[32]
	Plastic waste	[53]
	Air-entrainer	[54]
	Recycled Aggregate	[34-38]
	High-volume FA	[33]
	Waste Tire Rubber	[55,56]
	UHPC	[57]
	Textile Reinforced Concrete	[58]
Special applications	Tunnel/underground structures	[59]
	3D printing	[60]
	Self-sensing concrete	[41]
	Self-healing concrete	[42-44]

This review fills a gap in the existing literature by systematically mapping research on FT cycles of concrete dating back to the 1970s. To the best of the authors' knowledge, it provides the first organized and detailed overview of this extensive body of work. In the past decade (since 2015), over a hundred review papers have addressed FT cycles in some capacity (Table 1). However, none have offered a comprehensive and systematic overview. Most of the reviews focus on the general durability of specific materials such as geopolymers [30,31], concrete with high amounts of SCMs [32,33] or recycled aggregate [34-38], with only dedicated sections involving FT. Some studies analyze the possible mechanism coupled with other actions such as sulfates, chlorides, or mechanical loads [39,40]. FT properties also appear in the review papers related to smart cementitious materials such as self-sensing [41] or self-healing concrete [42-44]. Nevertheless, possibly due to the large body of knowledge, none have comprehensively covered all the information.

Gaining prompt access to current research trends in materials science is critical for researchers, industry, policymakers, and other stakeholders as a basis for forming collaborations and formulating research strategies [12]. This paper enables identifying research gaps around the FT durability of cementitious materials and facilitates setting up future research directions by suggesting more targeted studies. The application of advanced analytical techniques, such as machine learning and NLP, demonstrates their advantages in providing systematic and computerized state-of-the-art analyses. This review's methodologies and findings have broader implications beyond concrete research, illustrating the potential for automated literature reviews in other scientific and engineering disciplines. Using computer-assisted topic modeling and grouping, the review provides a fresh perspective on the FT area, uncovering new relationships between distinct research themes and enabling a more objective analysis.

3. Methodology

The methodology used in this study encompassed multiple steps, i.e., text data acquisition, text preprocessing, model training, and validation (Fig. 1). The following sections provide detailed descriptions of each step.

3.1. Dataset creation

Research articles were selected from the Web of Science in May 2024 using the search phrase: ("freeze and thaw" OR frost OR "freeze-thaw" OR "freezing and thawing") AND (concrete OR mortar OR cementitious OR "cement paste"). Additionally, terms such as "soil," "rock," "asphalt," "cells," and "mortar and pestle" were excluded from the results. The selection was limited to peer-reviewed journal publications in English, and review papers were excluded. Only papers with abstracts in the database were considered for analysis. Conference papers were also removed to avoid duplicates, which often arise from articles being published in both conference proceedings and peer-reviewed journals [29]. The final raw dataset constitutes 3794 abstract texts. Previous studies revealed that relying on abstracts instead of full texts does not significantly impact the quality of results while offering practical benefits such as improved accessibility and reduced computational complexity [29,61].

The selected articles belong to three main categories (as defined by the Web of Science): Materials Science Multidisciplinary (2236), Construction Building Technology (2088), and Civil Engineering (1882). The research span is from 1975 until 2024, excluding Early Access publications, with a dominant share in the last decade (Fig. 2a). The dataset comprises abstracts from diverse countries, with most research done in China, contributing to 1639 abstracts. The USA follows with 585, Canada 240, Poland 184, Turkey 179, South Korea 134, Japan 126, Iran 91, Spain 86, and England 76. The distribution of research contributions among countries has markedly shifted over the years (Fig. 2b). China substantially increased publications, while Europe maintained a similar fraction of papers. On the other hand, a significant decrease was observed in the USA and Canada (Fig. 2b). Nations such as Turkey, South Korea, and Iran gradually emerged as notable contributors.

The abstracts in the dataset are categorized under the following Sustainable Development Goals (SDGs), as defined in the Web of Science, emphasizing the global importance and relevance of the research: 2943 under SDG 12 (Responsible Consumption and Production), 401 under SDG 11 (Sustainable Cities and Communities), 67 under SDG 6 (Clean Water and Sanitation), 50 under SDG 13 (Climate Action), and 36 under SDG 7 (Affordable and Clean Energy). Most articles were published in "Construction and Building Materials" (817, 21.5 %), "Materials" (266, 7 %), "Journal of Materials in Civil Engineering" (145, 3.8 %), "Journal of Building Engineering" (138, 3.6 %), and "Cement and Concrete Research" (132, 3.5 %). Most cited articles (Table 2) show themes emerging in recent years concerning FT durability, such as the use of environmentally friendly materials, fiber-reinforced concrete, or self-healing properties.

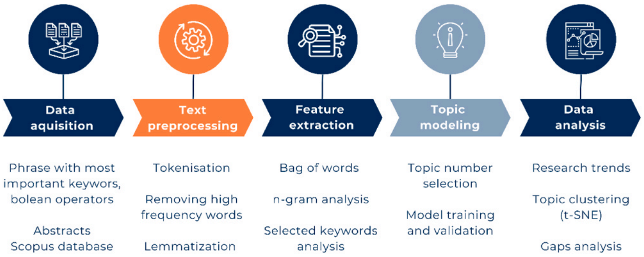


Fig. 1. Schematic diagram of the methodological workflow.

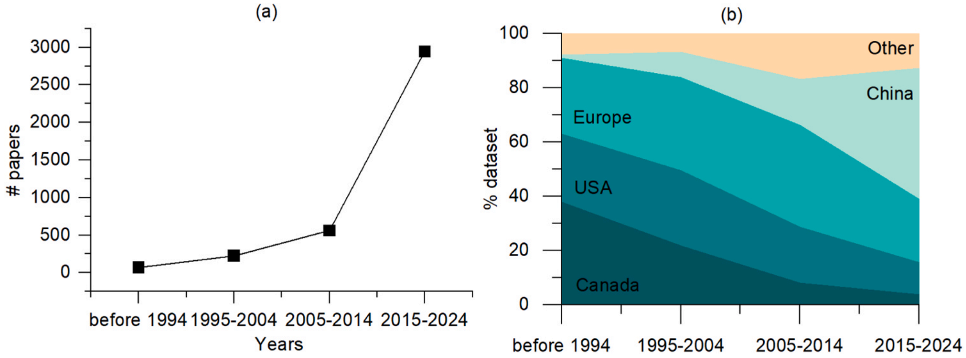


Fig. 2. (a) Distribution of papers in the dataset over the years, (b) Geographical distribution of papers over the years.

Table 2
Ten most cited papers from the dataset.

#	First author	Year	Title	Journal	Citations	Ref.
1	Ajdukiewicz, A	2002	Influence of recycled aggregates on mechanical properties of HS/HPC	Cement & Concrete Composites	462	[62]
2	De Muynck, W	2008	Bacterial carbonate precipitation improves the durability of cementitious materials	Cement and Concrete Research	453	[63]
3	Yang, J	2003	Experimental study on properties of pervious concrete pavement materials	Cement and Concrete Research	394	[64]
4	Topçu, IB	2004	Properties of concretes produced with waste concrete aggregate	Cement and Concrete Research	392	[65]
5	Chen, Y	2007	Accelerated aging tests for evaluations of durability performance of FRP reinforcing bars for concrete structures	Composite Structures	382	[66]
6	Zhang, P	2017	Influence of FT cycles on capillary absorption and chloride penetration into concrete	Cement and Concrete Research	318	[67]
7	Karahan, O	2011	The durability properties of polypropylene fiber reinforced FA concrete	Materials & Design	301	[68]
8	Yazici, H	2008	The effect of SF and high-volume Class C FA on mechanical properties, chloride penetration and FT resistance of self-compacting concrete	Construction and Building Materials	292	[69]
9	Micelli, F	2004	Durability of FRP rods for concrete structures	Construction and Building Materials	280	[70]
10	Puertas, F	2003	Mechanical and durable behaviour of alkaline cement mortars reinforced with polypropylene fibres	Cement and Concrete Research	260	[71]

3.2. Text pre-processing

Data preprocessing was conducted using MATLAB’s Text Analytics Toolbox, version R2024a. The abstract texts were extracted from a CSV file exported from Web of Science. To facilitate robust text analysis, it was essential to perform multi-step data cleaning [72]. The preprocessing began with tokenizing the textual data to segment it into discrete lexical units. Subsequently, high-frequency, low-value, or stop words were removed to enhance the dataset’s quality. Lemmatization was applied to standardize the text by converting words to their root forms. Non-alphanumeric characters, including punctuation, were removed, and words shorter than two

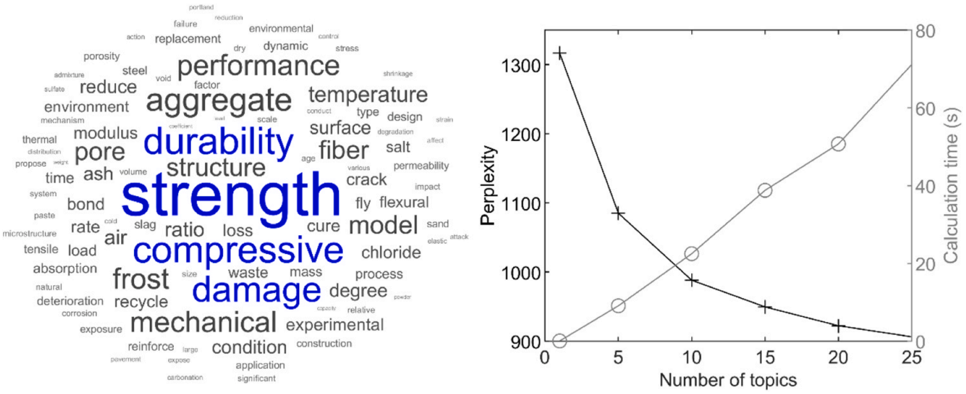


Fig. 3. (a) bag of words created from cleaned text, (b) perplexity vs calculation time.

characters or longer than fifteen characters were filtered out. Additionally, common domain-specific terms, such as "concrete," were excluded to allow for a more targeted examination of the remaining data.

Post-cleaning, a model was constructed to quantify the frequency of each word (unigram) in the dataset, creating a "bag of words" as a virtual container of all the cleaned tokens. Words with a frequency count lower than two were excluded to enhance computational efficiency. Furthermore, a "bag of bigrams," comprising pairs of consecutive words, was generated. This approach facilitates a deeper understanding of the context and relationships between words, providing insights that single-word (unigram) analysis alone cannot achieve.

3.3. Topic modeling and post-processing

Topic modeling was done on the created "bag of words" (Fig. 3a) based on the LDA semi-automated approach [13] implemented in MATLAB's Text Analytics Toolbox, version R2024a. By uncovering the hidden patterns within the text, the LDA algorithm categorizes articles from a sample into groups (topics) [29]. Each abstract text comprises multiple topics, represented by a specific probabilistic distribution of the same tokens, disregarding the sequence of words. LDA is an unsupervised method that requires pre-selection of the number of topics, which is a trial-and-error process [11,29]. In this study, perplexity is used to evaluate how effectively a statistical model represents a dataset [73]. Perplexity is a statistical measure that evaluates how well a probabilistic model predicts a sample of unseen data, with lower perplexity values indicating better generalization and model performance [23]. Specifically, perplexity assesses the model's ability to assign higher probabilities to the actual word sequences in the test data, thereby reflecting the distinctiveness of the identified topics. The text dataset is divided into two partitions: training data (85 % of the total data), used to run the LDA model, and test data (15 % of the total data), used to validate the model. Perplexity and computation time are evaluated by running the analysis with varying numbers of topics, ranging from 1 to 25. The objective is to minimize perplexity while keeping computational complexity reasonable (Fig. 3b).

An interval between 10 and 15 (Fig. 3b) was identified where changes in perplexity were minimal, indicating a balance between model fit and complexity. A midpoint within this interval, corresponding to 12 topics, was selected to achieve a more detailed analysis while avoiding overly broad categorizations. It is acknowledged that while perplexity is an indicator of model performance, it does not account for the semantic coherence of topics, thereby necessitating complementary qualitative assessments. Research topics relevant for use in the FT literature are identified and labeled by analyzing the probabilities of words and reviewing the most frequent words for each topic. This process is conducted based on the researcher's experience, which introduces a level of subjectivity. Semantic validation is then carried out to ensure that the topics accurately represent meaningful themes within the dataset [11,74].

t-distributed Stochastic Neighbor Embedding (t-SNE) was employed in MATLAB to visualize clusters of documents based on their topic distributions derived from the LDA model. t-SNE is a widely used technique for visualizing high-dimensional data, transforming data into a lower-dimensional space while preserving the relationships between data points [75,76]. The trained model was applied to the preprocessed text data. This generated a matrix of document-topic probabilities, representing the distribution of each topic within every document. For each document, the topic with the highest probability was identified to determine the dominant topic. The top three words for each topic were extracted to facilitate the interpretation of the identified clusters. The t-SNE algorithm was utilized to reduce the high-dimensional topic distributions to a two-dimensional space for visualization purposes. The hyperparameters for t-SNE were chosen based on a combination of literature guidelines and empirical testing to optimize the visualization quality. The resulting two-dimensional t-SNE embeddings were plotted with color-coded documents based on their dominant topic assignments.

Further clustering was applied to divide the t-SNE results into clusters representing larger themes for analysis. The k-means algorithm was applied using MATLAB. K-means clustering is an unsupervised machine learning algorithm used to partition a dataset into K distinct, non-overlapping subsets or clusters based on the proximity of data points to the centroids of each cluster. By iteratively updating the centroids and reassigning points to the nearest centroid, K-means aims to minimize the within-cluster variance, making it an effective tool for identifying underlying patterns and structures in complex datasets [77].

3.4. Model validation

To validate the effectiveness of the topic modeling approach, 50 abstracts were randomly selected from the initial list of documents, and their dominant topics were identified using the trained LDA model. Manual verification was then conducted by reading the abstracts and reviewing the papers, with grading performed on a scale from 0 to 3, where 0 represented inadequate matching and 3 referred to excellent matching. Additionally, a review paper [39] was selected to serve as a benchmark for further validation. The abstracts of all the references cited within this review paper were compiled to form a dataset reflective of the literature discussed in the review. The LDA model was applied separately to the full text of the review paper and the combined text of all the compiled abstracts from the paper's references. A comparative assessment was performed by analyzing the topic distributions generated from these two applications. This comparison aimed to evaluate the consistency of the model's topic extraction when applied to both the review paper and the body of work it references, thereby assessing the model's ability to capture the thematic structures present in related but distinct textual sources.

4. Results

The topic modeling analysis provided insights into the primary themes within the dataset, identifying twelve distinct topics, each characterized by a set of unigrams (Table 3). These topics highlighted various aspects of FT research.

The first topic focused on the performance and durability of concrete structures, particularly concerning pavements and bridges. This topic demonstrates the primary application of FT research and the initial motivation for these studies. As FT research is well-established, modeling emerged as the second most prominent topic, featuring associated unigrams such as "temperature," "frost," "degree," and "pore structure." The material composition was another significant area, encompassing topics 4, 6, 9, and 11, which focused on the effects of fibers, air entrainment, aggregates, and different binders, with keywords emphasizing waste materials, e.g., "ash" or "slag." Additional factors like porosity and microstructure (Topics 7 and 8), as well as curing regime-related research, were also visible in the analysis. Mechanical properties, critical due to concrete's role as a structural material, formed a separate topic (Topic 3). However, these properties were interconnected with most other topics, with the unigram "strength" and bigram "compressive strength" being the most frequently found terms in the text corpus (Fig. 3a and Fig. 5a). Topic 12 addressed cracking and internal damage at the structural element level, particularly concerning engineered cementitious composites (ECC). Topic 10 focused on FT in relation to other degradation processes and interconnected mechanisms, with unigrams such as "chlorides" and "sulfates" being the most frequent. Interestingly, the analysis did not highlight specific topics related to different testing techniques or accelerated FT tests.

The validation results demonstrated the effectiveness of the topic modeling approach. Among the 50 randomly selected abstracts, over 78 % received a manual evaluation score of 2 or higher, indicating adequate or excellent topic assignment (Fig. 4a). Discrepancies were observed in some cases, which could primarily be attributed to the multi-thematic nature of the papers. When the probabilities of multiple topics are close to each other, the dominant topic might not fully represent the abstract's content, leading to potential misjudgment. The dominant topic probabilities for the selected abstracts ranged from 0.23 to 0.84, reflecting varying degrees of topic dominance and highlighting the complexity of assigning a single topic to multidimensional texts.

In analyzing a review paper and the combined abstracts of its cited references (Fig. 4b), the dominant and second most prominent topics were consistent in both cases (Topics 10 and 5). However, the review paper's third topic was identified as mechanical properties (Topic 3), whereas in the combined abstracts, SCM (Topic 9) and aggregate effects (Topic 4) were more pronounced. This difference may result from the review paper summarizing mechanical properties, while the referenced papers refer to specific aspects such as mix composition. Overall, the results confirm that the topic modeling approach effectively captures the thematic structure of the corpus.

Additionally, the correlation matrix of the identified topics was analyzed (Fig. 5b). The highest correlation coefficient, approximately 0.45, was found between Topic 3 (Mechanical properties) and Topic 6 (Fiber reinforcement effect), suggesting a relationship between these two areas (Fig. 5a). This correlation indicates that advancements in fiber reinforcement are closely linked to improvements in the mechanical properties of concrete. Topic 3 showed weak correlations with several themes (Topics 2, 4, 7, 8, 9), highlighting the interconnection between mechanical parameters and other research areas such as modeling, porosity, microstructure, and material composition. This emphasizes the crucial role of mechanical performance in the broader context of FT concrete durability. Similarly, Topics 7 (Porosity and microstructure) and 8 (Curing effect) exhibited weak correlations with several other topics, reflecting their influence on concrete properties and the importance of understanding these parameters for enhancing concrete quality. On the other hand, Topic 12, which focuses on cracking, internal damage, and ECC, showed no correlation with any other topic. This lack of correlation could be related to the fact that Topic 12 is a relatively new and emerging area of research that has been growing over the past decade (Fig. 6ab), indicating a specialized focus on mitigating internal damage and improving the resilience of concrete through advanced materials like ECC.

Each document in the corpus acquired from Web of Science is associated with a specific publication year. This allowed for the time-based segmentation of the dataset, enabling an analysis of how topic distributions evolved. An LDA model was trained on the entire document corpus to identify the underlying topics. The model assigned a topic distribution to each document, indicating the proportion of each topic present. The corpus was divided into time intervals: before 1995, 1995–2004, 2005–2014, and 2015–2024 based on the publication year of each abstract. The topic distributions of the documents within that interval were computed to determine the influence of each topic during that period (Fig. 6b).

Table 3
Identified topics with their probability in the corpus and high-frequency words.

#	Topic name	Topic probability	High-frequency words
1	Structural performance	0.097	Performance, thermal, design, durability, pavement, construction, bridge, application, condition, structure
2	FT damage modeling	0.090	Model, damage, temperature, frost, degree, propose, pore, structure, process, predict
3	Mechanical properties	0.089	Strength, modulus, compressive, dynamic, loss, damage, relative, elastic, mass, rate
4	Aggregate effect	0.088	Aggregate, strength, recycle, waste, compressive, replacement, durability, natural, sand, coarse
5	Surface scaling	0.086	Surface, salt, scale, damage, absorption, treatment, frost, capillary, formation, expansion
6	Fiber reinforcement effect	0.083	Fiber, strength, compressive, flexural, durability, steel, mechanical, volume, rubber, performance
7	Porosity and microstructure	0.083	Pore, structure, microstructure, hydration, strength, scan, electron, SEM, porosity, foam
8	Curing effect	0.081	Strength, bond, temperature, cure, condition, degree, exposure, polymer, age, durability
9	SCMs effect	0.080	Ash, fly, strength, slag, durability, Portland, compressive, binder, silica, replacement
10	Coupling FT with other degradation processes	0.080	Chloride, corrosion, environment, sulfate, ion, salt, durability, attack, couple, structure
11	Air-entraining and air void systems	0.075	Air, void, pore, admixture, factor, frost, size, entrain, space, air-entraining
12	Cracking and internal damage	0.068	Load, crack, beam, failure, capacity, fracture, reinforce, stress, ECC, damage

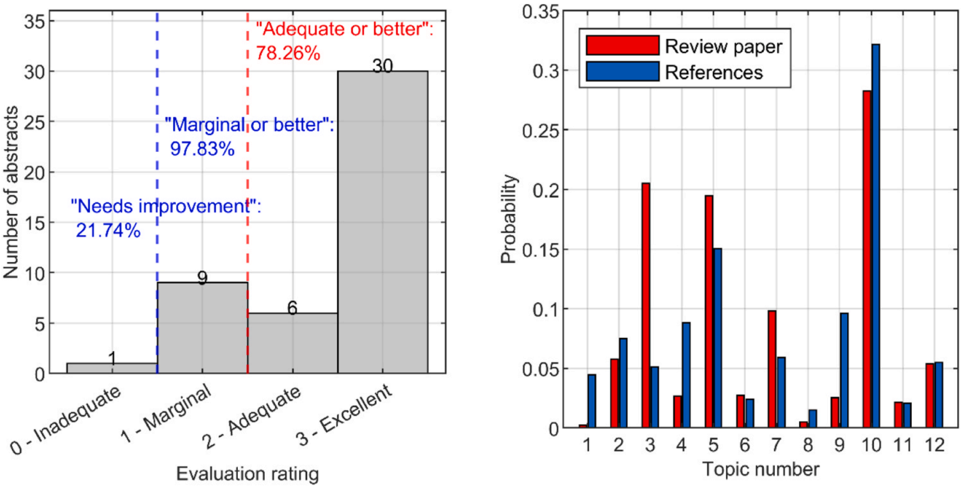


Fig. 4. Model validation results (a) manual verification, (b) review paper analysis.

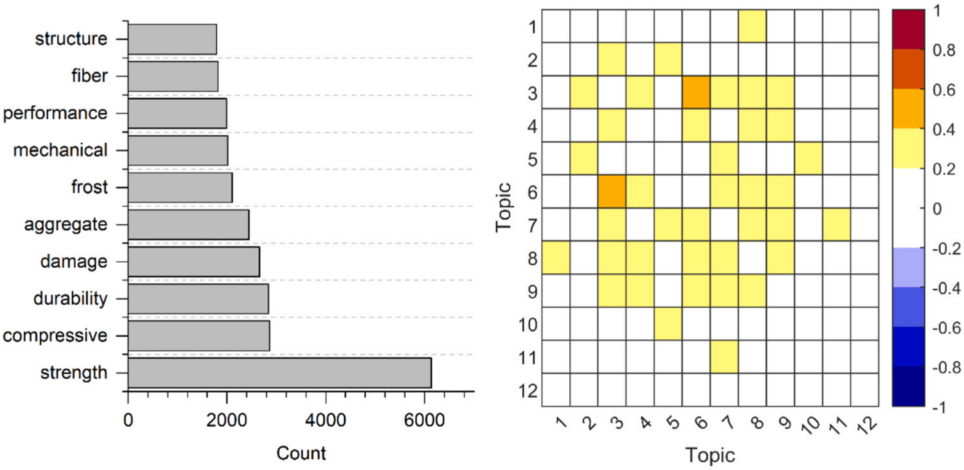
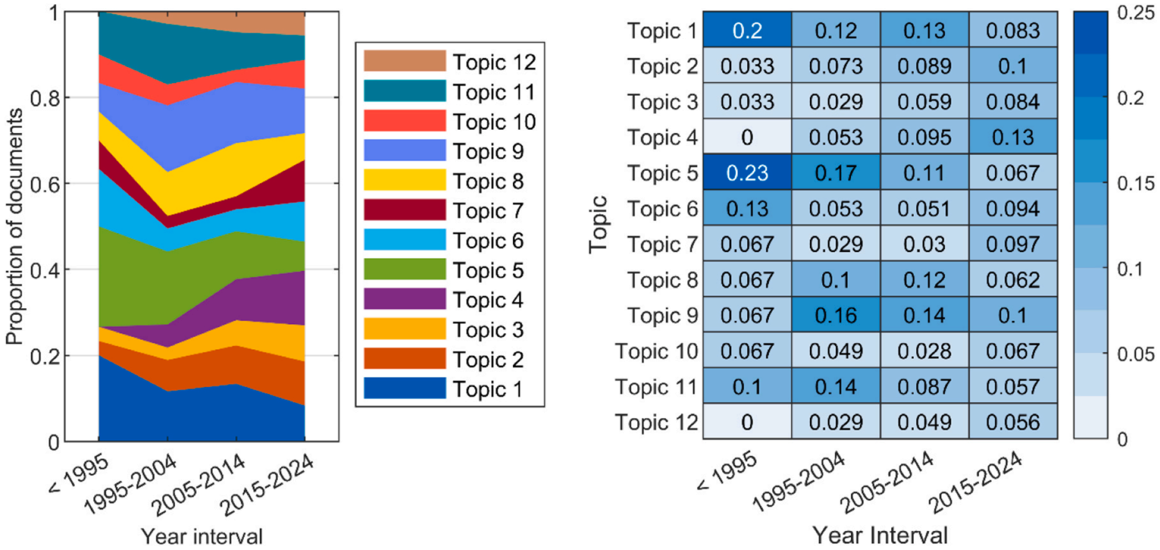


Fig. 5. (a) High-frequency unigrams, (b) Topic correlation matrix.

The time-based analysis revealed shifts in FT research focus over the past decades. In the early years, before 1995, research on structural performance (Topic 1) and surface scaling (Topic 5) dominated. However, the relative importance of these topics gradually decreased over time (Fig. 6ab). Conversely, the number of publications related to waste aggregate and SCMs increased (Topics 4 and 9). This trend highlights a growing awareness and prioritization of sustainable practices in concrete research. Certain topics, such as the “Fiber reinforcement effect” (Topic 6) and “Coupling FT with other degradation processes” (Topic 10), remained steady over time. This consistency indicates that these areas remain fundamental to the field. The analysis of topics revealed that research on air entrainment has been declining over the years, suggesting that substantial progress has already been made in this area. For instance, in Finland, although the initial use of air entrainment for frost resistance in the 1980s often failed, it has been relatively successful since the early 1990s [78]. Consequently, the research focus may shift towards exploring new methods and materials for ensuring concrete’s frost resistance.

Changes in research topics over time often correspond to external factors such as regulatory changes and global priority shifts. The overall increase in publications (Fig. 2a) reflects a transformation in scientific research practices, with a rise in the number of documents produced annually. In Europe, adopting the European Green Deal [79] in 2019 led to more studies focused on sustainable construction materials (Topics 4 and 9), reflecting a shift towards environmentally friendly building practices. Additionally, RILEM (International Union of Laboratories and Experts in Construction Materials, Systems, and Structures) has advanced FT durability research through committees such as TC-117 FDC (1990–1996), 176-IDC (1996–2004), TC 246-TDC (2011–2018), FTC (2018–2023) contributing testing methods like the CDF test [80] and CIF test [81]. The Eurocodes, particularly Eurocode 2 [82], have continuously influenced research on concrete durability and performance under FT conditions. First published between 2004 and 2006, Eurocode 2 includes guidelines on the design and durability of concrete structures, addressing various environmental conditions to ensure long-term performance and safety. Similarly, in recent years in the US, provisional specification AASHTO PP-84 was developed by the



Topic	< 1995	1995-2004	2005-2014	2015-2024
Topic 1	0.2	0.12	0.13	0.083
Topic 2	0.033	0.073	0.089	0.1
Topic 3	0.033	0.029	0.059	0.084
Topic 4	0	0.053	0.095	0.13
Topic 5	0.23	0.17	0.11	0.067
Topic 6	0.13	0.053	0.051	0.094
Topic 7	0.067	0.029	0.03	0.097
Topic 8	0.067	0.1	0.12	0.062
Topic 9	0.067	0.16	0.14	0.1
Topic 10	0.067	0.049	0.028	0.067
Topic 11	0.1	0.14	0.087	0.057
Topic 12	0	0.029	0.049	0.056

Fig. 6. (a) proportions of documents in each topic in time (b) the relative importance of each topic in time.

Federal Highway Administration (FHWA) and the American Association of State and Highway Transportation Officials (AASHTO), where FT is a dominating performance factor [83].

Visualizing the reduced dimensions with t-SNE (Fig. 7a) helps identify groups of documents that share similar topic distributions, revealing patterns that may not be immediately apparent in the high-dimensional space. Each point in Fig. 7a represents a single document, and the proximity of points reflects the similarity in their topic compositions. Each topic is assigned a color, and the top three corresponding keywords are listed next to it.

The t-SNE visualization reveals distinct point clouds, indicating that the data points are well-separated based on their features (Fig. 7a). In the center of the scatter plot, two topics are visible: Topic 7 (Porosity and microstructure) and Topic 10 (Coupling FT with other degradation processes), which suggests their close relationship with the other topics. A few topic clouds have overlapping points that may indicate interdisciplinary research areas or topics with shared characteristics, e.g., Topic 7 (Porosity and microstructure) or Topic 4 (Fiber reinforcement effect). Topics positioned farther apart on the t-SNE plot indicate less similarity, highlighting distinct research areas such as Topic 2 (FT damage modeling) and Topic 4 (Aggregate effect). This separation could suggest that research on the aggregate effect on FT performance has not yet progressed to the modeling phase.

The results of t-SNE were grouped into larger themes based on clustering results obtained using the K-means algorithm (Fig. 5c). The "elbow method" (e.g., [84]) was employed to determine the optimal number of clusters by plotting the inertia, representing the total squared distances from each sample to the nearest cluster center, against the number of clusters (Fig. 7b). The "elbow point" was defined as the point where the rate of decrease in inertia significantly slowed down. This analysis indicated that four clusters were optimal. The four themes identified based on the topics and keywords within each cluster (Fig. 7c) are discussed in the following section.

5. Cluster discussion

5.1. *Cluster 1: mechanical performance under FT (Topics 3, 6, 7, 8, 10, 12)*

The first cluster comprises articles primarily focused on mechanical performance under FT, encompassing topics 3, 6, 7, 8, and 12 (Fig. 8). FT cycles affect the mechanical properties of concrete, which are critical for its durability and longevity in various applications.

Concrete durability depends on the pre-FT mechanical properties. The evolution of material strength is influenced by hydration reaction kinetics, binder reactivity, and the curing regime (Topic 8), e.g., curing temperature and humidity [85]. The curing regime affects the FT durability more than the water-to-binder ratio [85]. The specimens that undergo dry curing exhibit approximately 24 % lower hydration levels before the onset of FT cycles, whereas the moist-cured specimens show about a 10 % reduction [86]. Lower temperature and humidity combined with a high water-to-binder ratio results in a larger volume of macropores and microcracks [85]. Capillary porosity is significantly decreased by CO_2 curing, hindering water access and surface scaling [87]. Slow refinement of porosity can also be achieved by internal curing using porous particles and aggregates, e.g., lightweight aggregate [88,89], Super absorbent polymers (SAP) [89,90], or prewetted calcined zeolite [91], leading to the improved FT resistance, especially in the mid and later cycles [91]. The reduction in air content, increase in the spacing factor, and decrease in specific surface area are observed when curing at higher temperatures [92]. The short curing time negatively affects the FT resistance of low-reactivity binder-blended concrete, e.g., with fly ash (FA) and slag (GGBS), due to strength reduction [93]. Early-age frost damage negatively affects the later

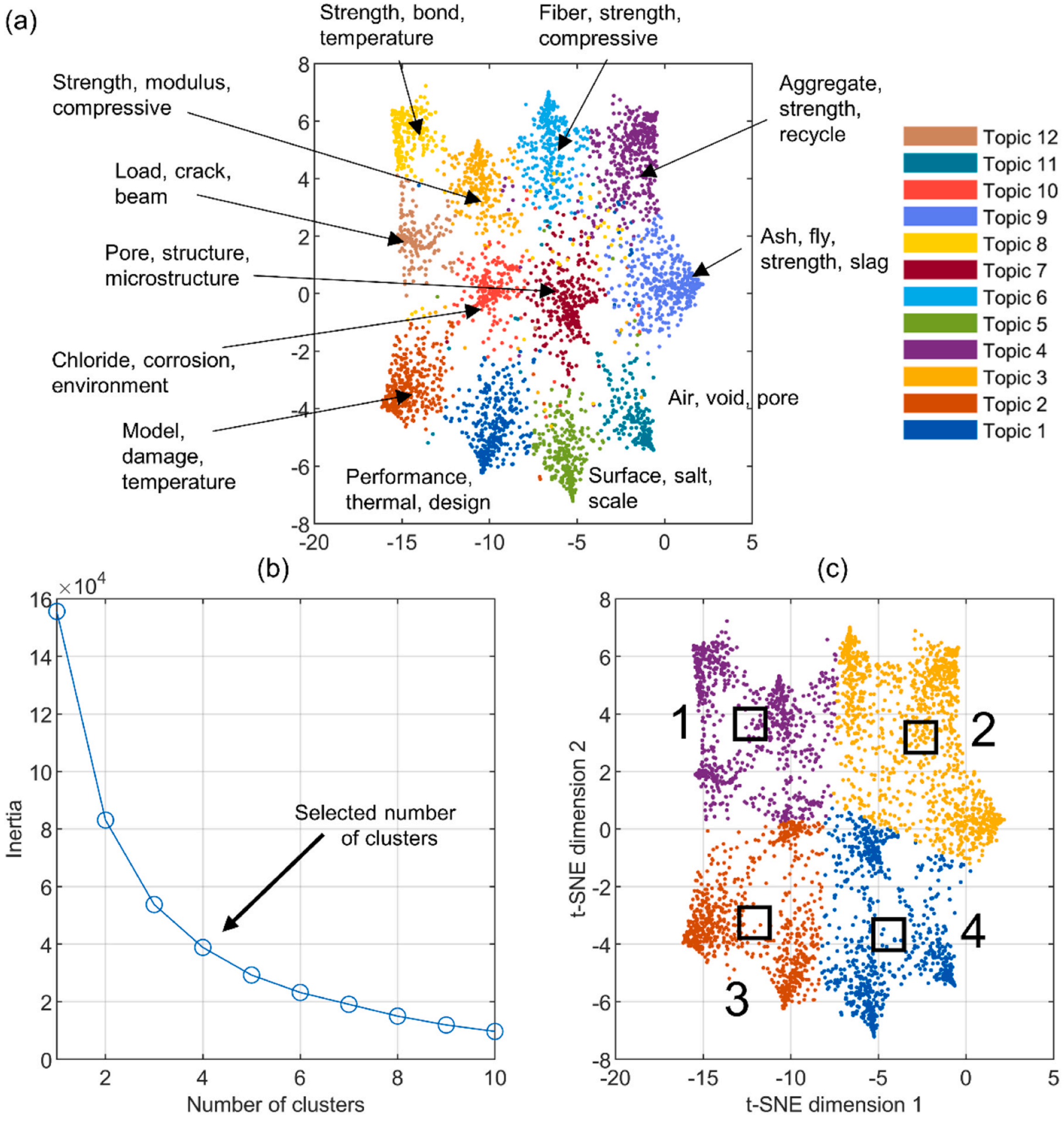


Fig. 7. (a) Results of t-SNE analysis: (b) Verification of the optimum number of clusters with the elbow method; (b) Four cluster visualizations with marked computed k-means centroids.

durability of concrete – the longer the pre-curing time, the better the FT resistance [94]. Later-age water curing after FT damage may facilitate partial damage restoration [95]. Air curing proves ineffective for both PC and blended concrete, having an even more detrimental effect on FA. Elevated temperature curing benefits the FA blend, but for PC, it hinders later-age mechanical performance [92]. Longer curing in freezing temperatures, e.g., −3 degrees, can equalize the strength, but FT resistance and service life are still shorter [96]. On the other hand, thermal curing in temperatures up to 60 degrees increases the early strength of GGBS blended concrete while having a negligibly negative effect on long-term FT durability [97]. For curing times of 28 days at 20°C, a more homogeneous microstructure and porosity are achieved compared to 5°C and 50°C. However, a double-sided effect is observed with more extended curing periods, e.g., 90 days. In the early stages of the FT process (before 50 cycles), the results are similar to those at 28 days. As the FT cycles increase, prolonged hydration evens out the pore distribution, and a curing temperature of 5°C provides better FT resistance than 20°C [98]. Steam curing provides a denser microstructure for FA-based alkali-activated materials than standard curing [99].

In general, as the number of FT cycles increases, the mechanical properties of concrete decrease [100]. Due to the damage characteristics caused by the FT mechanism, tensile strength in concrete is more significantly affected than compressive strength [101]. As FT cycles increase, the test results indicate a decrease in the relative dynamic modulus of elasticity, dynamic compressive

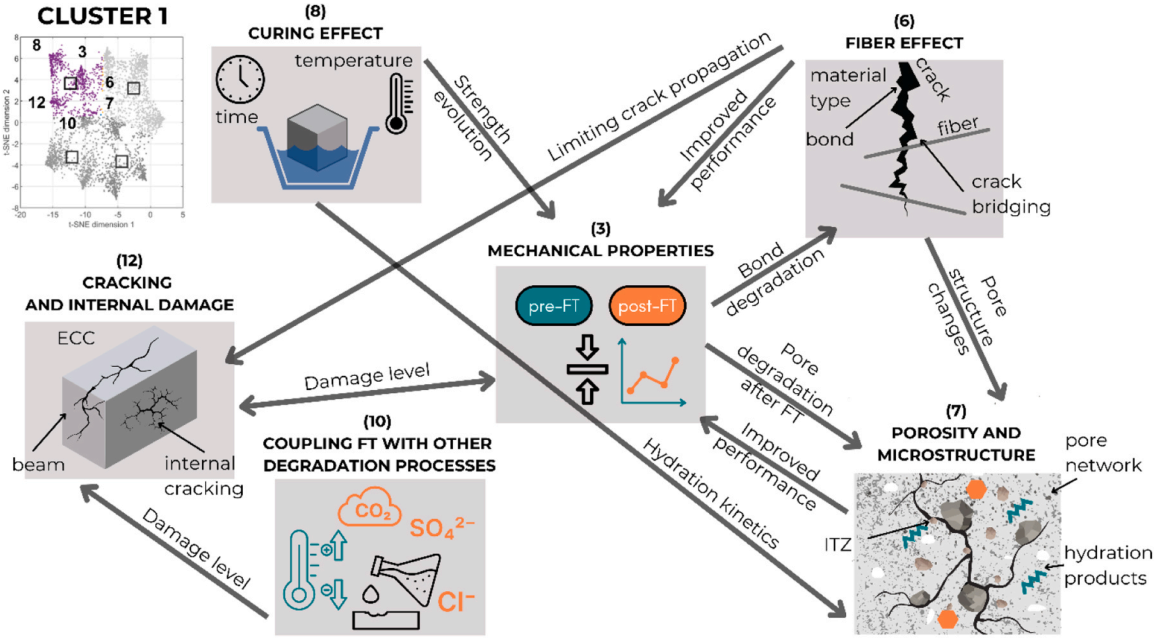


Fig. 8. Cluster 1 topic connections.

strength, flexural strength, and splitting tensile strength of concrete [102]. While ultimate stiffness remains relatively unchanged, the increased FT damage leads to a decrease in peak stress, initial stiffness, and reloading stiffness range, with peak strain gradually delayed [103]. FT damage, hydration, and strain rate influence concrete's dynamic compressive mechanical strength under FT. The changes in dynamic compressive strength involve an initial increase up to approximately 23 cycles, followed by a decrease later in the FT deterioration process [104]. Dual dynamics of compressive strength reduction are also observed in other studies. For instance, in the case of concrete exposed to FT and sulfate attack, slow reduction is followed by rapid reduction, in contrast to mass loss, which continually increases [105]. On the other hand, recycled concrete exhibits an initial decrease followed by an increase in mass loss, while the relative dynamic elastic modulus shows a consistent decline [106]. As the number of FT cycles increases, the porosity of ECC specimens increases due to the rise in micropores and mesopores, leading to a gradual decrease in both uniaxial tensile strength and uniaxial compressive strength [107] Under triaxial loads, the macroscopic fracture of concrete gradually propagates toward the direction of axial compression as FT cycles increase, transitioning from a single fracture to multiple fractures [108]. Distress features from the FT mechanism do not develop linearly with specimen damage. Initially, new cement paste cracks form in low FT cycles, which then spread to the ITZ and, at advanced stages, into aggregate particles [101].

Fibers can enhance concrete's FT durability and mechanical performance [1], [109]. However, FT cycles degrade the bond between

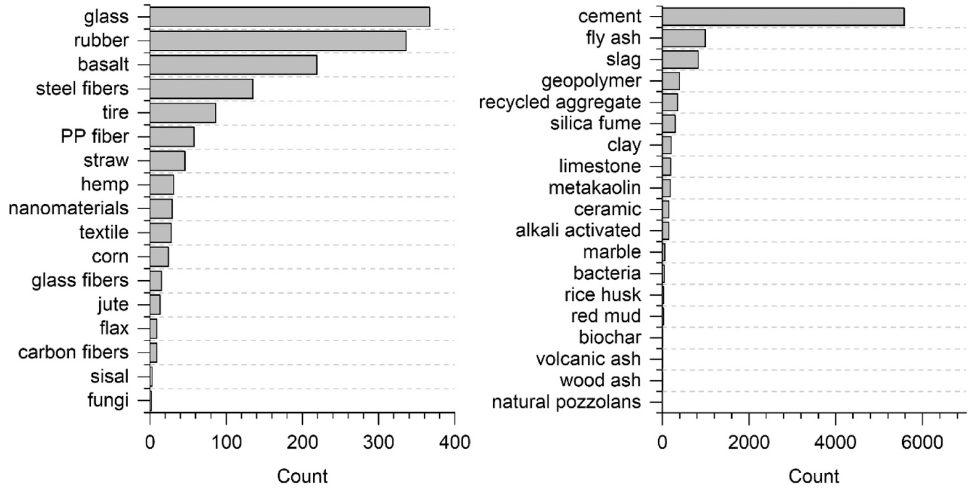


Fig. 9. Keyword count within the text corpus related to (a) Fibers, alternative aggregates, and other materials; (b) Binders and fillers.

fibers and the matrix, reducing deformability [110]. Improvement in FT resistance depends on the type of fiber material, its length, shape, and volume fraction or interaction between different fiber types. The analyzed abstract dataset was processed using a large number of specific keywords related to different fibers, aggregate types, binders, fillers, and other materials, such as nanomaterials (Fig. 9). Various potential fiber materials were identified, with glass, rubber, basalt, and steel being the most frequent in the literature (Fig. 9a). Concrete samples reinforced with carbon nanotubes exhibit superior dynamic mechanical properties and FT resistance compared to conventional plain concrete samples [111]. Jute fiber reinforced concrete shows higher mass loss due to jute fibers' water absorption but benefits from an enhanced toughness index that helps control void propagation during FT cycles [112]. The disturbance zone of the pore structure from textile reinforcement in concrete results in reduced FT durability [113]. Adding steel (ST) and polyvinyl alcohol (PVA) fibers enhances the flexural strength of lightweight concrete (LC) [114]. Increasing the basalt (BA) fiber ratio from 0.5 % to 1 % decreases compressive strength but increases flexural strength, with shorter fibers (5 mm) being slightly more effective than 10 mm [115]. Further research is needed on the ultra-low temperature FT properties of BA fibers [109].

The primary mechanism of fiber action involves limiting crack propagation and bridging macro cracks [115]. BA fibers mitigate macro crack formation in the matrix by impeding crack propagation and reducing crack speed through their bridging effect [115]. 3D, 4D, and 5D steel fibers limit the formation of micro and macro cracks in the material [116].

Combining different types of fibers in the hybrid composite is promising. Hybrid ST/BA fibers show the most strength improvement [109] and effectively prevent the formation and propagation of cracks during FT cycles [1]. Hybrid ST and polypropylene (PP) fibers improve compressive and splitting tensile strength before and after salt FT cycles but show little to no benefit and sometimes have a negative impact on the mass loss rate, dynamic modulus of elasticity, and chloride diffusion coefficient [117]. While 3D, 4D, and 5D steel fibers do not reduce mass loss after FT cycles, they improve mechanical properties, i.e., relative dynamic modulus of elasticity, residual compressive strength, residual flexural strength, and residual flexural toughness [116]. Different FRCs have optimal fiber dosages to resist both FT effects and salt erosion; For instance, in the case of ST, PP, and BA fibers, the optimal dosages are 2 %, 2 ‰, and 0.5 ‰, respectively [118]. The effectiveness of fiber also depends on the type of exposure applied. Increasing BA fiber content improves reactive powder concrete (RPC) mechanical properties and FT resistance, but chloride-salt FT cycles cause more damage than fresh-water cycles [119]. The mechanical properties of FRC are most affected by a 5 % sodium chloride solution, followed by a mixture of sodium sulfate and sodium chloride, sodium sulfate alone, water, and natural air in FT conditions [118].

5.2. Cluster 2: material composition and microstructure (Topics 4, 6, 7, 9)

The second cluster focuses on material composition and microstructure and their effects on FT performance. Cluster 2 includes studies on binders, aggregates, and fiber reinforcement (Fig. 10). PC is the primary binder in the studied text corpus, with nearly 6000 mentions (Fig. 9b). Following PC, GGBS and FA were the most applied SCMs (Fig. 9b). However, due to concerns over the decreasing availability of GGBS and FA [120], new types of binders, such as clay [121] and geopolymers [122], emerged. These new binders, including their durability and FT resistance, are currently the focus of ongoing studies. Despite this, as reflected in the keyword counts, they still constitute a minority of the research papers (Fig. 9b).

Concrete comprises binder, water, aggregates (such as sand and gravel), and admixtures, with each ingredient significantly influencing its overall durability and FT performance. The FT degradation mechanism is a well-known process for traditional concrete [123]. Natural and recycled aggregates each have distinct properties that affect their performance under FT cycles. Key factors include porosity, size, moisture content, and the quality of the interfacial transition zone (ITZ). With increasing FT cycles, the mechanical

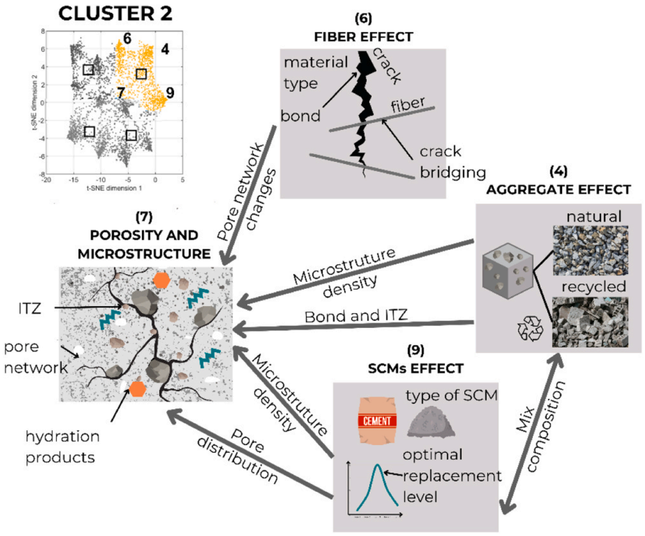


Fig. 10. Cluster 2 topic connections.

properties of recycled aggregate concrete (RAC) declined due to the proliferation of micro-cracks, resulting in a looser internal structure of the specimens [124]. Structural damage within the ITZ primarily causes the difference in FT capability between RAC and natural aggregate concrete (NAC) [100,125,126]. RAC shows better FT resistance and durability than NAC under the same FT attacks and cyclic mechanical loading in a salt solution since the ITZ deteriorates faster in NAC [127]. Adding nano silica and surface-modified BA fibers improves the FT durability of RAC [100]. The properties of RAC are significantly improved by the combined incorporation of 15 % GGBS and 15 % FA [128]. Increasing the rice husk ash (RHA) replacement ratio enhanced RAC's chloride penetration resistance more effectively than NAC [129]. RAC with silica fume (SF) showed significantly higher strength at the same number of cycles than RAC without SF [124]. Air-entrained RAC with 50 % aggregate replacement decreases the porosity of concrete, leading to optimal frost resistance [130]. Treatments and modifications such as pre-wetting and coatings of recycled aggregates can enhance the FT resistance of RAC [131]. For instance, carbonation, immersion in lime with carbonation, immersion in acetic acid, immersion in acetic acid with rubbing, and immersion in acetic acid with carbonation reduce mass loss by approximately 20 % due to improved porosity, a denser ITZ and fewer cracks [132]. CO_2 curing of recycled aggregate led to nearly 50 % less scaling and improved mechanical properties [133]. Internal curing by the moisture released from porous recycled aggregate [134,135] and calcined natural zeolite particles [91] enhances the FT resistance by supporting the cement's continued hydration. FT resistance in water and sulfate solutions is endured most effectively by concrete mixtures with 20 % and 50 % of recycled aggregate [136]. On the other hand, some studies show that FT resistance is more influenced by the water-cement ratio than by the aggregate type, with surface scaling being more severe in concrete containing fine recycled concrete aggregate [137]. The mixing method [138] and maximum aggregate diameter do not affect frost resistance [139].

The hydration products and microstructure of PC-concrete influence its FT durability by interacting with water during freezing. If added in optimum proportions, SCMs like GGBS, FA, SF, and natural pozzolans often contribute to a refined pore structure, reduced permeability, and enhanced chemical resistance. However, an increase in the content of GGBS harms the FT durability of concrete, particularly at higher dosages, when surface scaling is considered [140-142]. The opposite effect applies in the case of FT internal damage [140]. The effect of FA depends on its type and level of replacement. Air-entrained mortars with 20 % calcium-rich FA demonstrate better resistance to combined frost damage and sulfate corrosion, with the inclusion of air pores significantly enhancing this resistance. However, when 40 % FA is added without air entrainment, the FT durability is weaker [143]. Low-volume FA positively affects FT resistance combined with sulfate attack, contrary to high-volume FA [136]. On the other hand, carbonation treatment and carbonation curing of high-calcium FA reduced Portlandite content, improving the mechanical performance at FT and coupled FT-sulfate deterioration [144]. Despite similar air content between fresh PC and FA concrete, the FA concrete exhibited fewer microvoids (air voids smaller than 300 μm), a larger spacing factor, and a smaller specific surface area, regardless of curing conditions [92]. With NaCl FT cycles reaching 300, the reactive powder concrete with 10 % waste FA demonstrated a roughly 30 % reduction in mass loss rate, achieving optimal salt-freezing resistance due to more dense microstructure [145].

Combining several SCMs in a ternary binder mix is also explored in the context of FT. Compared to plain and binary concrete mixtures, ternary cementitious composites with FA and SF, up to 45 wt% total binder replacement, demonstrate higher frost resistance [146]. A mix comprising 75 % PC, 15 % FA, and 10 % SF effectively mitigates FT damage in concrete [142]. Research indicates that incorporating 30 % FA diminishes both early and final FT resistance, while adding 5 % SF adversely impacts FT resistance at later stages. [147].

Adding a small amount of filler to the mix, e.g., up to 10 %, can improve the FT resistance by densifying the concrete matrix. Incorporating 10 % SF and 1 % PVA fiber significantly reduces mass loss and improves aggregate spalling by decreasing portlandite content and reducing pore space [148]. Adding 10 % metakaolin increases the strength and durability of the samples after FT cycles by filling voids and promoting the formation of calcium-silicate-hydrate (C-S-H) gels in the matrix [1]. However, larger volumes of filler may lead to an opposite effect. Limestone replacement between 30 % and 50 % has a negative effect on FT resistance, significantly reducing hydration products and providing a loose matrix [98].

Recently, novel types of cementitious composites, including waste-derived ingredients and biomass-originating materials, have been studied. Sandstone waste as partial binder replacement in self-compacting concrete improves frost resistance, with microstructural images showing dense structure and strong bonding up to 15 wt%, and more voids and cracks appear above 15 wt% [149]. Increasing the RHA replacement ratio reduces cement paste compactness during FT cycles and significantly increases porosity and internal cracking in concrete [106]. Due to poor iron-ore-tailings-mortar adhesion, concrete surfaces experience increased scaling during FT cycles, highlighting the need to limit tailings content to 20 % [150]. Vegetal concrete with a magnesium phosphate cement (MPC) binder containing high percentages of red mud and FA, mixed with corn stalk-based vegetal aggregates, exhibits no cracking upon FT cycles but reduced compressive strength and increased mass loss [151]. Few studies exist on biochar cementitious materials. While 5 % municipal solid waste biochar does not impact FT resistance, it promotes carbonation. However, 10 % biochar replacement enhances frost resistance by creating more independent macro pores, reducing pore spacing, and providing a larger area for frozen water [152].

The water-binder ratio, followed by SF and ST fiber, are the most important mix composition factors for the FT resistance of UHPC [153]. Reducing the water-binder ratio in UHPC enhances its FT resistance by decreasing average pore size and cumulative pore volume. A small change of 0.05 in w/c leads to over 20 % improvement in compressive strength reduction. [153].

The optimal ratios of nanoparticles for concretes modified with nano-SiO_2 (NS) and nano-TiO_2 are 1 % and 2 %, respectively, with NS demonstrating superior behavior and contributing to a denser microstructure [154]. Concrete with 2 % NS exhibits enhanced performance following 200 FT cycles, outperforming untreated concrete after only 100 cycles [155]. Similarly, the addition of microbeads improved the ITZ, mechanical performance, and frost resistance of expanded polystyrene (EPS) concrete by up to 400 % [156].

Recent studies on FT resistance have highlighted the potential of geopolymers and alkali-activated materials as alternatives to traditional concrete. Improved FT resistance of geopolymer foam concrete results from the densification of the matrix due to the incorporation of graphene oxide [100]. Properly adjusting the content of GGBS and the alkali activator modulus can improve the FT resistance by more than double [157]. Compatibility in the ITZ between fibers, paste, and recycled fines enhances the FT durability of ultra-high-performance geopolymer concrete [158]. Adding up to 1 % nano-silica (NS) positively impacts the compressive strength and FT resistance of alkali-activated concrete, though the improvement is modest, yielding only a 1–2 % enhancement in compressive strength reduction [159]. Ternary system geopolymers, replacing GGBS and FA with RHA, strengthen FT resistance due to synergistic effects, leading to a denser microstructure [158]. Using up to 10 % crumb rubber as fine aggregates in FA/GGBS-based geopolymer concrete leads to higher relative dynamic elasticity modulus and lower mass loss. Despite weaker bonding with geopolymer, crumb rubber reduces internal cracks and porosity compared to river sand due to its superior energy absorption performance [160]. Nevertheless, some studies indicate that the FT resistance of geopolymers can be worse under certain conditions, underscoring the need for further research and testing. For instance, while higher GGBS content improves the durability properties of alkali-activated concrete, its performance against chloride and FT is not as good as that of PC concrete [161].

5.3. *Cluster 3: FT durability and structural integrity (Topics 1, 2, and 10)*

The third cluster of papers addresses FT durability and structural integrity, examining the interactions between various degradation mechanisms and degradation models (Fig. 11a). These studies are particularly relevant to applications in structures such as road pavements and bridges. Frost, along with wet conditions and exposure to deicing salt, commonly affects curbs, safety barriers, submerged vertical elements like pillars, and hydraulic structures such as dams. [162].

FT exposure, combined with other physical and chemical processes, such as sulfates, chlorides, or carbonation, decreases concrete service life [163]. FT-related corrosion of reinforcing steel is a critical factor impacting the service life of a bridge deck [164,165]. The type of structural element also influences the extent of damage. For instance, wet, epoxied, and dry construction joints determine concrete's resistance to carbonation, chloride ions, and FT damage from standing water [166,167]. Structures with reduced durability often demand additional maintenance to attain their expected service life, resulting in higher costs and increased material usage over their operational period, increasing the carbon footprint. Extending the service life of concrete structures by 50 % can cut CO_2 emissions from concrete production by 14 % [168,169]. Some studies establish a proportional relationship between concrete's service life under rapid laboratory FT cycles and natural conditions, providing a basis for designing frost-resistant concrete [170,171].

The Eurocode 1992 [82] includes standards for the design of concrete structures, e.g., specific guidelines for durability under different environmental conditions – exposure resistance classes (ERC). Selecting concrete to resist deterioration and corrosion for relevant ERC should follow the EN 206 standard [172] and local regulations. Classes XF1 to XF4 categorize the severity of FT depending on the water saturation and presence of de-icing salts [82,172]. The requirements for ERC must cover permitted constituent types and classes, maximum water/cement ratio, minimum cement content, minimum compressive strength class, and, in the case of FT, minimum air content. These criteria can be determined using performance-based methods, such as the FT scaling test [173], and

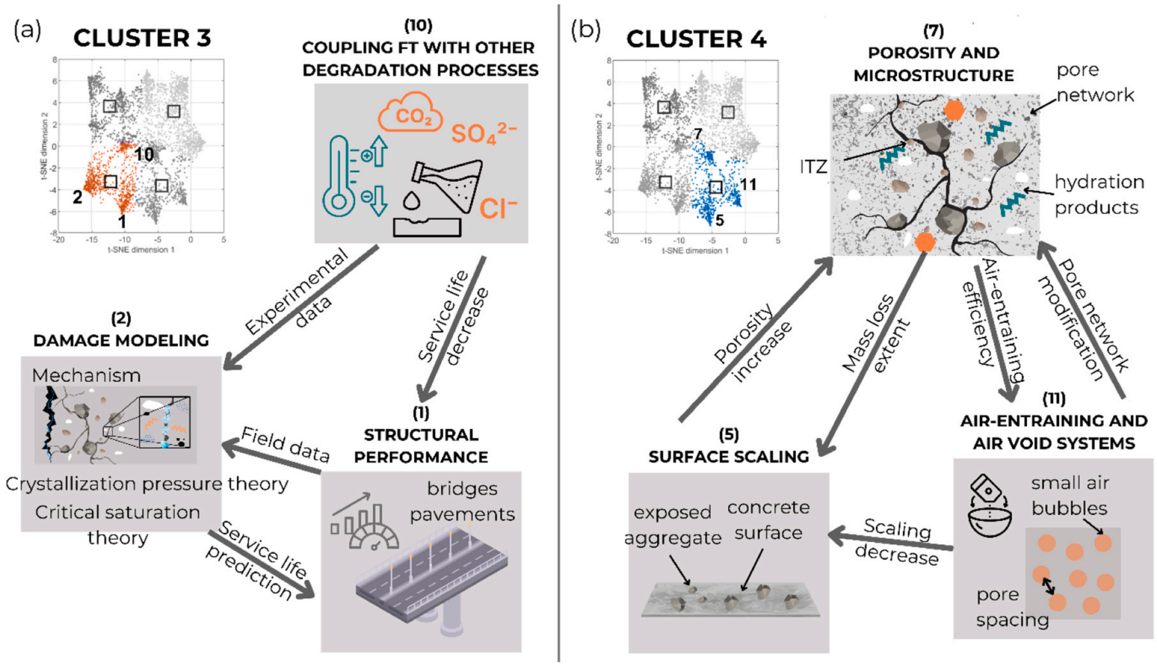


Fig. 11. (a) Cluster 3 topic connections; (b) Cluster 4 topic connections.

must align with local standards, assuming a design life of at least 50 years under expected maintenance [172]. Nevertheless, combined degradation processes, i.e., FT with sulfate attack or ASR, pose significant challenges. Performance-based specifications require more research to understand deterioration mechanisms, adapt testing procedures, and identify durability indicators [173]. A comprehensive summary of testing methods and requirements in different countries and regions can be found in [174]

Numerous experimental studies have investigated the combined effects of FT cycles and other exposures [143]. Methodologies include accelerated aging tests and multi-factorial experiments. The FT damage can be exacerbated when FT cycles are combined with other degradation processes, such as chemical attacks and mechanical loads [175], affecting the load-bearing capacity of concrete. Flexural loads applied externally accelerated the deterioration of concrete performance during FT cycles, although they have minimal impact on the weight loss of the concrete [175]. With higher compressive stress levels and more repetitive loading cycles, the compressive strength losses due to FT cycles for both RAC and NAC concrete increase [127].

There is no consensus regarding the interaction between sulfates and FT cycles, as some studies report positive while others have adverse effects. The deterioration process in concrete is worsened as sulfate attack and FT cycles mutually influence each other [105,136,176]. Freezing temperatures slow down sulfate ion diffusion in concrete [176], yet sulfate attack speeds up microcrack formation, magnifying damage [150,176]. On the other hand, a predominantly positive effect of sulfate attack on FT cycles was demonstrated in another study [136]. Some results show that before 100 FT cycles, specimens in water experience more considerable deterioration than those in sulfate solutions; however, after 200 cycles, 5 % sodium sulfate solution causes more damage [105]. Similarly, early damage is less significant in sulfate solution compared to water; however, it increases in later stages [176]. Initial frost damage in non-air-entrained composites with 40 % FA reduces their resistance to sulfate solution effects [143]. Magnesium sulfate salts cause the most excessive damage [176].

The carbonation of the binder influences the extent of FT surface scaling, which suggests that revised accelerated testing procedures to simulate field conditions are crucial [177]. For instance, due to decreased permeability from CO_2 curing, which enhances strength and reduces pore space for ice crystallization, surface scaling in PC and 20 wt% FA concrete is decreased significantly after 150 FT cycles [87,178].

FT cycles can accelerate the ingress of chlorides into concrete, leading to the corrosion of embedded steel reinforcement. Studies have demonstrated the synergistic effect of FT cycles and chloride-induced corrosion, which can compromise structural integrity. Plain concrete experiences severe surface scaling and more significant weight loss in a 3.5 % NaCl solution, enduring 20 % more cycles than in water [175]. Seawater and FT exhibit different mechanisms, negatively affecting mechanical parameters for non-air-entrained concrete [179-181].

ASR can partially restore the deteriorated mechanical properties caused by FT cycles [182]. ASR gel around coarse aggregates can enter FT-induced cracks but only fills a small area. Early-stage concrete damage occurs in low ion concentration environments, as insufficient ionic crystallization fails to fill cracks and pores, while FT cycles extend cracks and loosen the structure [183].

Since physical testing is time-consuming and resource-intensive, modeling approaches are essential for understanding and predicting the interactions between various degradation processes in concrete. Early theories on FT degradation of concrete include several analytical models: hydraulic pressure theory [184,185], osmotic pressure theory [186], critical saturation theory [187,188], and crystallization pressure theory [189]. Numerical modeling approaches, such as the finite element method (FEM) and the discrete element method (DEM), have been applied to study FT cycles. FEM uses the physical and mechanical properties of concrete to simulate FT cycles, predicting stress, strain, and damage distribution [139,190-193]. DEM, on the other hand, models the behavior of individual particles within the concrete, focusing on micro-mechanical interactions and damage mechanisms during FT [194-197]. Different types of concrete are analyzed, such as pervious concrete [194,196], FA concrete [198], self-compacting concrete [197], aeolian sand concrete [199], seawater sea-sand concrete [181], sandstone–concrete [195], FRC [200], RAC [201], graphene oxide concrete [202]. The models consider various parameters related to the concrete mix, e.g., water-cement ratio, different aggregate diameter [139], air content, and curing time [203], degree of saturation inside concrete [204]. Multi-scale modeling combines micro-scale (pore level) and macro-scale (structural level) changes to capture FT effects more accurately. Relationships between micro/meso properties and FT damage have been established, such as the fractal dimension of pores [205], micro defects [206], ITZ characteristics [207], detailed microstructure interactions between air voids, ITZ, and aggregates [193]. Using computational homogenization methods, these relationships help estimate effective material properties [208].

Recent advancements in artificial intelligence (AI) and ML have impacted the study of FT cycles in concrete. These technologies enable the modeling of FT concrete degradation, e.g., by prediction of the relative dynamic modulus [209-211] or F-T damage indicator [212], offering a deeper understanding of microstructural changes and facilitating optimal material design based on concrete ingredients [6]. Key factors identified in modeling are cement content, coarse and fine aggregate content, superplasticizer, and FA content [6], initial strength of concrete, air entrainment [213], water-to-binder ratio [6,213] or adding rubber particles [214].

The models employed, such as artificial neural network (ANN) [210,213,214], support vector machine regression (SVR) [210,213,214], and extreme learning machine (ELM) [210], random forests (RF) [213,214], XGBoost, and Stacking [214], demonstrate strong correlations with available measurement results. However, the relatively small amount of available empirical data limits the broader application of these models [6,211]. Combining FEM with ML may compensate for the lack of experimental data. For instance, multiscale numerical simulations have generated a large dataset containing 8096 data points of FT cycles, facilitating an interpretable analysis of concrete incorporating phase change materials via ANN [215].

5.4. Cluster 4: surface scaling and air-entrained pore network (Topics 5, 7, and 11)

Cluster 4 captures the focus on surface scaling, the role of air entrainment, and the analysis of pore networks in concrete, emphasizing their impact on durability and resistance to conditions like frost and salt exposure (Fig. 11b).

The pore network structure is a critical factor for the FT performance of concrete, with deterioration processes accelerated by the distribution characteristics and pore structure [86,216]. Two types of pore networks can be considered: the inherent and the air-entrained pore network.

The inherent pore network in concrete consists of irregularly shaped and sized pores formed during the hydration process and ITZ between the binder matrix and aggregate, depending on the mix composition. For instance, FA reduces the number of smaller air voids, leading to an increased presence of larger air voids in the concrete [146]. Establishing an adequate air-void system is essential for the FT resistance of ternary blended concrete [146]. ITZ is identified as a weak point in both RAC and NAC according to microhardness and SEM characterization results [127]. The flexural strength of RAC is significantly influenced by the total proportion of mesopores and macropores, showing higher strength when this proportion ranged between 55 % and 74 % [130]. The inclusion of fibers affects the pore structure, which can influence the overall durability and performance of the RAC. Hybrid ST and PP fibers decrease overall air-void content and improve spacing in concrete but increase the number and surface area of air voids significantly. They also alter the shape of air voids, making them simpler and rounder, though larger voids show more complex tortuosity [117]. Based on the modeling results, refining pores to transform larger voids into smaller, evenly distributed air voids can enhance concrete's resistance to frost [52].

The inherent pore network structure can be altered using chemical admixtures, leading to an air-entrained pore network. Air-entraining agents (AEAs) create uniformly distributed, small air bubbles that help relieve internal pressure during freezing. Air entrainment improves FT durability by creating larger pores that serve as expansion chambers for water during freezing, reducing stress and potential damage [217]. A comprehensive review of AEAs and existing research gaps can be found in [54,218]. AEAs were discovered accidentally in the 1930s when it was noticed that concrete made with cement from certain plants showed better FT durability than others, thanks to finely dispersed air bubbles introduced by specific grinding aids during clinker milling [219]. AEAs typically introduce approximately 16–25 % by cement paste volume or around 4–10 % by volume of concrete as entrained air [219,220]. Adding AEAs to concrete significantly alters both porosity and pore structure, including increased pore size and shape factor [221], affecting the mechanical properties pre- and post-FT [130]. Having similar air content does not guarantee identical air void structures; other parameters, such as spacing factor, are crucial in making concrete structures less vulnerable to FT damage [54,92,222]. Concrete's air-void system (AVS) parameters include total air void volume, size distribution, specific surface area, and spacing factor—the distance from any point in the cement paste to the nearest air void boundary [54].

In the case of waste-derived binders, the compatibility of the AEAs is under investigation. For instance, interactions between FA materials from biomass and coal combustion and AEAs have been observed, resulting in reduced effectiveness of AEAs [223] and increased AEA requirements [224]. A high Loss of Ignition (LOI) of the binder can compromise the effectiveness of AEAs [225,226]. Air entrainment and the quality of the parent concrete are crucial when using recycled concrete aggregate. RAC from high-strength or air-entrained concrete shows high FT resistance and durability comparable to conventional air-entrained concrete. In contrast, RAC from non-air-entrained concrete exhibits poor frost resistance. In RAC originating from non-air-entrained concrete, FT cycling damages the adhering mortar early, leading to ITZ cracks and FT failure [138]. On the other hand, previous ASR damage decreases the frost resistance of concrete, regardless of whether air entrainment is present.

While the pre-FT pore network influences FT degradation, the FT process simultaneously causes pore deterioration, reducing strength and resistance to chloride penetration (Zhang et al.). As the number of FT cycles increases, void propagation increases [102,221], and a significant number of micro and macropores form in the matrix [102,107,115]. For high-strength concrete, initially, FT cycles reduce porosity, which later recovers over time [221]. However, if hydration is not sufficiently developed, the pore sizes and porosity are larger before FT [86]. FT cycles impact not only the overall porosity but also the pore size distribution. Alterations in pore size distribution, rather than changes in pore volume, cause concrete damage at the microscale [205]. Microcracks and macropores increase while micro and mesopores decrease [85]. When sodium sulfate solution was applied, gel micro-pore (<10 nm) proportions decreased with FT cycles in FRCs, while capillary (10–5000 nm) and macro-pore (>5000 nm) proportions increased [107]. In concretes modified with nano-TiO_2 and NS nanoparticles, gel micro-pores (<10 nm) increase and macro-pores (>5000 nm) decrease during the first 90 FT cycles, but this trend reverses between 90 and 150 cycles [154].

The air-entrained pore network mitigates FT deterioration. Two processes are observed: surface scaling and internal damage, with different mechanisms. Surface scaling is driven by capillary suction in the surface layer during freezing, while internal frost damage depends on the overall pore saturation influenced by bulk moisture uptake [227]. Although salt scaling alone does not render a structure unusable, it facilitates the accelerated ingress of aggressive species like chlorides and increases the likelihood of high saturation [228]. As a result, salt scaling has become a significant durability issue for cementitious materials in cold climates, where salts are commonly used to de-ice roadways and walkways [228].

The mechanism of surface scaling has been investigated by many researchers [87,113,228-231]. The level of damage is assessed by measuring the mass of particles that have detached from the surface [232]. The primary factor contributing to scaling during FT cycles is moisture in the pores, which is exacerbated by salt solutions [233]. Chloride-based deicing salts like NaCl, $CaCl_2$, and $MgCl_2$ are commonly used on concrete pavements in cold regions to melt snow and ice, enhancing safety for drivers and pedestrians [234-238]. Scaling in water and de-icing salt solutions lacks a universal explanation, as different mechanisms may apply, and scaling can occur without surface ice [162]. Exposure to chloride-based deicers results in the formation of mineral phases like calcium oxychloride, leading to significant leaching of portlandite, a 23 % increase in hydrate porosity, and subsequent microstructural damage [236].

Other important factors include sorptivity and the counterbalancing effects of salt ions, which influence the movement and distribution of water within the pores and the available salt solution in contact with the surface [233]. The amount of water frozen in the pores depends on temperature, the radius of the capillary, and the salt concentration in the pore solution [239,240]. Both inner and outer salt concentrations are essential due to the effect on ice growth [233,241,242].

6. Research outlook

6.1. Environmentally friendly materials (Clusters 1 and 2)

Recognizing the growing need for sustainable construction practices, future research within Cluster 1 and 2 should focus on developing environmentally friendly materials. New concrete binders, e.g., specific blends of SCMs, show promise for improving FT durability, but the existing results are scattered and inconsistent [243]. Therefore, there is a pressing need to develop more robust and reliable methodologies. While higher GGBS content improves the durability properties of alkali-activated concrete, its performance against chloride and FT is not as good as that of PC concrete [161]. Understanding the curing and experimental conditions is crucial before FT tests (with or without deicing salts) can be widely applied, as these factors significantly influence the results when testing alkali-activated concretes [243]. Moreover, the effect of carbonation on FT durability remains an area requiring further investigation. Early-age carbonation is generally more pronounced in concretes with SCM-rich binders [243,244]

The effects of entraining admixtures are well understood for traditional PC-based concrete. However, these admixtures are often incompatible with new binders, such as those incorporating ashes. To ensure their reliability, studying the impact of air-entraining admixtures and their interaction with different binders is essential. Additionally, producing current admixtures leads to high carbon emissions when used in larger quantities. Therefore, it is important to investigate new admixtures that can reduce these emissions.

6.2. Enhanced FT durability (Cluster 3)

Cluster 3 deals with the critical role of FT durability and its impact on the structural performance of concrete. Recognizing this, future research should focus on studying innovative materials with improved FT resistance since this path did not prominently appear in the topic analysis. For instance, nanomaterials can potentially improve concrete's durability and mechanical properties under FT conditions. Protective measures, such as coatings, sealants, and surface treatments, can enhance concrete's resistance to combined FT and chemical/mechanical degradation. For instance, a hydrophobic coating based on mica powder, which is treated with a silane coupling agent and polydimethylsiloxane, improves FT resistance by providing a hydrophobic functional group and enhancing the pore network [245]. Silane hydrophobic coatings reduce surface scaling by over 90 % in high water-to-binder ratio concrete but cannot stop overall moisture absorption during FT exposure, leading to internal damage [227].

A novel avenue in Cluster 3 is investigating self-healing concrete technologies for mitigating FT damage. Both autogenous and autonomous methods may be employed. Using a bacterial agent, chloride penetration is reduced by 46 %, and concrete scaling decreases by 90 % [229]. Although FT cycles with water and deicing salts can deteriorate ECC properties, the material exhibits greater self-healing in water FT cycles compared to those with deicing salts [246]. Adding crystalline admixture in UHPC leads to efficient healing of cracked concrete under FT conditions [247]. Further research is needed to assess the reliability of these self-healing processes under FT field conditions.

Despite being included in the topics (Cluster 3, topic 2), modeling remains a critical study area. Performance-based models are required to accurately forecast concrete longevity in cold environments, utilizing inputs from material composition, mixture proportions, and quality control tests [83]. Advanced computational models are needed to predict the effects of FT cycles on concrete at both macro and micro scales. Utilizing extensive data generated over past decades, constructing a comprehensive database, and applying machine learning to develop AI models can provide impactful results.

6.3. Accelerated testing methods vs field conditions (Cluster 4)

Building on the insights from Cluster 4, which emphasizes FT surface scaling and air entrainment, it is recommended that future research focuses on bridging the gap between accelerated laboratory testing methods and actual field conditions. Frost damage is primarily investigated in laboratories using accelerated FT cycles despite the lack of a clear correlation between these cycles and those occurring under natural environmental conditions [248]. The standardized accelerated testing protocols are designed to simulate FT conditions within a short time, enabling the assessment of concrete durability over several years in a matter of weeks. Although crucial, testing did not emerge as a significant topic in the modeling analysis in Section 4.

Different accelerated tests exist, e.g., CDF-test [80], CIF-test [249], Slab test [250], varying sample size, curing, and cycle length, leading to lengthy procedures and scattered results across labs. In February 2024, the American standard ASTM C666/C666M was withdrawn due to negative feedback, and it is currently under revision. In Sweden, the standard SIS-CEN/TS 12390–9:2016 includes an annex from 2021 that extends curing to up to 90 days for binders with cement replacements over 35 %. Given the geographical diversity in FT research (Fig. 2b), with a majority from China based on local standards, whether these can be applied to the US and European climates remains questionable. Long-term structural performance under FT cycles and the cumulative effects of prolonged FT cycles on concrete structures should be investigated. Furthermore, exploring new technologies such as self-sensing concrete [251] for real-time damage assessment during FT cycles could be a future path.

Accelerated lab tests often fail to accurately reflect real-world conditions [252]. They tend to be too conservative, yielding poor results for new binder types. For example, natural FT cycles that cross the 0°C threshold twice daily occur five times less frequently than in standardized 24-hour tests [253]. ASTM C666 samples undergo about 4 FT cycles per day, significantly faster than the 1–0.4 cycles per day typically encountered during winter, and they remain constantly surrounded by moisture [254,255]. Instead of the standard 40°C temperature change (+20/-20°C), typical field thermal fluctuations are around 15°C (+10/-5°C or +5/-10°C), which only aligns with climatic conditions in Nordic regions [253]. Both the condition of the exposed surface and its carbonation should be considered when evaluating differences between field and laboratory conditions [252].

Changes in porosity and phase assemblage in composite types of cement, such as limestone ternary blends, due to carbonation and leaching contribute to their susceptibility to FT damage [256]. Concrete with SCMs, such as GGBS or limestone, and without air entrainment shows poor performance in laboratory tests but performs better in real-world conditions [256]. To evaluate the FT resistance of new binder materials, unified methodologies, supported by more round-robin tests, are needed.

Future research should study how changing climatic conditions affect the frequency and severity of FT cycles in different geographical regions and their impact on concrete structures. A recent study that analyzed the air temperature from 1981 to 2020 in Minnesota, US, has shown that climate change has altered the frequency and intensity of FT events [257]. There has been a reduction in FT events during late fall (November) and spring (April and May). The consequences of these changes on structural elements' performance should be verified. Additionally, it is crucial to investigate how pollutants and environmental contaminants interact with FT cycles to affect concrete durability.

7. Conclusions

This paper presented the analysis of trends in research on the FT durability of concrete. The topic modeling using NLP techniques was used to study a large text corpus, including over 3700 abstracts from almost four decades. The key innovation of this research lies in the systematic application of semi-automatic NLP topic modeling to categorize underlying research themes, providing a structured framework for understanding current trends and identifying gaps within a large body of text. This study's findings offer insights for researchers and industry practitioners dealing with the FT durability of concrete. By identifying and clustering key research themes, the study provides a roadmap for addressing current challenges and exploring new opportunities within the field.

The following conclusions can be drawn from this study:

- The paper shows the usefulness of NLP and t-SNE in the semi-automated interpretation of large amounts of technical text data to review the current state of the art in a scientific field. The methodology is accessible and facilitates the interpretation of data to narrow down the research focus in case a vast number of papers are available. It can potentially be used in other research areas related to cementitious materials. Its usefulness is fundamental in the current era, where the number of papers produced annually has drastically increased.
- Topic modeling using LDA included 12 topics, revealing several dominant themes related to FT research, such as mechanical properties, material composition (aggregates, SCMs, fibers), air entrainment effects, and pore and microstructure. The model showed accuracy close to 80 % in recognizing the dominant topic in a paper.
- A shift in topic fractions within the documents was observed over the past four decades. Initially, structural performance and surface scaling dominated the studies, whereas, in the past 10 years, new topics have emerged, such as cracking and internal damage in ECC, the effect of aggregates, including recycled aggregates, and FT of blended binders with SCMs.
- t-SNE analysis combined with K-means clustering revealed distinct groups of documents corresponding to each topic, identifying four main clusters: concrete mechanical performance under FT, material composition and microstructure, FT durability and structural integrity, and surface scaling and air-entrained pore network.
- Three future research paths were suggested: FT durability of environmentally friendly materials, the relationship between accelerated testing and field conditions, and studying materials with enhanced FT durability.

The practical implications derived from this analysis:

- The emphasis on material composition and microstructure underlines the need to develop concrete mixes incorporating SCMs and recycled aggregates for the cold climate. This can lead to more sustainable and durable concrete, reducing environmental impact while enhancing performance in FT conditions.
- The cluster on FT durability and structural integrity highlights the necessity for advanced testing methods that more accurately simulate real-world FT cycles. Implementing region-specific protocols, considering factors such as asymmetric temperature profiles and variable freeze-thaw durations, can improve the reliability of durability assessments. This can ensure concrete structures perform optimally across diverse climatic regions like Europe and China.

Despite the usefulness of the NLP-based review method, the study has several limitations:

- Since only abstracts were analyzed, some detailed information may have been overlooked. Analyzing full-text documents could be a viable option; however, this would significantly increase computational time and require more extensive preprocessing due to redundant elements, e.g., acknowledgments, references, figures, and table descriptions. Updating acquired data with results from other search databases such as Scopus or Google Scholar could increase the comprehensiveness of the text corpus.
- The number of topics chosen in the LDA model is somewhat arbitrary and may not fully capture the underlying thematic structure of the corpus. Additionally, topic naming relies on expert knowledge, making the approach only semi-automatic. Perplexity, which was used as a method for topic number selection, could be updated with other parameters to asses interpretability and topic coherence, such as pointwise mutual information or rank biased overlap for the topic stability measurement [23].

- Dimensionality reduction using t-SNE has several limitations. It cannot guarantee that the cost function will reach a global optimum; its mainly local behavior makes it prone to intrinsic dimensionality challenges, and its performance in standard dimensionality reduction tasks is still ambiguous [76]. Alternative methods could be considered and compared.
- MATLAB Text Analytics Toolbox, used in this study, has limited functionality compared to the Python environment. However, Python requires more advanced programming skills. Despite this, Python could be a viable option for expanding the analysis, utilizing libraries such as NLTK, SpaCy, Gensim, TOMOTOPY toolkit for NLP, and Scikit-learn for t-SNE. It offers other methods like sentiment analysis, text classification, or named entity recognition.

CRediT authorship contribution statement

Adeolu Adediran: Writing – review & editing, Validation, Resources, Investigation, Conceptualization. **Priyadharshini Perumal:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Ólafur Haralds Wallevik:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Andrzej Cwirzen:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Magdalena Rajczakowska:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Iveta Novakova:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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